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1 A and 120 mA THIN-FILM MULTIJUNCTION THERMAL CONVERTERS

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Abstract

We report on the development of thin-film multijunction thermal converters for the measurement of ac current. The materials and designs chosen for these devices have been optimized to provide high accuracy over a wide range of input levels and frequencies. The design details of the MJTCs will be presented, and their performance described.

Introduction

Thin-film multijunction thermal converters (MJTCs) exhibit low ac-dc transfer differences in the frequency range from 10 Hz to 1 MHz. As thermal current converters they may be used as standards for current up to 10 mA [1]. For higher currents parallel shunts may be used, but they present problems from both stray capacitance to ground and thermal drifts, and exhibit greater errors from skin effect at 20 kHz and above. The goal of the present work is to realize the ac-dc current scale up to 10 A, while avoiding the use of shunts. This realization is based on 120 mA and 1 A MJTCs, which in parallel combinations can be used to build a scale up to 10 A [2]. The main advantages of using MJTCs instead of shunts are:

1) MJTCs can have a lower voltage drop across the heater of the converter (0.1 V at rated input current). This limits the heat produced and reduces temperature-dependent errors.
2) MJTCs can have a higher impedance to a parallel shunt and a higher impedance to ground.
3) MJTCs can have a reduced skin effect at high frequencies, reducing the high-frequency error.

Design of the 1 A MJTC

At the beginning of the design process, trade-offs were made among the low voltage desired across the heater, the dissipated power, the characteristics of the heater alloy and the size of the chip. For the desired voltage drop across the heater of 0.1 V at 1 A, this results in 100 mW of power in the heater, or about 5 to 10 times the power dissipated in common MJTCs. Dissipating this power in a 0.1 Ω heater required both a new chip design and the selection of an appropriate low resistivity alloy.

Heater Alloy. Low resistivity metals and alloys exhibit high temperature coefficients of resistance. This temperature coefficient plays a crucial role on the temperature coefficient of the sensitivity. The sensitivity S can be calculated as,

$$S = \frac{U_o}{P_J} = \frac{\alpha_{A/B}\Delta T}{P_{Jo}(1+\alpha T)} = \frac{\alpha_{A/B}}{G_T}(1-\alpha T) \qquad (1)$$

where U_o is the output voltage, P_J the joule heat in the heater, $\alpha_{A/B}$ the Seebeck coefficient of the thermocouples, ΔT the temperature rise of the hot junctions, G_T the total thermal conductance of the device, P_{Jo} the joule heat of the heater resistance at ambient temperature (T) and α the temperature coefficient of the heater resistance. The temperature coefficient of the sensitivity β_S is

$$\beta_S = \frac{1}{S}\frac{\partial S}{\partial T} \approx \frac{1}{\alpha_{A/B}}\frac{\partial \alpha_{A/B}}{\partial T} - \frac{1}{G_T}\frac{\partial G_T}{\partial T} - \alpha \qquad (2)$$

For a thermal converter that will be used only as a current converter the temperature coefficient of the resistivity can be used to compensate for the difference in the temperature coefficient of the Seebeck coefficient and the total thermal conductance. Previously fabricated MJTCs with gold heaters show a β_S of $+3.2\times10^{-3}$ K^{-1} compared to -6.0×10^{-4} K^{-1} for those with Evanohm† heaters. This difference agrees with the temperature coefficient of resistivity for gold. To get an optimum β_S for the 0.1 Ω heater we selected a copper-gold alloy (80%Cu-20%Au), that has a resistivity of 5.3×10^{-8} Ωm at 273 K and α of 1.1×10^{-3} K^{-1}. One ampere devices made with this alloy show a β_S of -2.5×10^{-4} K^{-1}. This improves the stability of the output voltage and the low frequency transfer difference [3].

Thermal Design. The low current chip [1] dissipates 10 mW in the heater. To achieve approximately the same temperature rise in the 1 A heater with 100 mW dissipated, the chip geometry was dramatically changed. Figure 1 shows the 1 A design. The dimensions of the membrane are 5 mm x 5 mm, the obelisk (a silicon structure left beneath the heater to increase the thermal time constant) is 4 mm x 4 mm and the heater 5 mm x 3.8 mm x 1 µm. Twenty thermocouples are placed at each side of the heater.

Figure 2 shows the simulation of the temperature distribution on the membrane. Most of the heat is conducted though the heater itself due to the high thermal conductance arising from the high conductivity and large cross-section.

†The use of commercial names does not imply endorsement from NIST, nor that the product is the best available for the application.

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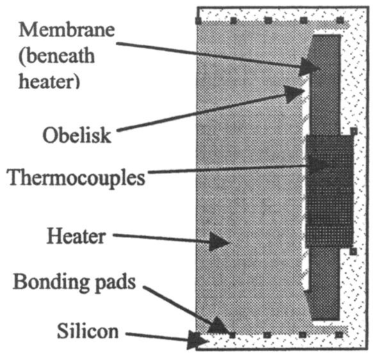

Figure 1. Layout of one-half of the 1 A chip. The various structures are noted.

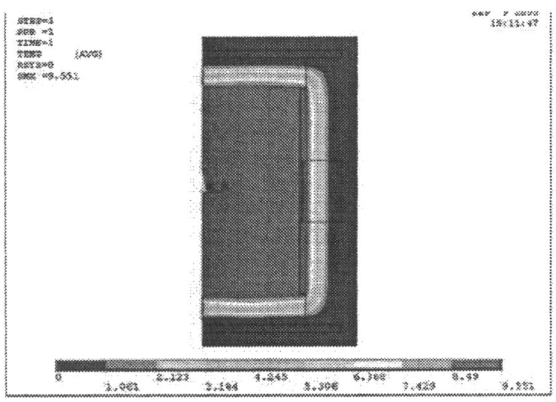

Figure 2. Temperature distribution on half of the chip. The scale at the bottom indicates temperature above ambient in K.

The temperature gradient across the heater is quite small. Thermal simulations have shown that the temperature difference along the edge of the heater at the obelisk is less than 10 mK.

The Peltier effect was included in the simulation as a heat source at the connection between the pads (Au) and the heater (CuAu). Results show no influence from the Peltier heat in the temperature at the heater on the obelisk. Simulations of the Thomson heat indicate that it has a negligible effect on the temperature of the heater. As the influence on thermoelectric effects is so low, the number of thermocouples will be doubled in the next fabrication run in order to increase the output emf.

Measurement Results

Thermal converters were fabricated in accord with the design described above. They show, typically, time constants of 0.5 s to 0.7 s. The measured ac-dc differences for a representative converter with an input current of 1 A is presented in Table 1.

Table 1. Measured ac-dc transfer difference in μA/A with 1 A applied.

10 Hz	100 Hz	1 kHz	10 kHz	20 kHz	100 kHz
-3.3 ± 20	-4.9 ± 12	+0.4 ± 12	+4.0 ± 12	-2.5 ± 8	+4.6 ± 26

120 mA Converter Design

The same chip layout used for the 1 A MJTC was used for the 120 mA design. Several performance issues were noted using this design. The 1 A chip was intended to dissipate 100 mW of power. The 120 mA chip required a voltage drop of 833 mV to dissipate the same power. This relatively high voltage increases the ac-dc difference produced by the leakage capacitance at high frequency. The design goal is to maintain a voltage drop in the heater of about 100 mV at 120 mA, requiring a heater resistance of 0.83 Ω. In this design, the input power will be 12 mW.

To realize the 120 mA thermal converter, we propose the use of the basic design of the previously reported 400 Ω chip [4], with three modifications:

1) The connection between the two arms of the thermocouples should be removed from the chip and the series connection made outside the chip package to reduce coupling into the heater circuit.
2) The thermocouples should be placed at a distance of 10 μm from the edge of the silicon obelisk, to reduce the capacitance.
3) The heater should be made of CuAu, and have the following dimensions: a thickness of 1 μm, a width of 220 μm, and a length of 3000 μm.

Simulations of this design indicate that, in air, the output voltage is 20 mV, with a temperature coefficient of 1×10^{-3} K^{-1}. The influences of Peltier and Thomson Effect were also calculated and were found to be negligible. These devices have been fabricated and are awaiting testing as this summary is submitted.

Conclusions

New 1 A and 120 mA thin-film MJTCs have been designed and fabricated. A finite element model that includes all non-linear parameters was used to calculate the influence of thermoelectric effects on the performance of the MJTCs and used to choose the appropriate material for the heater. Measurement on the 1 A MJTCs show that the new converters may be used to establish a new ac-dc current scale avoiding shunts up to 10 A.

References

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