Performance of Multilayer Thin-Film Multijunction Thermal Converters

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***Abstract*—New multilayer, thin-film multijunction thermal converters (MJTC's) suitable as high performance ac-dc transfer standards have been fabricated and studied at NIST. This paper describes their thermal and physical features and the materials chosen to improve performance. Performance data are given over a wide range of frequencies and conditions.**

I. Introduction

MULTIJUNCTION thermal converters (MJTC's) are used in very high-accuracy ac-dc difference metrology because they have very small ac-dc differences, good square-law characteristic, mean-square response, and high output emfs. MJTC's have been traditionally fabricated from wire heater resistors and thermocouples. For more than a decade there has been considerable interest in the use of micro-machining of silicon and photo-lithography on thin-films to produce high-performance thermal sensors as well as many other types of sensors. A recommendation to design and fabricate new, thin-film MJTC's at the National Institute of Standards and Technology was made in [1], and several versions of these devices have subsequently been made [2]–[4].

II. Multijunction Thermal Converter Designs

New multi-layer, thin-film multijunction thermal converters for the measurement of ac voltage and current have been designed, fabricated, and tested at NIST. Hundreds of these new chips have been made. The basic elements of the devices are a thin-film heater supported on a thin dielectric membrane, a silicon frame surrounding the structure, and thin-film thermocouples positioned with hot junctions near the heater and cold junctions over the silicon. The heater and thermocouples are sputter deposited and photolithographically patterned. The various thin-film MJTC's are as follows:

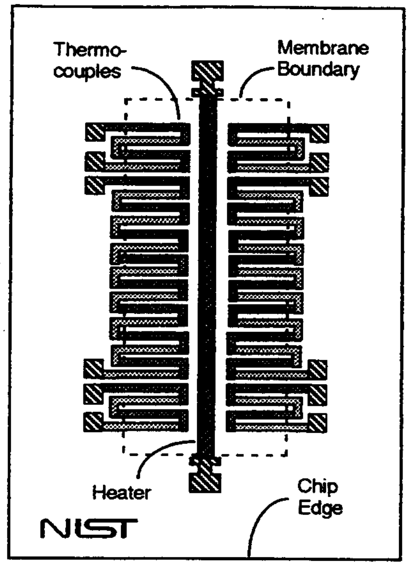

Fig. 1. Schematic diagram of thin-film multijunction thermal converter with coaxial heater geometry. The membrane size is approximately 2 × 4 mm.

1) The first design, Fig. 1, is a coaxial converter with a linear heater which can be assembled in a coaxial geometry. This design contains 64 measuring thermocouples and eight additional thermocouples for testing and guard functions.
2) The second design, Fig. 2, has a bifilar heater similar to the thin-film MJTC's constructed at the Physikalisch Technische Bundesanstalt [3]. The geometries of the NIST coaxial and bifilar converters were chosen so that the same thermocouple structures could be used for both. The output emfs for these two MJTC's are around 100 mV and their frequency ranges are from audio frequency to a few megahertz.
3) The third converter, Fig. 3, is a high-frequency MJTC, also of the coaxial type. It contains fewer thermocouples than the above coaxial MJTC and the couples are located directly over the heater instead of adjacent to it. It is intended for measurements up to several tens of megahertz or higher. The output emf in the final versions is about 10 mV.

A. Geometric Design

Several geometric features have been incorporated in these new MJTC's to improve their performance. Examples in-

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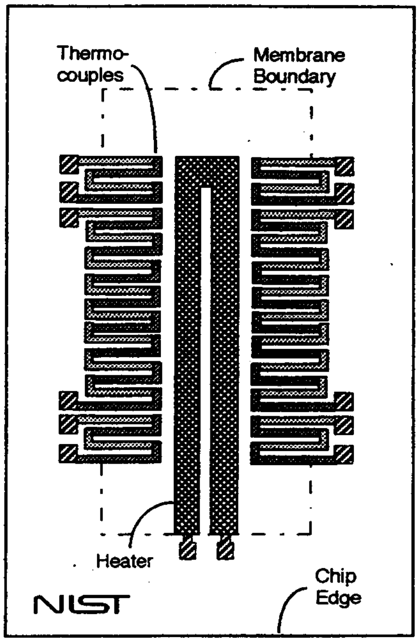

Fig. 2. Schematic diagram of thin-film multijunction thermal converter with bifilar heater geometry. The membrane size is approximately 2 × 4 mm.

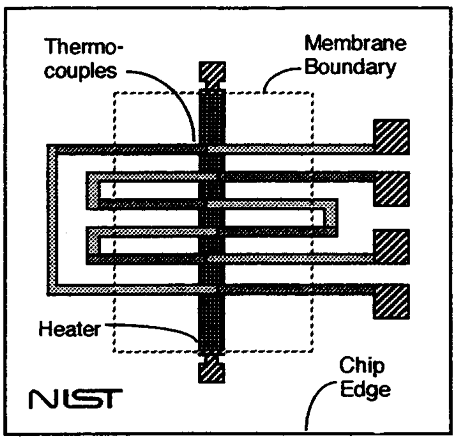

Fig. 3. Schematic diagram of high fre quency thin-film multijunction thermal converter with thermocouples located over the heater. The membrane size is approximately 2 × 3 mm.

clude very small contact pads to improve current converter performance and guard or ground return paths to reduce electromagnetic coupling between the heater and thermocouples and extend the frequency range beyond 1 MHz. The materials and geometric features have been chosen to reduce Thomson and Peltier effects in the heaters and their contacts in order to achieve very small dc reversal errors and ac-dc differences of a few ppm at audio frequencies.

Photolithographic fabrication used for thin-film MJTC's produces more accurate dimensions of the heater and thermocouples than is attainable with wire MJTC's built by hand [5]. Because of the planar design, and by optimization of the distance between the thermocouples and the edge of the membrane, the temperature distribution along the heater and hot junctions in the film MJTC can be made more uniform than for wire MJTC's. The infrared image, shown in Fig. 4,

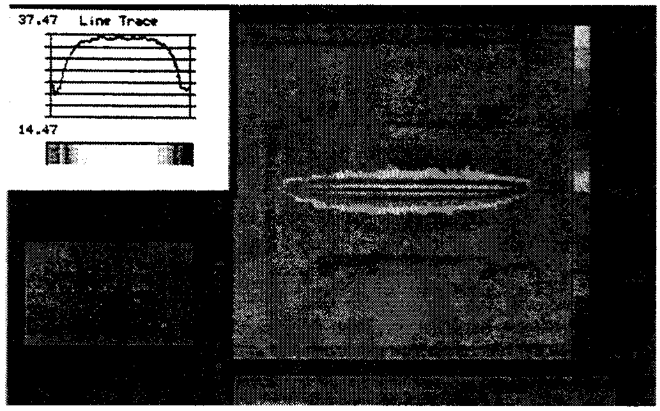

Fig. 4. Infrared image of coaxial thin-film MJTC shown in upper right with horizontal scan line located along the heater axis. Temperature profile along scan line shown in upper left.

indicates that the temperature distribution is quite uniform. The contribution to ac-dc difference from the Thomson effect is reduced by this constant temperature along the heater as well as by the use of a quaternary alloy for the heater. The temperature coefficient of resistance of the heater is minimized by choosing this sputtering alloy and by thermal conditioning; the typical value is about 11 ppm/°C.

B. Thermal Design for Small AC-DC Differences

To provide mechanical stability and good thermal efficiency, a thin, multilayer membrane has been used to support the heater structure and the thermocouple hot junctions. Low overall stress and low dielectric loss have been achieved in the membrane by the fabrication of balanced layers of SiO_2 and Si_3N_4. The heater was placed on the membrane, without silicon underneath, to reduce the dielectric loss and therefore reduce the ac-dc difference and voltage coefficient. Low ac-dc difference, small dc reversal, and high thermal efficiency have been achieved by the thermal design, physical arrangement, and careful selection of materials for the heater and thermocouples.

The thermal conductivity of silicon is higher than that of many metals, so the bulk silicon under the window is etched away to maximize the thermal efficiency, and the silicon frame forms a good heat sink for the thermocouple cold junctions. The silicon frame is mounted directly on a thermally conductive, aluminum oxide ceramic substrate to provide an even more effective heat sink, and the active elements are connected by wire bonds to solder tabs. To reduce errors due to the Peltier effect, the contact pads for wire-bonding leads are placed over the silicon frame. These thermal and physical design characteristics also contribute to very small dc reversal errors.

C. Test Features

Various test features have been included in the prototype MJTC's. Different thermocouple geometries and guard couples have been included to investigate the heater temperature distribution and to study ways to optimize other characteristics. Various metals have also been investigated for use as the heater and thermocouples. Test features are provided to determine useful dimensions and materials for the membranes.

One of the major goals of the project has been to develop methods and designs that would be suitable for fabrication using routine processes found in the thin-film and thick-film industries and that would result in commercial products. Membranes in earlier thin-film test structures were too thin and were easily broken. To overcome this problem, multilayer membranes with very low overall stress were developed. Low stress is important to achieve a mechanically reliable membrane. The stresses of each dielectric and metal film were measured, and the final stress of the composite membrane balanced to have a lower value. The final stress of the multilayer membrane has been measured to be only a few tens of MPa.

III. Sensitivity and Reliability of Structure

Very thin membranes and metals for heaters and thermocouples have been chosen to achieve very low thermal conductivity, high thermal efficiency, and, therefore, very high overall sensitivity. Sensitivities of more than 10 mV per mW for these converters have been obtained. Such sensitivities permit lower heater temperatures which reduce ac-dc difference further and improve tolerance to overload heater currents. Generally, the temperature rise in the heater is less than 30°C.

To investigate the structural reliability of the thin-film MJTC's and the variations in thermalconductivities of the materials, converter overall efficiency was measured from room temperature down to −262°C. Not only did the MJTC not fail, but its overall efficiency increased with falling temperature by about 42% at −196°C compared with room temperature. The increase in output occurs, even though the Seebeck coefficient is falling, because the thermal resistances of the membrane and metals are increasing proportionally faster, thus producing a net gain in efficiency. Another device withstood the thermal stress of going from room temperature to liquid helium temperature and back without failure. The new converters routinely undergo commercial cleaning, mounting, wire bonding, and sealing, thus demonstrating that they are not too delicate to withstand these necessary operations. Many of the new converters have undergone repeated measurement-related thermal cycling for more than three years and can withstand 100% overload for several minutes.

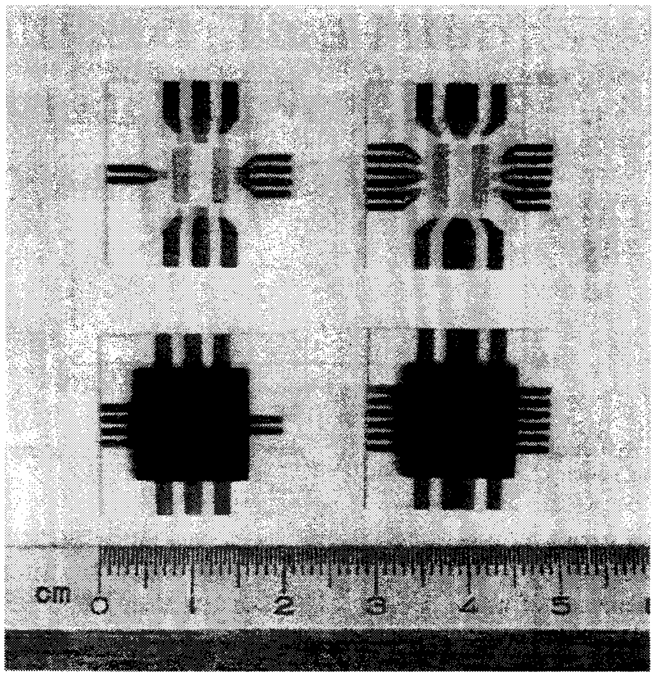

Fig. 5. Two versions of the ceramic pack ages shown with and without lids.

TABLE I
Ac-dc Differences of Thin-Film MJTCs at Atmospheric Pressure and Room Temperature (23°C)

Frequency (kHz)	MJTC B-2 as Voltage Converter	MJTC B-2 as Current Converter	MJTC B-3 as Voltage Converter
0.1	44	144	62
0.3	3	9	1
1	-0.6	-0.6	-1
20	5	5	1
50	8	23	3
100	11	47	7
200	12	77	7
500	25	145	21
1000	45	273	47
DC Reversal	4	0.3	3

IV. Packages

Custom packages have been designed and fabricated to provide long-term stability, small distributed capacitance and inductance, and minimum skin effect through the use of all nonmagnetic materials. These packages preserve the inherent ac-dc differences of the thin-film MJTC's as voltage converters of only a few tens of ppm. The packages contain aluminum oxide substrates patterned with thick-film conductors. Fig. 5 shows the NIST package with a ceramic lid. A vacuum package, also of nonmagnetic materials, is under development.

V. Measured Performance

AC-DC difference measurements indicate good performance; however, some characteristics, e.g. capacitance-to-ground from the heater structure, may be open to further improvement. Representative results include ac-dc differences of a few ppm or less from 1 to 100 kHz and several tens of ppm at 1 MHz for a bifilar-heater MJTC used as a voltage converter. The dc reversal errors are only a few ppm or less, as expected. Representative values of the measured ac-dc differences, at atmospheric pressure and room temperature, for two bifilar, thin-film MJTC's are given in Table I. Sub-