Design and Fabrication of MJTCs on Quartz Substrates at NIST

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***Abstract*—Wet and dry etching is employed in the fabrication of new planar thin-film multijunction thermal converters (MJTCs) on quartz membranes and crystalline quartz chips at the National Institute of Standards and Technology (NIST). The use of crystalline quartz as a material for the membrane and chip improves the performance of the MJTC in the frequency range of 100 kHz–100 MHz. Simulations of the ac–dc voltage transfer difference for a heater resistance of 400 Ω in the frequency range of 1–100 MHz show a reduction in the ac–dc transfer difference of more than one order of magnitude, in comparison with the MJTCs fabricated on silicon chips. The devices that have been fabricated, although not optimized for 100 MHz, have been shown to have reasonable performance for their 20-V maximum input.**

***Index Terms*—Ac–dc difference, ac voltage, multijunction thermal converter (MJTC), quartz wafers, thermal voltage converter, voltage metrology.**

I. Introduction

THE STANDARD planar multijunction thermal converters (MJTCs) used as working standards at the National Institute of Standards and Technology (NIST) are fabricated on a silicon chip with a thin-film dielectric membrane [1]–[3]. Coaxial (straight) and bifilar (∩ shaped) resistive heaters and an array of thermocouples that sense small differences in temperature between dc and ac excitations are sputtered on the thin-film membrane. The hot junctions of the thermocouples are located along the heater, and the cold junctions are located on the silicon frame, which acts as a heat sink.

A new generation of planar MJTCs on quartz membranes and quartz crystal substrates has been fabricated and evaluated at the Physikalisch-Technische Bundesanstalt, Braunschweig, Germany [4]. The use of crystalline quartz as a material for the membrane and the chip improves the frequency response of the MJTC in the frequency range of 100 kHz–100 MHz and leads to reductions in uncertainties. Crystalline quartz has a smaller relative permittivity than silicon ($\varepsilon_r \approx 4.5$, as opposed to 11.8). This reduces the capacitive coupling at the bonding pads of the heater and improves the high-frequency response [5]. In this paper, we report the development of thin-film MJTCs on crystalline quartz substrates at NIST.

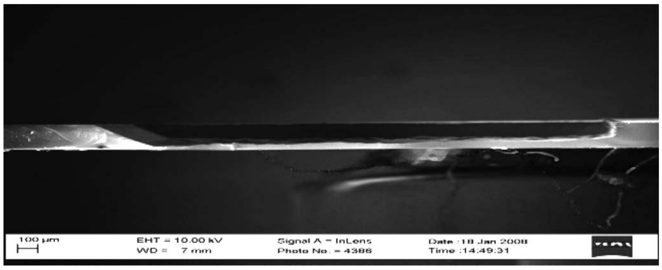

Fig. 1. Scanning-electron-microscope cross section of a quartz membrane.

II. Fabrication

AT-cut monocrystalline quartz wafers with a diameter of 76 mm and a thickness of 250 μm were chosen as the substrate material. The mask material for the initial wet etching consists of a 100-nm Au layer sputtered over a 30-nm Cr layer. The window with the membrane is anisotropically etched from the backside into the quartz crystal chip. The quartz etchant is a mixture of HF and NH_4F, at a constant temperature of 60 °C in a Teflon jar. The wet etching is stopped after several hours when a membrane thickness of less than 20 μm is measured. To further reduce the thickness of the membrane, plasma etching can then be used. The gas used for plasma etching is CHF_3 with some O_2, at a radio-frequency power of 200 W. For this etching, the etching speed is about 20 nm/min. Fig. 1 shows the quartz membrane obtained on the AT-cut quartz wafer after etching for 10 h.

The heater is of NiCrAlCu alloy ($w_{\mathrm{Cr}} = 0.2$, $w_{\mathrm{Al}} = 0.025$, and $w_{\mathrm{Cu}} = 0.025$) for thermal voltage converters. This alloy composition results in heaters with a small temperature coefficient of resistance of about 10 $(\mu\Omega/\Omega)/^{\circ}\mathrm{C}$. All the fabricated devices use thermocouples of CuNi alloy $(w_{\mathrm{Ni}} = 0.45)$ and NiCr alloy $(w_{\mathrm{Cr}} = 0.1)$. The Seebeck coefficient for such a thermocouple pair is approximately 65 μV/K. Both the coaxial and bifilar heater structures and the array of 100 thermocouples were fabricated using a standard photolithographic process. Wet chemical etching was used for the heater, and photoresist liftoff was used for the thermocouples and pads. The liftoff technique is widely used for evaporated metals and results in a reduction in processing steps.

Gold bonding pads are placed at the input–output ends of the heater and at the ends of the thermocouple array. The chip is bonded to an Al_2O_3 carrier using conductive epoxy, and the

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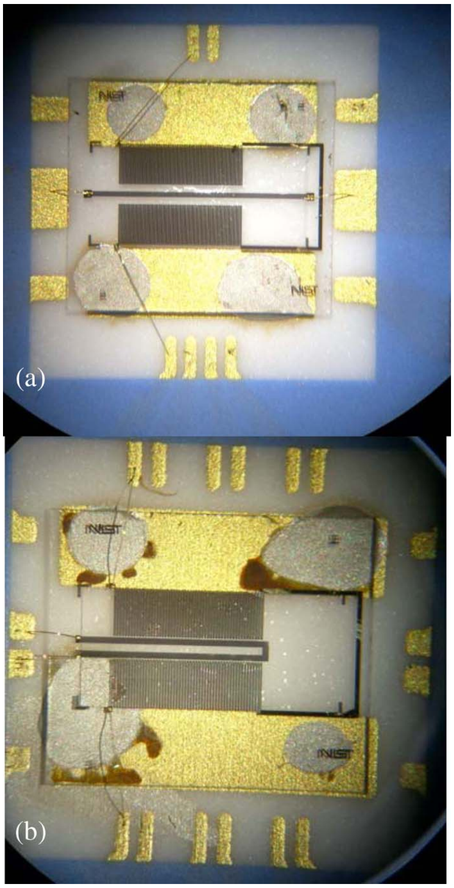

Fig. 2. MJTCs with (a) coaxial and (b) bifilar heaters. The die sizes are 8 mm × 6 mm.

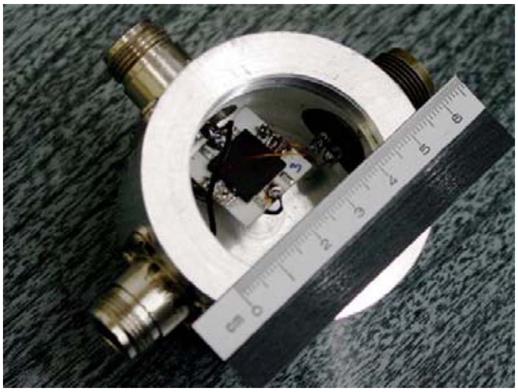

Fig. 3. (Top) Housing with integrated Tee for the calculable quartz MJTC. (Left) Connector for the standard thermal voltage converter (TVC).

connections between the chip and carrier are wire bonded using thin Au wires [2], [3]. Fig. 2(a) and (b) shows the coaxial and bifilar MJTCs fabricated on quartz crystal chips.

III. SIMULATION OF QUARTZ-MJTC

To minimize the contribution to the ac–dc voltage transfer difference due to the inductance, skin effect in the leads from the carrier to the input connectors of the housing, and voltage standing wave in the input connectors, the quartz MJTC is mounted on a housing using an integrated Tee structure (see Fig. 3).

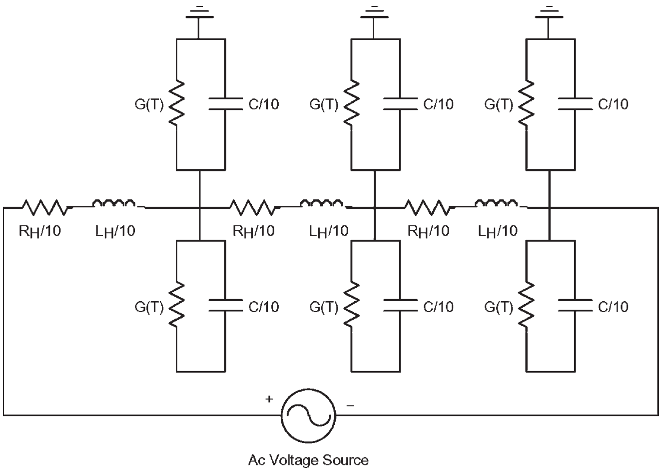

Fig. 4. Basic element of the transmission line modeling the heater and thermocouples.

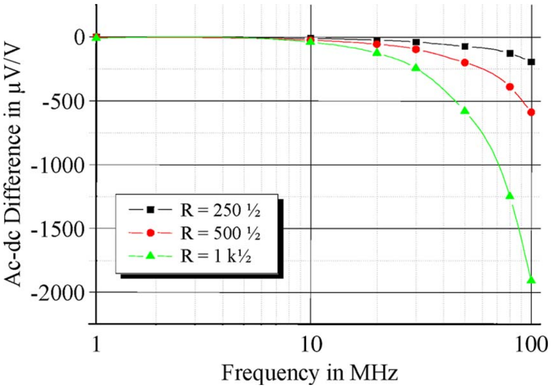

Fig. 5. Calculated values of the ac–dc difference for different heater resistances.

The model for the calculation of the ac–dc voltage transfer difference of the quartz MJTC using the integrated Tee includes the ac–dc differences arising from the following [6]:

1) change in the real part of the heater impedance with frequency;
2) skin effect and inductance in the Au bonding wires.

To calculate the contribution of the ac–dc differences arising from the change in the real part of the heater impedance with frequency, the coaxial heater is modeled as a lossy transmission line of ten elements. The model includes lumped elements, i.e., heater resistance R_H, capacitances between the heater and thermocouples C, heater inductance L_H, and conductances G. Fig. 4 shows a section of the transmission line.

The ac–dc differences were calculated using

$$\delta_u = \frac{|\underline{Z}|}{\sqrt{R_H \mathrm{Re}\{\underline{Z}\}}} - 1 \qquad (1)$$

where $\mathrm{Re}\{\underline{Z}\}$ and $|\underline{Z}|$ denote the real part and the modulus of the complex input impedance $\underline{Z}$ of the PMJTC, respectively.

The model was calculated for different heater resistances, and the results are shown in Fig. 5. Not surprisingly, the ac–dc differences are calculated to be small for low-resistance heaters.

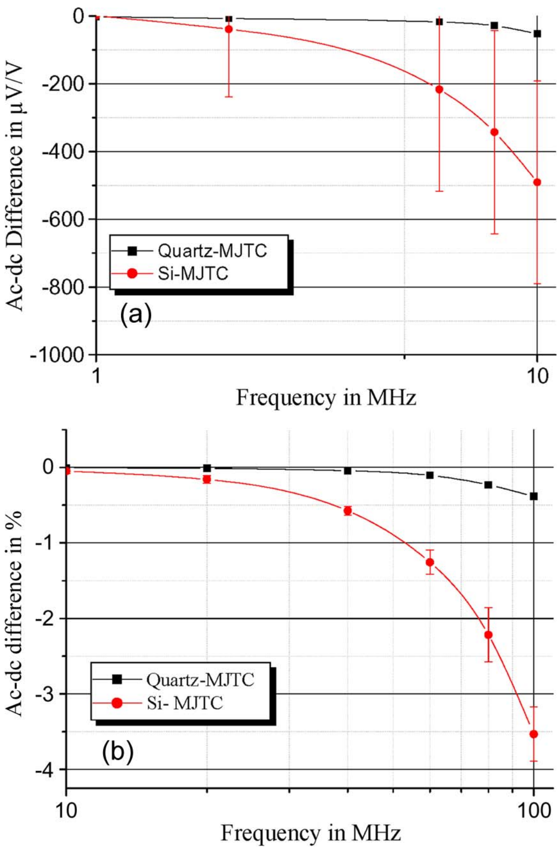

Fig. 6. Measured high-frequency ac–dc differences of Si MJTC and calculated values of the quartz MJTC with a heater resistance of 400 Ω for (a) frequencies of up to 10 MHz and (b) frequencies between 10 and 100 MHz. Note the scale differences.

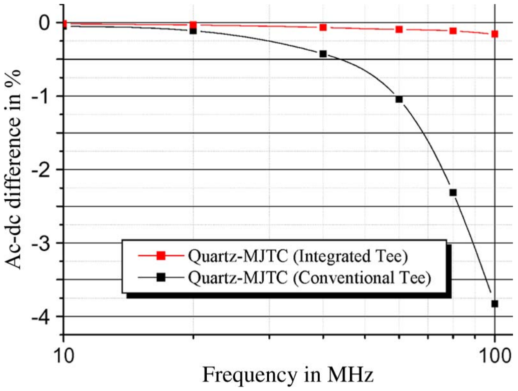

Fig. 7. Comparison between the calculations with the integrated Tee and the conventional Tee for a thermal converter with a heater resistance of $R_H = 400\,\Omega$.

Fig. 6(a) and (b) shows a comparison between the measured ac–dc transfer differences of a silicon-based MJTC and the calculated values of the quartz MJTC for a coaxial heater resistance of 400 Ω and frequencies ranging from 1 to 100 MHz. This comparison clearly shows the advantages of crystalline quartz as a material for the membrane and the chip.

The design of the voltage input structure plays a significant role in the ac–dc difference of the device at frequencies exceeding about 1 MHz. In general, long input structures increase the ac–dc difference [7]–[9]. As a test to optimize the input structure, MJTCs were assembled using an integrated Tee structure with short legs and compared with MJTCs housed in enclosures with type-N connectors, requiring an external Tee. Fig. 7 shows a comparison between the calculations of the ac–dc transfer difference with the integrated Tee and that with the conventional Tee for a thermal converter with a heater resistance of $R_H = 400\ \Omega$.

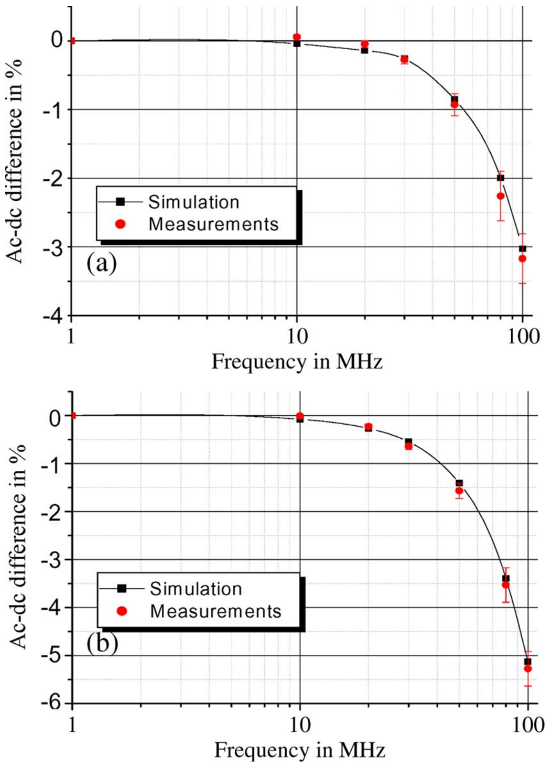

Fig. 8. Measurements and simulations of the ac–dc voltage transfer differences of the quartz MJTCs with (a) coaxial and (b) bifilar heaters.

IV. HIGH-FREQUENCY AC–DC DIFFERENCES

Fig. 8(a) and (b) shows a comparison between the measured ac–dc transfer differences and the calculated values of the quartz MJTC for bifilar and coaxial heaters with resistances of 4 and 3.5 kΩ, respectively, and for frequencies ranging from 1 to 100 MHz. This comparison shows that the uncertainty bars overlap the simulation at all points and that the measurements fit the simulation quite well.

V. PRESENT ACTIVITIES

To reduce the ac–dc differences of the quartz MJTCs at higher frequencies, a new set of converters with smaller heater resistances is being fabricated. The thickness of the NiCrAlCu heaters of these MJTCs is about 125 nm, resulting in a resistance of about 550 Ω. Thicker thermocouple depositions are also being used to reduce the thermocouple resistances from about 40 kΩ to less than 20 kΩ. These devices will be characterized as they become available.

VI. CONCLUSION

A new generation of MJTCs on crystal quartz chips and membranes are being fabricated at NIST. The results of the simulation show that the use of crystalline quartz allows significant reductions in the standard uncertainties and the ac–dc differences of the MJTCs in the frequency range of 100 kHz–100 MHz. The MJTCs successfully fabricated so far are not optimized for high-frequency applications at low voltages; however, given that the maximum applied voltage is 20 V, the ac–dc differences at 100 MHz are quite reasonable.

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Mr. Kinard is the recipient of the U.S. Department of Commerce Gold Medal, two Silver Medals, and the R&D 100 Award.