Advanced Sensors for Accurate, Broadband AC Voltage Metrology

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Abstract. We report on advances in ac voltage metrology made possible by a new generation of Multijunction Thermal Converters (MJTCs). Although intended for use primarily in high-frequency (1 MHz to 100 MHz) metrology, their exceptional low-frequency qualities, combined with a large dynamic range, makes these MJTCs excellent devices for the frequency range 10 Hz to 100 MHz at voltages from 1 V to 20 V, depending on the design. We anticipate that these devices will form the future basis for ac voltage metrology at the National Institute of Standards and Technology (NIST).

1. Introduction
The most accurate method of ac voltage measurement at frequencies from 10 Hz to 100 MHz is by comparing the heating effects of the unknown ac signal to that of a known dc reference using thermal voltage converters [1]-[4], a technique known as ac-dc transfer. These devices use one or more thermocouples arrayed along a heater structure to sense the heat generated by reference and unknown signals; comparing the output emfs allows us to determine the ac voltage in terms of the dc reference. Many National Metrology Institutes (NMIs) worldwide use planar multijunction thermal converters (MJTCs), fabricated on silicon substrates, as standards for ac-dc difference measurements [5,6]. Unfortunately, silicon has a relatively high dielectric permittivity (\(\varepsilon_r \approx 11.8\)) resulting in increased capacitive coupling between the heater and thermocouples through the thin silicon nitride membrane and silicon obelisk at high frequencies [7]. The large ac-dc differences (2 % or more at 100 MHz) resulting from this coupling largely restricts the use of silicon-based MJTCs to frequencies of less than 1 MHz. To obtain standards with improved performance at higher frequencies, NIST and other NMIs have developed MJTCs based on both crystalline quartz and fused silica substrates [8]-[10]. Both materials have significantly smaller relative permittivities than silicon (\(\varepsilon_r \approx 3.8\)) that reduces the high-frequency errors; however, crystalline quartz often exhibits microfractures that make the material too fragile for reliable fabrication, and so we have concentrated our work on electronics grade fused silica.

This paper describes the design and fabrication of fused silica MJTCs, their present use as ac voltage standards in the NIST AC-DC Difference Project, and their future use as both standards and as possible integrated parts of larger-scale sensor arrays.

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2. Design of High-Frequency MJTCs

2.1 Membrane

All planar MJTCs share several design features, shown in figure 1. The heater structure is fabricated on a thin membrane, with the hot junctions of the thermocouples in close proximity to the heater. The first silicon-based MJTCs had membranes composed of layers of Si$_3$N$_4$ and SiO$_2$ to compensate the compressive and tensile stresses of each material. The layers were deposited on a silicon wafer using chemical vapor deposition, and then the silicon beneath the membrane removed using KOH etching. After much experimentation, this method reliably resulted in membranes a few micrometers thick. Later generations of silicon-based MJTCs featured pre-deposited, low-stress nitride layers forming the membranes, with the silicon removal accomplished using XeF$_2$ etching. This method is advantageous when including obelisks beneath the heater to increase the thermal mass and time constant, and reduce low-frequency errors.

The first high-frequency MJTCs fabricated on crystalline quartz used the quartz itself for the membrane; the backside etching was done using a 60:40 mixture of HF and NH$_4$F at 60 ºC to achieve a membrane thickness of about 20 µm. To reduce etching time, the quartz wafers were only 250 µm thick. After etching, the wafers were often so fragile that they broke before any post-etching processing could be done. The few devices that were completely fabricated showed good performance, and served as testbeds for new fabrication techniques.

To increase the yield of the MJTCs, we investigated thicker (500 µm-thick) fused silica wafers back-etched using physical means to form membranes about 15 µm – 25 µm thick. This process is known as micropowder blasting and employs a fine spray of microscopic beads to physically remove material. Control of such a process can be quite good, and we experienced only a few isolated membrane failures due to the backside etching. The resulting membrane is stiff enough to support the heater, but still provide good thermal efficiency.

2.2 Heater

The heater presents possibly the greatest design challenge. The ac-dc difference of a thermal converter depends on both frequency-dependent effects (skin effect and transmission line effects) and on thermoelectric dc effects (Thomson and Joule heating) and any heater design that results in small ac-dc differences will necessitate a compromise between the two. The thermoelectric effects can be minimized using quality resistance material for the heater. We have chosen an alloy of Ni$_{75}$Cr$_{20}$Al$_{2.5}$Cu$_{2.5}$, a well-understood material with a temperature coefficient of resistance of about 10 µΩ/°C. This material has been used for over a century in the construction of high-precision resistance standards. Although readily sputtered, this material is prone to crazing at deposition thicknesses of more than a few hundred nanometers. We therefore used two heater designs and two heater widths to finely control the resistance. One design features a straight (coaxial) heater, while the other is shaped like a \( \bigcap \) (bifilar), and both designs are made in 140-µm and 200-µm widths.

Of the frequency-dependent errors, skin effect results in a positive, generally linear error that is inversely dependent on heater resistance. Capacitive errors include distributed coupling between the heater and thermocouples through the membrane, and coupling between the heater bonding pads, and generally make a negative, square-law contribution. Simulations of our design indicate that the frequency-dependent effects should cancel at a heater resistance of about 800 Ω.
2.3. Thermocouples

Our thermocouples are Cu$_{55}$Ni$_{45}$ and Ni$_{90}$Cu$_{10}$, with a Seebeck coefficient for the pair of about 65 $\mu$V/K. In early devices, problems were encountered with the adhesion of the metals at the thermocouple interfaces. This was caused by material building up at the side of the feature, leading to the “bat ears” shown in figure 2. This effect, combined with inconsistent liftoff during fabrication, led to poor yields.

![“Bat ear”](image)

**Figure 2.** Electron microscope image of thermocouple interface, showing delamination from the material buildup during the metallization (left), and a profilometer image showing a “bat ear” (right). This feature is roughly 500 nm high, compared to the metallization of about 400 nm.

The thermocouple deposition was improved using several techniques. We discovered that the “bat ears” were the result of sputtering the thermocouple metals at a 60º incidence to the vertical. By siting the wafer on a wedge and keeping the platen stationary (instead of rotating), we were able to sputter the metals at normal incidence and prevent the buildup of material at the edges of the metal. The Ni$_{90}$Cu$_{10}$ tracks are sputtered as a continuous track with the Cu$_{55}$Ni$_{45}$ legs deposited atop the underlying layer, a structure commonly known as plated thermocouples. The thermocouple junctions are made at the interface between the two metals. Fabricating the thermocouples in this fashion eliminates possible open circuits if the two metals do not form good contacts at the interfaces, and significantly improves the yield. The thermocouple legs are each about 380 nm thick, about 1015 $\mu$m in length, and 50 $\mu$m wide. With 104 thermocouples in total, these design parameters result in an output resistance of 12 k$\Omega$ to 15 k$\Omega$. While it is desirable to reduce the output resistance to prevent common-mode voltage issues when using certain voltmeters, thicker metallization often results in cracking of the metal films.

In the original MJTC designs, the thermocouple banks were rectangular in shape, with the hot junctions equally distant from the heater at both the high and low potential ends, resulting in more leakage current from the heater to the thermocouples at the high potential end. To reduce this effect, more recent MJTCs have wedge-shaped thermocouple banks, designed to present an equipotential gap between the thermocouple banks and heater. Gold contact pads 220 nm thick are deposited at the ends of the heater, and thermocouples, and over the bridge between thermocouple banks to reduce the output resistance.

Figure 3 shows the various designs fabricated and used at NIST.

2.4. Mounting

The MJTCs are mounted on ADS-96R alumina substrates. To test the effect of capacitive coupling from the heater through the silica to the alumina, we tested chips with and without the backside gold etch mask, and fixed to the alumina substrate using both conductive epoxy and nonconductive adhesive. After wire bonding the chips, a protective lid is glued to the substrate.
The reference plane for ac–dc transfer measurements is usually defined at the center of a tee structure between a reference standard MJTC and a unit under test (UUT). At frequencies exceeding about 1 MHz the length of transmission line between the plane of reference and the MJTC can make a significant contribution to the overall ac–dc difference of the device. The best results were obtained by mounting the MJTCs in a cylindrical enclosure with a tee structure integrated into the front face of the enclosure, minimizing the electrical length between reference plane and MJTC [11].

3. Testing and Results
As the MJTCs were completed, they were mounted as described in Section 2, and measured against the NIST standards for ac–dc and RF–dc difference from 10 Hz to 100 MHz. The applied voltage depended on the resistance of the heater; devices with resistances ranging from 200 Ω to 3.5 kΩ were measured. A summary of the results at frequencies from 1 MHz to 100 MHz follows. The ac–dc differences at lower frequencies are negligible compared to the uncertainties.

3.1. Effect of heater design
To test the effect of heater design on the ac–dc difference, two MJTCs with nearly identical heater resistances were measured against the NIST standards. Both devices have rectangular thermocouple banks, wide heater design, and intact backside gold layer, and are mounted in the same enclosure; the only difference is in the type of heater. The results of the measurements are shown in figure 4a. The positive trend of the coaxial heater can be explained by assuming that a fraction of the heater current couples from the heater to the substrate through the silica membrane and gold etch mask, effectively bypassing the heater. Since this is an ac effect, the thermocouples sense less heat with ac voltage applied, leading by definition to a positive ac–dc difference. The bifilar design would be less prone to this effect because the fields are constrained to a smaller area.

3.2. Effect of backside gold layer
In the early chips, the backside gold layer was left intact during fabrication to facilitate the processing. This layer contributes to the ac–dc difference by creating a ground path for leakage currents from the heater. To determine the magnitude of this effect, two coaxial MJTCs from the same wafer and identical in all respects except that one had the gold layer stripped prior to measurement, were compared to NIST standards. As shown in figure 4b, the gold layer creates a noticeable effect on the performance.
3.3. Effect of thermocouple design

The original MJTC designs featured rectangular thermocouples. In order to reduce the leakage current through the membrane at the high potential end of the heater, a wedge-shaped thermocouple design was developed. This design maintains nearly equal potential along the length of the heater, and was applied to both coaxial and bifilar designs. Figure 5a shows the effect of the thermocouple design on the ac-de difference for both types of heaters. As expected, the effect of the thermocouple design is more pronounced when used with coaxial heaters.

3.4. Voltage and frequency coefficients

The large number of thermocouples, compared to a traditional single junction thermal converter (SJTC), allows the MJTCs to be used effectively with input voltages ranging from less than 20 % to 100 % of rated voltage, as compared to 50 % to 100 % common with SJTCs. In addition, the construction of MJTCs reduced the risk of damage due to over-ranging of the converter. A key demand for the use of MJTCs in a calibration environment is that the variation in ac-de difference with changing input voltage levels be small. Similarly, these devices are designed to be broadband, with minimal variation in ac-de difference between 10 Hz and 100 MHz. Figure 5b shows both voltage and frequency coefficients for a typical bifilar MJTC with wedge thermocouples.

| Table 1. Uncertainties for ac-de differences reported in Figures 4 and 5 (k = 2) |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                                  | 1 MHz           | 10 MHz          | 20 MHz          | 30 MHz          | 50 MHz          | 80 MHz          | 100 MHz         |
|----------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Uncertainty                      | 0.0018 %        | 0.015 %         | 0.025 %         | 0.035 %         | 0.080 %         | 0.150 %         | 0.180 %         |
4. Revised Uncertainties
The large dynamic range of the new MJTCs, and their relatively flat frequency response from 10 Hz to 1 MHz will allow us to populate the uncertainty parameter space using significantly fewer scaling steps than are presently used. Preliminary calculations indicate that the uncertainties over the parameter space from 0.5 V through 10 V or possibly 20 V may be reduced by about half through the use of MJTCs. At frequencies above 1 MHz, the small dependence on ac-dc difference with increasing frequencies will allow us to significantly reduce the uncertainties at these points as well. Coupled with the development of an ac standard based on quantum effects [12], MJTCs will enable NIST to meet customers’ future requirements for very accurate, broadband ac voltage measurements.

5. Other Applications
MJTCs of similar design have been used in applications such as low-flow gas measurements [13], and pressure sensors. Owing to their small size and fabrication techniques, we envision these devices as components of integrated sensor packages where ac voltages must be accurately known or supplied. For example, a sensor package may require a well-known voltage for measurement of a particular quantity; either an MJTC could accurately sense an external voltage supplied to the package, or an MJTC with integrated micropotentiometer [14] could be used to supply a regulated voltage. In either case, the accuracy of the sensor package would benefit from the integration of an MJTC.

6. Conclusions
MJTCs fabricated on fused silica substrates have ac-dc differences significantly smaller than traditional thermal converters at frequencies up to 100 MHz from 1 V to 10 V. Combined with the small input voltage dependence (negligible at frequencies below 1 MHz) and a large dynamic range, these devices are presently replacing the older designs for ac-dc difference metrology at NIST. It is anticipated that the use of these standards will lead to significant reductions in uncertainty for the NIST calibration services for ac-dc difference and ac voltage. It is also envisioned that similar devices will be integrated into larger sensors or networks to monitor and/or supply accurate ac voltages.

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