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Design of Cold-Junction Compensation and Disconnection Detection Circuits of Various Thermocouples and Implementation of Multi-Channel Interfaces Using Them — A Secondary Publication

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Abstract: Cold-junction compensation (CJC) and disconnection detection circuit design of various thermocouples (TC) and multi-channel TC interface circuits were designed. The CJC and disconnection detection circuit consists of a CJC semiconductor device, an instrumentation amplifier (IA), two resistors, and a diode for disconnection detection. Based on the basic circuit, a multi-channel interface circuit was also implemented. The CJC was implemented using compensation semiconductor and IA, and disconnection detection was detected by using two resistors and a diode so that IA input voltage became -0.42 V. As a result of the experiment using R-type TC, the error of the designed circuit was reduced from 0.14 mV to 3 μV after CJC in the temperature range of 0°C to 1400°C. In addition, it was confirmed that the output voltage of IA was saturated from 88 mV to -14.2 V when TC was disconnected from normal. The output voltage of the designed circuit was 0 V to 10 V in the temperature range of 0°C to 1400°C. The results of the 4-channel interface experiment using R-type TC were almost identical to the CJC and disconnection detection results for each channel. The implemented multi-channel interface has a feature that can be applied equally to E, J, K, T, R, and S-type TCs by changing the terminals of CJC semiconductor devices and adjusting the IA gain.

Keywords: R-type thermocouple (TC); Cold-junction compensation (CJC); TC disconnection detection; Multi-channel interface circuit; Sensor interface

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1. Introduction

High-temperature, high-precision heat treatment devices are rapidly increasing in the industries of semiconductors, new materials, and MEMS (Micro Electro Mechanical Systems). In these heat treatments, it is important to have a temperature control device that maintains a constant temperature in the chemical processing area (e.g., 300 mm wafer oxidation and deposition process) and verifies the presence of abnormalities (breaks, short circuits).

Although the localization of various semiconductor manufacturing equipment is actively taking place in Korea, in the case of electric furnaces, high-temperature heaters and temperature controllers are imported and the entire electric furnace is localized. For the temperature control of an electric furnace for 300 mm wafers, it is necessary to control the temperature in a quartz tube with a diameter of 400 mm and a height of 1.5 m to ensure that the set temperature is constant in the range of 0°C to 1400°C. In this case, the tube is divided into four zones, and thermocouple (TC) temperature sensors are used for precise temperature control.

Figure 1 shows the voltage characteristics generated by various TCs as the temperature changes. From this figure, it can be seen that TCs of types R, S, and B should be used for measuring temperatures ranging from 0°C to 1400°C. Since all TCs are temperature sensors that generate voltages at arbitrary temperatures with 0°C as the reference, the electromotive force must be corrected for 0°C, which is the cold junction for room temperature (25°C) [1].

A primitive method of cold-junction compensation is to use ice water to measure electromotive force by placing TC1 outside (the environment to be measured) and TC2 inside the ice, as shown in **Figure 2**. In this case, it is difficult to apply in practice because the measurement system is complex, has a large appearance, and is particularly difficult to supply ice. These problems have recently been solved using zero-calibration semiconductor chips [1-3].

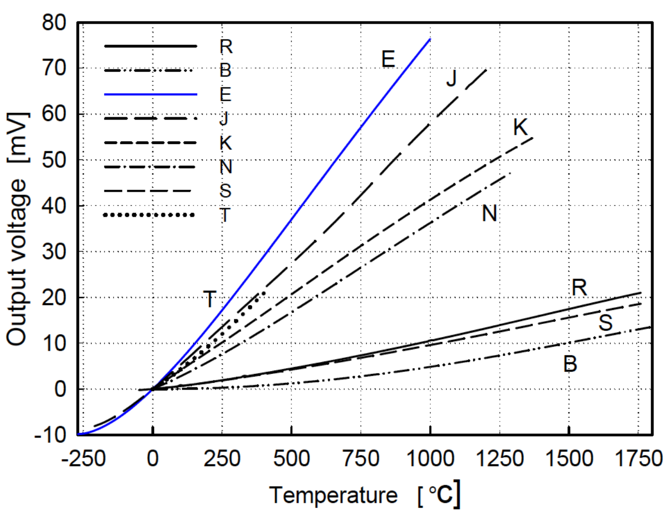

Figure 1. Voltage characteristics generated according to temperature for each type of TC

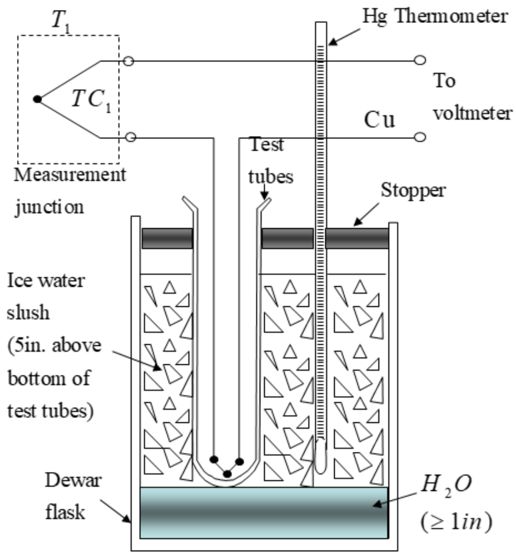

Figure 2. Physical coolness correction principle of TC

In addition, since the TC is open due to degradation when used at high temperature for a long time, it is essential to have a function to detect the breakage of the TC in order to quickly maintain the heat treatment device. In general, electric furnaces used in semiconductor processes use four or more multichannel TCs, so it is possible to use a high-performance microprocessor to measure the temperature, check for breaks, and linearize the TCs by program coding.

Prior to this study, we presented a cold-junction compensation (CJC) and disconnection detection circuit of R-type TC sensor for localization of temperature controller of electric furnace for 300 mm or larger wafers [4]. In this paper, the applicability of various TCs was not confirmed, and it was suggested that multi-channel application was possible for R-type TCs. Since then, Microchip has developed a dedicated chip that can use various TCs (e.g., K, J, T, N, S, E, B, R-type) and commercialized it as a temperature-to-digital signal conversion module [6-8]. In this case, it was possible to process signals from multiple TCs through I^2C communication. However, in this case, depending on the number of TCs used, a conversion module is required, and additional circuits are required to detect disconnection.

In this study, we investigate whether CJC and disconnection detection circuit can be applied not only to R-type TC sensors but also to E, J, K, T, and S-type TCs, and design a complementary design. Based on the designed circuit, a cold compensation and open wire detection interface that can be used up to multi-channel (using n TCs) is designed and its performance is analyzed.

2. Circuitry and how it works

2.1. Behavioral characteristics of TCs

As shown in **Figure 3**, a TC is a device that generates electromotive force by the seedback effect when two dissimilar materials are joined and then subjected to a temperature difference, and the electromotive force is proportional to the temperature difference between the cold junction of 0°C and any temperature. The electromotive force of TC is given by the following formula [3].

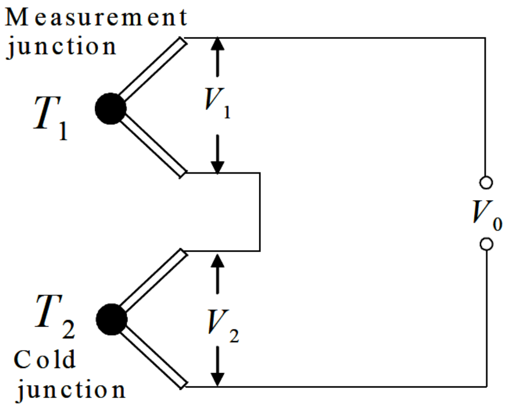

Figure 3. Principle diagram of voltage generation in TC

$$V_O = V_1 + V_2 = \alpha(T_1 - T_2) + \gamma(T_1^2 - T_2^2) \quad (1)$$

Here, α and ɣ are constants given by the junction material and T_1 and T_2 are the respective temperatures for V_1 and V_2. From **Figure 3** and Equation (1), it can be seen that if we make T_2 = 0°C, V_2 = 0V, and Equation (1) is given by $V_0 = V_1 = \alpha T_1 + ɣ$. In addition, at room temperature (20°C), $T_1 = T_2$ and $V_0 = 0$, so the TC sensor cannot measure the room temperature. Therefore, the voltage compensation of the TC for the room temperature, that is, the cold-junction compensation (CJC) must be performed so that V_2 is 0V.

TCs differ in their measurable temperature range, magnitude of electromotive force, and linear characteristics depending on the material being junctioned. In the case of electric furnaces, R-type TCs are commonly used because they are always in a standby state and the process time is repeated. The R-type TC generates electromotive force from 0 mV to 16.04 mV from 0°C to 1400°C and has a temperature sensitivity of 11.457 μV/°C.

2.2. Working principle of cold-junction compensation (CJC) semiconductor devices

Figure 4 shows the pin designation (a) and internal block diagram (b) of the TC CJC semiconductor device

(LT1025). The chip has four outputs of 60.9 μV/°C (E-type TC), 51.7 μV/°C (J-type TC), 40.6 μV/°C (K and T-type TC), and 6 μV/°C (R and S-type TC) [5]. The internal block consists of a temperature sensor with a sensitivity of 10 mV/°C, a bow correction voltage, an amplifier (buffer), and a TC-specific temperature sensitivity (slope) adjustment resistor.

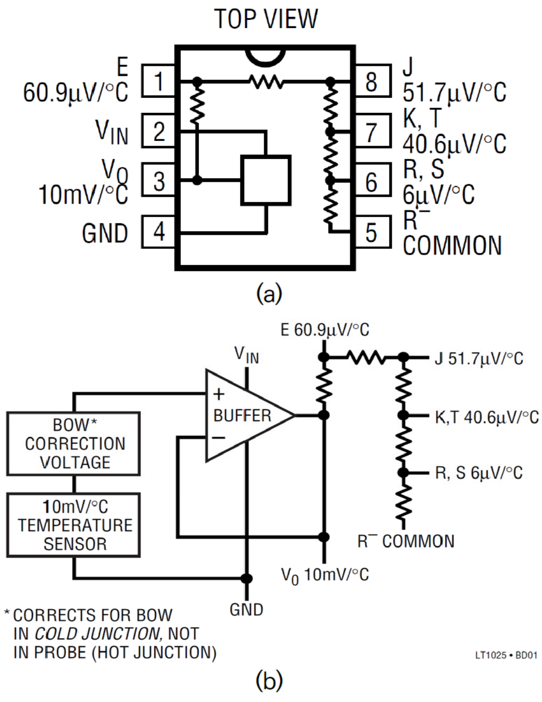

Figure 4. (a) Pin name and (b) internal block diagram of TC's CJC semiconductor chip (LT1025)

2.3. Conventional K-type TC cold compensation interface circuit

The cold compensation circuit of a conventional K-type TC is shown in **Figure 5** [5]. The circuit consists of a cold compensation device LT1025, a K-type TC, and a voltage amplifier [4]. This circuit has a sensitivity of 10 mV/°C for the output voltage depending on the temperature, but there is a problem that the output voltage becomes 0V when the TC is disconnected, so it is not possible to distinguish whether the output of the TC is actually at 0°C or disconnected. In particular, no compensation circuit for R-type TCs has been announced, and no disconnection detection circuit has been announced.

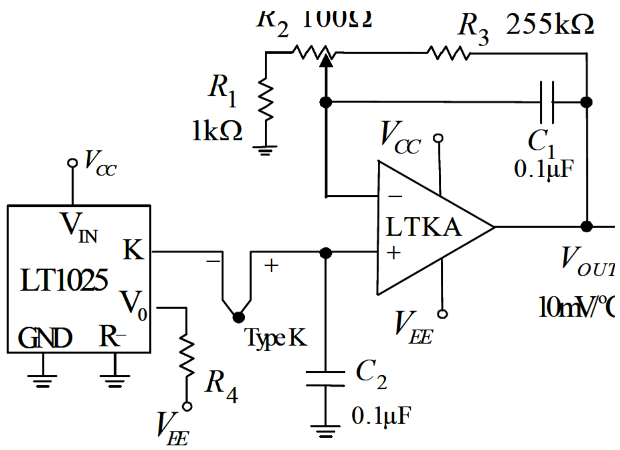

Figure 5. Schematic of conventional K-Type TC interface [5]

2.4. Design of cold-junction compensation and disconnection detection circuits of various TCs and multi-channel application circuits

2.4.1. Design of cold-junction compensation and disconnection detection circuit for various TCs

A circuit to detect cold-junction compensation and TC disconnection for various TCs was designed, and the designed circuit is shown in **Figure 6**. The circuit consists of 1) a cold-junction compensation device LT1025, an R-type TC, a gain adjustment resistor RG, and an instrument amplifier (IA) for cold-junction compensation, and 2) a circuit consisting of R_1, R_2, D_1, and IA for disconnection detection.

The principle of cold-junction compensation is as follows. In other words, if only the first term in the TC electromotive force characteristic in Equation (1) is considered, the electromotive force of an R-type TC sensor under room temperature conditions can be represented by Equation (2).

$$\begin{aligned} V_{TC}(R) &= \alpha(T_P - T_{ROOM}) + \alpha T_{CJC} \\ &= \alpha T_P - \alpha T_{ROOM} + \alpha T_{CJC} \end{aligned} \qquad (2)$$

Where T_P is the temperature of any space where the TC sensor measures the temperature (in the case of an electric furnace, the temperature in the quartz tube), T_{ROOM} is the room temperature, and T_{CJC} is the cold-junction compensation temperature.

Generally, the arbitrary space has a temperature corresponding to room temperature, so the electromotive force of the TC sensor is 0V because $TP = T_{ROOM}$ is established at room temperature. However, since the TC generates electromotive force for any temperature difference relative to 0°C, it is necessary to add the electromotive force αT_{CJC} corresponding to room temperature, that is, $-\alpha T_{ROOM} + \alpha T_{CJC} = 0$. Therefore, if R_2 is very large in the circuit shown in **Figure 6**, this resistor can be considered open, so $V_{IN} = \alpha T_P$, and the electromotive force equal to the value in the characteristic table of the R-type TC is obtained. This electromotive force is the input to the instrumentation amplifier (AD620), so the final output voltage V_{OIA} of the cold-junction compensation circuit is given as follows [10].

$$V_{OIA} = \left(\frac{49.4\text{k}}{R_G} + 1\right)\alpha T_P \qquad (3)$$

Since the electromotive force is 0 mV–16.04 mV for the R-type TC in the temperature range of 0°C–1400°C, using the above equation, $R_G = 79.4\ \Omega$ (gain is 623.44) can be used to obtain an output voltage of 0–10 V, and $R_G = 158.84\ \Omega$ (gain is 311.72) can be used to obtain an output voltage of 0–5 V.

In the circuit diagram of TC cold compensation and disconnection detection shown in **Figure 6**, R (pin 6) of the LT1025 chip is used for R-type TC, but E (pin 1), J (pin 8), K and T (pin 7), and S (pin 6) terminals of the LT1025 chip shown in **Figure 4** can be used to perform cold-junction compensation and disconnection detection for each TC at the same time by using E, J, K, T, and S-type TC. In other words, if other TCs are used as shown in **Figure 6**, the value of R_G, which adjusts the gain of the measurement amplifier in the dotted circuit, must be changed, and the terminals of the LT1025 chip can be used for that TC.

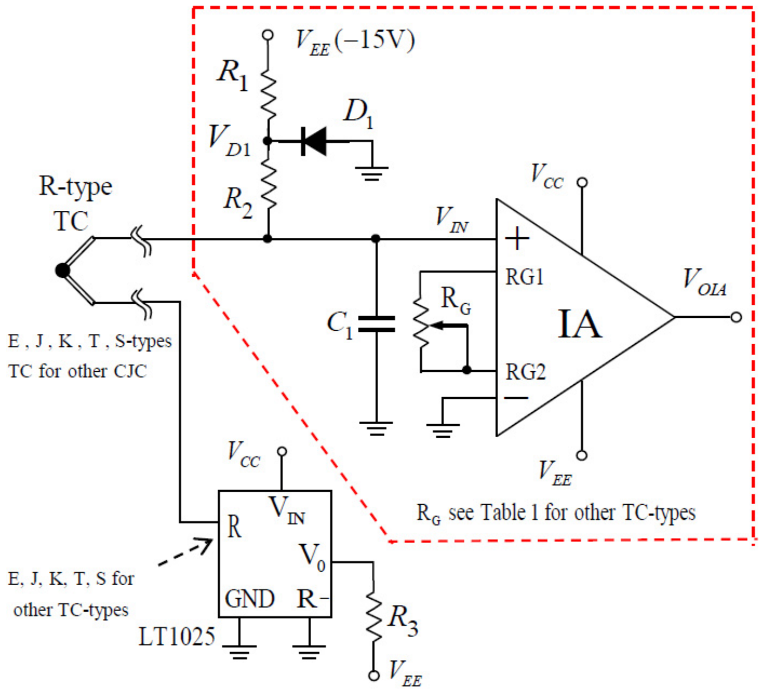

Figure 6. Cold-junction compensation and disconnection detection circuit diagram of various TCs [4]

Since the TCs have different sensitivities to temperature and different electromotive forces at room temperature (25°C), the gain of the measurement amplifier must be adjusted separately. For various TCs, the measuring temperature range, electromotive force range, gain of the measurement amplifier, and R_G value for each TC to obtain 0–10 V output of the measurement amplifier are shown in **Table 1**.

Table 1. Measuring temperature range and output voltage of TCs, gain of the instrumentation amplifier (IA), and R_G of IA for each TC to obtain the output voltage of 0–10 V of IA

TC type	Temperature range (°C) [6]	Output voltage of TC (mV) [6]	Gain of IA	R_G (Ω)
E	0–1,000	0–76.37	130.09	382.68
J	0–1,200	0–69.55	143.78	345.98
K	0–1,350	0–54.82	182.41	272.31
T	0–400	0–20.87	479.16	103.31
S	0–1,760	0–18.61	537.34	92.11

2.4.2. Principle of TC disconnection detection circuit

If the TC is disconnected, the circuit in **Figure 6** can be modified as shown in **Figure 7** [4]. In this circuit, D_1 is forward through -15 V (V_{EE}), R_1, D_1, and ground, resulting in $V_{D1} \cong$ -0.6 V (forward voltage of the diode). When TC is disconnected, the voltage accumulated on C1, $V_{IN} = \alpha T_P$, discharges to -0.6 V through R_1 and R_2, so V_{IN} can be represented as follows.

$$V_{IN} = a T_P - \frac{(a T_P + V_{D1})}{C_1 (R_1 + R_2)} t \qquad (4)$$

From this expression, it can be seen that $V_{IN} \simeq -V_D$ when time t becomes equal to the time constant $C_1(R_1+R_2)$. For R-type TCs, V_{IN} will have a value close to -0.6 V because the maximum value of αT_P is about 16 mV. This voltage is converted to a negative saturation voltage by the measurement amplifier IA. Therefore, since the temperature change value of the TC is converted to a positive voltage, it can be judged that the TC is disconnected when the measurement amplifier output voltage is converted from a positive voltage to a negative saturation voltage. In other words, if the output V_{OIA} of the measurement amplifier is a negative saturation voltage, the TC is disconnected. Therefore, the circuit shown in **Figure 7** can be used to detect the breakdown of various TCs, namely E, J, K, T, and S-type TCs. However, the value of the gain adjustment resistor R_G of the measuring amplifier should be adjusted as shown in **Table 1** according to the TC.

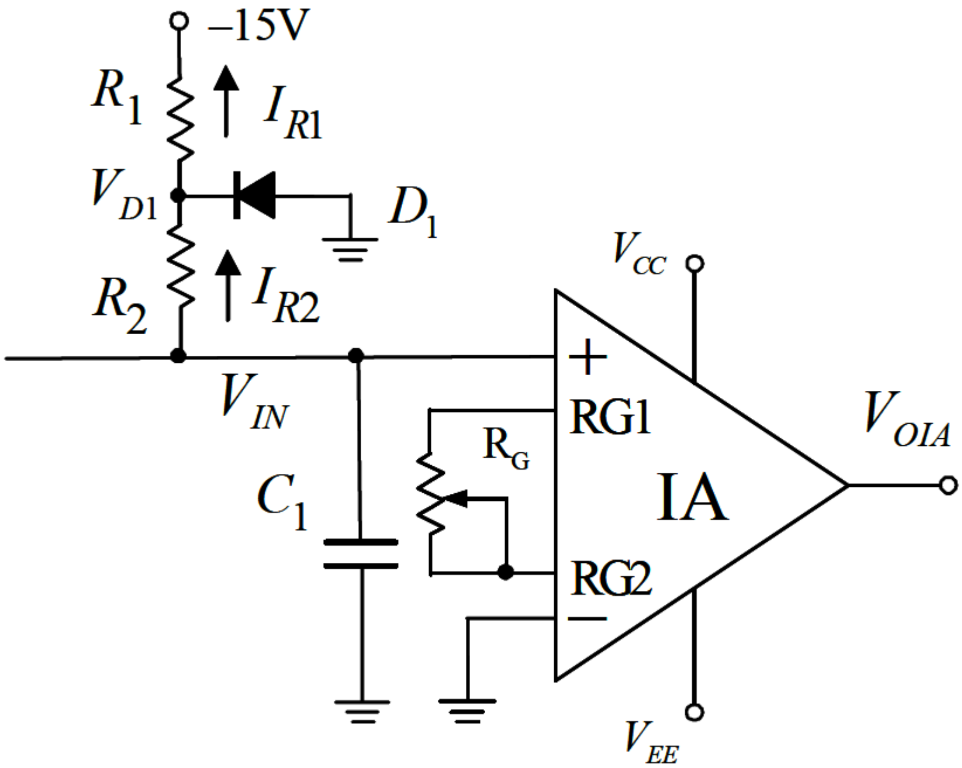

Figure 7. Circuit diagram explaining the TC open detection principle

2.4.3. Interface circuit design for multi-channel, various TC cold-junction compensation and disconnection detection circuit

Based on the cold-junction compensation (CJC) of various TCs and the TC disconnection detection circuit shown in **Figure 6**, multi-channel TC cold-junction compensation and disconnection detection can be designed for various TCs, and the interface circuit applicable to multi-channel R-type TCs or E, J, K, T, S-type TCs is shown in **Figure 8**. The circuit consists of n TCs, one cold-junction compensation semiconductor, n break detection circuits and instrumentation amplifiers, a multiplexer (MUX) to select one of the multichannel TCs, and an instrumentation amplifier to amplify the final input signal to an analogue-to-digital (A/D) converter.

In **Figure 8**, the R terminal of the LT1025 is connected as a TC, so TC1 to TCn can be used as R-type TCs. When used as a multichannel interface to E, J, K, T, and S-type TCs, the E, J, K, T, and S terminals of the LT1025 device (**Figure 4**) can be used and the corresponding TCs can be used. Moreover, since the electromotive force is different depending on the TC, the value of R_3 inside the dotted line in **Figure 8** can be selected as the resistor value shown in **Table 1**.

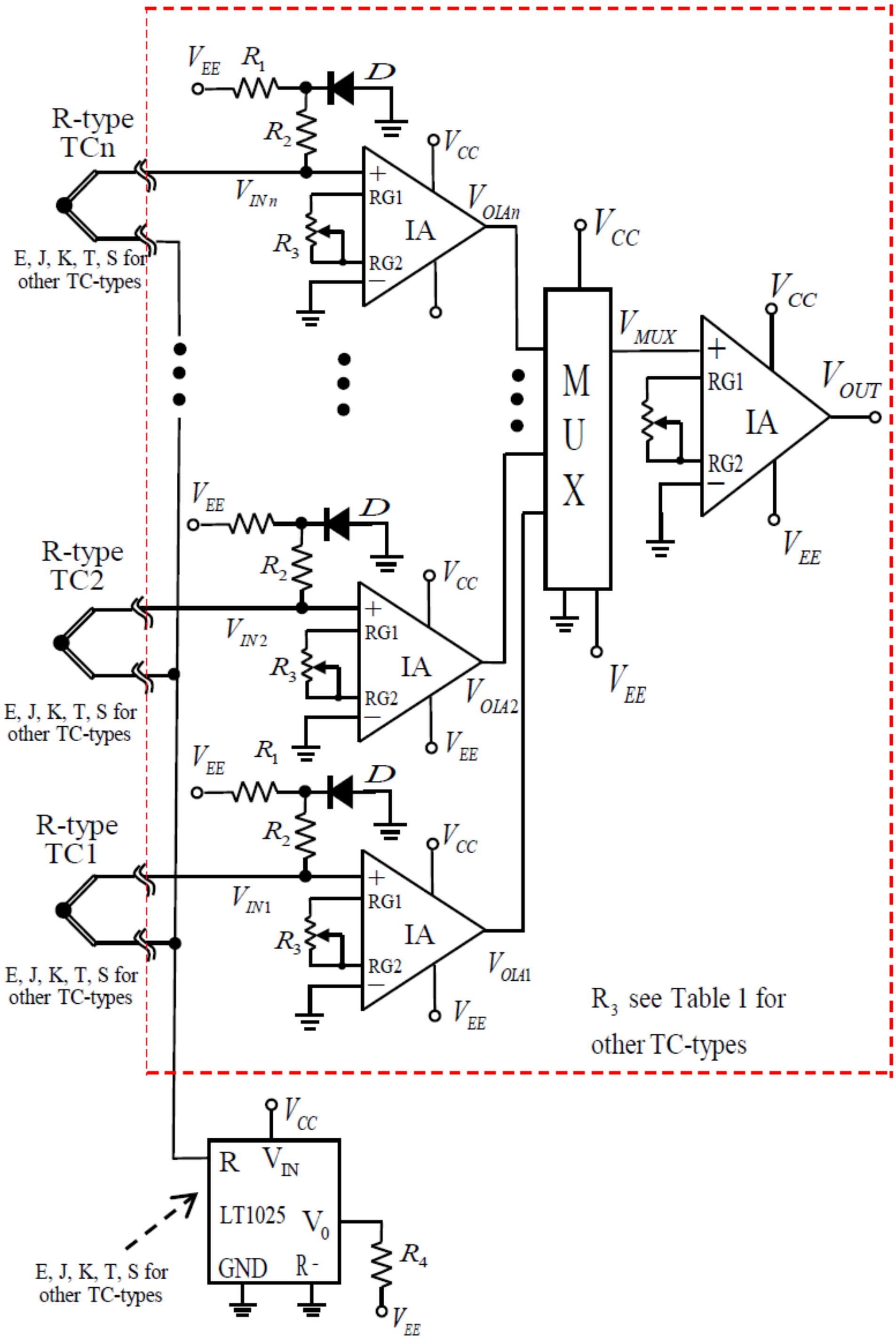

Figure 8. Interface circuit applicable to multi-channel R-type TC or E, J, K, T, S-type TC based on Figure 6

Using the multichannel (n) cold-junction compensation and disconnection detection circuit shown in **Figure 8**, which is implemented with a measurement system consisting of a 16-bit or higher A/D converter and a microprocessor, it is possible to measure the temperature at n different locations and detect whether the TC used at each location is disconnected.

3. Results

The designed **Figures 6** and **8** were experimented using individual devices. The devices used are D_1 = IN4937, IA = AD 620, MUX = ADG406, CJC device = LT1025, R_1 = 10 MΩ, R_2 = 50 MΩ, R_G = 79.4 Ω, C_1 = 1 μF. The supply voltage was set to V_{cc} = 15 V and V_{EE} = -15 V. In addition, among the E, J, K, T, R, and S-type TCs in **Figures 6** and **8**, the R-type TC of Sentech, which is widely used in electric furnaces and is semiconductor processing equipment, was used [2,9]. In the circuit in **Figure 8**, the circuit for 4 channels was verified through experiments with n = 4.

Figure 9 shows the difference between the input voltage V_{IN} of the measurement amplifier and the electromotive force output given in the characteristic table of the R-type TC for the case of cold-junction compensation in the circuit shown in **Figure 6**. The temperature-dependent electromotive force of the R-type TC was used as an input signal using YOKOGAWA's TC Calibrator CA320 [10-12]. In the graph in **Figure 9**, the dotted line shows the difference between the V_{IN} and TC electromotive force before cold-junction compensation, and the solid line shows the difference between the V_{IN} and TC electromotive force after cold-junction compensation. From this result, it can be seen that the difference between the TC's electromotive force and the input voltage V_{IN} is 3 μV in the temperature range of 0°C–1400°C through cold-junction compensation. In other words, the error after zeroing the TC is reduced from 0.14 mV to 3 μV, which is a reduction of about 97.8%.

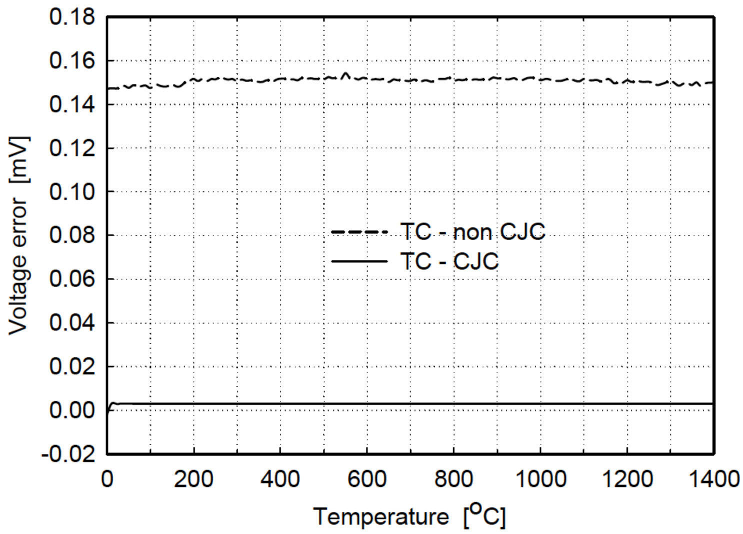

Figure 9. Input voltage error for the cold-junction compensation result of the circuit shown in Figure 6

Figure 10 shows the output voltage of the instrumentation amplifier (IA) with and without cold-junction compensation in the circuit shown in **Figure 6**. Here, R_G = 79.4 Ω was set to increase the gain by 632.44 times to output a voltage of 0 V to 10 V for temperatures from 0°C to 1400°C. In the graph in **Figure 10**, the solid line is the instrumentation amplifier output voltage before cold-junction compensation and the dashed line is the result of cold-junction compensation. From this result, it can be seen that the output voltage for the temperature range of 0°C–1400°C can be accurately obtained from 0–10 V by cold-junction compensation.

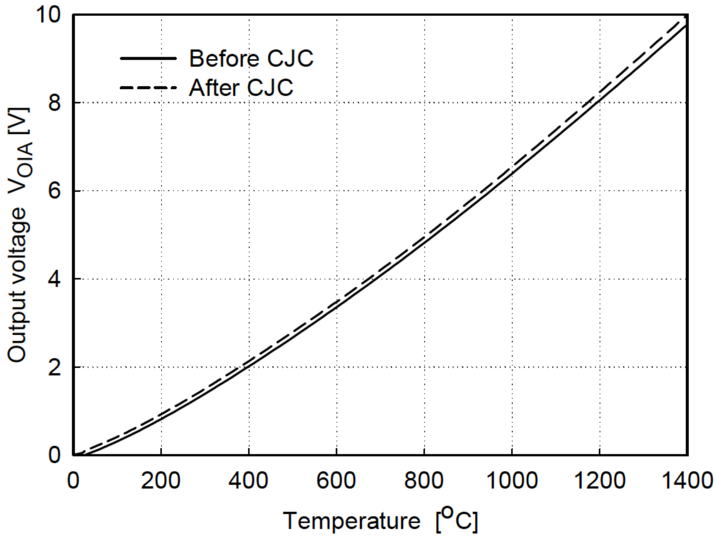

Figure 10. Output voltage of the result of cold-junction compensation for the circuit shown in Figure 6

In the circuit shown in **Figure 8**, the input voltage V_{IN} and output voltage V_{OIA1} to V_{OIA4} of the instrumentation amplifier (IA) are shown in **Tables 2** and **3**, respectively, when four R-type TCs are used in the 4-channel interface circuit and one is disconnected. From **Table 2**, it can be seen that the input V_{IN} is about -421 mV when each TC is disconnected, and the V_{IN} is about 0.14 mV when the TC is not disconnected (electromotive force of the TC at room temperature 25°C).

Table 2. Input voltage status of IA when TC is disconnected in the circuit of **Figure 8**

	TC1	TC2	TC3	TC4
Vin1 [mV]	-421.0	0.141	0.141	0.141
Vin2 [mV]	0.141	-420.5	0.141	0.141
Vin3 [mV]	0.141	0.141	-420.6	0.141
Vin4 [mV]	0.142	0.141	0.141	-420.5

From **Table 3**, it can be seen that the output voltage V_{OIA} is about -14.22 V when each TC is disconnected and about 87 mV (= 0.14 mV × 632.44) when it is not disconnected, as a result of amplifying the input signal of the TC by about 632.44 times with an instrumentation amplifier. Therefore, it is possible to measure V_{OIA} using an A/D converter and program the TC to be disconnected if a negative voltage appears.

Table 3. Output voltage status of IA when TC is disconnected in the circuit of **Figure 8**

	TC1	TC2	TC3	TC4
V_{OIA1} [V]	-14.215	0.087	0.088	0.087
V_{OIA2} [V]	0.087	-14.215	0.087	0.088
V_{OIA3} [V]	0.088	0.088	-14.215	0.088
V_{OIA4} [V]	0.087	0.087	0.087	-14.215

The actual photograph of the experimental environment is shown in **Figure 11**, where (a) the R-type TC of Sentech, (b) the experimental board of **Figure 8**, and (c) the TC Calibrator CA 320 of YOKOGAWA [2,11,12].

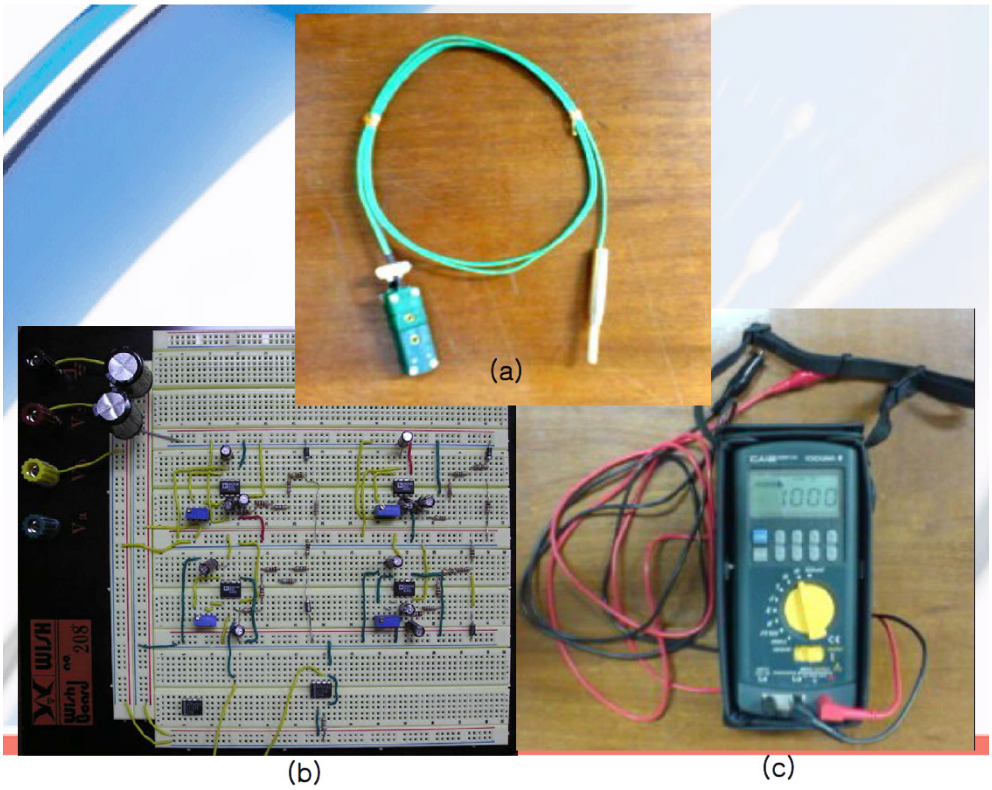

Figure 11. Experimental environment: (a) R-type TC, (b) test board, (c) TC simulator

In the cold compensation and disconnection detection circuit of various TCs in **Figure 6**, the measured values of the input voltage V_{IN} and output voltage V_{IOA} of the measurement amplifier for the steady-state and short-circuit detection circuits of various TCs (E, J, K, T, S-type) under the conditions in **Table 1** are shown in **Table 4**. In this table, the steady-state V_{IN} voltage is the electromotive force for each TC at room temperature (25℃) [9].

A summary of the characteristics of the conventional TC compensation and interface circuits [4,6-8] and the TC cold compensation and disconnection detection circuits proposed in this study is shown in **Table 5**. Compared with the conventional interfaces, the advantages of the interface limited in this study are 1) it is easy to implement TC cold compensation and disconnection detection for 8 channels, 2) the unit cost of interface construction is low, and 3) the cold point compensation is 97.8%.

Table 4. Input and output voltages of the instrumentation amplifier in case of disconnection and steady-state for various TCs

TC type	TC states			
	Normal		TC open	
	V_{IN} [mV]	V_{OIA} [V]	V_{IN} [mV]	V_{OIA} [V]
E	1.460	0.1899	-421.0	-14.215
J	1.278	0.1837	-420.5	-14.214
K	1.001	0.1825	-420.5	-14.215
T	0.993	0.4758	-421.0	-14.216
S	0.143	0.0768	-421.0	-14.215

Table 5. Summary of characteristics of conventional and proposed TC cold-junction compensation and disconnection detection circuits

Contents	Reference [4]	References [6–8]	This work
Supply voltage	-15 V – +15 V	2.7–5.5 V	-15 V – +15 V
Applicable TC type	R	K, J, T, N, S, E, B, R	K, J, T, S, E, R
Number of channels	1	1 (8 주 1)	8
Disconnection detection function	Yes	Yes (need to add circuits)	Yes
Unit price for o8-channel system configuration	LOW	High	LOW
Cold-junction compensation factor	97.8%	-	97.8%

8 주 1: 8 MCP9600 modules needed when configuring 8 channels with I^2C communication

Recently, due to the large capacity of memory, excellent linear characteristics of linear elements, and high speed of microprocessors, linearization of TCs is a trend to be processed by S/W. In this study, based on this, a program can be developed to store the electromotive force of TC according to temperature in memory, and then compare the analogue value measured from the TC interface circuit and the value stored in memory to determine the final linearized temperature value [13].

4. Conclusion

A circuit design with a thermocouple (TC) cold-junction compensation function and a disconnection detection function was developed, and a multi-channel interface circuit applicable to various TCs was implemented. When using an R-type TC, the error after cold-junction compensation of the TC was reduced by 97.8% from 0.14 mV to 3 μV. In addition, the output voltage of the measurement amplifier saturated from 88 mV to -14.2 V when the TC was disconnected from normal. In the designed multichannel interface circuit, only 4 channels were considered, and similar performance was obtained by applying and experimenting with R-type TCs. In addition, the cold-junction compensation and disconnection detection circuits and multichannel interface circuits of TCs limited in this study can be applied to E, J, K, T, and S-type TCs, and the conditions for use are presented. The results of this study will be very useful for the furnace for 300 mm wafers and the multichannel temperature control system using various TCs.

Disclosure statement

The author declares no conflict of interest.

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