Microtechnology and Microsystems in Measurement Applications

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Microelectromechanical systems (MEMS) technology has enabled silicon sensors to evolve into microsystems or microinstruments. The application areas served by MEMS technologies include automotive, medicine, optical communication, and analytical chemistry. MEMS technology is gradually penetrating mainstream I&M applications [7]. One traditional discipline within the I&M field is metrology, which considers calibration and standards of stability, accuracy, and portability of reference elements. The crucial specification in metrology is reproducibility of the device structure, which relates to stability. Consequently, microsystems based on crystalline silicon, and the associated bulk micromachining technologies, are more reproducible and stable when compared to microsystems fabricated using surface micromachining on deposited materials.

MEMS technology can contribute to critical components in ac-to-dc converters, internal dc references, and in thermal RMS-to-dc converters. The major focus of research is:

- Stability (i.e., the reproducibility of the pull-in voltage in dc devices and the electrostatic deflection of ac devices),
- Thermo-mechanical noise level,
- Circuits required for practical operation.

DC Standard Using the Pull-In Voltage of a Microstructure

An important device within electrical metrology is the dc reference. Zener references are widely used as the transfer standard. The operation of a Zener diode uses avalanche breakdown and has a high noise level. Recent research has demonstrated that the pull-in voltage of a micromechanical structure can be used as a dc reference with a reduced noise level [4], [7].

Electrostatic force in a vertical field is inversely proportional to the square of the deflection of a beam. The restoring force of the beam is, in a first approximation, linear with deflection. An unstable system results for deflection, v, beyond a critical value, v_{crit}. The pull-in voltage, V_{pi}, is the voltage that obtains this critical deflection. For a stable equilibrium deflection the second derivative of the potential energy of the system to deflection should be positive: $\partial^2 U_p / \partial v^2 > 0$, thus V_{pi} results from $\partial^2 U_p / \partial v^2 = 0$ and is uniquely determined by the beam material, dimensions, and residual stress [5]. The pull-in voltage is widely used to measure the residual stress in a beam that is clamped at both ends. Such a structure is not suitable as a voltage reference because the long-term drift, due to stress relaxation, limits the reproducibility. Therefore, a single-ended, clamped beam or a plate with folded suspension should be used.

Thermo-mechanical energy provides an additional excitation term in the potential energy of the system. For low-noise operation, squeeze film damping should be minimized. Reliability concerns inhibit continuous bouncing of the beam. Moreover, the pull-in voltage should be made available continuously, which results in a circuit with the structure operating as a seesaw [4], [7] or in feedback.

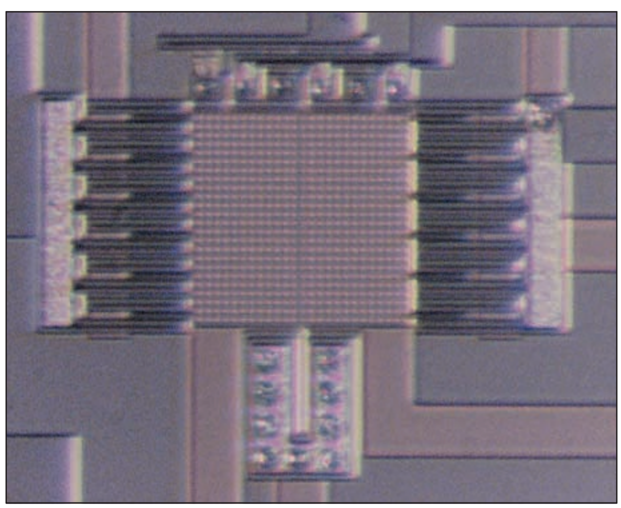

Fig. 1. Photograph of a detailed view of the tip of a fabricated microstructure.

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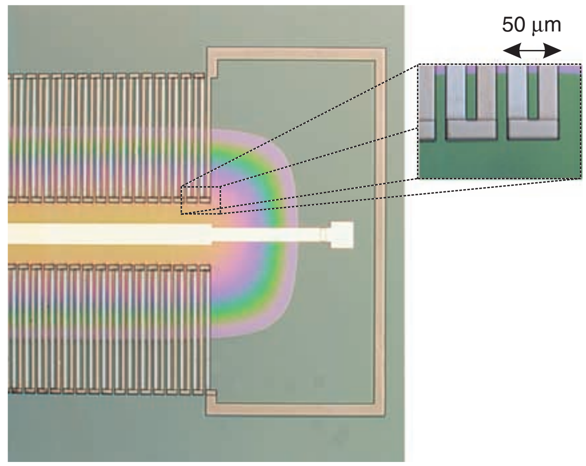

Fig. 2. Fabricated thin-film MJTC with an EvanOhm heater for voltage and Gold heater for current applications and with details of heater and obilisk. The arrow indicates 50 µm. (Courtesy of J. Kinard, NIST, U.S.A. and T. Wunch, Sandia National Laboratories, U.S.A.)

Surface micromachining is required, but devices composed of crystalline material should give better stability. An epipoly process makes this feasible [1]. Basically, an 11-µm thick structural polysilicon layer is patterned and released in a duplicating surface-micromachining process. Fig. 1 shows the devices as single-ended, clamped beams that move in the plane of the wafer with localized parallel, plate actuation at the free-standing tip. Extending to left and right are two sets of comb drive electrodes. The electrostatic force in the comb drive can restore the position of the beam since it is independent of electrode position (in a first approximation).

Thermal ac-to-dc Converter

MEMS devices based on electrostatic force provide an alternative to conventional thermal ac measurement. Microtechnology has been introduced in those devices to scale down the dimensions of the thermal converter and to improve the performance.

Conventional thermal ac measurement uses the temperature increase of a resistor in either a thermopile or a transistor differential pair. Typically, analog circuits perform the square and integration functions. Thermal ac measurement uses the equivalent Joule heat generated in a resistor by an ac or dc voltage or current. Devices operating on this principle comprise a heater, to which the ac input is connected, and a thermal sensor that provides a dc output. The heater design strives for both reproducibility, by using a material with low temperature coefficient of resistivity (TCR) in the heating resistor, and wide bandwidth, by using a low-resistance heater with minimum parasitic, series inductance, and parallel capacitance. The heating of the resistor with respect to ambient temperature is measured differentially and for that reason the resistor is placed on a thermally isolating membrane.

Fabricating these devices using silicon-based MEMS technology shows great potential because [6]:

- Silicon oxide and silicon nitride membranes can be fabricated using micromachining technologies.
- Compatible sensor technologies can be used for the fabrication of NiCr resistors.
- Bulk micromaching increases the thermal capacitance of the heated membrane, thus enabling the integration of time that is required for the RMS value.
- Thermopiles can be integrated in silicon using doped or deposited layers.

Two different implementations are available. Fig. 2 shows the first one; it comprises a ring-shaped heating resistor and a large number of Cu-CuNi thermocouples on a membrane layered 200 nm Si_3N_4, 400 nm SiO_2, and 200 nm Si_3N_4. Bulk micromachining enables the formation of a large suspended thermal mass (obelisk) that improves the low-frequency response [3], [7].

Fig. 3 shows the alternative for measuring the temperature difference with a bipolar differential transistor pair. The ac input drives R_1, and the temperature of the thermally isolated island containing R_1 and Q_1 increases as a result. A feedback configuration drives R_2 until Q_2 and Q_1 are at the same temperature. At steady state, the voltage U_{out} is the dc equivalent of

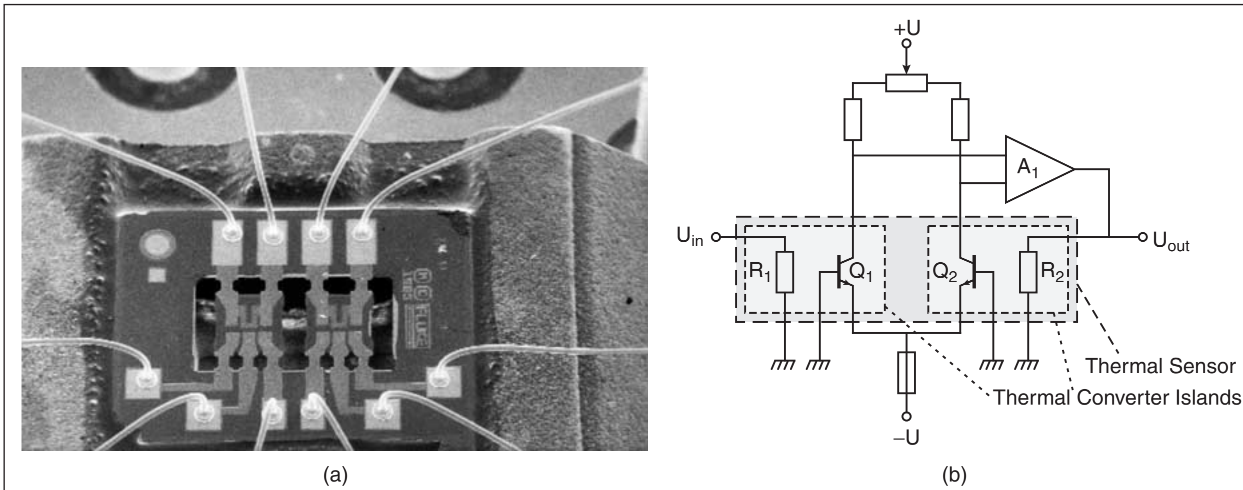

Fig. 3. (a) The Fluke RMS sensor (Courtesy of Fluke Cooperation, U.S.A.) and (b) circuit diagram of the feedback configuration using two transistor sensed thermal converters.

the RMS voltage at the input (in a first approximation). It is important that the two sets of heating resistor/temperature-sensing resistor combinations are thermally isolated with respect to ambient conditions and to each other. This is the operating mode in a typical handheld multimeter. In metrology both the ac voltage and the dc reference are applied at the input, and a sequence of measurements of U_{out} (while applying ac, dc, dc with reverse polarity, etc., at the input) cancels out various sources of uncertainty.

Electrostatic ac-to-dc Converter

The electrostatic ac-to-dc converter has two wafers: one silicon wafer with a bulk-micromachined suspended membrane, and one glass wafer with a fixed electrode. Bonding typically results in a 4-μm spacing between the membranes. The electrostatic force between the membranes is proportional to the square of the voltage. Squaring an ac voltage with frequency ω_{ac} results in a dc component and a component at $2\omega_{ac}$. Operation is based on capacitive measurement of the slow, varying (dc) displacement and requires suppression of non-dc displacements. The membrane area and suspension beam dimensions set the static displacement. The squeeze-film damping and the suspension beams arrangement determine the dynamics of the displacement.

Fig. 4 shows the fabricated device. Membrane area and suspension beam cross-sectional area and length have a nominal device capacitance of 5-10 pF. Membrane area, electrode spacing, and suspension beam dimensions were designed for a 10 mV threshold of detection, a 10 V full scale, and maximum attenuation of the second harmonic.

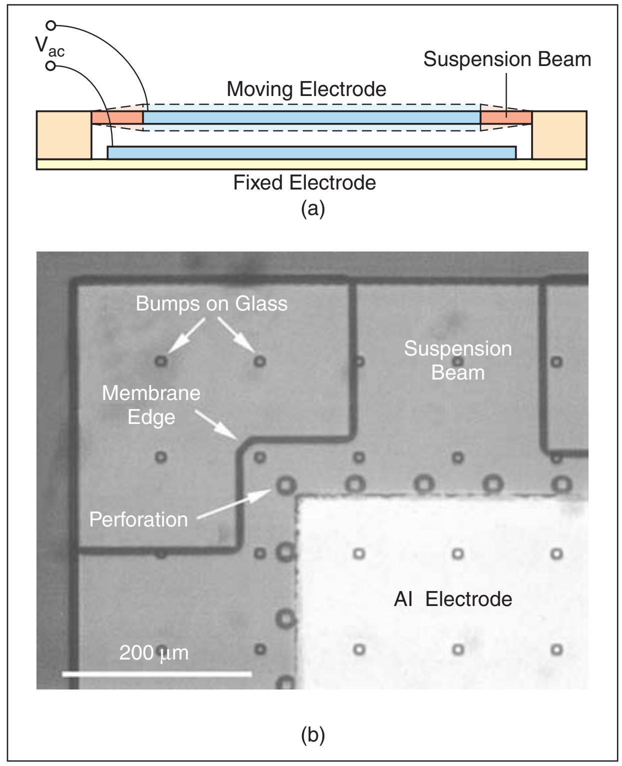

Fig. 4. (a) Structure of the electrostatic RMS-to-dc converter and (b) a detailed view through the glass on the upper left corner of the device showing the 200-mm-wide suspension, the aluminum electrode, the antisticking bumps, and the perforated membrane.

Summary

Microtechnology has made inroads into metrology. MEMS structures in thermal RMS-to-dc conversion are at a mature stage. Many more applications are in their infancy and require more basic and applied research. Next to metrology, these may open doors to the higher performance instruments. A characteristic of MEMS is the reproducibility of the structure, which is important in metrology. Standard microelectronic processing and low-cost batch fabrication, which are often the main driving force in other applications areas, are less important in metrology because of the modest production volumes. Compatibility becomes an important issue when one tries to implement a reference element in a microsystem.

References

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