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Improvement of Thin-Film Multijunction Thermal Converters at KRISS

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Thin-film multijunction thermal converters (MJTCs) were fabricated using silicon semiconductor production and bulk micromachining. The converters consisted of a bifilar heater and thermocouple hot junctions on the $Si_3N_4/SiO_2/Si_3N_4$ membrane and cold junctions supported by the silicon frame. The voltage sensitivity of the converter was 21.41 V/W in vacuum, which is higher than 5.82 V/W in air. In the case of a 500-nm-thick heater, the ac-dc transfer differences taken at 1 V and 40 Hz were 42.1 ppm in air and 11.8 ppm in vacuum. The ac-dc transfer differences were stabilized below 1 ppm in the frequency range from 1 kHz to 500 kHz. A process of fabricating advanced converters with a thermal island under the heater to decrease ac-dc transfer difference at low frequencies was developed. In the case of the converter, the transfer difference was about 2.9 ppm at 1.0 V and 40 Hz.

1. Introduction

A thermal ac-dc transfer converter, which is a measurement device for evaluating ac quantities precisely through comparing equivalence with dc standards, finds the ac rms value by comparing the respective heat generated by the average power consumption with heater resistance by dc and ac. Three-dimensional multijunction and single-junction thermal converters (3-D MJTCs / SJTCs) have been used for the most precise ways of ensuring ac standards in many standard laboratories for a long time. However, planar thin-film MJTCs using well-developed semiconductor fabrication processes and micromachining technology have been recently studied and developed to replace 3-D MJTCs, which have

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low production yields and other drawbacks. Moreover, the efficiency of planar thin-film MJTCs has also been gradually improved to reach practical ac standards.[1-6]

The ac-dc transfer difference δ that characterizes the performance of a thermal ac-dc converter is defined as $\delta = (Q_a - Q_d)/Q_d$, where Q_a is the ac input quantity and Q_d is the dc input quantity which produces the same mean output voltage as Q_a. The ac-dc converting accuracy is affected by the dc reversal error, frequency error, square rule error, and temperature conversion error, which are divided into frequency-related and non-frequency-related errors.

In the frequency range above 10 kHz, unexpected ac-dc transfer differences may come from the following sources: the positive influence of the skin effect in the leads and the negative influence of the dielectric losses in heater and heater/thermocouple capacitances.[3,7] In this work, we attempted to improve transfer characteristics in the high-frequency ranges by adjusting the heater resistances for compensating the skin effect and dielectric losses.

In addition, double-frequency thermal ripples are created due to an insufficient thermal inertia of the heater in the frequency range below 100 Hz.[8] To solve this problem, the thermal time constant of the converter must be increased. We chose to increase the thermal time constant using vacuum packages and leaving marginal Si mass under the heater.

2. Device Preparation

2.1 *General fabrication process*

We have used 6-inch (100), 550-μm-thick, double-side-polished, 8–10 Ω·cm, p-type silicon substrates. After the initial cleaning of the wafers, the three layers of 200 nm Si_3N_4/1000 nm SiO_2/200 nm Si_3N_4 were deposited on a 6-inch diameter Si wafer using low-pressure chemical vapor deposition (LPCVD). The measured residual stress of the Si_3N_4 (200 nm) and SiO_2 (1000 nm) layers were about 1087 MPa and –93 MPa, respectively. To make 200-nm-and 500-nm-thick bifilar heaters, evanohm R (Ni_{75}-Cr_{20}-$Al_{2.5}$-$Cu_{2.5}$) alloy was dc-magnetron-sputtered on the photolithographically patterned structures and lifted-off. In the next step, chromel(Ni_{90}-Cr_{10})-constantan(Cu_{55}-Ni_{45}) thermocouples were fabricated, which were patterned by the sequential sputtering of chromel and constantan along with photoresist lift-off. After making all the structures, extension electrodes of Ti/Au were made as the electrical connections. Finally, the back side of the silicon substrate was etched in the KOH anisotropic etchant. The remaining frame of silicon situated exactly underneath the cold junctions of the thermocouples was used as a heat sink. Figure 1 shows the general thermal converter fabricated in this study.

2.2 *Fabrication of improved thin-film MJTCs for low-frequency range*

As mentioned above, in order to increase the thermal time constant in the converter, a process for forming a thermal mass under the heater and thermocouple hot junctions is needed. For this procedure, a deep reactive ion etching method using the Bosch process has been employed.[9] In the case of Si back-side etching using KOH solution, it is difficult to achieve precise shape control as well as to ensure high process yield. To make up for these weaknesses, we developed a new device-producing technique using the Bosch process (Fig. 2). The features of the newly designed thermal converter are illustrated in Fig. 3.

(a) (b)

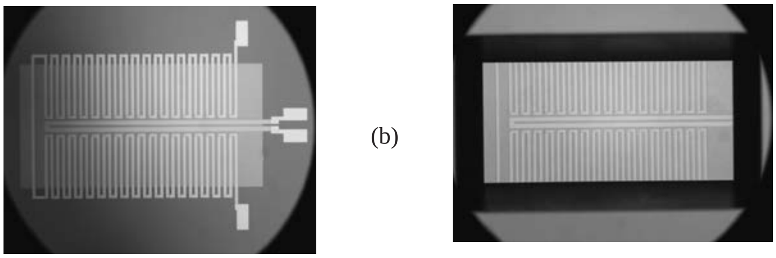


Fig. 1. (a) Front- and (b) back-side views of the thin-film MJTC fabricated.

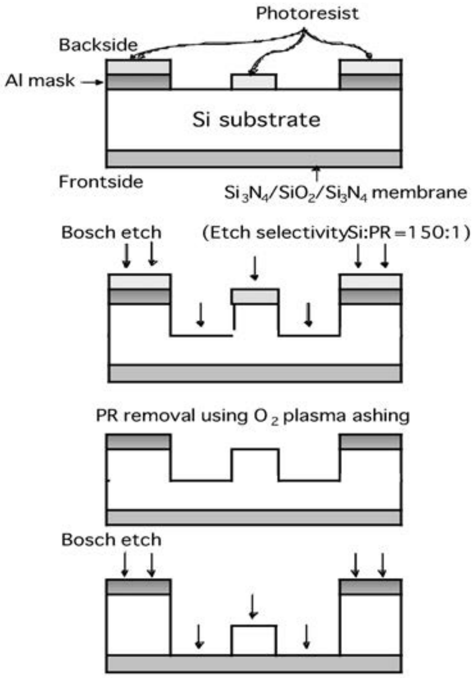


Fig. 2. Newly developed fabrication process using Bosch technique.

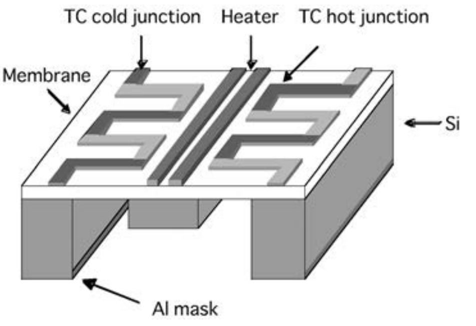


Fig. 3. Schematic figure of new thermal converter for low frequencies.

This technique, using a photoresist layer as an etching delay layer for the thermal mass structure, guarantees high yield and productivity, which are unexpected in the former procedure[10] that used silicon nitride as an etching delay layer. Figure 4 shows the low-frequency version of the actual thermal converter fabricated using this process.

3. Characteristics of Thin-Film MJTCs

3.1 *Characteristics of general thermal converter*

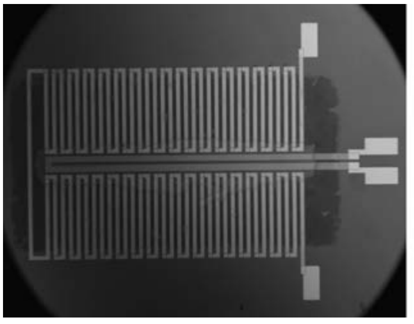
The dual-channel ac-dc transfer difference measurement system[11] was used to determine the ac-dc transfer difference δ. Figure 5 shows the ac-dc transfer differences for 500-nm- and 200-nm-thick converters in the frequency range from 40 Hz to 1 MHz with input voltages of 0.5, 1.0 and 2.0 V.

The results obtained with input voltages of 0.5, 1.0, and 2.0 V at 1 MHz are about 89.4 ppm, 88.8 ppm and 85.8 ppm, respectively, for the 500 nm converter (heater resistance of 222 Ω). For the 200 nm converter (heater resistance of 524 Ω), the results were approximately 14.4 ppm, 13.5 ppm, and 15.6 ppm. In the case of the 500-nm converter, the transfer differences were increased greatly in high frequency ranges over 10 kHz, which can be explained by the increase in the positive influence from the skin effect in the leads.[7] For the 200 nm converter, the ac-dc transfer differences at high frequencies were decreased compared with those for the 500 nm converter, which can be understood by the decreased influence of the skin effect; and this compensates for the influence of the dielectric losses. Moreover, in the frequency range from 1 kHz to 500 kHz, the values were below 1 ppm.

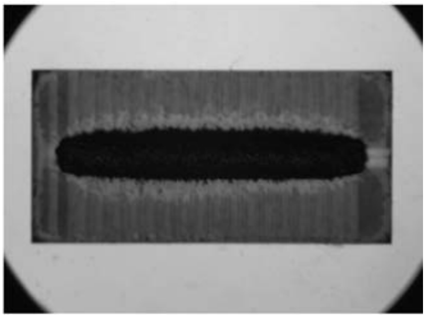
3.2 *Properties of thermal converter for low-frequency range*

Figure 6 shows the variation of voltage sensitivities (output voltage/input power) from atmospheric pressure down to 0.23 Pa. The sensitivity of the converter with the 500-nm-thick heater (heater resistance of 215 Ω) is 21.41 V/W at 0.23 Pa, which is higher than the 5.82 V/W in air. This effect is due to the reduced heat loss of the heater in a vacuum.

Figure 7 shows the changes in thermal time constant in accordance with the degree of

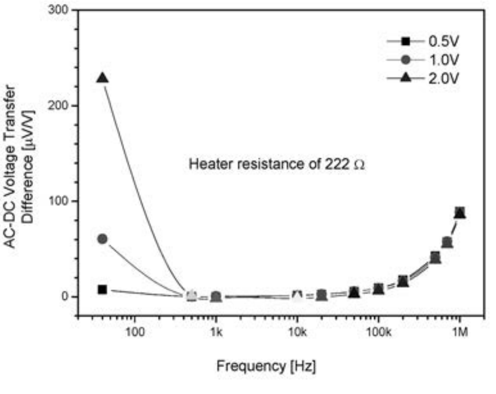


(a)

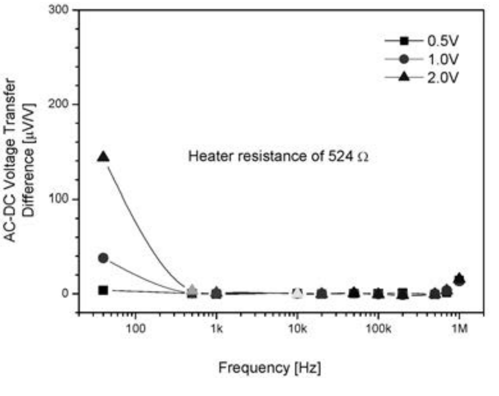


(b)

Fig. 4. (a) Front- and (b) back-side views of a fabricated low-frequency version of a thin-film MJTC.



(a)



(b)

Fig. 5. AC-DC transfer characteristics vs frequency and input voltage: heater thicknesses of (a) 500 nm and (b) 200 nm.

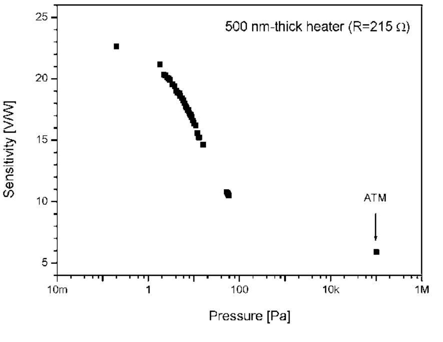


Fig. 6. Voltage sensitivities at various pressures.

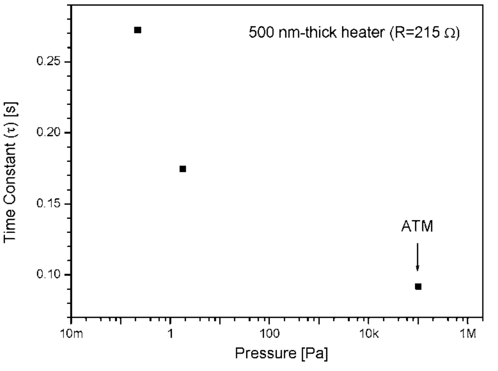


Fig. 7. Thermal time-constant vs pressure.

the vacuum. As illustrated, the thermal time constant increases at lower pressures. Accordingly, the characteristics of the thermal ac-dc converter below 100 Hz were improved over those in air. In other words, Fig. 8 shows that the transfer differences at a frequency of 40 Hz and 1 V of input voltage were 42.1 ppm in regular air and 11.8 ppm at 63 Pa; they decrease at lower pressures.

The transfer differences below 50 kHz for the new thermal converter using the Bosch technique are shown in Fig. 9. The heater resistance of 767 Ω of this device indicates values lower than those of the general thermal converter presented previously. The transfer differences with input voltages of 1.0 V, 2.0 V, 3.0 V, and 4.0 V at 40 Hz are about 2.9 ppm, 14.9 ppm, 29.0 ppm, and 53.3 ppm in air, respectively. We are conducting additional studies to improve the characteristics of our device for practical ac standards.

4. Conclusion

In this study, we designed and developed thin-film MJTCs for use as ac-dc transfer standards. We adopted a Si micromachining technology using KOH etching and an upgraded Bosch process. Highly recommendable were the ac-dc transfer difference characteristics of the elements produced that were acquired in the high frequency range in which the influence of skin effect was controlled by varying thicknesses of heaters. At 200 nm-converter (heater resistance of 524 Ω), the skin effect compensates to some degree for dielectric losses on transfer differences.

When using vacuum packaging to improve higher characteristics in the low-frequency range, we noted valuable results of higher voltage sensitivity, higher thermal time constant, and better ac-dc transfer difference characteristics. In addition, improving the single-step Bosch etching technique enabled us to have higher production yield. The addition of a thermal mass structure also contributed to superior transfer differences in the low-frequency range when using general elements. In the case of the heater resistance of 767 Ω, the transfer difference with input voltages of 1.0 V at 40 Hz was about 2.9 ppm in air.

In summary, developing MJTCs with more reliable characteristics in both high-and

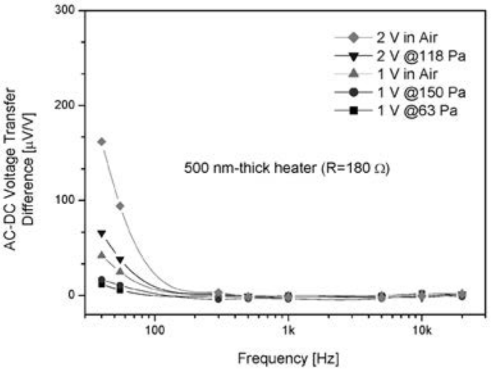


Fig. 8. AC-DC transfer characteristics vs frequency and pressure.

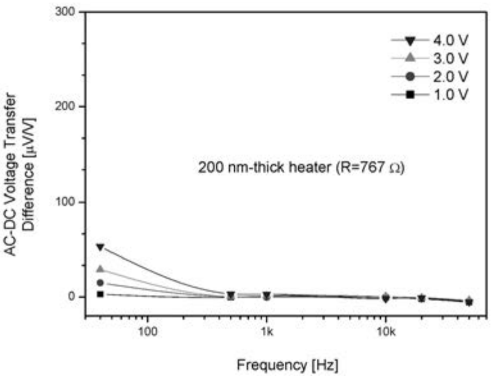


Fig. 9. AC-DC transfer characteristics of new thermal converter.

low-frequency ranges through optimum element design simulation, using more specific processes and using improved measuring devices still must be done. Eventually, these techniques may be applied as national ac-dc standards.

Acknowledgements

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