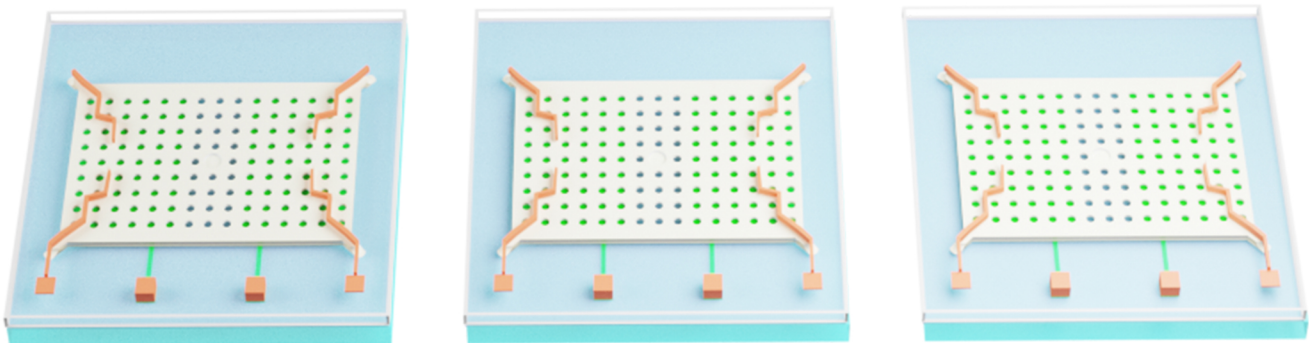
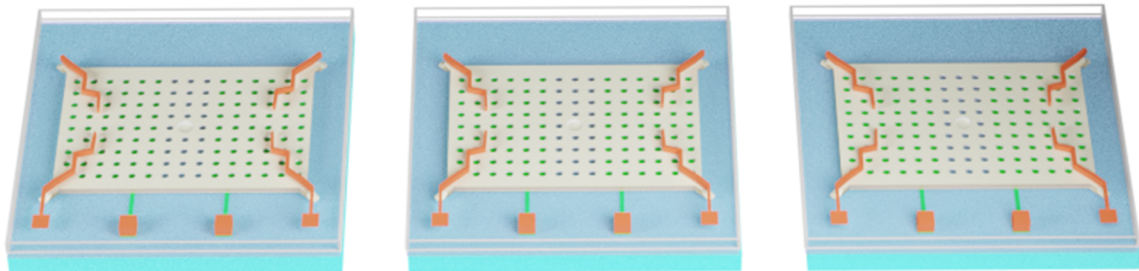
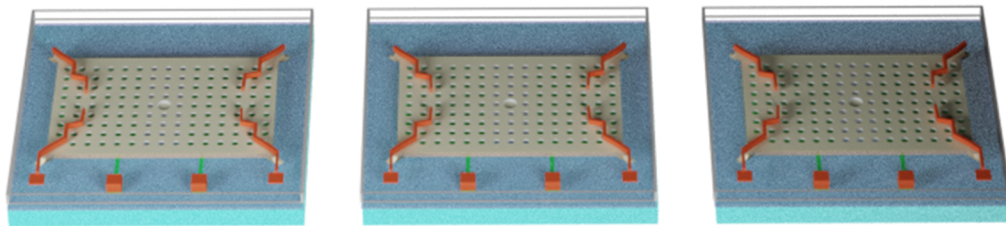


A Capacitive Hair-like MEMS Airflow Sensor for Flapping Wing Micro Air Vehicles.

Faculty of Electrical Engineering
Laveena Manjunath.



A Capacitive Hair-like MEMS Airflow Sensor for Flapping Wing Micro Air Vehicles.

by

Student number:	5336732	
Defense Date:	27 October 2023	
Thesis committee:	Prof. dr. Lina Sarro	TU Delft, Supervisor and chair
	Dr. ir. C.J.M Verhoeven	TU Delft, Examiner
	Dr. Massimo Mastrangeli	TU Delft, Examiner
	ir. Sunyi Wang	TU Delft, Daily supervisor
Institution:	Delft University of Technology	

This thesis is confidential and cannot be made public until 27 October 2028.

An electronic version of this thesis is available at <http://repository.tudelft.nl/>.



Abstract

Airspeed information plays a crucial role in the takeoff, flight, and landing processes in animal flyers and aerial vehicles. Among the aerial vehicles, Flapping Wing Micro Air Vehicles (FWMAVs) represent the novel engineering approach of learning and mimicking animal flyers in the past two decades. A few prototypes of various sizes and functionalities of FWMAVs have been developed by MAVLab in the TU Delft Aerospace department since 2005. For these small and lightweight platforms, stable control under disturbances remains a challenge, and could further benefit from integrating effective airflow sensing into control system design.

Current commercial products are either not suitable due to size, weight, and power (SWaP) restrictions of the drone platform, or have very limited low-speed sensitivity. Therefore, to facilitate this, this thesis aims to develop a MEMS-based capacitive airflow sensor for a miniaturized and low-power implementation. Inspired by the filiform hair structure of arthropods, the sensor design comprises two key parts: the hair structure, whose displacement is governed by the drag force induced by the incident airflow, and the sensing base, located at the hair structure's base, which translates the structural displacement into a change in capacitance. The sensor exhibits the capability to sense airflow in one dimension and can be further adapted for omnidirectional sensing.

This thesis predominately focuses on the design and reliable fabrication of the sensing base. It is comprised of a suspended membrane supported by corner beams, supplemented by a pivoting dimple and anti-stitching dimples to facilitate robust hair movement and ensure optimal sensor functionality. The sensing base is fabricated at the TU Delft EKL cleanroom facility, equipped with sophisticated machinery that enables fabrication at micro and nano scales. Furthermore, the membrane suspension is achieved through the implementation of Vapor HF etching of a sacrificial layer beneath the membrane.

In conclusion, the devised sensors aspire to optimize flight control for FWMAVs within the constraints of SWaP, by drawing profound inspiration from the intricate workings of nature.

Acknowledgments

First and foremost I would like to thank Dr. Henk van Zeijl for giving me the opportunity to work on this amazing interdepartmental project between the Electrical and Aerospace departments. Your weekly guidance and honest feedback throughout the project was really helpful. I would also like to thank Sunyi Wang for guiding me daily throughout the project. Your detailed attention to things and project tracking mechanism maintained the quality of the project. I have learnt a lot from both Dr. Henk and Sunyi. I would also like to thank all the collaborators from MAVlab, for enabling the collaboration. I would like to specially thank Christophe for your valuable inputs and support through the project.

Additionally I would like to thank the EKL team for their unwavering support. I would like to specially thank Mario, Tom, Johannes, Daniel, Paolo, Bruno, Francesco and Hande for helping us out at various stages of the fabrication process. Thank you Mario for your support with the Omega and Novellus tools, Tom for providing input on the flowchart, Johannes for all the trainings and Woollam measurements and Daniel for wafer stepper programming. Paolo, Bruno, Francesco and Hande, thank you for your time and input during the delamination issue. I would also like to thank Roberto and Francesco for keeping me encouraged in the cleanroom. I would like to thank Samhitha wholeheartedly for your unwavering support through all the phases of the master's degree. Thank you for helping me with the 3D printing sessions and cleanroom buddy support on the weekends.

My friends from home have been very supportive during all the times I have been low and unmotivated. Additionally, I would like to thank Öykü, Tariq, Francesco and Alex through all the low and high times during the Microelectronics TU Delft journey. And most importantly, I would like to thank my parents for providing me with this opportunity to pursue a degree so far from them. They have been the most encouraging and supportive parents I could ask for. Finally I would like to thank my fiancé Karthik for your unwavering and relentless support day in and out. If it weren't for you I could not have completed this difficult feat and complete this degree. Thank you so much for taking care of me and keeping me motivated to achieve my goals.

Laveena Manjunath
Delft, October 2023

Contents

Abstract	i
Acknowledgments	iii
Acronyms	xvii
List of Acronyms	xvii
1 Introduction	1
1-1 Motivation	1
1-1-1 Airflow Sensing	1
1-1-2 Why MEMS technology?	2
1-1-3 Flapping Wing Micro Air Vehicle (FWMAV)	2
1-2 Objectives and research statement	3
1-3 Outline	4
2 Literature Review	5
2-1 Background	5
2-1-1 Sensor performance parameters	5
2-2 Thermal	7
2-2-1 Related work	8
2-3 Piezoresistive	9
2-3-1 Related Work	11
2-4 Capacitive	13

2-4-1	Related Work	14
2-5	Discussion and Conclusions	15
3	Concept formulation	19
3-1	Design approach	19
3-1-1	What are we looking for?	19
3-1-2	Concept exploration	20
3-2	Bio-inspiration	21
3-3	Envisioned sensor structure	23
3-4	Discussion	24
4	Design	25
4-1	Material Selection	25
4-1-1	Membrane + Support + dimples	26
4-1-2	Electrodes	27
4-2	Analytical analysis	27
4-2-1	Electrodes	27
4-2-2	Cavity	29
4-2-3	Membrane and Surrounding support	30
4-2-4	Hair	32
4-3	Simulations	33
4-3-1	Electrostatics	34
4-3-2	Solid mechanics	35
4-3-3	Electromechanical	36
4-4	Discussion	46
5	Fabrication	47
5-1	Proposed Fabrication stages	47
5-2	Photomask Design	49
5-2-1	Pre-requisites for designing	49
5-2-2	Design on L-edit	49
5-3	Bottom electrode	54
5-3-1	Passivation layer	54
5-3-2	Metallization	55

5-3-3	Patterning	56
5-4	Cavity Shaping	61
5-4-1	Anti-stitching and Pivoting dimples	62
5-4-2	MESA	63
5-5	Top electrode	64
5-5-1	Patterning	64
5-5-2	Via openings	67
5-6	Interconnect	68
5-7	Membrane construction	69
5-7-1	Membrane shaping	69
5-7-2	Membrane suspension	70
5-8	Discussion	73
6	Results	75
6-1	Preventing fences	75
6-2	The delamination problem	77
6-3	SiC membrane suspension without electrode	78
6-4	Results of cold metal deposition	81
6-5	Rudimentary measurements	84
6-6	Membrane suspension after second fabrication cycle	86
6-7	Discussion	87
7	Conclusion	91
7-1	Project Summary and Objectives Achieved	91
7-2	Future Work and Recommendations	91
	Bibliography	95
A	Appendix A	101
A-1	Capacitance of tilted electrode under membrane	101
A-2	Pull-in voltage derivation	102
B	Appendix B	103
B-1	Pre-requisites for designing	103
B-2	Additional features designed onto the mask	104
C	Appendix C	107
C-1	Rounding the corners of the beam	107

List of Figures

1-1	Early airflow sensing methods.	1
1-2	An example of an FWMAV from the company <i>Flapper Drones</i>	2
2-1	Theory of hot-wire anemometry [34].	8
2-2	Micro-thermal mesh membrane sensor [12].	9
2-3	Performance of two dimensions of 3C-SiC on glass thermal flow sensor [48]. . . .	10
2-4	Cantilever implementations of piezoresistive sensors.	12
2-5	Self-bent implementations of micro-cantilever piezoresistive sensors [31].	12
2-6	Shape variations of paddle for sensitivity variation.	12
2-7	Bio-inspired airflow sensors with hair-like configuration [56].	13
2-8	Example of in-plane capacitive airflow sensor [42].	14
2-9	Artificial biomimetic flow sensor based on cricket mechano-sensory hairs [23]. . .	14
2-10	Improved artificial biomimetic flow sensor based on cricket mechano-sensory hairs [35].	15
2-11	3D printed bio-inspired hair sensor for directional airflow sensing [54].	16
3-1	Various configurations of capacitive sensors [4].	20
3-2	Cantilever approaches to capacitive airflow sensors.	21
3-3	SEM images of mechano-receptive filiform hair.	22
3-4	Mechanical model of filiform hair [11].	22
3-5	Model translating filiform hair.	23
4-1	Block diagram illustrating chapter outline.	25

4-2	Electrode placements.	28
4-3	Representation of tilted electrodes for the two electrode placements.	29
4-4	Options for surrounding support.	30
4-5	Types of beam support.	31
4-6	Cross section of sensing base depicting forces without pivoting dimple.	31
4-7	Spring constant distribution for 8-beam and 4-beam variation.	32
4-8	Various hair shapes.	32
4-9	FSI simulation correlating drag force and velocity.	33
4-10	Parallel capacitors on COMSOL.	34
4-11	Tilted electrode plate on COMSOL.	34
4-12	Set-up and results from solid mechanics COMSOL simulations.	36
4-13	Results of solid mechanics simulation.	37
4-14	3D displacement graph of electromechanical simulations on COMSOL.	38
4-15	4-beam width variation.	39
4-18	8-beam length variation.	39
4-16	8-beam width variation.	40
4-17	4-beam length variation.	40
4-19	8-beam vs 4-beam: Constant distance maintained between membrane and external for both configurations.	41
4-20	Pivoting dimple (green structure) implemented within the cavity in the COMSOL set-up.	42
4-21	Comparison of solid mechanics with and without underlying pivoting dimple. . . .	42
4-22	Pull-in voltage comparison with and without dimple.	43
4-23	Thickness variation.	43
4-24	Cavity variation.	44
4-25	Voltage sweep of 4-beam sensor.	45
5-1	Constructing bottom electrode.	47
5-2	Shaping the cavity between electrodes.	47
5-3	Embedded top electrode.	48
5-4	Via and interconnect.	48
5-5	Membrane suspension.	48
5-6	Blade system of stepper.	49
5-7	L-edit designs.	50

5-8	L-edit design of top electrode accommodating sacrificial holes with 7 μ m radius openings.	51
5-9	L-edit design of bottom electrode via.	51
5-10	L-edit design of interconnect incorporating top via and sacrificial holes.	52
5-11	Design of sacrificial holes on L-edit.	53
5-12	Final design of sensing base.	54
5-13	Measurement tools.	55
5-14	FR-scanner measurements.	56
5-15	Inspection tools.	58
5-16	Electrode damage with TiN4Al30 overetch recipe.	58
5-17	SEM inspection of TiN delamination.	59
5-18	Fence formation after bottom electrode M1 etching.	59
5-19	Measurement at 4-probe station.	60
5-20	Keyence dimension measurement of M1.	60
5-21	Wafers with delaminated TiN electrodes.	61
5-22	Axiotron inspection of anti-stitching and pivoting dimple.	63
5-23	MESA under etching.	64
5-24	Blue blotting after M2 electrode etch.	65
5-25	Dimple structures under SEM after M2 etching.	65
5-26	SEM images after M2 etching.	66
5-27	Delamination of M2 electrodes after deposition of SiC3 membrane.	66
5-28	Bottom electrode via opening.	68
5-29	Top via opening.	68
5-30	Features measurements after M3 etching.	69
5-31	Aluminium fence of M3 interconnect.	70
5-32	SEM images of 8 beam sensing base before VHF.	71
5-33	SEM images of 4 beam sensing base before VHF.	71
5-34	Steps before VHF etch.	72
5-35	SEM inspection of cleaved dies depicting VHF results.	73
5-36	Axiotron inspection of damaged dies resulted after VHF etch.	73
5-37	SEM measurement of cleaved dies after VHF etch.	74
6-1	Types of photoresist sidewall profile [21].	75

6-2	Sidewall profile of photoresist with varying Post Exposure Bake (PEB) temperatures [59].	76
6-3	Comparison of photoresist sidewall for different exposure energy with PEB = 115°C and Hard bake = 170°C.	76
6-4	Sidewall profile of photoresist with various Hard Bake temperatures [59].	76
6-5	Result of experimentation with sidewall profile: a) Sidewall profile with exposure energy = 120mJ/cm ² , PEB = 115°C, HB = 170°C, b) Underexposed nLOF photoresist for small feature size.	77
6-6	Result of back side SiC deposition.	78
6-7	a) Dark residue over SiC landing layer after metal etching, b) Visual comparison between hot and cold deposition	79
6-8	Membrane suspension without electrodes I: a) Uniform TEOS etch under membrane, b) Wafer depicting sensor variation with detached membrane.	79
6-9	Membrane suspension without electrodes II: a) Without extended MESA, b) With extended MESA.	80
6-10	Keyence inspection of released SiC membrane without electrodes depicting upward buckling.	81
6-11	No Al fence formation after bottom electrode M1 etch.	81
6-12	Comparison between results of bottom electrode M1 etching.	82
6-13	Stress measurements during thermal treatment.	82
6-14	TiN texture after thermal treatment.	83
6-15	Second fabrication cycle a) Wafer after MESA etching, b) Wafer after top electrode M2 etching.	83
6-16	No Al fence after top electrode M2 etch.	83
6-17	Measurement of sacrificial hole openings.	84
6-18	Comparison between completed fabrication wafers.	85
6-19	Details of the rudimentary measurement session.	85
6-20	Distribution of sensor measurements on wafer.	86
6-21	VHF etching after second fabrication cycle	87
6-22	VHF etching after second fabrication cycle.	87
6-23	SEM inspection of cleaved dies after second fabrication cycle VHF etching. . . .	88
6-24	Keyence image of sensing base after membrane suspension.	89
A-1	Illustration for tilted electrode derivation (below-membrane).	101
A-2	Cross section of sensing base depicting forces without pivoting dimple.	102
B-1	ASML PAS5500/80 wafer stepper system.	103

List of Figures

B-2	Vital information to design photomask.	104
B-3	Implemented exposure jobs.	104
B-4	Mask 1.	105
B-5	Mask 2.	105
C-1	Result of varying focus offset.	107

List of Tables

2-1	Summary of sensing methods.	17
4-1	Electrode dimensions for Base capacitance = 2.44pF and Area (A) = 552450(μm) ²	28
4-2	Differential capacitance for electrode placements above-membrane (am) and below-membrane (bm).	29
4-3	Values for V_{max} calculations.	31
4-4	Calculated spring constants for single beam and pull-in voltages without dimple.	31
4-5	Conditions of electrostatic simulations.	34
4-6	Relevant dimensions.	35
4-7	Computed differential capacitance for the two electrode orientations.	35
4-8	Conditions of solid mechanics simulation.	36
4-9	Relevant dimensions for solid mechanics simulations.	37
4-10	Conditions of electromechanical simulation.	38
4-11	Sensing base variations shortlisted for fabrication.	46
5-1	Resistance of interconnects.	52
5-2	Beam variations shortlisted for fabrication.	53
5-3	Process conditions for SiC1 deposition	55
5-4	Process conditions for AlSi/TiN metallization.	56
5-5	Results of CDE device.	56
5-6	Recipe with overetch step in Omega plasma etcher.	57
5-7	Recipe with isotropic etch step in Omega plasma etcher.	57

5-8	Etch time of Al fence removal for the two etch recipes.	59
5-9	SiC1 and SiC2a thickness.	61
5-10	Flexus measurements for bottom electrode stage.	61
5-11	Process conditions for TEOS deposition	62
5-12	TEOS thickness at various stages.	62
5-13	Anti-stitching and Pivoting dimple dimensions comparison.	63
5-14	Mesa dimensions after etch.	64
5-15	SiC thickness at various stages.	66
5-16	Thickness measurements and deposition time of SiC.	67
5-17	Recipe for SiC etching in Omega.	67
5-18	Etch time of metal layers at the bulk etching step of the etch recipe in Omega.	69
5-19	SiC etching time with SIC20DEG etch recipe on Omega.	70
5-20	Flexus measurements.	70
5-21	Beam dimensions from SEM inspection.	71
5-22	Relevant details about patterning.	72
5-23	Etching recipes with defined etch rates in the μ Etch VHF machine.	73
6-1	Results of membrane suspension.	79
6-2	Intrafield overlay shift for each MESA exposure.	80
6-3	Thermal treatment recipe.	82
6-4	Measurements of sacrificial holes.	84
6-5	Resistance of interconnects on the sensor.	85
6-6	VHF etching results after first fabrication cycle.	86
6-7	VHF etching results after second fabrication cycle.	88

Acronyms

List of Acronyms

MEMS	Micro Electronic Mechanical System
FWMAV	Flapping Wing Micro Air Vehicles
HVAC	Heating, Ventilation and Air Conditioning
MAVLab	Micro Air Vehicles Lab
EKL	Else Kooi Lab
TEOS	TetraEthyl OrthoSilicate
PECVD	Plasma-Enhanced Chemical Vapor Deposition
FSI	Fluid-Structure Interaction

Introduction

The growing use of unmanned aerial vehicles has prompted a greater need for enhanced capabilities, particularly in the areas of flight pattern control and stability. Consequently, the exploration of airflow-sensing solutions has gained significant attention. This chapter provides an introduction to airflow sensing, highlights the importance of MEMS technology, and outlines the specific requirements of the Flapping Wing Micro Air Vehicles (FWMAVs).

1-1 Motivation

1-1-1 Airflow Sensing

The direction and flow speed of air movement have been measured by humans for ages. This measurement has either occurred through external measuring tools or hair sensors provided by nature. Skin and body hair which are predominantly used as protection, have also enabled humans to make approximate estimations about flow sensing. Early humans used these rudimentary estimations to predict the weather, avoid unpleasant or dangerous odours, etc. Ancient humans further adopted rudimentary tools to measure a more precise flow speed and direction. Windsock or basic anemometers measuring airflow, were largely implemented in agriculture, sea navigation, and windmills to harness wind power.



(a) Windsock.



(b) Cup anemometer.

Figure 1-1: Early airflow sensing methods.

With the advancement of technology, airflow sensing is now customized for various applications. HVAC (Heating, Ventilation and Air Conditioning), automotive, and aerodynamics require precise mechanisms for airflow sensing. These sensing tools, or sensors, optimize the performance and efficiency of the adopted systems. Agriculture and navigation still continue to use airflow sensors updated by advancements.

1-1-2 Why MEMS technology?

Since the start of the mid-twentieth century, many devices and instruments have been scaling down in size to improve portability and integration capability. The novel introduction of Integrated circuits (ICs) enabled the scaling down of electronic circuits using semiconductor fabrication technologies. These technologies gave way to the development of various kinds of devices including Micro-Electro-Mechanical Systems (MEMS). MEMS sensors are pivotal in various fields due to their compact size, lightweight design, and multi-function integration capability, which allows the development of complex systems in limited space. Their low power consumption, high sensitivity, and improved performance in measuring various physical parameters make them suitable for applications with energy constraints and demanding precision requirements. Additionally, their cost-effectiveness, reliability, and durability contribute to their widespread adoption in industries such as consumer electronics, healthcare, and aerospace, where reduced size and weight are critical factors for success.

The first silicon-based airflow sensor was patented in the year 1987 as a mass airflow sensor for automobile application [60]. Airflow sensors of macro-, meso- and micro-scale have been researched and customized for specific applications. Many methods have been adopted to perform these measurements, some include, capacitive, resonating mass, piezoresistive and thermal. Each measuring approach has recorded varying sensitivity, accuracy, directionality, weight, dynamic range, and power consumption. In the following sections, we will explore these various implementations and establish the best approach to measure airflow for the established specifications.

1-1-3 Flapping Wing Micro Air Vehicle (FWMAV)



Figure 1-2: An example of an FWMAV from the company *Flapper Drones*.

In recent years, unmanned aerial vehicles, commonly known as drones, have gained widespread application across various sectors, including agriculture, disaster management, commercial ventures, and military operations. These versatile vehicles are categorized based on their design, size, flight characteristics, and intended use. Among the different types, Flapping Wing Micro Air Vehicles (FWMAVs) have emerged, drawing inspiration from the flight patterns of birds and insects. The research group at the aerospace department of TU Delft, known as MAVLab, has been instrumental in developing various versions of FWMAVs. These vehicles aim to replicate the intricate flight maneuvers observed in nature, necessitating precise control and a deep understanding of the surrounding airflow and disturbances.

⁰<https://flapper-drones.com/wp/>

The FWMAVs are built to embody lightweight structures with wing attachments. The weight of air vehicles ranges from a few tens to hundreds of grams, with lower payload capability. The flight endurance is usually greater than 3min with a power supply below 10V. Due to the low payload capability, heavy batteries cannot be accommodated, therefore it is imperative to implement airflow sensors which require a low power budget. To facilitate airflow sensing, numerous studies have been conducted including MEMS-based sensors that enable miniaturization and seamless integration.

Maintaining the inspiration from aerial creatures and insects, a bio-inspired solution for airflow sensing is best suited. Many creatures sense airflow using protruding hair structures. The airflow displaces the hair position and is further sensed by dendrites at the base of the hair. The hair is an aerodynamic protruding structure, whereas the network of dendrites comprises a sensing base. A similar concept of airflow sensing is introduced, designed, and fabricated, implementing MEMS technology, for the FWMAVs at MAVLab.

1-2 Objectives and research statement

The primary objective of the project is to develop a MEMS-based airflow sensor to seamlessly integrate into a flapping wing micro air vehicle (FWMAV). The sensor aims at consuming low power with sensing capability at low airflow velocity. The incorporation of MEMS technology is instrumental in fulfilling the stringent requirements for minimal weight and compact form factor for optimal FWMAV integration. Capacitive sensing in MEMS sensors are inherently low power consumption sensors. Therefore, a capacitive-based airflow sensor is preferred.

Inspired by the aerial creatures in nature, a hair-like design concept is adapted to enable accurate directional sensing in at least 1D. The scope of the project is outlined around developing a sensing base capable of incorporating the hair-like structure with optimum aerodynamic functionality. This leads to the formulation of the research statement:

A capacitive hair-like MEMS airflow sensor for flapping wing micro air vehicles (FWMAVs).

The objectives of the project include:

1. Formulate a robust sensor design with:
 - Directional sensing
 - Low power consumption
 - Minimal weight and size
 - Sensing range between 0 - 5m/s.
2. Analyse the defining aspects of the proposed structure.
 - Analytical, mechanical, and electromechanical analysis
 - Sensor parameters and limitations
3. Propose, implement, and optimize compatible fabrication strategy.
4. Prove the working of the concept.

1-3 Outline

The report is divided into seven chapters including the introduction. Chapter 2 provides an overview of the existing state-of-the-art airflow sensors implementing various sensing mechanisms. It also introduces the crucial parameters defining airflow sensors. Chapter 3 highlights the various non-bio and bio-inspirations for sensor structure and concludes with a proposed sensor design. Chapter 4 covers the design analysis, analytical, mechanical, and electromechanical COMSOL simulations. This chapter concludes with specific sensor variations to proceed with fabrication. Chapter 5 elucidates the upgraded sensor design compatible with fabrication processes, proposes the fabrication stages, and details the fabrication process and issues experienced. Chapter 6 discusses the improved fabrication process and its results. Chapter 7 summarises the project and achieved objectives, along with a discussion on future work and recommendations.

Literature Review

2-1 Background

2-1-1 Sensor performance parameters

Movement of air is a crucial phenomenon which determines multiple factors in flight pattern, therefore it is imperative to evaluate the following properties of airflow:

- Velocity
- Direction
- Temperature
- Humidity
- Turbulence

While humidity and temperature have dedicated sensors for measurement, airflow sensors are designed to measure speed, turbulence and optionally direction of the flow. In this section we delve into the fundamental considerations of MEMS airflow sensors, exploring key parameters that ascertain its performance.

Sensitivity

Sensitivity is the measure of change in sensor output with respect to change in airflow velocity at sensor input. A sensitive sensor is capable of detecting a more minute change in airflow. This measure is typically evaluated with equation 2-1. Specific to airflow sensors, change in output co-relates to various factors, primarily on sensor type, structure, dimensions and material choice. It is imperative to ensure sensitivity remains constant across the measuring range therefore maintaining a linear characteristic.

$$\text{Sensitivity } S = \frac{\Delta \text{Output}}{\Delta \text{Input}} \quad (2-1)$$

A MEMS based free standing micro-cantilever structure facilitating airflow sensing depicts the direct dependency of sensitivity on cantilever beam width and structure. Increasing width displayed higher sensitivity [26]. In case of thermal based airflow sensors, material choice, thermal isolation consequently sensor structure are some of the factors that attribute to sensitivity [34]. Therefore corroborating sensitivity dependency on sensor type.

Range

Range is the difference between the minimum and maximum measurable airflow speed of the sensor. The minimum detectable speed is measured at rest state and the maximum speed is

measured within the reliable operational limit of the sensor. Similar to sensitivity, the sensing range is related to the structure, dimensions, choice of material and many more.

Platinum based micro-thermal sensor has a sensing range limit of 1.5 - 11 m/s with a sensitivity of 7.98 mV/(m/s) [12]. This hot-film sensor consists of a mesh-membrane support structure which aids to sensitivity but limits range. Similarly, a hot-wire airflow sensor with an array of hair-like micro-wire-bonded structure has a sensing range of 0.01 - 17.5 m/s with a sensitivity of 0.196 V/(m/s) [37]. The sensing mechanism of the cited sensors operate using the principle of hot-wire anemometer, whereas the structures of the two sensors vastly vary thus determining the range and sensitivity. Typically thermal sensors provide low accuracy measurements at the lower end of the measuring range which is further discussed in the subsequent sections. Numerous airflow sensors are available, each capable of detecting a distinct speed range, making each sensor suitable for diverse applications according to specific needs.

Response time of sensor

Response time is the time the sensor takes to produce an output from the time of airflow incidence on the sensing surface. A shorter sensing time avoids delayed sensor reading and consequently maintains accurate measurements in real time. On the contrary, delayed response time can lead to measurements that do not reflect the actual conditions, therefore providing faulty/inaccurate data in real time, making it unsuitable for fluctuating airflow.

The micro-thermal sensor described above has a response time of less than 5ms [12]. Whereas the micro wire-bonded-structure has a response time of less than 70ms [37], implying micro-thermal sensor is the best suited from among the two for capturing real-time measurements of a fluctuating airflow. Depending on the fluctuation rate both sensors might be suitable for fluctuating airflow.

Power consumption

Power consumption is an crucial performance evaluation parameter for sensors. It is of paramount importance specifically for battery-operated applications. This is due to the limited power budget available to efficiently support a system.

Directionality

Considering airflow is a phenomenon with inherent directional variability, single or a group of airflow sensors should possess the capability to determine the direction of movement. Often, it is facilitated by incorporating more than one sensing module or element in various orientations.

Micro-thermal sensor is unidirectional because of the sensing structure [12] i.e; the sensor is capable of providing only the airflow speed. On the contrary, wire-bonded-structure can be multi-directional depending on the array and its orientation [37].

Robustness

Robustness is ascertained by the ability of the sensor to effectively maintain functionality, performance and integrity even under harsh or uncertain environment. It is especially important for airflow sensors installed onto drones due to a myriad of uncertainties. Some of which include weather conditions, collisions, battery life, loss of communication, terrain, equipment failure and environmental interaction. Therefore, it is imperative to take measures to ensure the sensors are robust.

Accuracy and Stability

Accuracy is a measure of acceptable deviation of a measured value from the true or actual value. This indicates the absence or presence of errors during measurement. Stability on the other hand is the ability of a measurement to maintain consistency and reliability of the measuring value over time. It is independent of external condition or factors. A stable measurement provides consistent values but might not be a true value, implying inaccuracy. An accurate measurement provides the true value but might not be a stable and can vary significantly over time.

The subsequent sections of this chapter will provide a brief summary of the distinct categories of airflow sensors. Each section describes the sensing principle to the specific sensor type and further elucidates the significant developments over the years. The final section consolidates the findings of the various sensors to formulate a conclusion regarding the optimal sensor type to implement on FWMAVs.

2-2 Thermal

Thermal sensors function on basic principle of convection or heat transfer. Hot-wire anemometer are examples of thermal sensors. An electrically heated wire when placed in flowing fluid, like airflow, transfers heat to the fluid. The temperature or resistance change provides information about the velocity of the fluid. In the early 1900s rudimentary approaches relied on constant current and later adopted constant temperature or resistance method [1]. Typically, these systems comprises of two fundamental components; heating and sensing elements. The sensing element detects the change in heat when the air flows over the heating element [50] which facilitates the transduction of heat to electrical signal. Consequently the sensitivity increases with a large increase in heat transfer for small change in airflow. Conventional thermal sensors largely depend on thermal isolation and maintenance of temperature of both the heating element and the fluid (air) to ensure accuracy [45]. A well isolated heating element from the sensing element minimizes thermal loss and therefore improves accuracy. Additionally sensor performance depends on the material properties of the heating element. The sensor does not necessitate any mechanically moving component for operation.

As stated, the heating element of these thermal sensors comprises of a resistive wire or thin film structure. The element experiencing airflow is subjected to convective heat loss. Increase in airflow increases convective heat loss [34]. Figure-2-1 illustrates the principle of hot-wire anemometry. The material of the wire or film determines the convective heat loss and its transduction to change in resistance or voltage. The sensitivity of the sensor is predominately ascertained by the temperature co-efficient of resistivity of the sensing material [45].

$$R(T) = R(T_0)[1 + \alpha(T - T_0)] \Rightarrow \frac{\Delta R}{R} = \alpha \Delta T \quad (2-2)$$

Equation 2-2 illustrates the relationship between the change in resistance ΔR of the sensing element and change in temperature ΔT due to airflow where α represents Temperature Co-efficient of Resistivity (TCR) of the material. It is imperative to select material which exhibit corrosion resistance to ensure efficient sensor performance. The hot-wire configuration function in various operation modes. Some of those include, constant heater power mode to

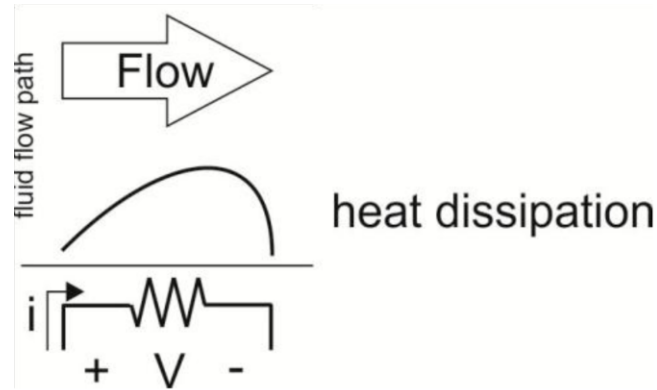


Figure 2-1: Theory of hot-wire anemometry [34].

monitor ΔR or ΔV , constant temperature mode which requires a feedback control to maintain temperature and further monitor change in power consumption or ΔV [34]. Wheatstone bridge is one of the best implementations for this kind of configuration [32]. The micro wire-bonded-structure, previously discussed in section 2-1-1, also refers to a hot-wire configuration [37].

2-2-1 Related work

Extensive research has been conducted on hot-wire and hot-film sensors over the years. With the advent of MEMS sensors, numerous studies on hot-wire and hot-film sensors have integrated this innovative technology since its inception. Micro-thermal mesh-membrane sensors, briefly discussed in section 2-1-1, developed by Hung et al. demonstrates a hot-film thermoresistive sensor. The sensor design incorporates a mesh-membrane structure, reducing fabrication time while ensuring optimal stiffness for efficient operation. Platinum is integrated into the mesh-membrane as the heating and sensing element. Closed and floating membranes along with cantilevers are more prominent approaches to fabricate membrane structures. Closed membranes typically necessitate a double-sided bulk micromachining process, while floating membranes require a longer etching time to suspend the membrane [5] [3]. Cantilevers on the other hand tend to depict an unintended outward deformation when etched to release and form a free standing structure implying complex fabrication steps [3]. Therefore the mesh-membrane, illustrated in figure-2-2, is incorporated for this micro-thermal sensor. The sensor operates in two modes: constant current and constant voltage modes. Constant voltage mode the resistance decreases with increase in flow velocity i.e; current increases, whereas in constant current mode the resistance decreases with flow velocity along with voltage [12].

The micro-thermal mesh-membrane sensor is characterized to possess a sensing range of 1.5m/s - 11m/s. Below the sensing range, the sensor's output decreases before it starts to increase for higher velocities. Heat convection usually occurs in two forms, natural and forced convection. When airflow velocity is high, forced convection is predominant, therefore providing accurate velocity measurements. At lower velocities, natural convection is predominant. The stagnant condition provides an environment for natural convection and therefore increasing surface temperature of the membrane. At these low airflow velocities, the air is unable to move quickly enough to carry the heat. Additionally the cavities in the membrane also accumulate air and consequently pronouncing the heat around the membrane [12]. The

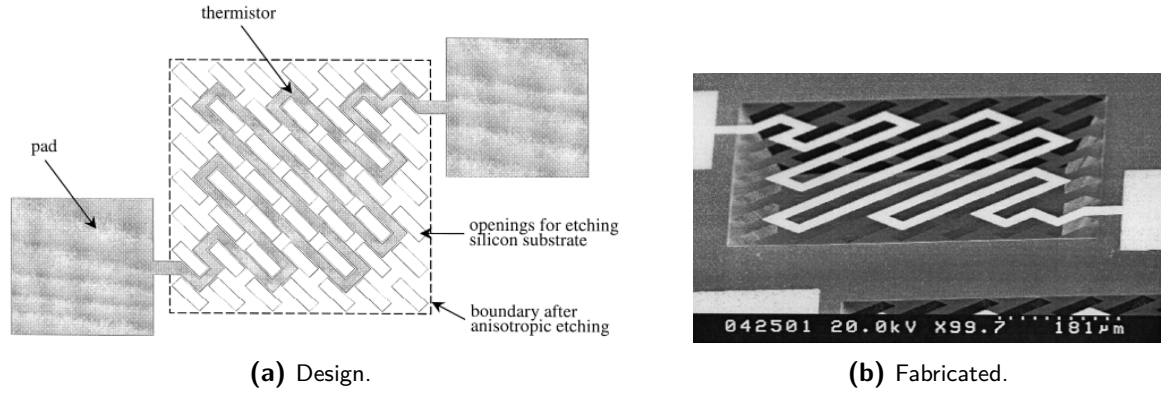


Figure 2-2: Micro-thermal mesh membrane sensor [12].

TCR is found to be $0.00249 \text{ } 1/(\text{°C})$. At constant voltage mode (2V), the sensitivity is $0.01433 \text{ mA(m/s)}^{-\frac{1}{2}}$ with a power consumption of 14.56 mW. At constant current mode (23.08mA), the sensitivity is measured to be $27.35 \text{ mV(m/s)}^{-\frac{1}{2}}$ with a power consumption of 157.61 mW.

The 3C-SiC on glass thermal flow sensor developed by V.Balakrishnan et al. focuses on improving sensitivity by integrating 3C-SiC as a heating element as opposed to conventional metal options like platinum. 3C-SiC exhibits a high thermosensitivity, making it one of the most suitable materials for this particular application [48]. The SiC is deposited on the glass substrate with a bonding technique and further patterned.

The sensor demonstrates a higher TCR compared to other metal-based sensors. The sensor also has good reproducibility which is attributed to the ability of SiC on glass to return to its original temperature during the cooling phase [48]. The effective sensing range spans from 0.2 to 9 m/s, above which the sensor exhibited instability. Characterising these sensors revealed a noticeable relationship between sensitivity and power consumption for this specific sensor design. The sensor consumed minimal power to ensure stable functionality, beyond this threshold, an increase in power consumption resulted in enhanced sensitivity. Furthermore, increasing the sensor dimensions also correlated with an increase in sensitivity.

Figure-2-3 illustrates the diminishing sensor accuracy with increase in power consumption. The operating temperature of the sensor is limited to 170°C . The response time of the sensor is approximately estimated to be 2s, whereas most MEMS based thermal sensors display response time in the ms range.

2-3 Piezoresistive

Piezoresistive materials exhibit transduction properties which enable measurement of external stress or strain in the form of resistivity or electrical signals. When these materials are exposed to mechanical stress or strain, they exhibit an inherent change in displacement, i.e; internal atomic and lattice positions. These changes subsequently lead to change in resistivity [50]. Airflow sensors harness the momentum of fluid which translates to stress or strain on the sensing element. The momentum of fluid is observed as drag force or pressure on the surface of the sensing element. Drag force acting on the incident surface of the sensing element is proportional to the incident surface area (A_i), drag-coefficient (C_d) of the incident object along with velocity (v) and density of airflow (ρ_{air}), illustrated in equation 2-3. Relation

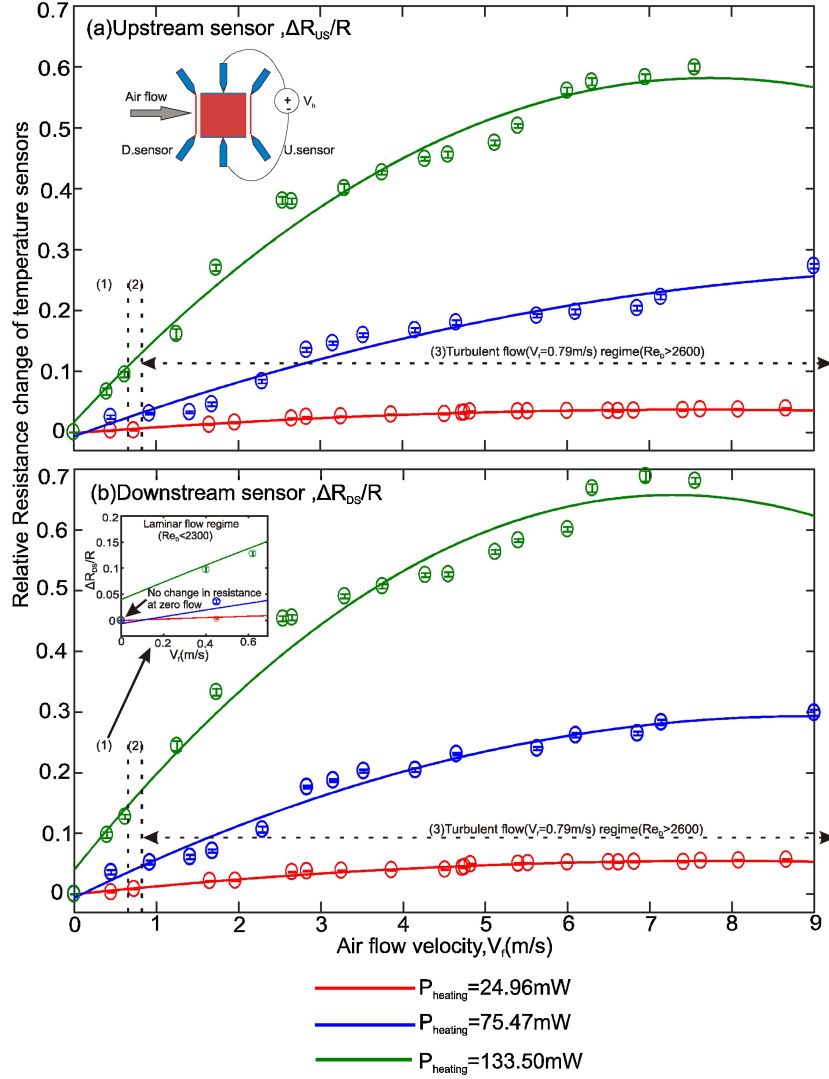


Figure 2-3: Performance of two dimensions of 3C-SiC on glass thermal flow sensor [48].

between pressure and airflow velocity is demonstrated by Bernoulli's equation 2-4. Pressure acting on a surface due to velocity of fluid, in this case air, has a quadratic dependency on airflow velocity [10].

$$\text{Drag force} = \frac{\rho_{\text{air}} A_i v_{\text{air}}^2 C_d}{2} \quad (2-3)$$

$$P_{\text{air}} = \frac{\rho_{\text{air}} v_{\text{air}}^2}{2} \quad (2-4)$$

The resistance of the piezoresistor is illustrated in equation 2-5 where l_R is the resistor length, ρ_r is the resistivity and A_r is the cross-sectional area of the resistor. Furthermore, the displacement caused due to the drag force of airflow and change in resistance are related by the consequent strain [56]. Poisson's ratio, ratio between lateral strain and axial strain, is another important term pivotal to determine the vital relationship between change in resistance and change in velocity [46]. This relationship may vary depending on structure, dimensions,

material and mechanism.

$$R = \frac{l_R \rho_r}{A_r} \quad (2-5)$$

Piezoresistive materials are implemented in airflow sensors without the requirement of thermal isolation, consequently improving accuracy and reducing design requirement.

2-3-1 Related Work

Microcantilevers are free standing structures which resemble beams protruding from a support surface. The free standing structures provide an unsupported surface area which enable movement of the beam when it experiences a force acting on the top or bottom surface of the beam [26]. Due to this cantilever movement, the structure can be implemented into a piezoresistive MEMS sensor. These structures are optionally designed with paddles at the free end of the beam to maximize surface area exposed to airflow to consequently improve sensitivity.

Fabrication of microcantilevers commonly involves bulk micromachining, where the silicon is etched from both sides of the wafer or the cantilever structure is formed around a sacrificial layer to materialize the design [13]. Several microcantilever designs have been developed to optimize the various performance parameters for a range of applications.

The first gas flow sensor implementing microcantilever piezoresistive sensor was presented as silicon-flow sensor based on lift force designed to be insensitive to acceleration [9]. This sensing principle and mechanism was adopted and modified in various studies for versatile applications. One such piezoresistive sensor developed by Wang et al. adopted a free standing microcantilever of silicon nitride with a platinum piezoresistive layer patterned at the supporting edge. Figure-2-4a depicts the sensor design and showcases the inherent upward bend induced during the bulk micromachining fabrication process. The upward bend is caused due to the residual stress released during the back-etching processing to form the microcantilever structure [26]. The sensor is characterized with a sensor range of 0 - 45 m/s at 25°C, power consumption of 0.15 mW and accuracy of 2%. The sensitivity as discussed in section 2-1-1 depends on the design structure and dimensions. In this study of Wang et al. the best sensitivity measured is 0.0284 $\Omega/(m/s)$ with a response time of 0.53s.

Consequently, microcantilever piezoresistive sensors were implemented into a flapping wing based air vehicles. One of the early implementations was adapted by H Takahashi et al. illustrated in figure-2-4b. The sensors are affixed at the leading edges of the wing such that the cantilevers are exposed to airflow interaction from all possible directions. The fabrication of this sensor comprised an N-type resistor formed on the SOI (Silicon On Insulator) wafer with gold patterned layer. The sensing range spans from -0.7 m/s to 0.7 m/s with a sensitivity of 0.56 - 0.96 $\times 10^{-3}(m/s)^{-2}$ [27].

Another similar implementation of the bent piezoresistive sensor was developed by Q Zhang et al. depicted in figure-2-5. This particular sensor has a sensing range of 0 - 23 cm/s with a sensitivity of 1.5 - 3.5 $\Omega/(cm/s)$. Silicon is implemented as a piezoresistor and in order to fabricate a bend in the structure, the silicon cantilever layer is sandwiched between two layers of silicon dioxide [31]. When the two layers are sacrificed, the residual stress causes the cantilever structure to bend. This bent structure enables the interfacing surface to the airflow to protrude and establish a sensing mechanism at low velocity.

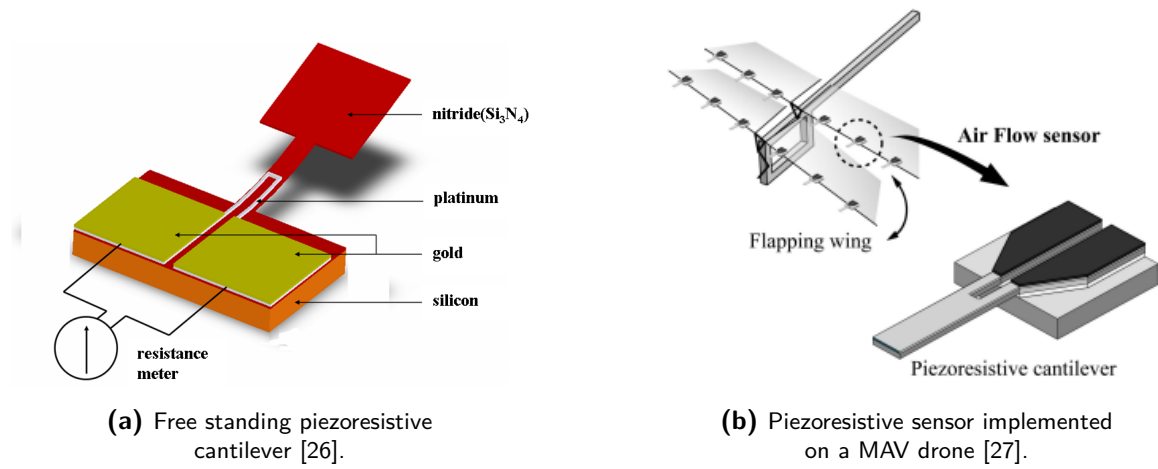


Figure 2-4: Cantilever implementations of piezoresistive sensors.

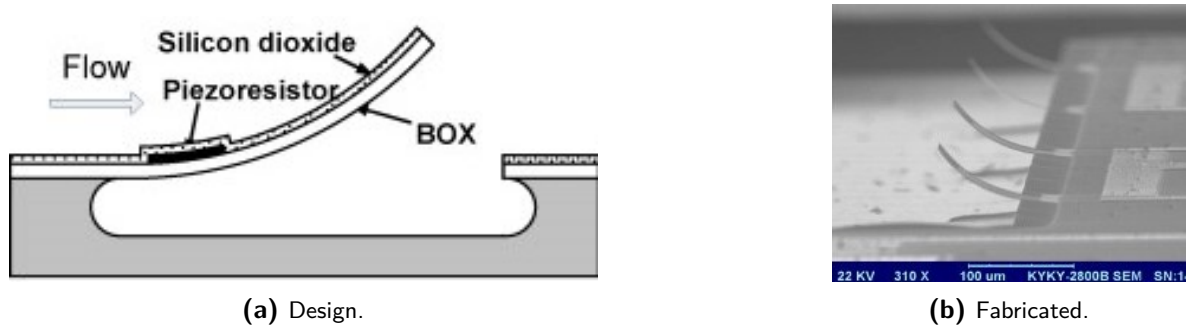


Figure 2-5: Self-bent implementations of micro-cantilever piezoresistive sensors [31].

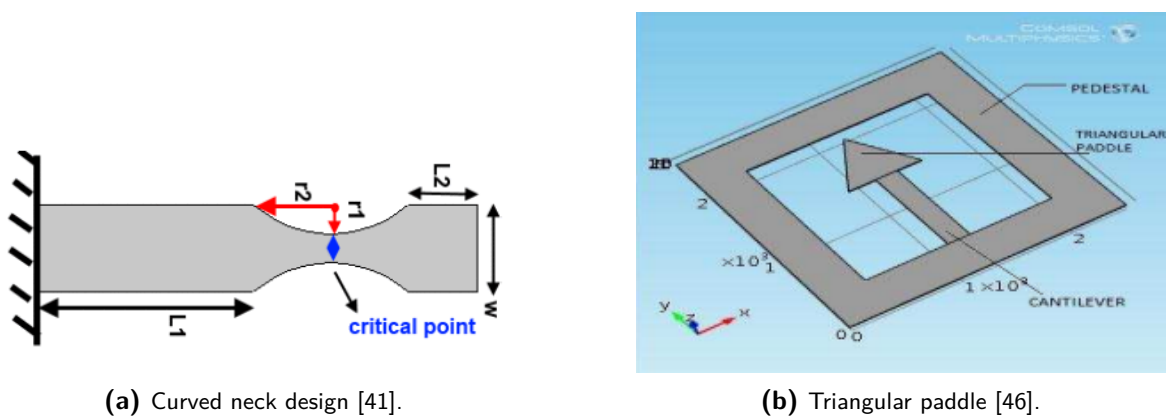
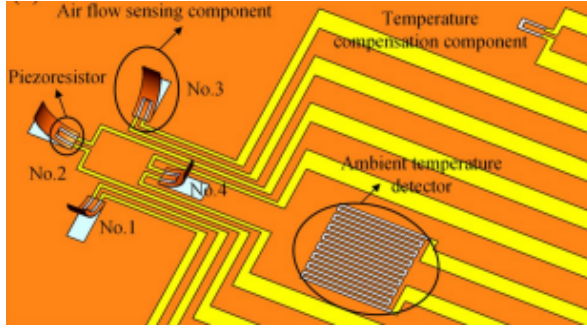


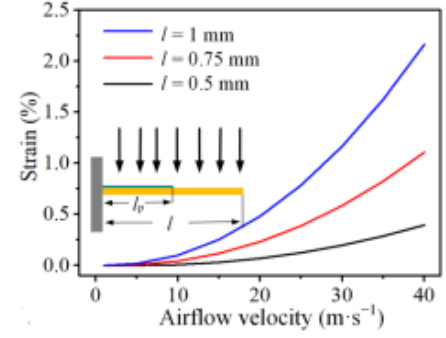
Figure 2-6: Shape variations of paddle for sensitivity variation.

Furthermore, various studies experimented with cantilever shape and size to improve the various performance parameters. Figure-2-6 depicts such examples. A curved neck from a

particular distance from the edge of the cantilever improves sensitivity along with an increase in noise, therefore it is imperative to balance these trade offs during design [41]. Similarly, a triangular paddle implemented as an extended surface to the cantilever improves the sensitivity compared to the traditional rectangular paddle[46].



(a) Design.



(b) Result for one cantilever.

Figure 2-7: Bio-inspired airflow sensors with hair-like configuration [56].

A more bio-inspired piezoresistive approach was studied by D Shen et al. which incorporated directionality into the sensor design. The sensor structure comprises of polyamide and platinum as the piezoresistor at the base of the cantilever. A Wheatstone half bridge is implemented to readout the change in resistance and compensate for temperature and decrease noise [56]. Figure-2-7 illustrates the sensor design and results of the implemented microcantilever structure. The change in strain (%) vs airflow velocity graph portrays the dependency of sensitivity on structure dimension. Increase in microcantilever length increases sensitivity. Additionally, increase in length also decreases accuracy and increases noise. At lower velocities the sensitivity is measured to be 1.714 mV/(m/s) and at higher velocities of 38.5 m/s the sensitivity is measured to be 60.35 mV/(m/s) with a sensing range of 0 - 40.5 m/s. The developed sensor demonstrates omnidirectional airflow detection successfully.

2-4 Capacitive

Capacitive airflow sensors are designed to implement a transductive sensing mechanism to detect change in airflow velocity by measuring change in capacitance. Capacitive sensors typically consist of two closely spaced parallel electrodes with a dielectric medium in between, effectively forming a capacitor. The dielectric medium, area of the electrodes (A) and the distance between the electrodes (d_o) define the base capacitance (C_o), illustrated by equation 2-6. Similar to piezoresistive airflow sensors, the incidence of a drag force upon the intended exposed surface induces a shift in the position of one of the electrodes, thereby instigating a change in d_o consequently causing a change in capacitance [17]. The performance parameters depend on the structure, dimension, material choice and many other factors specific to the sensor design.

$$\text{Capacitance } C_o = \frac{\epsilon A}{d_o} \quad (2-6)$$

Capacitive sensors exhibit various configurations. In specific airflow sensors are broadly categorized into in-plane and out-of-plane configurations based on their design. Out-of-plane configuration involves a protruding element from the resting surface contrary to in-plane

sensors. In-plane capacitive sensors, depicted in figure-2-8, are incapable of sensing the direction of airflow due to its limiting design structures. Since the sensor requirement include directionality, the subsequent investigations are dedicated to elucidating out-of-plane sensor configurations.

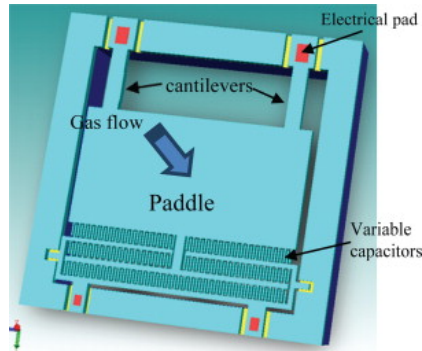


Figure 2-8: Example of in-plane capacitive airflow sensor [42].

2-4-1 Related Work

Out-of-plane capacitive sensors are predominantly bio-inspired hair-like sensors [42]. One of the early implementations of these hair-like sensors was developed by M Dijkstra et al. which employed capacitive sensing. Inspired by filiform hair on the cerci of crickets as shown in figure-2-9b, the sensor utilizes its mechanical model to mimic the movement induced by drag force and consequently aid in capacitive sensing [17]. It comprises a hair-like structure made of SU-8 polymer supported by a suspended silicon nitride membrane. One of the crucial steps of fabrication is the final step to dry etch the sacrificial layer after the patterning step of the SU-8 hair structure.

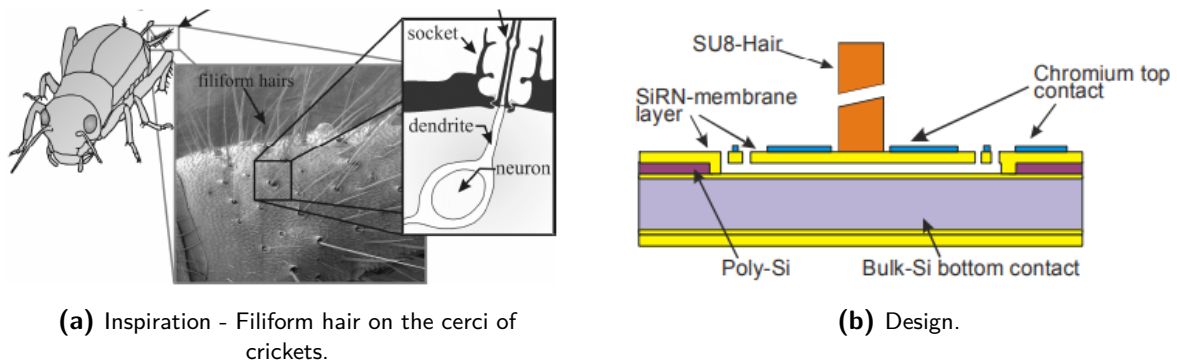


Figure 2-9: Artificial biomimetic flow sensor based on cricket mechano-sensory hairs [23].

The sensor characterization included an array of hair sensors with a collective sensing range between 0.1 - 1 m/s and a sensitivity in the order of 10 - 100 fF/(m/s). The directional sensitivity was estimated at 1.39pF/rad [23]. Consequently, C.M Bruinink et al. improved the cricket-inspired hair-like sensor with higher capacitive output by modifying design dimensions and implementing aluminum electrodes [29]. The minimum sensing velocity improved to 2 mm/s with resolution in the order of 1 mm/s attempting to match the sensitivity of cricket

hair. A further improvement by A.M.K Dagamesh et al. reduced the sensing lower limit to 1 mm/s, illustrated in figure-2-10. Due to its capacitive sensing nature, the relative power consumption is low compared to other sensing mechanisms [35].

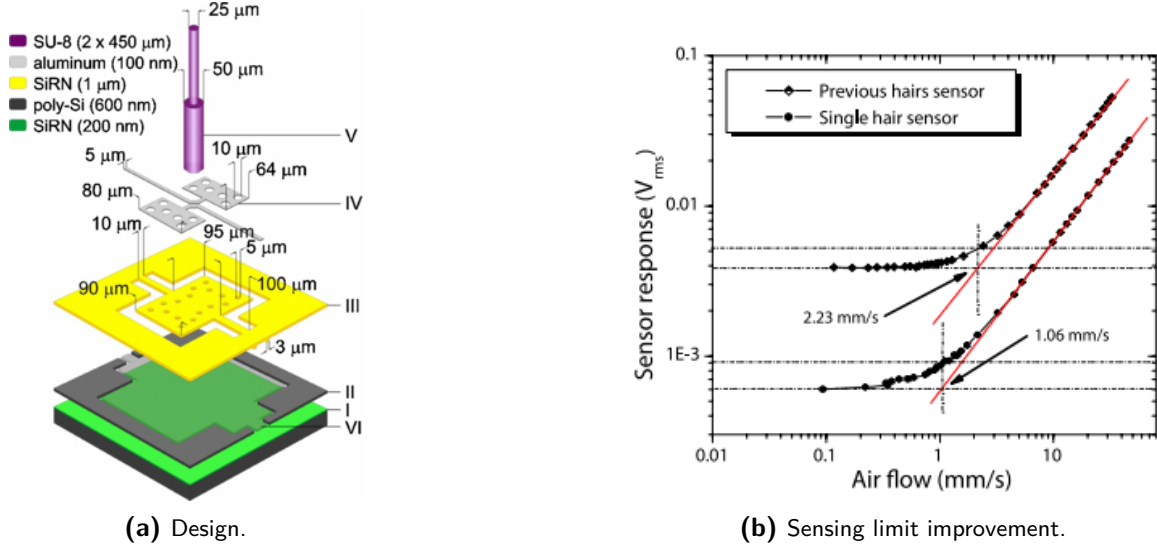


Figure 2-10: Improved artificial biomimetic flow sensor based on cricket mechano-sensory hairs [35].

Another implementation of a capacitive membrane is an adaptation by A Castro et al. with a parylene membrane and UV curable hair. The sensor is characterized with a sensing range of 0.5 - 3 m/s with a resolution of 4 fF [44].

The latest study on bio-inspired capacitive MEMS sensors is conducted by K Rajasekaran et al. that comprises of four pairs of electrodes consolidated into a single circular flexible top surface. The working principle illustrated in figure-2-11 depends on the drag force incident on the hair surface to cause a change in position of top electrode and consequently change in capacitance. Depending on airflow direction the two opposite electrode pairs provide maximum change in capacitance roughly indicating airflow direction. The electrodes squeezed towards the bottom electrode display increase in capacitance and the opposite electrodes display decreasing capacitance [54].

The 3D printed component of the sensor is assembled with UV curable polymer onto the PCB design comprising the four bottom electrodes.

The sensor characterization measures a sensing range of 5 m/s to 10.2 m/s with a sensitivity of approximately 1.17 - 3.8 fF/(m/s). The differential capacitance change is in the range of 0 - 20 fF for the sensing range. The sensor successfully displayed directionality with good accuracy. Enhancements to the fabrication process have the potential to improve sensor performance.

2-5 Discussion and Conclusions

In addition to the three primary sensing mechanisms, several studies are conducted on piezo-electric sensing as a viable alternative. Piezoelectric airflow sensors consume power for exci-

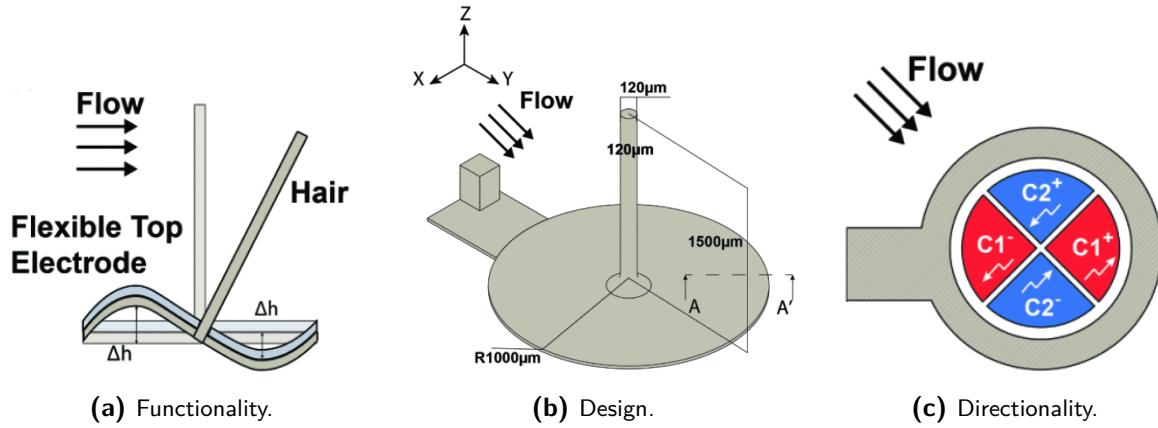


Figure 2-11: 3D printed bio-inspired hair sensor for directional airflow sensing [54].

tation and read out electronics, therefore have a relatively low power consumption budget. In contrast to traditional sensing mechanisms, piezoelectric sensors rely on the conversion of mechanical strain into electrical signals, thus rendering them incapable of detecting static airflow conditions [50]. Many airflow sensor studies combine various mechanisms to enable sensing. Sensors developed by B Peterson et al. implement micro-hydraulics with silicone oil that convert drag force to change in pressure measured by a change in capacitance. The inclusion of micro-hydraulics prevents electrode contact, stitching and provides an opposing force [36]. On the contrary, micro-hydraulics increases fabrication complexity, therefore many other design choices with simpler fabrication process can be implemented to prevent electrode contact and stitching. Upon consolidating pertinent research on airflow sensors across the three primary sensing mechanisms, it becomes imperative to select a suitable sensing mechanism for the modeling or conceptualization of our airflow sensor.

Depending on sensor design, thermal sensors are characterized by high sensitivities and variable sensing ranges. They are notable for a relatively robust accuracy and represent the most extensively explored sensing mechanism, with a diverse array of commercially available airflow sensors. Nevertheless, thermal sensors must be carefully designed keeping in mind the need for an effective thermal isolation between the heating element and sensing element. Due to the low forced convection at low airflow velocities, thermal sensors do not produce reliable measurements at these velocity ranges. Additionally, parasitic thermal losses reduce measurement accuracy and sensitivity, therefore necessitating an emphasis on maximizing the produced temperature difference through efficient thermal isolation strategies. Thermal sensors inherently consume a high percentage of the power budget as depicted in table 2-1. Additional thermal losses only contribute to an escalation in power consumption.

Piezoresistive sensors, in contrast to thermal sensors, exhibit lower power consumption with cost-effective fabrication processes. However, sensor performance is dependent on temperature and therefore introduces limitations in various temperature dependent conditions. Conversely, capacitive sensors are temperature independent and are capable of adopting a passive or active mode of sensing. Piezoresistive sensors constantly consume power while functioning, whereas capacitive sensors intrinsically consume low power. Therefore, capacitive sensing

Sensing method	Power (mW)	Range (m/s)	Sensitivity	Direction	Response time	Accuracy
Thermal						
Mesh membrane - Hung et al.	14.56	1.5 - 11	27.35 mV/(m/s)	-	<5ms	-
3C - SiC - V Balakrishnan et al.	24.96	0.2 - 9	0.091 s/m	2D	2s	1.3%
Piezoresistive						
Si ₃ N ₄ Microcantilever - Wang et al.	0.15	0 - 45	0.0284 Ω /(m/s)	Yes	0.53s	2%
MAV - H Takahashi et al.	-	-0.7 - 0.7	0.96 (s/m) ²	-	0.05s	-
Bio-inspired - D Shen et al.	-	0 - 40.5	60.35 mV/(m/s)	2D	-	-
Capacitive						
Biomimetic AMK Dagamesh et al.	-	0.001 - 1	10 - 100 fF/(m/s)	1.39pF/rad	-	-
Bat inspired - A Castro et al.	-	0.5 - 3	-	2D	-	-
3D printed - K Rajasekaran et al.	low	5 - 10.2	3.8fF/(m/s)	2D	-	-

Table 2-1: Summary of sensing methods.

mechanisms are widely implemented in low power applications. A MEMS-based out-of-plane mechanical airflow sensor co-integrated with CMOS technology, developed by Andre et al., achieves remarkable ultra-low power consumption, measuring in the order of 1 μ W [38]. Similarly in the domain of pressure sensing, capacitive sensors are favoured over piezoresistive sensors due to the very low power consumption capability [40]. Because power consumption is of paramount importance for FWMVs, it prudent to consider capacitive sensing solutions. Furthermore, MEMS out of plane capacitive sensors also enable the integration of additional 3D structures like bio-inspired hair and mechanical protection structures to create enhanced sensitivity.

Concept formulation

3-1 Design approach

Capacitive sensors are designed and implemented in a multitude of applications that detect material properties, motion, and proximity [4]. Each of these applications requires custom configuration and design for optimal implementation. The sensor design is predominantly constructed considering functionality, effective performance, reliability, and fabrication requirements.

3-1-1 What are we looking for?

In the context of airflow sensors, the design of a capacitive sensor must include a surface that interfaces with the incident airflow. Consequently, the interfacing surface experiences a drag force which can be harnessed to produce an interpretable output corresponding to the incident flow velocity. Since movable electrode(s) enable change in capacitance (ΔC), the sensor structure can be designed to facilitate efficient transduction from the incident drag force to ΔC . Equation 2-6 illustrates the dependency of capacitance on physical parameters such as area (A), distance between electrodes (d_o), and dielectric material of the capacitor. This is indicative of the possibility to measure change in mechanical properties due to electrode displacement, translating to ΔC . Sensor calibration correlates ΔC to the incident airflow change. Additionally, the design must be structured such that the electrodes are sufficiently held in place and enable a defined movement. Directional sensing is another imperative feature of an airflow sensor essential to determine flow characteristics. The sensor design should have the capability to exhibit a high differential capacitance, on top of an adequate base capacitance, and low parasitic capacitance to mitigate noise and maintain accuracy. Higher base and differential capacitance reduce the influence of parasitic capacitance.

As discussed previously, structure and dimensions predominately determine sensor performance. The displacement of interfacing surface and electrodes limits the dynamic range of the sensor. Similarly, sensitivity and response time of the device is determined by the change in displacement or capacitance to the change in flow velocity. This change in displacement is typically dependent on the structure, shape, dimensions, and material stiffness.

Sensor reliability ensures the repeatability and stability of the device. Additionally, a reliable sensor prevents unintended phenomena such as irreversible contact of the capacitor electrodes. It is essential for the sensing element to be well supported or must include a support structure to minimize interference and damping effects. Each element of the sensor structure requires suitable materials depending on functionality. It is important to consider the limitations of the fabrication processes, and therefore, the sensor should be designed to facilitate ease of

fabrication.

With the above-mentioned requirements in consideration, our exploration delves into various capacitive sensor configurations and concepts. The objective is to identify and assess diverse sensor designs that could meet the criteria of high differential capacitance, low parasitics, efficient transduction and reliability, while maintaining fabrication feasibility. The following section briefly describes the concept exploration which led to a final sensor design.

3-1-2 Concept exploration

Capacitive sensors are designed with various electrode configurations, each with unique electrode movement that aids to changes in sensor capacitance for various applications. Depending on the application, the customization involves identifying input parameter which enables changes in capacitance. Figure-3-1 depicts some of the sensor configurations considered. Spacing variation involves change in distance between the electrodes, whereas area variation refers to change in overlapping area of the electrodes [4]. Similarly, variation in dielectric properties can also be measured with capacitive sensing. Few applications also include more than two electrodes in sensor design to improve sensitivity and accuracy [4]. However, it is optimal to consider area variation or spacing variation due to its design & fabrication simplicity and applicability in airflow sensors.

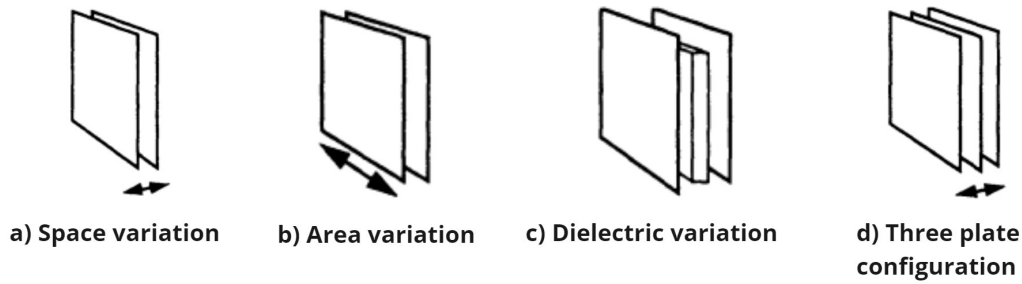


Figure 3-1: Various configurations of capacitive sensors [4].

Spacing variation is the most commonly implemented configuration for airflow sensors. Area variation is predominantly applicable for motion detection of large movements [4]. Area variation relies on the parallel movement of the moving electrodes, therefore, achieving this translation movement is challenging and may not be applicable for relatively small movements induced by low velocity airflow.

Similar to the piezoresistive approaches, two types of cantilever beam structures can be implemented, the self-bent and straight cantilever structures. The self-bent cantilever structure can incorporate a metal layer undercoated by a dielectric material which prevents contact of electrodes. One such implementation is observed in the airflow sensor co-integrated with CMOS technology depicted in figure-3-2a. The sensor has a very low power consumption rate and measures airflow velocity between 0 - 120 m/s [38]. The straight cantilever also finds itself in another study of airflow sensor applied in airplane health monitoring system [47]. Although both implementations previously depict positive results, the sensitivity of these sensors, depicted in figure-3-2b are very low, implying low differential capacitance. The surface area

is relatively low compared to membrane based sensors implying low base capacitance. Additionally, these sensors are incapable of directional sensing due to its structure. Therefore membrane based structures are relatively more suitable to incorporate these features.

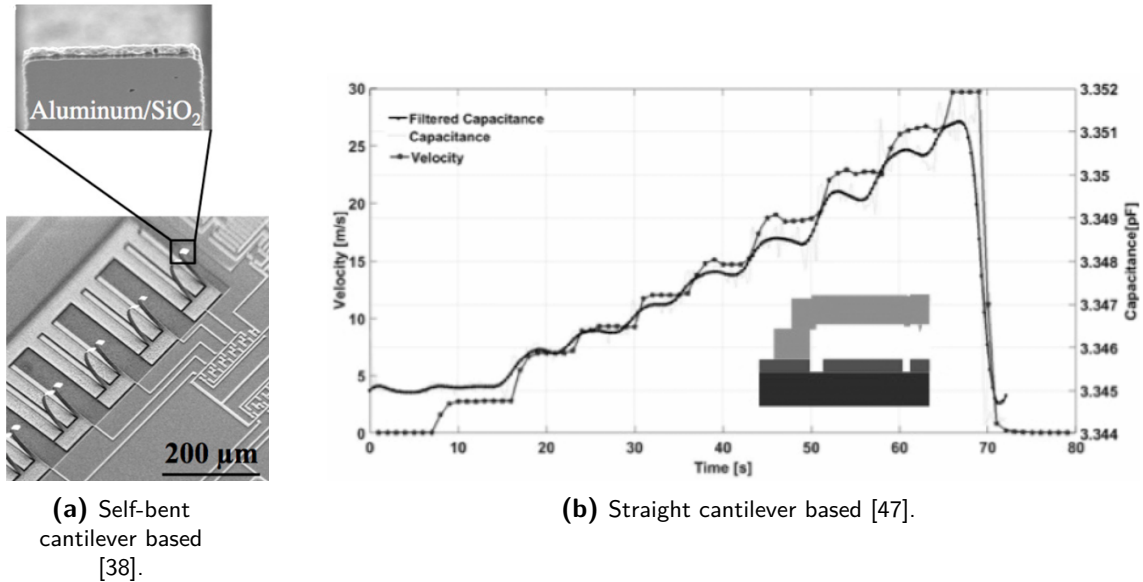


Figure 3-2: Cantilever approaches to capacitive airflow sensors.

The previously discussed bio-inspired approach in section 2-4, provides a membrane based, directional capacitive sensing solution. The base capacitance and directional sensing features can be customized depending on requirements. Additionally, this concept provides ample room for performance optimization and feature addition along with fabrication feasibility.

3-2 Bio-inspiration

A wide spread of inventions have been inspired by various mechanisms available in nature. The aerospace field is a primary example of this implementation. Wings of planes and of some Unmanned Aerial Vehicles (UAVs) are examples of bio-inspired technology. The FWMAVs mimic the flapping mechanism of many winged aerial animals. The drone consists of many control units and sensors to navigate and maintain flight. This leads to the question - Do animals or insects with flight/flying ability also use these units to control their flight? A closer look into such creatures might provide an answer.

Many aerial, aquatic, and terrestrial animals have the ability to sense flow patterns. This is an essential ability/feature enabling them to prey signal identification, sensation in the darkness, and aid in efficient movement [39]. Consequently, this helps protect themselves and survive in the wild.

Bats are the only mammals with the ability of powered flight, meaning bats have the ability to fly long distances with controlled maneuvers. The wing of the bat is comprised of a membrane covered with stiff hair which provides aerodynamic feedback like airflow velocity and direction, enabling a controlled flight [33]. This sensor system comprising the hair and its follicles are situated in an array thus enabling sensing of low-speed airflow [39].

Terrestrial animals and insects like anthropods have similar sensory systems. Anthropods are invertebrate animals with exoskeletons and segmented bodies. Spiders and crickets are prime examples. Crickets typically employ these sensory systems to detect prey, avoid predators, and enable navigation. In addition to these applications, spiders also implement this system to maintain their web network. The sensory hair, usually referred as filiform hair or trichobothria (figure-3-3), is found on the exoskeleton. Filiform hair is a mechanosensory system that transduces the mechanical input, i.e., drag force of airflow, to nerve signals [11].

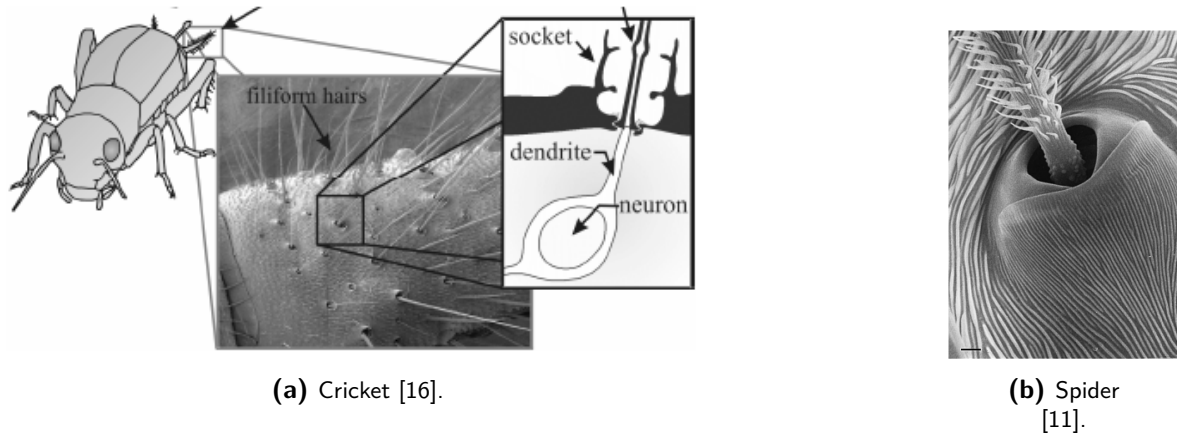


Figure 3-3: SEM images of mechano-receptive filiform hair.

The shaft of the hair is the mechanical interface which senses external movement due to deflection. This further causes a strain at the base of the hair which is converted to nerve signals by dendrites, and is further provided as feedback signals to enable flight control. To implement this inspiration from nature, a series of mechanical model of the filiform form, depicted in figure-3-4, is developed by F Barth et al. and J C Humphrey et al. [2]. Consequently, T Shimozawa et al. have developed a widely implemented model of an inverted pendulum due to the resemblance of the hair movement [8].

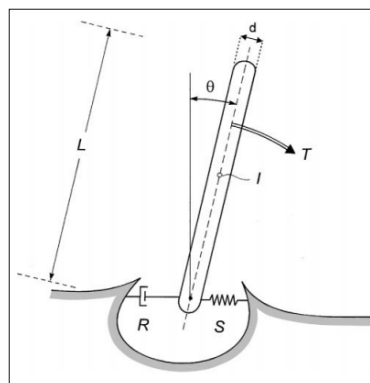


Figure 3-4: Mechanical model of filiform hair [11].

3-3 Envisioned sensor structure

Consolidating the findings of the literature review and the various inspirations, a capacitive sensor structure is envisioned, predominantly inspired by the mechano-sensitive hair structure and mechanism. The sensor is designed in two parts:

- **Hair:** The hair represents the interfacing structure which experiences the incident airflow. It is affixed on a sensing base. Upon airflow incidence, the hair structure displaces due to drag force resulting in torque. This torque translates to a displacement or strain on the sensing base.
- **Sensing base:** The sensing base is comprised of the capacitive sensing module with electrodes separated by a cavity of air. The cavity between the membrane and substrate enables microfluidic damping. Two pairs of electrodes are designed into a suspended support membrane situated on opposite sides of the hair. A pair of electrodes are encapsulated in the membrane while the other pair is affixed at the immovable base. Each pair of affixed and movable electrodes, separated by an air cavity, together form the left and right capacitors. The supported hair translates the resultant torque as a deformation of the membrane and further displacement of electrodes, thus leading to a change in capacitance. The membrane support act as springs, therefore, the cavity and support combined represent the mechanical model of filiform in figure-3-4.

The resulting design, illustrated in figure-3-5, provides an optimal design to convert change in fluid flow to a measurable change in capacitance. The current two-pair electrode design is adopted to prove the design concept. A further iteration of the design could comprise four or more pairs of electrodes to accommodate for accurate directional sensing. In the course of this thesis, the primary focus will be on designing and optimizing the sensor base, while accommodating and analysing the influence of a hair structure it would potentially support.

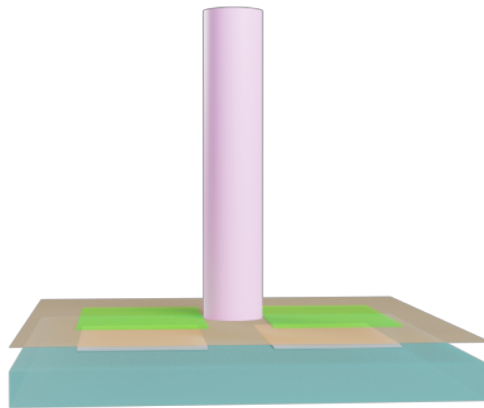


Figure 3-5: Model translating filiform hair.

Electrodes

As discussed previously, the base capacitance of the sensor is a vital parameter to account for in the sensor design. The electrode dimensions are determined by the desired magnitude of base capacitance. Additionally, a crucial consideration is the metal material and deposition temperature to guarantee an efficient and compatible fabrication process.

Membrane + Pivoting dimple + Anti-stitching dimples

The proposed sensor design must include a pair of suspended electrodes to ensure displacement corresponding to hair movement. This can be efficiently achieved by incorporating a membrane to suspend the electrodes and facilitate sufficient deformation in response to the hair movement. There are various methods for suspending a membrane, commonly found in many applications. Two of these implementations include, MEMS gas sensors [6] and MEMS accelerometers [24]. The electrodes can be situated either on top of the membrane or embedded within it.

An additional support at the centre of the suspended membrane could potentially aid to the sensor's functionality by enabling a robust movement of the hair which would be placed atop it. The additional support, referred to as the pivoting dimple, facilitates the pivoting movement of the hair and limits movement in the z-direction, therefore allowing increased applied voltage (discussed in section 4). The dimensions of this structure is expected to be significantly smaller compared to footprint of the hair, ensuring no restrictions on hair movement.

Similarly, numerous dimple structures are integrated across the lower surface of the suspended electrodes. These dimples are minute bumps that do not impede membrane deformation, but exist to prevent the electrodes from potentially stitching when the displacing electrode (referred as top electrode) comes in contact with the electrode affixed at the bottom (referred as bottom electrode). These dimples are referred to as anti-stitching dimples.

For ease of fabrication, it is crucial to ensure coherence among these elements. Therefore, maintaining a uniform material choice for each element is optimal. Any variation in materials could potentially impact the adhesion between elements, which is vital for membrane deformation.

Hair

The sensitivity of the sensor is primarily determined by various characteristics of the hair structure, including its shape, size, and material composition. To optimize sensor performance, it is essential to ensure that the membrane surface provides enough area to securely attach the hair. Additionally, the sensor's design should accommodate either an externally fabricated hair structure or an integrated fabrication process that aligns with the production of the hair and the sensor base.

3-4 Discussion

The envisioned bio-inspired sensor design comprises various elements vital for effective functionality. The hair structure serves as a surface for airflow incidence enabling hair displacement. The sensing base provides a platform to demonstrate capacitive sensing corresponding to the hair displacement. It is imperative that the elements of the design for different layer features are coherent on a system level. Additionally, the design should be compatible with a low-complexity fabrication process. The dimensions and material choices for each element define the various performance parameters previously discussed. The elements comprising the proposed design require an in-depth analysis to accurately define characteristics in accordance with the sensor requirement and further ensure optimal and efficient performance.

Design

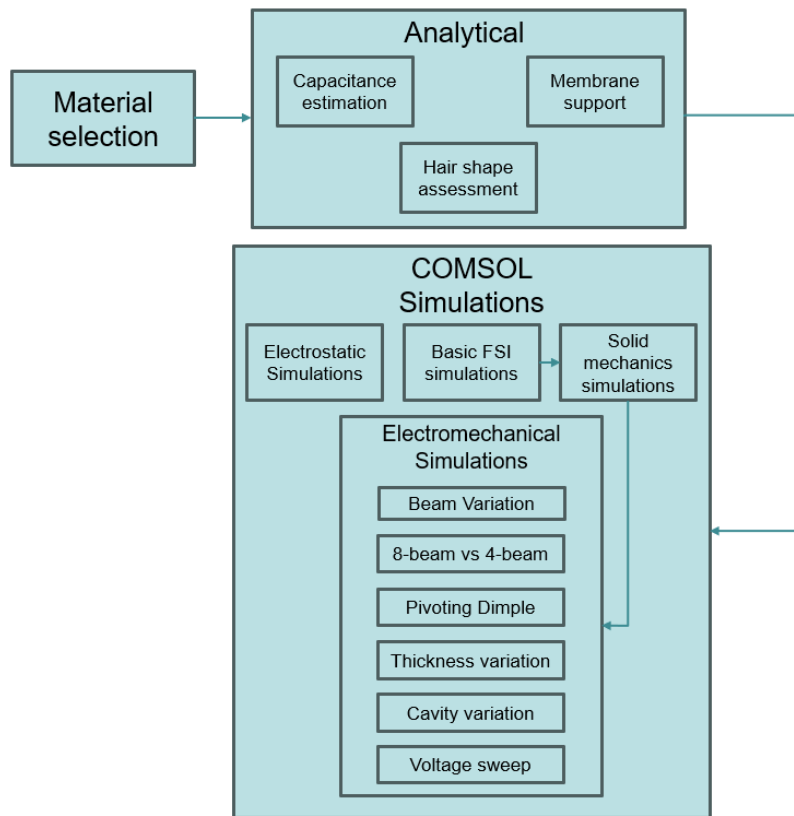


Figure 4-1: Block diagram illustrating chapter outline.

This section follows the outline as illustrated in figure-4-1.

4-1 Material Selection

The hair and membrane structures incorporated in the proposed design are the closest approach that embodies the bio-inspiration from various species. Although the structure of the design attributes significantly in the functioning of the sensor, the choice of material for different feature elements can aid or hamper performance. Young's modulus of the material is one such example that defines material deformation, vital for the membrane. Additionally, the fabrication process depends on the material choices, therefore it is imperative to select materials that maintain a low fabrication complexity.

While selecting materials, crucial steps of the fabrication process must be considered. The proposed design leads to the sandwich of patterned layers with distinct functionality, therefore material adhesion and cohesive layering is important. Furthermore, to fabricate the cavity between the electrodes, a temporary sacrificial layer in the shape of the cavity is included to aid in constructing the elements around it. After the sensor structure is complete, the temporary layer is sacrificed, leaving behind a cavity. This 'sacrificing' process involves vapour HF etching or wet etching. Therefore, materials of the exposed feature layers must be compatible to the etching processes.

4-1-1 Membrane + Support + dimples

The membrane and surrounding support for the membrane are the main structures of the proposed design. To ensure coherence, integrity, and uniformity, it is optimal to fabricate the surrounding support concurrently with the membrane structure, as well as for the pivoting and anti-stitching dimples. Consequently, the material implemented for these structures would remain the same.

Many materials can be taken into account to materialize these structures, but only few materials are viably fabricated as thin films in cleanroom facilities compatible with MEMS devices. Some of them include organic films, Silicon Carbide (SiC), silicon nitride (Si_3N_4), poly-Si and metals [19]. Metal and metal nitrides are conductive, therefore cannot be considered for this application. Polymers on the other hand have the ability to retain vapour HF and eventually emit toxic fumes when exposed to it. Therefore the material is known to be incompatible with vapour HF etching process. Consequently, SiC, Si_3N_4 and poly-Si are best implementable for membrane applications.

The FWMAVs typically operate at room temperature and experience various kinds of impact upon collision during the testing and development process. Therefore, materials considered for the sensor do not particularly have a temperature requirement but are expected to maintain mechanical durability and some degree of resistance to harsh environments. The pivoting dimple is implemented to improve robustness and limit movement in the z-direction, therefore the chosen material must be compatible with structure functionality. Similarly, anti-stitching dimples would tend to come in contact with the base electrode, therefore are prone to wearing. Furthermore, the membrane material must possess sufficient elastic properties to allow deformation when subjected to an external force.

Out of the aforementioned three potentially ideal materials, SiC exhibits the highest abrasive wear resistance, therefore ensuring mechanical durability and robustness [20]. It is also typically implemented as a protective coating layer in erosive environments due to its chemical resistance [18][22]. Additionally, the sensor would be constantly exposed to air, moisture, and vibrations due to flapping. SiC deposited at a temperature above 325°C displays high stability when exposed to such environments [49][28]. From a fabrication point of view, SiC is also the preferred option since it is compatible with the vapour HF process. On the contrary, most forms of silicon nitride are incompatible with vapour HF since they experience etching with some unintended residue [14].

Material deposition processes have been developed over the years such that material properties can be customized depending on the application. A slight tensile stress is required during membrane release to avoid buckling of the free-standing membrane. Therefore, a low-stress

material deposition is best suitable for the "sandwiching" of layers. This material optimization will be further elucidated in Chapter 5.

4-1-2 Electrodes

The EKL cleanroom facility categorizes metals into two groups: green and red metals, based on their potential to contaminate equipment. In this context, contamination refers to the presence of metal residues in the equipment, which requires extra handling to prevent contamination. Red metals are considered contaminating metals. Consequently, green metals are the preferred choice of materials for fabricating these electrodes to circumvent any limitations on the utilization of cleanroom equipment.

Aluminium (Al), classified as a green metal, is the most commonly used metal material in MEMS fabrication. It is corrosion-resistant and offers a balance between strength and flexibility making it a ductile and malleable metal. Many applications that require flexible structures employ aluminium due to its ductility [30]. This ensures a smooth deformation of the membrane without hindering functionality. Since aluminium has been implemented in multiple studies over the years, it is compatible with various fabrication processes.

A previous study conducted at EKL included the deposition of SiC directly onto an aluminium surface resulting in a yet unknown dark residue caused due to a reaction between Al and the precursor gases involved in the SiC deposition. Considering the same deposition conditions and components are intended to be used for this application, it is prudent to implement a solution to mitigate this issue. Consequent to the previous study, Titanium Nitride (TiN) was deposited onto the aluminium surface as a protective layer to prevent the unintended reaction. Similarly, a TiN layer is implemented onto the sensor electrodes to provide the same kind of protection.

4-2 Analytical analysis

To incorporate the proposed design and the chosen materials, a rudimentary analytical analysis is conducted to provide a foundation for the different variations of the design. This analysis aids in eliminating or proceeding with certain design choices and further elucidate the analysis with COMSOL simulations. The following sections are segmented into the various parts of the design to simplify the analysis.

4-2-1 Electrodes

A simplified model of parallel plate and tilted plate is adapted to estimate the base and differential capacitance respectively. Electrode dimensions predominantly determine membrane dimensions and are derived from an estimation of the base capacitance. The estimation is made by accounting for the base capacitance supported by available read-out circuits [57][58]. Additionally, fabricating larger device dimensions have limitation in terms of the fabrication process. Furthermore, the design can accommodate two potential locations to place the electrodes with respect to the deforming membrane:

- Below-membrane
- Above-membrane

Equations 4-1 and 4-2 describe the base capacitance of electrode placements above and below the membrane respectively (figure-4-3).

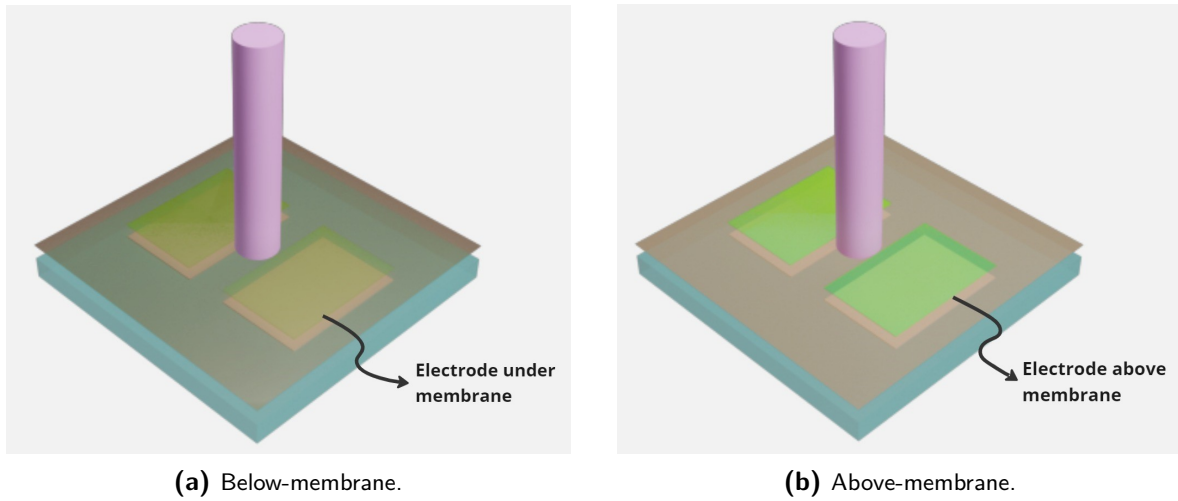


Figure 4-2: Electrode placements.

$$\text{Capacitance } C_{\text{am}} = \frac{\epsilon_r \epsilon_{\text{SiC}} A}{\epsilon_{\text{SiC}} d_o + \epsilon_r d_{\text{SiC}}} \quad (4-1)$$

$$\text{Capacitance } C_{\text{bm}} = \frac{\epsilon_r A}{d_o} \quad (4-2)$$

Width (μm)	Length (μm)
381	1450
290	1905
435	1270
635	870

Table 4-1: Electrode dimensions for Base capacitance = 2.44pF and Area (A) = 552450(μm)².

Considering the input capacitance range of commercially available AD7746 and Universal Transducer Interface (UTI) read-out circuits, a base capacitance of around 2pF is considered to derive electrode area. Additionally, an initial estimation of the distance between electrodes (2 μm) is required to derive electrode area which is further discussed in section 4-2-2 and elaborated with simulation results in section 4-3. Implementing equation 4-2, various electrode dimensions are estimated using the calculated area (A), tabulated in table 4-1. Since two electrodes are to be incorporated in the membrane structure, it is prudent to maintain minimal dimensions to avoid limitations in fabrication like wafer stepper resolution.

An approximate estimation of the achievable capacitance range can be derived when the electrode experiences a maximum tilt. The membrane is assumed to be stiff, therefore the electrode displacement is expected to be tilted as depicted in figure-4-3. A flexible membrane enables the deformation of a larger area, therefore providing a larger capacitance range. Consequently, a tilted stiff membrane provides a minimal range of capacitance. Equations 4-3 and 4-4 describe the capacitance of a tilted membrane for electrode placements below and

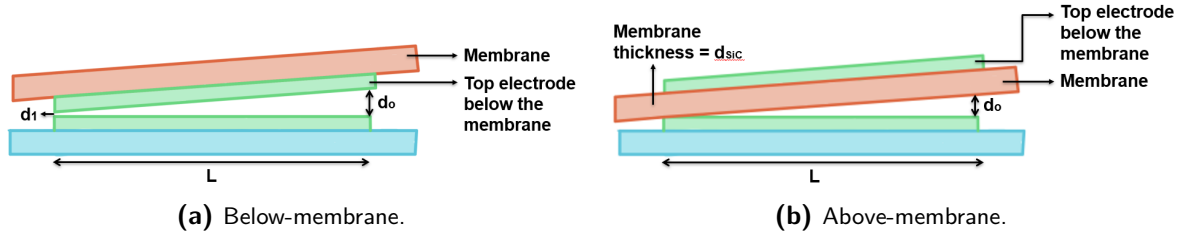


Figure 4-3: Representation of tilted electrodes for the two electrode placements.

above the membrane respectively. Table 4-2 provides the differential capacitance of one pair of electrodes for the two electrode placements.

$$C_{\text{tilt}bm} = \frac{\epsilon_o A}{d_o - d_1} \ln\left(\frac{d_o}{d_1}\right) \quad (4-3)$$

$$C_{\text{tilt}am} = \frac{\epsilon_r A}{d_o} \ln\left(\frac{\epsilon_{SiC} d_o + \epsilon_r d_{SiC}}{d_{SiC} \epsilon_r}\right) \quad (4-4)$$

Capacitance	Value
C_{am}	2.326pF
$C_{\text{tilt}am}$	7.377pF
$C_{\text{tilt}am} - C_{am}$	5.051pF
C_{bm}	2.446pF
$C_{\text{tilt}bm}$	20.29pF
$C_{\text{tilt}bm} - C_{bm}$	17.844pF

Table 4-2: Differential capacitance for electrode placements above-membrane (am) and below-membrane (bm).

Electrodes below the membrane showcase higher differential capacitance with a larger dynamic range, without being constricted by the membrane thickness. Therefore, the underneath-membrane electrode placement is considered over the above-membrane electrode.

4-2-2 Cavity

As established previously, the device is comprised of a suspended membrane, implying a hollow gap between the resting surface (bottom electrode) of the device and the deformable membrane. The hollow gap here is referred to as a cavity. The dimensions of this cavity are vital in defining the dynamic range, damping, and bulk capacitance. The cavity dimensions are a trade-off between these parameters. Damping is a phenomenon that causes a structure or material to experience oscillations or vibrations. Typically in MEMS sensors, thin films or thin cavities lead to a similar damping effect called squeeze film damping [55]. Here, it is important to note that the cavity thickness of the sensor either thins or enlarges depending on the applied drag force to the hair. As the cavity thins, the membrane experiences a small upward resistance as the air in the cavity tries to escape. This phenomenon causes damping. The resistance experienced is negligible compared to the electrostatic pull-in force. The study of this phenomenon for this device aids in the estimation of cavity thickness which can be potentially conducted in the future.

More vital considerations include:

- Range of dynamic membrane deformation to provide sufficient differential capacitance.
- The above must be implemented without significantly influencing the base capacitance to avoid limitation of the capacitance range. The differential capacitance should be able to sufficiently correspond to wind speeds or applied force.

Considering previous implementations and experiences, $2\mu\text{m}$ of cavity thickness is a good start to begin estimation and further simulation analysis.

4-2-3 Membrane and Surrounding support

For efficient electrode and capacitance estimation, the membrane is assumed to be stiff. Realistically, force applied to the membrane results in a deforming membrane as opposed to a stiff motion. Considering this deformation, it is essential to determine a support structure for the membrane. It is a vital element to ensure optimal membrane deformation. The support structure is approached in two methods, closed membrane and beam support. Closed membrane support refers to an extended membrane with a reduced thickness dimension which is supported by a larger surrounding structure as the example depicted in figure-4-4a. Alternatively, the corners of the membrane are supported by cantilever type of beams modelled after a spring.

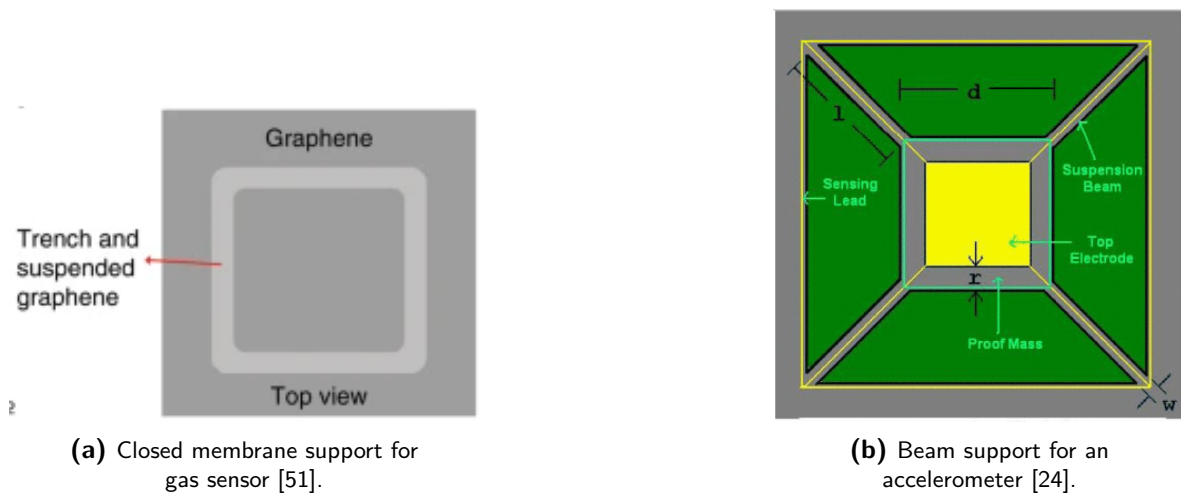


Figure 4-4: Options for surrounding support.

Flexible membrane deformation provides higher differential capacitance but has a risk of stitching to the base. Thin membranes are more prone to damages compared to stiff membranes. A solid mechanics COMSOL simulation of the two types of support enables further definition of the sensor structure.

A further look into beam support showcases multiple configurations of beams, but the 4 and 8-beam support (figure-4-5) enable symmetric deformation to avoid interference and maintain uniformity in sensing. Each beam support has a spring constant defined by k_z represented in equation 4-6. To evaluate the overall spring constant, k_z is multiplied by the number of implemented beams.

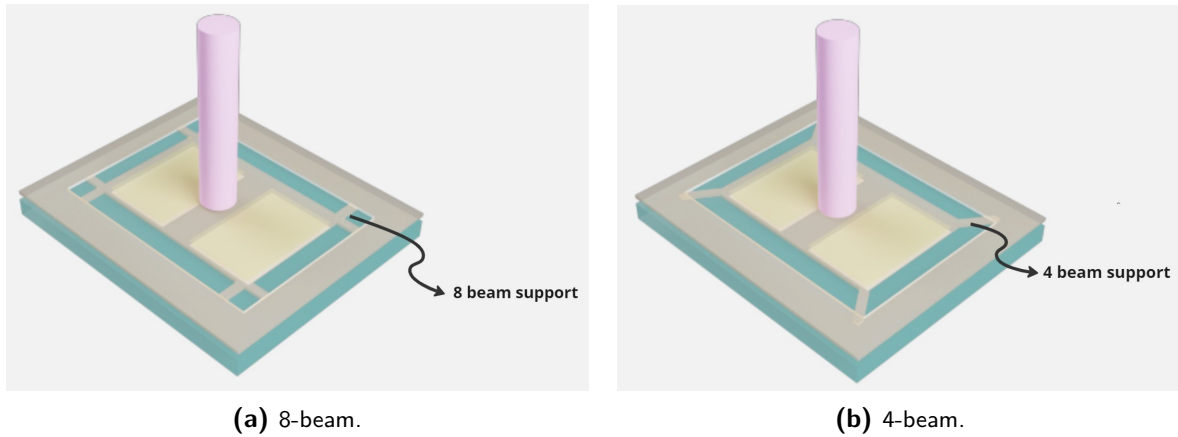


Figure 4-5: Types of beam support.

The maximum applied voltage on the top electrodes is determined by the spring constants of the beam. The strength of the beams establishes the electrostatic forces it can sustain. This phenomenon is typically addressed as the pull-in effect and the maximum applied voltage is also known as the pull-in voltage.

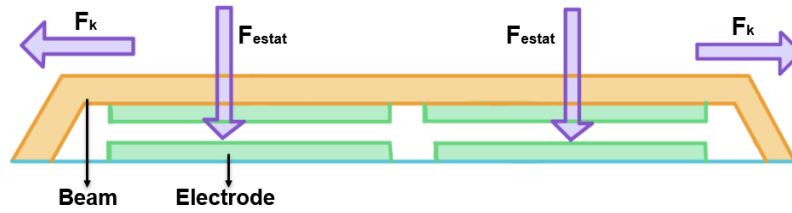


Figure 4-6: Cross section of sensing base depicting forces without pivoting dimple.

$$V_{\max} = \frac{2d_o}{3} \sqrt{\frac{k}{1.5C_{bm}}} \quad (4-5)$$

Spring constants of the various beam dimensions enable efficient filtering and selection. The beam dimensions are short-listed such that a distributed spring constant is maintained.

$$k = \frac{Ew_b h_b^3}{l_b^3} \quad (4-6)$$

Features	Value
Young's Modulus (E)	448 GPa
Base capacitance (C_{bm})	2.446 pF
Membrane thickness (h_b)	1 μm
Cavity thickness (d_o)	2 μm

Table 4-3: Values for $V_{\max}$ calculations.

Width (w_b)	Length (l_b)	k	$V_{\max}$ (V)
60 μm	210 μm	4.846	1.532
60 μm	300 μm	1.66	0.8968
100 μm	425 μm	0.974	0.686

Table 4-4: Calculated spring constants for single beam and pull-in voltages without dimple.

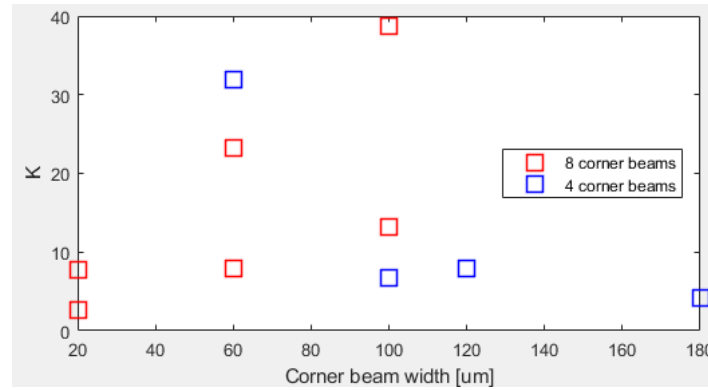


Figure 4-7: Spring constant distribution for 8-beam and 4-beam variation.

4-2-4 Hair

A detailed analysis of the hair is conducted simultaneously as an extension of the current project. Considering a hair structure will potentially be implemented, it is prudent to briefly estimate the nature of this structure. The drag force acting on the hair surface is predominantly dependent on the interfacing surface area and the drag coefficient of the structure. Various shapes depict varied drag coefficients illustrated in figure-4-8.

$$\text{Drag force} = \frac{\rho_{\text{air}} A_i v_{\text{air}}^2 C_d}{2} \quad (4-7)$$

ρ_{air} = Density of airflow,
 A_i = Incident surface area,
 C_d = Drag co-efficient,
 v_{air} = Velocity of air.

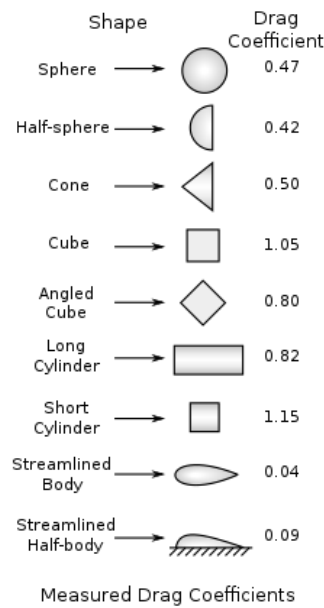


Figure 4-8: Various hair shapes.

A cylindrical hair structure has a relatively lower drag coefficient, therefore if the sensor performance requires potential improvement, the shape and dimension of the hair structure can be improved and modified to a shape with a higher drag coefficient. Therefore, the sensing base is optimized with the worst-case scenario.

4-3 Simulations

COMSOL simulations are conducted to corroborate the analytical analysis of the design. The preliminary analytical analysis provides a rudimentary structure for more detailed estimations through the simulations. Additionally, the interrelated effects of each part of the structure and various physics can be consolidated and estimated. Electrostatics, solid mechanics, electromechanical and Fluid Structure Interaction (FSI) simulations were conducted.

Basic Fluid Structure Interaction (FSI) simulations

For the proposed simulation structure, an FSI simulation was simultaneously run and provided to estimate the velocity range correlated to the drag force acting on the cylindrical hair. Figure-4-9 illustrates the graph resulting from a parametric sweep of hair radius and length depicting the influence of hair structure and dimensions on membrane deformation. The conditions for the simulations were provided by a set of parallel run simulations to analyse the hair structure.

The estimated range of forces helps guide the electromechanical simulations with reasonable boundary conditions without having to conduct more computationally expensive fluid structure interaction simulations when an electromechanical property is being studied. Consequently, the fluid environment is implemented onto the different variations of the sensors to assess the velocity range and resulting differential capacitance.

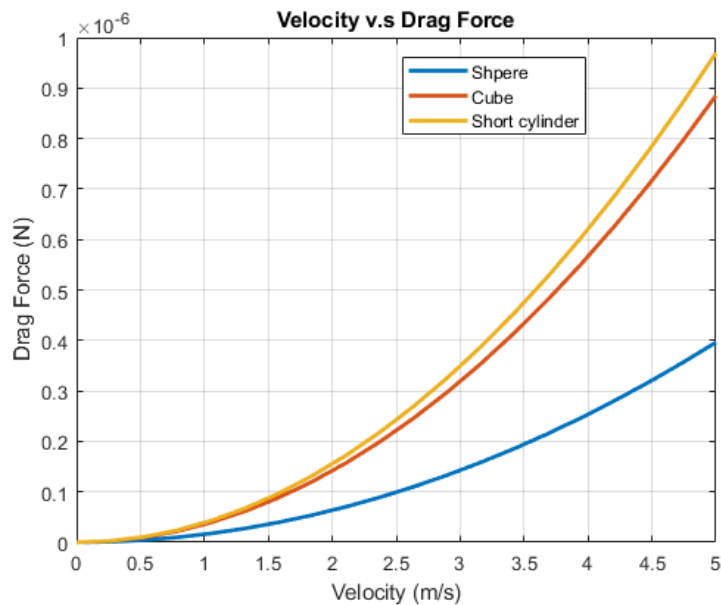


Figure 4-9: FSI simulation correlating drag force and velocity.

4-3-1 Electrostatics

Basic electrostatic simulations provide results to support the analytical analysis for base capacitance and differential capacitance. Two simulations are conducted with distinct geometry, one with a parallel "sandwich" of layers and the other with a tilted membrane and electrode. The parallel sandwich of layers provides the base capacitance and tilted layers provide a range of differential capacitance.

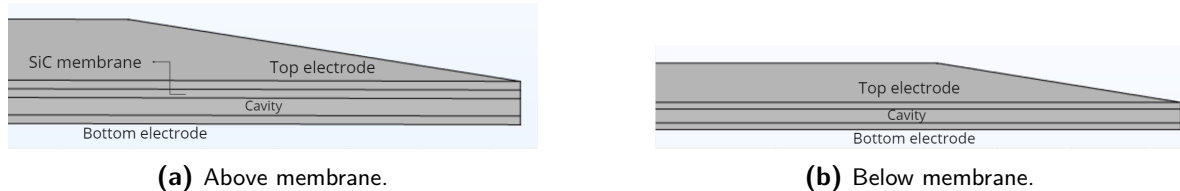


Figure 4-10: Parallel capacitors on COMSOL.

Simulation set-up

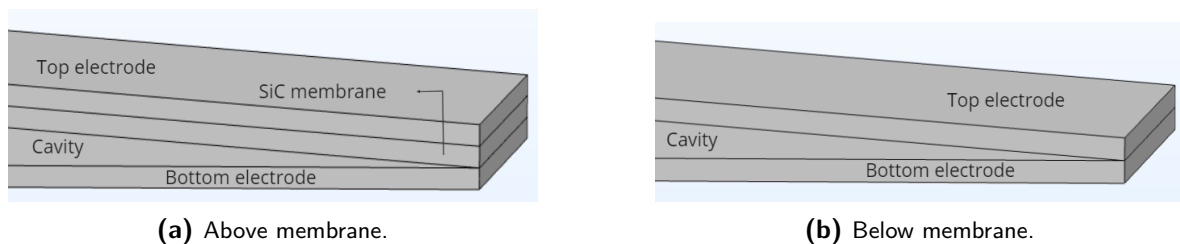


Figure 4-11: Tilted electrode plate on COMSOL.

In both simulation scenarios, a rudimentary geometry of the structures is built by layering four blocks, retaining the dimensions of the analytical analysis from chapter 4-2. The area of the membrane and cavity is that of the electrode. Above the membrane and below the membrane electrode configurations, represented in figure-4-10, are built to estimate the base capacitance associated with each scenario. Similarly, a maximum stiff membrane tilt is achieved by a geometry with hard coded tilt represented in figure-4-11. Materials assigned to layered blocks are shown as follows:

- Cavity: Air
- Electrodes: Aluminium
- Membrane: SiC

Simulation	Physics	Mesh	Study	Results Interpretation
Parallel electrodes	Electrostatics	Free tetrahedral - Fine	Stationary	1D parameter plot
Titled electrodes	Electrostatics	Free tetrahedral - Fine	Stationary	1D parameter plot

Table 4-5: Conditions of electrostatic simulations.

The resulting simulations corroborate the basic analytical analysis of base and differential capacitance estimation. The results are tabulated in table 4-7. For the configuration of the electrodes below the membrane, the electrodes do not come in contact, therefore a distance

$d_1 = 0.1\mu\text{m}$ is maintained.

Features	Dimension (μm)
Electrode width	635
Electrode length	870
Membrane thickness	1
Cavity thickness	2

Table 4-6: Relevant dimensions.

Capacitance	Analytical	Simulated
C_{am}	2.326pF	2.326pF
C_{tiltam}	7.377pF	7.117pF
$C_{\text{tiltam}} - C_{\text{am}}$	5.051pF	4.791pF
C_{bm}	2.446pF	2.445pF
C_{tiltbm}	20.29pF	-
$C_{\text{tiltbm}(d1=0.1\mu\text{m})}$	7.714pF	7.7125pF
$C_{\text{tiltbm}(d1=0.1\mu\text{m})} - C_{\text{bm}}$	5.268pF	5.2675pF

Table 4-7: Computed differential capacitance for the two electrode orientations.

4-3-2 Solid mechanics

Elucidating from the discussion in section 4-2-3, the results of the solid mechanics simulations determine the kind of support suitable for membrane deformation. The two main approaches for beam support are closed membrane and beam support which can be emulated by the various constraint options available.

Simulation set-up

A simple design with a hair structure atop a suspended membrane is implemented with a cylinder and block geometries respectively. The hair is implemented as a lever to deform the membrane with a point load at the top of the cylindrical structure. The point load is applied parallel to the base as depicted in figure-4-12 such that the membrane experiences maximum deformation. The stationary study conducted performs an auxiliary sweep on the point load between 0 and $35/40\mu\text{N}$.

The simulations are conducted with two main types of constraints:

1. Point fixed constraints: Set to the four corners of the membrane.
2. Edge fixed constraints: Set to the four edges of the membrane.

The material assigned to the block geometry is SiC. It is also assigned as linear elastic material under solid mechanics to describe the property of the membrane. SU-8 is assigned as the hair temporarily. The pivoting dimple is not included in this set-up. This is included in a consequent set-up, discussed in section 4-3-3. implemented with point constraint at the corner or the membrane.

Comparison between fixed constraints and results

Figure-4-13 displays the nature of membrane deformation. Point fixed constraints set at the four corners of the membrane display higher displacement of membrane deformation upon applied force on the hair. Therefore, this point constraints can be realistically emulated by beam supports to suspend the membrane. The beams are modelled after cantilever beams and therefore are mechanically modelled as springs. The following section implements the proposed beam models and is tested with electromechanical simulations.

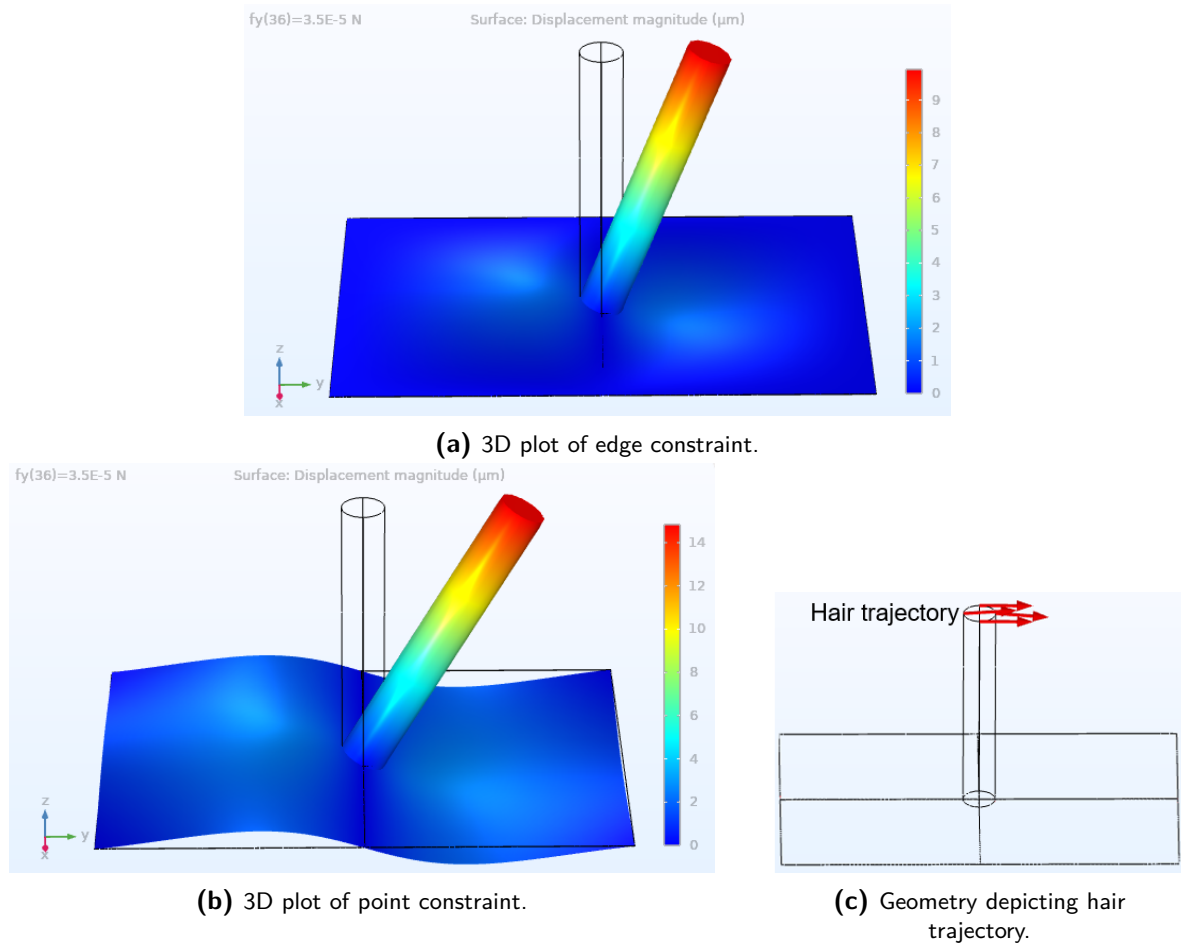


Figure 4-12: Set-up and results from solid mechanics COMSOL simulations.

Simulation	Physics	Mesh	Study	Results Interpretation
Fixed points	Solid mechanics	Free tetrahedral - Fine	Stationary- Auxiliary sweep	3D surface plot 1D displacement plot
Fixed edges	Solid mechanics	Free tetrahedral - Fine	Stationary- Auxiliary sweep	3D surface plot 1D displacement plot

Table 4-8: Conditions of solid mechanics simulation.

4-3-3 Electromechanical

A series of electromechanical simulations are conducted to analyse the various aspects of the proposed design. Here, the solid mechanics and electrostatic physics, along with the conditions and geometry, are combined to ensure all relevant forces are taken into account during the analysis.

Simulation set-up

Developing from the geometry of previous solid mechanics simulation, the beam structures are constructed with thin blocks merged between the membrane and surrounding support

Features	Value
Membrane width	982 μm
Membrane length	1492 μm
Hair radius	60 μm
Hair height	800 μm
Membrane thickness	1 μm
SiC Young's Modulus	448 GPa

Table 4-9: Relevant dimensions for solid mechanics simulations.

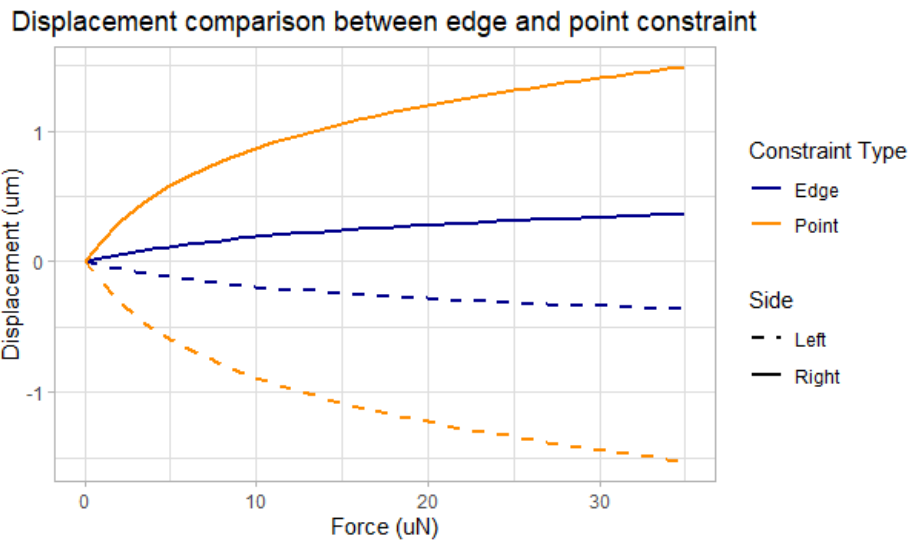


Figure 4-13: Results of solid mechanics simulation.

structure as depicted in figure-4-14. A truncated cone is inserted at the centre, under the membrane and hair structure. The entire structure is placed atop a base block with two additional blocks with electrode dimensions that represent the bottom electrodes. Two blocks are built under the membrane structure representing the top electrodes. The gap around the dimple, between the electrodes represents the cavity with air as the designated material. Considering the best differential capacitance is obtained with the electrode below the membrane, a detailed analysis is conducted for this electrode configuration.

Following is the list of materials assigned to the various features of the sensing base:

- Membrane, beams, all dimples: SiC.
- Cavity: Air.
- Electrodes: Aluminium.
- Hair: SU8 (temporary).

To assess the influence of dimensions on each element of the structure and the applied voltage, the following sections are dedicated to each element.

Beam variation

The membrane support now boils down to two configurations: 4-beam and 8-beam. The two configurations of beams provide a symmetrical corner membrane support. It is imperative to

Simulation	Physics	Mesh	Study	Results Interpretation
• Beam variation • 8-beam vs 4-beam • Thickness variation • Cavity variation • Voltage sweep	Electro-mechanical	Free tetrahe-dral - Fine	• Stationary Auxiliary sweep • Parametric sweep	• 3D surface plot • 1D displacement plot

Table 4-10: Conditions of electromechanical simulation.

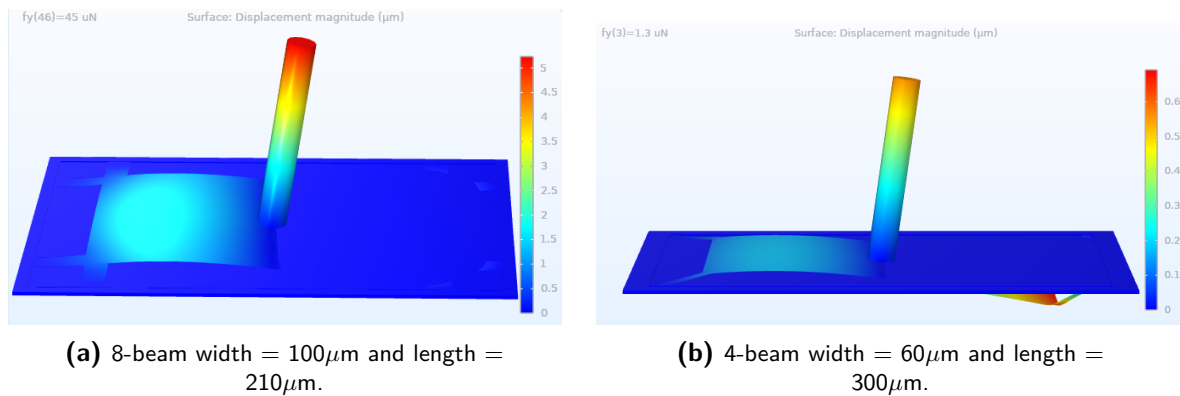


Figure 4-14: 3D displacement graph of electromechanical simulations on COMSOL.

assess the influence of the width and length of these support beams. The thickness of the beam, as discussed in section 4-2-3 has a strong influence on membrane deformation in the third order as opposed to beam width (refer to equation 4-6). For the current design, the thickness of the beam is considered to be the thickness of the membrane. This design choice maintains simplicity for the analysis and the proof of concept. Additionally, this minimizes complexity and fabrication steps. Future implementations of the concept can adopt thinner beam supports with thicker membrane structure independently.

To demonstrate the influence of beam width of the 8-beam and 4-beam support, an electromechanical simulation with parameterized width is conducted with constant beam length. Figures-4-15 and 4-16 illustrate the resulting graphs of this simulation. With a constant length of 300 μm for both 4-beam and 8-beam support, increasing width increases sensing range but reduces the differential capacitance i.e.: sensitivity. Similarly, variation in length is assessed by retaining a constant width in an electromechanical parametric sweep of varying length depicted in figures-4-17 to 4-23. In both the 4-beam and 8-beam variations the width of the beams are maintained at 60 μm. Longer beam lengths tend to portray a shorter range of sensing force i.e.: velocity. On the contrary, longer beam lengths portray increased sensitivity or higher sensed differential capacitance. Shorter length and wider beams have more sturdy structures and require more force to deform the membrane contrary to longer length and shorter beam width. Width variation does not have a significant influence on sensor performance as opposed to beam length which is in the order of third magnitude.

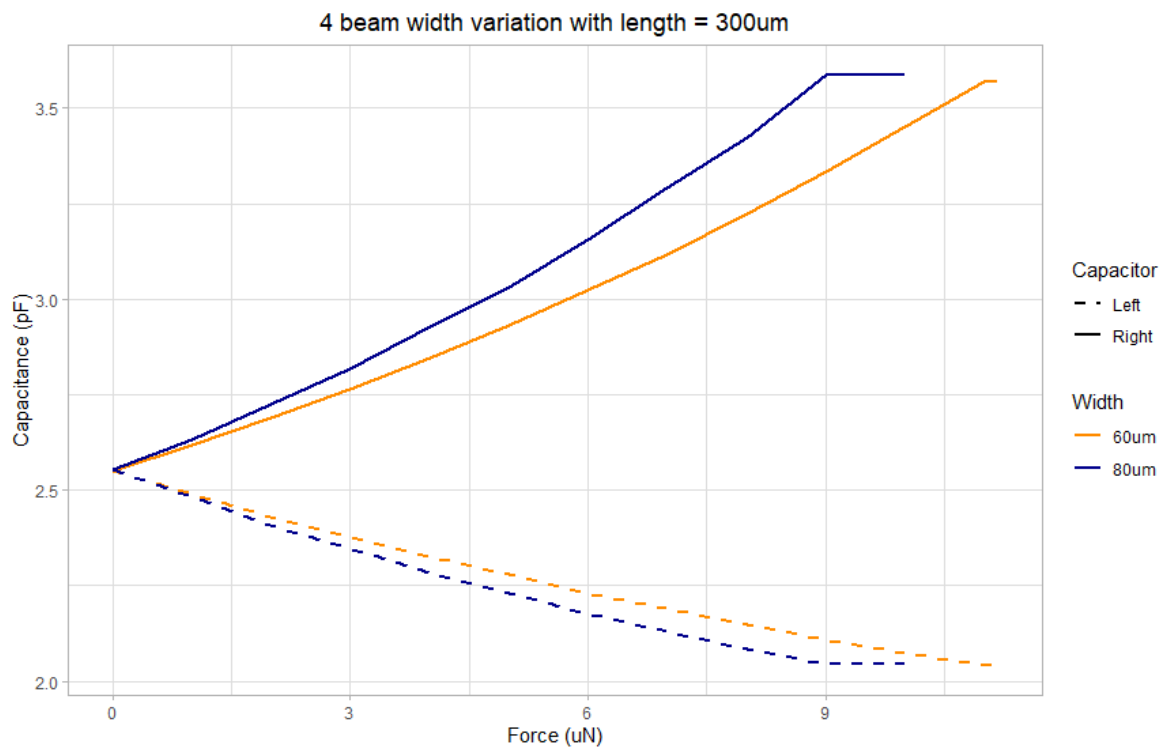


Figure 4-15: 4-beam width variation.

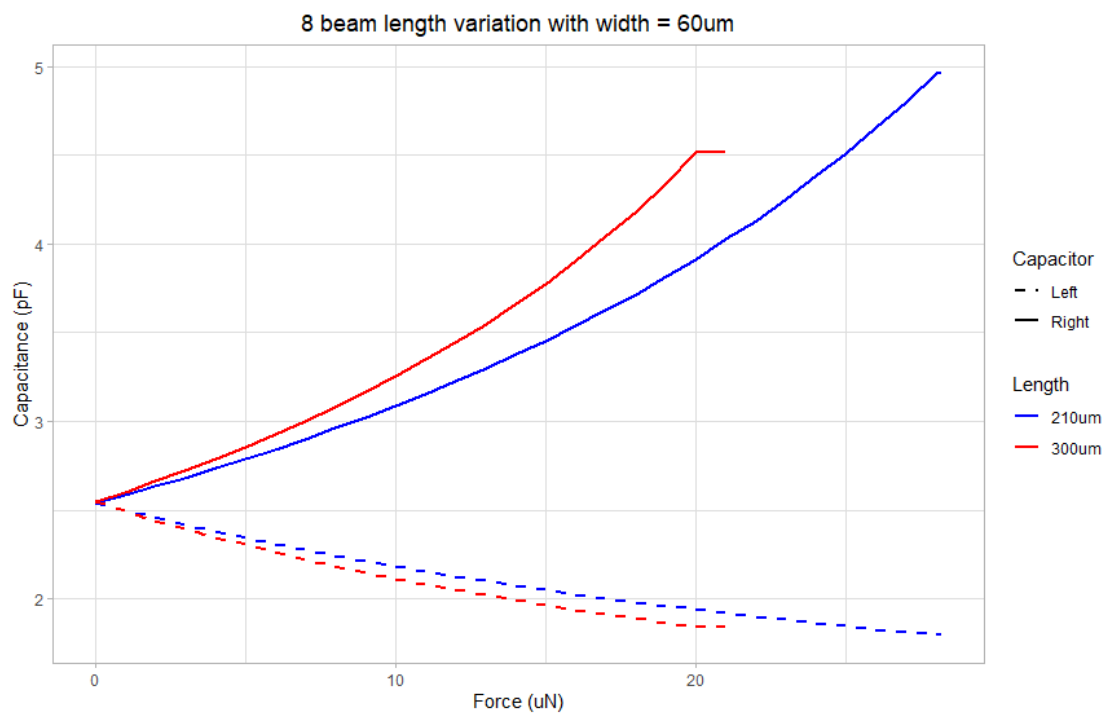


Figure 4-18: 8-beam length variation.

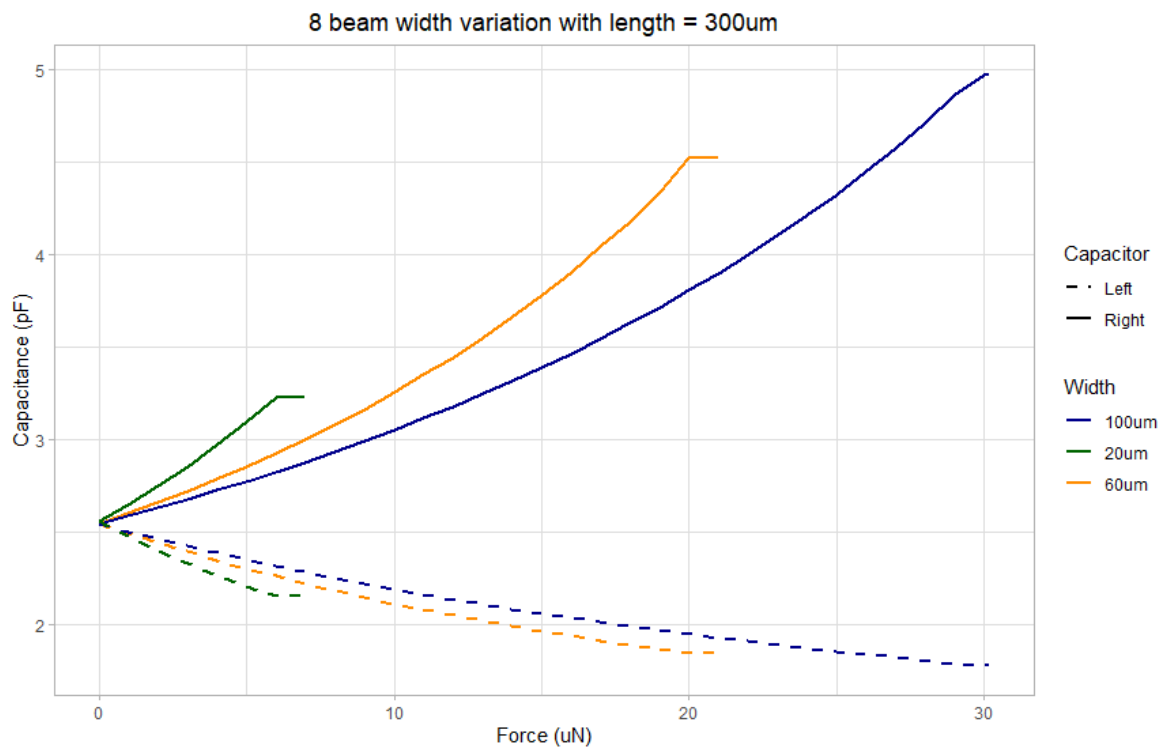


Figure 4-16: 8-beam width variation.

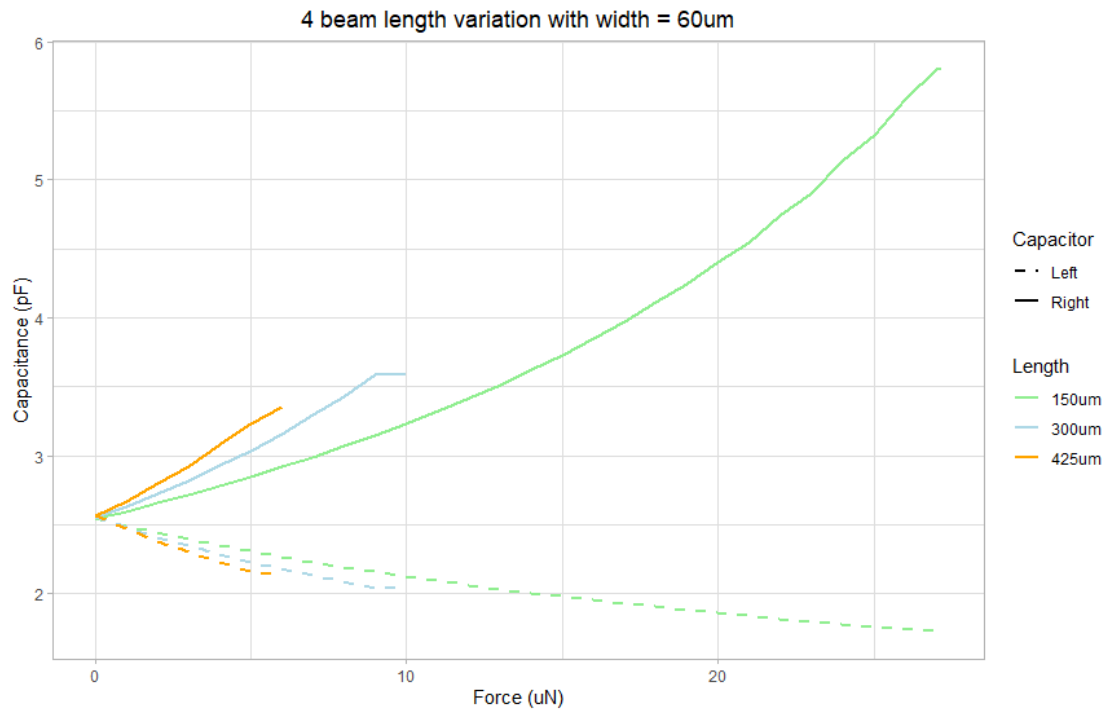


Figure 4-17: 4-beam length variation.

8-beam vs 4-beam

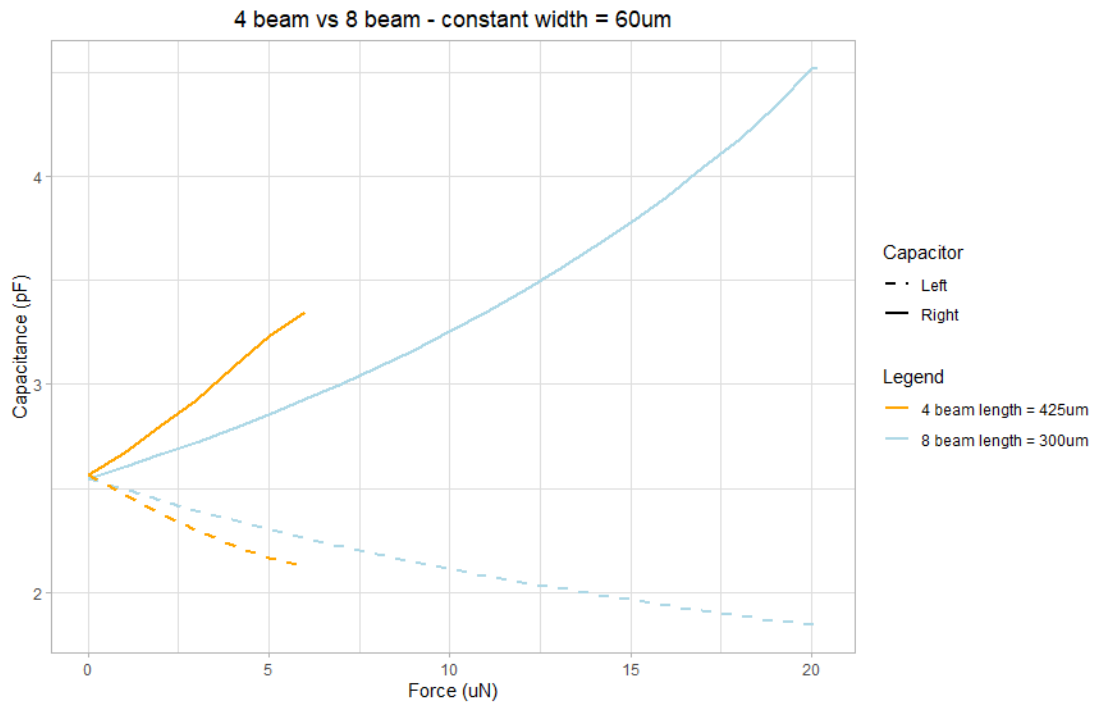


Figure 4-19: 8-beam vs 4-beam: Constant distance maintained between membrane and external for both configurations.

8-beam and 4-beam variations emulate point-fixed corner constraints to support the membrane. At each corner of the membrane, the 8-beam variation has two support beams perpendicular to each other, whereas the 4-beam has a single diagonal support beam. Therefore, assuming beam width and suspended membrane distance of both 8-beam and 4-beam are the same, 8-beam extends a stronger support as opposed to a single 4-beam support. Consequently, in the 8-beam sensor, the membrane requires a stronger force to deform and has a higher sensing range of force or velocity. On the contrary, 4-beam has a lower sensing range but might be sufficient to meet the required sensing range and display higher differential capacitance to an input i.e.: has higher sensitivity as depicted in figure 4-23.

With and without pivoting dimple configuration

The pivoting dimple underneath the membrane and hair enables a robust deformation of the membrane. Additionally, this dimple structure restricts z-direction movement. This also allows an increased applied voltage and prevents membrane collapse, thereby allowing for a higher input voltage to counteract the pull-in effect.

The solid mechanics simulation setup here is conducted with point constraints as membrane support at the corners of the membrane. Furthermore, a dimple-like structure illustrated in figure-4-20 is implemented. Figure-4-21 illustrates a slight decrease in membrane displacement with the dimple as opposed to the condition without dimple.

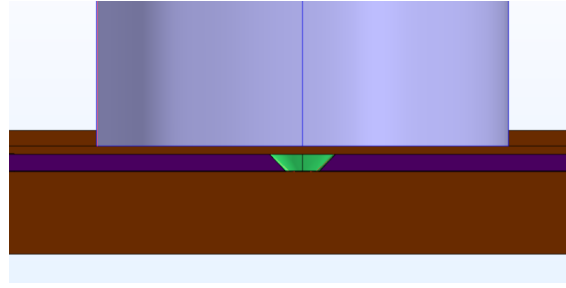


Figure 4-20: Pivoting dimple (green structure) implemented within the cavity in the COMSOL set-up.

Figure-4-22 represents a graph resulting from electromechanical simulations that compare the membrane collapse based on increasing applied voltage with and without the implementation of pivoting dimple. The average displacement of the membrane depicts membrane collapse for a particular applied voltage. The electromechanical simulation set-up is comprised of 8 beams (width = $60\mu\text{m}$, length = $210\mu\text{m}$), implemented with and without dimple configuration. The applied voltage is 1V.

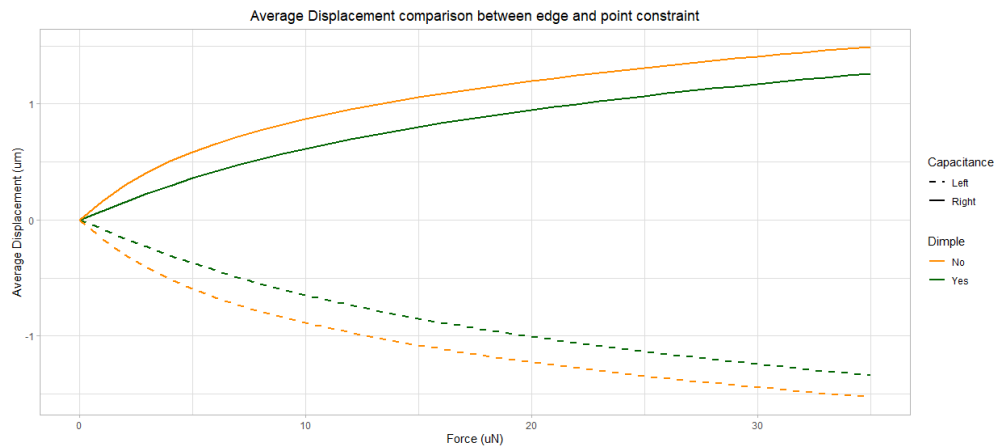


Figure 4-21: Comparison of solid mechanics with and without underlying pivoting dimple.

Thickness variation

Similar to the beam length, thickness of the membrane has a significant influence on sensor performance in the order of third magnitude. A thinner membrane improves sensitivity but reduces sensing range, as depicted in figure 4-23. Thicker membranes provide stability and reliability but require significantly higher force to deform the membrane slightly, therefore, might be challenging to reliably sense a lower velocity range or force. A note to be made in terms of the simulation environment is that a parametric study is conducted only on the membrane and beam thickness together. 8-beam sensor variation also depicts the same trend therefore indicating independence from support configuration in terms of thickness. A 4-beam variation with the following constant dimensions of the sensor, showcasing the best differential capacitance for a decent sensing range, includes:

- Cylindrical hair

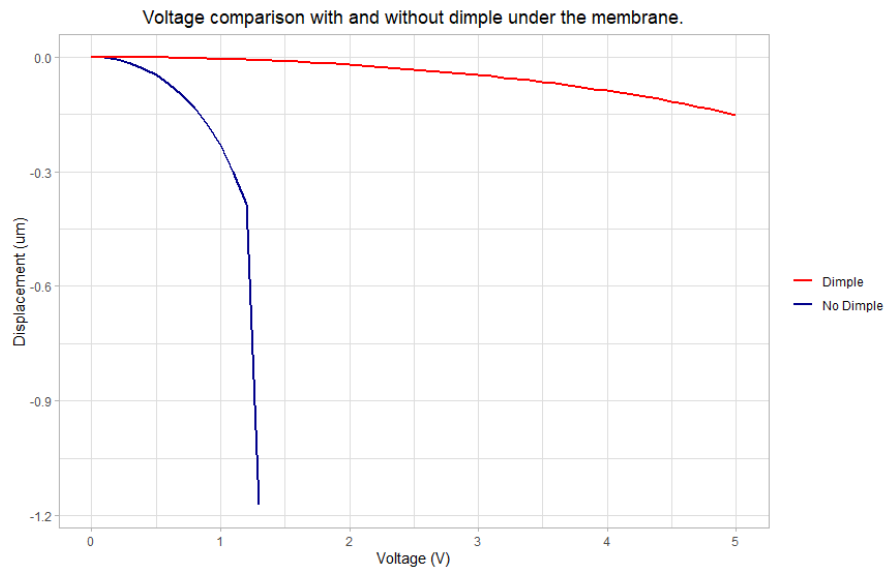


Figure 4-22: Pull-in voltage comparison with and without dimple.

- Hair radius = $60\mu\text{m}$
- Cavity = $2\mu\text{m}$
- Beam width = $60\mu\text{m}$
- Beam length = $300\mu\text{m}$

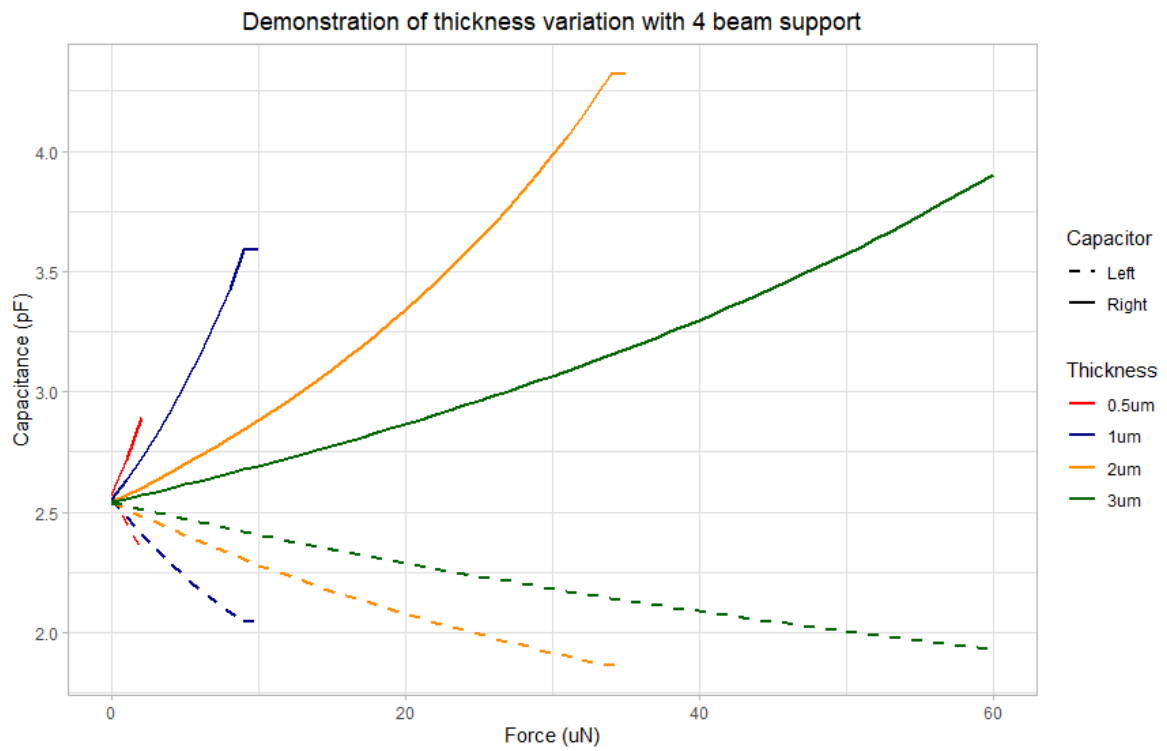


Figure 4-23: Thickness variation.

Cavity variation

As discussed previously, the practical estimation of cavity thickness is $2\mu\text{m}$. Simulation results provide a corroboration to the estimated value. The simulation environment and dimensions are retained from the previous section 4-3-3 with a fixed membrane and beam thickness of $1\mu\text{m}$ with a parametric cavity thickness. Figure-4-24 depicts the effect of a parametric study of cavity thickness variation. The base capacitance significantly changes and affects sensor performance. A wider gap between electrodes reduces electrostatic forces and therefore has lower differential capacitance or sensitivity but does increase sensing range. Evidently from graph 4-24, $2\mu\text{m}$ cavity thickness is a balanced cavity thickness, considering the force range expected is between 0 - $10\mu\text{N}$.

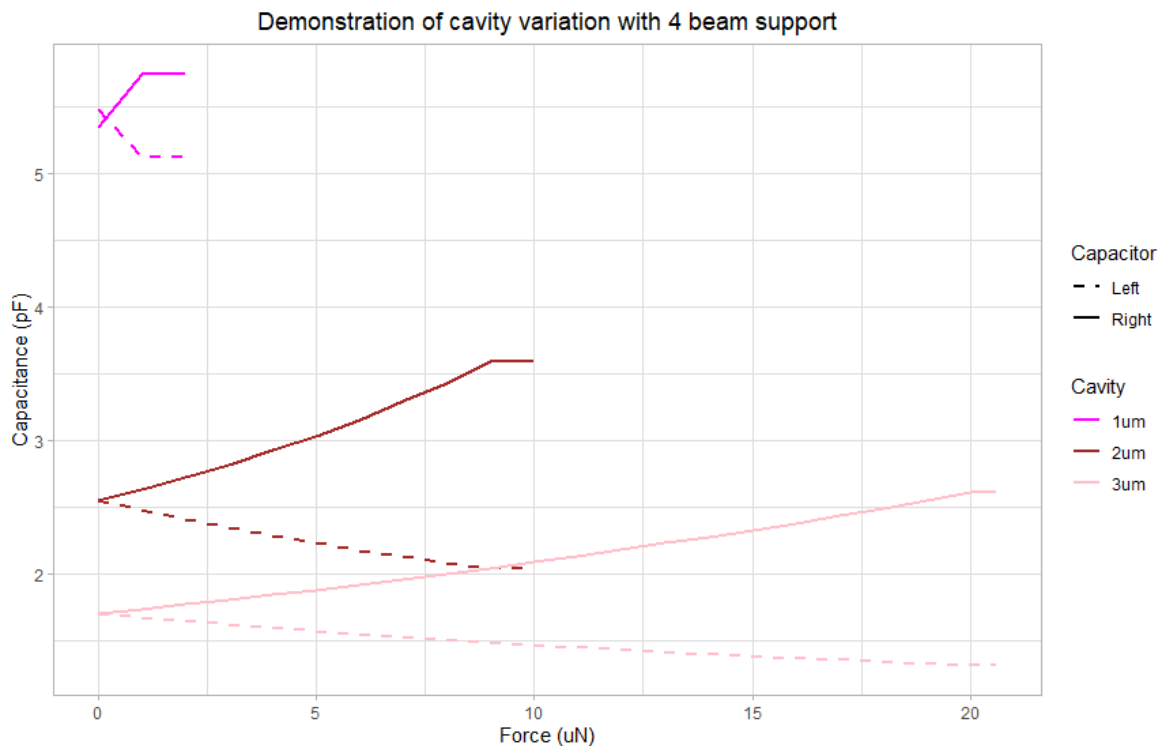


Figure 4-24: Cavity variation.

Voltage sweep

A parameterized voltage sweep between 1V and 2.7V performed on the 4-beam sensor with width of $60\mu\text{m}$ and length of $300\mu\text{m}$ displayed the effect of pull-in voltage. Figure-4-25 shows an increase in base capacitance with increasing applied voltage, this is due to the increase in electrostatic force between the electrodes. An increase in applied voltage also displays unstable functioning and reduced sensing range. Due to the increase in electrostatic force, the top electrode deforming towards the bottom electrode requires lesser drag force to deform the membrane, therefore resulting in higher differential and sensitivity. Further increase in drag force cannot be sustained by the beam support, therefore limiting functionality with decreased sensing range at higher voltages.

The electrode moving away from the bottom electrode experiences a lesser electrostatic force

with increasing distance between the electrodes. Consequently, if the electrode is moved beyond the range of electrostatic forces, only the spring forces of the beams and applied drag force influence the structure. In figure-4-25, the graphs of various applied voltages (left capacitor) indicate overlapping beyond $3.75\mu\text{N}$. Since the left capacitor is moving away from the bottom electrode, electrostatic forces do not influence deformation at this range. To decrease the influence of electrostatic forces at higher voltages, a thicker membrane can be implemented.

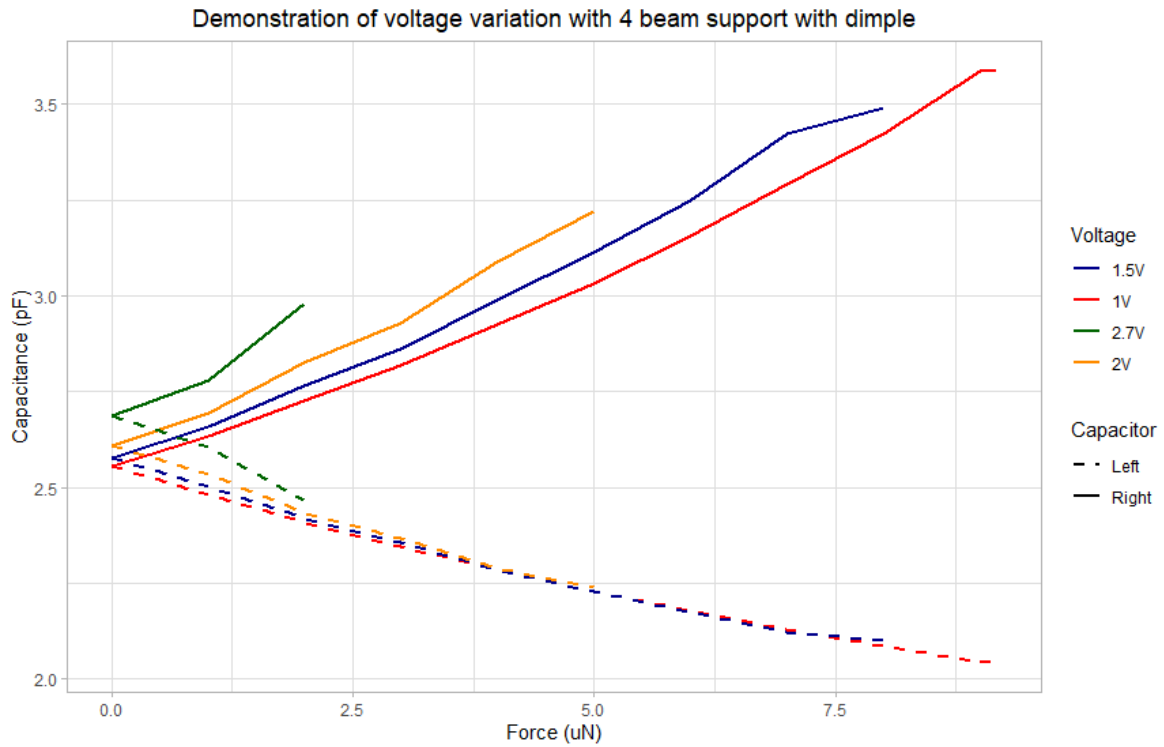


Figure 4-25: Voltage sweep of 4-beam sensor.

4-4 Discussion

To summarise, this chapter provides a detailed analysis of the various aspects of the sensing base. A basic estimation is conducted with analytical analysis and is proceeded with simulations for detailed estimations of the various segments. Furthermore, to prove the viability of the proposed concept, four sensing base variations are selected to proceed with fabrication. The variations are selected by predominantly accounting for stability and differential capacitance/sensitivity. Estimated parameter details of the selected variations are tabulated in 4-11. Note: Variations of electrode area are also studied, but for simplification one electrode area is opted here.

Beam	Beam width (μm)	Beam Length (μm)	Membrane thickness (μm)	Cavity (μm)	Electrode dimensions ($\mu\text{m} \times \mu\text{m}$)	Differential capacitance (pF)	Force (μN)
8	60	210	1	2	635 x 870	2.42	28
8	60	300	1	2	635 x 870	1.972	20
4	100	425	1	2	635 x 870	1.483	9
4	60	300	1	2	635 x 870	1.033	12

Table 4-11: Sensing base variations shortlisted for fabrication.

Fabrication

With the established structures from the concept model, each part is fabricated keeping in caution various structural and chemical compatibility. The concept model is further updated to ensure compatibility with fabrication processes. Consequently, the sensor is fabricated with the proposed steps. The chapter further elucidates on the challenges associated with the fabrication processes.

5-1 Proposed Fabrication stages

The Fabrication process starts by procuring a substrate, typically a bare silicon Si wafer. A 300 μm thick, 100mm diameter, and double side polished Si wafer with $\langle 100 \rangle$ orientation is best suited for sensor fabrication. The main fabrication process is divided into five crucial sequential stages:

- **Bottom electrodes:** A passivation PECVD SiC layer (SiC1) is deposited as the first layer on the Si wafer. Furthermore, a metal layer of AlSi + TiN is deposited, patterned, and etched to form the bottom electrodes (M1), along with the associated interconnect and contact pad. A PECVD SiC layer (SiC2a) over the electrode protects the electrodes from repeated contact by anti-stitching dimples.

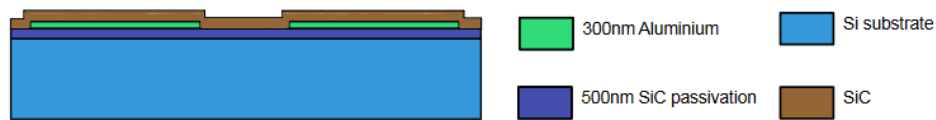


Figure 5-1: Constructing bottom electrode.

- **Cavity shaping:** A sacrificial layer of PECVD TEOS (MESA) enables shaping of the cavity, anti-stitching dimples of $2\mu\text{m}$ diameter and pivoting dimple of $4\mu\text{m}$ diameter before proceeding to deposit SiC layer (SiC2b) that will protect the top electrodes. The patterned shapes are etched by employing wet etching. This vital layer determines the dynamic range of the sensor.

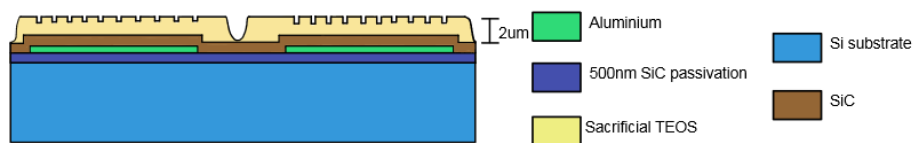


Figure 5-2: Shaping the cavity between electrodes.

- **Embedded top electrodes:** The proposed embedded electrodes are fabricated as a layered sandwich of PECVD SiC and AlSi + TiN electrodes. An initial layer of 150nm SiC (SiC2b) over the shaped cavity creates the anti-stitching dimples and a partial structure of the pivoting dimple. Furthermore, AlSi + TiN metal layers are deposited and patterned to form the top electrodes (M2). All etching steps of SiC and metal layers employ plasma etching for precise structures and dimensions. Consequently, a thick 1 μ m of PECVD SiC (SiC3) embeds the electrodes to form the membrane layer.

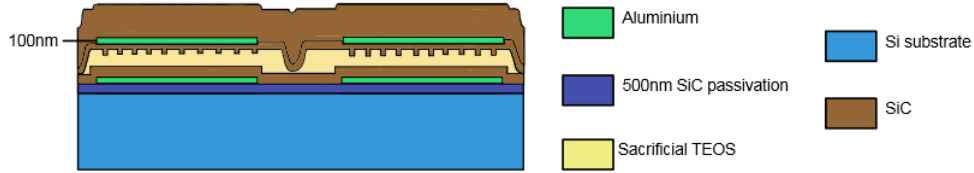


Figure 5-3: Embedded top electrode.

- **Interconnect:** At this stage, the bottom electrode pads and top electrodes are covered by PECVD SiC, therefore these electrodes are accessed through via openings which are further filled by AlSi of 1 μ m. Consequently, to efficiently access the electrodes, the metal layer is patterned and etched to form interconnects (M3).

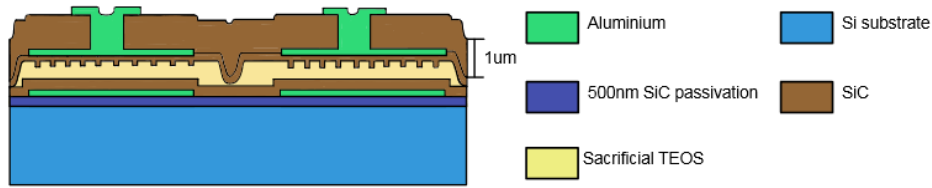


Figure 5-4: Via and interconnect.

- **Membrane construction:** With the fabricated interconnects, the final stage comprises shaping and suspension of the SiC3 membrane. The relevant beam structures of the SiC3 membrane are patterned and etched till the sacrificial TEOS layer. Furthermore, the suspended membrane is achieved by sacrificing the TEOS layer through vapour HF after dicing the wafer.

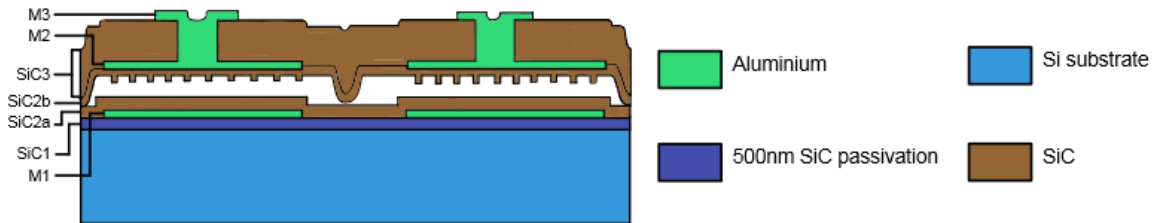


Figure 5-5: Membrane suspension.

Now that the layers of the sensor are defined, the patterns of each layers are to be determined. Photomask design is an important aspect of dimension and pattern definition for the various layers. The following section details the mask design used during fabrication.

5-2 Photomask Design

5-2-1 Pre-requisites for designing

Since glass masks are expensive to fabricate, a multi-image mask layout is a typical design option. To incorporate this type of mask layout, the PAS5500/80 stepper comprises a blade system that covers all the images except the one to be exposed. The blade system has an accuracy of 0.5mm, therefore 1mm of dark area (on the wafer level) is incorporated around each image to avoid unintended exposures with stray light. The dimensions of the image field are vital to designing a photomask. Considering the various variations of sensor design, a multi-image mask exposure job is implemented to ensure unique exposures on each quarter of the wafer. Further details of the mask exposure and mask layout are elucidated in Appendix B-1.

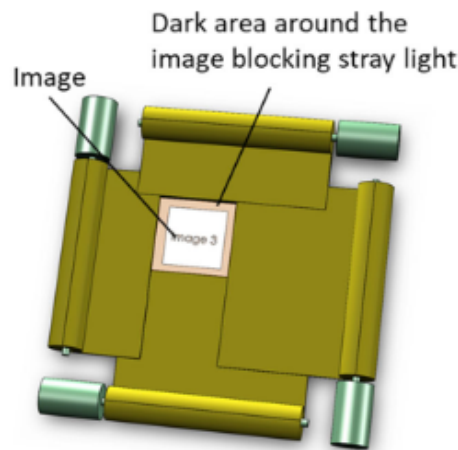


Figure 5-6: Blade system of stepper.

5-2-2 Design on L-edit

The patterns of each layer are designed in the L-edit software. Each pattern is meticulously designed to account for various limitations in fabrication processes.

Bottom electrode (M1)

The design comprises of the bottom electrode pair, interconnects, and respective contact pads. Interconnect dimensions are determined such that the contact pads are located outside the MESA area. Equation 5-1 determines the resistance of each interconnect according to its dimensions. It is imperative to maintain R_{int} between 1Ω - 2Ω with optimal dimensions such that the width and distance separating the interconnects maintain minimal parasitic capacitance. Dimensions depicted in figure-5-7a provide an interconnect resistance of 1.823Ω with an interconnect thickness of 300nm, therein determining electrode thickness.

$$\text{Resistance } R_{int} = \frac{\rho_{int} l_{int}}{t_{int} w_{int}} \quad (5-1)$$

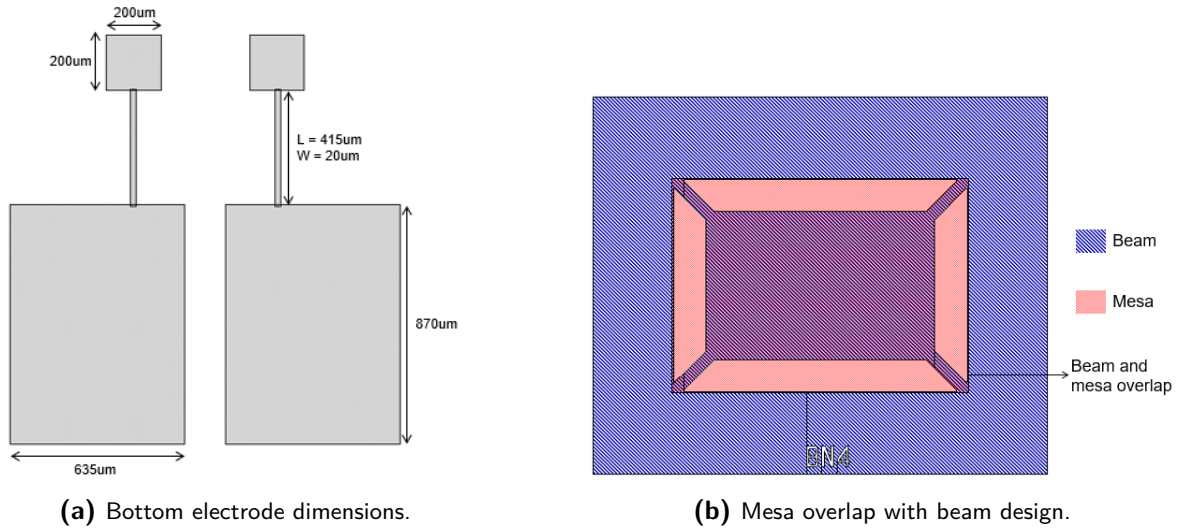


Figure 5-7: L-edit designs.

TEOS patterning

The cavity is defined by patterning the TEOS deposition with pivoting dimple, anti-stitching dimples and appropriate MESA dimensions.

- **Anti-stitching dimples:** A 6x13 array of $1\mu\text{m}$ radius circles, at an intermittent distance of $122\mu\text{m} \times 70\mu\text{m}$ are distributed over each electrode.
- **Pivoting Dimple:** The design comprises circles with various radius dimensions. For the first set of variations, the pivoting dimple is set to a radius of $1\mu\text{m}$. The variations of dimple design are depicted in the mask layout in the appendix B-2. Additionally, it should be noted that an isotropic wet etching is implemented to define the dimple structure, since the vertical etch dimension is the height of the cavity, the isotropic etch defines the actual radius to $2\mu\text{m}$.
- **Mesa:** A rectangular object is defined such that an extension of $7\mu\text{m}$ overlap is maintained around the beam opening under the external support structure to ensure sufficient support during VHF etching for a slow release.

Top electrode (M2)

Sacrificial holes are openings incorporated in the design to ensure an efficient etching of the sacrificial layer. The membrane release process requires several days to release the membrane. Considering that these openings will etch through till the TEOS layer, the embedded top electrodes require inbuilt openings or holes. A margin of $2\mu\text{m}$ (M2 holes $2\mu\text{m}$ larger than sacrificial holes) is added to the radius of the openings to prevent electrode etch due to misalignment and protect the electrode during VHF etching. Therefore, the electrodes are completely encapsulated and embedded within the SiC3 membrane, depicted in figure-5-8.

Via patterning

The electrodes at this stage are embedded and therefore accessed through vias. The M1 and M2 vias ensure reliable contact with M3 to enable access outside the device area.

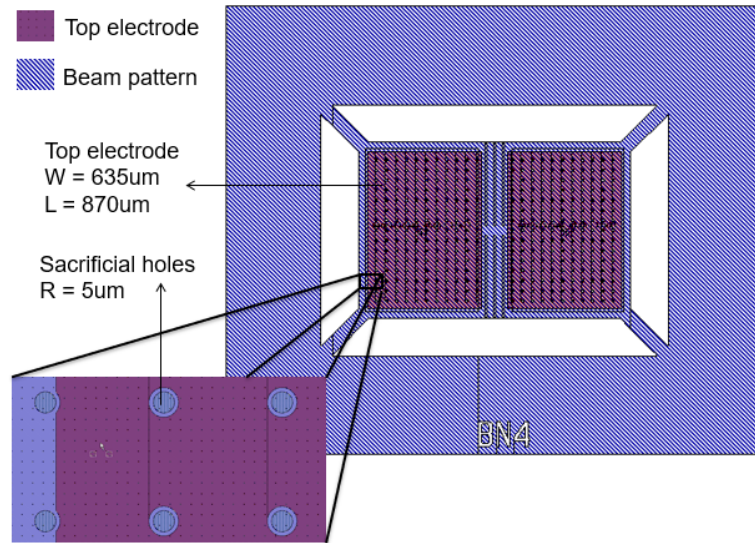


Figure 5-8: L-edit design of top electrode accommodating sacrificial holes with 7um radius openings.

- **M1 via:** M1 is accessed via the bottom electrode contact pad outside the active area, therefore the via opening does not require any customization and maintains a standard via design, depicted in figure-5-9.

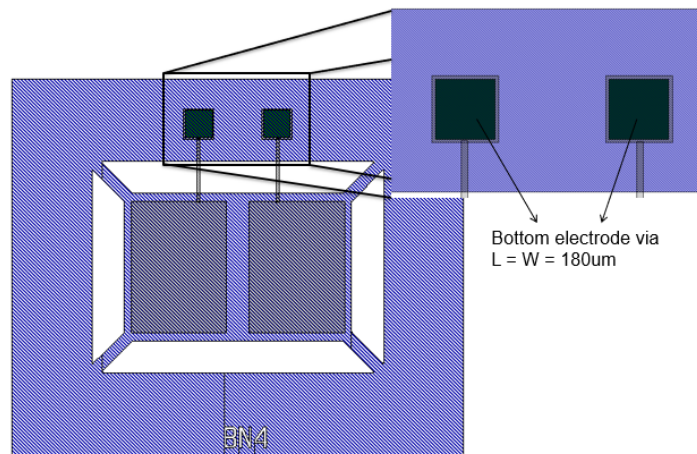


Figure 5-9: L-edit design of bottom electrode via.

- **M2 via:** The via for M2 on the contrary requires meticulous customization. The suspended membrane is subject to constant deformation thereby causing varying mechanical stress potentially tampering with contact at the vias. Therefore, The matrix of via openings depicted in figure-5-10, is designed to install reliable contact. In case of any disconnection at one contact, a connection is retained at other connections.

Top interconnect (M3)

The interconnect between M2 via and contact pad is designed to ensure minimal resistance similar to the bottom electrode interconnect. The sacrificial holes on the membrane neces-

sitate a customized design of interconnect around the holes. This design criterion is also considered to create contact through M2 via. The M3 design retains minimal width to ensure optimal beam functionality, and this is facilitated by the ductile nature of AlSi without any adverse impact on performance. Additionally, to maintain design symmetry, dummy interconnects are incorporated at the lower half of the sensor design. The dummy interconnects are not connected to the via contact.

For future work, it is foreseen that a hair protection structure needs to be added. The protection structure can be incorporated at the top and bottom of the sensor at the edge of the active area, making the pads inaccessible (D1-D4). Therefore, additional contact pads (U1 -U4) are implemented and connected via extended interconnects.

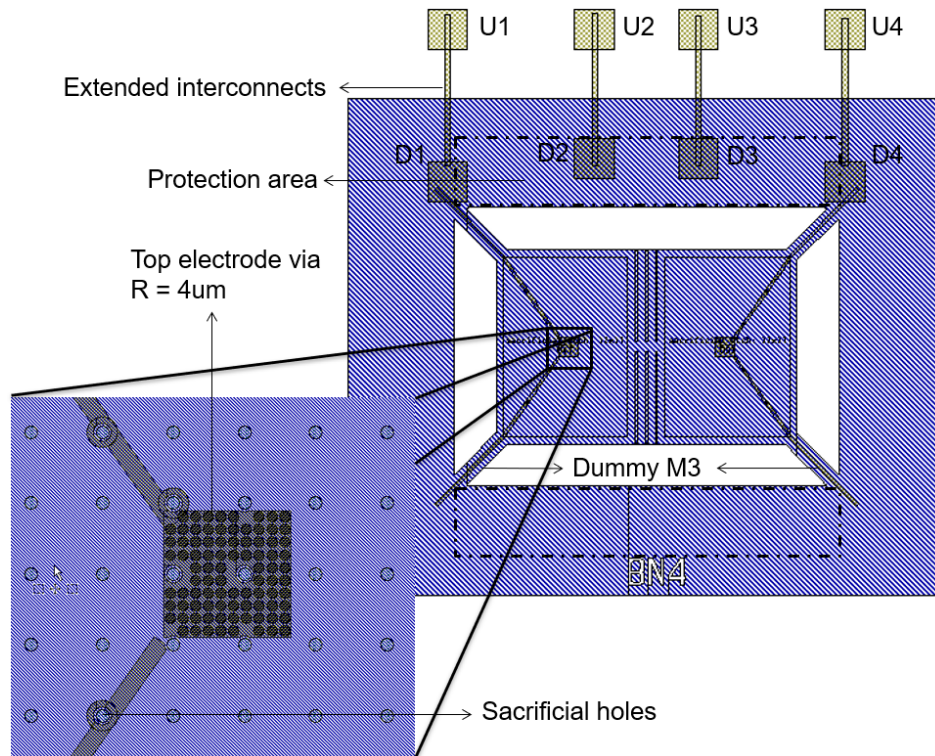


Figure 5-10: L-edit design of interconnect incorporating top via and sacrificial holes.

Interconnect	ρ (n Ω /m)	Width (μ m)	Length (μ m)	Thickness (μ m)	Resistance (Ω)
Electrode-D2/D3	0.265	20	415	0.3	1.8
U2-D2; U3-D3	0.265	30	450	1	0.3975
U1-D1; U4-D4	0.265	30	Variable	1	Variable

Table 5-1: Resistance of interconnects.

Beam Patterning and sensor nomenclature

Multiple designs of 8- and 4-beam variations are incorporated into the mask design. All corners comprise rounded edges for stronger beam design and reduce wear and tear at these

corners. Rounded edges contribute to reducing stress concentration at corners. Additionally, each beam variation is assigned a nomenclature to identify the design, tabulated in table 5-2. Although all 22 variations are implemented in the mask design, only four variations have been shortlisted to proceed with fabrication to validate the sensor concept. Other variations may be fabricated in the future for additional study on sensor performance.

Nomenclature	Beam type	Width (μm)	Length (μm)	Mesa ($\mu\text{m} \times \mu\text{m}$)
AN1	8 beam	60	210	1946 x 1416
AN3	8 beam	60	300	2126 x 1596
BN3	4 beam	100	425	2130 x 1594
BN5	4 beam	60	300	1954 x 1416

Table 5-2: Beam variations shortlisted for fabrication.

Sacrificial holes

As previously established, sacrificial holes are incorporated to reduce the etch time of TEOS. Additionally, sacrificial holes reduce the effect of squeeze film damping in perforated plates [15]. The hole dimensions and distribution are determined by the trade-off between the percentage of capacitance reduction and lateral etch time between two holes. The holes are evenly and symmetrically distributed on the membrane. The maximum diagonal distance to be etched is approximately $40\mu\text{m}$ with each hole located $56\mu\text{m}$ from each other. The sacrificial hole radius is $5\mu\text{m}$ and is distributed in an array of 12×17 across each electrode, implying a reduction of capacitance by 2.9%.

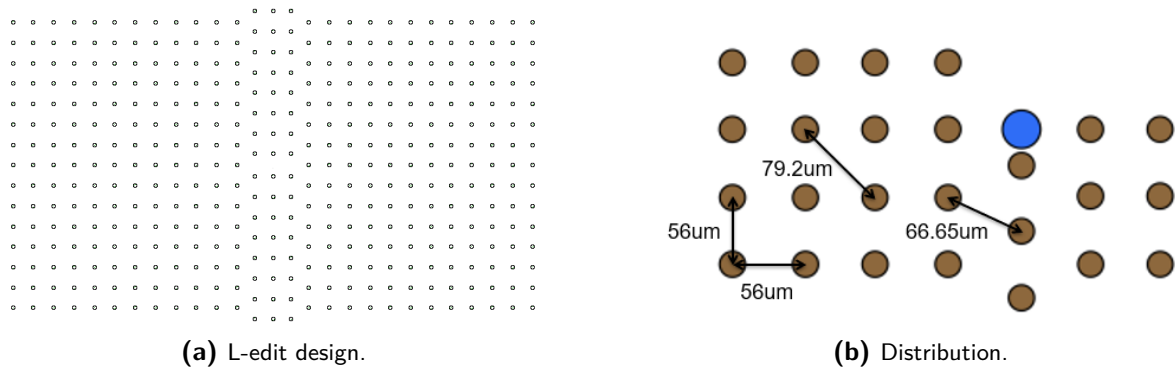


Figure 5-11: Design of sacrificial holes on L-edit.

Dicing markers are included in the mask design to provide guidance during dicing. Hair size along with shape variation and protection structure images are some of the additional patterns designed for future implementations.

Accounting for the area of each image, the die size is fixed at $4\text{mm} \times 4\text{mm}$. All images are expected to be incorporated into two photomasks on account of budget. Therefore, the final mask design consists of the distributed images separated with varying pitch in the x and y direction. During the programming of the exposure job, it is imperative to account for varying pitches and ensure exposed images are die-centered. The feature layer of each design

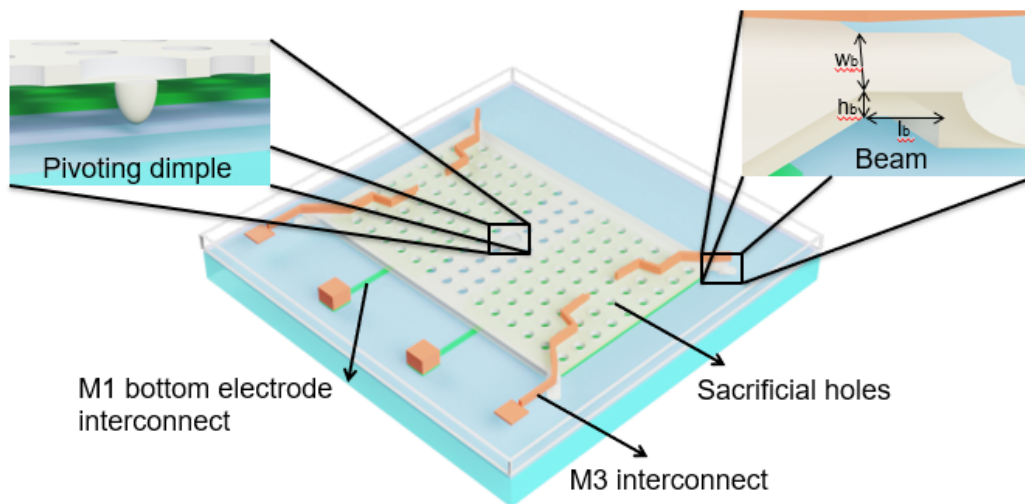


Figure 5-12: Final design of sensing base.

has to be applied correctly due to the four design patterns present on the wafer. Figure-5-12 illustrates the final design of the sensor before proceeding to fabrication.

5-3 Bottom electrode

Before delving into the main fabrication process, a zero-layer etch step is performed. The zero layer comprises alignment markers for the wafer stepper and contact aligners. The alignment markers, as the name suggests, enable the alignment of wafers during exposure to consequently develop desired aligned patterns.

Each etch step is preceded by a sequence that includes cleaning, coating with a photoresist layer, exposing it with the appropriate exposure energy and focus, and then further developing it to create the intended pattern within the photoresist. This resulting pattern generates openings in the exposed areas for either isotropic or anisotropic etching processes. Following successful etching, the photoresist is removed using the Tepla Plasma 300 system until the wafer is entirely free of any photoresist residue. An additional cleaning step is carried out to eliminate any organic photoresist remnants from the wafer. These sets of steps are performed cyclically throughout all the etching processes.

5-3-1 Passivation layer

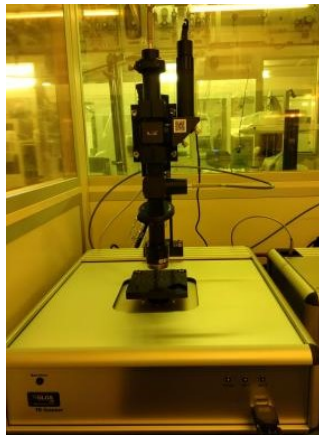
The passivation layer provides an initial base layer, separating the Si wafer and bottom electrode structure. Since the sensor is not a temperature-sensitive device, therefore, PECVD a-SiC is a preferred material. A major advantage of PECVD deposition is deposition at temperatures compatible with subsequent metal depositions. Furthermore, manipulating the deposition conditions enables control over the properties of the PECVD deposited film [52], [49], [43], [53]. Table-5-3 provides details about the process condition to deposit a low-stress PECVD SiC layer.

NOTE: All deposition times related to Novellus are station deposition time, therefore the total deposition must be x7 due to the total number of stations being seven.

Recipe: ls800nm_2	
Device	Novellus
Temperature	400°C
Deposition time	56.1 sec
Expected thickness	500 nm

Table 5-3: Process conditions for SiC1 deposition

The layer thickness is measured either with the Woollam Ellipsometer or the FR-scanner Reflectometer. Both systems employ the reflectance of a light source from the analysing material. The reflected light source experiences some interference, which is further measured and used to determine the film thickness. The Woollam Ellipsometer, for example, implements polarized light. The reflected light experiences a change in the state of polarization determining film thickness. The optical constants obtained from the Woollam measurements are used to calibrate the Reflectometer. The Woollam system provides reliable measurements for non-topographic surfaces, whereas the Reflectometer provides more reliable measurements at desired specific spots. Therefore, initial measurements were conducted with the Woollam system and consequently measured with the Reflectometer in later processes. Using the Reflectometer, the thickness is measured at five spots distributed around the wafers to ensure consistent deposition. Figure-5-14b tabulates all the expected and measured values of SiC depositions. After each deposition, stress caused by the film and bow of the wafer is measured with Flexus 2320-S.

**(a)** FR-scanner Reflectometer.**(b)** Woollam.**(c)** Flexus 2320-S.**Figure 5-13:** Measurement tools.

5-3-2 Metallization

The metallisation step provides a layer to pattern the bottom electrode. The deposition of the AlSi/TiN layer stack is sputter-coated in the Trikon Sigma 204 machine. Table-5-4 tabulates the process conditions. Prior to proceeding to the stack deposition, a single metallisation step of 300nm AlSi enables a resistivity check using the sheet resistance measured in the CDE green metal device. The calculated resistivity from sheet resistance R_s is close to the

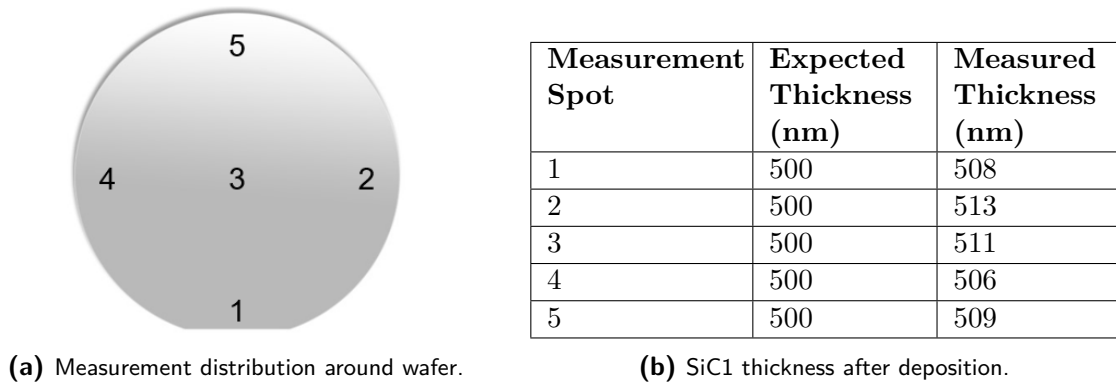


Figure 5-14: FR-scanner measurements.

resistivity of AlSi used in the previous calculations.

Recipe: AlSi_300_TiN40_350C				
Module recipe	Target	Temperature	Gases & flow	Target power
AlSi_300nm_350C	99% Al, 1% Si	350°C	Ar = 100 sccm	10kW
TiN_40nm_350C	pure Ti	350°C	Ar/N ₂ = 20/70 sccm	6kW

Table 5-4: Process conditions for AlSi/TiN metallization.

Parameter	Value
Rs Avg	0.10193 Ω/sq
Min	97.51 m Ω/sq
Max	0.1056 Ω/sq
Std Dev	2.8869 m Ω/sq
$\frac{(Mx-Mn)}{Mx+Mn}$	3.98%
Calculated ρ	0.3058 n Ω/m

Table 5-5: Results of CDE device.

5-3-3 Patterning

The metal stack at this stage is ready to be patterned and is subject to lithography. Negative photoresist AZ nLOF 2000 series is employed to pattern metal layers. Since the mask design comprises multiple images separated with varying pitches, the area allocated for each image is smaller than the die area. Therefore, to eliminate unintended metal surfaces, negative photoresist is preferred for metal layers. The coated wafer is subjected to exposure and further development to retain a cross-linked photoresist pattern of the bottom electrode. Photoresist coating and developing are conducted using the EVG 120 machine. Exposure energy and developing recipes are deduced from the EVG 120 legacy recipes, wafer stepper manuals and nLOF technical datasheet. Details of coating, exposure, and development of all patterning steps are tabulated in 5-22.

In this case, wet etching is the preferred etch method due to the tilted sidewalls, but due to the metal stack of AlSi/TiN, a second etch chemistry is required for TiN. Therefore, reactive

Ion etching/plasma etching is implemented which can etch both metals. The etch recipe for the metal stack TiN/AlSi resembles the recipe of AlSi alone. AlSi etching requires an initial breakthrough step to etch the natural passivating Al_2O_3 layer. Similarly, the TiN layer requires an initial breakthrough step to etch through it. TiN has a higher etch rate compared to AlSi. Consequently, the exposed AlSi is bulk etched with a chlorine chemistry. Typically, after a bulk etch, an overetch step is conducted. Two variations of the recipe with distinctive overetch steps are implemented and tested. One of the recipes comprises an anisotropic plasma 55% overetch step (TiN4Al30), whereas the other recipe consists of an undirected isotropic etch step (TiN4Al3i). The details of the two recipes are tabulated in 5-6 and 5-7. Endpoint detection is implemented for the TiN and bulk AlSi etch steps.

Recipe: TiN4Al30			
Parameter	TiN	Bulk etch	Overetch
Temperature ($^{\circ}\text{C}$)	25	25	25
Pressure (mTorr)	$5\pm 10\%$	$5\pm 10\%$	$5\pm 10\%$
Cl (sccm)	$30\pm 10\%$	$30\pm 10\%$	$15\pm 10\%$
HBr (sccm)	$40\pm 10\%$	$40\pm 10\%$	$30\pm 10\%$
RF Power (W)	$40\pm 10\%$	$40\pm 10\%$	$40\pm 10\%$
ICP Power (W)	$500\pm 10\%$	$500\pm 10\%$	$500\pm 10\%$
Endpoint	Rising	Falling	Disabled
Step Time (sec)	25	50	5

Table 5-6: Recipe with overetch step in Omega plasma etcher.

Recipe: TiN4Al3i			
Parameter	TiN	Bulk etch	Isotropic etch
Temperature ($^{\circ}\text{C}$)	25	25	25
Pressure (mTorr)	$5\pm 10\%$	$5\pm 10\%$	$5\pm 10\%$
Cl (sccm)	$30\pm 10\%$	$30\pm 10\%$	$30\pm 10\%$
HBr (sccm)	$40\pm 10\%$	$40\pm 10\%$	$0\pm 10\%$
N_2 (sccm)	$0\pm 10\%$	$0\pm 10\%$	$7\pm 25\%$
RF Power (W)	$40\pm 10\%$	$40\pm 10\%$	$0\pm 10\%$
ICP Power (W)	$500\pm 10\%$	$500\pm 10\%$	$250\pm 10\%$
Endpoint	Rising	Falling	Disabled
Step Time (sec)	25	50	7

Table 5-7: Recipe with isotropic etch step in Omega plasma etcher.

Results of the two etching recipes are deduced with a basic visual inspection along with Axiotron microscope and SEM inspections (figure-5-15). Visual inspections indicate a clear SiCl landing layer.

Visual and Axiotron inspection

Initial visual inspection indicated large dark spots on a few electrodes for recipe TiN4Al30 contrary to TiN4Al3i which resulted in a much cleaner electrode surface. Axiotron images



(a) Axiotron Microscope.



(b) Scanning Electron Microscope (SEM).

Figure 5-15: Inspection tools.

further indicate electrode damage with the former recipe. Due to microscope resolution, no observations are made about fence formation around the electrode. Additionally, visual inspection indicates a dark residue on the landing SiC surface for both etch recipes.

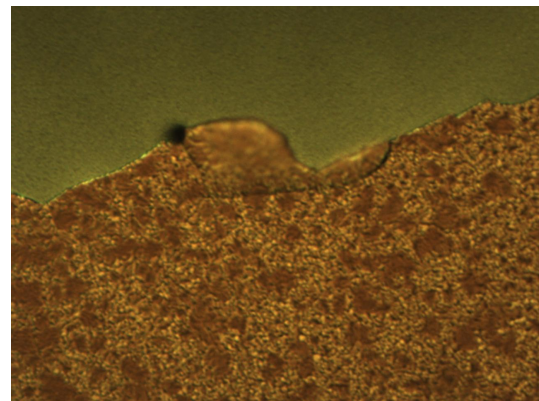
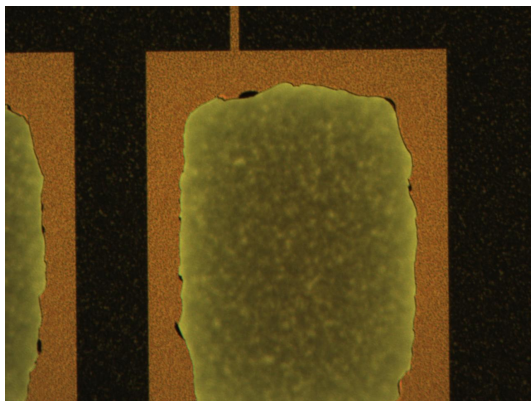


Figure 5-16: Electrode damage with TiN4Al30 overetch recipe.

SEM inspection

SEM inspections indicate two major revelations:

- Fencing around electrodes.
- Delamination of TiN with TiN4Al30 overetch recipe.

The fencing effect (figure-5-18) is observed with both etching recipes, depicted in figure-5-18. whereas the delamination effect of TiN (figure-5-16, 5-17) is observed with only one of the recipes. The fence formation with TiN4Al30 overetch recipe is larger compared to the TiN4Al3i isotropic etch recipe. This is due to the nature of etching, isotropic etch allows for lateral etch as opposed to the anisotropic overetch, therefore, reducing fence dimension.

Additionally, a fence removal etching step at the PES Al etch wet bench indicates reduced etch time for TiN4Al3i isotropic etch recipe. Fence removal is imperative to maintain surface uniformity which may affect suspension and quality of the membrane after Vapour HF.

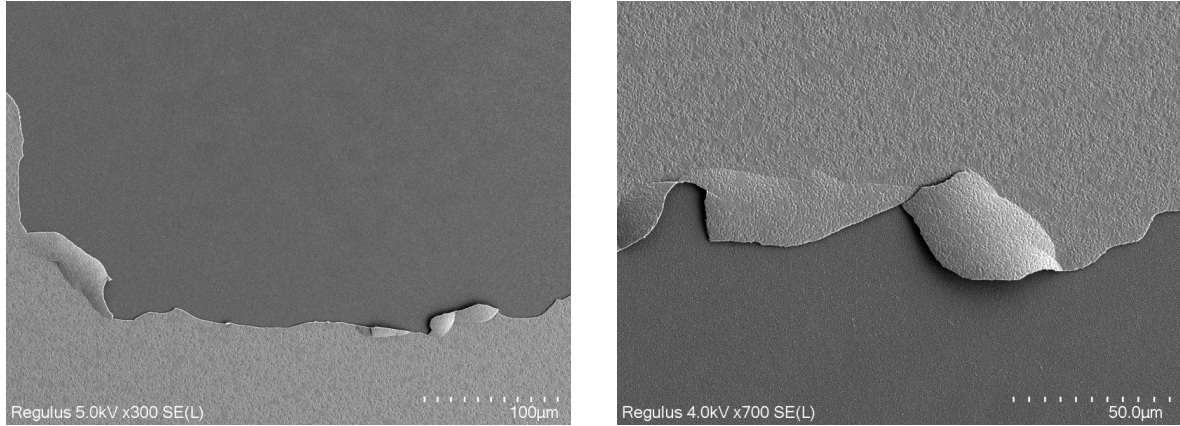


Figure 5-17: SEM inspection of TiN delamination.

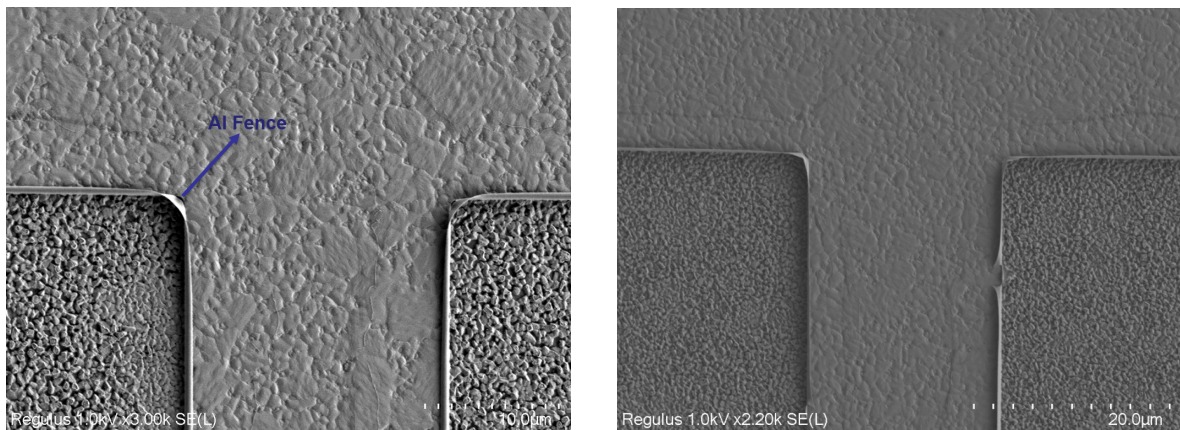


Figure 5-18: Fence formation after bottom electrode M1 etching.

Etch recipe	Etch time
TiN4Al30 overetch	1min 50sec
TiN4Al3i isotropic etch	45sec

Table 5-8: Etch time of Al fence removal for the two etch recipes.

Considering the drawbacks of the etch recipe with overetch step, TiN4Al3i with the isotropic etch step is the preferred etch recipe. The landing SiC1 surface after bottom electrode etching must visually appear similar to post deposition of SiC. SEM and Axiotron images indicate a rough SiC surface after etching, this is due to the chlorine etch chemistry which attacks SiC as well.

Due to the ambiguity of black residue on SiC, an isolation check between the two electrodes is conducted utilizing the 4-probe station. A single probe is connected to each electrode. And the multimeter measures an open loop for most electrodes, but measures 8.7M Ω - 9M Ω for some.

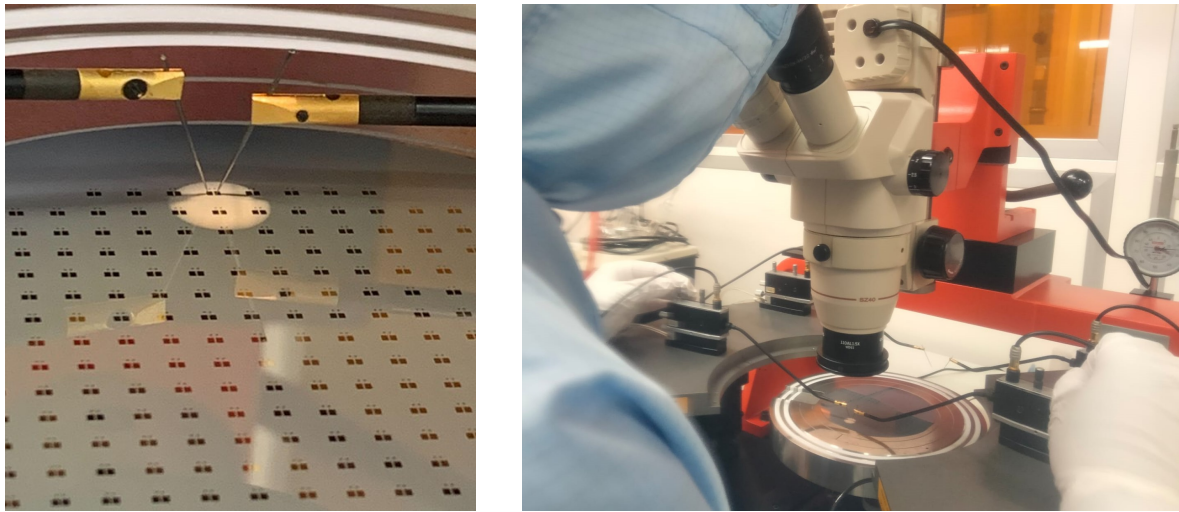


Figure 5-19: Measurement at 4-probe station.

Two probes connected to the same electrodes measure around 2.6Ω . These measurements indicate no stray connection, allowing us to proceed to the next fabrication steps with low yield.

The Keyence microscope facilitates profile construction of the inspected area under the microscope. Therefore, a Keyence measurement is conducted to study the profile and dimensions of the bottom electrode (figure-5-20a). Furthermore, a 150nm SiC2a deposition is conducted

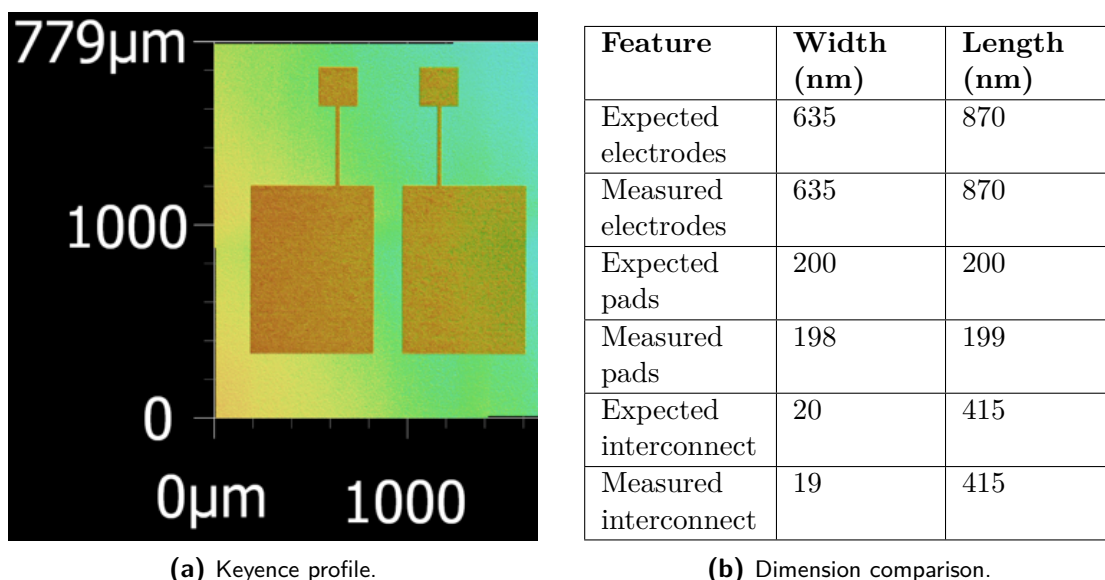


Figure 5-20: Keyence dimension measurement of M1.

to protect the bottom electrode. After deposition, the electrodes further experience TiN delamination on all wafers regardless of the etch recipe.

Measurement Spot	SiC1 after M1 etch		SiC2a 16.7sec deposition	
	Expected Thickness (nm)	Measured Thickness (nm)	Expected Thickness (nm)	Measured Thickness (nm)
1	510	453.5	150	171
2	510	455	150	172.5
3	510	454	150	173
4	510	457	150	171
5	510	461.5	150	170

Table 5-9: SiC1 and SiC2a thickness.

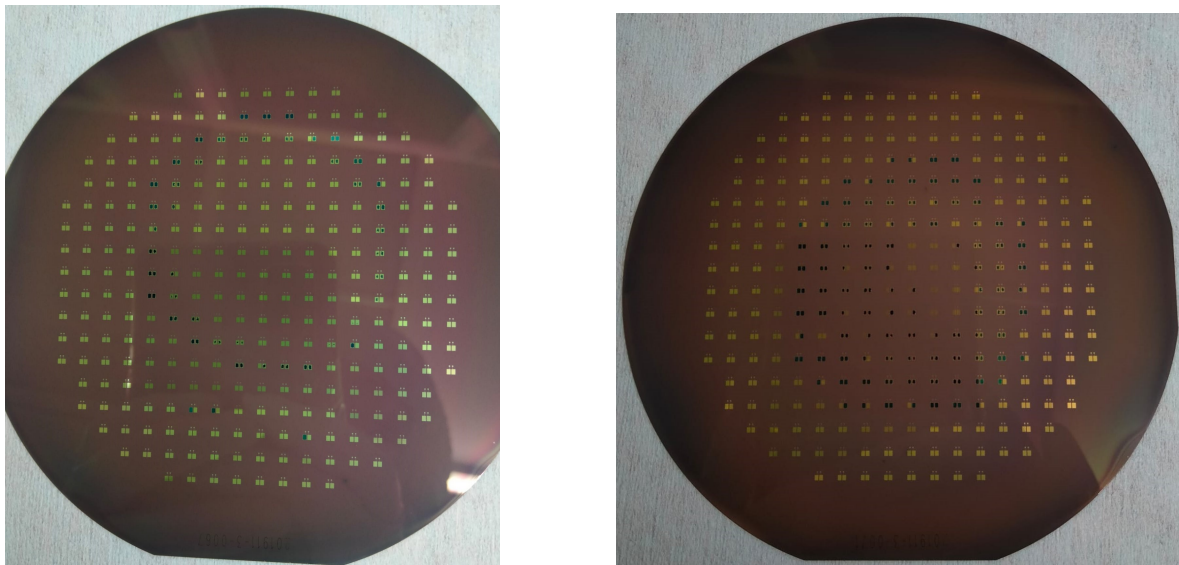


Figure 5-21: Wafers with delaminated TiN electrodes.

Fabrication stage	Stress (MPa)	Bow (um)
No film	N/A	0.87
SiC1 deposition	42.3624	-5.6
M1 etched	119.6973	-19.89

Table 5-10: Flexus measurements for bottom electrode stage.

5-4 Cavity Shaping

In order to provide structure to a cavity, it is vital to select an appropriate sacrificial material. The material should be compatible with the Vapour HF etch chemistry. PECVD oxide deposition based on TEOS (Tetra ethyl ortho silicate) and SiH_4 (Silane) are materials typically implemented as sacrificial layers due to high reactivity with HF etchant. Since sacrificial layers are to be etched, a high-quality deposition is not required. A fast low-temperature deposition is preferred, therefore PECVD deposition is implemented.

Recipe: .xxxnmTEOS	
Device	Novellus
Temperature	350°C
Deposition time	70 sec
Expected thickness	2000 nm

Table 5-11: Process conditions for TEOS deposition

The fabrication process is proceeded with a 2 μm TEOS deposition. To analyse and ensure deposited thickness and etch rate, TEOS is deposited for 70 sec on a bare Si test wafer. The deposited layer is measured using the FR-scanner Reflectometer and further wet etched at the etching line with BHF 1:7 for 3 mins. The etch rate is found to be 202.23 nm/min.

	70sec TEOS deposition		3.5sec extra TEOS deposition	
Measurement Spot	Expected Thickness (nm)	Measured Thickness (nm)	Expected Thickness (nm)	Measured Thickness (nm)
1	2000	1998	100	129
2	2000	1946	100	112.2
3	2000	2015	100	111.8
4	2000	1957	100	115
5	2000	1988	100	112

Table 5-12: TEOS thickness at various stages.

Additionally, due to layer buildup on the front side of the wafer, a backside deposition of 1.5 μm SiC is conducted to compensate for the resulting bow. This exacerbated the delamination at contact pads and other electrodes (figure-5-21), further reducing yield. Due to delamination, further processing is conducted after ultrasound cleaning to avoid contamination. Loose TiN particles in combination with gas movement can also cause disruption during VHF, therefore damaging the membrane.

5-4-1 Anti-stitching and Pivoting dimples

The test TEOS wafer is used to experiment with various aspects of processing anti-stitching dimples. Patterning is begun with a coat of Shipley SPR3012 positive photoresist, and further exposed with an anti-stitching dimple array and developed. The opening of the etch site on the developed photoresist is measured under Axiotron to ensure the intended dimension. Wet etching is a preferred etching method to construct the shape of the cavity. Curved structures for the dimple are achievable by implementing wet etching. Due to the nature of isotropic etching, the resulting radius of anti-stitching openings is larger than 1 μm . However, the etch depth is 100nm, and the radius dimensions post-etching does not vary by a large margin. The etch rate, on the other hand, varies with the dimensions of the etch openings. Therefore a test etch is conducted on the test wafers to identify the etch time. Similarly, a test etch for pivoting dimple. Consequently, anti-stitching dimples are etched for 1min 30sec, whereas pivoting dimple is etched between 9 and 10mins. The pivoting dimple is etched through the

cavity thickness, therefore the opening of the pivoting dimple is expected to be larger than the photoresist patterned opening. Figure-5-22 represents the dimensions of both kinds of dimples. Additionally, Dektak measurements corroborate the radius dimension of the pivoting dimple.

In order to prevent the initial stitching of the pivoting dimple to the SiC base, an additional 100nm of TEOS is deposited for 3.5sec before proceeding to mesa construction. Thickness measurements are tabulated in 5-12.

Feature	Expected radius (μm)	Measured radius (μm)
Anti-stitching dimple	1	1.045
Pivoting dimple	2	2.03

Table 5-13: Anti-stitching and Pivoting dimple dimensions comparison.

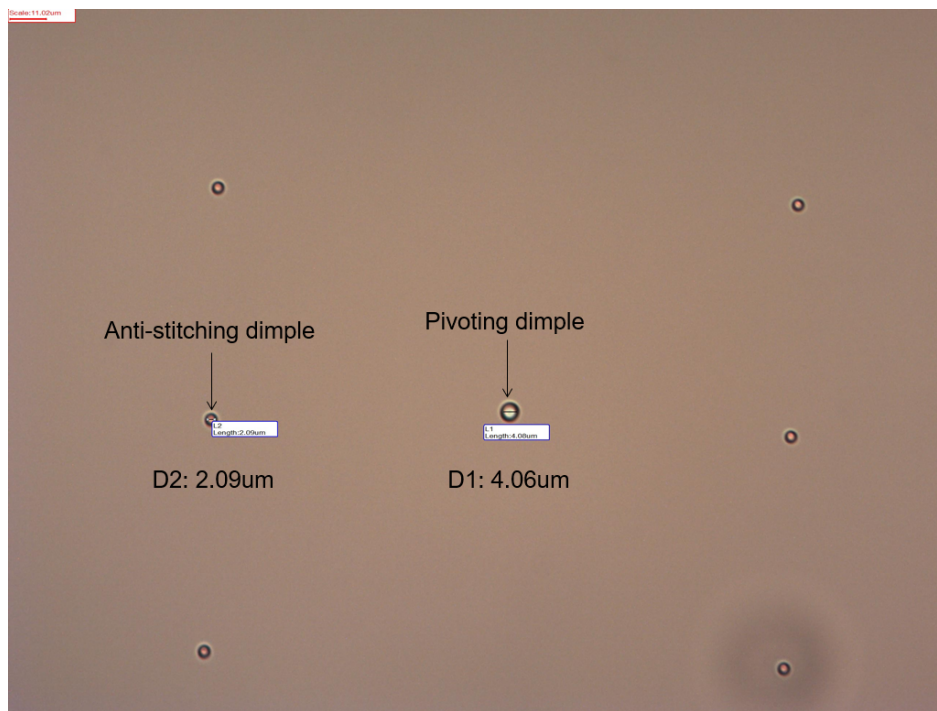


Figure 5-22: Axiotron inspection of anti-stitching and pivoting dimple.

5-4-2 MESA

Mesa patterning is imperative to define the dimensions of the suspension area. To prevent unintended etching during membrane release VHF, all areas excluding mesa area must be cleared of TEOS, therefore, the negative photoresist is employed for patterning. The etching process is conducted till the SiC underneath is exposed. TEOS etching in this step lands on SiC. Visual inspection can be compared with a wafer comprising only SiC deposition. 1:7 BHF etch does not etch SiC. The etch time is noted to be approximately 13min. Reflectometer measurements around the etched mesa indicated no reminiscence of TEOS and unetched SiC. Due to lateral etch, mesa dimensions are reduced by $4\mu\text{m}$ - $6\mu\text{m}$ from each exposed

side, indicating underetch (figure-5-23), tabulated in 5-14. Reduced mesa dimensions might weaken the beam support structure.

Mesa variation	L-edit		Estimation after etch	
	Length (μm)	Width(μm)	Length (μm)	Width (μm)
AN1	1946	1416	1934	1404
AN3	2126	1596	2114	1584
BN3	2130	1594	2118	1582
BN5	1954	1416	1942	1404

Table 5-14: Mesa dimensions after etch.

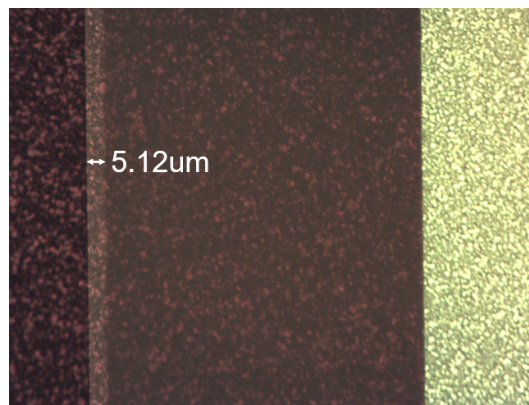


Figure 5-23: MESA under etching.

Consequently, SiC2b of 150nm thickness is deposited for 16.7sec, similar to SiC2a. This layer provides structure to the dimples and a base to embed the top electrodes into the membrane.

5-5 Top electrode

Implementing the same chemistry as the bottom electrode (M1) metallization, a 100nm AlSi and 40nm TiN metal stack is deposited on top of SiC2b. The reduced metal thickness increases ductility to allow optimal deformation.

5-5-1 Patterning

The increasing topography requires thicker photoresist to avoid insufficient thickness during etching at higher topography. The thickness of the photoresist and exposure energy is adequately adjusted corresponding to the topography change in the active area. The etch recipe from M1 etching is retained with an altered step time to 20sec in the bulk etching step of AlSi. Post etching (figure-5-25), it is important to ensure minimal to no fences to avoid non-uniformity in the membrane.

After etching, an initial inspection under Axiotron indicated blue blotting (figure-5-24) observed on the metal. This effect is observed due to Cl gas used during etching. Cl bi-products can cause corrosion on metal layers when leftover for a certain time. Therefore to avoid this

corrosive effect, the wafer is immediately dipped in DI water after etching for a quick cleaning.

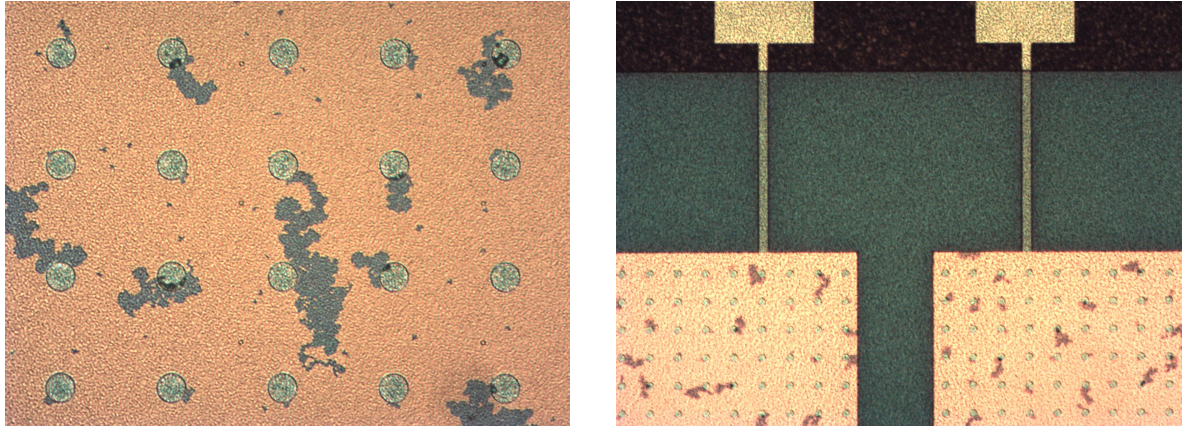


Figure 5-24: Blue blotting after M2 electrode etch.

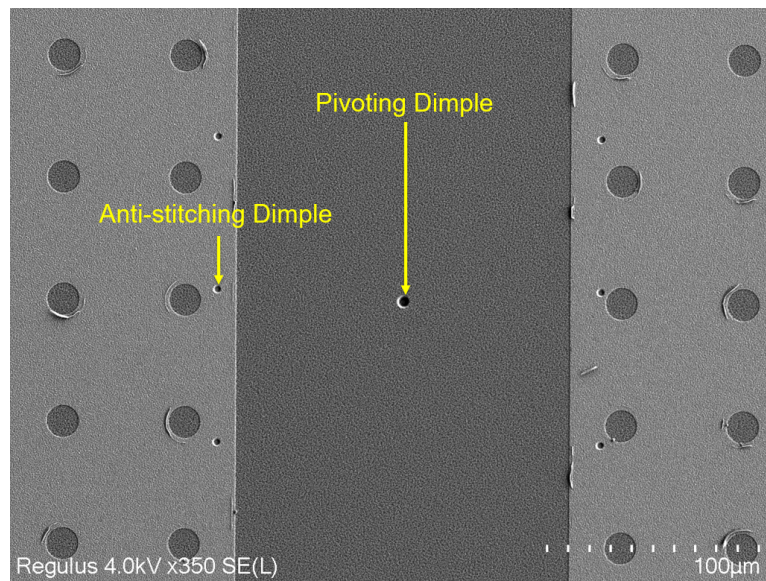
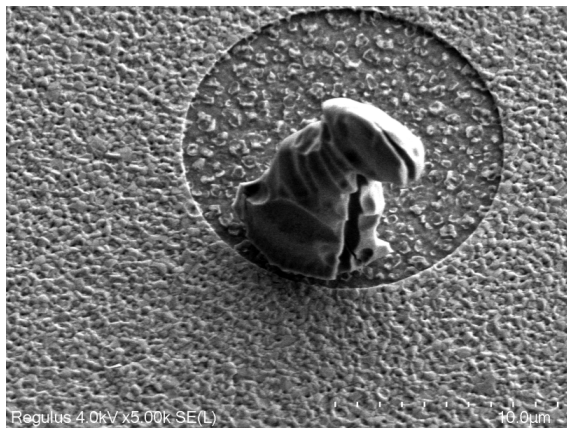


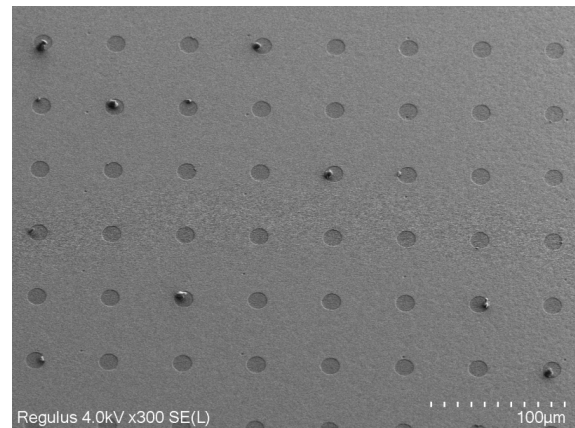
Figure 5-25: Dimple structures under SEM after M2 etching.

M2 etch resulted in large bulb-like Al fences at the sacrificial holes (figure-5-26). Long Al fence removal step of over 2min and 30sec proved insufficient to entirely clear the fences. Therefore, it is of paramount importance to rectify this issue during etching, with sidewall rectification.

The SiC3 membrane deposition is similar to other SiC depositions with varied deposition time. Post deposition, visual inspection along with Axiotron inspection, indicated delamination of TiN for top electrodes as well (figure-5-27). The sacrificial holes implemented into the top electrode aided in relieving stress, therefore reducing the number of electrodes with delamination.



(a) Bulb like Al fence in sacrificial holes.



(b) Al fence distribution.

Figure 5-26: SEM images after M2 etching.

Measurement Spot	SiC2b after M2 etching		SiC3 deposition	
	Expected Thickness (nm)	Measured Thickness (nm)	Expected Thickness (nm)	Measured Thickness (nm)
1	170	71	1000	913
2	170	78.5	1000	905
3	170	73.5	1000	799
4	170	82.5	1000	912.5
5	170	77	1000	905

Table 5-15: SiC thickness at various stages.

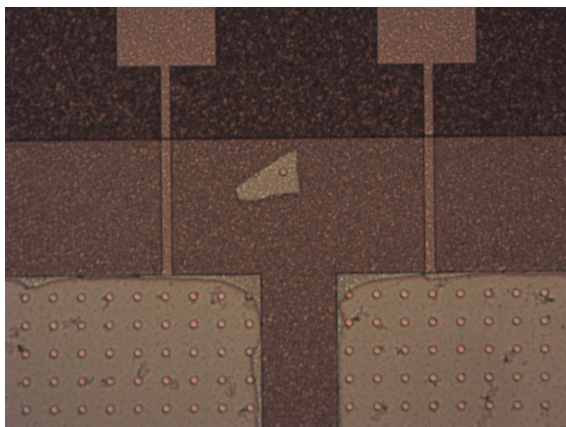


Figure 5-27: Delamination of M2 electrodes after deposition of SiC3 membrane.

Deposition Time (sec)	Expected thickness (nm)	Measured thickness (nm)
56.1	510	508
16.7	150	172
90.35	1000	910

Table 5-16: Thickness measurements and deposition time of SiC.

5-5-2 Via openings

Since there are two pairs of electrodes, there are two pairs of via openings to be etched.

- Top electrode via
- Bottom electrode via

Both openings are fabricated with similar parameters except for etch time due to different feature sizes.

Anisotropic etch is the preferred mode of etching for defined and precise openings. Critical dimensions are imperative for this pattern. The landing material is TiN but since the thickness of the layer is significantly thin, the layer is etched through. Therefore, the landing material is AlSi. A Si etch recipe of fluorine chemistry is adopted such that the SiC is etched while retaining AlSi from the landing material. The O₂ in the plasma forms a thin Al₂O₃ layer at the exposed AlSi, thus forming a passivation layer and protecting it from further etch. The recipe is tabulated in 5-17.

Recipe: SIC20DEG	
Parameter	SiC_etch
Temperature (°C)	20
Pressure (mTorr)	9.5±5%
HBr (sccm)	40±10%
O ₂ (sccm)	20±10%
SF ₆ (W)	20±10%
RF Power (W)	15±10%
ICP Power (W)	500±25%
Endpoint	Disabled

Table 5-17: Recipe for SiC etching in Omega.

An approximate indication of the etch time is estimated first on a test wafer with only SiC for both vias. Measurements of the reflectometer indicate the etched thickness of SiC at the bottom electrode via. Due to feature size, the reflectometer is unable to estimate etched thickness. Etch time varies with feature size, therefore etch time of one feature cannot be translated to other features. The SiC to be etched for the bottom electrode via (figure-5-28) has a larger etch surface compared to the top electrode via, hence has a shorter etch time. Therefore, Axiotron inspection proves vital to verify via opening and ensure exposure of the metal layer.

To further ensure top via is completely etched with AlSi exposed, a PES Al etching is performed on a test wafer (figure-5-29). Consequently, the Axiotron inspection indicates etched AlSi electrodes in figure-5-29b, therefore indicating a previously successful etch.

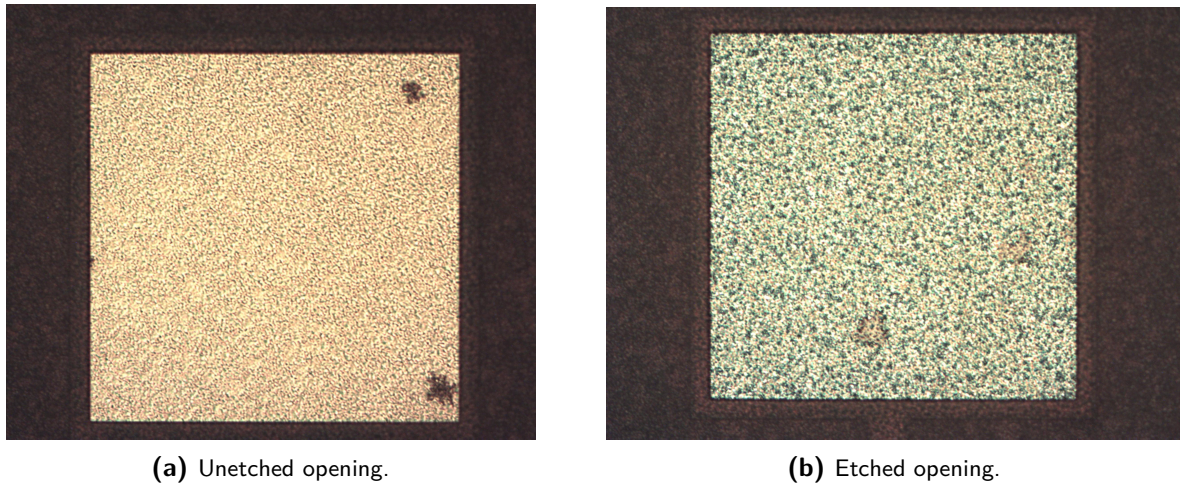


Figure 5-28: Bottom electrode via opening.

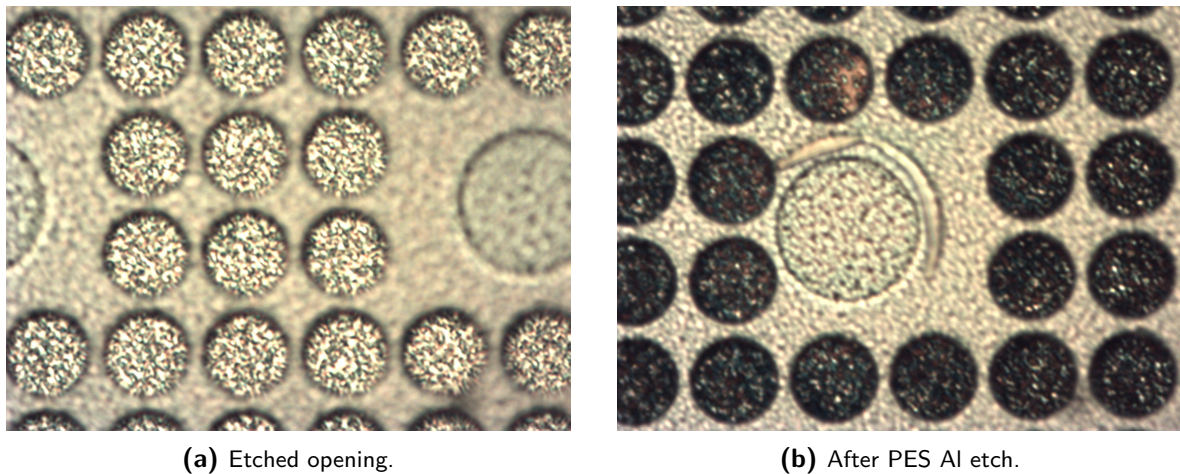


Figure 5-29: Top via opening.

5-6 Interconnect

With the exposed AlSi, a $1\mu\text{m}$ thick AlSi is deposited onto the wafer. The thickness of interconnect M3 is determined by the thickness of the SiC3 membrane to ensure reliable connectivity. A thin metal deposition may result in disconnections at the via openings. A pre-RF etch is incorporated before the AlSi deposition to etch the naturally formed passivation layer of Al_2O_3 . Therefore, the pre-RF etch step enables a breakthrough to reliably expose AlSi. The M3 deposited metal is coated with a thick layer of negative nLOF photoresist, exposed with M3 interconnect image and developed.

Similar to the other metal layers plasma etching for anisotropic etch is opted. The same recipe implemented for the electrodes is employed but with a longer etch time. Dektak is a measurement device that tracks the displacement of a needle scanning over the sample surface, resulting in a side profile of the sample. Figure-5-30a represents a Dektak scan of a portion of the sensing base which measures the beam opening and interconnect thickness and

width.

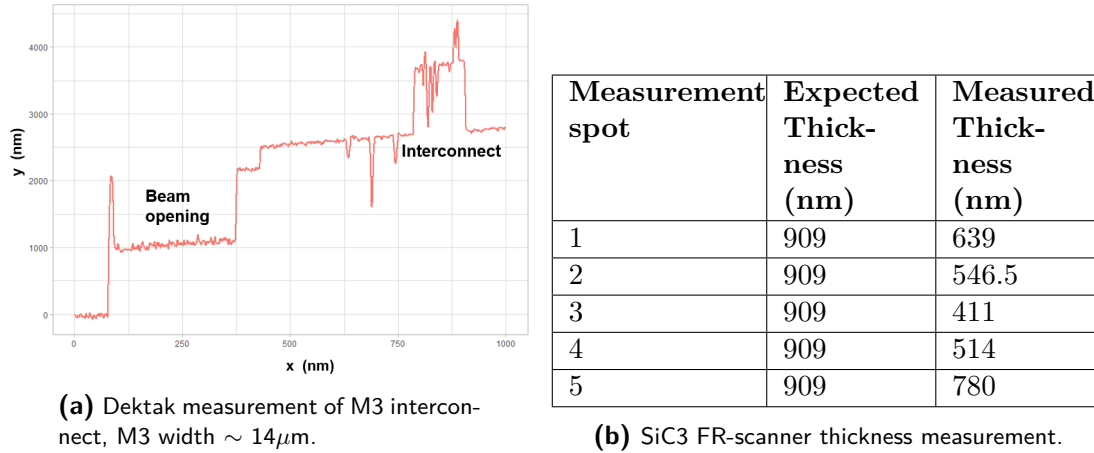


Figure 5-30: Features measurements after M3 etching.

SEM inspections indicate large Al fences post M3 etching. Fence removal is imperative as it can possibly disrupt membrane structure during VHF membrane release etching. Figure-5-31a depicts large Al fences. Fence removal eliminated minor sections of fences, therefore ultrasound cleaning is implemented and further deemed successful post-cleaning. Figure-5-31b depicts the result of ultrasound cleaning. The cleaning method is conducted after beam structures and sacrificial holes are constructed. This affects the MEMS structure enabling chipping at the boundary of sacrificial holes and beam edges.

5-7 Membrane construction

The membrane construction is conducted in two stages, shaping the deposited SiC3 with sacrificial holes and beam structures and consequently performing VHF TEOS etching to suspend the shaped membrane.

5-7-1 Membrane shaping

A thick coating of 10XT photoresist is spin-coated onto the wafer and further reticle images of sacrificial holes, beam structure, nomenclature, and dicing markers are exposed in series and manually developed with a mixture of AZ 400K and DI water in a 1:4 proportion for 420sec. Post manual development a hard bake step is conducted for 10mins between 90°C and 100°C . Details of coating and exposure are tabulated in 5-22. Further, implementing the etch recipe SIC20DEG to perform SiC etching. It is imperative to ensure the SiC is etched through till

Feature	Etch time in bulk etching step(sec)
Bottom electrode M1	50
Top electrode M2	20
Interconnect M3	80

Table 5-18: Etch time of metal layers at the bulk etching step of the etch recipe in Omega.

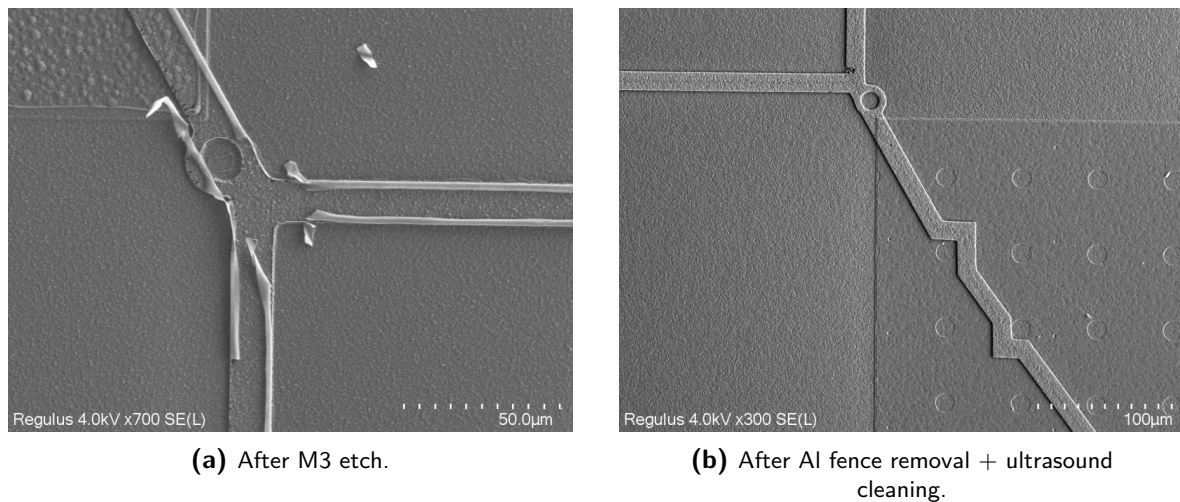


Figure 5-31: Aluminium fence of M3 interconnect.

the TEOS layer to further enable VHF etching to suspend the membrane. The photoresist is further stripped in Tepla and cleaned, preparing the wafer for dicing. An optional alloying step is conducted to improve contact between M3 and M2 at the via openings. Since a pre-RF etch is conducted before M3 metallisation, the alloying process would not largely improve the contact. Since alloying is conducted at 400°C, it causes the membrane to become more tensile.

Feature	Etch time (sec)
Bottom electrode via	88
Top electrode via	94
Beam shaping	120

Table 5-19: SiC etching time with SIC20DEG etch recipe on Omega.

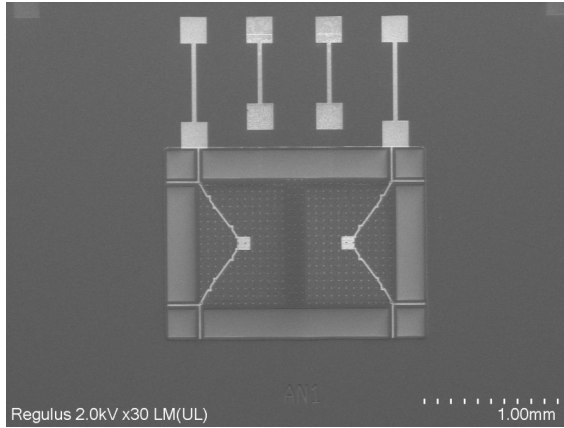
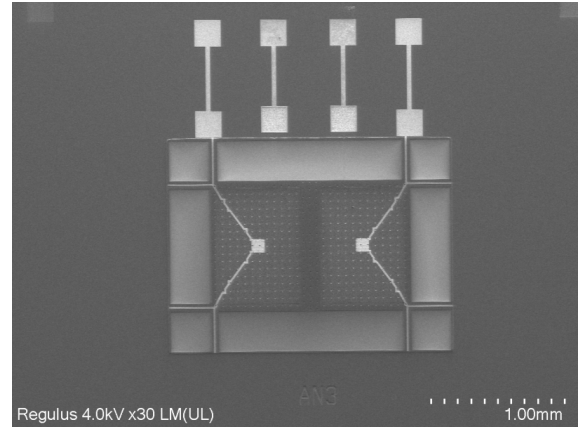
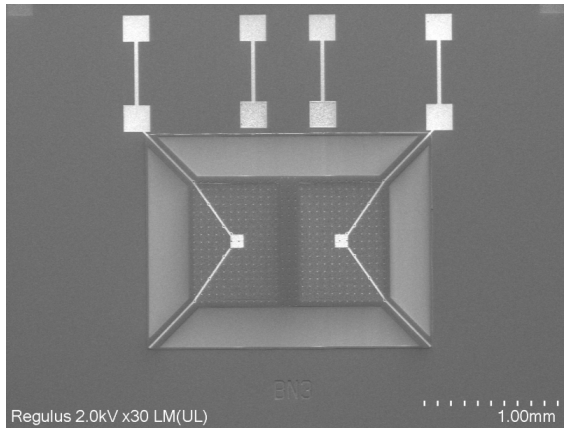
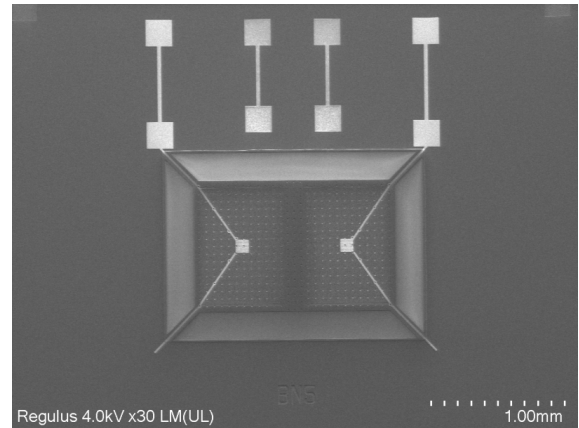
Fabrication stage	Stress (MPa)	Bow (µm)
TEOS deposition	-27.68	51.23
Etched MESA	-34.956	30.39
Etched M2	-24.321	32.44
SiC3 deposition	69.589	81.17

Table 5-20: Flexus measurements.

5-7-2 Membrane suspension

Dicing is performed prior to Vapour HF etching to prevent membrane damage due to the violent procedure. Figure-5-34a depicts the diced wafer. Dies are arranged on an empty wafer and placed into the μ Etch machine. Further, the desired recipe i.e.: etch rate, is selected to initiate etch. Table-5-23 compiles the details of the implemented recipes. VHF etching is conducted in a selected number of cycles of the same recipe. Various combinations

Sensor ID	Expected		Measured	
	Length (μm)	Width (μm)	Length (μm)	Width (μm)
AN1	210	60	209.95	61.119
AN3	300	60	300.83	61.12
BN3	425	100	420.15	100.47
BN5	300	60	300.01	58.65

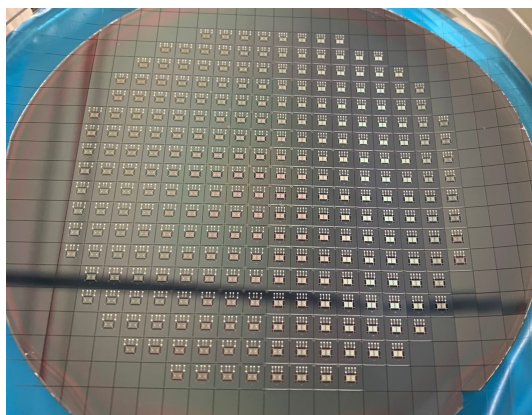
Table 5-21: Beam dimensions from SEM inspection.**(a)** AN1.**(b)** AN3.**Figure 5-32:** SEM images of 8 beam sensing base before VHF.**(a)** BN3.**(b)** BN5.**Figure 5-33:** SEM images of 4 beam sensing base before VHF.

of recipes and etch time are implemented to experiment with the membrane release.

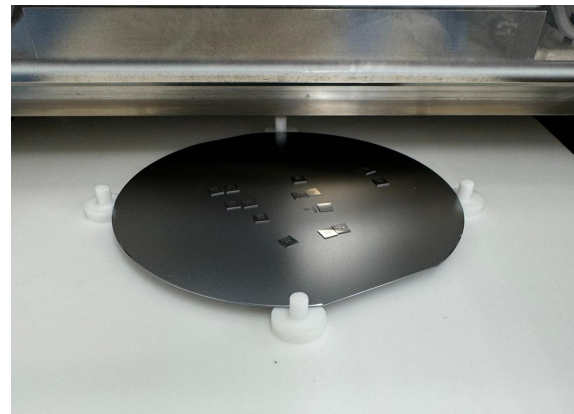
The initial etch combination of recipe and etch time is decided according to vertical and lateral etch dimensions. Most etch combinations resulted in damaged or collapsed beams and membranes with a large portion of unetched TEOS under the membrane, depicted in figure-5-35. None of the dies from multiple batches, regardless of beam variation, survived

Reticle image	Coating		Exposure
	Photoresist	Thickness (μm)	Exposure Energy (mJ)
Zero layer	Shipley SPR3012 Positive	1.4	120
Bottom electrode M1	AZ nLOF 2000s - Negative	1.5	50
Anti-stitching dimples	Shipley SPR3012 - Positive	1.4	95
Pivoting dimple	Shipley SPR3012 - Positive	1.4	140
MESA	AZ nLOF 2000s - Negative	3	55
Top electrode	AZ nLOF 2000s - Negative	3.5	57
Vias	AZ-ECI3027 - Positive	3.1	420
Interconnect	AZ nLOF 2000s - Negative	6	80
Membrane shaping	AZ 10XT - Positive	6	550

Table 5-22: Relevant details about patterning.



(a) Diced wafer.



(b) Dies ready for VHF etching.

Figure 5-34: Steps before VHF etch.

VHF etching. Figure-5-36 illustrates Axiotron inspection of sensor damage resulting from VHF etching. Few dies experienced delamination of SiC at the in-active area of the sensor. Measurements of etched area, figure-5-37 under the membrane of cleaved die depict uneven etching indicating uneven distribution of VHF during etching. This is possible due to the placement of diced dies on a dummy wafer.

Recipe	Etch Rate (nm/min)
1	14.3
2	47.3
3	108.6
4	132.1
5	159.9

Table 5-23: Etching recipes with defined etch rates in the μ Etch VHF machine.

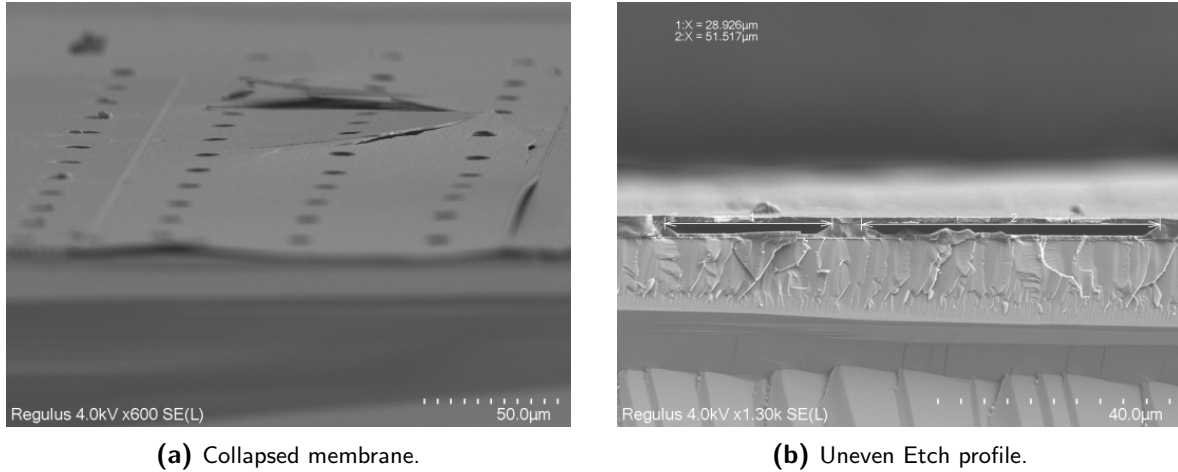


Figure 5-35: SEM inspection of cleaved dies depicting VHF results.

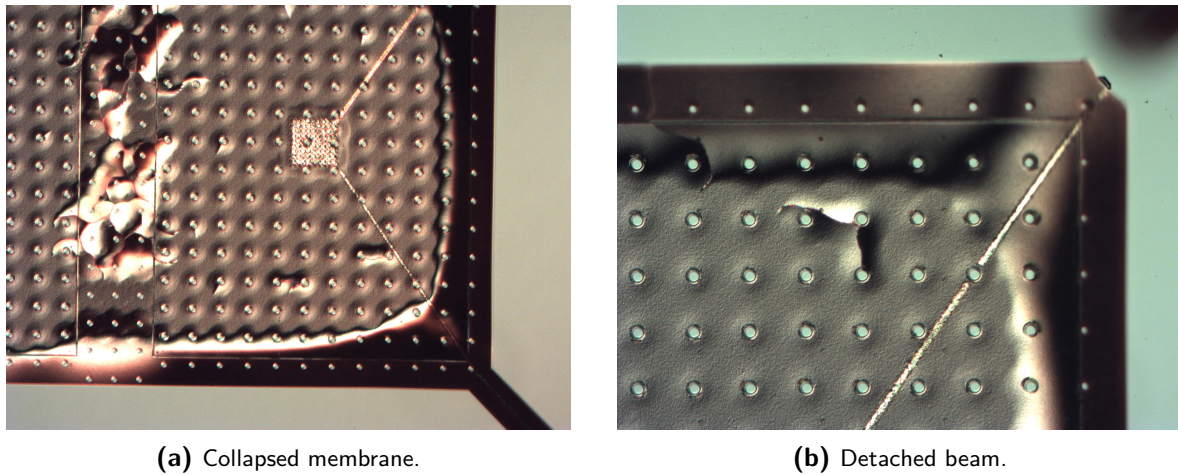


Figure 5-36: Axiotron inspection of damaged dies resulted after VHF etch.

5-8 Discussion

The fabrication process replicated the design of the sensing base with precise feature dimensions. The incorporation of four distinct variations in the beam design offered valuable insights into the beam suspension, particularly in the context of VHF etching. However, upon the completion of multiple batches of VHF etching, the root causes of the membrane suspension failure remain uncertain, without the possibility of testing out new designs to verify our

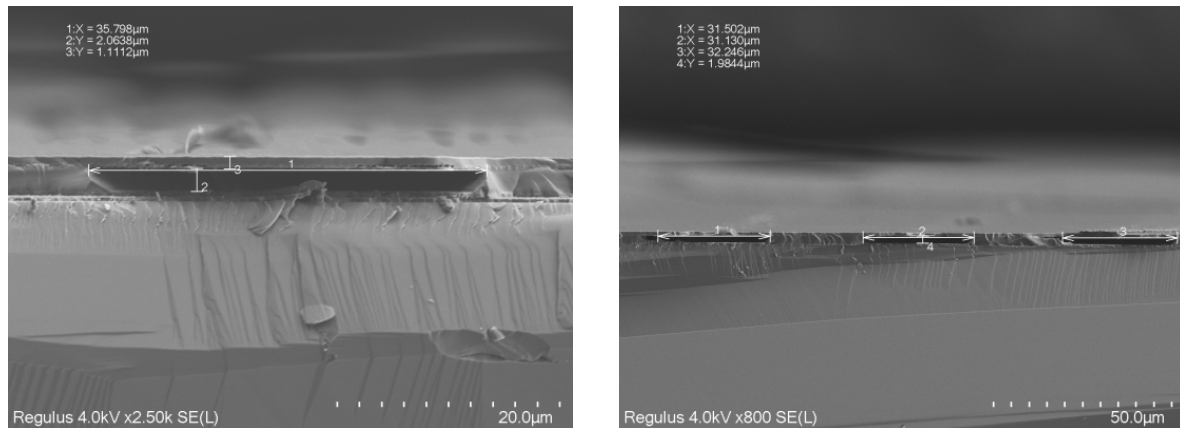


Figure 5-37: SEM measurement of cleaved dies after VHF etch.

educated guess inferred from all the collected evidence.

Notably, several unambiguous issues surfaced during the various fabrication stages of the sensing base. These complications encompassed concerns such as:

- TiN delamination
- The presence of unidentified black residues following M1 etching
- The formation of Al fencing around etched metal features
- an insufficiency in the suspension's load-bearing capacity to withstand VHF etching conditions

Addressing these issues is of paramount importance to ensure the successful completion of the fabrication process.

Results

6-1 Preventing fences

The Al fence formed after metal etching causes unreliable sensor structure, which possibly hindered membrane suspension. Therefore, to reduce the fencing problem, it is imperative to understand the formation of Al fences.

During plasma metal etching, the exposed metal experiences ion bombardment. Consequently, during this process, a re-deposition occurs on the sidewalls of the photoresist [25]. Post etching, the photoresist is stripped, leaving behind a thin tall film of Al surrounding the etched metal pattern. The profile of the sidewall determines the nature of this re-deposition, therefore an experiment is conducted, according to specifications of the nLOF photoresist datasheet [59]. Figure-6-1 depicts the three types of sidewall profile

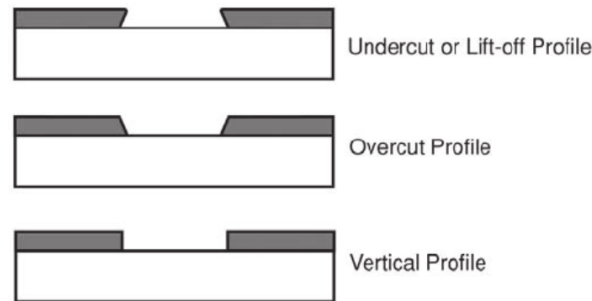


Figure 6-1: Types of photoresist sidewall profile [21].

Previously, the exposure energy and developing recipes were determined by previous processes at EKL and EVG 120/ASML PAS5500-80 wafer stepper manual. Feature dimension is a primary factor that determines the conditions of patterning. Therefore, an experiment is conducted to determine the optimal sidewall profile to avoid fence formation for the metal patterns. Vertical and undercut sidewalls attribute to re-deposition during plasma etching [7]. On the contrary, an overcut profile for the nLOF photoresist prevents the re-deposition of Al on the sidewall, consequently preventing fence formations.

Exposure energy, Post Exposure Bake (PEB) temperature and time, along with post-development hard bake (HB) temperature and time are conditions that determine the profile and properties of the developed photoresist. The previously implemented 50 - 60mJ/cm² exposure energy results in vertical to slightly undercut sidewalls, therefore forming fences. Figure-6-2 and 6-4

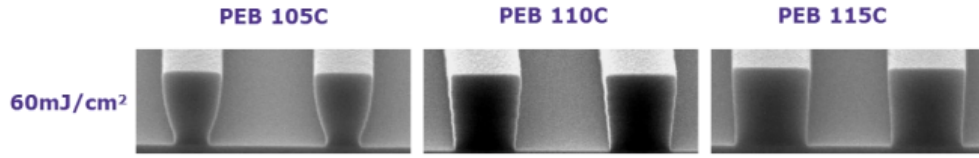


Figure 6-2: Sidewall profile of photoresist with varying Post Exposure Bake (PEB) temperatures [59].

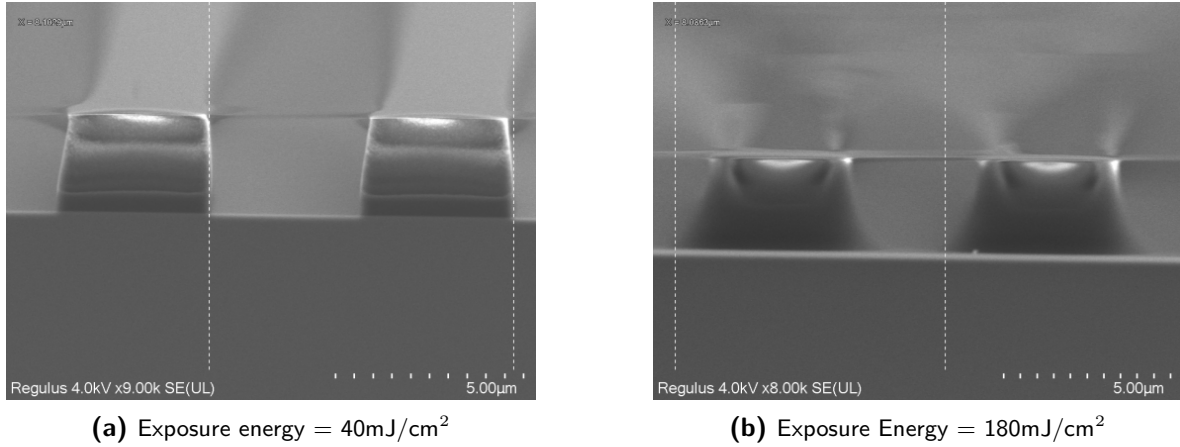


Figure 6-3: Comparison of photoresist sidewall for different exposure energy with PEB = 115°C and Hard bake = 170°C.

depict the sidewall profiles for various PEB and HB temperatures. Considering this information, a $3\mu\text{m}$ thick nLOF photoresist is exposed with exposure energies between $20\text{mJ}/\text{cm}^2$ and $180\text{mJ}/\text{cm}^2$ by implementing a matrix meander for one test wafer exposure (figure-6-5). Other experiment conditions include 110°C and 115°C for the PEB temperatures and 170°C for the HB temperature.

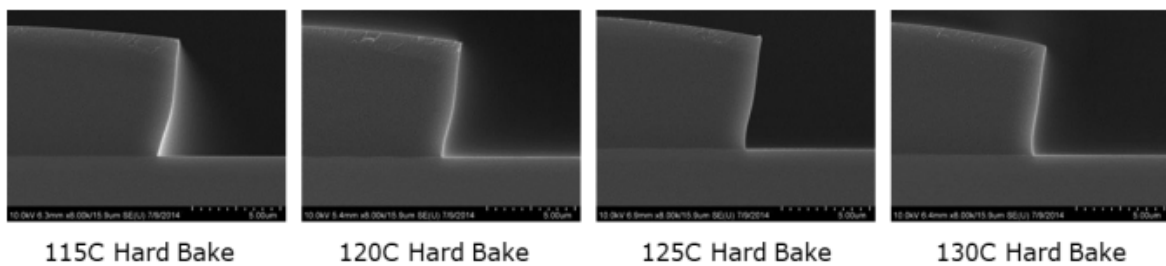


Figure 6-4: Sidewall profile of photoresist with various Hard Bake temperatures [59].

Figure-6-5 depicts the comparison of sidewalls with exposure energy from the lower and upper end of the experimenting range. An overexposure increases pattern dimension with curved corners. Therefore, large exposure energy is unsuitable. SEM inspections are conducted on cleaved samples of the experimented wafers. Figure-6-5b depicts thick destabilized nLOF photoresist patterns of small underexposed features. Consequently, figure-6-5a depicts the optimal sidewall profile and the conditions to achieve it. This optimal sidewall is implemented

in the second fabrication cycle for the sensing base after observing the issues encountered during the first one.

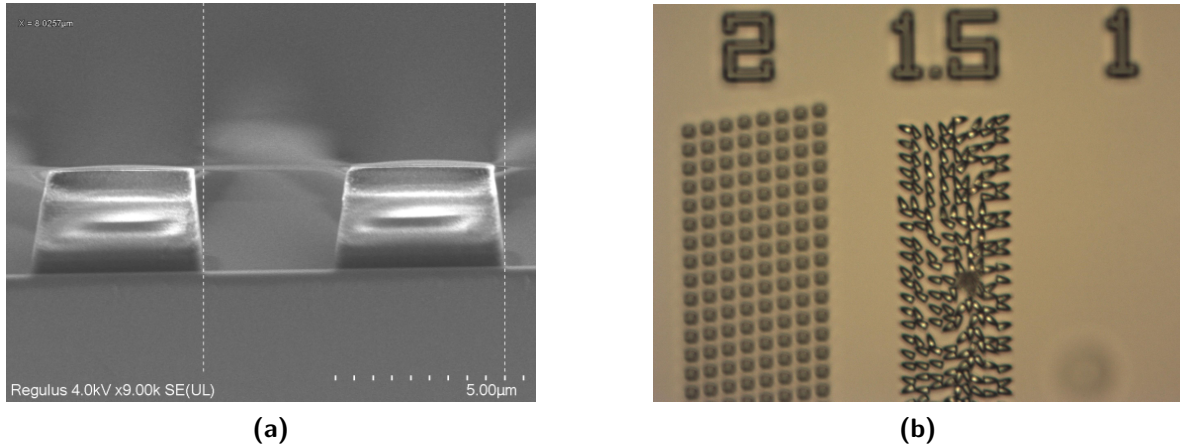


Figure 6-5: Result of experimentation with sidewall profile: a) Sidewall profile with exposure energy = $120\text{mJ}/\text{cm}^2$, PEB = 115°C , HB = 170°C , b) Underexposed nLOF photoresist for small feature size.

6-2 The delamination problem

The delamination of TiN from the first metal stack layers propagates many irregularities in the consequent processing steps. To test the underlying cause, many parameters are assessed such as adhesion between layers, stress measurements after various depositions, and deposition temperature.

- **"Scotch tape" test:** This "rule-of-thumb" experiment can quickly test the adhesion between the various layers through simply applying an adhesive tape directly on the investigated wafer area and stripping it. The test is conducted on two wafers:
 1. Un-patterned, clean TiN-AlSi deposition over the SiC passivation layer.
 2. Bottom electrode patterned on TiN-AlSi deposition over passivation layer SiC.
 A piece of tape is stuck onto the layers and stripped multiple times at multiple points.
- **Stress measurements:** Stress levels are recorded with Flexus at critical deposition stages and a backside compensation layer of SiC $1.5\mu\text{m}$ is deposited to compensate for bow and stress.
- **Cold metal deposition:** Testing fabrication process with cold deposition of metal at 50°C , as opposed to hot deposition at 350°C .

The scotch tape test proved good adhesion between the layers. No material is delaminated on either wafer when stripped multiple times.

Following the stress measurements, data obtained are analysed which did not indicate any abnormally large differences in stress levels. The SiC depositions do not largely increase layer stress since SiC deposition is a low stress deposition. Further, the backside compensation deposition causes more electrodes to delaminate on main processing wafers. Furthermore, an unpatterned wafer with front side deposition of SiC passivation layer and metal is compensated with $1.5\mu\text{m}$ of SiC deposition on the backside. This resulted in complete delamination of the metal layer, indicated in the figure-6-6.

AlSi deposition at 350°C, i.e. hot deposition, results in better step coverage deposition,

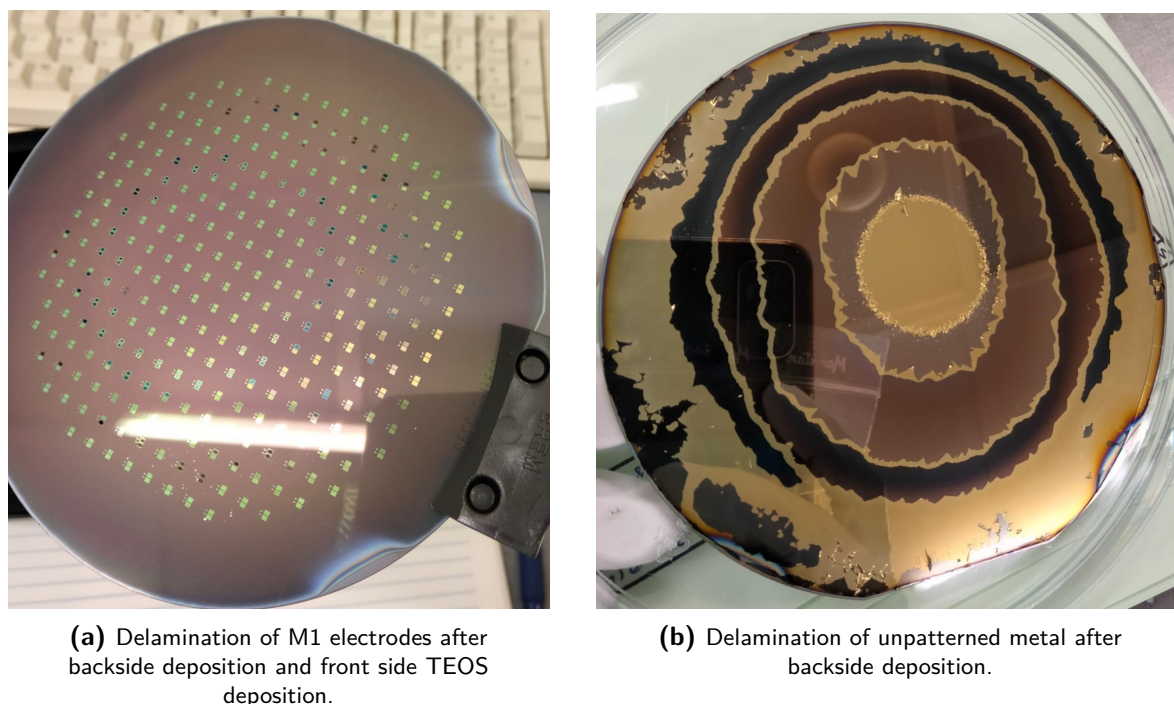


Figure 6-6: Result of back side SiC deposition.

whereas low-temperature depositions result in smooth surfaces. Therefore, high-temperature deposition is implemented. However, visual inspection of AlSi deposition indicated a hazy appearance as opposed to a clean shiny/smooth deposition. Additionally, following a thorough etching of TiN and AlSi, a persistent dark residue is observed on the landing SiC layer, even after a longer over etch. This phenomenon is believed to be linked to the release of residual precursor gases from the PECVD layers during high-temperature post-deposition treatment. This could possibly account for the low-quality AlSi deposition. Therefore, a low-temperature metal stack deposition is implemented. Visual inspection of the cold metal deposition varies from the hot metal deposition, depicted in figure-6-7b. Therefore, to further experiment with the cold deposition, processing is conducted with cold metal deposition at 50°C.

6-3 SiC membrane suspension without electrode

During the previous fabrication cycle, membrane suspension through VHF etching proved challenging. This potentially arose due to the multiple challenges faced during fabrication. Therefore, to test the possibility of the SiC membrane suspension, a test wafer is prepared by fabricating only the cavity and membrane features, enabling a membrane suspension test for the designed sensing base structure. Further, a VHF etching step is conducted to fully release and suspend the membrane without wafer dicing.

The VHF etching is conducted with two recipe combinations with distinct etch rates, 14.3 nm/min and 108.6 nm/min (Recipe 1 and Recipe 3 provided in the EKL HF Vapor Etcher Primaxx uEtch HF SPTS), each for 300sec in every etch cycle. A uniform TEOS etch pattern is observed under the membrane. The results of the membrane suspension are tabulated in

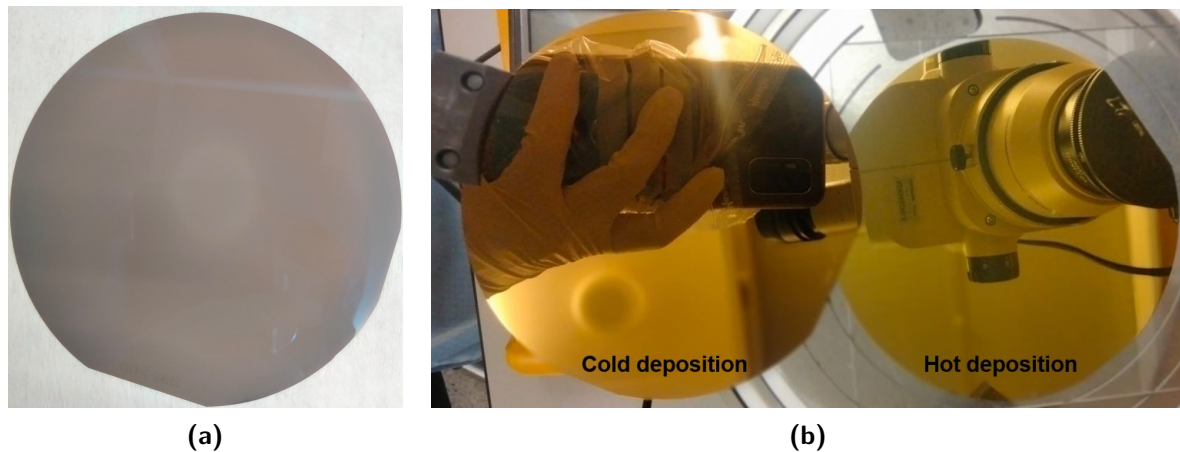


Figure 6-7: a) Dark residue over SiC landing layer after metal etching, b) Visual comparison between hot and cold deposition

6-1. Figure-6-8b depicts the sensor variation with detached beams on the wafer. The results indicate a predominantly successful membrane suspension. A rudimentary sustenance test

Variation	Result
AN1: 8 beam	Detached beams.
BN3: 4 beam	Wider beams, more etch time.
BN5: 4 beam	Successfully released.
AN3: 8 beam	Successfully released with TEOS reminiscence under membrane.

Table 6-1: Results of membrane suspension.

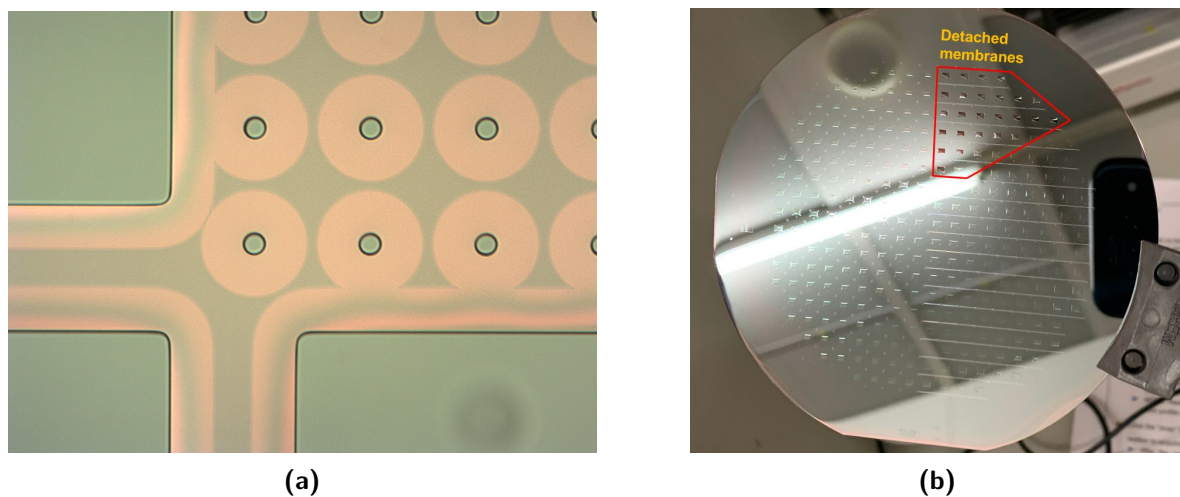


Figure 6-8: Membrane suspension without electrodes I: a) Uniform TEOS etch under membrane, b) Wafer depicting sensor variation with detached membrane.

is conducted by tapping the successfully suspended membrane with a tweezer (equipped with a blunt plastic tip) to quickly determine beam and membrane survivability. The manually

applied force is significantly larger than the estimated applied force. The beams successfully sustain the applied force, displaying membrane deformation and restoring to the suspended rest position without damage post-tapping.

NOTE: Due to uncontrolled rudimentary test conditions and primitive test tools, minor damages are caused to the membrane during tapping. Successful tapping without damage displayed membrane and beam properties.

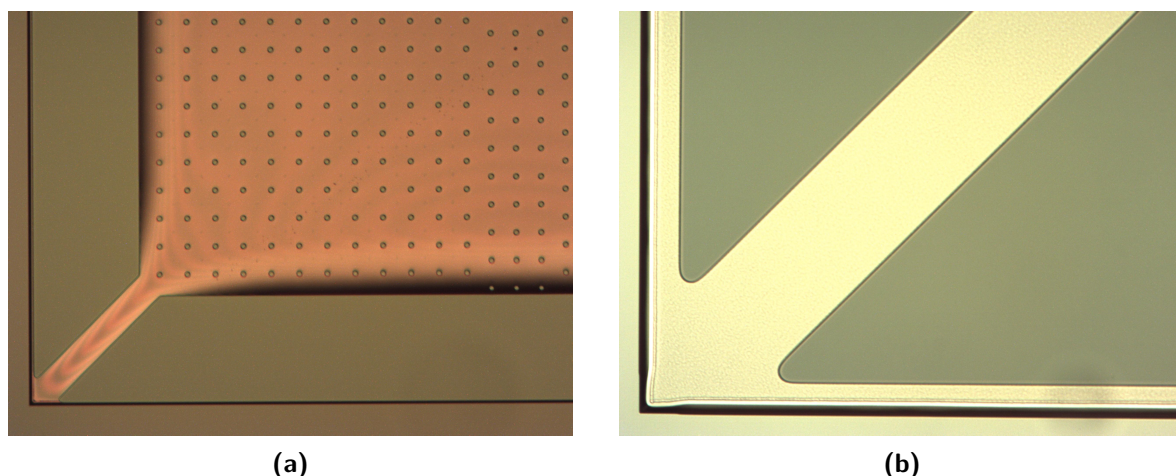


Figure 6-9: Membrane suspension without electrodes II: a) Without extended MESA, b) With extended MESA.

The above test indicates that the membranes without electrodes are capable of surviving the VHF etching process. This is not entirely corroborated for AN1 variation. The beam detachment is observed at the MESA end of the beams. Therefore, indicating insufficient support consequently weakening the beam support structure. Consequently, a larger MESA area is required to provide sufficient support. Hence to implement the demand, the MESA reticle image is exposed four times, each with an x and y intrafield overlay shift of $\pm 10\mu\text{m}$, thus resulting in an extended mesa. After membrane deposition and shaping, a VHF etch is conducted with a 108.6nm/min etch rate recipe for 300sec in each cycle. The membrane suspension required fewer etch cycles compared to the previous VHF etching. All membrane variations are successfully suspended without beam detachment or membrane damage. Therefore, an extended MESA provides additional support to successfully suspend all membranes, potentially with embedded electrodes.

A Keyence inspection is conducted to observe the profile of the released SiC membrane. Figure-6-10 indicates an upward buckling at the edges of the membrane.

Repeated exposure	Intrafield overlay shift (x, y)
1	(10, 10)
2	(-10, 10)
3	(-10, -10)
4	(10, -10)

Table 6-2: Intrafield overlay shift for each MESA exposure.

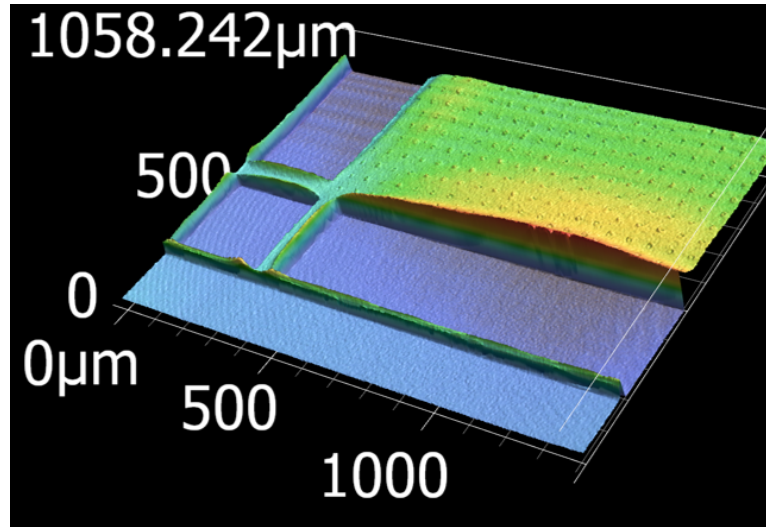


Figure 6-10: Keyence inspection of released SiC membrane without electrodes depicting upward buckling.

6-4 Results of cold metal deposition

The sensing base fabrication process is repeated with cold metal deposition in an attempt to mitigate the delamination issue. Additionally, the optimal sidewall profile of the negative photoresist is implemented to prevent Al fence formation.

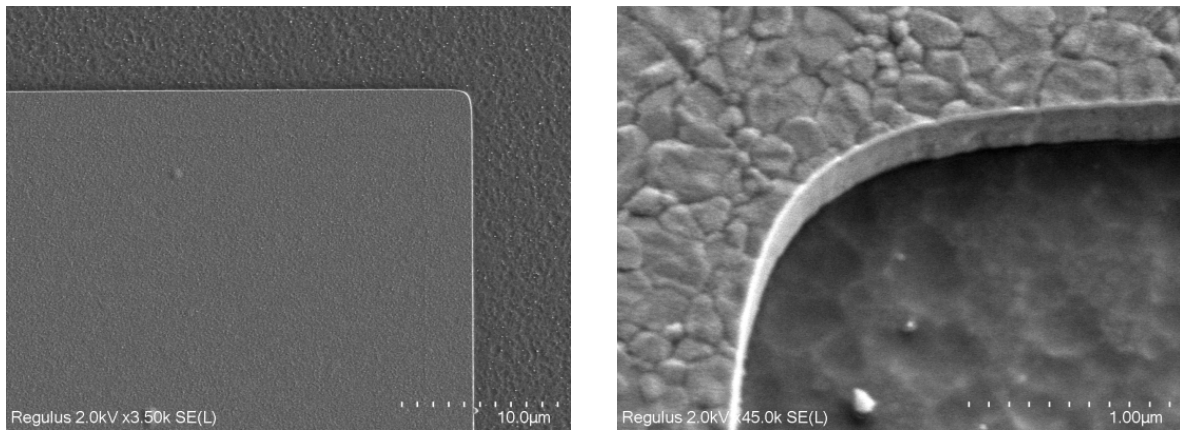
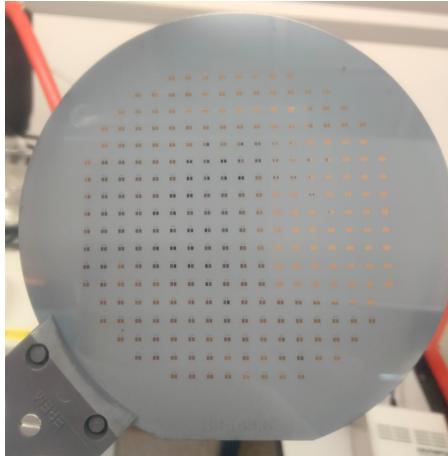
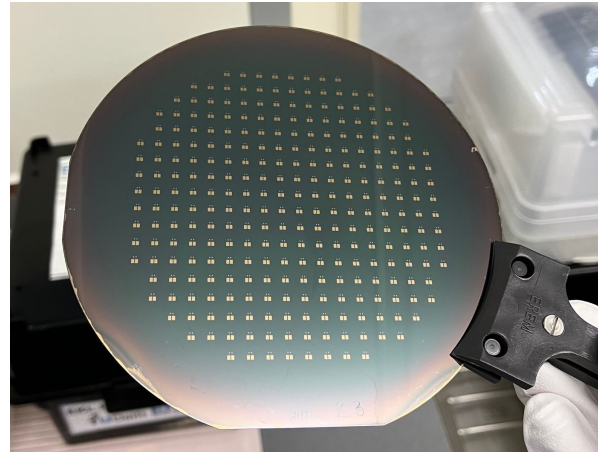


Figure 6-11: No Al fence formation after bottom electrode M1 etch.

The results of the bottom electrode etch are depicted in figure-6-11 and 6-12. The landing surface SiC1 has a clear light blue color after M1 etch, unlike the previous reminiscence of dark residue. Due to the implementation of an overcut sidewall profile, no Al fence is formed around the electrode pattern. Similarly, with top electrode M2 etch, no bulb-like Al fence effect is observed, as depicted in figure-6-16. Furthermore, to test the delamination effect, a thermal test cycle is conducted in the Flexus 2320-S while monitoring the stress measurements. The details of the thermal test are tabulated in 6-3. Although stress measurements do not indicate



(a) First fabrication cycle.

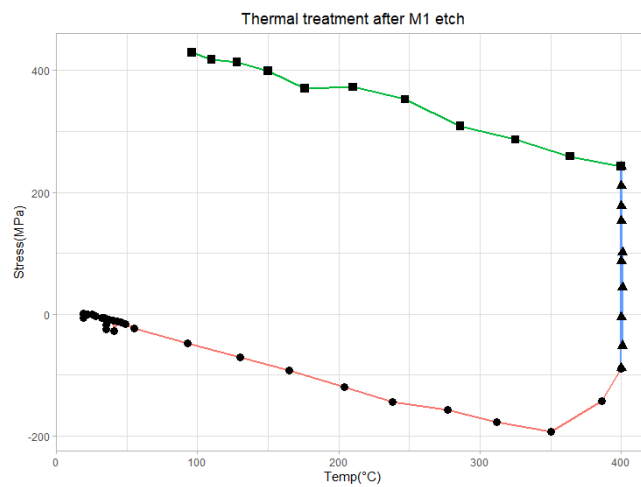


(b) Second fabrication cycle.

Figure 6-12: Comparison between results of bottom electrode M1 etching.

large differences that would induce delamination, the film stress changes from compressive to tensile stress (figure-6-13). Additionally, the surface texture of TiN (depicted in figure-6-14) becomes coarse after the thermal treatment due to the re-crystallization of Al. No delamination of TiN is observed.

Thermal cycle	Start Temperature (°C)	Stop Temperature (°C)	Time (hrs:min)	Number of measurements
Increasing cycle	19	400	01:30	25
Maintaining cycle	400	400	00:30	10
Decreasing cycle	400	90	00:30	10

Table 6-3: Thermal treatment recipe.**Figure 6-13:** Stress measurements during thermal treatment.

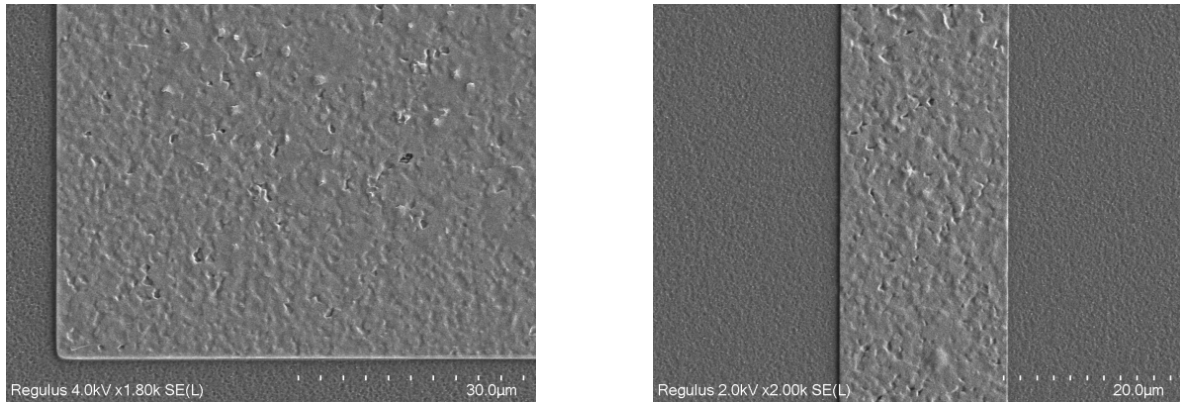


Figure 6-14: TiN texture after thermal treatment.

The consequent fabrication steps, deposition of SiC₂a and TEOS, are conducted with no additional delamination. Cavity shaping with extended MESA and top electrode (M2) fabrication stages is conducted with no delamination or additional fabrication issues (figure-6-15).

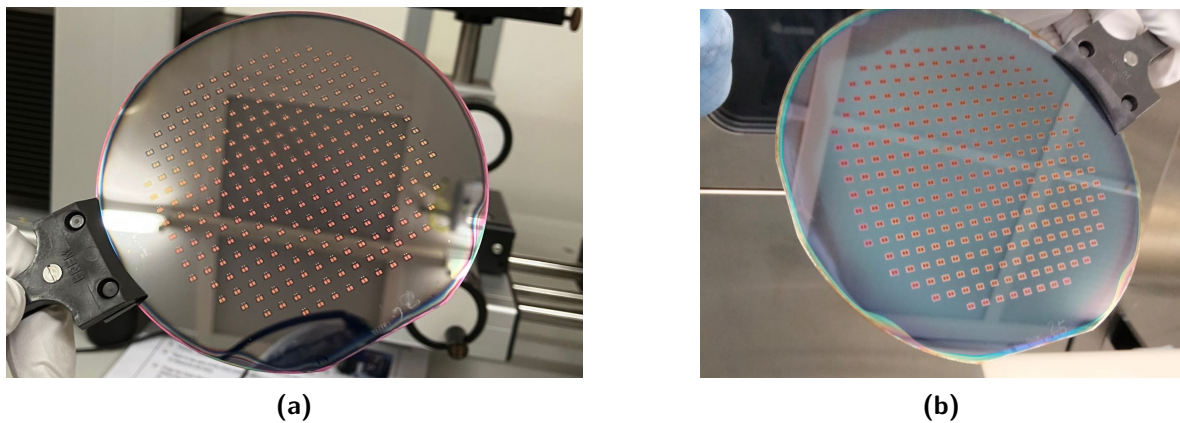


Figure 6-15: Second fabrication cycle a) Wafer after MESA etching, b) Wafer after top electrode M2 etching.

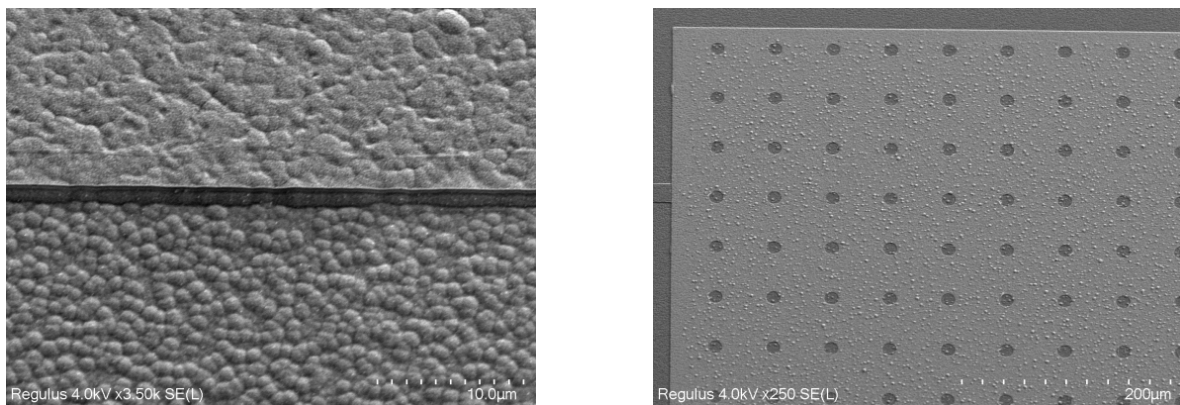


Figure 6-16: No Al fence after top electrode M2 etch.

Similarly, the same sidewall profile is implemented for interconnect M3 etch, however, due to a thicker photoresist, some loose fences are formed which are cleared with Al fence removal. Further, during membrane shaping, two wafers with and without rounding of corner beams are implemented to test the effect during VHF etch/membrane suspension. Figure-6-17 depicts the measurements of sacrificial hole openings implemented into top electrode design and after etching of SiC3 respectively.

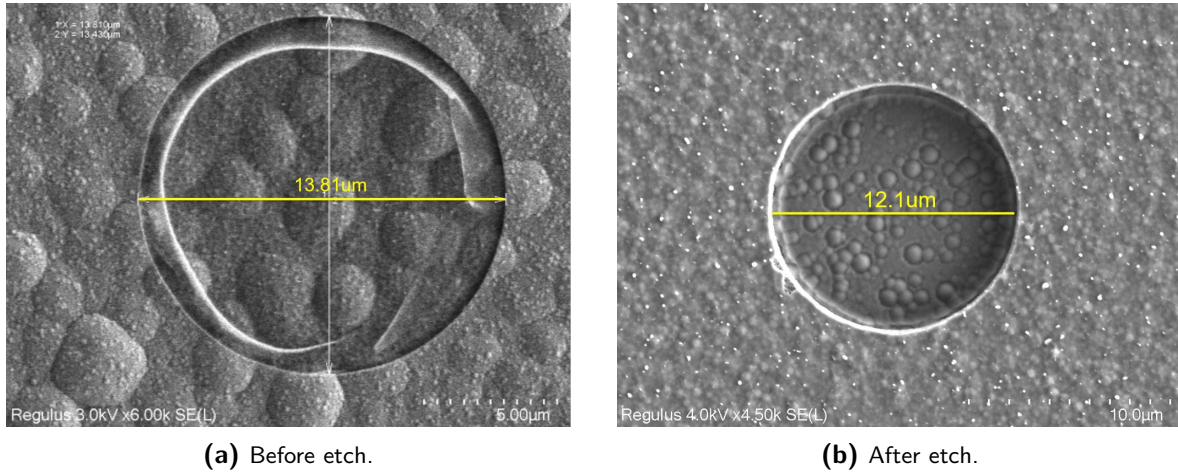


Figure 6-17: Measurement of sacrificial hole openings.

Feature	Estimated diameter (μm)	Measured diameter (μm)
Top electrode sacrificial holes	14	13.81
Sacrificial holes on membrane	10	11.6 - 12.1

Table 6-4: Measurements of sacrificial holes.

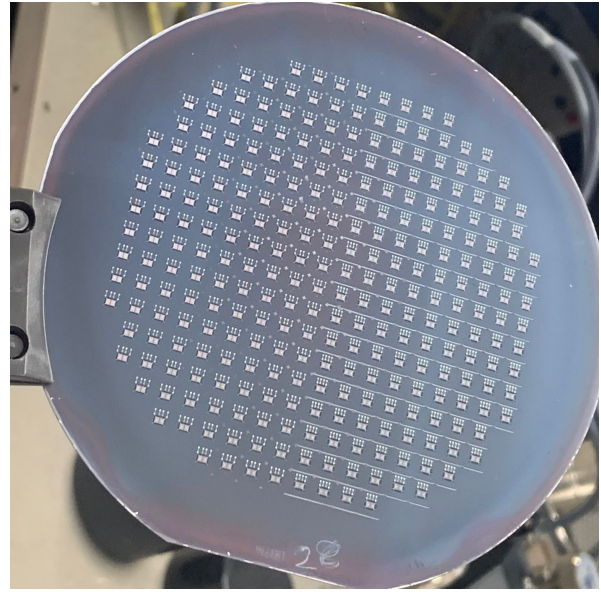
Due to the over-etching of M3 interconnect and M2 top electrodes, the measured thickness of the membrane is thinner than the expected $1\mu\text{m}$. Therefore, for one of the wafers, a $1.4\mu\text{m}$ of SiC3 membrane is deposited to compensate for the overetch. In this case, the final membrane thickness is measured to be $1.1\mu\text{m}$. The additional thickness is expected to help with a better survival chance for the membrane during the release process. Figure-6-18 depicts the visual difference between the wafers after the completion of first and second fabrication cycles.

6-5 Rudimentary measurements

Before dicing the wafers, rudimentary full wafer measurements are conducted to ensure basic sensor characteristics. Basic capacitance and interconnect resistances are measured and tabulated in 6-5 and figure-6-19b. The capacitance measurements account for the unetched TEOS in the cavity as a dielectric and therefore fall within the theoretic capacitance range of the base sensor. On the contrary, the interconnect resistances vary from calculated values potentially due to fabrication variations or uncertainties. However, resistance values remain in the minimally acceptable range. Figure-6-20 depicts the distribution of the sensors measured on the wafer.

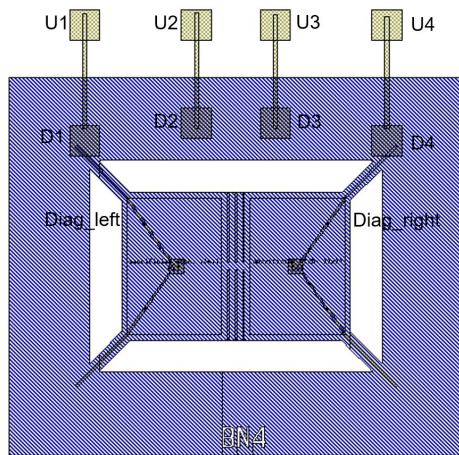


(a) First fabrication cycle.



(b) Second fabrication cycle.

Figure 6-18: Comparison between completed fabrication wafers.



(a) Relevant nomenclature during measurement.

Sensor ID	Capacitance (pF)	
	1U-2U	3U-4U
AN1: D1	12.5875	12.4836
BN3: D4	12.0131	11.9181
BN5: D9	11.9046	11.5144
AN3: D12	11.9985	11.5489

(b) Capacitance measurements around the wafer.

Figure 6-19: Details of the rudimentary measurement session.

Sensor ID	Interconnect Resistance (Ω)					
	diag_left	diag_left	1U-1D	2U-2D	3U-3D	4U-4D
AN1: D1	3.0119	3.0496	1.4427	1.2594	1.2349	1.3305
BN3: D4	3.7985	3.741	1.4164	1.2342	1.2992	1.2975
BN5: D9	3.443	3.4571	1.4472	1.2858	1.3131	1.4609
AN3: D12	3.319	3.3375	1.3355	1.2588	1.2069	1.211

Table 6-5: Resistance of interconnects on the sensor.

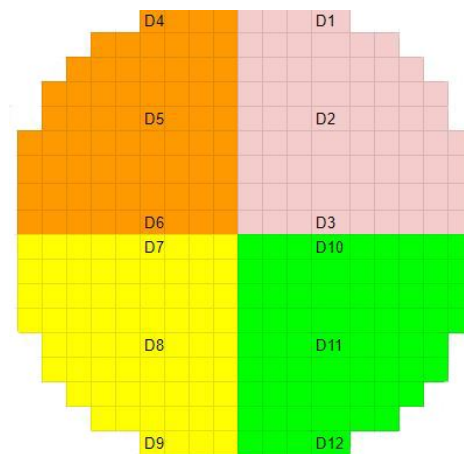


Figure 6-20: Distribution of sensor measurements on wafer.

6-6 Membrane suspension after second fabrication cycle

The previously discussed improvements in the fabrication process are estimated to aid the suspension of the membrane and beam structures during Vapour HF etching. The fabricated wafer is diced and the resulting dies are arranged onto a dummy wafer and proceeded with the Vapour HF process. The previous fabrication cycle depicted membrane and beam collapse with most of the TEOS unetched under the membrane. The best results from the first round of Vapour HF etch are tabulated in 6-6.

Run	Etch rate (nm/min)	Time/cycle (sec)	Number of cycles	Result after etch
1	14.3	300	4	• Two dies had severe SiC peeling. • Few dies had no cracks or no beam detachments. • TEOS to be etched.
2	14.3	300	4	• No major damage on remaining dies. • Cracks on membrane. • TEOS to be etched.
3	14.3	300	4	• Membrane collapse in the middle. • Many beams detached. • Large area of unetched TEOS under electrode area.

Table 6-6: VHF etching results after first fabrication cycle.

Vapour HF in the second fabrication cycle significantly improved with predominantly released membranes and beams. After a significant area of TEOS is etched under the membrane (figure-

6-23), the membrane starts to crack close to complete release (figure-6-21). Table 6-7 details the VHF etch conducted during the second fabrication cycle.

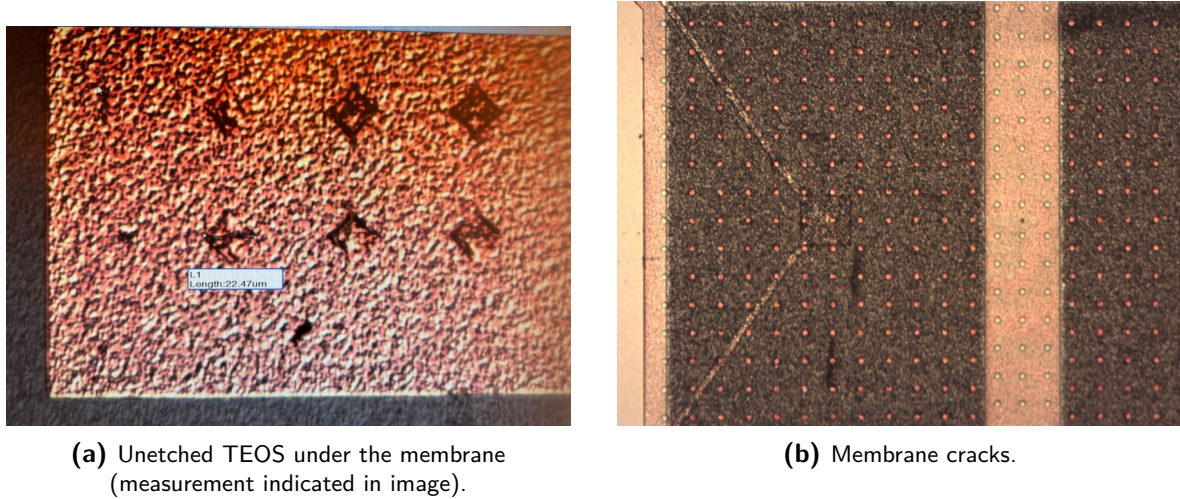


Figure 6-21: VHF etching after second fabrication cycle .

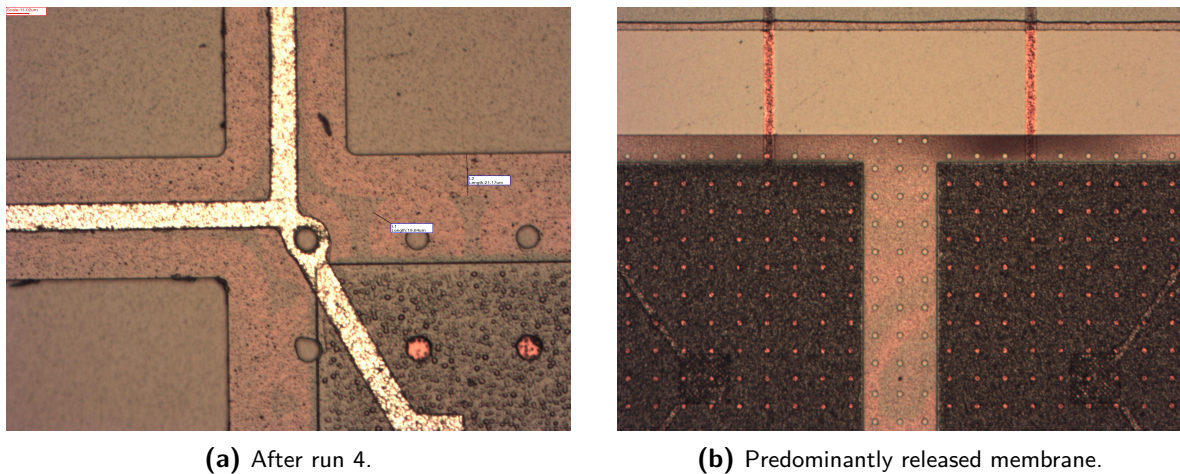


Figure 6-22: VHF etching after second fabrication cycle.

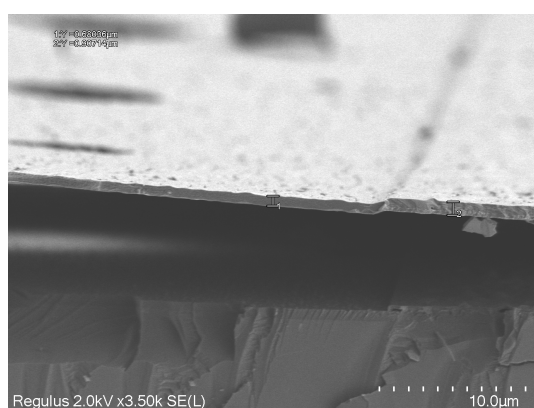
Comparing the results, the second VHF etching evidently depicts improved sensor quality and membrane release (figure-6-22 and 6-24). The membrane thickness of the sensing base is approximately 700nm. Therefore, the membrane release can be further emboldened by increasing membrane thickness and potentially increasing the rounding effect at the corners of the beam support.

6-7 Discussion

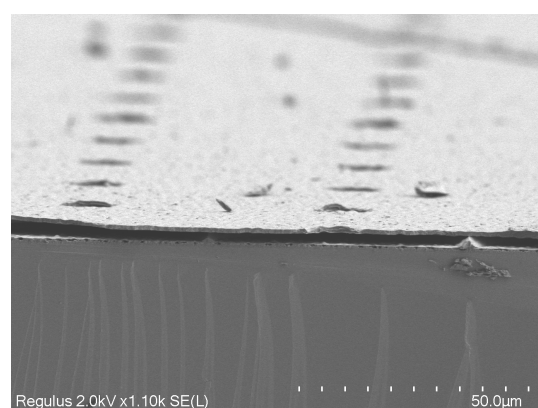
All the previously mentioned fabrication issues of Al fencing and TiN delamination are addressed and mitigated during the second fabrication cycle, resulting in improved membrane

Run	Etch rate (nm/min)	Time/cycle (sec)	Number of cycles	Result after etch
1	108.6	300	2	All dies survived.
2	108.6	300	2	All dies survived.
3	108.6	300	2	All dies survived.
4	108.6	300	2	All dies survived.
5	108.6	300	2	All dies survived.
6	108.6	300	2	• Few 8 beams detached. • Large area of TEOS etched.
7	14.3	300	1	• Membrane collapse in the middle for few dies. • Half the number of dies survived, mostly 4 beam variation.
8-10	14.3	300	1,2	• Cracks and rip on membrane on majority of dies. • Majority of TEOS area etched.
11-13	14.3	300, 500	1	• No 4 beam detachment, few 8 beams detached. • Few membranes collapsed, all membranes indicated cracks. • Very small area of TEOS remains.
14-16	14.3, 108.6	800, 500	1, 2	One die with released membrane and cracks.

Table 6-7: VHF etching results after second fabrication cycle.



(a) Membrane measurement.



(b) Predominantly released membrane.

Figure 6-23: SEM inspection of cleaved dies after second fabrication cycle VHF etching.

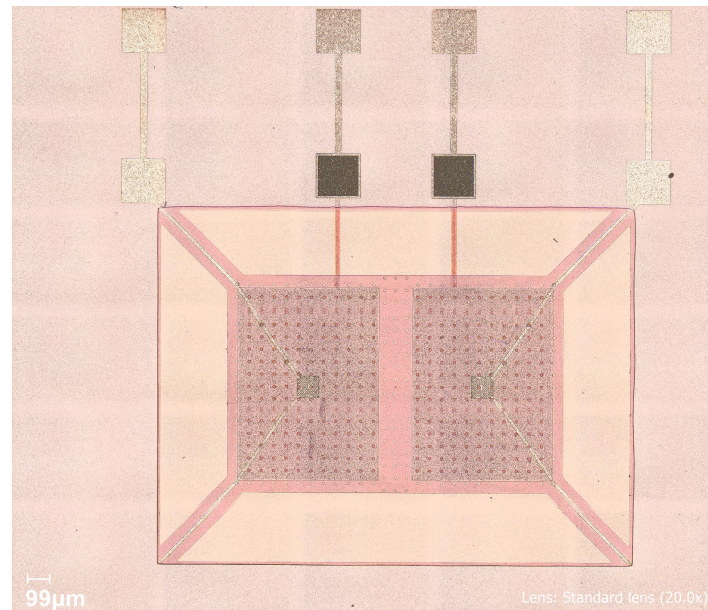


Figure 6-24: Keyence image of sensing base after membrane suspension.

suspension during Vapour HF etching. Prior to membrane suspension and dicing, basic measurements of capacitance and interconnect resistance are measured.

Although membrane suspension drastically improved after the first fabrication cycle, cracked membranes and beam collapses were observed, indicating a requirement for further improvement in the design and fabrication process. This can be improved by implementing a thicker membrane and/or rounding of corner beams (Refer to appendix C-1).

Conclusion

7-1 Project Summary and Objectives Achieved

A MEMS-based airflow sensor design is proposed and developed through a comprehensive analysis of various design aspects. Drawing inspiration from the hair structures observed in different arthropods, the design aims to enable airflow sensing for maintaining an optimal flight pattern. The proposed design incorporates a capacitive sensing mechanism, imitating the sensory capabilities of arthropods. The sensing base emulates the dendrites found at the base of the hair, which facilitates the sensing process.

Various aspects of the capacitive sensors are observed to be interlinked, therefore are analysed and estimated for sensor functionality. Variations of the sensing base are further fabricated. The sensing base fabrication process is faced with multiple issues. They are addressed and rectified, resulting in a predominantly successful fabrication. Delamination of AlSi/TiN metal layer stack for the electrode and Al fencing effect are some of the key rectified fabrication issues. Consequently, membrane suspension is improved during Vapor HF.

The main objectives achieved during the course of the project:

- A bio-inspired robust sensor design is formulated with 1D airflow sensing ability. Capacitive sensing is implemented due to the inherent low power consumption as opposed to other sensing methods. Variations of the sensing base enable multiple sensing range ability.
- Membrane support, base and differential capacitance, the impact of pivoting dimple and pull-in voltage are interlinked parameters that are analysed with basic analytical calculations, along with mechanical and electromechanical simulations.
- The proposed design concept is materialized with a compatible fabrication strategy. Issues faced during the fabrication process are assessed and rectified to improve the quality of membrane suspension.
- The fabrication process is demonstrated to be feasible for the proposed design concept, albeit with slight improvements required to ensure proper membrane suspension without the occurrence of cracks or collapsed beams.

7-2 Future Work and Recommendations

The fabricated sensing base will be considered fully developed only after a clean membrane suspension, a successful installment of the hair-like structure, further testing, and characterisation of the completed sensor on various platforms.

Fabrication improvement

- **Membrane thickness:** The thickness of the membrane is measured to be approximately 700 nm due to overetching of the M3 interconnect. Therefore, the thin membrane is likely unable to sustain the local stress created during the various cycles of vapor HF causing membrane cracking. Hence a thicker membrane could better sustain this local stress.
- **Amplified rounding at corner beams:** The beams have inbuilt rounded corners of $5\mu\text{m}$ radius to avoid cracks and rips. Sharp corners are prone to this phenomenon. Therefore it is hypothesised that larger rounded corners could sustain local stress during Vapor HF more reliably.
- **Optimizing Vapor HF etching of sacrificial layer:** A combination of thicker membrane and/or rounded beam corners along with various combinations of VHF recipes and slow membrane release could possibly improve membrane suspension. A local stress analysis during membrane release could provide vital information for successful membrane suspension.
- **Design update and fabrication of variations:** The membrane design could be updated such that no buckling is experienced at the edges of the released membrane. Further, many variations (beam variations, electrode area variations, and pivoting dimple variations) are yet to be materialised to identify the most suitable sensor for FWMAVs.

Implementation of hair structure

- **Modelling hair structure:** FSI simulations of hair structures could provide vital information on optimal shape and dimensions compatible with the fabricated sensing base.
- **Pick and place:** After a successful membrane suspension, hair-like structures are to be installed on the membrane. The pick and place tools with the tip of the hair structure dipped in a suitable glue could affix the hair structure on the membrane. Glass fiber or 3D printed resin structures could also be implemented as hair. Similarly, the protection structures can be implemented.
- **Fabrication:** Polymers such as cured SU-8 could be laminated or spin-coated and further exposed, developed, etched, and UV cured to construct the hair structure and protection structure, making the full microfabrication process integrated inside the cleanroom entirely.

Testing and Sensor Characterisation

- **Differential capacitance:** Prior to and postimplementation of hair structures, the differential capacitance of the different sensor variations must be measured. The Nanomechanical testing systems (FT-NMT03) from the TU Delft Mechanical Engineering Faculty can be best implemented for this purpose. A controlled force can be applied at the desired location to estimate the membrane displacement. A combination of one of these tools along with read-out electronics should provide a differential capacitance. A simpler test involving incrementally applied voltage or asymmetrically applied voltage on the two capacitors could also provide information on the achievable differential capacitance.
- **Wind tunnel platform:** The sensor is considered developed only after sensor calibration and characterisation with controlled applied airflow. This can be achieved at

the low-speed wind tunnel facilities available at TU Delft Aerospace department. As an extension to the project, a customized test set-up is built to specifically test the fabricated airflow sensors.

- **Drone platform:** Consequently, the characterised airflow sensor is to be integrated onto the FWMAVs and assessed if the implementation aids flight control.

A successful extension of the project would provide a novel onboard working solution to optimize flight control on FWMAVs with extremely small and lightweight hair-like airflow sensors, and provide the first useable prototype onboard an actual micro air vehicle outside of the laboratory environment.

Bibliography

- [1] L. V. King, "Lvii. on the precision measurement of air velocity by means of the linear hot-wire anemometer," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 29, no. 172, pp. 556–577, 1915.
- [2] J. A. Humphrey, R. Devarakonda, I. Iglesias, and F. G. Barth, "Dynamics of arthropod filiform hairs. i. mathematical modelling of the hair and air motions," *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, vol. 340, no. 1294, pp. 423–444, 1993.
- [3] F. Mayer, G. Salis, J. Funk, O. Paul, and H. Baltes, "Scaling of thermal cmos gas flow microsensors: Experiment and simulation," in *Proceedings of Ninth International Workshop on Micro Electromechanical Systems*, IEEE, 1996, pp. 116–121.
- [4] L. K. Baxter, "Capacitive sensors," *Design and Applications*, 1997.
- [5] U. Dillner, E. Kessler, S. Poser, V. Baier, and J. Müller, "Low power consumption thermal gas-flow sensor based on thermopiles of highly effective thermoelectric materials," *Sensors and Actuators A: Physical*, vol. 60, no. 1-3, pp. 1–4, 1997.
- [6] J.-W. Lim, H.-H. Kim, B.-H. Kang, D.-D. Lee, and W.-Y. Chung, "Fabrication and characteristics of suspended-type micro gas sensor," *Journal of the Korean Physical Society*, vol. 33, no. 9, p. 432, 1998.
- [7] G. S. Oehrlein and Y. Kurogi, "Sidewall surface chemistry in directional etching processes," *Materials Science and Engineering: R: Reports*, vol. 24, no. 4, pp. 153–183, 1998, ISSN: 0927-796X. DOI: [https://doi.org/10.1016/S0927-796X\(98\)00016-3](https://doi.org/10.1016/S0927-796X(98)00016-3). [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0927796X98000163>.
- [8] T. Shimozawa, T. Kumagai, and Y. Baba, "Structural scaling and functional design of the cercal wind-receptor hairs of cricket," *Journal of Comparative Physiology A*, vol. 183, pp. 171–186, 1998.
- [9] N. Svedin, E. Kalvesten, E. Stemme, and G. Stemme, "A new silicon gas-flow sensor based on lift force," *Journal of Microelectromechanical Systems*, vol. 7, no. 3, pp. 303–308, 1998. DOI: [10.1109/84.709647](https://doi.org/10.1109/84.709647).

-
- [10] R. Oosterbroek, T. S. Lammerink, J. W. Berenschot, G. J. Krijnen, M. C. Elwenspoek, and A. van den Berg, "A micromachined pressure/flow-sensor," *Sensors and Actuators A: Physical*, vol. 77, no. 3, pp. 167–177, 1999.
 - [11] F. Barth, "How to catch the wind: Spider hairs specialized for sensing the movement of air.," *Die Naturwissenschaften*, vol. 87, no. 2, pp. 51–58, 2000.
 - [12] S.-T. Hung, S.-C. Wong, and W. Fang, "The development and application of microthermal sensors with a mesh-membrane supporting structure," *Sensors and Actuators A: Physical*, vol. 84, no. 1-2, pp. 70–75, 2000.
 - [13] D.-K. Kim, S.-G. Kang, J.-H. Sim, J.-K. Shin, P. Choi, and J.-H. Lee, "Characteristics of piezoresistive mass flow sensors fabricated by porous silicon micromachining," *Japanese Journal of Applied Physics*, vol. 39, no. 12S, p. 7134, 2000.
 - [14] B. Du Bois, G. Vereecke, A. Witvrouw, *et al.*, "Hf etching of si-oxides and si-nitrides for surface micromachining," in *Sensor Technology 2001: Proceedings of the Sensor Technology Conference 2001, held in Enschede, The Netherlands 14–15 May, 2001*, Springer, 2001, pp. 131–136.
 - [15] M. Bao, H. Yang, Y. Sun, and P. J. French, "Modified reynolds' equation and analytical analysis of squeeze-film air damping of perforated structures," *Journal of Micromechanics and Microengineering*, vol. 13, no. 6, p. 795, 2003.
 - [16] O. Dangles, C. Magal, D. Pierre, A. Olivier, and J. Casas, "Variation in morphology and performance of predator-sensing system in wild cricket populations," *Journal of Experimental Biology*, vol. 208, no. 3, pp. 461–468, 2005.
 - [17] M. Dijkstra, J. Van Baar, R. J. Wiegerink, T. S. Lammerink, J. De Boer, and G. J. Krijnen, "Artificial sensory hairs based on the flow sensitive receptor hairs of crickets," *Journal of micromechanics and microengineering*, vol. 15, no. 7, S132, 2005.
 - [18] H. Guo, Y. Wang, S. Chen, G. Zhang, H. Zhang, and Z. Li, "Pecvd sic as a chemical resistant material in mems," in *2006 1st IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, 2006, pp. 805–808. DOI: [10.1109/NEMS.2006.334900](https://doi.org/10.1109/NEMS.2006.334900).
 - [19] H. Huang, Y. Wu, K. Winchester, *et al.*, "Structural materials for nems/mems devices," in *2006 International Conference on Nanoscience and Nanotechnology*, 2006. DOI: [10.1109/ICONN.2006.340717](https://doi.org/10.1109/ICONN.2006.340717).
 - [20] V. Ivashchenko, S. Dub, O. Porada, L. Ivashchenko, P. Skrynsky, and A. Stegny, "Mechanical properties of pecvd a-sic:h thin films prepared from methyltrichlorosilane," *Surface and Coatings Technology*, vol. 200, no. 22, pp. 6533–6537, 2006, EMRS 2005 Symposium K, ISSN: 0257-8972. DOI: <https://doi.org/10.1016/j.surfcoat.2005.11.087>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0257897205012971>.
 - [21] R. Zaouk, B. Y. Park, and M. J. Madou, "Introduction to microfabrication techniques," *Microfluidic Techniques: Reviews and Protocols*, pp. 5–15, 2006.
 - [22] A. Hess, R. Parro, J. Du, J. Dunning, M. Scardelletti, and C. A. Zorman, "Pecvd silicon carbide as a thin film packaging material for microfabricated neural electrodes," *MRS Online Proceedings Library (OPL)*, vol. 1009, 1009–U04–03, 2007. DOI: [10.1557/PROC-1009-U04-03](https://doi.org/10.1557/PROC-1009-U04-03).

- [23] G. Krijnen, T. Lammerink, R. Wiegerink, and J. Casas, "Cricket inspired flow-sensor arrays," in *SENSORS, 2007 IEEE*, IEEE, 2007, pp. 539–546.
- [24] J. E. Rogers, R. Ramadoss, P. M. Ozmun, and R. N. Dean, "Mems accelerometer fabricated using printed circuit processing techniques," in *2007 IEEE International Symposium on Industrial Electronics*, 2007, pp. 3250–3254. DOI: [10.1109/ISIE.2007.4375135](https://doi.org/10.1109/ISIE.2007.4375135).
- [25] L. Stafford, J. Margot, S. Delprat, M. Chaker, and S. Pearton, "Influence of redeposition on the plasma etching dynamics," *Journal of applied physics*, vol. 101, no. 8, 2007.
- [26] Y.-H. Wang, C.-Y. Lee, and C.-M. Chiang, "A mems-based air flow sensor with a free-standing micro-cantilever structure," *Sensors*, vol. 7, no. 10, pp. 2389–2401, 2007.
- [27] H. Takahashi, E. Iwase, K. Matsumoto, and I. Shimoyama, "Air flow sensor for an insect-like flapping wing," in *2008 IEEE 21st International Conference on Micro Electro Mechanical Systems*, IEEE, 2008, pp. 916–919.
- [28] *Fabrication of SiC MEMS Pressure Sensor Based on Novel Vacuum-Sealed Method*, vol. 2008 Second International Conference on Integration and Commercialization of Micro and Nanosystems, International Conference on Integration and Commercialization of Micro and Nanosystems, Jun. 2008, pp. 623–626. DOI: [10.1115/MicroNano2008-70136](https://doi.org/10.1115/MicroNano2008-70136). eprint: <https://asmedigitalcollection.asme.org/MNC/proceedings-pdf/MICRONANO2008/42940/623/2684103/623\1.pdf>. [Online]. Available: <https://doi.org/10.1115/MicroNano2008-70136>.
- [29] C. Bruinink, R. Jaganatharaja, M. de Boer, *et al.*, "Advancements in technology and design of biomimetic flow-sensor arrays," in *2009 IEEE 22nd International Conference on Micro Electro Mechanical Systems*, 2009, pp. 152–155. DOI: [10.1109/MEMSYS.2009.4805341](https://doi.org/10.1109/MEMSYS.2009.4805341).
- [30] E. Zampetti, S. Pantalei, A. Pecora, *et al.*, "Design and optimization of an ultra thin flexible capacitive humidity sensor," *Sensors and Actuators B: Chemical*, vol. 143, no. 1, pp. 302–307, 2009.
- [31] Q. Zhang, W. Ruan, H. Wang, Y. Zhou, Z. Wang, and L. Liu, "A self-bended piezoresistive microcantilever flow sensor for low flow rate measurement," *Sensors and Actuators A: Physical*, vol. 158, no. 2, pp. 273–279, 2010, ISSN: 0924-4247. DOI: <https://doi.org/10.1016/j.sna.2010.02.002>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0924424710000518>.
- [32] J. T. Kuo, L.-Y. Chang, P.-Y. Li, T. Hoang, and E. Meng, "A microfluidic platform with integrated flow sensing for focal chemical stimulation of cells and tissue," *Sensors and Actuators B: Chemical*, vol. 152, no. 2, pp. 267–276, 2011.
- [33] S. Sterbing-D'Angelo, M. Chadha, C. Chiu, *et al.*, "Bat wing sensors support flight control," *Proceedings of the National Academy of Sciences*, vol. 108, no. 27, pp. 11 291–11 296, 2011.
- [34] J. T. Kuo, L. Yu, and E. Meng, "Micromachined thermal flow sensors—a review," *Micromachines*, vol. 3, no. 3, pp. 550–573, 2012.

-
- [35] A. Dagamseh, C. Bruinink, R. J. Wiegerink, T. S. Lammerink, H. Droogendijk, and G. J. Krijnen, "Interfacing of differential-capacitive biomimetic hair flow-sensors for optimal sensitivity," *Journal of micromechanics and microengineering*, vol. 23, no. 3, p. 035 010, 2013.
 - [36] M. M. Sadeghi, R. L. Peterson, and K. Najafi, "A 2-d directional air flow sensor array made using stereolithography and mems micro-hydraulic structures," in *2013 Transducers & Eurosensors XXVII: The 17th International Conference on Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS & EUROSENSORS XXVII)*, IEEE, 2013, pp. 722–725.
 - [37] M. Sadeghi, R. Peterson, and K. Najafi, "Air flow sensing using micro-wire-bonded hair-like hot-wire anemometry," *Journal of Micromechanics and Microengineering*, vol. 23, no. 8, p. 085 017, 2013.
 - [38] N. André, B. Rue, G. Scheen, D. Flandre, L. A. Francis, and J.-P. Raskin, "Out-of-plane mems-based mechanical airflow sensor co-integrated in soi cmos technology," *Sensors and Actuators A: Physical*, vol. 206, pp. 67–74, 2014, ISSN: 0924-4247. DOI: <https://doi.org/10.1016/j.sna.2013.11.017>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0924424713005712>.
 - [39] H. Bleckmann, J. Mogdans, and S. L. Coombs, "Flow sensing in air and water," *Berlin, Germany*, vol. 976, 2014.
 - [40] S. D. Min, Y. Yun, and H. Shin, "Simplified structural textile respiration sensor based on capacitive pressure sensing method," *IEEE Sensors Journal*, vol. 14, no. 9, pp. 3245–3251, 2014. DOI: [10.1109/JSEN.2014.2327991](https://doi.org/10.1109/JSEN.2014.2327991).
 - [41] P. N. Patel, R. Yadav, and M. Adhvaryu, "Design and analysis of diversified micro-cantilever structure for sensor applications," in *2014 2nd International Conference on Emerging Technology Trends in Electronics, Communication and Networking*, 2014, pp. 1–5. DOI: [10.1109/ET2ECN.2014.7044966](https://doi.org/10.1109/ET2ECN.2014.7044966).
 - [42] S. D. Nguyen, I. Paprotny, P. K. Wright, and R. M. White, "Mems capacitive flow sensor for natural gas pipelines," *Sensors and Actuators A: Physical*, vol. 231, pp. 28–34, 2015, Special Issue of the Micromechanics Section of Sensors and Actuators based upon contributions revised from the Technical Digest of the 27th IEEE International Conference on MICRO ELECTRO MECHANICAL SYSTEMS (MEMS-14; 26–30 January 2014, San Francisco, CA, USA), ISSN: 0924-4247. DOI: <https://doi.org/10.1016/j.sna.2014.10.013>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0924424714004476>.
 - [43] B. Peri, B. Borah, and R. K. Dash, "Effect of rf power and gas flow ratio on the growth and morphology of the pecvd sic thin film s for mems applications," *Bulletin of Materials Science*, vol. 38, pp. 1105–1112, 2015.
 - [44] A. Castro, H. Bae, M. Yu, and P. Abshire, "Bat-inspired hair sensor," in *2016 IEEE Biomedical Circuits and Systems Conference (BioCAS)*, 2016, pp. 556–559. DOI: [10.1109/BioCAS.2016.7833855](https://doi.org/10.1109/BioCAS.2016.7833855).
 - [45] C.-H. Wu, D. Kang, P.-H. Chen, and Y.-C. Tai, "Mems thermal flow sensors," *Sensors and Actuators A: Physical*, vol. 241, pp. 135–144, 2016.

- [46] A. K. Dhonkal, V. Agarwal, and K. Sengar, "Sensitivity of the mems based piezoresistive wind speed sensor with comparative study of different shapes of paddles," *Int. Res. J. Eng. Technol*, vol. 4, no. 2, pp. 1693–1697, 2017.
- [47] A. Panahi, M. H. Sabour, and E. Ghafar-Zadeh, "A new multidisciplinary approach towards airplane health monitoring using cantilever airflow sensors," in *2017 IEEE 30th Canadian Conference on Electrical and Computer Engineering (CCECE)*, 2017, pp. 1–4. DOI: [10.1109/CCECE.2017.7946823](https://doi.org/10.1109/CCECE.2017.7946823).
- [48] V. Balakrishnan, T. Dinh, H.-P. Phan, D. V. Dao, and N.-T. Nguyen, "Highly sensitive 3c-sic on glass based thermal flow sensor realized using mems technology," *Sensors and Actuators A: Physical*, vol. 279, pp. 293–305, 2018, ISSN: 0924-4247. DOI: <https://doi.org/10.1016/j.sna.2018.06.025>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0924424718301638>.
- [49] F. Deku, S. Mohammed, A. Joshi-Imre, *et al.*, "Effect of oxidation on intrinsic residual stress in amorphous silicon carbide films," *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, vol. 107, no. 5, pp. 1654–1661, 2019.
- [50] F. Ejeian, S. Azadi, A. Razmjou, *et al.*, "Design and applications of mems flow sensors: A review," *Sensors and Actuators A: Physical*, vol. 295, pp. 483–502, 2019, ISSN: 0924-4247. DOI: <https://doi.org/10.1016/j.sna.2019.06.020>. [Online]. Available: <https://www.sciencedirect.com/science/article/pii/S0924424719302559>.
- [51] X. Fan, A. D. Smith, F. Forsberg, *et al.*, "Manufacture and characterization of graphene membranes with suspended silicon proof masses for mems and nems applications," *Microsystems & Nanoengineering*, vol. 6, no. 1, p. 17, 2020.
- [52] S. Kwon, Y. Park, W. Ban, *et al.*, "Effect of plasma power on properties of hydrogenated amorphous silicon carbide hardmask films deposited by pecvd," *Vacuum*, vol. 174, p. 109 187, 2020.
- [53] S. Peter, R. Ehrler, T. Seyller, and F. Speck, "Annealing effects on a-sic: H and a-sicn: H films deposited by plasma cvd methods," *Vacuum*, vol. 178, p. 109 410, 2020.
- [54] K. Rajasekaran, H. D. Bae, S. Bergbreiter, and M. Yu, "3d printed bio-inspired hair sensor for directional airflow sensing," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, IEEE, 2020, pp. 8945–8950.
- [55] Q. Lu, W. Fang, C. Wang, *et al.*, "Investigation of a complete squeeze-film damping model for mems devices," *Microsystems & Nanoengineering*, vol. 7, no. 1, p. 54, 2021.
- [56] D. Shen, Y. Jiang, Z. Ma, *et al.*, "Bio-inspired flexible airflow sensor with self-bended 3d hair-like configurations," *Journal of Bionic Engineering*, pp. 1–10, 2022.
- [57] [Online]. Available: https://www.analog.com/media/en/technical-documentation/data-sheets/ad7745_7746.pdf.
- [58] [Online]. Available: <https://smartec-sensors.eu/cms/pages/products/uti-interface.php>.
- [59] *Microchemicals: Technical datasheet, az® nlof™ 2000 series, negative tone photoresists for single layer lift-off*. [Online]. Available: https://www.microchemicals.com/micro/tds_az_nlof2000_series.pdf.
- [60] K. Won Lee and I.-H. Choi, *Silicon based mass airflow sensor*.

Appendix A

A-1 Capacitance of tilted electrode under membrane

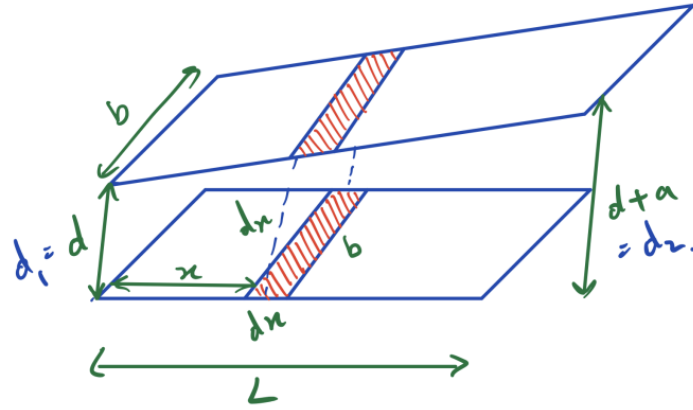


Figure A-1: Illustration for tilted electrode derivation (below-membrane).

$$C = \frac{\varepsilon_o A}{d_o} \quad (\text{A-1})$$

Considering an infinitesimally small length dx from the length of the electrode, the capacitance from this area is implemented to integrate and identify the capacitance of this electrode configuration.

$$\int dC = \int_0^L \frac{(b dx)}{d + \frac{ax}{L}} \quad (\text{A-2})$$

$$\Rightarrow C = \frac{\varepsilon_o b \ln \left[d + \frac{ax}{L} \right]}{a/L} \quad (\text{A-3})$$

$$C = \frac{\varepsilon_o (Lb)}{a} \ln \left[d + \frac{ax}{L} \right] \quad (\text{A-4})$$

$$\frac{\varepsilon_o A}{a} [\ln(d + a) - \ln(d)] \quad (\text{A-5})$$

$$\Rightarrow C = \frac{\varepsilon_o A}{a} \left[\ln \left[\frac{d + a}{d} \right] \right] \quad (\text{A-6})$$

$$d = d_1; d_2 = d + a; \Rightarrow a = d_2 - d_1; \quad (\text{A-7})$$

$$\Rightarrow C = \frac{\varepsilon_0 A}{d_2 - d_1} \ln \left[\frac{d_2}{d_1} \right]. \quad (\text{A-8})$$

A-2 Pull-in voltage derivation

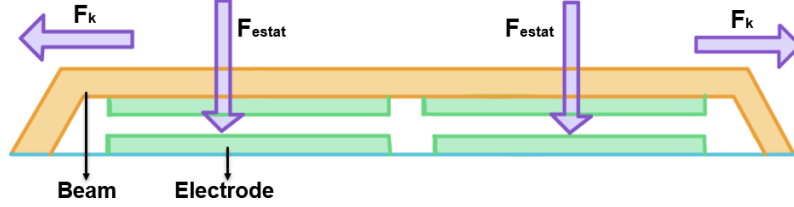


Figure A-2: Cross section of sensing base depicting forces without pivoting dimple.

The electrostatic force between the electrodes is sustained by the spring force of the suspended beam. Using this, the electrostatic force by the electrodes is equated to the spring force of the beams.

$$\frac{\varepsilon_0 A v^2}{2(d_0 - x)^2} = k_x \quad (\text{A-9})$$

$$(d_0 - x) \sqrt{\frac{2kx}{\varepsilon_0 A}} = V \quad (\text{A-10})$$

The membrane displacement at maximum applied voltage is determined (just before membrane collapse), which in turn can be used to find the maximum applied voltage.

$$\Rightarrow \frac{dV}{dx} = 0 \quad (\text{A-11})$$

$$\frac{d_0}{2\sqrt{x}} \sqrt{\frac{2k}{\varepsilon_0 A}} - \frac{3}{2} \sqrt{\frac{2kx}{\varepsilon_0 A}} = 0 \quad (\text{A-12})$$

$$\frac{d_0}{2\sqrt{x}} = \frac{3\sqrt{x}}{2} \quad (\text{A-13})$$

$$\Rightarrow x = \frac{d_0}{3} \quad (\text{A-14})$$

$$V_{\max} = \left(d_0 - \frac{d_0}{3} \right) \sqrt{\frac{2kd_0}{3\varepsilon_0 A}} \quad (\text{A-15})$$

$$V_{\max} = \frac{2d_0}{3} \sqrt{\frac{2kd_0}{3\varepsilon_0 A}} \quad (\text{A-16})$$

$$V_{\max} = \frac{2d_0}{3} \sqrt{\frac{2k}{3C_0}} \quad (\text{A-17})$$

Appendix B

B-1 Pre-requisites for designing

The PAS5500-80 wafer stepper imaging system comprises of a stack of lens, a light source and other optics. A mask is typically inserted between the light source and the lens system with a wafer coated with photoresist at the opposite side, illustrated in figure-B-1. When the photoresist is exposed to the light source through the image on the mask, the same image is transferred onto each die, therefore forming a pattern on the photoresist. Depending on the type of photoresist, the exposed or unexposed area becomes soluble. Consequently, the photoresist from the unwanted area is cleared using the appropriate developer solutions.

The lens system is capable of reducing the image by a factor of 5. Therefore the mask

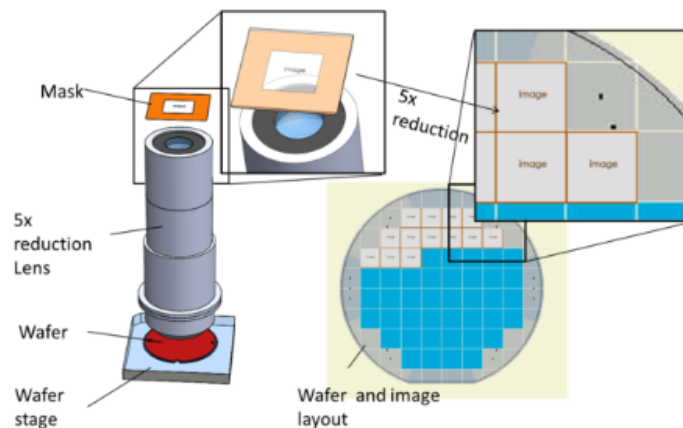


Figure B-1: ASML PAS5500/80 wafer stepper system.

is fabricated with images 5x larger than the expected image pattern. Typically the mask images are fabricated with chromium (Cr) on side side of a glass mask. The pattern on the photomask is a mirrored image with Cr-side up, when inserted in the stepper, it is Cr-side down.

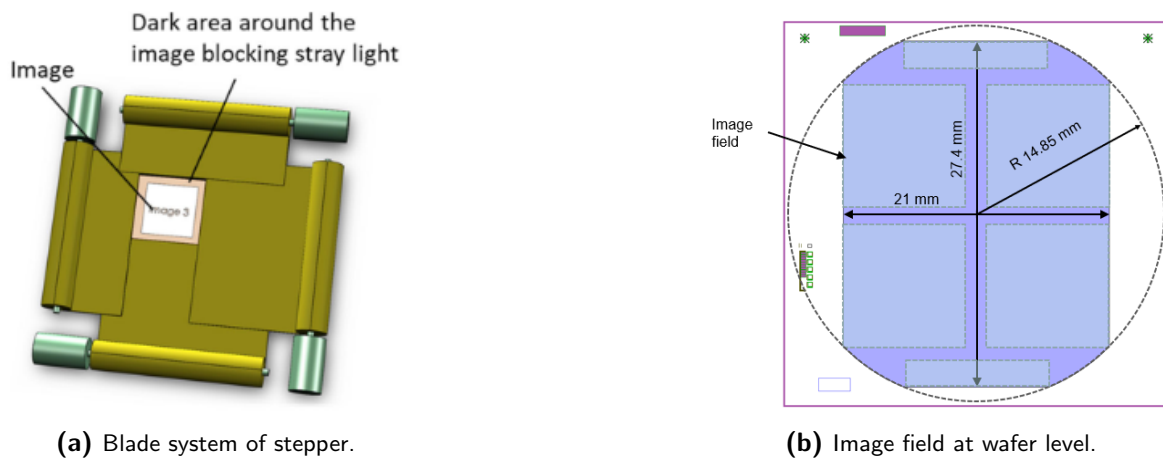


Figure B-2: Vital information to design photomask.

Figure-B-3b illustrates the image field dimensions at the wafer level.

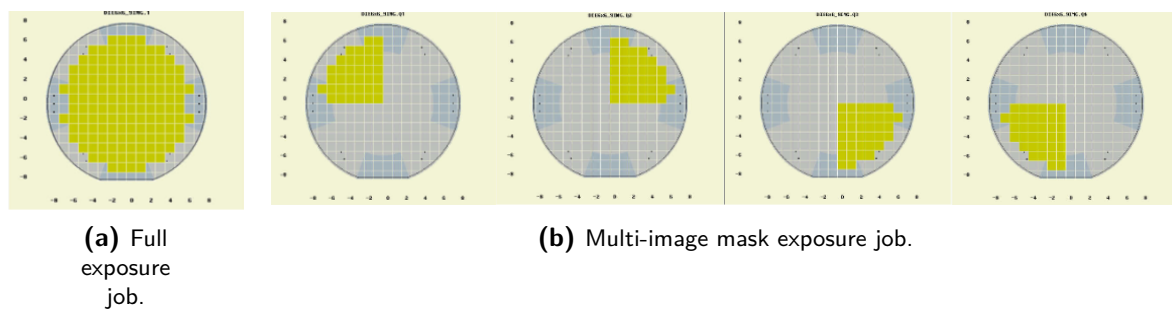


Figure B-3: Implemented exposure jobs.

B-2 Additional features designed onto the mask

Figure-B-4 and B-5 depict the photomask layout. Various dimensions of the pivoting dimples and hair structures, along with the variations of smaller electrodes and associated beams.

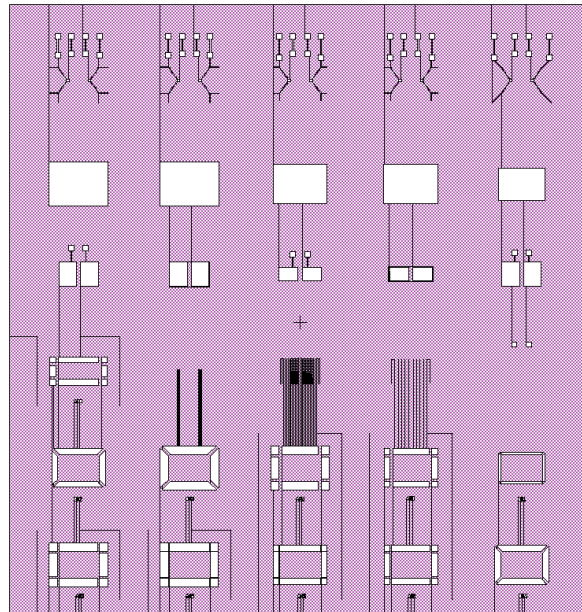


Figure B-4: Mask 1.

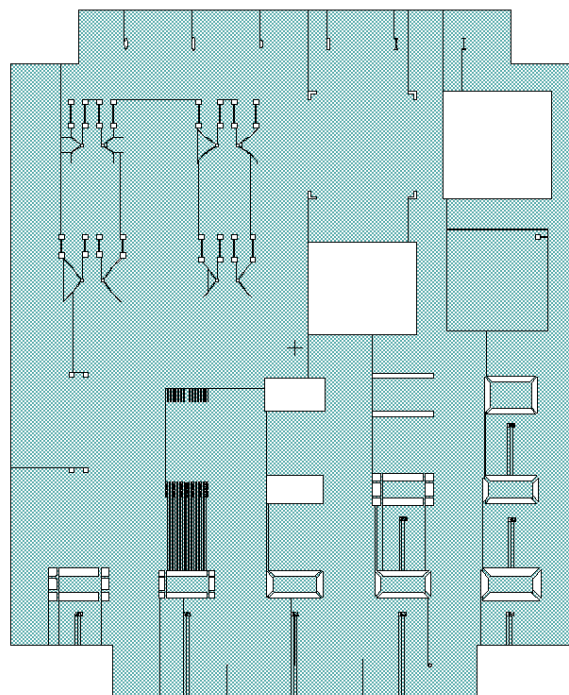


Figure B-5: Mask 2.

Appendix C

C-1 Rounding the corners of the beam

Considering the mask design is complete and the beam corners require additional rounding, this can be achieved by applying a focus offset during the exposure of the desired reticle image. Figure-C-1 illustrates the effect of focus offset. A matrix meander with varying offsets is implemented to assess the rounding.

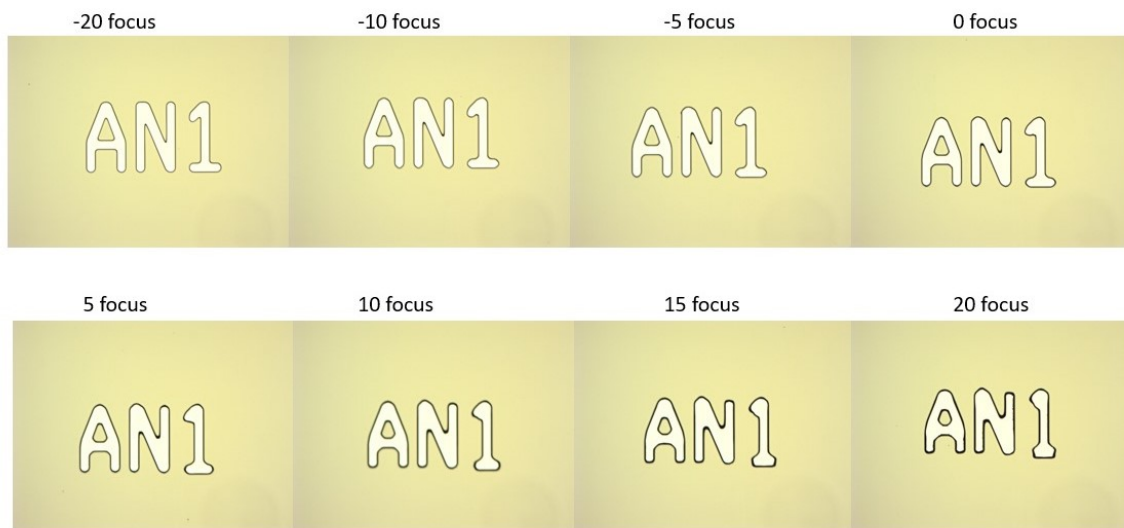


Figure C-1: Result of varying focus offset.

Hair sensors.

An integrated test set-up in a low speed wind tunnel.

L Manjunath

The internship report documents the process of setting up an integrated test environment at low speed wind tunnel to characterize the hairlike airflow sensors fabricated during the thesis project at EKL Laboratory.

Hair sensors.

An integrated test set-up in a low speed wind tunnel.

by

L Manjunath

Student number: 5336732

Contents

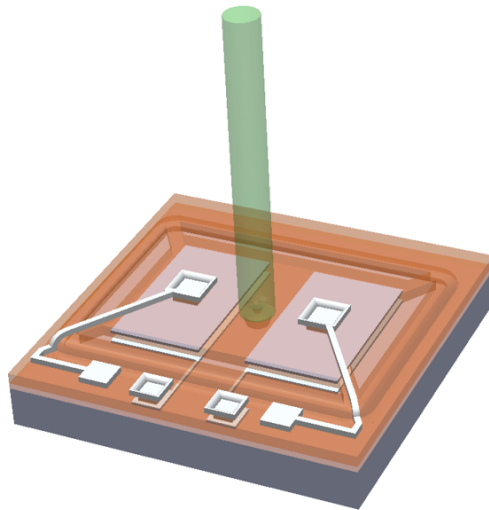
1	Introduction	1
1.1	Block Diagram	2
2	Rotation system for sensor platform	3
2.1	Motor selection	3
2.2	Motor control	5
3	Mechanical set-up	7
3.1	Sensor base	7
3.1.1	PCB structure.	7
3.1.2	Inspiration and concept exploration	7
3.2	3D printing	9
3.2.1	Structure Build	9
3.2.2	Printing procedure	11
3.2.3	Printing Iterations.	13
3.3	Base frame set-up	16
3.3.1	Dimensions of Tunnel	16
3.3.2	Types of assembly configurations	17
3.3.3	Evolution of Base Frame.	18
3.4	Final Assembly	21
3.4.1	External assembly	22
3.4.2	Internal assembly.	23
4	Conclusion	25
4.1	Future Work.	25

Introduction

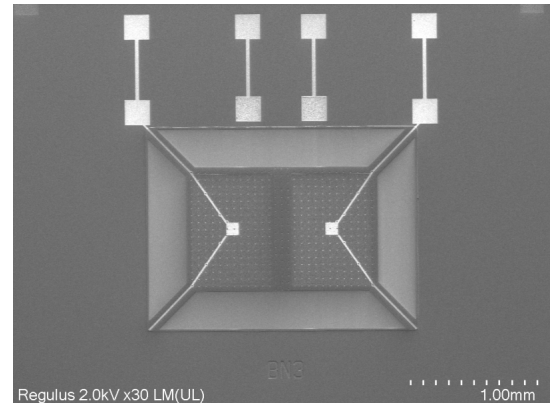
Airflow sensors are vital components used to measure the rate of airflow in various applications, playing a pivotal role in monitoring, controlling, and optimizing airflow within different systems. These sensors function by detecting the movement of air or gases and converting this flow rate into an electrical signal, employing various mechanisms such as thermal mass flow, piezoresistive, hot wire anemometers capacitive hair-like sensors and many more. Their significance lies in their ability to provide input to regulate and maintain desired airflow levels or manipulate and readjust air vehicles according to airflow. This results in improved energy efficiency, accuracy, safety, and quality control. Airflow sensors find widespread use in heating, ventilation, and air conditioning (HVAC) systems for comfortable indoor environments, automotive engines for performance and emissions control, aerospace for cabin airflow management, industrial processes for product quality and efficiency, and environmental monitoring to measure air quality and pollution levels. They are also essential in medical devices, laboratory equipment, and consumer electronics, contributing to enhanced control, safety, and efficiency across various industries and applications.

This internship focuses on the testing setup for evaluating an airflow sensor specifically designed for the flapping winged micro air vehicle project led by MAVLab at the TU Delft aerospace faculty. Flapping winged micro air vehicles, inspired by birds and insects, rely on controlled flapping motions for flight maneuverability. To achieve this, it is crucial for the micro air vehicle to sense airflow patterns and velocities accurately, allowing it to adjust its flapping motion dynamically for stable flight. As a result, the development of an efficient airflow sensor becomes imperative. In response, a capacitive airflow sensor has been meticulously designed and fabricated at the Elsi Kooi Laboratory to fulfill this essential function. This sensor comprises two capacitors combined with an elongated, hair-like structure capable of detecting airflow in two directions. The capacitive readings obtained from this sensor provide valuable data on airflow speed. Each capacitor features an embedded electrode within a SiC membrane, suspended directly above a paired electrode. The sensor dimensions is 4mm x 4mm, without any packaging.

The internship builds upon the thesis project's foundation, which concentrated on the conception, development, and fabrication of the airflow sensor. In this subsequent phase, the primary focus is on creating a comprehensive testing infrastructure in the wind tunnel facility to evaluate and characterize the sensor's performance. This involves the design and construction of a specialized holder or support system capable of securely mounting the compact sensor device, which is affixed to a PCB. An essential criterion for this mounting support is reusability, allowing for repetitive testing of multiple identical sensors. Moreover, the mounting system is to be linked to a rotation mechanism, which enables comprehensive testing of the sensor with airflow incident from all sides, effectively characterizing its directionality properties. To ensure stability and precision throughout the testing process, a robust mechanical setup tailored to the wind tunnel environment is integrated, thereby mitigating any potential interference arising from unintended movements. Additionally, the set-up should allow for the accommodation of read-out electronics affiliated with the test sensor and rotation motor electronics. This holistic approach ensures the thorough evaluation and optimization of the airflow sensor's capabilities within a controlled testing environment.



(a) Sensor concept.



(b) Fabricated sensor without hair.

Figure 1.1: Developed capacitive airflow sensor.

1.1. Block Diagram

The wind tunnel setup comprises several essential components for precise data acquisition and control. Within this setup, two pressure sensors, along with a thermometer, play a pivotal role in capturing crucial airflow parameters. Data received from these sensors is processed through an expander, specifically the MCP23017, ensuring efficient management of data. Given the range of pressures encountered in the wind tunnel, with the highest measurement reaching approximately 670 Pa, the pressure sensors are selected such that the capacity extends up to 1 kPa or 1250 Pa, offering an adequate margin for accurate measurements. The system also incorporates a NPA201 barometric pressure sensor, and later, the Bosch bmp388 was introduced, equipping the setup with two barometric pressure sensors for enhanced accuracy. Additionally, a max31865 unit interfaces with a PT100 temperature sensor, while an MCP23017/MCP23S17 I/O expander facilitates the seamless reading of all sensors. Precise control of the wind tunnel's mechanics is achieved through a stepper motor managed by an Arduino setup. To ensure data synchronicity and minimize the risk of misreadings, data from various sources such as angle of rotation, capacitive readings, temperature and humidity within the wind tunnel, and barometric data are efficiently transmitted to the LabView software, offering a comprehensive oversight and analysis capabilities for this wind tunnel testing system. Figure-1.2 depicts the block diagram associated with the test set-up.

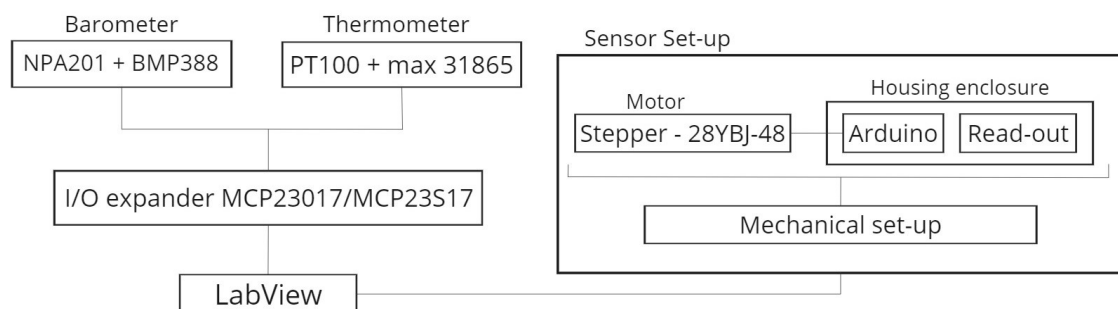


Figure 1.2: Block Diagram of test set-up.

Rotation system for sensor platform

The fabricated air flow sensor is designed to effectively measure the speed and velocity of airflow over the sensor. Therefore, it is not only imperative to test the sensor for various ranges of airflow speed but also to test the directionality. The m - wind tunnel testing facility available to conduct this sensor characterization is equipped to generate a controlled airflow from only one end of the tunnel. Consequently the sensors slated for testing must have a controlled rotation mechanism for effective characterization. This enables the sensor to experience airflow from various angles of incidence on the surface of the electrodes and hair. The following sections of the chapter elaborates on the rotation system adopted for the sensor platform.

2.1. Motor selection

The rotation system comprises of multiple facets to facilitate the rotation mechanism. The rotation mechanism is required to rotate to smallest angular distance possible and maintain the position for a designated amount of time. The choice of motor is the primary component to establish this required functionality. The torque of the motor should be capable of facilitating the rotation of a larger rod coupled to the shaft. Electric motors are best appropriate which enable a compact system. It is of paramount importance to eliminate any unintended disturbances in airflow. Therefore, compact rotation system is desired. Consequently, electric motors are considered to facilitate the compact system. There are several types of electric motors designed for specific applications and offer distinct characteristics. Some relevant motors for this application include:

- **Stepper Motor:** Stepper motors are brushless DC motors that move in a series of fixed discrete angular steps or increments. The steps are defined by the number of coils and magnetic poles that enable the angular movement. Figure 2.1 illustrates the internal schematic of the stepper motor. The magnetic interaction between the rotor poles and poles of the energized stator coils enables the discrete angular rotation [2]. The motors function accurately when a sequence of pulses are driven to the controlling coils. The sequence of pulses allows for digital actuation with a microprocessor [1].

Advantages:

- Digital control.
- Variable speed control.
- High position control accuracy.
- Durability
- Fast response to stimulation.

Disadvantages:

- Possible electrical resonance.

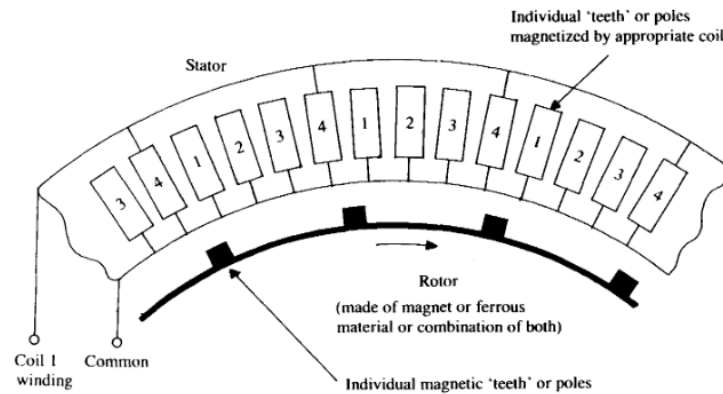


Figure 2.1: Internal schematic of stepper motor [1].

- Limiting resolution.
- Lower speed compared to other DC motors.
- **Servo motor:** Servo motors control the rotation to a specific angle or position. These motors can be AC or DC motors. Servo motors provide high control facilitated by controlling voltage or current applied to the stator coils. Similar to stepper motor, the speed is controlled by the current frequency. Additionally, servo motors consist of a feedback mechanism which monitor the position of the permanent magnet to the input position and adjust the current accordingly. Some motors consist of encoders used with controllers for closed loop control and feedback [4]. Figure 2.2 illustrates the internal schematic of a servo motor.

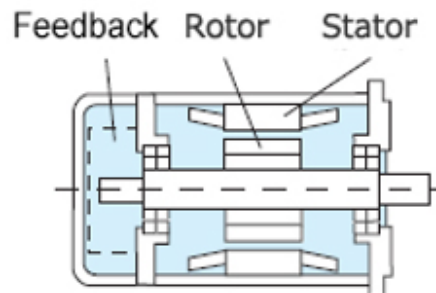


Figure 2.2: Internal schematic of servo motor [10].

Advantages:

- Closed-loop system.
- High speed.
- High torque at high speed.
- High accuracy and resolution.

Disadvantages:

- Pulsate or vibrate at standstill.
- Requires encoder.
- Higher cost.

The following table 2.1 depicts the comparison between relevant features of the shortlisted motors.

Feature	28YBJ-48 [5]	NEMA-8 [8]	X06H [6]	HV06H [7]
Motor Type	Stepper	Stepper	Servo	Servo
Control Method	Step and Direction	Step and Direction	PWM Signal	PWN Signal
Voltage	5V	5V	4.8V - 6V	4.8V - 6V
Speed Range	Moderate	Moderate	Variable	Variable
Torque	Low to Moderate	Moderate	Moderate	Low to Moderate
Size	Compact	Compact	Miniature	Sub-Micro
Cost	Affordable	Affordable	Mid-Range	Mid-Range

Table 2.1: Comparison between shortlisted motors.

2.2. Motor control

Stepper motor 28YBJ-48 was chosen to implement into the rotation system. A stepper motor is the most suitable option due to the accurate incremental step functionality. Additionally, the 28YBJ-48 motor displays sufficient torque to translate the rotational movement to a coupled rod efficiently. The motor dimensions are sufficient to materialize and install a compact system. The same series of motors were previously implemented for a similar test set-up. Consequently, accessories such as motor housing is readily available for utilization.

Stepper motors are available in two main kinds:

- **Unipolar:** The internal structure of a unipolar stepper motor consists of two coils with a centre tap each. The centre taps are accessed through either two separate wires or a single wire connected to each other [3].
- **Bipolar:** Similarly, the internal structure of the bipolar stepper motor consists of two coils but contrarily, the coils have no centre taps and are accessed via 4 wires from either ends of the two coils [3].

Depending of the type of stepper motor, control electronics are chosen accordingly. The 28YBJ-48 is a unipolar stepper motor.

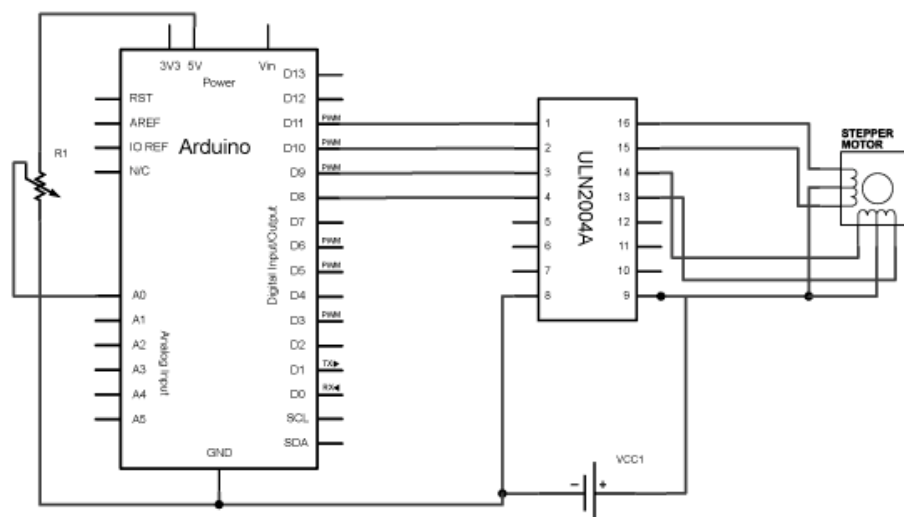


Figure 2.3: Schematic to facilitate motor control [9].

Figure 2.3 illustrates the schematic adopted to facilitate motor control such as speed, step size, delay time and direction. The controller implemented to establish this control is Arduino Uno due to

availability. The ULN2004A Darlington Array IC interfaces between the controller and motor to boost the current supplied from the Arduino [11]. The 5V supply is delivered to the motor directly. All ground pins are connected to a common ground. The drive signals from the Arduino are connected to input pins of ULN2004A which experiences a current gain. The current gained drive signals are further input to the motor for effective performance. The OUT pin of the darlington array IC is the collector and the emitter is the GND pin. A diode is connected between the COM and OUT pin to allow current to flow back into the motor once the driving current stops, this is because the motor has inductance therefore cannot drop to zero instantaneously. A motor driver comprising of the Darlington Array IC, pull up/down resistors, connector pins and LEDs provides a compact solution for the required circuitry. Once the circuit is complete, the pins connected to the coils of the motor are excited through the controller.

3

Mechanical set-up

The testing set up is a vital component to extract sensor reading with minimal noise. An unstable set up can cause movement or vibrations of sensor during testing, attributing to noise. The fabricated sensors are glued to 2 kinds of PCBs, which require a base that enables the rotation mechanism. The rotation mechanism must further be mounted to a sturdy support set-up.

3.1. Sensor base

The sensor base is structured such that the dimension is compatible with the sensor and is adequately dimensioned to minimize airflow disturbances. It must also be dimensioned to be supported by stepper rod or supporting rod.

3.1.1. PCB structure

The PCB structures used for the sensor are of rigid and one-sided/two-sided type. There are two PCB designs adopted:

- **PCB A:** The layout comprises of area/ square pad for affixing a sensor along with five plated through-hole connectors. Among these connectors, four are designated to the bottom and top electrode plates of the sensor and the fifth is connected to the ground plane, which also extends as a connection to the optional Faraday ring incorporated in the sensor. Figure-3.1a depicts PCB dimensions.
- **PCB B:** Similar to PCB A, it consists of the 5 plated through holes and the exposed square pad at the extended PCB area is dedicated to glue the sensor. The layout also consists of a footprint designated for the 16-pin capacitance read out AD7746. The sensor read out is further discussed in section 4.1. Figure-3.1b depicts the PCB dimensions.

In order to ensure optimal functionality and stability of these designed PCBs, a dedicated base has been crafted to securely accommodate the circuit boards. The base structure, also referred to as 'Sliders' are engineered to align with the dimensions and layout of the PCB.

3.1.2. Inspiration and concept exploration

The MEMS hair sensors slated for testing exhibit sensitivity to vibrations and unintended disturbances. Therefore it becomes imperative that the base to encompass these sensors be customized for the designed circuit boards. Furthermore, the tests are iterated for multiple sensors, necessitating the base to retain rigid grip, structural integrity and exhibit adeptness in accommodating for dimension tolerances between the various PCBs. The base should also accommodate for possible forthcoming circuit boards designed at the the same scale. Additionally the supporting base should not compromise the conducted tests by obstructing or interfering with the airflow on the sensor.

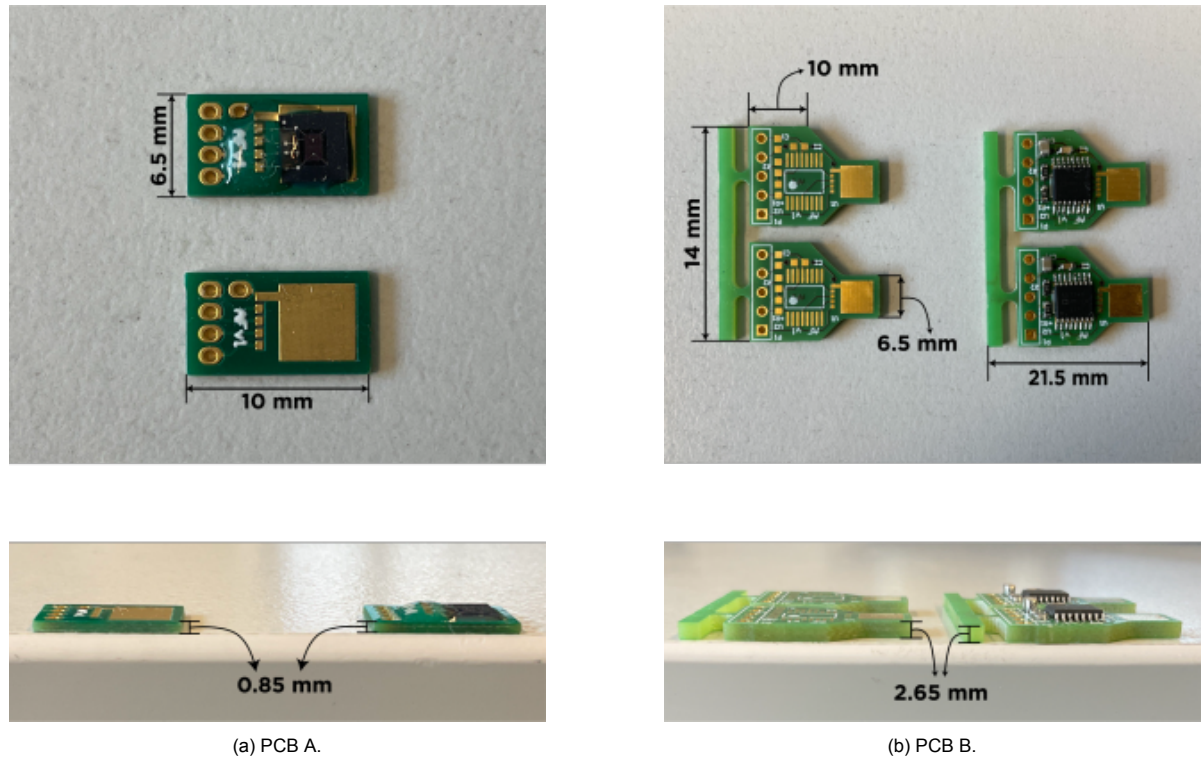


Figure 3.1: Dimensions of the Printed Circuit Boards used for iterative testing.



Figure 3.2: Simple single clamp mechanism.

Considering the above requirements, the base should implement a resting surface, with an adhesive, movable or stationary clamp mechanism at the scale of the PCB dimensions. Initial exploration of basic methods such as double-sided tape or adhesive bonding to secure the PCBs proved to be insufficient due to the inability to exhibit repeatability in stability, thus attributing to potential undesirable noise and inconsistencies. Consequently, movable and stationary clamp mechanisms were explored.

A simple single stationary clamp mechanism depicted in Figure-3.2a provides a rigid grip. Although this minimalist design provides stability, the rotation mechanism connected to the supporting base makes the PCB revolve around the rotating rod. Due to the revolving phenomenon, the location of the PCB in the wind tunnel varies, consequently the airflow on the sensor can potentially be inconsistent. Additionally, at a particular range of angles, the rod or clamp could potentially obstruct the airflow. Hence, the PCB should be aligned directly above the rotating rod. A single clamp enabling this would not provide stability during rotation on a perpendicular axis as depicted in Figure-3.2b. Therefore, the best solution

lies with movable clamping mechanism.

The sliding fit concept refers to a concept where one component can easily slide along the surface of another component. This concept enables the movement of the employed clamps, also referred to as sliding components. A transition fit between two components is a balance between an interference fit and clearance fit thus enabling a controlled clearance between the resting and moving components. This ensures a snug fit during rest state and embodies just enough clearance for the component to slide during movement. The clearance tolerance is crucial for functionality.

Examples of sliding fit can be found in everyday items like drawers and rails attached to the furniture. The drawers are designed to slide smoothly without excessive force or resistance. The clearance between the drawer and rails ensures easy movement while still maintaining a secure and aligned position. Another example is wafer holders in cleanroom facilities. The holders are specially designed to safely secure single wafers when immersed into beakers filled with hazardous liquid.

Utilizing the principle of sliding fit, a model was formulated for the supporting base, which will be elaborated in the subsequent section.

3.2. 3D printing

3D printing is a revolutionary process that materializes digital designs into tangible and physically usable objects by layering a specific material in a precise and controlled manner. This technology has enabled the creation of complex and customized items with efficiency. The constructive layering method provides immense freedom in design and material choice, thus making it a multidisciplinary tool.

There are many types of 3D printing procedures:

- Selective Laser Sintering (SLS) uses a high-powered laser to fuse powdered material into a solid 3D object layer by layer.
- Fused Deposition Modeling (FDM) deposits melted thermoplastic material layer by layer to build a 3D object.
- Digital Light Processing (DLP) employs a digital light projector to cure a liquid photopolymer resin layer by layer to create a 3D object.
- Multi Jet Fusion (MJF) applies a fusing agent and energy source to selectively bond powder particles in a 3D printing bed.
- PolyJet utilizes jetted photopolymer droplets that solidify layer by layer to produce a 3D object with diverse material properties.
- Electron Beam Melting (EBM) melts and fuses metal powder in a high-energy electron beam environment to construct metal 3D objects.

Out of the mentioned types of printing, DLP 3D printing provides excellent resolution as it uses a digital light projector to cure each layer of photopolymer resin with high precision, allowing for fine feature details and a smooth finish. Considering the scale of the print and the necessity for smooth surfaces (to avoid airflow perturbation) DLP is an appropriate method of printing. Additionally, a DLP based printing equipment, Asiga MAX X27, is available for use.

3.2.1. Structure Build

The initial conceptual model comprises two supporting rails and a sliding component designed to evaluate the sliding fit and mechanism. Additionally, the two rails are mounted on a base along with a vertical support, perpendicular to the parallel rails and base. The vertical support encapsulates the sliding component within the limits of the rails. However, this enclosure is limited to just one end of the rails; the opposite end remains open to facilitate the assembly of the movable component into the rails. This base structure is further referred to as Sliders in the subsequent sections. The inner surface of each rail has an inbuilt groove which aligns the sliding component during assembly and also aids for

effective sliding movement. Figure-3.4a depicts the details of the slider. The pair of cylindrical structures function as anchoring pins to a cap designed to neatly fit into these pins. The cap secures the sliding components within the confines of the rails and maintains structural integrity to prevent accidental openings.

The sliding component on the other hand is meticulously designed such that the block meant to

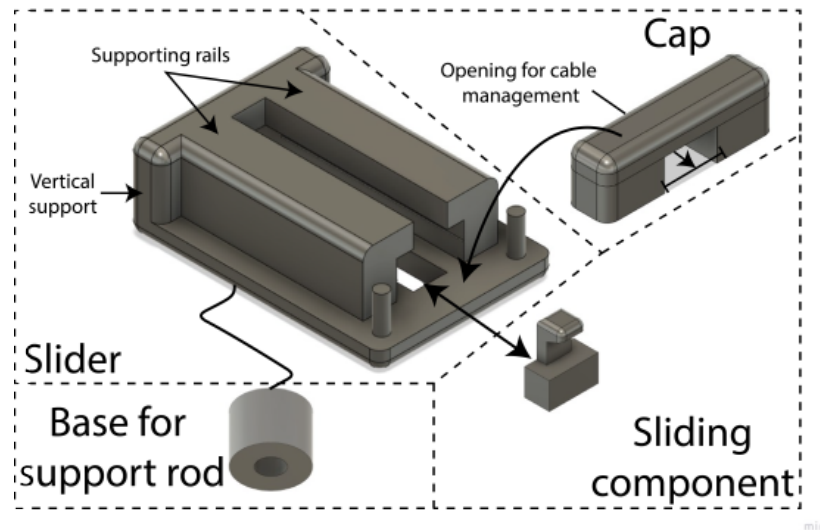


Figure 3.3: Various elements of the slider system.

be assembled into the sliding fit opening is minutely smaller. During post processing assembly, the block is precisely filled for a controlled clearance between the sliding surface and opening. The sliding component also comprises of a supporting neck extending from the top surface of the sliding block to the base of the tooth. The tooth is intricately designed to grip the edges of the PCB also accommodating for the inherent tolerance of the PCB thickness. This is accomplished by integrating a slope to a surface of the tooth which interfaces the PCB. Figure-3.4b illustrates the various elements of the sliding component.

The final assembly consists of pair of sliding components assembled in a facing manner with the neck

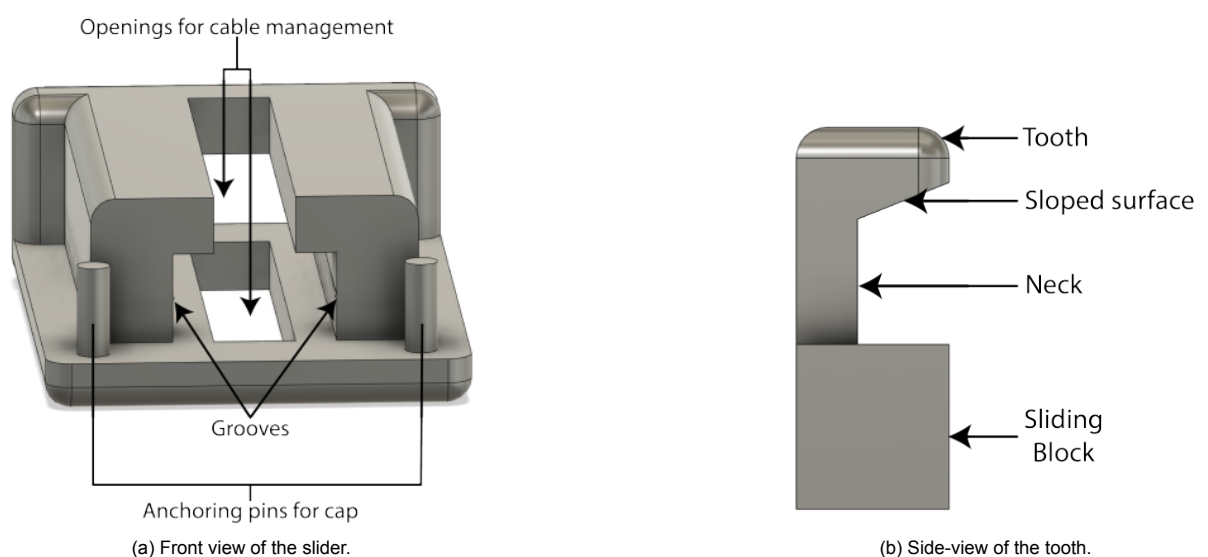


Figure 3.4: Details of slider elements.

designed to fit into the uppermost opening between the rails. The space between the topmost rail surface and the inclined tooth surface should be adequate to allow for a snug fit of the PCB. The PCBs are intended to be placed on the topmost surface of the rails between the two sliding components. The two sliding components are moved close to each other and as the components approach the PCB, the tooth should securely grip the edges.

The outer dimensions of the Slider are determined by the dimensions of the PCB. The two types of PCBs intended to be tested, vary in terms of scale. Therefore two distinct sliders are custom designed for each PCB type. The conceptual model subsequently underwent a sequence of minor enhancements leading to several iterations of the design, further discussed in section 3.2.3.

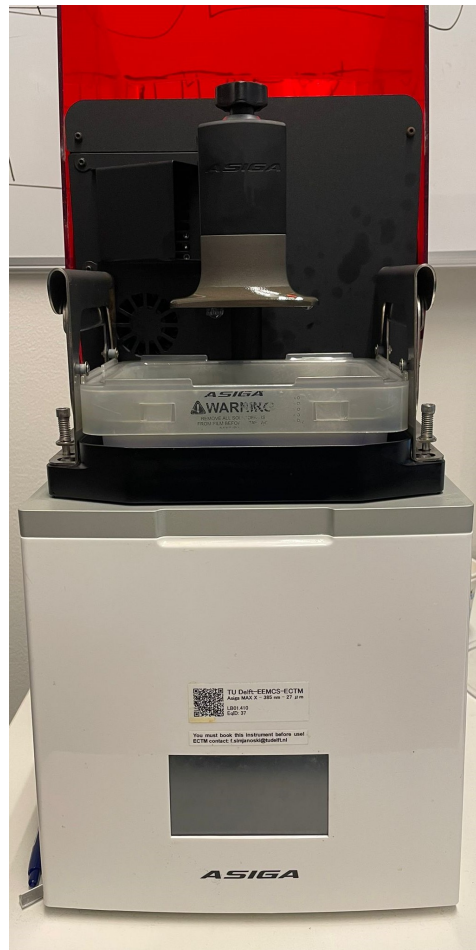


Figure 3.5: Asiga MAX X27 UV printer.

3.2.2. Printing procedure

This section provides a brief description of the steps involved in 3D printing the designed model of the holder.

- **Step 1:** All segments of the conceptual model is built on the Autodesk Fusion 360. The exported 3D model is uploaded to the Asiga Composer Software which issues commands to the Asiga MAX X27 UV printer which accounts for the printing configuration.
- **Step 2:** Upon uploading the image, the printing parameters like print range, slice thickness, print range height etc. are updated and uploaded to the printer. The build volume of the printer is 51.8 mm x 29.3 mm x 75 mm with a print resolution of 27 μm . Depending on the model being printed, it is

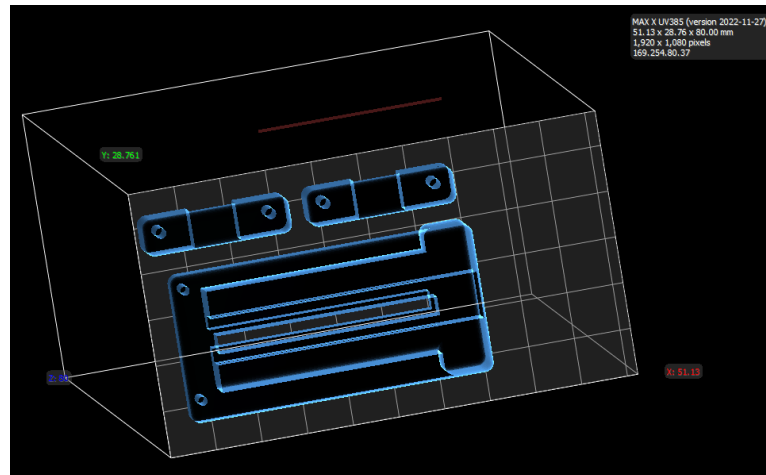


Figure 3.6: Uploaded 3D model to the Asiga software.

divided into various horizontal cross sections to efficiently determine the slice thickness. Curved sections of the model are assigned thinner slice thickness for a clean defined curvature. The various printed parts do not require a printing support since all structures have a flat resting side.

Name	Minimum	Burn-In	1	2	3	Maximum	Units
Print Range From	0.000	0.000	0.050	3.050	8.000	12.000	mm
Print Range To	0.000	0.050	3.050	8.000	12.000	12.000	mm
Slice Thickness	0.001	0.025	0.050	0.150	0.050	0.400	mm
Slice Count	0	2	60	33	80		
Print Range Height	0.000	0.050	3.000	4.950	4.000	12.000	mm
> Advanced Settings							

Figure 3.7: Parameters for printing.

- **Step 3:** With the printing parameters set, the printing procedure is begun. It must be noted that the surface on which the printer is placed must not be disturbed due to its sensitivity. Figure-3.8 displays the printer screen during printing.

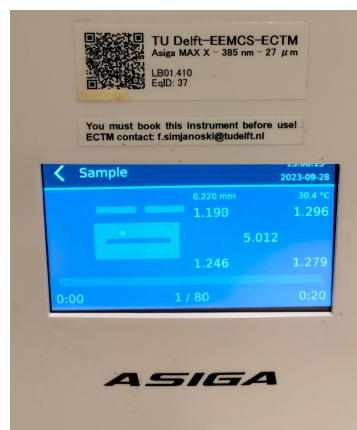


Figure 3.8: Screen on printer during print.

- **Step 4:** Once the print is complete, the 3D model is scrapped off the printed surface (figure-3.9a). The scrapped model is cleaned with IPA and a basic visual check is performed to ensure sound structure. Further, an air-gun is used to clear any loosely closed opening.



(a) 3D model on printed surface.



(b) Air-gun for clearing loose openings.

Figure 3.9: Post print steps.

- **Step 5:** After clearing and ensuring integrity of the printed structures, the structures are placed on microscope sample slides and into the UV curing equipment. This step is important to further harden/cure the printed model and eliminate any sticky residue of resin paste on the structure. The UV curing equipment flashes UV light repeatedly. The number of flashes can be controlled by dialing in the number in the equipment. 2000 flashes is a standard typically used after printing.

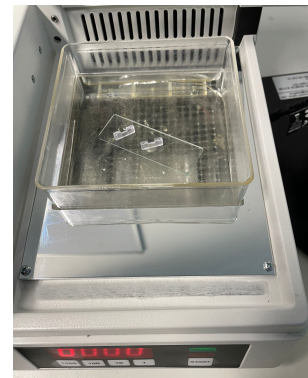


Figure 3.10: UV curing.

After following the above steps, all segments of the structure is ready and further assembled. The post processing during assembly includes shaving edges of the sliding component with a razor to ensure the perfect slide fit. This step must be conducted as soon as the print is complete, since the resin hardens over time.

3.2.3. Printing Iterations

The slider, sliding component and cap underwent several iterations and tests to finalise on a refined and functional model. Although most iterations had minor adjustments, there were three instances with significant changes. Table 3.1, 3.2 and 3.3 tabulates these iterations.

Table 3.1 illustrates the notable iterations of the slider base. Version v3, downsized by approximately 1.5x, is designed to accommodate for PCB A. The integration of openings in the vertical support and base facilitates efficient cable management from sensor to the external readout. Improving from v3, v5 features rounded edges to prevent generation of turbulent airflow. The overall length of the slider is reduced by 3.5mm to enhance compactness and eliminate unused space. The height of the vertical

support is lowered and aligned with the upper surface of the rails. Slider v5 meets all design requirements and is successfully tested to ensure optimal functionality. Dimensions of Slider v1 proved to be suitable for PCB B and therefore are retained in v6, along with the nuanced improvements to v5. All rounded edges are filleted to 1mm radius.

Similarly, the iterations of the sliding components are also tabulated in table 3.2. The Sliding component v3 is downsized by 2x of v2 with a remodelled tooth suitable to accommodate the edges of PCB A. Considering PCB A has a relatively small width, the tooth is made longer with a rounded surface in v4. The slider that accommodates PCB B requires dimensions of v2, therefore the design retains v2 structure with a rounded tooth.

The cap, as described in section 3.2.1, secures the sliding component within the boundaries of the rails. The initial version of the cap model, v1, serves as a rudimentary design that aligns with the Slider v1 test model. Cap v2 is designed as a complementary component to Slider v3, incorporating openings for efficient cable management. The design is further refined in v3 by adjusting the cable openings to match the dimensions of the cable openings in the vertical support of the Sliders. This maintains symmetry in the overall design. Additionally, the edges are rounded to prevent turbulent airflow in the vicinity of the sensor. As illustrated in table 3.3, cap v4 is tailored to be compatible component with Slider v6, therefore retaining the dimensions of v1 while integrating the finer enhancements of v3.

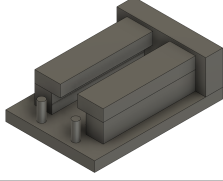
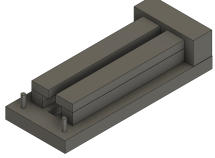
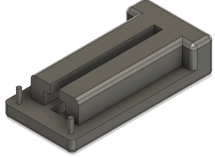
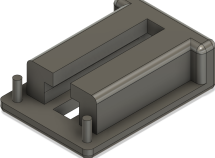
Si.No.	Version	PCB	Delta Change	Model Dimensions	Printed Models
1.	v1	B	–		
2.	v3	A	• Downsized • Cable openings		
3.	v5	A	• Rounded edges • Downsized vertical support • Downsized length		
4.	v6	B	Delta changes from v1: • Rounded edges • Cable openings • Downsized vertical support		

Table 3.1: Iteration I: Slider.

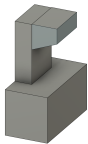
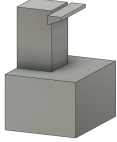
Si.No.	Version	PCB	Delta Change	Model Dimensions	Printed Models
1.	v2	B	–		
2.	v3	A	• Downsized • Remodelled tooth		
3.	v4	A	• Rounded edges • Elongated tooth		
4.	v5	B	Delta change from v1: Rounded edges		

Table 3.2: Iterations II: Sliding component.

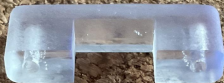
Si.No.	Version	PCB	Delta Change	Model Dimensions	Printed Models
1.	v1	B	–		
2.	v2	A	• Downsized • Cable opening		
3.	v3	A	• Rounded edges • Larger cable opening		
4.	v4	B	Delta change from v1: • Longer pin openings • Larger cable opening		

Table 3.3: Iterations III: Cap.

3.3. Base frame set-up

The slider base developed and tested for the PCBs designated for wind tunnel experimentation must be integrated into the wind tunnel apparatus. The integration process demands a robust and stable installation that adapts to the wind tunnel location and dimensions, while maintaining its structural integrity. Within the wind tunnel, it is imperative to install minimal components so as to prevent any interference with the established laminar airflow. Moreover, sealing any unintended openings further contributes to this prevention. Any installations can be performed around the wind tunnel. Accounting for the above prerequisites, various foundations are customized and checked for functionality and stability.

3.3.1. Dimensions of Tunnel

The wind tunnel apparatus is an elongated tunnel designed for generating laminar airflow, with a mechanism installed at one end to facilitate this flow. The internal dimensions of the wind tunnel are 40cm x 40cm. All relevant dimensions are illustrated in figure 3.11a. The tunnel is placed such that the bottom surface is 84cm from a resting surface on which the support structure lays. The opening end is encompassed by a metal ring like structure of width 7.5cm. The support structure of the wind tunnel is elevated by 5cm support rods, spaced 48cm apart.

The tunnel consists of various openings to incorporate any additional mechanical set up to support

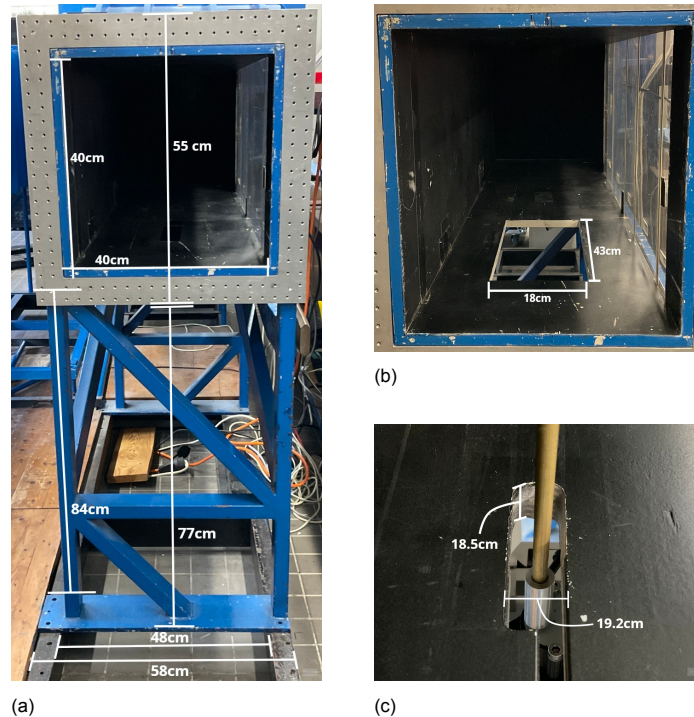


Figure 3.11: Dimensions of wind tunnel: (a) Frontal view of wind tunnel (b) Larger wind tunnel opening (c) smaller wind tunnel opening.

test samples. Figure 3.11b depicts the wider concealable opening at the bottom face of the tunnel. The opening allows for accessibility from the tunnel support structure area. A section of the wind tunnel base is excised to establish the opening. Further, the excised wooden plank is modified to be optionally incorporated depending on structural necessity. The plank additionally consists of smaller openings depicted in figure 3.11c which can be further sealed with black duct tape.

The lateral sides of the wind tunnel have distinctive features. One side is completely sealed and opaque, whereas the other comprises of five glass segments. Figure 3.12 depicts the transparent side and provided measurements of two detachable segments that could potentially aid to a support set-up.



Figure 3.12: Side view and measurements of wind tunnel.

3.3.2. Types of assembly configurations

Up to this point, each individual elements of the test setup has been fabricated independently. It is now imperative to cohesively assemble these elements to ensure stability and functionality within the test environment. Following are the list of available elements to be assembled:

- Assembled Slider base.
- Stepper motor + electronics.
- Stepper motor housing.
- Support rods of various dimensions.

These elements can be assembled in various orientations. This report discusses two such orientations illustrated in figure 3.13 which can be adapted into the test environment.

Test set up A incorporates the stepper motor set-up into the confines of the wind tunnel, supported by

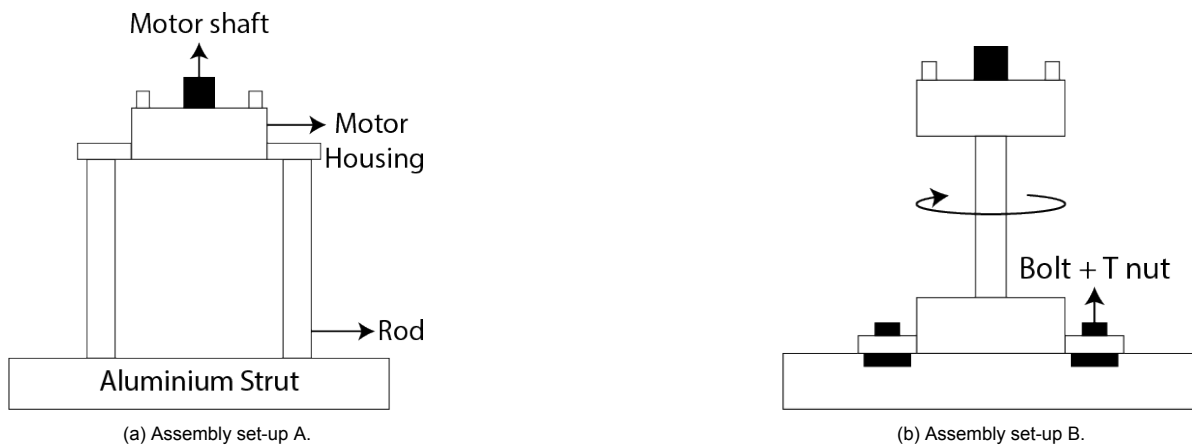


Figure 3.13: Two types of assembly orientation explored.

two M4 rods compatible with the stepper motor housing. This orientation would enable the slider base in close proximity to the stepper motor ensuring a stable and sturdy rotation mechanism. This implies the orientation relies on a levelled and stable installation of the stepper motor. Set-up A requires the larger opening at bottom face of the wind tunnel, discussed previously. This further suggests the large opening can cause unintended disturbances in airflow. The rotation mechanism set-up can potentially be rotated perpendicular to the depicted set-up, this would allow the utilization of the smaller opening at the bottom face.

Test set up B on the contrary only accommodates the slider set up and a supporting rod within the confines of the wind tunnel. This would imply, the set up requires only a portion of the smaller opening at the bottom face of the wind tunnel, therefore ensuring minimal disturbance in airflow. The stepper motor employed for the test has a slight degree of wobble in the shaft which translates to components attached to it. The longer the supporting rod attached to it, the larger the degree of wobble. This would require an additional component to keep the rotating rod in place. Therefore, it is imperative to maintain minimal distance between the stepper motor shaft and slider base.

The orientations discussed above are plausible implementations into the test environment. However in order to utilize either of the solutions, a strong foundational base to uphold these configurations is essential. The following section discusses the evolution of one such solution.

Content	Set-up A	Set-up B
Basic Description	stepper motor confined within tunnel.	stepper motor installed external to tunnel.
Pros	stepper motor close to slider base.	- Minimal disturbance of airflow. - Smaller opening used.
Cons	- Supported by two rods. - Might require larger bottom face opening. - stepper motor installation may cause slight airflow disturbances.	- Supporting rod from shaft has slight wobble. - Must maintain minimal distance between stepper motor shaft and slider base.

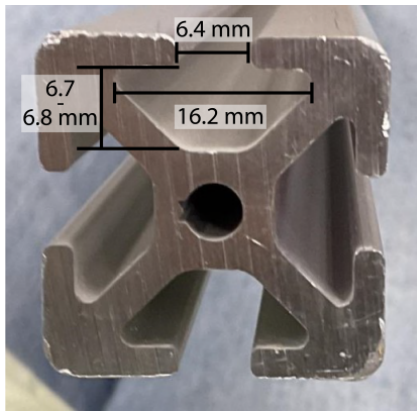
Table 3.4: Information about assembly types set-up A and set-up B.

Taking into account the advantages and disadvantages of both assembly configurations, set-up B is regarded as the primary choice.

3.3.3. Evolution of Base Frame

The foundational base is imperative to assemble a robust, rigid and functional set-up in the testing environment. A basic and elementary approach was employed for testing. An aluminium profile strut was clamped onto the corners of the wind tunnel. Aluminium profile struts are designed to accommodate various accessories to construct desirable structure by interconnecting different components. With this rudimentary approach, two T-nuts are accommodated into the 70cm profile strut (A) structure which have threaded openings. The dimensions for the T-nut opening is depicted in figure 3.14a. This solution is further discussed in section 3.4. The threaded openings can further accommodate threaded rods to fasten the housing of the stepper motor at the other end of the rods. The most suitable rods or bolts for the motor housing is of M4 type. The height and number of rods are decided depending on the assembly type implemented. Although the rudimentary approach can be implemented with set-up A, it is not adaptable for set-up B. The space between the bottom face of the wind tunnel and the profile strut is limiting which does not allow for installation of the stepper motor. Therefore to accommodate for this spacing issue, an available frame structure constructed from profile struts is implemented under the wind tunnel. Figures 3.15a and 3.15b illustrated the dimensions and installation. The previously used profile strut (A) is clamped onto Base frame A for an efficient installation of the stepper motor.

Base frame A is 44cm high from the resting surface, this implies that the distance between bottom face of the tunnel and topmost surface of this frame is large, implying set-up B would display a large wobble. Therefore, it is of paramount importance that the frame surface allows sufficient space

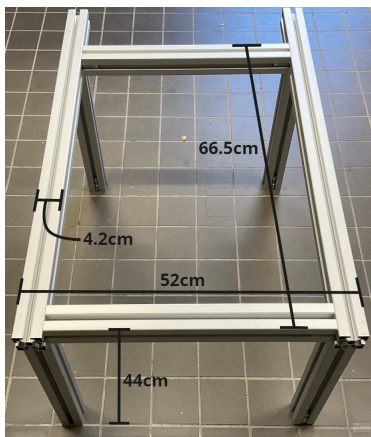


(a) Dimensions of aluminium profile strut openings.



(b) T-nut with M6 threaded opening.

Figure 3.14: Components of aluminium profile strut set-up.



(a) Dimensions.



(b) Installation.

Figure 3.15: Base frame A description.

to set-up a stepper motor while maintaining a minimal distance. This wades way to an opportunity to re-structure the support frame.

Considering the two types of assembly configurations and potential for future adaptations, a fundamental requirement is to re-structure the base frame to allow for adjustable support surface. Therefore, base frame B is updated such that the supporting frame can accommodate for varied height.

The original configuration of base frame B featured a single vertical x beam with a pair of X-95 carriers is affixed back to back perpendicular to each other. One of these X-95 carriers clamps the vertical support at the desired support height and while the other clamps the horizontal beam which would function as the supporting surface/beam. However, this arrangement led to an inherent imbalance in weight distribution, as the weight of the horizontal beam was supported only on one side of the upright beam. Consequently, an additional support mechanism is required to ensure overall stability.

Therefore to materialize this, two additional pairs of X-95 carriers were clamped on either sides of the vertical X beam at the base. This facilitated the incorporation of two more supporting support X beams at the base. An important consideration during assembly of the base frame is to meticulously align the components to avoid the possibility of an unstable structure.



(a) Step 1: Assembled X95 carrier.



(b) Step 2: Assembly without support X beam.



(c) Step 3: Assembled with support X beam.

Figure 3.16: Critical assembly stages of Base frame B (more images will be added with final assembly).

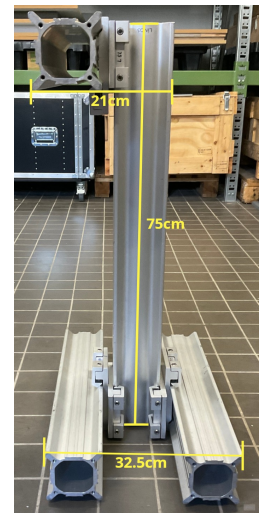
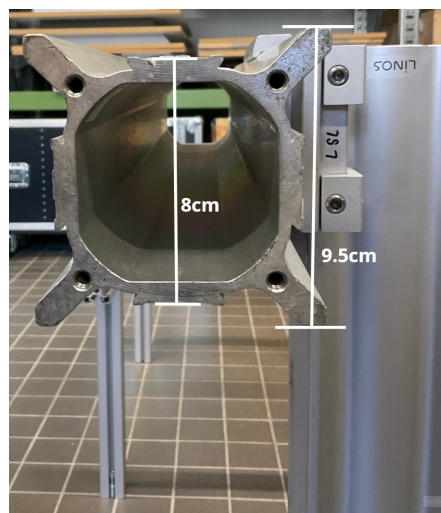
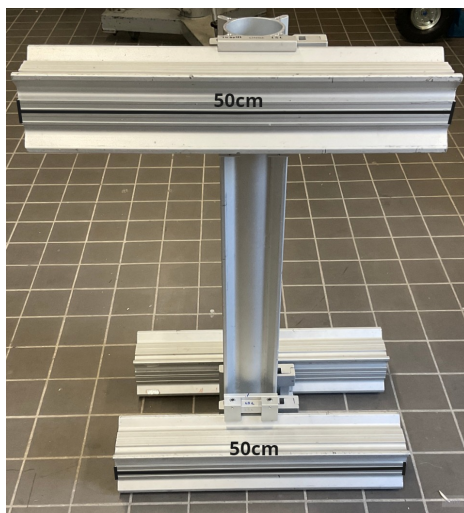
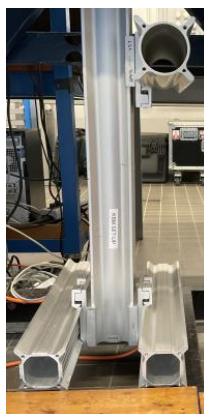


Figure 3.17: Base frame B description.



(a) Installed under wind tunnel.



(b) Levelled X beam.



(c) Support rod clamped onto X beam.

Figure 3.18: Installed Base frame B.

The final iteration of the base frame B is designed to accommodate for variable support height. The

aluminium profile strut equipped with T-nuts, is securely clamped to the support X beam.



Figure 3.19: Aluminium profile strut clamped on support X beam.

3.4. Final Assembly

The final assembly is conducted in two parts, the external and internal assembly. This pertains to a cohesive construction of the set-up outside and inside the wind tunnel respectively.

For better understanding of the assembly orientation let us consider the direction of the airflow to be fixed at x-axis in the wind tunnel, therefore to test the sensor at various angles the set-up must be able to accommodate for a rotation mechanism around various axes. The first mounting orientation should test the directionality with the sensor positioned such that the affixed hair is perpendicular to the xy-plane. Therefore, the rotation is set to be around z-axis. This would enable reading the differential capacitance at varied incidence of airflow perpendicular to the hair, parallel to the surface of the sensor along the xy-plane. Consequently, rotation around x-axis with hair of the sensor positioned along x-axis would enable sensor characterization at this orientation.

Subsequently, the sensor must also be characterized such that the airflow is incident on the hair at various angles on the xz-plane. This can be enabled by revolving around the y-axis in the xz-plane. Additionally, the sensor must also rotate 360° perpendicular to the sensor surface at every angle the sensor revolves around y-axis. Although, characterization with this orientation will be conducted in the second phase of testing, suggestions for the mechanical set-up will be further discussed in the following chapter 4.

For the final assembly, the required list of available elements is updated:

- Assembled slider base.
- Stepper motor + electronics.
- Coupler for shaft.
- Stepper motor housing.
- Support rods of various types.
- Aluminium profile strut.
- T-nuts.
- Nuts, bolts and washers.

- Clamps.
- Base frames A/B.
- Corner brace for x-axis rotation.

3.4.1. External assembly

Set-up B is considered as the primary option to adopt into the final assembly, therefore all intricacies of the assembly are detailed for set-up B. Optionally, the assemblies can also adopt set-up A. The stepper motor is fastened to the aluminium profile strut (A) with M4 bolts on either sides of stepper housing. The stepper motor requires a shaft coupler to couple the support rod. The coupler consists of two thread openings, one to bolt the shaft and the other to bolt a coupling rod, in this case the support rod. Consequently, this profile is mounted onto the support surface of the various base frames. The length of the support rod is designed such that the sample to be tested is located at the centre of the wind tunnel in the yz-plane. It also accounts for the dimensions of the components assembled around it such as length of the coupler (1.7-1.8cm), height of the slider base (1-1.5cm) and length between the topmost surface of the coupler, when attached to the stepper, and base of the slider (CB_L).

There are three kinds of variations the external assembly can adopt:

- **Aluminium profile strut clamped to the wind tunnel:** As discussed in the previous section, the elementary approach to a final set-up as depicted in figure 4.2a, cannot accommodate for sufficient space to install the stepper motor with set-up B. Additionally, this configuration is unable to account for the additional electronics associated with the readout and stepper motor.
- **Base frame A:** The aluminium profile strut (A) with the mounted stepper motor is clamped onto two profile struts of the base frame A installed underneath the wind tunnel. A 53cm support rod is required for this scenario. Figure 3.21 depicts the assembled set-up. The frame accommodates area to install any additional electronic or support elements like housing.

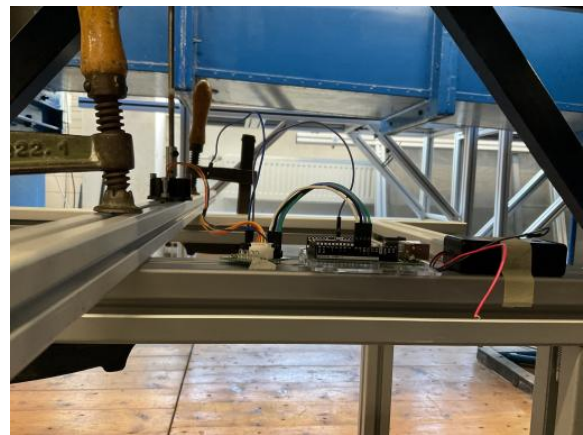
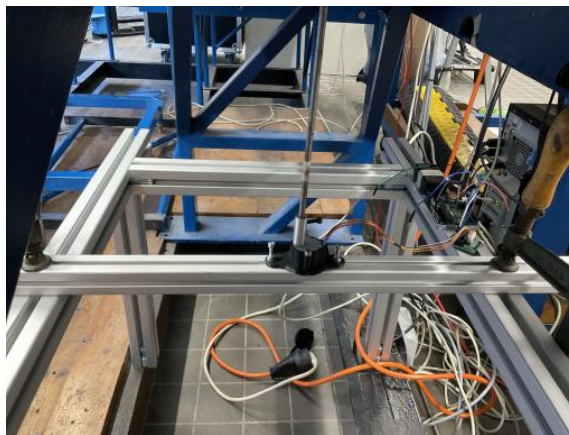


Figure 3.20: Stepper motor accommodation in base frame A.

- **Base frame B:** The design of the frame enables a custom height suitable to clamp the profile strut (A). The base frame B installed under the wind tunnel is adjusted such that the support surface, topmost horizontal X-beam, can incorporate the profile strut (A) with affixed stepper motor. It is imperative to maintain minimal distance to minimize the wobble effect of the support rod. The final assembly ensures $CB_L = 2.5\text{cm}$. Therefore the support rod is designed to be 23cm for this assembly. Additional electronics or it's housing can be installed on either the support X-beam or on the surface of the wind tunnel support structure.

The external assembly adopted to support x-axis rotation is a simple configuration. A T-nut with M6 threading is inserted into the opening of profile strut (A). This accommodates for a threaded M6 rod

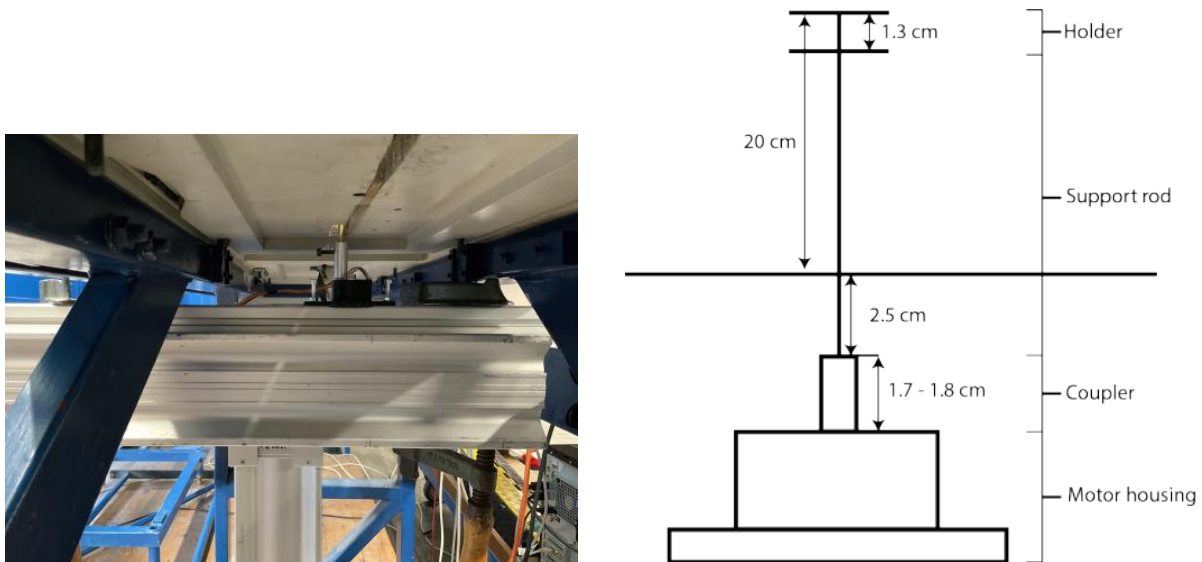


Figure 3.21: Stepper motor accommodation in base frame A.

of length 30cm which further supports other elements in the wind tunnel to materialize a set-up for x-axis rotation. Similar to the wobble tolerance experienced by the stepper shaft, the T-nut supporting the threaded rod also experiences some tolerance of wobble which is rectified within the tunnel. The following section also elaborates the internal assembly for this scenario.

3.4.2. Internal assembly

The assembly within the confines of the wind tunnel does not depend on the base frame incorporated underneath the wind tunnel. The slider, gripping the sample PCB, is the foremost component to be assembled. This is enabled by incorporating an interface structure between the slider and support rod. The 3D printed cylindrical base structure depicted in figure 3.22 consists of an opening of 6mm with a slide fit tolerance. The slide fit tolerance accommodates the M6 support rod such that it is gripped when inserted. The base is further affixed with super glue to the bottom of the slider base.

To account for the wobble tolerance of the support rods a 3D printed support structure is designed

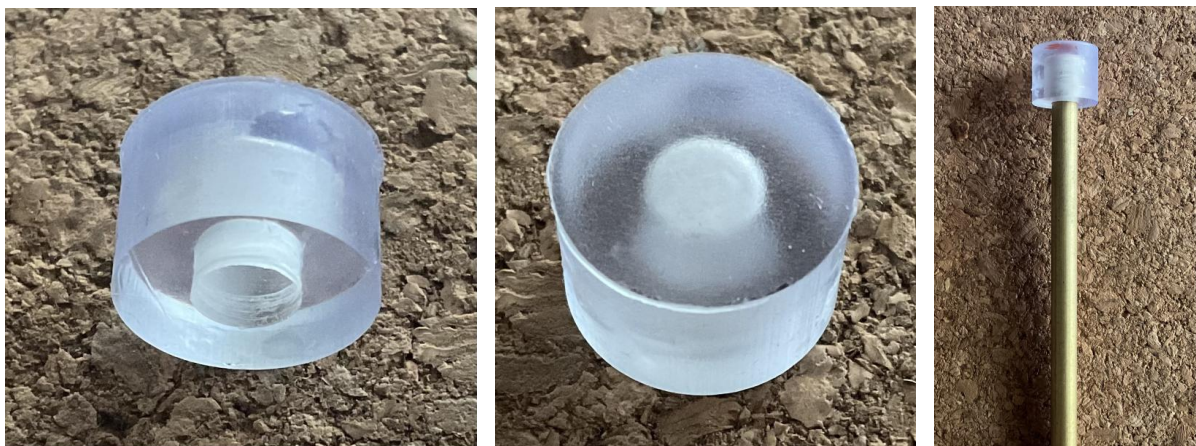


Figure 3.22: 3D printed base to interface slider and support rod.

to delicately prop the support rod parallel to the lateral faces and perpendicular to the bottom of the wind tunnel. The support structure is iterated twice as illustrated in table 3.5. Iteration v2 is downsized

to avoid material wastage. The diameter of opening area or support area is reduced to 6.2mm from 7mm. The structure width of approximately 19.2mm is designed to slide fit into the opening at the bottom surface of the wind tunnel. The slide fit tolerance is controlled during post process for both 3D printed structure. In case of z-axis rotation, the slider base along with the 3D printed base is fit onto the

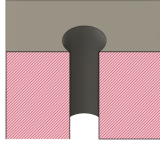
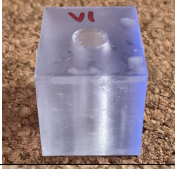
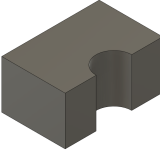
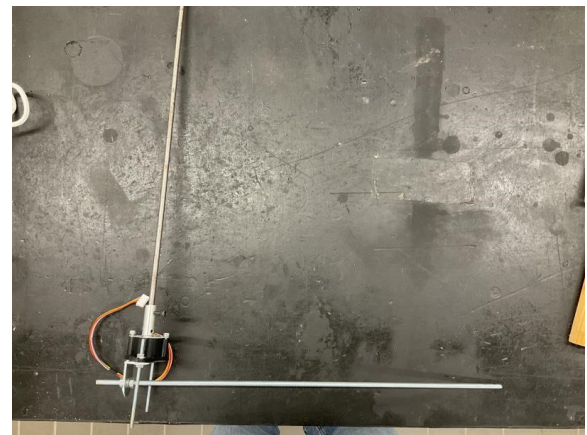
Si.No.	Version	Delta Change	Model Dimensions	Printed Models
1.	v1	–		
2.	v2	• Downsized. • Reduced diameter.		

Table 3.5: Support structure iteration.

support rod. The support structure is appropriately fit into wind tunnel as illustrated in figure 3.23a. In case of x/y-axis rotation, the airflow behind the sample placement does not contribute or interfere with the airflow at the sample. The threaded rod is fastened to a corner brace which further accommodates the fastening of the stepper motor. The coupler of the stepper motor supports a 5cm long M6 rod which is inserted into the slider base interface. This enables a sturdy support for the x/y-axis rotation.



(a) z-axis rotation.



(b) x/y-axis rotation (will be replaced with final assembly).

Figure 3.23: Types of set-up within the confines of the tunnels

Conclusion

The assembled slider is now ready to hold the PCB as depicted in figure-4.1. The image illustrates the PCB fit into the tooth of the sliding component. Consequently the assembled slider set-up is incorporated into the various mechanical set-ups depicted in figure-4.2. All three stages of the mechanical

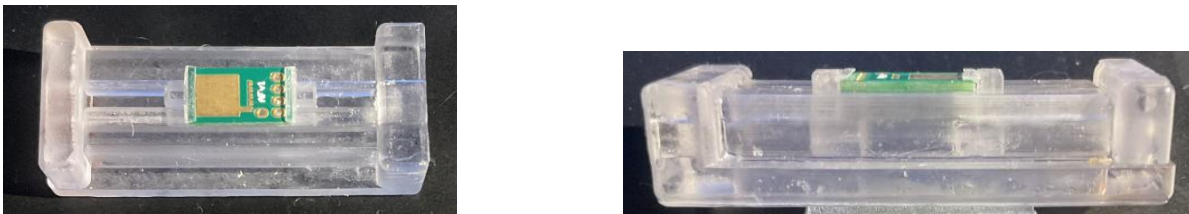


Figure 4.1: Assembled slider with PCB in place.

set-up depicted in figure-4.2 are easily implantable during testing. The rudimentary set-up incorporates simple clamps and adopts assembly type A. Although clamps do provide a sturdy support, the possible orientation and implementation depicted here are not as sturdy as expected. Therefore the assembly set-up is developed to base frame B with assembly type B. This assembly displays optimal stability and elements almost all sources of instability.

Before the start of the testing session, the stability and integrity of the set-up can be tested with a basic wind tunnel test at the maximum speed of velocity, potentially experienced by the sensor.

4.1. Future Work

There are some tasks to be performed before the testing session which include:

- Setting up read out electronics and housing: The end goal of the testing session is to obtain capacitance values co-relating incidence airflow on the hair. Therefore, it is imperative to set-up the read out electronics compatible with the sensor.
- Data acquisition: Synchronization of data between capacitive reading and incident airflow is of paramount importance to ensure testing reliability.
- Potential design for housing stepper electronics: For completeness and a tidy set-up, housing for these electronics is ideal.

The read out set-up and electronics along with synchronized data acquisition, is imperative to implement into the test set-up. Housing for these electronics is optional since the proposed set-up does not perturb testing, i.e; perturbation in airflow. In the course of this internship, all major tasks associated with test up is achieved and ready to be implemented, therefore enabling a quick start to the testing session.

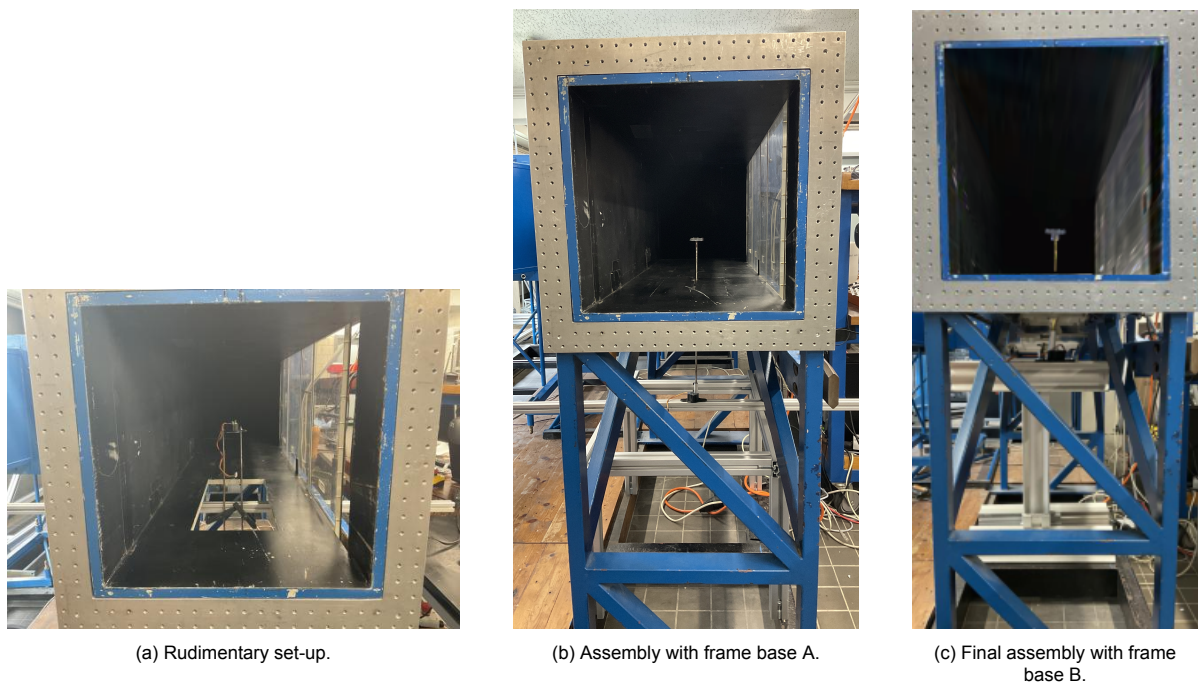


Figure 4.2: Development stages of mechanical set-up.

Bibliography

- [1] J. Cooke, "Stepper motors: Principles and characteristics," *Proceedings of the Institution of Mechanical Engineers, Part D: Transport Engineering*, vol. 202, no. 2, pp. 111–117, 1988.
- [2] V. Athani, *Stepper motors: fundamentals, applications and design*. New Age International, 1997.
- [3] R. Condit and D. W. Jones, "Stepping motors fundamentals," *Microchip Inc. Publication AN907*, pp. 1–22, 2004.
- [4] M. A. Baballe, M. I. Bello, A. A. Umar, A. K. Shehu, D. Bello, and F. T. Abdullahi, "Different types of servo motors and their applications," in *1st International Conference on Engineering and Applied Natural Sciences*, 2022, pp. 974–979.
- [5] [Online]. Available: <https://www.mouser.com/datasheet/2/758/stepd-01-data-sheet-1143075.pdf>.
- [6] [Online]. Available: <https://kstservos.com/products/x06h-v6-0-hv-micro-digital-metal-gear-glider-1-8kg-torque-servo-motor>.
- [7] *Hv06h sub micro servos 0.05sec 24n coreless dc motor chaservo*. [Online]. Available: http://www.chaservo.com/chaservo_Product_2064706151.html.
- [8] A. Industries, *Mini stepper motor - 200 steps - 20x30mm nema-8 size*. [Online]. Available: <https://www.adafruit.com/product/4411#description>.
- [9] T. A. Team, *Arduino and stepper motor configurations*. [Online]. Available: <https://docs.arduino.cc/learn/electronics/stepper-motors>.
- [10] *Tutorial: Stepper vs servo*. [Online]. Available: <https://www.amci.com/industrial-automation-resources/plc-automation-tutorials/stepper-vs-servo/>.
- [11] *ULn200x, ulq200x high-voltage, high-current darlington transistor arrays*. [Online]. Available: <https://www.ti.com/lit/ds/symlink/ulq2004a.pdf>.