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50 OHM MULTIJUNCTION THERMAL CONVERTERS FOR AC VOLTAGE MEASUREMENTS UP TO 100 MHZ

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Abstract – Multijunction thermal converters (MJTCs) are in use as standards for ac voltage measurements at frequencies up to 100 MHz. At the National Institute of Standards and Technology (NIST), MJTCs based on glassy substrates with 50 Ω input impedances are being developed to align more closely with common practice at high frequencies. Preliminary results indicate that 50 Ω MJTCs with excellent properties can be successfully fabricated.

Keywords: RF-DC Difference, thermal converters, ac voltage, measurement

1. INTRODUCTION

AC voltage is most accurately measured by thermal transfer techniques using thermal converters [1]. The basic thermal converter consists of a heater structure fabricated from a quality resistance alloy, and one or more thermocouples in close thermal proximity to the heater but isolated electrically. The thermal converter is used to compare the heat generated by an unknown ac signal to that of a reference dc voltage; in this way the rms value of the unknown ac voltage is determined.

Single junction thermal converters (SJTCs) have been used for more than fifty years for the measurement of ac voltages at frequencies from less than 10 Hz to more than 100 MHz [2]-[3] at voltages from about 0.5 V to 2 V, or, in series with a resistor, up to 1000 V. Thermoelectric errors limit the achievable uncertainties of SJTCs to a few parts in 10^6 at frequencies between 30 Hz and 30 kHz.

Multijunction thermal converters (MJTCs) use multiple thermocouples in series to sense the heat generated in a lengthy heater wire [4]. Because the output voltage is greater in MJTCs than SJTCs, the MJTCs can be used at lower temperatures, resulting in smaller thermoelectric errors and achievable uncertainties at mid-audio frequencies of less than 1 μV/V. Unfortunately, MJTCs based on long wire heaters are not useful at frequencies greater than 10 kHz owing to the transmission line errors of the long heater. In addition, they are very difficult to make, and generally not available to metrology laboratories [5].

Since the early 1990s, MJTCs fabricated on both silicon and glassy materials such as quartz and fused silica have largely replaced wire-based MJTCs as primary and working standards for ac voltage metrology at National Metrology Institutes (NMIs), including the U.S. National Institute of Standards and Technology (NIST). MJTCs fabricated on silicon substrates [6]-[8] show excellent performance at frequencies up to 1 MHz; however, the relatively poor dielectric properties of silicon at higher frequencies can lead to significant errors because of leakage currents through the silicon structure. Several NMIs have investigated alternative materials having lower dielectric loss at higher frequencies than silicon, including crystalline quartz [9]-[10], polyimide [11], and fused silica [12]. At NIST, we presently use MJTCs fabricated on fused silica substrates as standards for RF-DC transfer difference at frequencies from 10 Hz to 100 MHz, at signal levels of 0.5 V to 30 V.

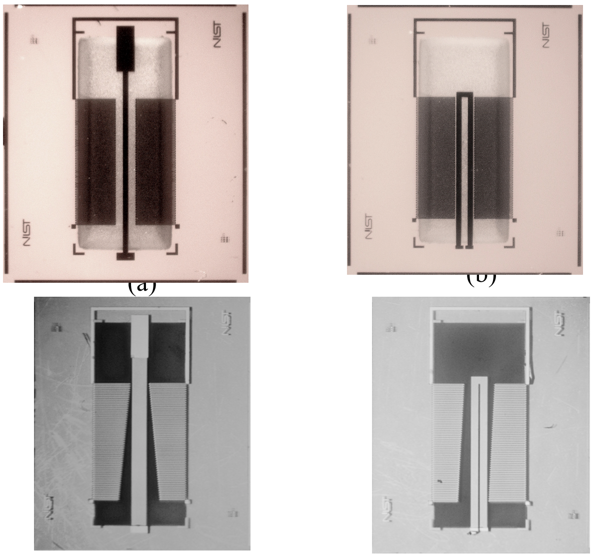
In addition to errors caused by leakage currents in the thin dielectric membrane, large RF-DC differences can be caused by transmission line effects in the input structure, including the wire bonds, and skin effect in the heater [13]. The transmission line effects generally scale with the square of the frequency and exhibit a negative trend, indicating that less ac voltage is required to match the power of the dc reference voltage. Skin effect errors, on the other hand, trend positive as the square root of the frequency and depend on the heater resistance. One can in principle make a device in which these errors cancel, and for the fused silica MJTCs fabricated at NIST, a heater resistance of about 850 Ω, in conjunction with the mounting arrangement used, yields RF-DC differences of less than (0.2 %± 0.1 %) at a few volts up to 100 MHz. Although these devices are excellent standards and are in everyday use as reference standards for RF-DC difference measurements at NIST, for a variety of reasons most standards for measurements at frequencies above 1 MHz have 50 Ω input impedances, and we are presently fabricating prototype MJTCs on fused silica substrates with on-chip resistors that yield a 50 Ω input resistance.

MJTCs of similar design have been used in applications such as low-flow gas measurements [14], sensors for material deposition in sputter deposition [15], and as 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 the measurement of a particular quantity; either an MJTC could accurately sense an external voltage supplied to the package, or an MJTC with integrated micropotentiometer [16] 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.

2. FUSED SILICA MJTCS

2.1. Traditional design

Two basic types of MJTCs have been fabricated at NIST. One (the coaxial type) employs a heater track laid straight across the chip with bonding pads at either end of the heater, as shown in Fig. 1a. The second (bifilar) design features a ∩ - shaped heater with bonding pads set close together on the chip, as shown in Fig. 1b. Several variations of the basic design have been fabricated, including MJTCs with wider heaters and wedge-shaped heaters to produce an equipotential region between the heater and thermocouple banks (Figs. 1c and 1d). The various designs allow us to vary parameters such as heater resistance in order to optimize the performance of these devices.



(c) (d)

Fig. 1. Photograph of coaxial MJTC (a) and a bifilar MJTC (b), with uniform thermocouple banks flanking the heater. The lighter area at the center of the chip is a thin silica membrane. MJTCs with wide heaters, wedge thermocouples and a backside gold layer are in (c) and (d). In these cases the dark areas are the membranes.

The heaters are deposited on a membrane (25 ± 10) μm thick formed by microbead-blasting the backside of the fused silica wafer. The membrane presents a very small thermal mass, assumed to be in equilibrium, in the region about the heater so that nearly all the heat generated in the heater is sensed by the thermocouples. The thickness of the membrane was chosen so that the thermal efficiency of the device is great enough to allow measurements at multiple input levels, while providing a thermal time constant long enough to allow measurements down to 10 Hz. A well-understood resistance metal, $Ni_{75}Cr_{20}Al_{2.5}Cu_{2.5}$, (160 ± 15) nm thick is used for the heaters. Using the designs shown in Fig. 1, this metallization thickness results in about a 2:1 ratio in resistance between the bifilar and coaxial designs for the narrow (140 μm) heaters and about 3.5:1 for the wider (200 μm) heaters. The 104 thermocouples are $Ni_{90}Cr_{10}$ – $Cu_{55}Ni_{45}$ pairs with a Seebeck coefficient of about 65 μV/K, and a resistance of about 12 kΩ. A gold etch mask is used for the backside etching, and can be either removed or left intact to provide grounding to the package if desired. The individual chips, 7 mm x 6 mm, are glued down to an alumina substrate and gold wire bonds used to connect the heater and thermocouple banks to solder tabs on the substrate. The completed chips are capped with a ceramic lid, and the assembly mounted in an enclosure with the appropriate input and output connectors.

2.2. 50 Ohm design

Thermal converters used for radio-frequency metrology are often designed with 50 Ω input impedances to reduce reflections in the circuit. Although the existing high-resistance devices show exceptionally good performance at frequencies up to 100 MHz [17], there exists a need for similar MJTCs with 50 Ω input impedances for similar and higher frequencies.

The most straightforward approach to designing a 50 Ω heater structure is to simply deposit sufficient material to create the required resistance for a given heater geometry. For the coaxial geometry, calculations show that a deposition of approximately 2500 nm of $Ni_{75}Cr_{20}Al_{2.5}Cu_{2.5}$ is required to achieve 50 Ω. However, both the heat generated by the deposition and the stress induced in the thin films are observed to increase rapidly with deposition time and metal thickness, so that at metallizations much less than the depth required the surface of the metal blisters and crazes and disrupts the fabrication process.

The lowest resistance we have achieved by increasing the film thickness using the coaxial design is about 85 Ω. With thick heaters, the skin effect errors become significant and can be more than 5 % at 100 MHz [10]. Clearly a different strategy for realizing 50 Ω heater structures is needed, and the difficulties present in depositing thick films suggests that modifications to the heater geometry are required. One alternative is to use a resistor in parallel with the heater to achieve the desired resistance.

To test the design concept prior to actual fabrication, two 100-Ω surface mount resistors with good high-frequency characteristics were placed in parallel between the heater solder tabs of a bifilar MJTC, and the resulting device measured at 0.5 V from 1 MHz to 100 MHz. The RF-DC differences are shown in Fig. 2, compared to the performance of a traditional, commercially-available single junction thermal converter. As Fig. 2 indicates, the preliminary measurements using a parallel resistor were quite encouraging, and provided essential information for the next steps [18].

Of the two designs, the bifilar heaters are better suited to the inclusion of on-chip resistor because of the proximity of the heater tracks. We originally assumed that gold would be suitable for the resistor, as a 140 μm x 140 μm x 48 nm layer will yield a resistance of about 53 Ω, which, combined in parallel with our 850 Ω bifilar design, yields approximately 50 Ω. However, the gold contact pads on our MJTCs are some 200 nm thick, so the parallel resistor and contact pads cannot be deposited at the same time. Since any additional processing steps increase the risk of failure, we decided to investigate making the parallel resistors from the heater material. Adjusting the geometry of the parallel resistor made it possible to create a heater with the required resistance in one deposition.

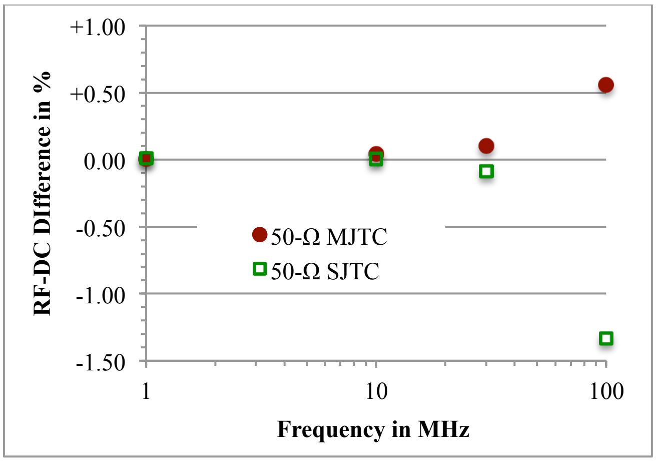
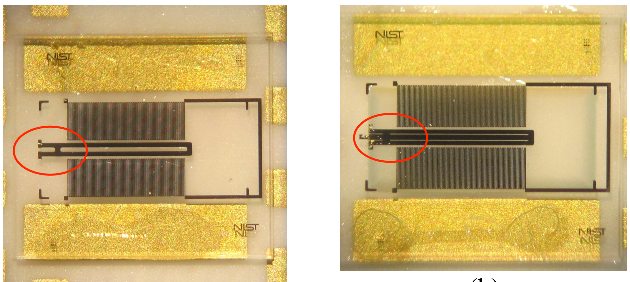


Fig. 2. Performance of a prototype 50 Ω MJTC with surface-mount resistors compared to a traditional SJTC. Error bars are omitted for clarity. Uncertainties are presented in Table 1.

Because it is difficult to add a parallel resistor to the coaxial design, this heater design was rearranged to create a three-legged "trifilar" heater. Such designs had been fabricated and measured very early in the NIST MJTC program, with good results at 1 MHz [19]. In this case, the parallel resistors were added across the legs of the heaters. Photographs of both designs are shown in Fig. 3.



(a) (b)

Fig. 3. Photographs of bifilar (a) and trifilar (b) MJTCs with parallel resistors (circled).

Measurements of the input resistance created by the new heater geometries indicate that the pre-fabrication estimates are borne out in the completed chips. Resistances for the bifilar chips ranged from about 46 Ω to 66 Ω with several chips measured at (50 ± 0.8) Ω. Similarly, resistances for the trifilar design ranged from about 41 Ω to 60 Ω, again with several chips measuring (50 ± 0.6) Ω.

One chip of each design was mounted in an enclosure with a Type N input connector. The mounting contributed only a few tenths of an ohm to the overall input resistance, which was considered acceptable.

3. RESULTS

The completed MJTCs with on-chip resistors were measured against the NIST standards for RF-DC difference in the 10 Hz to 100 MHz frequency range. The performance of a bifilar MJTC compared to a commercial MJTC and the bifilar MJTC with surface mount resistors shown in Fig. 2 is presented in Fig. 4, and an example of the trifilar design in Fig. 5. The RF-DC differences of the MJTCs with the integrated resistor compares quite favourably with those of the prototype MJTC, and are only about 1/3 the magnitude of a commercially-available SJTC.

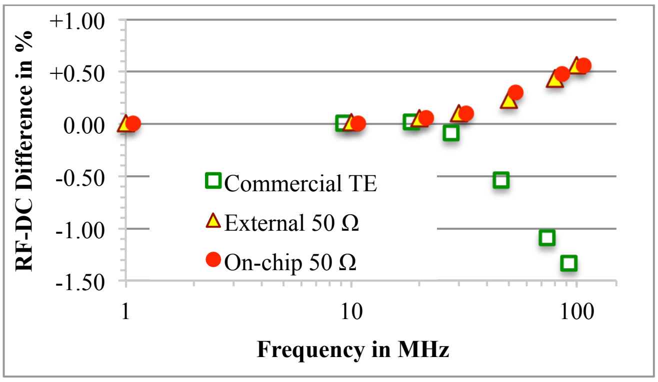


Fig. 4. Performance of a 50 Ω bifilar MJTC with on-chip resistor compared to a commercial SJTC and the prototype 50 Ω MJTC shown in Fig. 2. Error bars are omitted for clarity. Uncertainties are presented in Table 1.

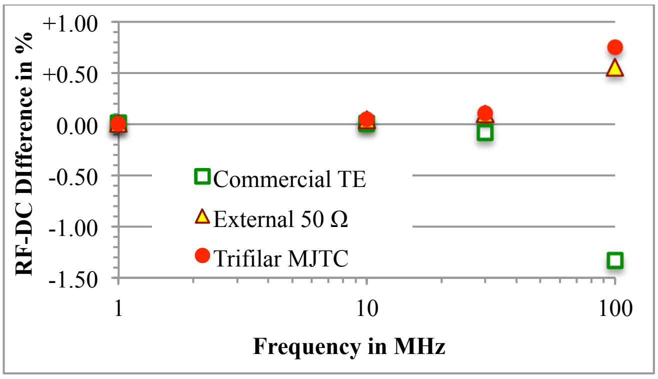


Fig. 5. Performance of a 50 Ω trifilar MJTC with on-chip resistor compared to a commercial SJTC and the prototype 50 Ω MJTC shown in Fig. 2. Error bars are omitted for clarity. Uncertainties are presented in Table 1

In addition to a small variation in RF-DC difference with frequency, the new 50 Ω MJTCs have a small voltage coefficient. This important property, made possible by the thermal efficiency imparted by the multiple thermocouples and isothermal membrane, allows a single MJTC to be used over a large range of input voltages. Fig. 6 presents measurements on a bifilar 50 Ω MJTC at several applied voltages. As can be seen in this graph, the variation in RF-DC difference with respect to input voltage is very small.

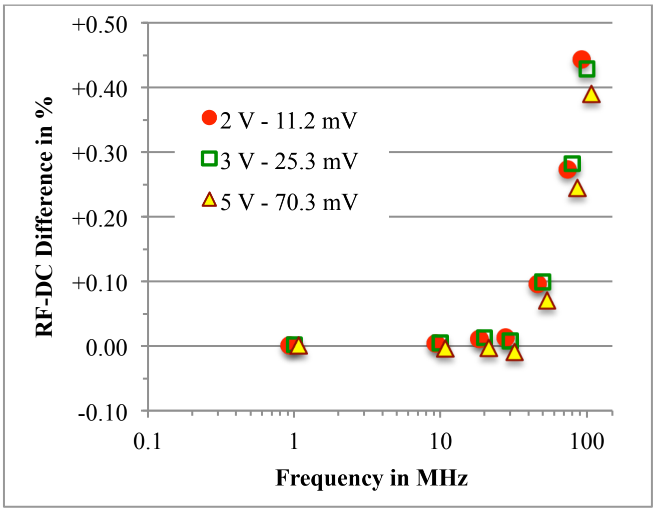


Fig. 6. Performance of bifilar 50 Ω MJTC at various voltages. The output emf is indicated for each voltage. Error bars are omitted for clarity. Uncertainties are given in Table 1.

Table 1. Expanded uncertainties (k = 2) for RF-DC differences in Figs. 2-6, in per cent (%) of applied voltage.

1 MHz	10 MHz	20 MHz	30 MHz	50 MHz	80 MHz	100 MHz
0.0018	0.015	0.025	0.035	0.080	0.150	0.180

4. DISCUSSION

Compared to commercially-available, traditional SJTCs, the new MJTCs typically have much smaller RF-DC differences at frequencies from 1 MHz to 100 MHz, as shown in Figs. 4 and 5. The small dependence of RF-DC difference on frequency makes the accurate calculation of the RF-DC difference at frequencies other than cardinal points much easier because the RF-DC difference is not changing rapidly. This small frequency dependence also allows calibration of these devices at fewer points.

In addition to the small RF-DC differences at higher frequencies, the voltage coefficient of RF-DC difference is also significant. Small voltage coefficients allow a single device to be used over a relatively broad range of input amplitudes. RF-DC differences of thermal converters are traditionally determined by range-to-range intercomparisons, wherein a higher-voltage device is compared at less than full-scale input to a reference device, and then used for calibration purposes at full scale. The variation of RF-DC difference with input voltage appears as a significant term in the uncertainty calculations. Small voltage coefficients, as shown in Fig. 6, allow this uncertainty term to be greatly reduced, resulting in smaller uncertainties for the MJTCs.

The low frequency performance of the 50 Ω MJTCs rivals that of the NIST silicon- and glass-based standards used in the calibration services. The performance of these MJTCs has allowed us to reduce the NIST uncertainties for RF-DC difference measurements by more than 50 % at some points, providing our customers with exceptional uncertainties [20].

Taken together with our other MJTCs, the new 50 Ω devices will allow us to maintain the lowest possible uncertainties in the NIST calibration service for AC-DC Difference and AC voltage metrology.

5. IMPROVEMENT IN DESIGN

Although the performance of these devices is already quite good, several improvements can be made. For example, the parallel resistor joining the heater legs of both designs was placed over the membrane, creating a warmer region at the bonding-pad end of the thermocouple banks. In addition to variations in temperature along the thermocouples, the additional heating of the bond pads and wire bonds is different when AC voltage is applied than when DC voltage is applied, resulting in an additional AC-DC Difference. The bonding pads for the heaters, especially in the trifilar design are placed too close to the membrane, creating additional temperature-related errors as described above.

To overcome these errors, the parallel resistor has been moved off the membrane and onto the bulk fused silica, and the bonding pads for the heater have been moved farther away. MJTCs of this design are presently being fabricated, and results will be reported as available.

Assuming that the new devices have the anticipated performance, we plan to make them available for purchase through the NIST Standard Reference Instrument program [21].

5. CONCLUSIONS

Thin-film multijunction thermal converters with 50 Ω input resistances have been fabricated on fused silica substrates as part of a research effort to improve AC voltage metrology in the 10 Hz to 100 MHz frequency range at 0.5 V to 3 V. The MJTCs designed and fabricated exhibit significantly reduced voltage and frequency coefficients compared to traditional devices. Using similar, high-resistance MJTCs has allowed us to sharply reduce uncertainties for AC-DC transfer difference in this frequency/voltage space, and we anticipate that the new chips will allow us to realize similar performance in a 50 Ω input device. Although optimized for AC voltage metrology, these devices can be used in a variety of applications ranging from pressure sensors to voltage monitoring in sensor arrays.

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