NEW MODULATED THERMO-COUPLE SENSOR

K.Yagita, K.Hino and J.Nakazoe*
Dept.of Electronics and Communication Eng. Faculty of Eng.
Musashi Institute of Technology, Japan

Abstract:This paper describes a new type temperature sensor using a modulated thermo-couple. The very low drift amplifier and the standard temperature cell used in the conventional thermo-couple sensor are not needed for the proposed sensor driven by modulating ac current. By the modulating current, both the Seebeck effect and the Pertier effect are occurred simultaneously. Therefore the output voltage by the Seebeck effect on the junction is proportional to an absolute temperature of the sensor. Especially, the method of the construction and the behaviors of the muiti-junction of the sensor at low temperature are shown.

Keywords: Thermo-couple, Multi-junction, Modulation

1   INTRODUCTION

A new type of the temperature sensor using a modulated thermo-couple was proposed by Dr.Abe et al. in 1993 [2]. Higher sensitivity of the sensor can be expected without the standard temperature cell and the very low drift dc amplifier in the modulated thermo-couple sensor system. The new proposed sensor is made of the thermo-couples which are driven by an ac current. By the modulating current, both the Seebeck effect and the Pertier effect are occurred simultaneously at the junction of two different metals. The output voltage of the sensor caused by the Seebeck effect between two metals is proportional to an absolute temperature of the junction. Therefore, the standard temperature cell to compare with the ambient temperature and the standard temperature is not needed for the temperature measurement in the system. Since the output voltage of the modulated thermo-couple sensor can be amplified by an ac amplifier, the very low drift dc amplifier is not needed. Hence high performance of the temperature measurement in low drift and low noise could be expected. However, there are some problems that change of sensitivity due to the effect of the joule heating caused by the modulating ac current limits the lowest temperature in measurements. And an error of the temperature measurement is increased by the joule heating of the junction and the sensitivity of the sensor is decreased by the changes of the Seebeck coefficient and the thermal conductivity of the junction at a very low temperature. To overcome these problems, the modulated thermo-couple sensor by use of multi-junctions of the thermo-couple connected in series is proposed in this paper.

2   BEHAVIORS OF THE MODULATED THERMO-COUPLE SENSOR

Fig.1 shows the schematic of the junction in the modulated thermo-couple [2]. The junction of the sensor consists of two uniform materials with an effective length l and an effective cross section S. The heat caused by the Peltier effect due to the modulating current $i = I_m \sin w t$ makes temperature rising DT in the neighborhood of the junction, and the temperature rising DT is determined by the thermal capacitance γ and the thermal conductance J in the junction. The fundamental relationship between the temperature rising DT and the modulating current i can be shown by the equation(1).

Fig.1. Schematic of the junction in the modulated thermo-couple

$$g \frac{d\boldsymbol{DT}}{dT} + J\boldsymbol{DT} = \boldsymbol{a}\,(T + \boldsymbol{DT}\,)I_m \sin\,\boldsymbol{w}t \tag{1}$$

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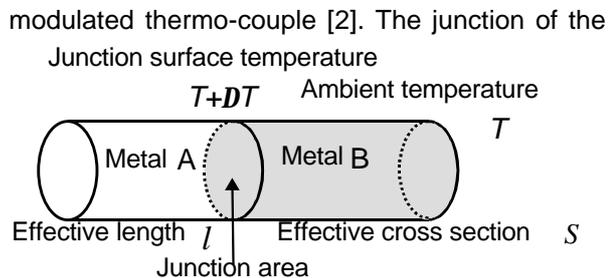
When $T \gg DT$, equation(1) can be rewritten as shown in equation(2)

$$\frac{dDT}{dT} = -\frac{J}{g} \cdot DT + \frac{a \cdot I_m \cdot T \sin wt}{g} \tag{2}$$

Solving DT in the equation(2) the following equation is obtained.

$$DT = \frac{a \cdot I_m \cdot T}{J}\left(\frac{\sin wt}{1+w^2t^2} - \frac{wt}{1+w^2t^2}\right) + \frac{a \cdot I_m \cdot T \cdot wt}{J(1+w^2t^2)}\exp\left(-\frac{t}{t}\right) + C \tag{3}$$

Because $\exp(-t/t) \to 0$ at $t \to \infty$ and an integration constant C=0 by the initial condition (DT =0 at $I_m = 0$), the equation(3) can be rewritten by the equation (4).

$$DT = \frac{a^2 \cdot I_m \cdot T}{J}\left(\frac{\sin wt}{1+w^2t^2} - \frac{wt \cdot \cos wt}{1+w^2t^2}\right) \tag{4}$$

Therefore, the output voltage V_T due to the Seebeck effect of the sensor is shown by the following equation.

$$V_T = a \cdot DT = \frac{a^2 \cdot I_m \cdot T}{J}\left(\frac{\sin wT}{1+w^2t^2} - \frac{wt \cdot \cos wt}{1+w^2t^2}\right) \tag{5}$$

where α : Seebeck coefficient(V/K), $J = lS/l$, J : thermal conductance(W/K), $t = g/J$, t : thermal time const(sec), r :material density(g/cm^3) l : thermal conductivity(W/m/K), C : specific heat(J/Kg/K), $g = CrlS$, g : thermal capacitance, (J/K).

The output voltage V_T consists of the sine and the cosine components in the equation(5). The calculations of two components of the output signal due to the modulating frequency are shown in Fig.2. In the output terminals of the sensor, the modulation output signal and the leakage of the modulating current are arisen simultaneously. Since the sine component $V_{T\sin}$ and the leakage component V_R which is caused by the modulating current in the residual resistance of the sensor are in phase, the sine component is not able to distinct from the leakage component in the output terminals of the sensor. The cosine component $V_{T\cos}$ can be detected by the phase sensitive detector (PSD) for the output signal of the modulator. The frequency at the maximum value of the cosine component $V_{T\cos}$ gives the optimum modulating frequency f_C and the optimum modulating frequency f_C is decided by the thermal time constant t in the relation of $f_C = 1/2pt$.
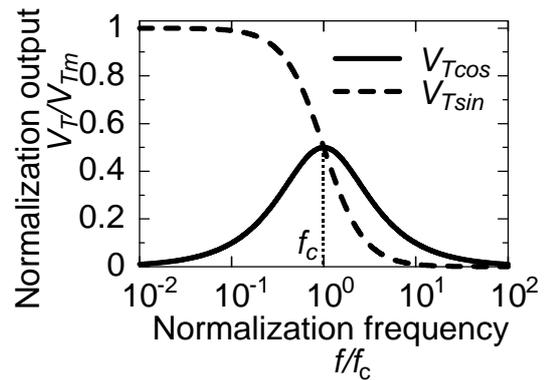

Fig.2. The calculations of two components of the output signal due to the modulating frequency

Substituting parameters of the junction to the equation(5), $V_{T\cos}$ is shown in the equation(6).

$$V_{T\cos} = -\frac{a^2 \cdot I_m \cdot T}{4pg}\frac{1}{f_C}\left(\frac{wt \cdot \cos wt}{1+w^2t^2}\right) = -\frac{a^2 \cdot I_m \cdot T}{4pCrlS}\frac{1}{f_C}\left(\frac{wt \cdot \cos wt}{1+w^2t^2}\right) = -\frac{a^2 \cdot I_m \cdot T}{l}\left(\frac{l}{S}\right)\left(\frac{wt \cdot \cos wt}{1+w^2t^2}\right)$$

(6)

It is desirable that the Seebeck coefficient a is large and, the effective cross section S of the junction of the thermo-couple is small in order to improve the output voltage of the modulator in the equation(6).

3 OPERATION OF THE MULTI-JUNCTION TYPE OF THE MODULATED THEMO-COUPLE

Fig.3 shows the structure of the multi-junction type of the modulated thermo-couple[2][4]. It is assumed that all effective cross sections of all junctions are equal. Heating by the Pertier effect is produced by the modulating current and then the electromotive force $+V_T$ by the Seebeck effect is caused simultaneously at the junction1, when a_1 of the copper is smaller than a_2 of the constantan shown in Fig.3. On the other hand, the heat absorption according to the Pertier effect is generated at the junction2, and polarity of the electromotive force $+V_T$ by the Seebeck effect of the junction2 is equal to that of the junction1, because the direction of the junction2 is reverse. It is assumed that the same operations are happened in other junctions. Since the junction is alternately in the reverse connection, the direction of each junction cancels the output voltage of each junction by the Joule heating of modulating current. Therefore, the output voltage of the sensor in series which has n pieces of the junction becomes $+nV_T$.
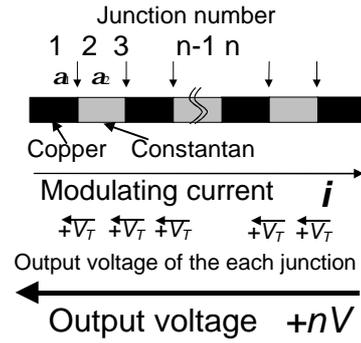

Fig.3. Multi-junction type

4 MEASUREMENT SYSTEM

The equivalent circuit of the modulated thermo-couple is shown in Fig.4. There are the leakage component V_R of the modulating current which arises in the residual resistance of the thermo-couple and both the sine and cosine components $V_{T\sin}, V_{T\cos}$ as shown in the output of the modulator. The leakage component V_R by the modulating current is more than 60 dB of the output signal $V_{T\cos}$ in the thermo-couple system. Then, the bridge circuit which includes the thermo-couple is used as shown in Fig.5 and the leakage component V_R is decreased by adjusting the bridge circuit. The unbalance signal of the bridge is amplified by the ac amplifier whose gain is 110 dB and is demodulated by the phase sensitive detector(PSD). The PSD feeds the sine component to the gate of the FET to achieve automatic balance condition of the bridge with changing of the resistance between the source and the dorein of the FET. Total attenuation of the output voltage of the PSD to the original leakage V_R will be established about −130 dB. On the other hand, the PSD feeds the cosine component $V_{T\cos}$ of the output signal to output terminals.
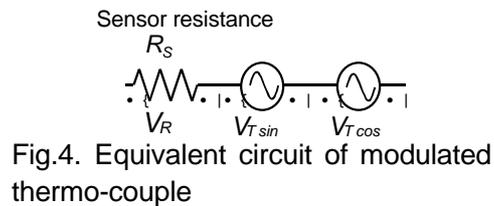

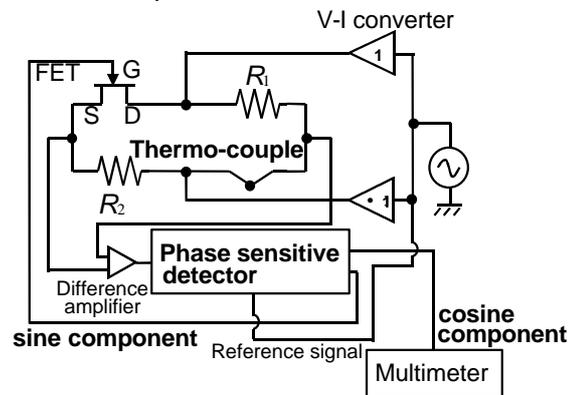Fig.4. Equivalent circuit of modulated thermo-couple

Fig.5. Measurement system

5 TEMPERATURE DEPENDENCY ON SENSITIVITY

This thermo-couple is constructed the copper and the constantan wires. The output voltage $V_{T\cos}$ of the modulator is proportional to the a^2 and is reverse proportional to the l as shown in the equation(6). With the lowering ambient temperature, the Seebeck coefficient a decreases and the thermal conductivity l increases. Therefore, the output voltage $V_{T\cos}$ of the modulator is decreased by changes of parameters a and l , and it is found that decrease of the sensitivity can be inevitable in the temperature measurement system with the modulated thermo-couple sensor. As a results, the ratio of the sensitivities between ambient temperatures of 50 K and 300 K becomes about 1/30.

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6   THE MULTI-JUNCTION TYPE THERMO-COUPLE

Fig.6 shows 3 thermo-couple sensors A, B and C, and the combinations of A and B, and of A, B and C in series. Since the resistance of the constantan wire is about 40 times of that of copper wire, the internal resistance of the sensor is almost governed by the constantan wire. The thermal agitation noise in the internal resistance limits the lowest output signal voltage of the sensor. When n junctions are connected in series, the total internal resistance and the resultant value of the output voltage of the series connected junction sensor are n times of these of one-junction sensor.
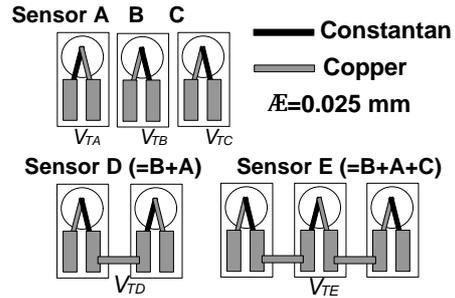

Fig.6. Explanation of measurement

Since the output voltage of the junction is proportional to the modulating current I_m, the output voltage of the n junction sensor is equal to that of the one-junction sensor when the modulating current is $1/n$ times of that of the one-junction sensor. Therefor, all joule heating of junctions of the sensor will be decreased by $1/n$ times of the modulating current. When the lowest output signal level is equal to the voltage of the thermal agitation noise in one-junction, signal/noise ratio of the multi-junction sensor is proportional to $\sqrt{n}$. It is found that improvement of signal/noise ratio can be achieved by the use of the series junction sensor in the temperature measurement system.

7   EXPERIMENTS AND DISCUSSION

Fig.7 shows frequency dependencies on the output voltages of the one-junction sensor (A, B and C), 2 junction sensor (D=A+B) and 3 junction sensor (E=A+B+C) shown in fig.6. The optimum modulating frequency f_C is decided by choosing the maximum value of the output voltage. From the experiment results, the each optimum frequency related to the output voltage of the sensor is shown individually in Table 1.It is found that the output voltages and the optimum modulating frequencies are proportional to the number of the junction in the sensor. Both the output voltages of two sensors(D,E) are experimentally larger than resultant values of the each sensor(A+B,A+B+C) respectively. Values of a, C, r are constant when values of I_m and T do not change at the measurement condition in the equation (6). Therefore, it seems that the effective length l and the effective cross section S of the junction are decreased by the use of the series connection of junctions. Then, when the amount of change of l and the amount of change of S are Dl and DS respectively, it seems that increasing of the $V_{T\cos}$ is mainly governed by the value of DS. While the optimum modulating frequency f_c is expressed in the following equation (7).

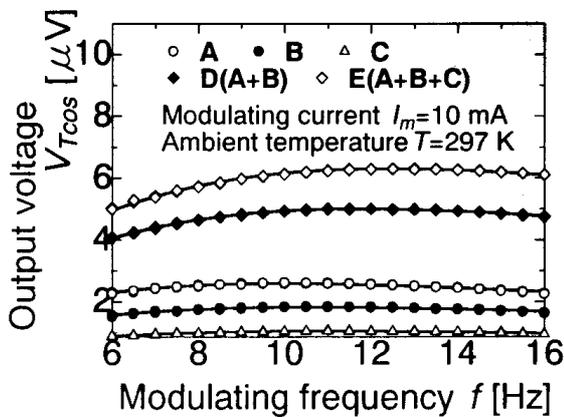$$f_C = \frac{1}{2pt} = \frac{J}{2pt} = \frac{lS}{2pgl} = \frac{l}{2pCr} \cdot \frac{1}{l^2} \tag{7}$$

Fig.7: Output voltages due to the modulating frequency

Table1. The maximum values of output voltages and optimal operating frequencies of sensors

	Output voltage V_{Tm} μV]	Optimal modulating frequency f_c [Hz]
SensorA	**2.62**	**10**
SensorB	**1.85**	**10.5**
SensorC	**1.07**	**11**
SensorD	**5.02**	**11.5**
SensorE	**6.32**	**12.5**
Resultant values		
Sensor A+B	**4.47**	**10.5**
Sensor A+B+C	**5.54**	**10.5**

In the equation (7) and the experiments, it is seen that the decrease of the effective length Dl causes the increase in the optimum modulating frequency f_c and it can be clearly explained that the experimental values are greater than that of resultant values of the output voltage in the series connected junction.

The ten junction-sensor is shown in Fig.8. The experimental results of the ten junction sensor are shown in Fig.9~Fig.12. Small copper sheets between junctions are used for radiating joule heating of the junction and decreasing interference of thermal connection between adjacent junctions as shown in Fig.8.

The modulating frequency characteristics of the output voltage of the ten junction sensor is shown in Fig.9. The maximum values of the output voltage of 32 μV, which is 12 times of the output voltage of one junction sensor is established. The optimum modulating frequency f_c of 15 Hz is achieved, which is 1.4 times of the one junction. The output voltage due to the modulating current is shown in Fig.10. The output voltage is proportional to the modulating current and is deviated from the linear relation in the range of more than 30 mA of the modulating current. It is estimated that the deviation from the linear relation will be effected by increasing joule heating by the modulating current.

The temperature dependencies on each output voltages which are normalized output voltage at 297 K of the modulator, at a range from 97 K to 297 K of ambient temperatures when the each modulating current I_m is 10 mA, 20 mA, 30 mA and 40 mA respectively, are shown in Fig.11. Calculations by the equation(6) are shown by the solid line when joule heating of the junction is neglected. It can be seem that the output voltage of the modulator in the temperature range less than 200 K is more than the calculated value as the ambient temperature T of the sensor drops. It can be estimated that increasing of the output voltage of the modulator at low temperature is due to joule heating by the modulating current, and limits the lowest temperature of the measuring sensor. Since the output voltage $V_{T\cos}$ of the junction is proportional to the modulation current I_m, the output voltage $V_{T\cos}$ is decreased when the modulating current I_m lowers. Therefore, the multi-junction sensor driven by low modulating current is useful for increasing the output voltage. In the multi-junction sensor, when n is the number of junction and the modulating current decreases to the value of $1/m$ times, the resultant value of the output voltage at the ambient temperature T is $(n/m) \cdot V_{T\cos}$ and the resultant value of the output voltage by joule heating is $(n/m^2) \cdot V_J$. If m is equal to the number of the junction n, the ratio of two output voltages, $(n/m) \cdot V_{T\cos}/(n/m^2) \cdot V_J$ is proportional to n. Because, the experimental
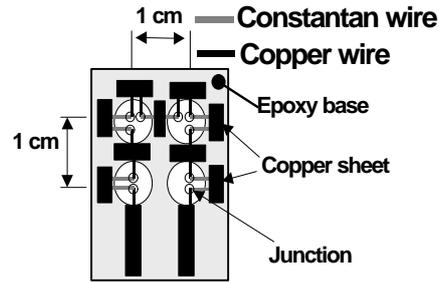

Fig.8. Wiring pattern of ten junction sensor
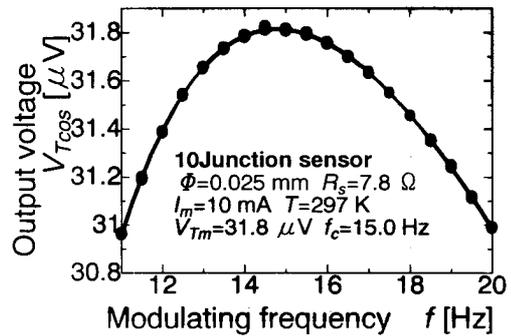

Fig.9. The modulating frequency characteristics of the output voltage
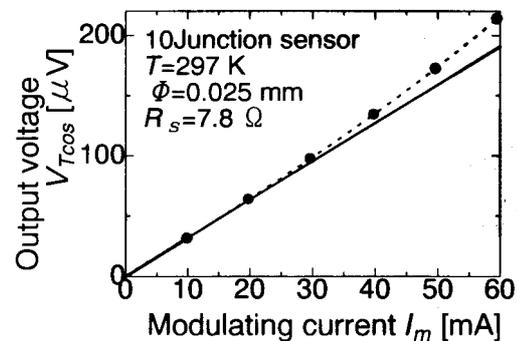

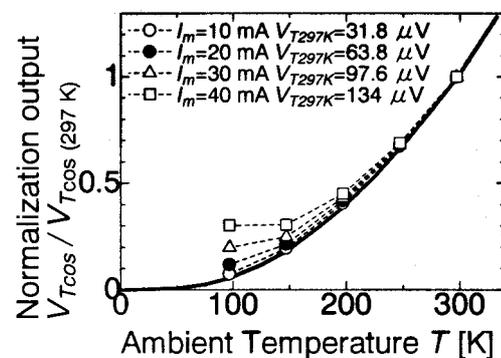Fig.10. The output voltage due to the modulating current

Fig.11. The temperature dependencies on output

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results of the output voltage are equal to the calculations, the effect of joule heating of the junction can be neglected when the modulating current is 10 mA. For example, when 10 junctions with the modulation current of 10 mA are used, the calculation of the output voltage $V_{T\cos}$ of the sensor at the ambient temperature T =50 K becomes about 0.2 µV, considering changes junction parameters a and l. However, by abrupt changes of a and l, calculation of the output voltage of the junction decreases to the about 0.64 nV at less than very low temperature of 10 K.

8   CONCLUSION

In this paper, new modulated thermo-couple sensor is described based on the principle of the modulation type of the thermo-couple sensor which has been proposed by the Dr. Abe. at all in 1993. The output of the new modulated thermo-sensor can be increased by the use of the series connection of 10 junctions. Therefore, it can be found that the lowest temperature of the present sensor will be less than 50K by decreasing joule heating with the modulating current in the system experimentally. In addition, the multi-junction thermo-couple sensor with more junctions will be able to expect the improvement of the performance if the integrated circuit of the thermo-couple becomes possible in the future.

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AUTHORS: Dept. of Electronics and Communication Eng, The Faculty of Eng. Musashi Institute of Technology, 1-28-1 Tamazutsumi, Setagaya-ku, Tokyo, Japan, Phone Int 03 3703 3111(extension2948), Fax 03 5707 2177 E-mail: hino@ee.ec.musashi-tech.ac.jp
*K.Yagita will belong to ADVANTEST in April, 2000.