RECENT ADVANCES IN AC-DC TRANSFER MEASUREMENTS USING THIN-FILM THERMAL CONVERTERS

Thomas F. Wunsch[*], Joseph R. Kinard[†], Ronald P. Manginell[*], Thomas E. Lipe[†],
Otis P. Solomon[*], and Kenneth C. Jungling[‡]

[*]Sandia National Laboratories
PO Box 5800
Albuquerque, NM 87185-0665
505-844-4359
tfwunsc@sandia.gov

[†]NIST
100 Bureau Drive
Gaithersburg, MD 20899-8111

[‡]University of New Mexico
1313 Goddard SE
Albuquerque, NM 87106

Abstract – New standards for ac current and voltage measurements, thin-film multijunction thermal converters (MJTCs), have been fabricated using thin-film and micro-electro-mechanical systems (MEMS) technology. Improved sensitivity and accuracy over single-junction thermoelements and targeted performance will allow new measurement approaches in traditionally troublesome areas such as the low frequency and high current regimes. A review is presented of new microfabrication techniques and packaging methods that have resulted from a collaborative effort at Sandia National Laboratories and the National Institute of Standards and Technology (NIST).

INTRODUCTION

Rapid development of micro-electro-mechanical systems (MEMS) technology over the past decade has enabled the development of new, inexpensive sensors. The broad application of miniaturized sensors in many disciplines (e.g. chemical, mechanical, and electrical) offers new approaches in addressing a variety of measurement applications. This rethinking has led to microfabricated accelerometers that are utilized in the determination of machine "health" [1], miniature pressure transducers (1 mm x 0.7 mm x 0.175 mm) small enough to be inserted into a catheter [2], and electrochemical sensors that redefine the technology of detecting explosive gases [3]. Metrology is also taking advantage of this technology revolution. Process metrology for the integrated circuit industry, for example, utilizes micromachined structures for overlay and linewidth critical dimension calibration [4] and standards and calibration laboratories can expect to see new integrated MEMS pressure transducers, strain gauges, and accelerometers as part of their everyday calibration workload. Thin-film technology has also resulted in a number of primary standards, such as Josephson Voltage arrays, quantum Hall resistance standards, single electron tunneling devices and infrared bolometers, that are employed in standards laboratories.


DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Electrical Metrology

Recently, MEMS technology has been applied in the field of ac metrology. Primary and secondary working standards for ac-dc difference measurements have been realized through the use of microfabricated multi-junction thermoelements. The new devices provide higher sensitivity and smaller thermoelectric errors than the familiar, traditional Single-Junction Thermal Converter (SJTC) elements. A larger design parameter space, allowing greater flexibility in material selection and more precise layout geometry, provides greater flexibility in design, uniform manufacturing, and targeted performance. Recent designs have targeted low-frequency performance improvement [5], low-voltage ranges [6], and high-current measurement [7].

ac-dc Transfer Measurements

Consistent use of the International System of Units (SI) units in ac measurements requires that some feature of the alternating waveform be related through measurement to an equivalent dc electrical quantity (this arises from the definition of the ampere in the SI in terms of a "constant current"). Although, peak-to-peak voltage, or any number of other measurements may be made, normally it is the root-mean-square (rms) voltage or current that is related to an accurately known dc signal. Thermal converters are a natural means of achieving this relationship due to the Joule heating of a resistive element that produces a mean square response. Figure 1 illustrates a simple thermoelement. The single thermocouple of the SJTC senses the relative heat produced near the mid-point of a SJTC heater wire. The heat produced under ac excitation can then be compared with that produced under dc excitation and the relationship is established between the unknown ac waveform and a dc standard. The dc signal can be known quite accurately due to the precision of modern dc voltage standards calibrated by extremely accurate dc Josephson standards that are used to realize the SI unit of voltage. Additionally, the output of the thermal converter is that due to the dc voltage produced by the thermocouple. This output can be measured with high precision to achieve resolution of a few parts in 10^7.
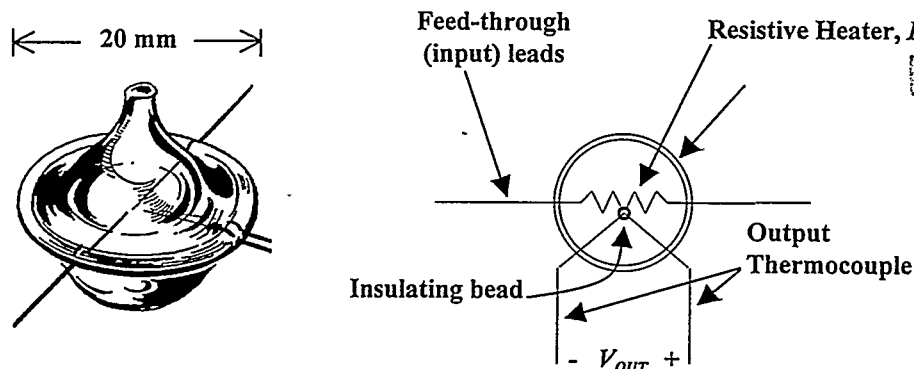
Figure 1. Conceptual drawing of a Single-Junction Thermal Converter (SJTC) and its schematic representation. The excitation (current or voltage) is applied to the feed-through leads of the resistive heater element. The element is often used in conjunction with a range multiplying resistor and housed in a coaxial assembly.

The measurement process can be time consuming for several reasons, including

1)   the thermal converter must stabilize at each measurement point,

2)   the thermal converter output must be determined for both polarities of the dc signal in order to average out any a asymmetric differences in output arising from polarity reversal,

3)   the parameter space is a combination of voltage (or current) level and frequency resulting in a large number of calibration points, and

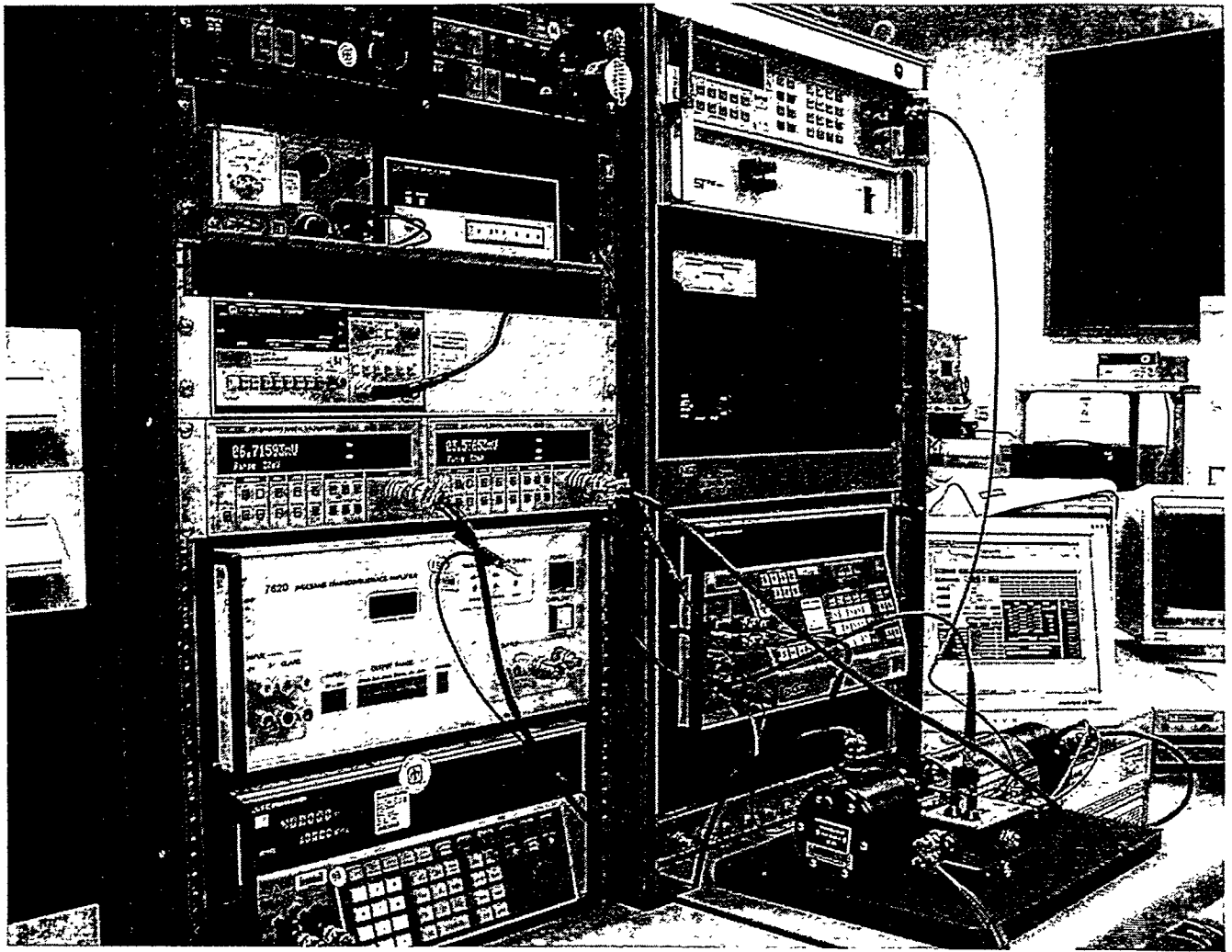4)   repeated measurements are necessary to obtain small Type-A uncertainty components.

Figure 2. An automated ac-dc difference measurement system running NIST software shows the intercomparison of two thermal transfer standards (as operated by the Primary Standards Laboratory at Sandia National Laboratories).

Fortunately, the measurement sequence can be automated [8] and the entire process occurs largely in the absence of an operator (Figure 2). Nevertheless, the calibration of a set of thermal converters can be costly and time consuming.

The difference in the response of a thermal converter to ac and dc signals is its ac-dc transfer difference, δ, defined as

$$\delta = \frac{Q_{ac} - Q_{dc}}{Q_{dc}}$$

where Q_{ac} *is* the ac voltage or current for a given output indication, and Q_{dc} is the dc signal for which the average of its two polarities produces the same output indication. The measurement is limited by the ability of the thermal converter to respond in precisely the same manner to the rms ac signal as it does to the dc signal. These ac-dc differences occur at low frequencies (< 40 Hz) by failure of the device to fully integrate the ac waveform, at midrange frequencies (40 Hz to 10 kHz) by the thermoelectric effects that are not present with ac applied, and at higher frequencies (greater than 10 kHz) by parasitic reactive effects and skin-effect in the heater, lead structure, or input connectors. For frequencies above about 10 MHz, signal reflection becomes an issue and careful consideration must be given to impedance matching.

The use of a multi-junction thermopile as a means of reducing the thermoelectric effects caused by Thompson and Peltier heating in the SJTC was realized by Wilkins of NPL [9], and later refined by Klonz at the Physikalisch-Technische Bundesanstalt (PTB) [10]. Subsequent to the development of the Multi-Junction Thermal Converter (MJTC), various designs have been used as primary standards at National Measurement Institutes (NMIs) around the world. The cost of manual assembly required in the MJTC precludes its acceptance as a transfer standard in many calibration laboratories, and the SJTC retains its role as a commonly employed transfer standard.

Overview

The objective of this paper is to describe the coupling of MEMS technology and ac metrology that has developed over the past decade. Early work to develop a thin-film micromachined replacement for the three-dimensional wire MJTC occurred at PTB [11] and NIST [12]. Subsequent work has included development of low-frequency, long thermal time constant voltage converters [5], low-voltage micropotentiometers (µPots) [6], thin-film thermal converters for current measurements [7], and less accurate CMOS compatible thermal converters [13,14]. More recently, Laiz, et. al., have reported that the errors that occur at low frequencies due to non-linearities in the heat transfer mechanism have been largely resolved through a novel compensation technique [15] and research at NIST and Sandia National Laboratories has resulted in simpler fabrication techniques and advanced packaging concepts for vacuum sealing the thin-film thermoelements [16].

Thin-film MJTC Construction

Construction of a thin-film thermal converter requires the microfabrication of each component of the conventional MJTC on a device that has the scale of a few millimeters on a side. The components include the heater, the thermopile, and the supporting substrate. Figure 3 shows a conceptual drawing of a thin-film MJTC. The silicon (Si) substrate acts to thermally isolate the device from changes in ambient temperature, and a thin-film dielectric membrane isolates the heater and thermopile "hot junctions" from the thermopile "cold junctions. This thermal isolation allows a temperature gradient to be developed across the thermopile. The temperature gradient generates a Seebeck emf in the thermopile that serves as the output signal of the thermoelement.
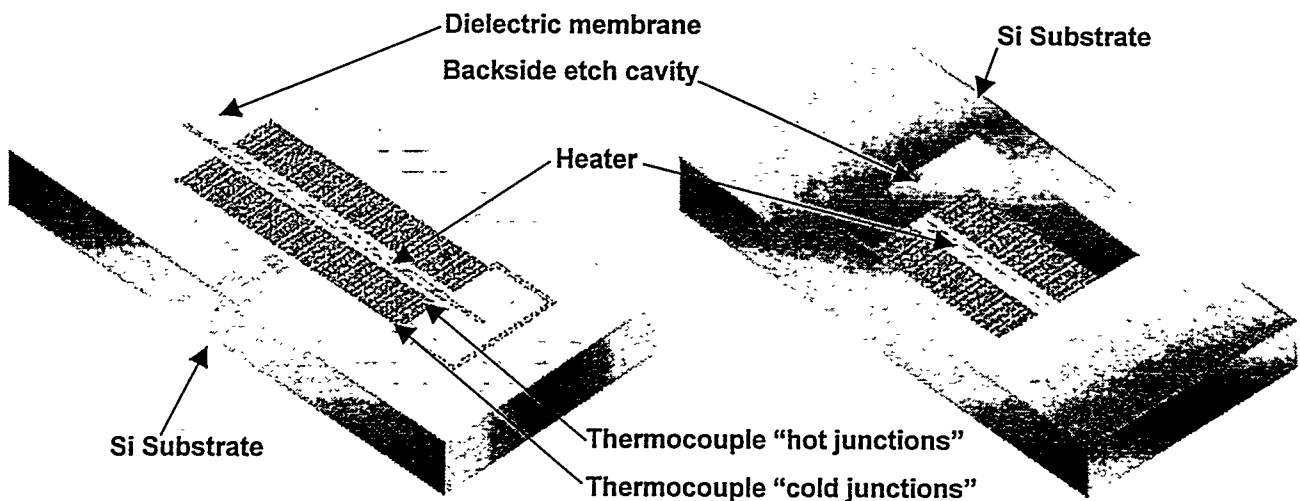

Figure 3. A conceptual drawing of a thin-film MJTC (6 mm x 3 mm x 0.4 mm) with 100 series connected thermocouples and a 400 Ω heater. On the left is a top perspective view. On the right, is a perspective view of the back-side of the die. The thermopile and heater are visible through the transparent dielectric membrane in the bottom view.

Microfabrication

Microfabrication begins with the design of a physical layout on a computer automated design (CAD) tool. The CAD layout may be exported in various standard file formats suitable for the generation of photolithographic masks. The layout data is also valuable for numerical simulation of thermal and electrical properties of the device, and automated means of importing the layout data into 3-dimensional finite-element codes have been developed. The design is replicated such that a 100 mm Si wafer will accommodate about 300 die in addition to necessary alignment and processing test structures.

Starting Material

Si wafers of 100 mm diameter and 400 μm thickness are used as the starting material in the fabrication process. The wafers are obtained from a commercial supplier with a 500 nm low-stress silicon nitride thin-film dielectric layer. The dielectric layer serves as electrical insulation between the metal layers (heater and thermocouple) and the conductive substrate. Following the back etch treatment described below, the nitride dielectric also provides physical support for the metal layers while maintaining good thermal isolation between the heater and the substrate. Initial processing of the wafer consists of a series of wet chemical and plasma cleaning steps.

Metal Deposition

Metals used in the heater and thermocouple structures can be evaporated or sputtered. Sputtering tends to maintain the alloy composition of the materials better than evaporation methods and is utilized exclusively in the Sandia technology. Metal deposition begins with a transfer of the metallic pattern to a photoresist mask. Following sputtering, the photoresist mask is removed in a lift-off technique and the patterned metal layer remains. The heater alloy is generally a nickel-chromium alloy that provides a low temperature coefficient of resistance (TCR). Thermal annealing of the deposited metal is required to achieve the low TCR.

It is desirable that the thermocouple metals have a low thermal conductivity and a high Seebeck coefficient. Unfortunately, high thermal conductivity generally corresponds with a low Seebeck coefficient and some compromise is necessary. The device pictured in Figure 4 utilizes nickel/chromium and copper/nickel alloys (essentially a Type-E thermocouple). The PTB has demonstrated enhanced sensitivity with bismuth-antimony thermocouples.

Deposition of a thin-film layer of gold on the backside and gold bond pads complete the metalization steps. The backside metal allows an Au/Si eutectic die attach that is desirable for package sealing under vacuum.
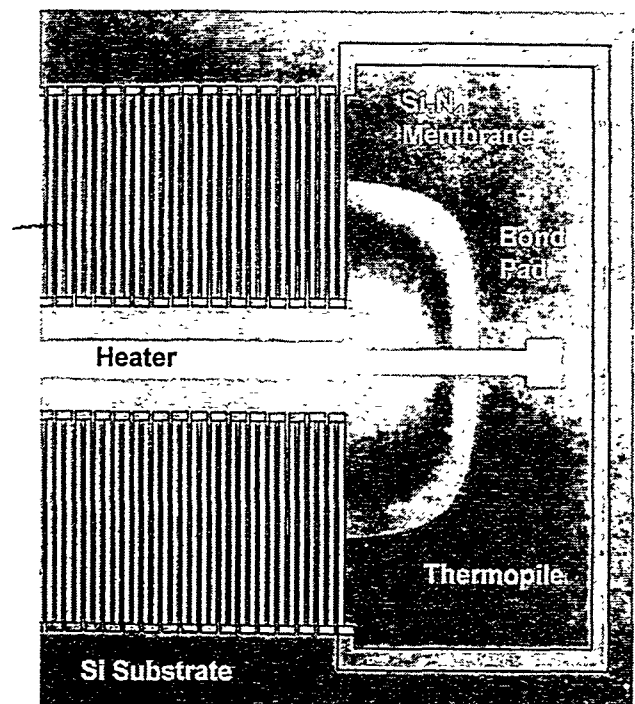

Figure 4. Microscope image of a portion of a thin-film MJTC fabricated at Sandia National Laboratories.

Backside Etching

Wet chemical etch technique

Wet chemical etching with acid or base solutions is often used to transfer patterns into semiconductor materials. The process involves either the oxidation or reduction of the Si surface followed by removal of the soluble reaction product. For a diffusion limited reaction, rates are limited by either the diffusion of reactive species to the surface or diffusion of the soluble reaction products from the surface. Diffusion limited reactions are often difficult to control due to the flow dynamics involved. Alternatively, for a reaction limited etch, chemical reaction at the substrate surface is the rate limiting step. These processes are much easier to control and are highly temperature dependent.

Wet etching is typically fast, low damage, and low cost. However, the isotropic etches obtained with wet chemical etchants are difficult to control and have poor resolution, thereby limiting the critical dimension of the etched features. Wet anisotropic etches are possible, but are severely constrained by the crystallography of the Si.

Thin-film thermal converter fabrication at NIST and PTB has relied on isotropic etching with KOH. Initial fabrication utilizing Si wafers with a thin-film silicon dioxide dielectric resulted in fragile dielectric membranes. Development of a "sandwich" nitride-oxide-nitride stacked dielectric resulted in a low-stress membrane that has shown good results [17]. A number of thin-film MJTC designs have been fabricated utilizing this technique both at NIST and at PTB.

Klonz has demonstrated the formation of a Si obelisk (useful for increasing the thermal time constant of the converter) in a wet chemical process [5]. The geometry of the obelisk, however, is constrained by the Si crystallography.

DRIE "Bosch" etch technique

As mentioned above, pattern transfer into Si has been very successful by wet chemical techniques. However, the fabrication of deep, high-aspect ratio Si structures is limited due to low etch selectivity to photoresist masks, slow etch rates, and poor lateral dimensional control. The development of a Deep Reactive Ion Etch (DRIE) process has resulted in anisotropic profiles at room temperature, etch rates greater than 3.0 µm/min, high aspect ratios, and good dimensional control. Additionally, the DRIE process has shown etch selectivities to photoresist greater than 75:1 thereby eliminating the process complexity of hard etch masks for features deeper than 100 µm.

The DRIE "Bosch" process (patented by Robert Bosch GmbH [17]) relies on an iterative Inductively Coupled Plasma (ICP) based deposition/etch cycle in which a polymer etch inhibitor is conformally deposited over the wafer during the deposition cycle. This is displayed schematically in Figure 5. The polymer deposits over the resist mask, the exposed Si field, and along the sidewall. During the ensuing etch cycle, the polymer film is preferentially sputtered from the Si trenches and the top of the resist mask (due to the acceleration of ions formed in the plasma) perpendicular to the surface of the wafer. Provided the ion scattering is relatively low, the polymer film on the sidewall is removed at a much slower rate, thus minimizing lateral etching of the Si. Before the sidewall polymer is completely removed, the deposition step is repeated and the cycle is continued until the desired etch depth is obtained.

Figure 5. 2-Step DRIE "Bosch" polymer deposition and etch cycle utilized in the backside etch formation of a thermally isolated free-standing dielectric membrane.

Using the DRIE "Bosch" process, a Si substrate can be etched with highly controlled lateral dimensions thus allowing accurate alignment of component features. Of particular interest to the fabrication of thermal converters is the ability of the technique to accurately back etch the Si leaving the thermally isolating freestanding membrane with a feature of Si
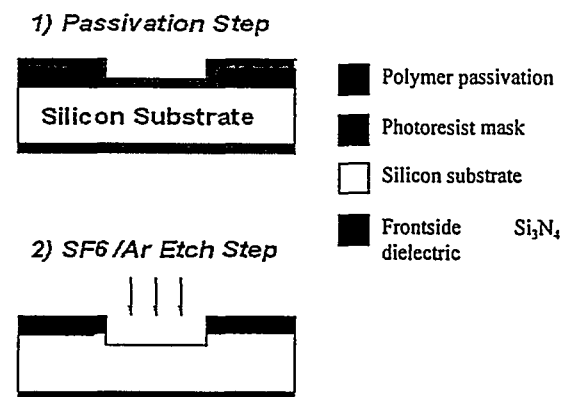
directly beneath the thermal converter heater. The feature achieved is illustrated in the front and backside microscope images of Figure 6. The additional thermal mass of such a feature has been shown by Klonz [17] to significantly reduce the low-frequency error due to incomplete integration of the applied ac waveform. The DRIE technique holds significant advantages over the wet chemical technique in engineering the thermal time constant. In addition to the improved etch rate mentioned previously, the method provides precise control over lateral geometry and feature placement. We have shown recently, that the use of an oxide delay layer or a double hard/soft baked photoresist process further allows control of the vertical dimension of the obelisk feature. The technique, therefore, allows precise control over the thermal time constant of the thin-film MJTC heater.
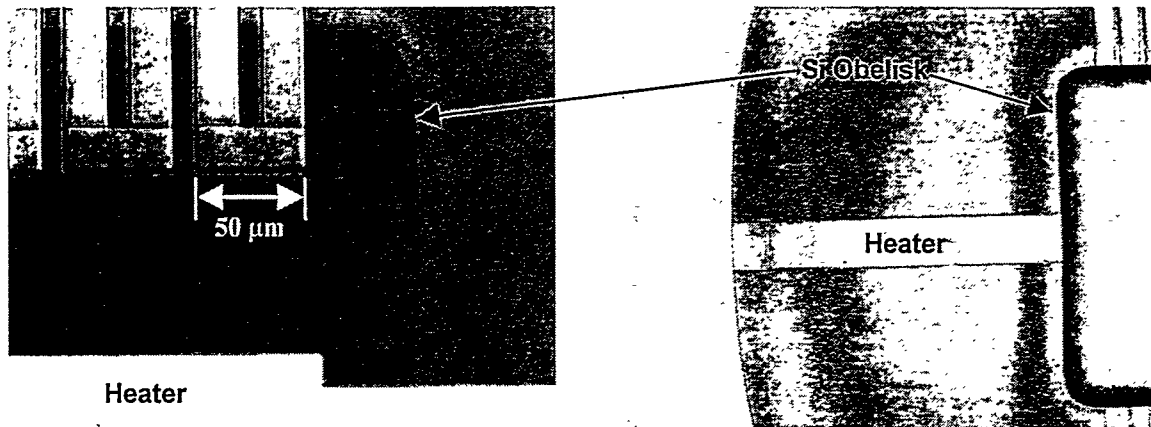

Figure 6. Microscope images of the frontside (left) and backside (right) of a thin-film MJTC illustrating the formation of a Si obelisk directly beneath the heater and the thermocouple "hot junctions". The obelisk serves to reduce the low frequency error of the thermal converter by increasing the thermal time constant of the heater, thereby more fully integrating the applied ac waveform.

Wafer Sawing and Die Separation

The wafer is protected by a 5 μm thick coating of photoresist and attached to a Mylar sheet prior to assembly in the wafer sawing tool. The photoresist protects the dielectric membrane from rupture due to vibration during the sawing process. Visual screening provides a means of sorting out obviously defective die. Good die are cleaned and baked out in preparation for packaging.

Packaging

Capitalizing further on MEMS technology, vacuum sealing is being exploited to further increase the sensitivity of the thin-film MJTC design. This packaging technology is currently under development at Sandia in support of a number of MEMS programs. For the purpose of this work, a 40 pin leadless chip carrier (LCC) ceramic package has been selected for vacuum assembly. The package has several features that are beneficial, including, the lack of magnetic material in the I/O pins (many packages have Kovar leads), ceramic construction for hermetic sealing, adequate well size to accommodate the die, and common usage and available tooling (thereby lowering the overall per device cost).

The vacuum sealing process is illustrated in Figure 7. The non-evaporable getter (NEG) material acts as a vacuum pump to relieve outgassing pressure following sealing. The material is soldered to the package lid prior to assembly and requires activation to achieve pumping capability. During getter activation, the package and lid are separated with the lid and getter held at approximately 500 °C. The relative spacing sets the degassing temperature of the package body and die attach epoxy at approximately 240 °C. After getter activation, the lid/getter temperature is decreased to approximately 320 °C, and the package lowered onto the lid to effect a seal.
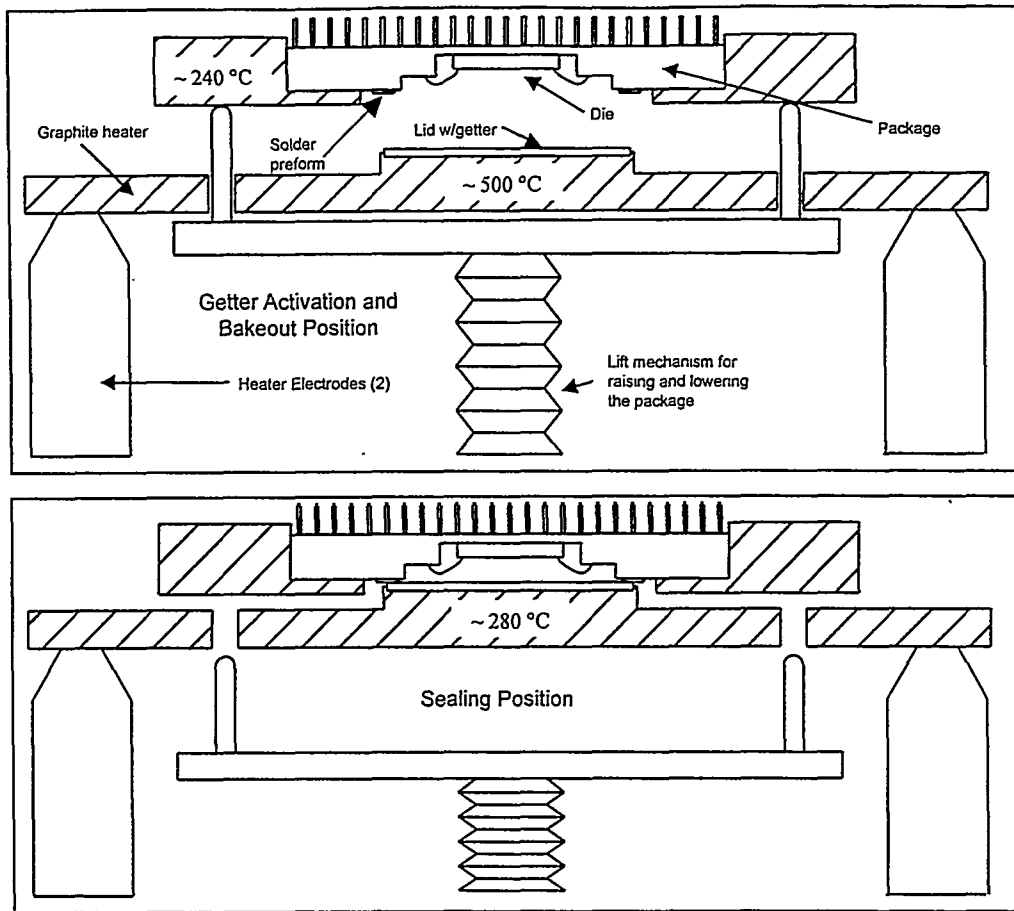
Figure 7. Vacuum sealing process. Positioned for getter activation and bakeout (top). Positioned for package lid sealing (bottom)
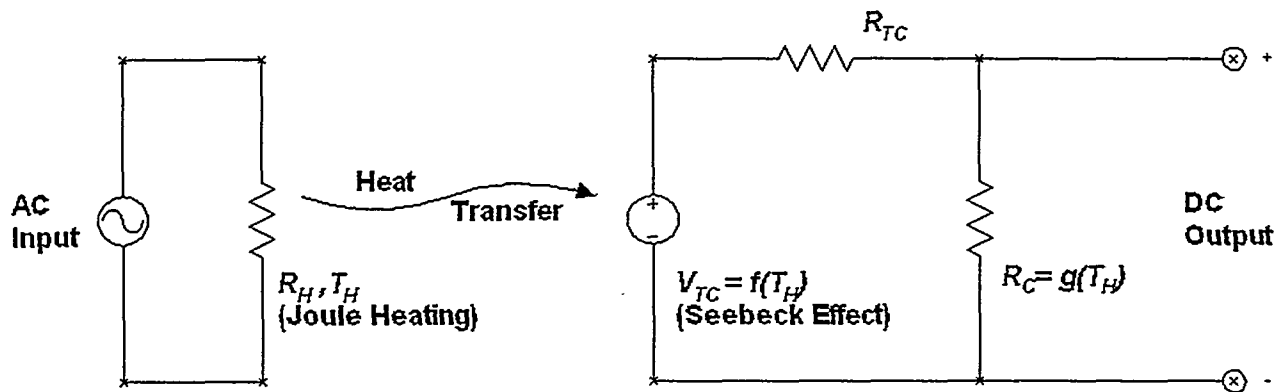

Figure 8. Simple model of the low-frequency compensation technique used by Laiz [14]. Through Joule heating, the input causes the temperature of the heater element to rise to some temperature, T_H. The thermal energy transferred to the thermocouple circuit (TC), is converted to a dc electrical signal through the Seebeck effect. This thermocouple circuit has some resistance R_{TC} that can be loaded by a compensation resistor, R_C. The temperature dependence of the compensation resistor allows some compensation of the non-linearities of the electrical-thermal-electrical conversion process.

Novel Thermal Converter Microstructures

Low-frequency Range Thermoelements

Previous attempts to limit the influence of the low-frequency error have been based on increasing the thermal time constant, compensation utilizing the temperature dependence of the thermal conductivity, or combinations of both techniques. Recently, Laiz, *et. al.*, have implemented a temperature dependent Ni resistor directly on the isolating membrane of a thin-film thermal converter. The resistor loads the output of the thermocouple circuit as shown in Figure 8. Provided that the resistance value is properly selected, the resistor acts to compensate the non-linearities in the heat transfer occurring under low-frequency ac excitation. The method is claimed to produce ac-dc differences below 1 part in 10^6 to 10 Hz and to provide usable performance to frequencies as low as 10 mHz [15].

Low-voltage Range Thermoelements

Three methods are available for producing MJTC elements capable of operating at full-scale ranges below 500 mV. The first method involves the use of low-resistance heater elements that produce significant heating under low-voltage excitation. This method suffers from thermal noise limitations. A second more practical technique, demonstrated at NIST [6], is to divide the input of a higher range thin-film element utilizing an on-chip resistor. The output of the resistor under ac excitation can be precisely compared with that under dc excitation by balancing the thermocouple output of the MJTC. This circuitry comprises a micro-potentiometer (µPot) useful in calibration of low-voltage ranges of ac calibrators and ac voltmeters. The third method is to employ a superconducting sensor [19]. Voltages as small as 10 mV have been measured directly with a prototype cryogenic thermal converter; however, the complexity of the measurement process makes the present realization unsuitable for anything other than a primary standard.

Current Converters and High-current Thermoelements

Recent work by Sandia and NIST has focused on the development of thermal current capable of handling currents of several Amperes. Several concepts are under investigation. If successful, high-current modules operating at tens of Amperes may be a practical and more accurate method of measuring ac currents than techniques employing standard ac shunts. Prior work at NIST has shown that modules of parallel combinations of thermal converters can be used in extending the achievable maximum operating current beyond that of single thermoelements [7].

A simple extension of the thin-film concept, employing low-resistance Au heaters, is shown in Figure 9. Resistances as low as 10 mΩ are possible in thin-film technology. Lower resistances may be achieved through electroplating or foil etching techniques.
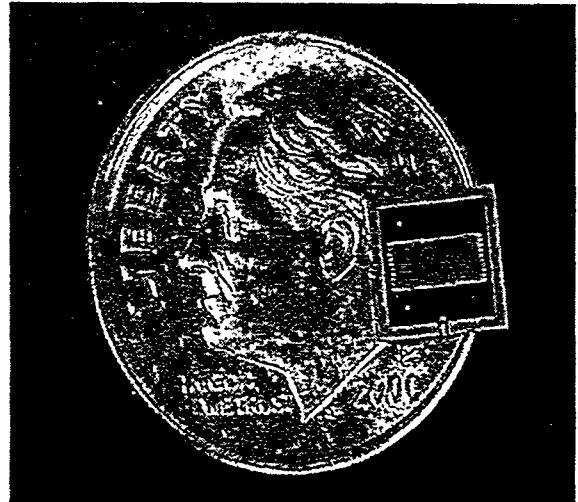

Figure 9. Photograph of a high-current thin-film MJTC.

Applications

Several applications are described here. Others are possible, including the use of the device as a primary or reference standard for ac voltage or current. In general, the thin-film MJTC is suitable for nearly any application in which a SJTC is currently being utilized.

Primary and Secondary ac Metrology

Direct replacement of an SJTC element is possible for various configurations of commercial thermal converters. Existing measurement systems for ac-dc comparison employing high impedance dc voltmeters are fully capable of performing calibrations with the new thermoelements. Older calibration systems, employing galvanometer circuitry, do not measure the thermal converter output in open-circuit mode, and may not be suitable. Thin-film MJTC elements have a higher thermopile output resistance due to the large number of thermocouple pairs and the smaller cross sectional area of the thermocouple wires. In galvanometer systems, a current flow may result prior to balancing that produces an unacceptable self-heating of the thermopile. Although some of these systems may still be in use, the low cost of high impedance dc voltmeters, the ability to automate measurements using these voltmeters, and the higher sensitivity of the MJTC elements are advantages that, in most cases, will outweigh the cost of reconfiguring an older system.

Instrumentation

The ability to mass fabricate uniform high performance thin-film MJTCs provides a significant advantage in economy of scale over the SJTC and the conventional MJTC. In addition, the volume of the die is only 7.2 mm^3. The combination of greatly reduced size and cost over previous methods of ac measurement allows consideration of instrumentation options not available with conventional thermal converters. A single die, for example, could be incorporated in a high-end ac voltmeter as an ac reference for internal calibration or as the core element of the measurement circuitry.

MJTC as a Pressure Transducer

The high sensitivity of the thin-film MJTC thermopile to changes in heater temperature allow detection of changes in convective cooling due to differences in ambient pressure. Kinard [17] has shown that changes in pressure in the range 0.0001 to 10 kPa are detectable. Although the present configuration may not be highly suitable as a pressure standard, the small size and low cost may provide opportunity for its use in determining the quality of vacuum sealing of advanced MEMS packages. Experimentation is underway to determine the effectiveness of this approach. One scenario would have every 10th or 100th package (in a MEMS sealing process) assembled with a thin-film MJTC. Over a period of time, the MJTC sensitivity could be measured to produce statistics about the assembly and sealing process and its ability to maintain vacuum level.

Conclusions

Thin-film MJTCs are now in use at NMIs as primary standards of ac-dc difference. Additional development will likely lead to government and commercial application of this newly developing technology.

Novel means of achieving targeted performance to specific ac measurement problems are being addressed. Several specific application areas, including low-frequency ac measurements, high-current measurements, and intermediate vacuum measurements are being addressed. Significant progress has been made in these areas. Other application areas are ripe for further development.

Commercial application will primarily depend on cost and performance. In particular, the long-term reliability of the technology needs to be established prior to commercial acceptance. Experiences gained in the short-term coupled with a more detailed understanding of the technology that is gained through experimentation and numerical modeling will aid in establishing parameters for accelerated reliability testing.

Acknowledgements

References

[1] A. Barkov, "Optimization of Monitoring and Diagnostics Methods for Rotating Machines Using Vibration and Noise Measurements", Proceedings of the 4th International Congress on Sound and Vibration, St. Petersburg, Russia, Volume 3, pp. 1573-1578 (June 1996).

[2] J. J. Judy, "Biomedical Applications of MEMS," Proceedings of the Measurement Science Conference, Anaheim, CA (January 2000).

[3] J. Smith, "Micromachined Sensor and Actuator Research at Sandia's Microelectronics Development Laboratory," Invited Presentation, Proceedings of the Sensors Expo Anaheim '96, pp. 119-123 (April 1996).

[4] Villarrubia, J., Dixson, R., Jones, S., Lowney, J. R., Postek, M., Allen, R. A., and Cresswell, M. W., Intercomparison of SEM, AFM, and Electrical Linewidths, Proceedings of the SPIE, The International Society for Optical Engineering, Integrated Circuit Metrology, Inspection, and Process Control XIII, Vol. 3677, pp. 587-598 (1998).

[5] M. Klonz and T. Weimann, "Increasing the Time-Constant of a Thin Film Multijunction Thermal Converter for Low Frequency Application," IEEE Trans. Instrum. Meas., IM-40, (1991)

[6] J. R. Kinard, D. -X. Huang, and D. B. Novotny, "Integrated Thin-Film Micropotentiometers," CPEM '94 Digest, pp. 380-381 (1994).

[7] J. R. Kinard, T. E. Lipe, C. B. Childers, D. B. Novotny, D. -X. Huang, "High-Current Thin-Film Multijunction Thermal Converters and Multiconverter Modules," IEEE Trans. Instrum. Meas., IM-46, pp. 391-394 (1997).

[8] E. S. Williams and J. R. Kinard, "A Dual-Channel Automated Comparator for ac-dc Difference Measuremnets," IEEE Trans. Instrum. Meas., IM-34, pp. 290-294 (1985). Reprinted in NIST Special Publication 250-27, J. R. Kinard, J. R. Hastings, T. E. Lipe, and C. B. Childers, pp. 186-190 (1989).

[9] F. J. Wilkins, T. A. Deacon, and R. S. Becker, "Multijunction thermal converter – An accurate d.c./a.c./transfer instrument," Proc. IEE, 112, p. 794 (1965).

[10] M. Klonz, "Ac-dc transfer difference of the PTB multijunction thermal converter in the frequency range from 10 Hz to 100 kHz," IEEE Trans. Instrum. Meas., IM-36, p. 320 (1987).

[11] M. Klonz and T. Weimann, "Accurate Thin Film Multijunction Thermal Converter on a Silicon Chip," IEEE Trans. Instrum. Meas., IM-38, pp. 335-337 (1989).

[12] J. R. Kinard, D. -X. Huang, and D. B. Novotny, "Hybrid Construction of Multijunction Thermal Converters," CPEM '90 Digest, pp. 62-63, 1990.

[13] D. Jaeggi, Thermal Converters by CMOS Technology, Ph.D. Thesis, Physical Electronics Laboratory, ETH Zurich (1996).

[14] M. Gaitan, J. R. Kinard, and D. -X. Huang, "Multijunction Thermal Converters by Commercial CMOS Fabrication," Proceedings of the Instrumentation and Measurement Technology Conferences, pp. 243-244, Irvine, CA (August 1993).

[15] H. M. Laiz, Low Frequency Behaviour of Thin-Film Multijunction Thermal Converters, Ph.D. Thesis, Braunschweig Technical University, March 1999.

[16] T. F. Wunsch, J. R. Kinard, R. P. Manginell, O. M. Solomon, and T. E. Lipe, "A New Fabrication Process for Planar Thin-Film Mulitjunction Thermal Converters, CPEM '00 Digest, 2000.

[17] J. R. Kinard, D. B. Novotny, T. E. Lipe, and D. -X. Huang, "Development of Thin Film Multijunction Thermal Converters at NIST," IEEE Trans. Instrum. Meas., IM-46, pp. 347-351 (1997).

[18] F. Laermer and A. Schlip, Patent No. 5501893: Method of Anisotropically Etching Silicon, Robert Bosch GmbH, March 26, 1996.

[19] T. E. Lipe, J. R. Kinard, and C. D. Reintsema, "Improvements in the NIST Cryogenic Thermal Transfer Standard," in CPEM '00 Digest, Conference on Precision Electromagnetic Measurements 2000, Sydney, NSW, Australia, May 14-19, 2000.