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Paper

Multijunction Thermal Converter with Improved Frequency Characteristics between 10 Hz and 1 MHz

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A new multijunction thermal converter (MJTC) for precision AC–DC transfer standard has been developed. A U-shaped heater pattern was sputter-deposited onto an AlN plate in order to reduce thermoelectric effect, which causes the frequency-independent AC–DC transfer difference. Both low-frequency and high-frequency characteristics improved as a result of the new configuration, and the AC–DC transfer difference of the MJTC was evaluated to be <1 μV/V between 10 Hz and 100 kHz and <10 μV/V up to 1 MHz. © 2012 Institute of Electrical Engineers of Japan. Published by John Wiley & Sons, Inc.

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1. Introduction

DC voltage standards accurate to 10^{-9} are achievable using Josephson junction arrays. The most common method to establish an AC voltage standard is through 'transfer' or comparison with the DC voltage standard. This is performed by comparing the root mean squared (RMS) power of the AC voltage with that of the DC voltage using a thermal voltage converter (TVC). TVCs are capable of comparing the power at the 10^{-7} level and are widely employed as the primary standards (AC–DC transfer standards) in national standards laboratories [1].

Single-junction thermal converters (SJTCs) were developed in the 1950s. A thin filament heater and a single-junction thermocouple are enclosed in an evacuated glass bulb. The thermocouple junction is in thermal contact with the heater at the midpoint of the heater, and is electrically insulated from it by a bead of glass or ceramic. The SJTC elements are known to show a flat frequency response up to 1 MHz, and the long-term drift in the AC–DC transfer difference is negligibly small because of its simple structure. However, a precise DC voltage measurement at the nanovolt level is required in order to obtain a resolution better than 1 μV/V, since the EMF output of the SJTC element is of the order of a few millivolts. Also, relatively large Thomson and Peltier effects are generated, resulting in non-negligible frequency-independent AC–DC transfer difference of a few μV/V around 1 KHz because of a large temperature gradient along the heater.

Multijunction thermal converters (MJTCs) were developed in 1970s and 1980s [2,3]. MJTCs were designed to reduce the thermoelectric effect, which is the main cause of AC–DC difference around 1 KHz. An MJTC employs a large number of thermocouples along the heater, so that the output EMF is increased to the 100 mV level. Owing to the uniform temperature distribution, the thermoelectric effects along the heater are reduced, and AC–DC difference better than 0.1 μV/V is realized.

However, due to the complicated structure of the MJTC elements, it is difficult to obtain a flat frequency response at both lower (<100 Hz) and higher (>100 kHz) frequency ranges.

In this paper, a new MJTC element, Type-JSTC06, with improved frequency characteristics for a wider frequency range (10 Hz to 1 MHz) is described. We have so far developed two types of precision MJTC elements, i.e., Type-JSTC04 [4] and Type-JSTC05 [5]. The high-frequency model, JSTC04, was specially designed to comply with the requirements for the 'self-calculability' of the frequency characteristics higher than 10 kHz. However, the special design to minimize the effect of stray inductances and capacitances degraded the frequency performance at frequencies lower than 1 kHz. In the case of the low-frequency model, JSTC05, the increased thermal time constant required a stabilization time longer than 30 s, which is unacceptable for the routine AC–DC difference measurements.

In the case of the JSTC06 elements, the frequency characteristics can be calibrated using the JSTC04 and JSTC05 elements as reference standards, and hence the self-calculability is not required. This compromise enabled us to employ a much simpler and more reliable structure, resulting in the reduction of the frequency characteristics at both lower and higher frequencies.

2. Structure of JSTC06 Thermal Converter

The structure of the new thermal converter element, JSTC06, is shown in Fig. 1. As in the case of the standard MJTC elements, the JSTC06 element is composed of the following three main components: (i) a heater which converts electric power of the input (AC or DC) to heat, (ii) a set of thermocouples which measure the

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temperature rise of the heater, and (iii) a heat sink which serves as the reference point for the thermocouples. By comparing the temperature of the heater for either the AC or DC input mode, the RMS input AC voltage is precisely compared with that of the DC voltage.

The structure of the JSTC06 element is basically the same as that of the former models, JSTC04 and JSTC05. The outer shell of JSTC06 is made up from two hollow alumina frames (9 mm × 15 mm × 0.63 mm), which also act as the heat sink. A thin polyimide membrane is sandwiched between the alumina frames, and the AlN (aluminum nitride) heater chip is mounted in the middle of the membrane.

As opposed to the flip-chip mounting in the case of the JSTC04 and JSTC05 elements, the input electrodes are deposited onto the three surfaces, extending via the side to the bottom of the AlN chip, which are then solder-connected to the copper input pattern on the polyimide membrane. This structure enabled us to overlap the heater pattern with the thermopile pattern, because these patterns are now separated by the AlN substrate. A U-shaped heater pattern (Ni–Cr, Cu) was sputter-deposited onto the surface of the AlN plate, aiming to reduce the reversal error due to Peltier effect on the contacts between the heater pattern and the copper input electrodes.

The heater resistance is selectable from 100 Ω to 2 kΩ, with a temperature coefficient of <25 ppm/K. The size (6 mm × 2 mm) and the thickness (0.3 mm) of the AlN chip determine the thermal time constant of standard JSTC06 elements as 2.5 s, which is adjustable by changing the thickness of the chip.

Series-connected 60 pairs of Bi–Sb thermocouples are sputter-deposited to both sides of the polyimide membrane, connecting to the output terminals. The structure of the thermocouple is almost exactly the same as that of JSTC04 and JSTC05, except that the number of thermocouples is slightly reduced.

For the evaluation of JSTC06 elements, eight test samples were fabricated. Measurement of AC–DC transfer difference and fast-reversed DC–DC (FRDC-DC) difference [6,7] were carried out using the ET2001 AC–DC Transfer Standard System at the AIST, as described in detail in the following section.

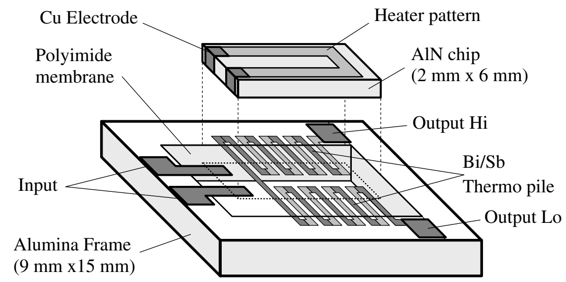

Fig. 1. Structure of JSTC06 thermal converter element

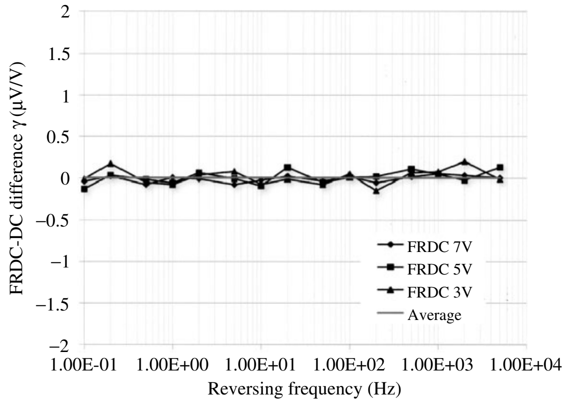

Fig. 2. FRDC-DC difference measurement of JSTC06 element

3. Evaluation of AC–DC Transfer Difference

In this section, an evaluation of the AC–DC transfer difference of a JSTC06 thermal converter element is described. The AC–DC transfer difference of a thermal converter element is characterized by the combination of (i) frequency-independent DC characteristics, (ii) low-frequency characteristics below 100 Hz, and (iii) high-frequency characteristic above 10 kHz. These characteristics are evaluated separately in the following subsections.

3.1. DC characteristics In the mid-frequency range between 100 Hz and 10 kHz, where both the low-frequency effect and the high-frequency effect are negligibly small (<1 μV/V), the AC–DC difference of a thermal converter is determined by the frequency-independent DC characteristic caused by the Thomson and Peltier effects. FRDC-DC difference measurement has been performed in order to determine the DC characteristic of a JSTC06 element.

The results of the FRDC-DC difference measurements are summarized in Fig. 2. The measurements were performed using a JSTC06 element (#02008) at three different voltage levels, i.e. 3, 5, and 7 V. As shown in the figure, the FRDC-DC difference was measured to be smaller than 0.1 μV/V in the (reversing) frequency range between 0.1 Hz and 10 kHz. The estimated value γ_{FRDC} and the standard deviation of measurement $\Delta\gamma_{\mathrm{FRDC}}$ are summarized as

$$\gamma_{\mathrm{FRDC}} = 0.01 \times 10^{-6} \quad (1)$$

$$\Delta\gamma_{\mathrm{FRDC}} = 0.08 \times 10^{-6} \quad (2)$$

3.2. Low-frequency characteristics In the frequency range below 100 Hz, the low-frequency effect may become the dominant factor in the AC–DC transfer difference of a thermal converter. Because of the limited thermal time constant of the heater, thermal converters tend to lose their precision at these frequencies as a result of thermally induced ripple in the heater temperature and the output voltage. In the case of a conventional thermal converter with a thermal time constant of less than a few seconds, the thermally induced ripple gives contribution to the AC–DC difference larger than 1 μV/V at around 10 Hz.

The low-frequency characteristic of a JSTC06 element (#02008) was evaluated by two methods, i.e. (i) AC to low-frequency AC difference (AC-LF) measurement and (ii) AC–DC difference comparison measurement. The AC-LF measurement was performed using a high-precision DSS (digital sine-wave synthesizer) circuit as the reference standard, while the AC–DC difference comparison measurements were performed using a low-frequency model, JSTC05, as a reference standard.[5] The results of the measurements are summarized in Fig. 3. The measurements were performed on a JSTC06 element (#02008) at three different voltage levels. The low-frequency characteristic was evaluated with respect to a fixed reference frequency (100 Hz) as the reference point. The results were curve-fitted to the second order in $1/f$. As shown in the figure, the AC–DC difference of the JSTC06 element was evaluated to be smaller than 0.1 μV/V in the low-frequency range between 10 Hz to 100 Hz. Hence the estimated value γ_{LF} and the standard deviation of measurement $\Delta\gamma_{\mathrm{LF}}$ are summarized as

$$\gamma_{\mathrm{LF}} = 0.0 \times 10^{-6} \quad (3)$$

$$\Delta\gamma_{\mathrm{LF}} = 0.1 \times 10^{-6} \quad (4)$$

3.3. High-frequency characteristics In the frequency range above 10 kHz, the high-frequency effect due to stray inductance and capacitance becomes the dominant factor in the AC–DC transfer difference on a JSTC06 thermal converter element. A JSTC06 element was mounted to the same high-frequency chassis as the JSTC04 thermal converters.[5] The AC–DC difference of a 500-Ω input JSTC06 element (SN#02001) was compared with a JSTC04 thermal converter (SN500-64001) as a reference standard. Since both thermal converters have the virtual TEE connector configuration,[5] another TVC (SN#ET07) was used as the intermediate transfer standard.

The results of the AC–DC difference measurements between the JSTC06 and the JSTC04 are summarized in Fig. 4. As shown in the figure, the relative AC–DC difference between the two TVCs was measured to be smaller than 1 μV/V in the frequency range between 100 kHz and 1 MHz. Hence the 500-Ω input JSTC06 element, mounted onto the high-frequency chassis, was assumed to have the same frequency dependence.

The frequency characteristics of the JSTC04 elements have been evaluated in Ref. 5. Hence the high-frequency characteristics of the AC–DC transfer difference γ_{HF} of the JSTC06 element and the estimated 1σ uncertainties $\Delta\gamma_{HF}$ are evaluated as

$$\gamma_{HF} = 7.5f^2 \times 10^{-18} \quad (5)$$

$$\Delta\gamma_{HF} = 4.0f \times 10^{-12} + 4.5f^2 \times 10^{-18} \quad (6)$$

3.4. Overall characteristics To check element-to-element variation in the frequency characteristics, the AC–DC difference comparison measurement was performed using eight JSTC06 elements from the same lot as SN#02001 and SN#02008. The AC–DC differences of the JSTC06 elements were compared using a thermal converter module (SN#ET07) as the intermediate standard.

The results are summarized in Fig. 5. One of the elements (SN#02003) showed high-frequency characteristics that were notably different from the other elements. The other seven elements showed very similar frequency characteristic as expected, and the relative variation was within ±1 μV/V between 10 Hz and 100 kHz, and within ±5 μV/V up to 1 MHz.

The average frequency characteristic of the AC–DC difference of the thermal converter module was evaluated using the three measurements described in the preceding subsections: (i) DC offset by FRDC-DC difference measurement, (ii) LF characteristic by AC–AC difference measurement with LF-TVC, and (iii) HF characteristic by AC–AC difference measurement with HF-TVC. The solid gray curves show the estimated average frequency performance γ_{AVE} of the 500-Ω JSTC thermal converter elements, which is characterized by the following formula:

$$\gamma_{EST} \equiv \gamma_{FRDC} + \gamma_{LF} + \gamma_{HF} \cong 7.5f^2 \times 10^{-18} \quad (7)$$

$$\Delta\gamma_{EST} \equiv \Delta\gamma_{FRDC} + \Delta\gamma_{LF} + \Delta\gamma_{HF} \quad (8)$$

$$= 0.2 \times 10^{-6} + 4.0f \times 10^{-12} + 4.5f^2 \times 10^{-18} \quad (9)$$

The relative variation in the AC–DC difference of each element (from the average of the seven elements) was plotted with respect to this curve. The dotted curves ($\gamma_{MIN}/\gamma_{MAX}$) represent the criteria for the selection of reliable JSTC06 elements, expressed by the following formula:

$$\gamma_{MIN} \cong \gamma_{EST} - 1.0 \times 10^{-6} - 5.0f \times 10^{-12} \quad (10)$$

$$\gamma_{MAX} \cong \gamma_{EST} + 1.0 \times 10^{-6} + 5.0f \times 10^{-12} \quad (11)$$

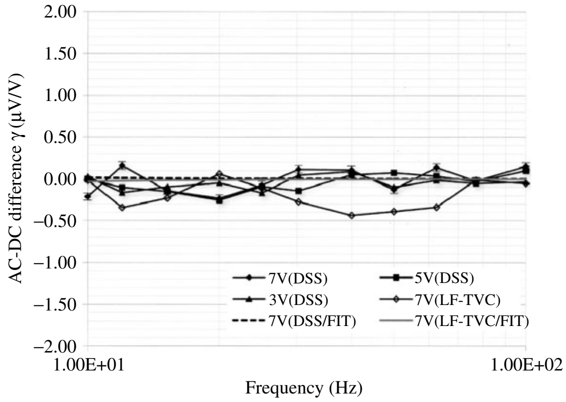

Fig. 3. Low-frequency characteristics of JSTC06 element

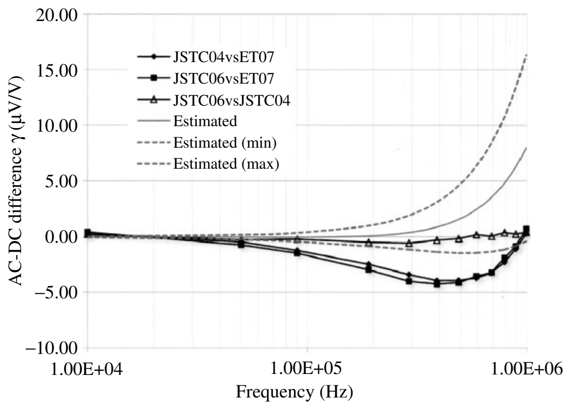

Fig. 4. High-frequency characteristics of JSTC06 element

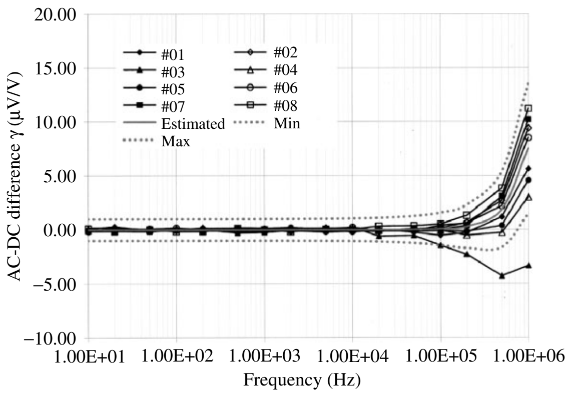

Fig. 5. AC–DC transfer differences of JSTC06 elements

4. Conclusion

A new MJTC element (type-JSTC06) for precision AC–DC transfer standard has been developed. The AC–DC transfer difference of the thermal converter element was evaluated as the combination of (i) frequency-independent DC characteristic due to thermoelectric effects, (ii) low-frequency characteristic below 100 Hz due to thermal ripple, and (iii) high-frequency characteristic above 10 kHz due to stray inductance and capacitances. The frequency characteristic of the JSTC06 elements were evaluated to be <1 μV/V between 10 Hz and 100 kHz and <10 μV/V up to 1 MHz.

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References

(1) Inglis BD. Standards for ac-dc transfer. *Metrologia* 1992; **29**:191–199.

(2) Klonz M. AC-DC transfer difference of the PTB multijunction thermal converter in the frequency range from 10 Hz to 100 kHz. *IEEE Transactions on Instrumentation and Measurement* 1987; **IM-36**:320–329.

(3) Kinard JR, Huang DX, Novotny DB. Performance of multilayer thin-film multijunction thermal converters. *IEEE Transactions on Instrumentation and Measurement* 1995; **44(2)**:383–386.

(4) Sasaki H, Yamamori H, Yamada T, Fujiki H, Shoji A, Budovsky I, Georgakopoulos D, Hagen T, Shimizume K. Evaluation of low-frequency characteristic of a thermal converter using programmable Josephson voltage standard. *IEEE Transactions on Instrumentation and Measurement* 2010; **59(11)**:2930–2935.

(5) Sasaki H, Shimizume K, Kasai N, Fujiki H, Shoji A. Development of a thermal voltage converter with calculable high-frequency characteristics. *IEEJ Transactions on Electrical and Electronic Engineering* 2011; **6**:293–298.

(6) Klonz M, Hammond G, Inglis BD, Sasaki H, Spiegel T, Stojanovic B, Takahashi K, Zirpel R. Measuring thermoelectric effects in thermal converters with a fast reversed DC. *IEEE Transactions on Instrumentation and Measurement* 1995; **44(2)**:379–382.

(7) Sasaki H, Takahashi K. A guide for the evaluation of thermoelectric effects in thermal converters using KST003 Fast-Reversed DC source. ETL Technical Report, TR-96-22, 1996.

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