The Relationship Between Microsystem Technology and Metrology

Reinoud F. Wolffenbuttel, *Senior Member, IEEE*, and Cees J. van Mullem

***Abstract*—Microsystem technology (MST) has enabled silicon sensors to evolve from simple transduction elements to microsystems (micro-instruments) that include readout circuits, self-test, and auto-zeroing facilities. This paper discusses the impact of MST in the instrumentation and measurement (I&M) field. In metrology, in particular, the development of electrical reference standards by using microtechnology has opened a wide variety of potential applications, such as the Josephson junction array (dc voltage reference) and thin-film multijunction thermal converters (ac voltage and ac current reference). It is shown that MST has even more to offer to the I&M field. Two devices that have highly benefited from MST: thermal and capacitive rms-to-dc converters are discussed in historical perspective. Subsequently, a recently developed microdevice, the pull-in voltage reference, which may have a huge impact in I&M applications, is outlined. Finally, it is demonstrated that recent developments in electrical and nonelectrical metrology system concepts offer special opportunities for on-chip cointegrated silicon microsystem realizations.**

***Index Terms*—MEMs-based reference, microsystem technology, on-chip reference, pull-in voltage, rms-to-dc converter.**

I. INTRODUCTION

THE ADVANCES in microsystem technology [(MST) in the U.S. and increasingly elsewhere also referred to as microelectro mechanical system (MEMS) technology], has enabled silicon sensors to evolve to microsystems (micro-instruments) that include readout circuits, self-test,and auto-zeroing facilities [1]. The application areas served by devices fabricated using MST technologies include, among others: automotive [2], (bio)medicine [3], optical switching for communication [4], control [5], and analytical chemistry [6], [7]. This technology is gradually also penetrating into mainstream instrumentation and measurement (I&M) application areas, such as metrology. The impact of MST on the I&M field and vice versa could be huge, due to the often overlooked common ground and the potential for future collaboration.

The relationship between MST and the I&M field is a confusing one and requires further analysis. One key observation is that there has always been interaction between the microsystem field and the metrology field, which are both representatives of the I&M discipline. The most obvious one is the characterization of the silicon material properties. Another fact is that a microsystem is, in principle, an instrument, albeit a very small one, and it should be acknowledged that special technologies are required for fabrication. Nevertheless, not unlike any conventional instrument developed within the I&M field, it is designed for measuring a (nonelectrical) quantity. This complicates the definition of the I&M application area, which is defined here as the application where the instrument is the purpose and not the means.

The unique features of the I&M field in general, and metrology in particular, make it a niche application area of high potential. Metrology is involved in calibration and the design and maintenance of standards of an ever increasing level of stability and portability. The aim for size and weight reduction associated with portability aligns well with the scaling trends in microsystems. This trend is supported by industry's need for more accurate references for electrical and nonelectrical parameters. Some of the advantages in the more traditional microsystem applications are also applicable to metrology, such as reliability of the integrated systems and low costs. However, in metrology applications, accuracy, reproducibility, and stability of the device is dominant over cost. The batch fabrication is important as it enables the reproducible fabrication of devices. However, production volume is typically very limited and the economies of scale do not apply. The potential for fabrication of an on-chip cointegrated reference system with some of the control subsystems may become a decisive factor in this application, as is discussed in Section V.

On the other hand, microsystems also pose a challenge to the metrology field. Although microsystems have evolved to genuine on-chip micro-instruments, no internal reference is available. It is widely recognized that the ultimate sensor system is an autonomous wireless microsystem. Such a device is expected to become pervasive in even more applications as being served already. An internal reference is essential in such a device. The complications are huge, as conventional nonatomic references rely on bulk effects, which do not scale down favorably; this calls for collaboration between the microsystem and metrology fields. In mainstream metrology, these efforts would be directly beneficial to on-chip integrated reference systems.

Josephson voltage array standards are very prominent devices in electrical metrology and rely on microfabrication technologies. The Josephson array is basically an integrated circuit with a large number of Josephson junctions in series and a planar waveguide to couple the microwave signal (frequency) to the Josephson array [8]. Each junction produces a voltage proportional to the frequency of the microwave. Depending on the number of junctions, nominal output voltages are in the range of 1 V or 10 V. A special measurement set-up is required to generate the high-accurated dc voltage. The array is operating at

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a cryogenic temperature (<4.2 K), implicating a measurement set-up around a dewar to be cooled down with liquid helium and special equipment to bring the microwave down to the array in the dewar and to get the dc signal from the array to room temperature. Improvements in microtechnology for the device realization have made it possible to put more and more junctions on one chip. Nowadays, 10 V-arrays with about 20 000 junctions are produced on a routine basis. The operating temperature is not easily compatible with CMOS circuit operation. For this reason, the Josephson array is not discussed in this paper.

The historic development of the thermal rms-to-dc converter and the electrostatic rms-to-dc converter from a precision-machined device toward a micromachined structure is described in the following sections. In both types of devices, the micromachining does not merely provide a downsizing of the converter dimensions, but, in addition, provides a genuine improvement of device specifications.

II. Thermal RMS-to-DC Converters

An ac voltage or current is generally referred to its dc equivalent using thermal techniques [9]. Alternatively, analog circuits are used to perform the squaring and integrating over time 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 are composed of a heater, to which the ac input is connected, and a thermal sensor that provides a dc output. The heater design aims on reproducibility by using a heating resistor material with low TCR and wide bandwidth by using a low-resistance with a minimum parasitic series inductance and parallel capacitance. The heating of the resistor with respect to ambient temperature is measured, and for that reason the resistor is to be placed on a thermally isolating membrane. Moreover, the measurement of a temperature difference, rather than the membrane temperature, is preferred.

Originally, fine mechanics was used for the fabrication of a three-dimensional multijunction thermal converter, as shown in Fig. 1 [10]. It is composed of a heating wire suspended on rectangular wired thermocouples, which are used to measure the temperature. This construction is placed on an isolated substrate and covered by a housing. It is operated in vacuum. Clearly, the device is complicated and expensive to manufacture, which is a severe limitation for introduction of such devices in professional equipment when used in outside metrological laboratories. The fragile and relatively large structure requires careful handling.

Silicon-based MEMS technology has a huge potential for fabrication of improved devices due to the following [11].

1) The smaller structures can be used outside a metrology laboratory.
2) Silicon oxide and silicon nitride membranes can be fabricated using micromachining technologies.
3) Compatible post-microelectronic sensor technologies can be used for the fabrication of NiCr resistors.
4) Bulk micromaching can be used to increase the thermal capacitance of the heated membrane, thus enabling the implementation of the time integration that is required for the rms value.

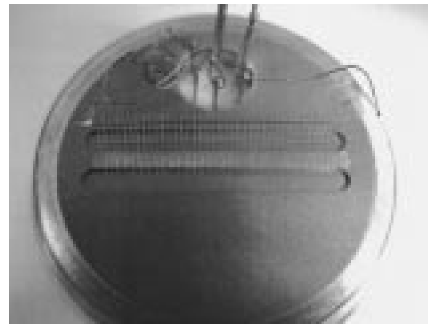


Fig. 1. First-generation thermal rms-to-dc converter using thermocouples [10].

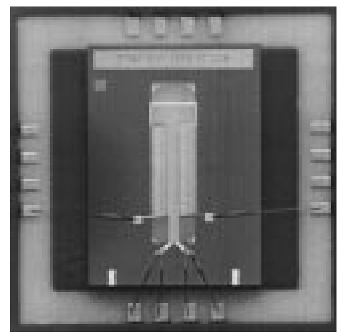


Fig. 2. Planar multijunction thermal converter chip on a Al_2O_3 carrier [11].

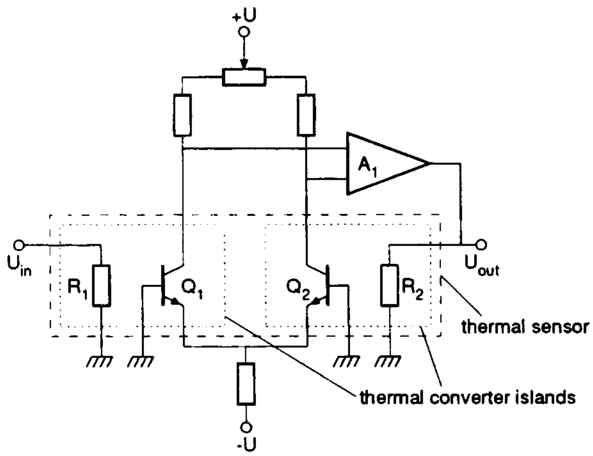
5) Thermopiles can be integrated in silicon using doped and/or deposited layers.

Two different implementations are available. The first is shown in Fig. 2 and is composed of a ring-shaped heating resistor and a large number of Cu–CuNi thermocouples on a 200-nm Si_3N_4–400-nm SiO_2–200-nm Si_3N_4 membrane. As shown in the figure, bulk micromachining enables the formation of a large suspended thermal mass (obelisk) that improves the low-frequency response.

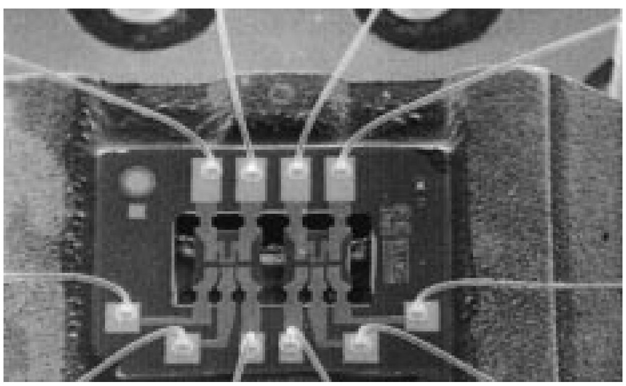
The alternative is based on the use of a bipolar differential transistor pair for measuring the temperature difference and is shown in Fig. 3 [12]. The ac input drives R_1 and the temperature of the thermally isolated island containing R_1 and Q_1 increases as a result. A feedback configuration is used that drives R_2 until Q_2 and $Q1$ are at the same temperature. At steady state, the voltage $U_{\rm out}$ is in a first approximation the dc equivalent of the rms voltage at the input. It is important to note that for proper operation, the two sets of heating resistor/temperature sensing resistor combinations are thermally isolated with respect to both ambient and each other. In metrology. both the ac voltage and the dc reference are applied at the input and a sequence of measurements of $U_{\rm out}$ (while applying ac, dc, dc with reverse polarity, etc. at the input) is performed to be able to cancel out various sources of inaccuracy.

III. Electrostatic RMS-to-DC Converter

Electrostatic ac voltage measurement involves the attractive Coulomb force between two conductive plates upon application of a voltage. The device structure is based on a suspended movable plate electrode with a counter electrode at a fixed position 1.



(a)



(b)

Fig. 3. (a) Circuit diagram and (b) structure of the Fluke rms sensor (courtesy of Fluke Corporation.).

Upon application of a voltage V, the suspended plate is deflected to a position at which the electrostatic force is counteracted by the spring force

$$\Delta d = \frac{\varepsilon A V^2}{2k\,(d_o - \Delta d)^2} \approx \frac{\varepsilon A V^2}{2k d_o^2}$$

where

- ε permittivity;
- d_o gap width between the plates;
- A plate area;
- k spring constant of the suspension.

The deflection is therefore depending on the voltage squared. The formal definition of the V_{RMS}^2 also includes the integration of the squared signal. This is realized using the squeeze film damping of the gas (air) in between the plates [13].

This principle has been used in very early versions of instruments for ac voltage measurement. An advantage is the relatively low loading of the source. One example is shown in Fig. 4 [14]. Fine mechanics is used for the fabrication. Multiple electrodes are used which are especially shaped to give a linear scale. The critical part is the spacing between and parallelism of the plates, which determines the sensitivity and the effectiveness of the damping mechanism. Conventional machining clearly has limitations in this respect [15]. Nevertheless, this approach has been used mainly for the measurement of relatively high ac voltage levels.

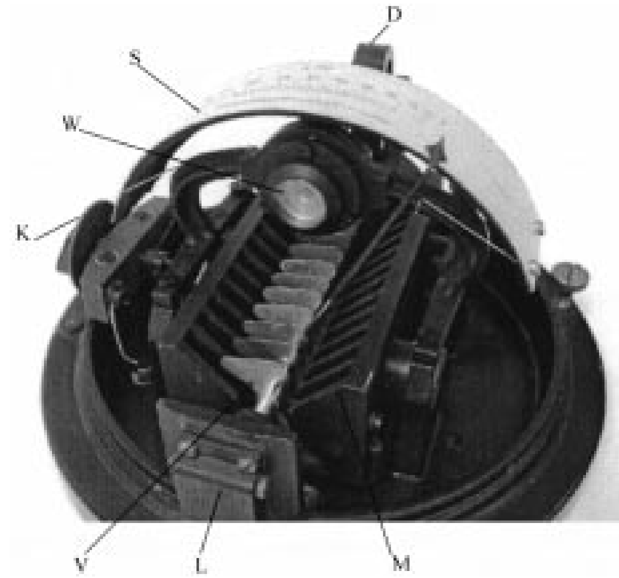


Fig. 4. Hartmann and Braun electrostatic volt meter, with V the specially-shaped movable electrodes, M the stator electrodes, L the bearing, S the indicator, K a switch for zeroing, and W a spirit level indicator used in precision measurements (courtesy of Bauer and de Keijzer [14]).

Silicon MST has revived the electrostatic approach, which has for some time been considered obsolete. A micromachined electrostatic rms-to-dc converter is shown in Fig. 5 [13]. The electrostatic ac-to-dc converter is composed of two wafers: one silicon wafer with a bulk-micromachined suspended membrane and one glass wafer with a fixed electrode. Bonding results in the membranes facing each other with typically 4-μm spacing. 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 $2\omega_{\mathrm{ac}}$. Operation is based on capacitive measurement of the slowly varying (dc) displacement and requires suppression of non-dc displacements. This static displacement is set by the membrane area and suspension beam dimensions. The dynamics of the displacement is set by the squeeze-film damping and the suspension beams arrangement.

Membrane area and suspension beam cross-sectional area and length are designed for a 5–10 pF nominal device capacitance. Membrane area, electrode spacing, and suspension beam dimensions were designed for a 10-mV threshold of detectivity, a 10-V full scale, and maximum attenuation of the second harmonic.

IV. New MST-Based Devices in I&M

The thermal rms-to-dc converter has been developed to a mature product. The electrostatic rms-to-dc converter is a more recent device, which is still in the research phase. An even more recent development is the realization of a dc transfer standard based on the pull-in voltage of a microstructure [16], [17], which offers the possibility for application in transfer standards to replace Zener diodes.

As the electrostatic force in a vertical field is inversely proportional to the square of the deflection and the restoring force of the beam is, in a first approximation, linear with deflection, an

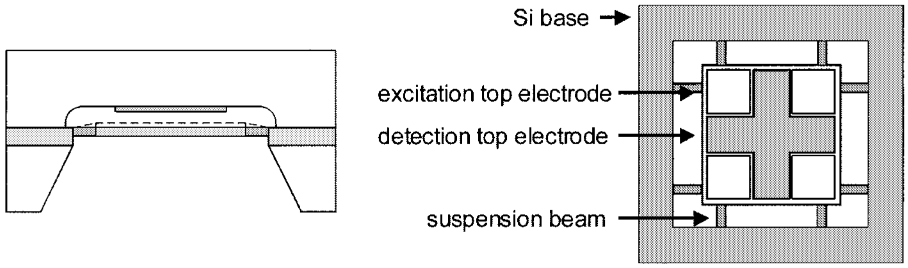


Fig. 5. Operating principle of the bulk-micromachined electrostatic rms-to-dc converter [13].

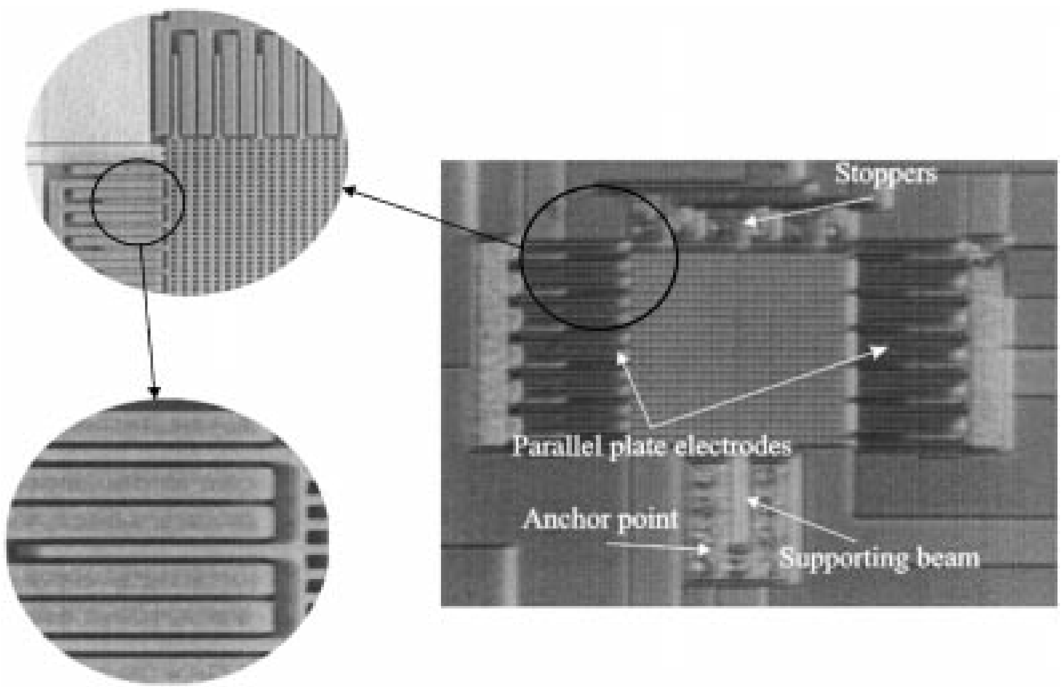


Fig. 6. Structure of the pull-in voltage reference [17].

unstable system results in case of a deflection v beyond a critical value, v_{crit}. The pull-in voltage V_{pi} is defined as the voltage that is required to obtain 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, the beam dimensions, and the residual stress. The pull-in voltage is actually widely used to measure the residual stress in a clamped-clamped beam. For this reason, such a device structure is not suitable as a voltage reference, as the reproducibility would be limited by long-term drift due to stress relaxation. Therefore, a single-ended clamped beam or a plate with folded suspension should be used.

Reliability concerns do not allow the continuous bouncing of the beam. Moreover, the pull-in voltage should preferable be made available continuously, which results in a circuits solution with the structure operating as a seesaw or in feedback.

An epi-poly process was used for the fabrication of 11-μm thick single-side clamped 200-μm long free-standing structures with electrode structures at the tip [18]. After deposition, the thick polysilicon layer can be patterned using deep reactive ion etching (DRIE). Microstructures can subsequently be released by selectively etching the underlying dielectric sacrificial layer using the DRIE holes as the access channel.

A fabricated pull-in device is shown in Fig. 6. The device is basically a free-standing lateral beam anchored at one end (the base) only. The beam can be deflected by electrostatic actuation in the plane of the wafer using a voltage applied across parallel plate capacitors composed of two sets of electrodes located alongside the free-standing tip, with counter electrodes anchored to the substrate. The deflection can be measured using the differential sense capacitor located directly on top of the substrate and aligned with the square-shaped electrode at the tip of the beam. These buried polysilicon electrodes are electrically isolated from the substrate and placed symmetrically on either side of a guard electrode placed directly underneath the axial direction of the undeflected beam. Finally, there are electrically isolated stoppers to limit the lateral motion. The electrodes beneath the movable structure are used for capacitive detection of the pull-in voltage.

V. MST-Based References in Microsystems

So far, the use of microfabrication technologies for the realization of rms-to-dc converters and voltage references has been

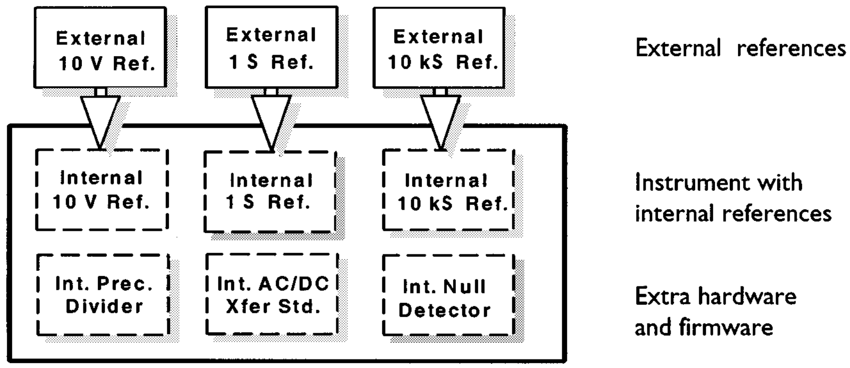


Fig. 7. Basic scheme of the multifunction calibrator with the artifact calibration functionality [19].

outlined. At this stage, it should be mentioned that the converter or reference is only a minor part in a metrology system. The most important advantage of the silicon MST has actually not yet been discussed. Silicon MST-based references fabricated in a CMOS compatible process have the huge advantage that much of the system functionality can be added. In an early stage of system development, the question should be asked in which way calibration/traceability is realized. The advantage of some degree of internal calibration is flexibility and reduced cost of the calibration procedure. However, without special precautions, traceability is better served when using an all external verification.

A good example of such a system on a macro scale is a multifunction calibrator with an artifact calibration option [19]. This calibrator has a large functionality by generating voltage, current, and resistance in a broad range. The system has three internal references; these are used for an internal calibration procedure for all ranges. The internal procedure uses additional hardware and software built into the system especially for this application. These internal references are calibrated against three external references on a regular basis. However, the internal calibration procedure can be operated as often as required by the specifications needed from the calibrator. Fig. 7 shows the principle scheme of this calibrator. When this concept is implemented in a microsystem, it means some internal reference on-chip near the sensors and actuators and these will be externally calibrated. The on-chip references will be used for the system characterization. However, the stability of the on-chip references is a important design issue, since they are probably exposed to the environment for the sensor application (high temperatures, pressures, etc.). Obviously, the MST-based references in a CMOS process offer huge opportunities for the realization of such high-performance metrology systems on a single chip.

VI. Conclusions

As shown, microtechnology has already made inroads in one particular application in I&M. 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 general use in high-performance instruments. The characteristics of MEMS, which are decisive in I&M applications, are the reproducibility of the structure and the compatibility with standard microelectronic processing. The opportunities the latter offers are mainly for on-chip reference systems. The low-cost batch fabrication, which is often the main driving force in other applications areas, is less important in I&M applications, due to the moderate production volumes.

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