Simple optical characterisation for biomimetic micromachined silicon strain-sensing structure

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ABSTRACT

This paper presents an on-going work to develop micromachined silicon-based strain sensor inspired from the campaniform sensillum of insects. We present simple optical setup for the characterisation of a membrane-in-recess structure as an early stage in mimicking the natural sensor. The microstructure is a 500 nm-thick SiO₂/SiN circular membrane, buried 13 µm from the surface of a 3x3 mm, 525 µm thick Si-chip. The chip was attached to a 45x10x0.525 mm Si beam. The simple optical characterisation setup is based on imaging the reflected laser beam from the biomimetic structure. Since an optical cavity between the membrane and the Si beams beneath was formed, ideal flat-parallel Fabry-Perot interferometer equation was applied to interpret the results semi-quantitatively. We obtained 2-D interference fringe pattern having 3 orders of maxima from the middle to the edge of the circular aperture, as a result of an initial internal membrane stress. The pattern changed non-linearly as we applied flexural strain from behind the beam up to 50 µm, most probably caused by nonlinear deflection of the membrane (i.e. the membrane did not deflect similarly as the beam beneath it). This phenomena might explain one of the strain-amplifying properties of this biomimetic strain sensing microstructure.

Keywords: Biomimetics, Strain Sensing, MEMS, Optical characterisation, Fabry-Perot interferometer

1. INTRODUCTION

Nature has long been an inspiration for engineer. Many of today’s world engineering masterpieces and work resemble those similar structures or systems found in nature [cf. 1-3]. However, it was not until recently that the sensor society started to take inspirations from high-performance sensors found in nature (see [4] for a comprehensive overview of current emerging development of nature-inspired sensors).

Campaniform sensillum is a kind of strain sensor found in insects, e.g. the Blowfly (Calliphora vicina). The campaniform sensillum is basically an opening in the cuticle (with a size of 5 to 10 µm in diameter for the circular shape one) covered by membrane layers (figure 1). The shape of the opening is generally ellipse and sometimes almost circular [5,6]. Deformation in the insect’s cuticular layer is sensed by the campaniform sensillum using mechanical coupling, transduction and encoding mechanism to transfer the environmental information to the insect’s nervous system. Previous work [7] showed that the mechanical coupling mechanism was resolved into discrete components: a cap surrounded by a collar, a joint membrane and an annulus-shaped socket septum with a spongy compliant zone (the spongy cuticle). The coupling mechanism is a mechanical linkage which transforms the stimulus into two deformations in different directions: monaxial transverse compression of the dendritic tip of a sensory neuron cell, which acts as a transducer, and vertical displacement of the cap. The natural campaniform sensilla, regardless of the high Young modulus of the exocuticle layer of the insect (k ≈ 10⁹ Nm⁻²), can still detect minute changes of strain. These sensors are as sensitive to displacement in that stiff structure as the receptors in the human ear are to sound [8]. This sensitivity is among others due to their unique membrane-in-recess microstructure. The membrane located inside a blind-hole amplifies the strain.

For a rather detail discussion on the sensing mechanism, refer to [7], as well as to [9] for our previous report on the design and development strategy for a biomimetics MEMS-based strain sensor inspired from Campaniform sensillum.

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MEMS-based strain sensor is advantageous compared to conventional thin metal foil strain gage and simple piezoresistive strain gage, in that MEMS-based strain sensor could provide higher sensitivity [10], as well as possibility for integration within a structure [11].

This paper describes the continuation of our work [9, 12, 13] in developing a MEMS-based strain sensor inspired from the Campaniform sensillum of insects, especially those found in *Calliphora vicina* (the Blowfly). Fabrication of the membrane-in-recess structure as an early stage in this research will be slightly described along with the results of our first attempt to characterise optically the strain-sensing property of these microstructures.

2. METHODOLOGY

2.1 Design and Fabrication of the biomimetic micromachined structure

To investigate the strain-sensing property of the campaniform sensillum, and apply it into a biomimetic MEMS strain sensor, we designed and fabricated two types of simple microstructures. The first is a blind hole structure, and the second is a membrane-in-recess structure. Both structures are illustrated in figure 2 (a and b). In this report, however, we focus on the characterisation of the second-type structure: the membrane-in-recess structure. For an explanation on the blind-hole structure, please refer to our previous report [13].

There are several parameters of interest that might have influence on the strain-sensing property. These are illustrated in figure 2: D, the diameter of the hole; t, the depth of the hole; and x, the thickness of the membrane. For the membrane-in-recess structure, the membrane thickness was still made constant at 500 nm as will be described later. The diameter of the circular membrane varies from 10µm, to 500µm, and 1000µm. At the moment, only membrane-in-recess with a 13 µm depth was fabricated. The processing yield before characterisation for this membrane-in-recess structures is estimated to be around 60%.

The fabrication scheme we used to produce samples was as follows: 1. Holes are first etched on the front side of a silicon wafer using Inductively Coupled Plasma (ICP) etching process in Trikon Omega 201 etcher. A 200 nm thermal SiO₂ was then oxide deposited. This layer will be used as the etch-stop during the later back etching process. Finally a LPCVD 300 nm low stress SiN is deposited. On the back side of the wafers the oxide and nitride layers are etched away. Then an oxide mask layer is formed for further backside etching of the bulk Si wafer.

The backside of the structures were etched using ICP etching process at cryogenic temperature (-125°C). The experiments have been performed in a high density ICP reactor (Alcatel MET). It has independent control of radical and ion fluxes and substrate temperature as is described elsewhere [14]. These process settings proved to be adequate for etching holes and open structures [15]. Other process details can be referred to our previous report in [12, 13].

2.2 Optical characterisation setup

The schematic of the optical measurement setup is illustrated in figure 3, while the photograph of the real configuration is shown in figure 4.
The He-Ne Laser Source has 2 mW output power (Melles-Griot, USA). The ND Filter 1 is a variable-rotating ND Filter (Melles-Griot, USA). While the ND Filter 2 had 10% rate of transmitted light (Edmund Optics, UK.). The two ND Filters were set such that the intensity of the light beam received by the Analog Video Camera (Fujitsu, Japan) did not saturate its CCD sensor elements. Results and discussions. We used a 50%/50% Beam Splitter (Melles-Griot, USA). The biomimetic strain-sensing microstructure was glued to a 45x10x0.525 mm Si beams to make a device sample which was then held with a clamp (Melles-Griot, USA), held in a XYZ Translation Stage (Eksma, Lithuania). Bending Strain was applied from behind using a µm screw (Mitutoyo, Japan). Images captured by the Analog Video Camera were then grabbed and converted into digital form by GrabBee III USB Audio/Video Grabber (VVmer, Taiwan). The digital images were then stored for further processing in the Data-Acquisition PC (Dell Inspiron, Ireland).

This measurement setup was using the fact that light-beams from the outer surface and the hole surface, are reflected and then traveled at different length-path towards the observing-screen (in this case the CCD analogue video camera). Furthermore, a cavity of around 512 µm is formed between the SiO2/SiN membrane and the Si beam beneath it. As both the membrane and the Si beam are partially reflective (with 𝑅SiO2/SiN = 9.3542% and 𝑅Si(100) = 34.7443%, both calculated at 0° angle of incidence), a Fabry-Perot Interferometer is formed.

3. RESULTS AND DISCUSSIONS

The two microstructures described in figure 2 are first stages in our work to mimic the natural campaniform sensillum [9,12]. Furthermore, fabrication and characterisation of these structures will help to elucidate the true mechanism of high sensitive strain sensing in the real campaniform sensillum. For example, based on previous report [7], we expected that the strain-concentrating hole is one of the mechanism used by the natural sensor to amplify strain before transducing it into neurosignal. And the membrane, we believe, transform the concentrated strain into a relatively amplified vertical and horizontal displacement. A qualitative optical characterisation result of the blind-hole structure (fig. 2a) has been presented elsewhere [13]. Here, we present the results of optical characterisation of the membrane-in-recess structure (fig. 2b).

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The reflectance coefficient was calculated using TFCALC software

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Figure 5 (a)-(l) shows the fringes pattern of the SiO-SiN-membrane-in-recess structure just before strain is implied (fig. 5a), and after relative strains from position shown if fig. 5a, were being implied on the Si-beam where the microstructure is glued (fig. 5b-5j); at a maximum strain of +50 µm (fig. 5f). Then fig. 5k shows the optical as the strain was reduced back again to 0 µm (initial position); while fig. 5l shows when the micrometer screw was further withdrawn 10 µm back, which basically shows no difference in the image result, in comparison with the initial position’s image result. We did the last step (fig. 5l) to investigate any appearance of hysteresis.

As we can see from figure 5; there appeared 2-D interference fringe pattern, having 3 orders of maxima from the middle to the edge of the circular apperture (the diameter from the edge to edge of the bright circular fringe resembles the diameter of the membrane, i.e. 500 µm). We also observed circular fringes outside the perimeter, but with much less intensity. As we put the 2nd lower-transmission-rate ND filter (ND filter 2 in fig. 3), the outer rings were not observed anymore. Comparing with blind-hole structure optical characterisation result [13], we expect that the fringes did not only come from interference between the reflected light beam from the upper surface of the Si chip and the membrane surface of the chip, alone; rather, we also believe that the optical cavity formed between the membrane and the Si-beam beneath, acted as a non-ideal Fabry-Perot interferometer.

If we try to examine the general Fabry-Perot Interferometer equation [16]:

\[
\frac{I}{I_0} = \frac{1}{1 + F \sin^2 \left( \frac{4mt \cos i}{\lambda} \right)}
\]

where \( I_0 = (1 - a) T^2 [1 - (1 - a)R]^2 \), \( F = 4 (1 - a) R [1 - (1 - a)R]^2 \), \( a = \) absorptivity of the medium, \( T = \) transmittivity of the plates, \( R = \) reflectivity of the plates, \( n = \) index of refraction of the medium, \( t = \) separation of the plates, \( i = \) angle of incidence, and \( \lambda = \) wavelength of incident light; then, under an ideal condition, where the beam and the membrane are
Figure 5. Images of reflected laser beam from the SiO-SiN Membrane-in-recess structure with 13 µm depth, 500 µm diameter length, and 500nm total membrane thickness, at different flexural strain stimulus, as applied from behind the Si-beam by a µm screw with 2µm precision (see figure 3): (a) 0 µm, (b) +10µm, (c) +20µm, (d) +30µm, (e) +40µm, (f) +50µm, then the movement was reversed again (g) +40 µm, (h) +30 µm, (i) +20 µm, (j) +10 µm, (k) 0 µm (initial condition), (l) –10 µm (further backward 10 µm)
completely in-parallel, \( i \) should be 0, and as \( \lambda \) and \( n \) is constant, as well as \( F \) (\( F \) is a function of \( R \), which is a function of \( i \)), then \( I/I_0 \) will only be determined by variation of \( t \); with the same value of \( t \) over all spatial distribution on the circular membrane. Meaning, we would have only seen a homogeneous ‘bright’ or ‘dark’ over the whole circular membrane area. But, instead, we see a circular fringes pattern. This could be explained by the occurrence of initial internal stress in the SiO\(_2\)/SiN membrane due to fabrication process, or internal stress of the Si chip, or also due to the measurement setup (Si beam clamped). Any of these thing would make the membrane bend a little, making a curve, which will result in a spatial variation of \( t \) and \( i \) over the circular area of the membrane.

Using MATLAB, we processed the images further by ‘slicing’ the middle part of the images (fig. 6) so that we can analyse better the results. As we applied the strain, the fringes maxima shifted, horizontally, towards the centre, and new

Figure 6. A ‘slice’ at the middle of the image results shown in fig. 5 (a) initial no strain condition, fig. 5 (f) +50 \( \mu \)m strain-stimulus, and fig. 5 (k), back again to 0 \( \mu \)m (no strain) condition; (a) the general image, (b) a zoom-in to the edge region of the membrane, (c) a zoom-in to the middle region of the membrane.
order ring appeared at the edge (see fig. 5d-5h). And by comparing fig. 6b and 6c, we can see that the center part’s intensity changed more sharply than the edge. Based on the results, we predict that as we applied the strain, the range of \( i \) (angle of incidence) as a function of spatial location on the membrane became higher, as a natural result of bending. But, in addition to that, we predict also a non linear deflection of the membrane, i.e. the membrane did not deflect similarly as the Si beam beneath it. To prove this proposition, assume that the membrane is very stiff; then as we applied the bending to the Si beam beneath, the membrane should have bended accordingly, maintaining the separation distance distribution \( t(r) \), where \( r \) is spatial location on the membrane. If the \( t(r) \) does not change, we would only have a change in the \( i \) range, but not in the distance. Then, the intensity in the centre would not have changed that much (fig. 6c). Yet, as a very sharp decrease of intensity in the centre of the membrane was observed as we applied flexural strain, we believe that a nonlinear deflection of the membrane should have occurred. This nonlinear deflection might contribute to the strain-amplifying property of the structure.

4. CONCLUSIONS

We have fabricated early biomimetic Si-based microstructures based on the structural features of the natural campaniform sensillum found in insects sensor. A simple optical characterisation based on the reflection image was devised. A semiquantitative analysis based on Fabry-Perot Interferometer, predicted that the structure behaved nonlinearly to a flexural strain stimulus, which might further contribute to its strain-amplifying properties.

ACKNOWLEDGMENTS

This research is made possible by the grant from The Dutch Technology Foundation, STW (under project DEL 6050), Applied Science Foundation of NWO and the technology programme of Ministry of Economic Affairs, The Netherlands. The authors would like to express its gratitude and thanks to the staffs and technicians of DIMES (Delft Institute for Microelectronics and Submicron Technologies). The authors would like also to thank Mr. P. Rao, Msc. for his insightful discussion on Fabry-Perot Interferometry. The first author would also like to thank Mrs. A. Dall’Acqua, M.Sc. for her helpful discussion on the mathematics of the Fabry-Perot equation.

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