A RESISTIVE TYPE RMS-TO-DC THERMOELECTRIC CONVERTER

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Abstract: RMS-to-DC conversion is best realized through thermoelectric principles where the heating of an input resistance, proportional to the applied power (Joule effect), is measured with a temperature detecting element that is placed around or on the sides of the heating element. The converter being reported, referred to as a resistive thermo-converter, RTC, consists of a resistive temperature detecting element fabricated using MEMS principles from the active layer of an SOI-wafer, which serves as a platform for the heating Cu:Ni-thin film-resistor, fabricated on top of the silicon resistor. The heater and detecting elements are separated by a thin oxide layer of a few hundred angstroms. The detecting element (silicon resistor) acts as a spatial thermal-integrator, through which other thermoelectric effects (e.g., Thomson effect) are effectively discriminated. Preliminary prototypes have been fabricated and characterized successfully. The conversion characteristics of the RTCs have been evaluated against presently used MJTC standard converters, from 0.5 V to 2 V and from 20 Hz to 1 MHz. Results indicate that the RTC may provide a good alternative for the measurement of the RMS value of AC-signals with low uncertainties. These devices exhibit transfer are a few parts per million away from those representing the MJTC devices.

1. INTRODUCTION

One very important parameter in the measurement of AC electrical signals is their root-mean- square (RMS) value, for it represents their energy contents. AC-converters are fundamental in a variety of instruments operating over a very wide range of accuracies. For middle and lower accuracy devices are simple rectifier circuits, which detect the signal peak values. The output is calibrated to give the equivalent RMS value of a sinusoidal signal. If the signal is noisy or the signal shape differs from sinusoidal, substantial errors can occur. The most accepted measurement standard, with the lowest uncertainty (a few parts of µV/V or ppm) over a wide range of frequency, is based on the heat produced by an AC-signal which is established against a response of an equivalent DC-signals. These in turn, can be referenced to a primary standard defined by the Josephson junctions array. The RMS-value has been measured very accurately through thermoelectric phenomena manifested on conductive materials, mainly the Joule effect which accounts for changes of the temperature of an electrical resistive element, proportional to the dissipated power across the load resistor. Thus, RMS-to-DC conversion is best realized through the heating of an input resistance, proportional to the applied power, is measured with a temperature detecting element that is placed around or near the heating element. Although other approaches that have been reported in the literature to develop AC-converters based on capacitive principles for true RMS-to-DC converters [8,9] (implemented using surface micro-machined[8] and bulk micromachined [9] devices), the dissipative (Joule effect) method is until now, the standard for the AC-DC conversion and the corresponding measurement of the AC-RMS contents.

Thin film, planar multijunction thermal converters (PMJTC), based on thin-film technology, can be realized to provide a zero AC-DC difference with an uncertainty below 1 ppm at 1 kHz [7]. Thermal conversion can be a complicated and time consuming measurement method where the main limitation is the necessary generation of heat for signal detection; ultimately the accuracy is limited by phonon noise. Multi-junction thermal converters can be manufactured using traditional technologies, but micro-electromechanical systems (MEMS) technology has enabled a substantial improvement in device performance. The decreased device size (thermal mass) and reproducible manufacturing process, utilizing well characterized materials, creates more accurate, faster, and less expensive devices. The most widely used converter which has been adopted as a conversion standard for DC- and AC-signals, was developed at PTB-Germany. It makes use of an array of thermocouples (thermopile) defined in the vicinity (side) of the input resistive element, on top of a silicon pyramidal structure (obelisk) fabricated by bulk micromachining principles, to thus establish a very reliable conversion device, with very low uncertainty[1]. Such a converter is referred to as the multi-junction thermoconverter (MJTC). MJTCs are an extension of the single-junction converter (SJTC) but can be fabricated very efficiently using MEMS wet- and dry-etching techniques which yield a converter of excellent performance.

The MJTC is illustrated in **Fig. 1**. The thermopile for the temperature detection part, has to satisfy stringent requirements for its best performance, including low thermal conductivity of the thermocouple wires as well as of the supporting media for the thermopile. In addition, the materials used on the implementation of thermocouples, have to have low electrical resistance and generate a relatively large thermo-voltage. MJTCs have been developed and optimized throughout the years [2-4] to provide with the best method for this purpose, including a support of quartz to replace the silicon substrate so as to improve the performance of this converter for very high frequency signals.

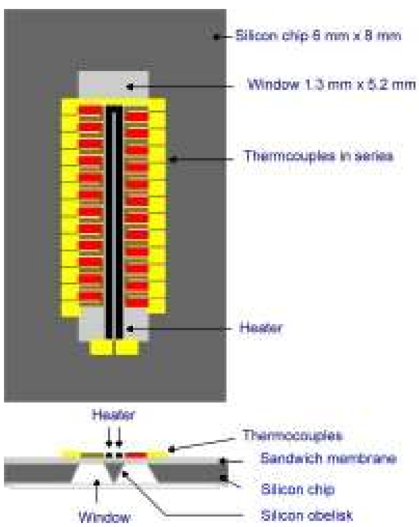

Figure 1. *Configuration of PTB´s Planar-MJTC, where 100 thermocouples in series (thermopile) surround the bifilar element or heater (center). Top and side view. http://www.ptb.de/en/org/2/21/212/pmjtc.htm*

The heating resistor is made of a NiCrSi-alloy whose value can be 90-900 Ω, with a temperature coefficient of resistance (TCR) of about 2 ppm/^{o}C. The supporting membrane for the thermocouples' wires consists of a three thin layers of dielectric material (Si_3N_4-SiO_2-Si_3N_4 of about 1-2 μm in thickness) of a width approximately 600 μm, defining the length of the TC-wires which are made of either Bi-Sb or Cu-CuNi44, of relatively high temperature sensitivity. These dielectrics have a relatively low thermal conductivity necessary for the optimum performance of the thermocouples.

Other types of thermoconverters have been reported in the literature, where the temperature detection is based on two resistive temperature detectors made out either aluminum films[5] or Vanadium oxide [6], illustrated in Fig. 2. In all cases, the input resistance (heater) has to have a very low temperature sensitivity of resistance (or TCR), 1-2 ppm/^{o}C at most.

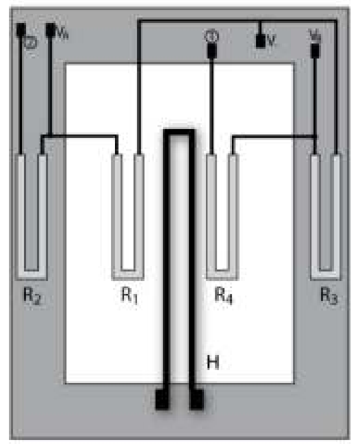

Figure 2. *Configuration of a resistive type thermoconverter[6] using two VO_2-resistors on the sides of the bifilar NiCr-heater, and configured within a Wheatstone bridge.*

The resistive thermoconverter (RTC) being reported here, is fabricated from a SOI-wafer, with an active layer of 10-100 μm thick. This converter, illustrated in Fig. 3, is configured so as to achieve a complete integration of the heat generated by the heater (input resistor) by defining it on top of the temperature detecting silicon element. The detector is defined out of the SOI's active layer, serving as platform for the heater. The temperature-detecting element (detector) is a silicon resistor bigger than the actual heater serving as platform for the resistor defined on top of it. The RTC was designed in such a way so as to allow the effective transfer of heat from the heater to the detector since these two resistors are separated by a very thin oxide layer of approximately 600-1,000 Å . For the first design and fabrication of the RTC, the detecting resistor's area is about 5x5 mm^2 in a double or triple bifilar configuration winding around on top of the detector. The heater is made of a thin-film Cu:Ni alloy about 6,000 Å thick. And although silicon oxide has a relatively low thermal conductivity, it is considerably

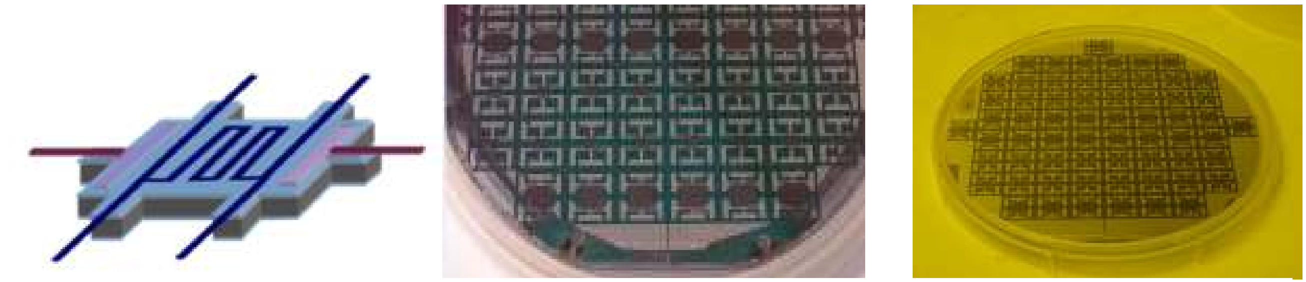

Figure 3. *Basic structure of the RTC concept, as designed and fabricated. The heater (Cu-Ni) lays on top of the detector element (Si-resistor)*

thin, thus, heat transfer to the detector can be considerably effective and rapid. With this configuration for the RTC, we expect to minimize all possible thermal gradients set along the heater and with it, eliminate all conversion differences for signals (currents) flowing in opposite directions, a common limitation of SJTC and MJTC. That is, in the case of temperature gradients, “hot” and “less-hot” are produced, they will have the same effect on the overall resistance of the detecting element; in this way, all thermal effects are integrated regardless of their location. Moreover, since silicon (used as the temperature detecting resistor) supporting the heater has a rather high thermal conductivity, much greater than oxides and nitrides, the temperature of the detector can be rapidly equilibrated, thermal gradients may be cancelled out.

The Cu:Ni-heater’ TCR has been characterized to be ~2 ppm/^{o}C. Because the insulating film separating the heater and the silicon detector is of a few hundred angstroms thick, the heat produced is readily sensed by the silicon resistor. The thermal sensitivity of the detector is greater when this is made out of a relatively low conductivity (1-10 Ω-cm) wafer, resulting in resistance changes of up to 1 %/^{o}C.

The fabrication of the RTC has been based on the MEMS principles that include micromachining of the active layer to define the detecting element, followed by the micromachining of the handle wafer which can either all the way to the buried oxide layer or allowing some pyramidal structure under the detector, so as to increase the thermal inertia (and stored heat) of the overall structure. The micromachining of the active layer can be either by chemical or plasma methods, while the handle wafer is removed by plasma etching.

2. OPERATIONAL PRINCIPLES AND TEST PROTOCOLS

In the case of the MJTC, the output voltage of the thermo- pile is proportional to the generated heat (or dissipated power); for the RTC, changes of the detecting element's resistance are determined to be proportional to the dissipated power. In both cases the generated voltage or the change in resistance are proportional to either V^n or I^n, where the value of n is theoretically (Joule effect) equal to 2.

The dependence of the output signals (thermopile’s voltage ifor the MTJC and resistance changes for

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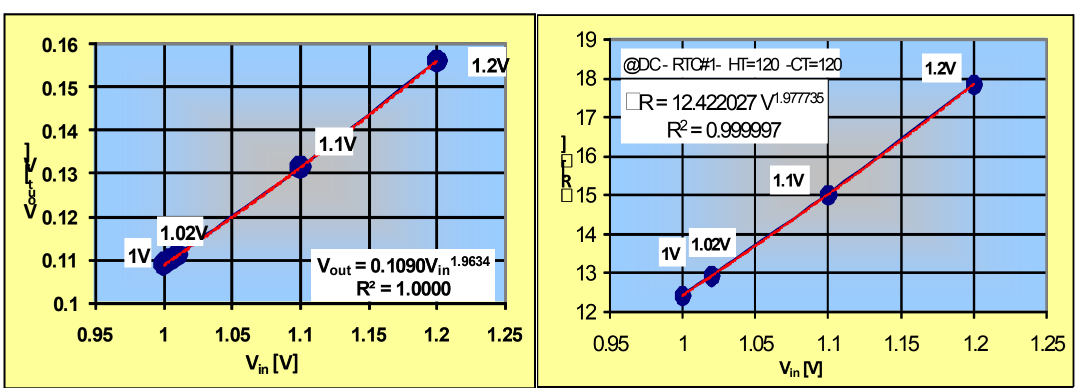

Figure 4. *Determination of the transfer constant, n, for both the MJTC (left) and the RTC (right). The value obtained for n of the MJTC concurs with the value reported by the manufacturing Lab. Both show an n-value very close to 2, with good correlation coefficient of the power curve fit.*

the RTC) with respect to the input voltage, applied to the heater element, was thoroughly characterized so to establish the ability of the RTC, under development, to be used as a reliable converter and to compare its performance with respect to the converter used as reference, MJTC

The results are illustrated in **Fig. 4** which shows that both, the thermopile's voltage, $E_{(thermopile)}$, and the change in resistance, ΔR, are indeed proportional to the square of the electrical signal. Although the RTC was characterized to higher voltage, the comparison shown in **Fig. 4** was limited to voltages below 2 V to insure the safe operation of the MJTC.

An additional characterization of the RTC was considered to adequately determine its performance over a range of frequencies for the AC-signals. An exploratory *test protocol* was implemented to identify the dynamic performance and repeatability, and to compare its response with that of the MJTC. This protocol was designed to establish the ability of the RTC to measure the conversion difference for both, AC and DC signals. This conversion was examined following the time response illustrated in **Fig. 5 and 6**, where both the reference converter (MJTC) and the device under test, (DUT or RTC) were connected in parallel while a high precision calibrator was used to supply the desired electrical

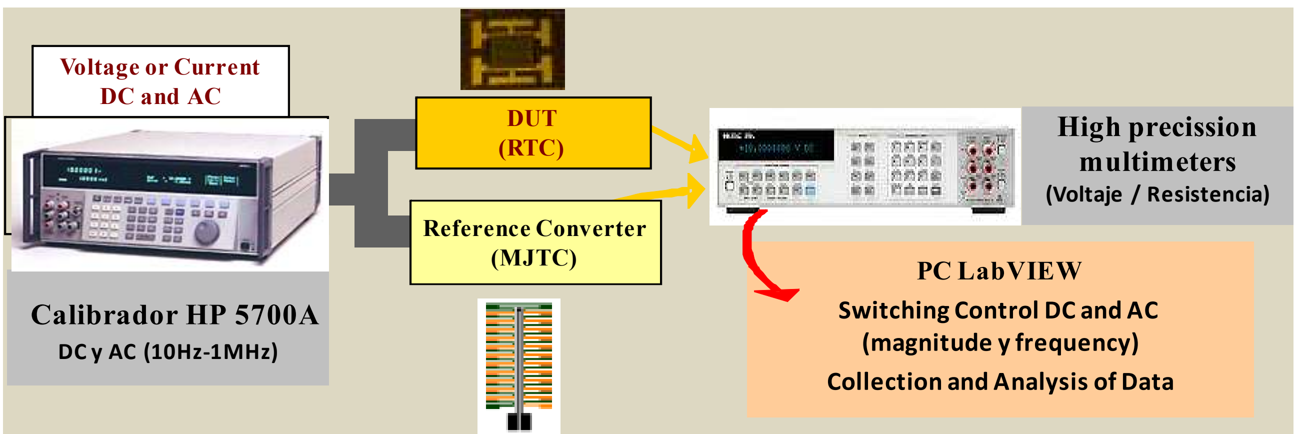

Figure 5. *Schematic of the test circuit used for the characterization of the AC-DC transfer difference of the RTC.*

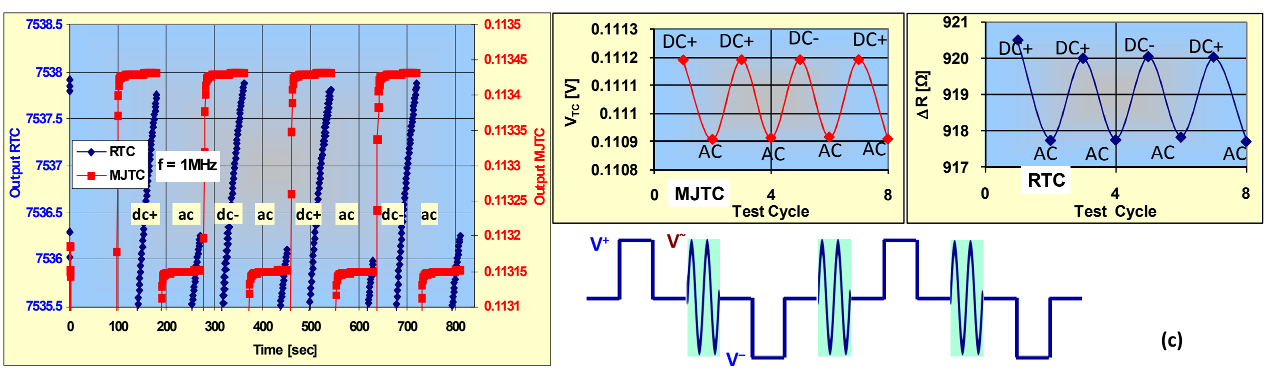

Figure 6. ***(a)*** *The output voltage of the MJTC (red) is recorded along the resistance of the RTC (blue) –maxima- as the applied signal is switched from DC to AC (1MHz); here the minima values of R are not shown. The calibration protocol of thermoconverters using reference MJTCs calls for the switching protocol for the DC signal DC+ to DC-), illustrated in **(c)**. The voltages and resistance changes are presented in **(b)**. It is clear that both, the MJTC and the RTC, show that the heat produced by the AC signal is less than that produced by the DC-voltage.*

signal at a given amplitude, over the frequency range of interest (20 Hz to 1 MHz).
The voltage signals applied that were applied to both converters was switched on and off, over a period of time of 90 or 120 seconds, allowing the signal acquisition system (based on LabVIEW) to record the output signals (thermopile's voltage for the MJTC and resistance for the RTC) continuously. Output data were recorded every second to determine the transient response when the signal was turned on and off and thus determine the time

response of each converter; the on-and-off cycle were repeated five times to study the converters' repeatability.

Since the calibration protocols for precision equipment and calibrators implemented by the industry, call for the application of DC- and AC-voltage signals in an alternating fashion, the implemented test protocol includes the following sequence: AC, DC+, AC, DC-, AC, on so on.

That is, the protocol implemented for the characterization of the RTC under development, is illustrated in **Fig. 6c**, includes the monitoring of the converters' response in time, over the on-and-off cycles, when signals of 1 V-DC and 1 V-AC (nominal effective value), are supplied by a HP-calibrator to both thermoconverters (connected in parallel) for DC and 1 MHz.

The values obtained for each response signals at a given time after the signal is turned on (90 or 120 seconds) are then averaged out, compared and normalized to establish the conversion differences for DC and AC-signals, as follows:

For the MJTC, the thermopile's voltage:

$$\boldsymbol{E_{ac}} = (E_{ac1}+E_{ac2}+E_{ac3})/3 \quad \text{and} \quad E_{dc} = (E_{dc+}+E_{dc-})/2 \qquad (1)$$

For the RTC, the resistance changes:

$$\begin{aligned}\boldsymbol{\Delta R_{ac}} = [&(R_{on90} - R_{off0^-})_{ac1} \\ &+ (R_{on90} - R_{off0^-})_{ac2} + (R_{on90} - R_{off0^-})_{ac3}]/3 \qquad (2)\end{aligned}$$

and $\Delta R_{dc} = [(R_{on90} - R_{off0^-})_{dc+} + (R_{on90} - R_{off0^-})_{dc-}]/2$

These values are used to establish the normalized response differences, in parts per million (ppm), between the AC- and DC-applied voltages:

$$\delta = (E_{ac} - E_{dc})/E_{dc} \times 10^6 \qquad \text{[ppm]}$$

or $$\delta = (\Delta R_{ac} - \Delta R_{dc})/\Delta R_{dc} \times 10^6 \qquad \text{[ppm]} \qquad (3)$$

which may represent an instrument's or a power supply/calibrator's error in measuring, or providing the proper value of an AC-signal whose RMS-value is equivalent the DC-signal of the same signal value.

The heat generated by the AC-signal must be compared to the heat produced by the equivalent DC-signal in view of the fact that this. Thus, the transfer difference between these can be established and quantified as follows:

$$\delta = (\boldsymbol{Q}_{ac} - \boldsymbol{Q}_{dc})/\boldsymbol{Q}_{dc} \quad \Rightarrow \qquad (4)$$

$$\Rightarrow \begin{cases} \delta = (\boldsymbol{E_{ac}} - \boldsymbol{E_{dc}})/\mathbf{n}\boldsymbol{E_{dc}}\ \big|_{V_{ac}=V_{dc}} & \text{MJTC} \\ \textbf{or} & \\ \delta = (\boldsymbol{\Delta R_{ac}} - \boldsymbol{\Delta R_{dc}})/\mathbf{n}\boldsymbol{\Delta R_{dc}}\ \big|_{V_{ac}=V_{dc}} & \text{RTC} \end{cases}$$

where **n** is the power constant that relates these differences to the Joule effect, thus **n** is considered to be equal to **2** (see **Fig. 4**). This is because the heating of the input resistive element (heater) is proportional to the effective (RMS) power that is dissipated across it. That is, by monitoring the generated voltage across the thermopile (in the case of the MJTC) or the changes in resistance (in the case of RTC), the power contents of the AC-signal can be determined with respect to that of a known DC-reference signal.

The calibration protocols call for further processing of these signals in order to determine the actual DC-voltage necessary to produce the same effects (response) as that of a AC-voltage amplitude. That is, a zero difference is sought by iteratively changing the applied DC-input voltage while maintaining the same AC-voltage level, until the recorded difference is less than 1 ppm between these signals.

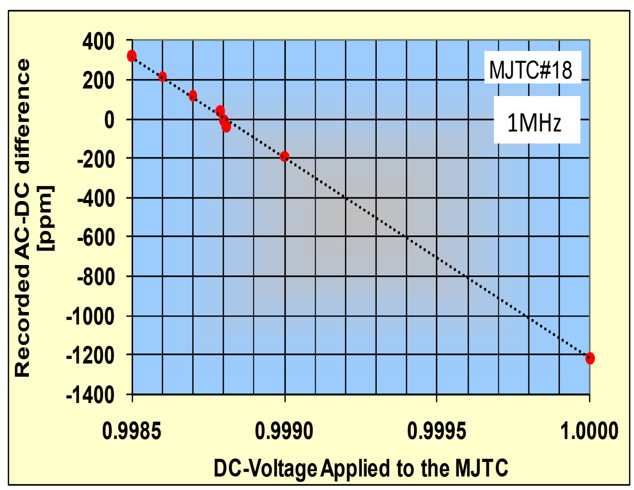

Figure 7. Recorded AC-DC differences versus the DC-voltage applied to the MJTC#18, at 1MHz. Nominal AC-voltages of 1V result in a negative difference indicating that these AC-signals produce less heating (a lower output voltage across the thermopile) than that produced by the 1V DC-signal. If the DC-voltage is lowered to approximately 0.9988V, the AC-DC difference becomes near-zero, becoming positive for lower DC-voltages.

This process is exemplified by the results presented in **Fig. 7** where the AC-DC differences obtained from a MJTC are plotted as a function of the DC-voltage set and supplied by the HP-calibrator. It is observed that when the DC-signal is approximately 0.9988 V, the AC-DC difference is ~0 ppm, which is the equivalent to the RMS-value of the applied AC-signal and that it is ~1 200 ppm, (at 1 MHz) below the expected value. This is without considering the possible intrinsic error that the MJTC exhibits at this frequency.

Such information for the conversion process, by which meters or signal generators are calibrated, can also be established numerically when these differences are calculated for a DC-signal of the (fixed) value of interest, e.g., 1 V, as a function of frequency. To illustrate this point consider, as an example, the data obtained from such an experiment, summarized through **Figs. 6a and 6b**, corresponding to the application of 1 V-DC and 1 MHz 1 V-nominal effective value signals applied to both, the MJTC and RTC connected in parallel to the HP-calibrator that generates these signals.

For such an example, one obtains that the calculated AC-DC difference, (from Eq. (4)), for both, the output voltage of the MJTC or the output ∆R from the RTC, is equal to:

$$\delta = (E_{ac} - E_{dc})/\mathbf{n}E_{dc} = -2512.13/\mathbf{2} = -1256.0 \quad \text{[ppm]}$$

$$\delta = (\Delta R_{ac} - \Delta R_{dc})/\mathbf{n}\Delta R_{dc} = -2418/\mathbf{2} = -1209.3 \quad \text{[ppm]} \qquad (5)$$

respectively; differences relatively close in value, and approximately equal to the value determined from **Fig. 7**, which suggest that both converters, MJTC and RTC, provide with equivalent information.

Thus, for the characterization of the RTC under development, such an iterative process was not implemented, and the assessment of its performance was based on a comparison between the data obtained from these converters while connected in parallel.

It is clear that the results summarized in **Figs. 6 and 7**, from both the reference MJTC and the RTC devices, may be interpreted as the calibrator's inability to provide at 1 MHz, the nominal set 1 V-effective AC signal, since the AC-conversion effects are of lesser amplitude than that of the DC-signal; the difference between DC and 1 MHz is summarized in **Fig. 6b** where the values of output signals (V_{out-TC} and ∆R) are plotted at the test cycles.

It should be mentioned that the protocol used for this study (summarized in **Fig. 6**), the data considered were those gathered after 90 o 120 seconds after the initiation of the heating cycle (i.e., when either the DC- or AC-signals were switched on). Ideally, after this time, the converters' response should reach a steady state condition. This can be assumed to be the case for the PMJTC, as it can be observed in **Fig. 6a** (red plot); for the RTCs tested within this study, the steady state condition is not fully reached for the larger time constant associated with these converters' exhibit. We attribute it to the large thermal conductivities associated with the connecting wires and the relatively large packaging substrate not adequate to limit heat losses towards the metallic fixture used for the entire converter. The time-response of the RTCs is illustrated in **Fig. 8a**, slower than that for the PMJTC presented in **Fig. 8c**. The time-response presented in Fig. 8b corresponds to most recent RTC-prototypes whose characterization is in progress and not presented in this work.

3. EXPERIMENTAL RESULTS

As earlier indicated, the RTC's characterization conducted in this study is mainly based on a detailed comparison of the measurements taken from both, the RTC and the MJTC which when connected in parallel, are affected by the same applied signals set through the HP-calibrator. The output data from both converters (voltage for the MJTC and resistance for the RTC) are hen processed according to Eq. 4, without the implementation of the iterative process which calls for a variation of the
DC-signal. The calculated AC-DC differences between are then unction of the signal's frequency, from 20 Hz to 1 MHz. to assess the performance of the RTC compared to that of the MJTC.

The output voltage signal of the MJTCs, generated across the thermopile's (output) terminals during the "heating cycle" was measured using a high-precision HP multimeter of 7.5 digits display resolution, whereas the resistance of the RTCs was measured using the 4-point method with 6.5digits display resolution Keithley multimeter. The measurement cycles consisted of 90 seconds heating time by either AC or DC applied voltages, followed by 90 seconds cooling time. This protocol, implemented in a LabVIEW-VI is slightly different than the one that is typically implemented for the calibration of reference converters and precision equipment, where the cooling cycle is practically eliminated. This modification was necessary to account for the net heating effects on the input resistor of the RTC by the applied electrical signals

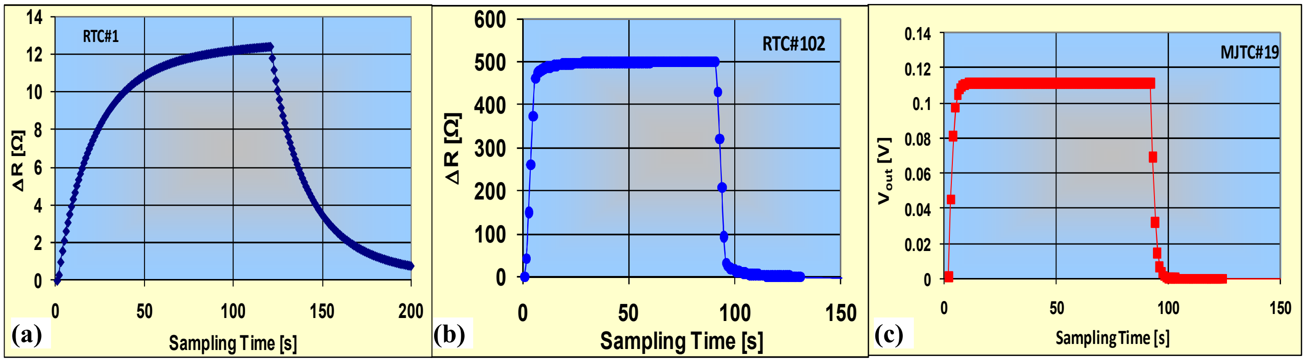

***Figure 8**. (a) Time constant of an RTC implemented on a rather thick wafer. (b) An RTC' time constant micro-machined from a 20µm thick active layer. (c) Typical time constant of the PMJTCs by the* PTB-Germany.

Thus, the resistance values prior to the application of the heating period (say t=0-, 180-, 360-, .. s) were recorded along with the resistance values at the end of the heating cycles (i.e., t=90, 270, .. s) to determine the net change in resistance, ΔR, caused by the Joule effect. The conversion differences AC-DC were calculated according to Eqn. 4 and plotted as a function of the AC-signal's frequency, as illustrated in **Fig. 9,** and numerically in **Table I**, where the conversion differences are numerically listed for the MJTC19 and the a reference MJTC (#19) and the RTC under development (#31), are plotted.

***Table I**. AC-DC conversion differences recorded by the MJTC19 and RTC21 from the HP-Calibrator*

Frequency kHz	Diff. AC-DC MJTC19 [ppm]	Diff. AC-DC RTC31 [ppm]
0.02	23.7	-26.0
0.05	6.0	23.9
0.1	4.8	5.2
0.2	3.0	5.6
0.5	1.7	2.9
1	1.8	1.4
2	-0.5	-7.2
5	-4.3	-11.0
10	-9.7	-9.9
20	-19.3	-26.1
50	-66.2	-69.2
100	-173.6	-176.3
200	-338.5	-337.3
500	-618.6	-633.1
1000	-1256.1	-1325.9

The recorded differences for these converters appear to be in considerable agreement in magnitude over the entire frequency range; both reveal a similar behavior for the HP-calibrator with a negative difference for the AC-signals above 1 kHz whereas a positive one for the frequencies below this point. For instance, the AC-DC difference at 1 MHz, it is -1,256 ppm, according to MJTC, whereas -1325 ppm is obtained with the RTC, values approximately the same and that value was the one obtained for the same calibrator using a different MJTC. These differences mean that the AC-voltage provided by the calibrator is not of the expected 1 V-nominal effective value, but rather it is approximately 0.99874 V.

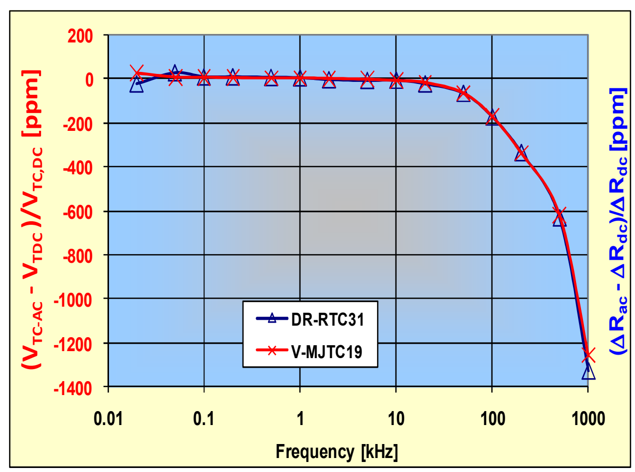

***Figure 9**. AC-DC conversion difference recorded for the HP- calibrator versus frequency. The MJTC's thermopile voltage difference (red) and the RTC's change in resistance of the detecting silicon resistor (blue).*

Further experimentation was targeted to insure that the conversion characteristics of the RTC were "equivalent" or comparable to those of the MJTC. This included the monitoring of the MJTC-thermopile's resistance along with the resistance of the RTC's detecting element. This resistance was also measured using a 4-point method during which a constant current is applied to the thermopile so as to measure the thermopile's resistance. The resulting voltage is converted to, and displayed as a resistance value by the high precision multimeter.

In principle, the resistance measurement of a thermocouple requires of a more careful and detailed analysis; the "resistance displayed" by the multimeter, especially during the heating cycle, because the displayed value is not only due to the resistance of the thermocouple's wires but also due to voltage generated (Seebeck effect) across the thermocouple terminals. In addition, the Seebeck voltage may add or subtract (increase or decrease) the voltage that is set across the thermopile's terminal by the injected current, depending on the current's direction with respect to the thermopile's wires (terminals). This was found to be a good test to determine the heating triggered during the measurement of resistance of a thermocouple, and from it, is concluded that it does not affect the performance of the MJTC and its ability to provide information of a thermoelectric conversion. In fact, this study can provide information of the temperature dependence of the MJTC's thermopile's voltage for this type of thermo-converters, and to determine the temperatures set at or near the region of the converter's input resistance, which otherwise, may not be so straightforward.

In view of the considerably low currents that are set in the detecting resistor during the 4-point resistance measurements, are considerably low (less than 100 μA), with the corresponding dissipated power during this process estimated at about 84 μW, it is concluded that self heating of the detecting resistor is negligible. Such power levels are much smaller than the power dissipated across the heating element, of ~10 mW, during the heating cycles.

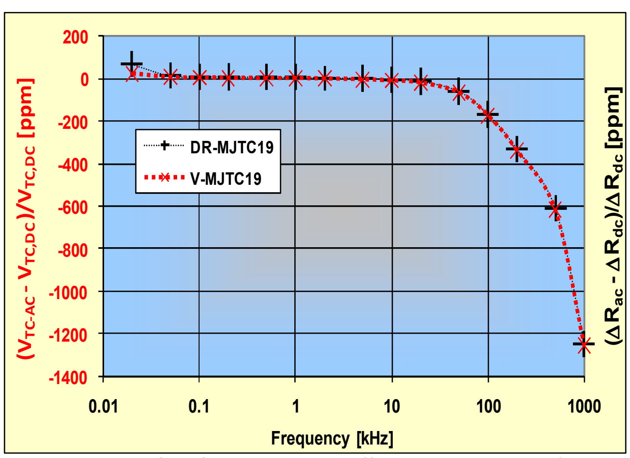

Figure 10. *AC-DC conversion difference recorded for the HP-calibrator versus frequency, established from the output voltage (red) and the resistance (black) of the MJTC's thermopile.*

Results of this study are illustrated by the calculated conversion differences when the MJTC's output is measured as voltage and as a resistance, shown in **Fig. 10**, were it can be observed that both curves are in full agreement, separated by 1-2 ppm, except at 20 Hz, where the stability of the HP-calibrated is known to be inadequate. These results enable us to conclude that the self-heating of the detecting element is negligible, and that the data obtained from the measurement of the MJTC's output resistance provide the same information than that obtained by the monitoring of the thermopile's voltage.

From this study, the RTC's response can be adequately compared to either the MJTC's response based on the monitoring of thermopile's output voltage (**Fig. 9**) or the thermopile's output resistance, presented in **Fig. 11**.

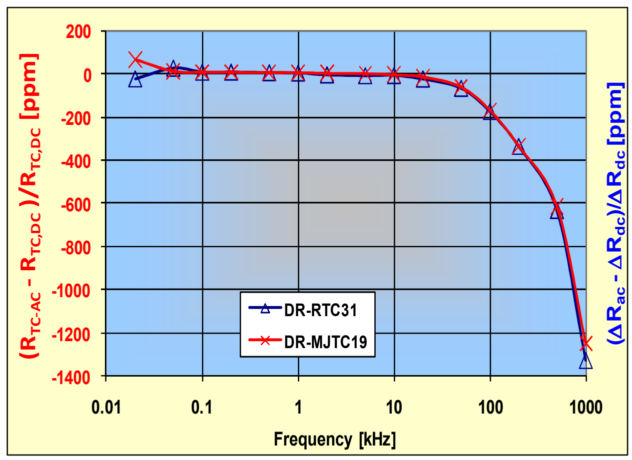

***Figure 11**. AC-DC conversion difference recorded for HP-calibrator versus frequency, established from the resistance of the MJTC's thermopile (red) and the resistance of the RTC (blue).*

In this graph is easy to observe that the RTC is about -40 ppm at 20 Hz and about -75 ppm at 1 MHz, with respect to the response of the MJTC at these frequencies. These are the two points where the RTC departs most from the results of that converter. Over the rest of the frequency range both converters exhibit a relatively similar response, from which we may conclude that the initial RTC prototypes may indeed be adequate to be used for the purpose. The response of new RTC-prototypes will be evaluated as some modifications are implemented for the fabrication and packaging of these devices.

4. CONCLUSSIONS AND FUTURE WORK

The results presented in **Fig. 9** enable us to conclude that the RTC performs relatively well and may be used as a conversion standard after some design optimization is implemented and improvements of the packaging are adapted in order to reduce, or adequately control the response time constant.

We are encouraged by the results that have thus far been obtained and are working on a new generation of MEMS-based converters which include the use of ceramic materials with greater thermal conductivity and lower dielectric constant that those for silicon.

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