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Silicon *p-n* Junction Electric Thermometer

(Received November 9, 1965)

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Abstract

The temperature dependence of forward bias voltages across Si *p-n* junction at a constant current is used as a temperature sensitive element of an electric thermometer. The thermometer which has been developed here covers the range −200°C to 150°C with linear scale.

I. Introduction

Nowadays, thermocouples such as chromel-alumel, platinum-rhodium have been widely used as an element of electric thermometer. They are applications of electromotive force between dissimilar metals with temperature dependence and the temperature can be measured from room temperature up to 1500°C.

Thermistor is also useful temperature sensitive element around room temperature and is used not only as a thermometer but also as elements for automatic temperature control systems and power detectors.

For the measurement of extremely low temperatures (lower than 10° in Kelvin), there is an investigation[1] concerning the impurity conduction in germanium with temperature. Thus, various semiconductor elements have been developed as temperature measuring units. But these are either *p*-type or *n*-type elements, applying their resistance variation with temperature.

p-n junctions are also applicable to the temperature sensitive elements, such as their reverse saturation current (I_s) and forward bias voltage (V) at a constant current. For example, transistor junction temperature has been measured through these parameters[2].

Generally speaking, temperature dependences of thermistor, *p*-type or *n*-type elements and the reverse saturation current of a *p-n* junction are insufficient for the linearity over the fairly wide range of temperature variation.

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1) J. S. Balkmore, Rev. Sci. Instrum. vol. 33, No. 1, Jan., 1962.

2) T. Suzuki and H. Hirose; This proceedings, Vol. 18, No. 2, 1965.

However, we have focused on the forward bias voltage at a constant current of *p-n* junctions with the range of −200°C to +150°C. More than ten Ge and Si *p-n* diodes in general use have been checked up on the linearity of temperature dependence over the above mentioned range, one of the Si *p-n* diodes was found to be appropriate for the use of linear scale electric thermometer.

II. Temperature dependence of *p-n* junction forward bias voltage

Reverse saturation currents of *p-n* junction are considerably sensitive to the temperature and show good performance in detecting temperatures. On the contrary, (1) their characteristics vs. temperature are not linear but logarithmic, (2) wider temperature variation makes difficult for the bigger current change such as 10^2 or 10^3 times of the initial current, (3) in the case of Si diode, reverse saturation current is too small to measure sometimes even at room temperature and also at lower temperature, (4) the current is affected with a leakage making error bigger and hysterisis effects are sometimes observed.

When external forward voltage V is applied to a *p-n* junction, the current I which flows through the junction is given as follows[3)]

$$I=I_s\left(\exp\frac{qV}{kT}-1\right) \tag{1}$$

But, I_s is expressed as

$$\begin{aligned} I_s &= q\left(\frac{D_p}{L_p}p_n+\frac{D_n}{L_n}n_p\right) \\ &= q n_i^2\left(\frac{D_p}{L_pN_d}+\frac{D_n}{L_nN_a}\right) \end{aligned}$$

where

$$n_i^2=KT^3\exp\frac{-qV_g}{kT} \tag{2}$$

qV_g is energy gap of the junction material and K is a constant. In equation (1), unity in the right hand side is much smaller than the exponential term even at 0.1 [V]. Then, we put equation (2) into (1)

$$I=K'T^3\exp\frac{q(V-V_g)}{kT} \tag{3}$$

where

$$K'=Kq\left(\frac{D_p}{L_pN_d}+\frac{D_n}{L_nN_a}\right)$$

3) R. A. Greiner, "Semiconductor Devices and Applications" p. 122, McGraw Hill, 1962.

Taking natural logarithm of equation (3)

$$V-V_g=\left(-\frac{k}{q}\ln\frac{K'T^3}{I}\right)T \tag{4}$$

If let the current I be constant and also $\ln K'T^3$ is supposed to be constant within the temperature range concerned, equation (4) leads to the linear relation between T and V. V is always smaller than V_g in the foward bias condition, and when T becomes 0° in Kelvin, V tends to V_g.

However, it should be noted that K' involves diffusion constants (D_p and D_n), diffusion lengths (L_p and L_n) of hole and electron, and donor and acceptor densities (N_d and N_a) of the material so that K' depends somewhat on temperature and quantity of doping. But we could expect the linear relation between V and T over the range concerned when these are appropriately selected and hence compensated each other.

Fig. 1 shows the temperature characteristics vs. forward bias voltage of 18 different kinds of Ge and Si diodes in general use (mostly juction type and some point-contact type).

In Fig. 1, the upper group is of Si diodes and the lower one is made of Germanium.

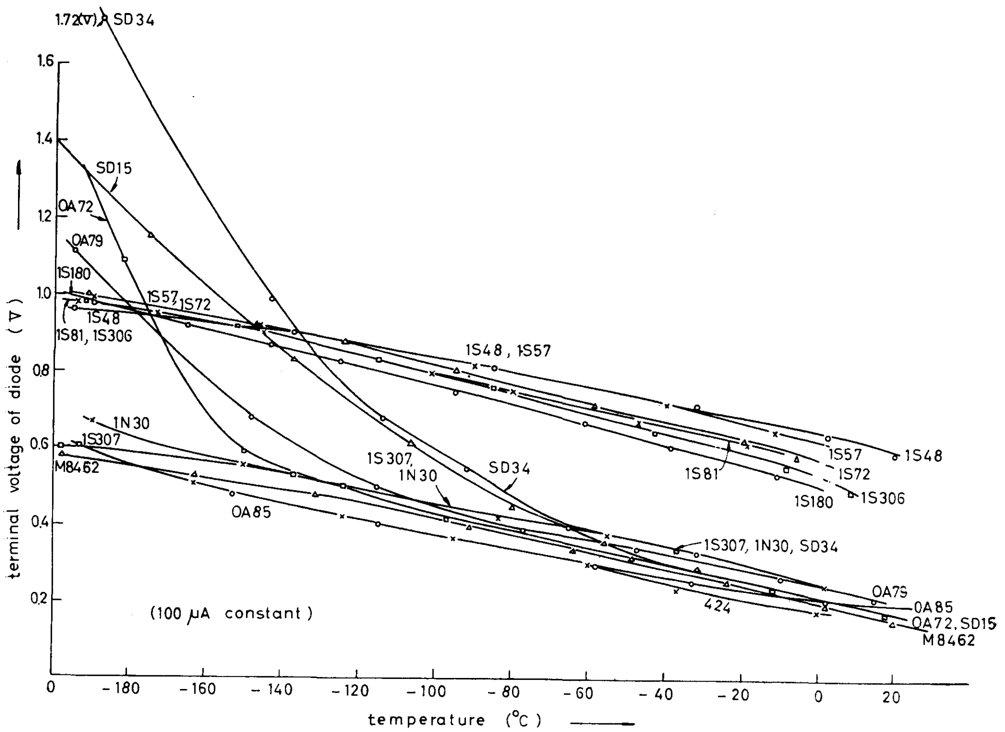

Fig. 1. Forward voltage vs. temperature for various type of Ge and Si diodes under the current constant.

Among 18 diodes, we decided to use 1S180 Si diode as a temperature sensitive element according to temperature linearity and availability over the range concerned. Of course bigger gradient must be better to get higher sensitivity.

We have checked the temperature vs. forward bias voltage characteristic curves of ten 1S180 diodes in different currents. One of the curves is shown in Fig. 2. In the case of 100 [μA], the average value of these ten diodes are : 0.17 [V] at 150°C, 0.53 [V] at 0°C and 1.00 [V] at −200°C and also its temperature coefficient is −2.37 [mV/°C]. All of them have sufficient linearity over the range between −200°C to +150°C.

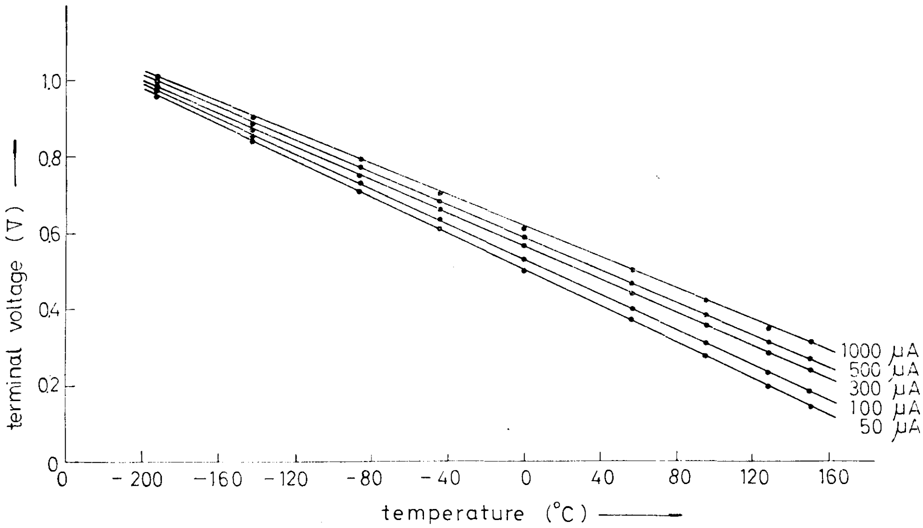

Fig. 2. Forward voltage vs. temperature characteristics of Si *p-n* diode 1S180 under various constant currents.

Under the investigation, we have used a chromel-alumel thermocouple as the temperature standard. The electromotive force of this thermocouple between −100°C and 100°C has a perfect coincidence with that of Circular 508, 1951 of National Bureau of Standards so that we have made an extrapolation of this curve lower to −200°C. We have checked by the temperature of liquid air (−195°C at 1 atm.) and liquid oxygen (−183°C) and got good agreement.

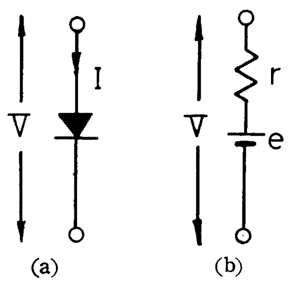

Fig. 3. An equivalent circuit of *p-n* diode.

The equivalent circuit of *p n* diode with forward bias voltage V and current I is given in Fig. 3 (b). The *p-n* junction consists of an electromotive force e (built-in potential) and dynamic internal resistance r. Therefore, the terminal voltage V is expressed as

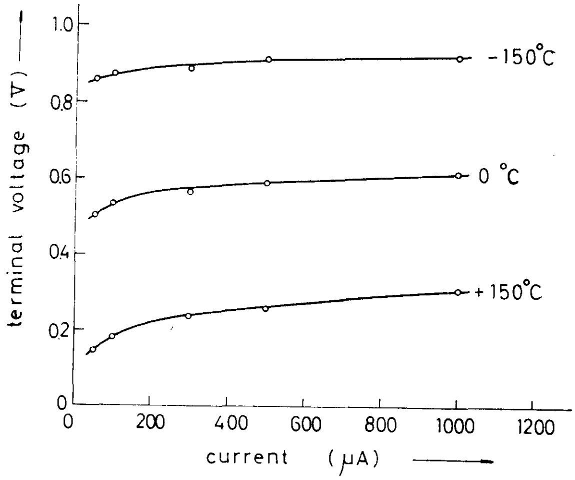

Fig. 4. The forward bias voltage vs. current characteristics of Si *p-n* junction diode at +150°C, 0°C and −150°C to know the dynamic internal resistance.

$$V = e + Ir \tag{5}$$

Fig. 4 illustrates an example of V-*I* characteristic curves with temperature constant. For example, when $T = 0°C$ and $I = 100$ [μA], r should be obtained from an inclination of the tangent at the point of 100 [μA]. e is obtained from the cross point of the vertical axis and the tangent. In this case, $r \doteqdot 500$ [Ω] and $e \doteqdot 0.49$ [V]. With increase of current or decrease of temperature, r becomes smaller.

III. Designing thermometer

Block diagram of the electric thermometer which has used Si *p-n* junction as the temperature sensitive element is shown in Fig. 5.

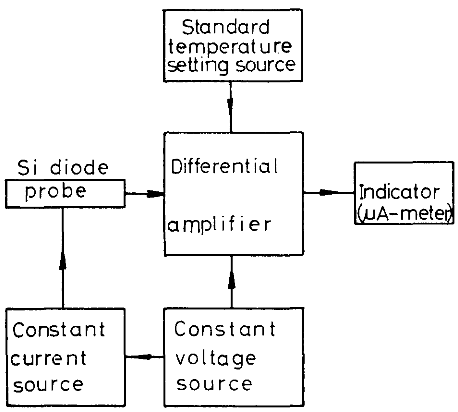

Fig. 5. Block diagram of the electric thermometer.

1. Temperature detecting probe

The probe for detecting temperature should satisfy the following requirements ; (1) high sensitivity, (2) quick response for temperature change, (3) good electrical insulation, (4) sufficient mechanical strength, (5) linearity with temperature change.

Its sensitivity can be achieved to some extent by means of amplifier added so we have put our intention to its linearity most. The response property is considered to be related to insulation, durability and deterioration, therefore, it will be discussed after the experiment.

Fig. 6 shows the side view of the probe used in the experiment. The lead-wires attached to 1S180 diode are fine copper wires to avoid the heat conduction through the wires. Capsulation is made of hard glass to protect against electrical leakage and mechanical damage.

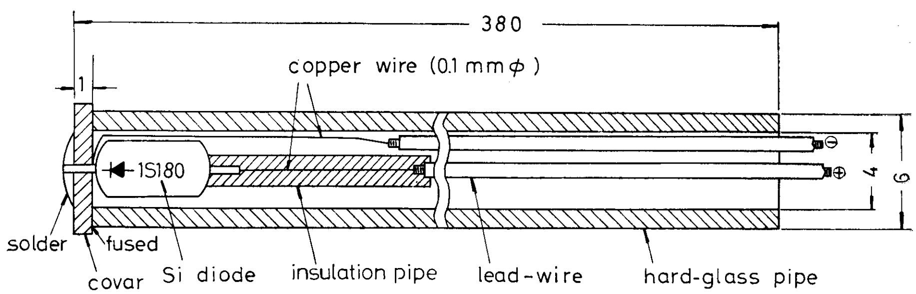

Fig. 6. Probe used as the experiment.

2. Constant current source

It is necessary to make current constant at any temperature flowing through the probe, i. e. Si *p-n* junction, for the sake of reliable measurements.

But the diode has the internal impedance which varies with temperature. Therefore, the source impedance should be high enough to neglect the change of the diode internal impedance. If the current through the diode increases, the internal impedance becomes smaller. On the other hand, the power dissipation in the diode becomes higher and would affect the temperature measurement to some extent. If the current is chosen smaller, leakage current would become a problem. Therefore, 50 or 100 [μA] is used for our measurement. To obtain the constant current (50 [μA]), we have made 200 [V] constants voltage source stabilized with one stage vacuum tube amplifier, which has the voltage regulation less than 1 % against 10 % *a-c* line variation. Then through a high resistance such as 4 [MΩ], the current is applied to the diode. It may be sufficient that the current regulation is less than 0.1 % when the internal resistance of the diode changes from 200 [Ω] to 2 [$k\Omega$] with temperature (from −200°C to 150°C).

3. Differential amplifier and 0°C reference voltage source

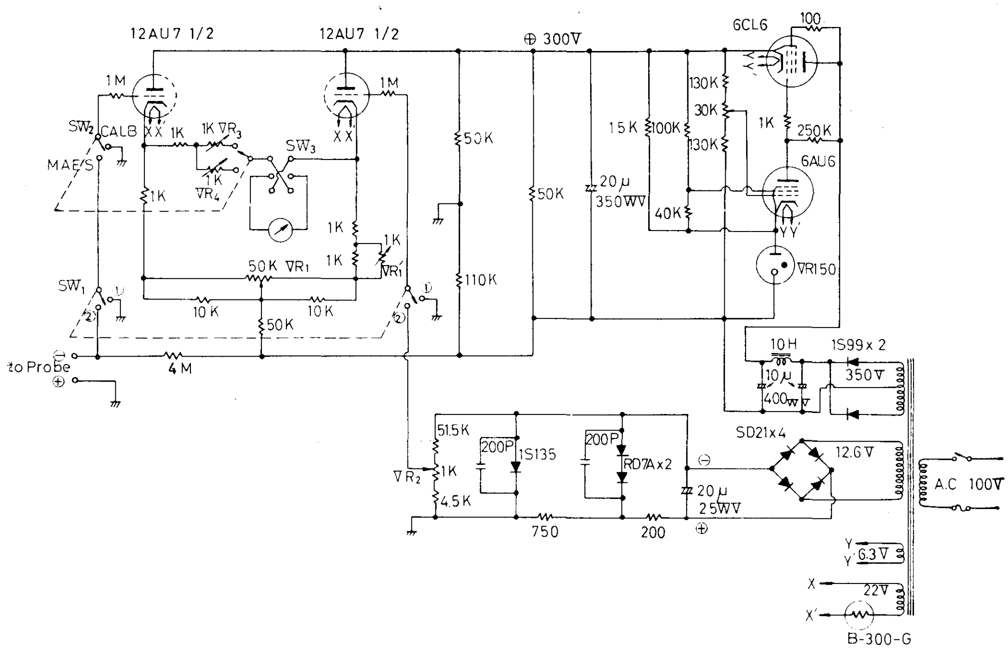

Fig. 7. Circuit diagram of the thermometer.

The reason of a differential amplifier used is to get easy calibration at 0°C as a reference temperature and also the amplifier has a linear output against 0.1 to 1 volt input. Vacuum tubes are used because of necessity of high input impedance in comparison with the diode internal impedance. Fig. 7 illustrates the differential amplifier, reference temperature source and constant voltage power supply. Input vs. output characteristics of the differential amplifier is given in Fig. 8 and shows good linearity.

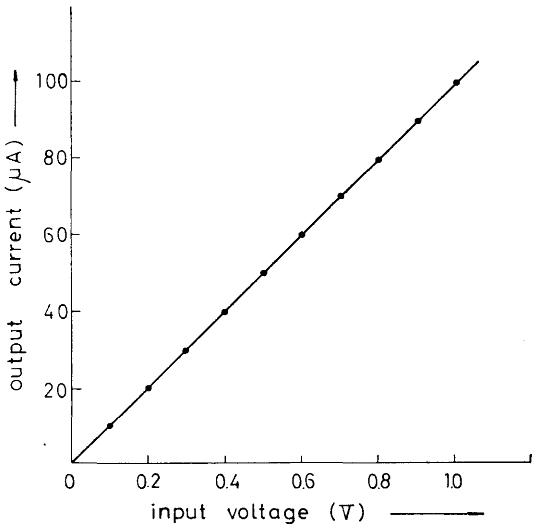

Fig. 8. Input-ouput characteristics of the differential amplifier.

0°C reference voltage (about 0.53 [V]) is given from 12 [V] *a-c* supply through the diode bridged rectifier stabilized with zener diodes. 1S135 zener diode has almost zero temperature coefficient. Moreover, the reference voltage is one-tenth of the zener voltage so that the variation of the reference voltage is considered to be negligible.

In order to avoid the drift of the differential amplifier mainly caused by the heater supply, the heater circuit has a balast tube to maintain the heater current constant.

IV. Results and discussion of the experiment

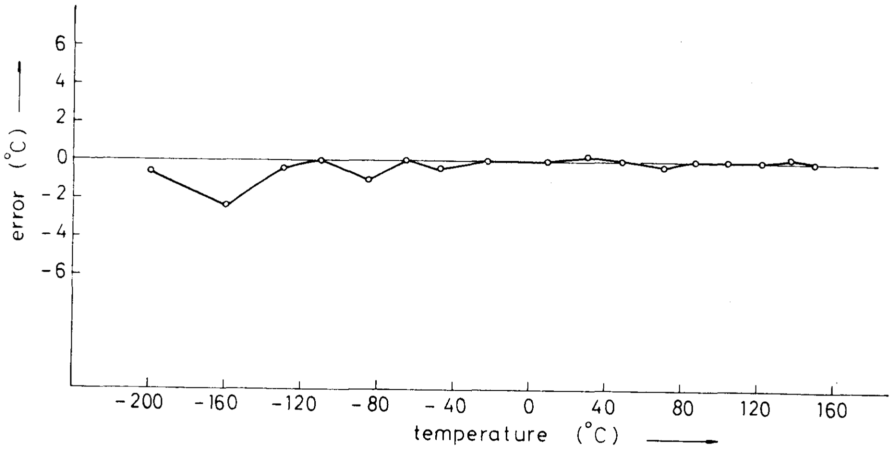

Fig. 9. One of the error curves for the *p-n* Si diode thermometer compared with the chromel-alumel standard thermo-junction.

Fig. 9 shows the differences i. e. the errors between temperatures measured by the Si *p-n* junction thermometer and by the standard chromel-alumel thermocouple. The error curves may be different when using other 1S180 diodes as the probe, then it might be better to have calibration curves for each diode to get more correct temperature measurements. Though, of ten diodes used for the probe, the errors at the temperatures above −100°C were within ±1°C and some showed 5°C difference at −180°C, the thermometer can be used sufficiently for practical purposes of temperature measurement.

The response characteristic curves of the probe are shown in Fig. 10. The solid lines show the response with time in second when the probes are put into 19°C water from 100°C boiling water. Probe (a) in Fig. 10 is the same of Fig. 6 and it takes about 40 seconds till 19°C from 100°C. Probe (b) has no capsule i. e. naked *p-n* junction and the lead-wire of *n*-type side is directly soldered to the covar mount. This type of the probe has rapid response and takes only 10 seconds under the same condition. The dotted lines show the cases when the probes are replaced in

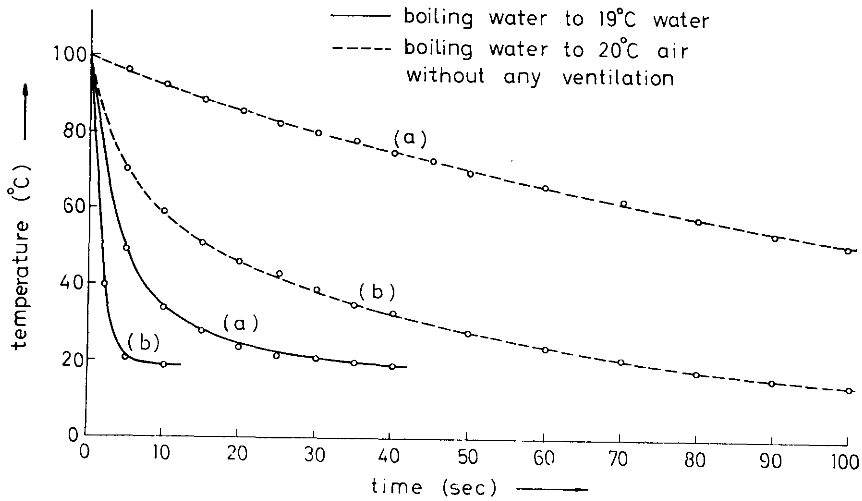

Fig. 10. Temperature response for the two kinds of probes, (a) probe shown in Fig. 6 and (b) naked probe

20°C air without any breeze from 100°C boiling water, and they take five times longer than those of the condition of the solid lines.

In the point of the response characteristics, heat capacity of the probe should be as small as possible, but at the same time, it is necessary to take electrical insulation and deterioration into consideration.

The temperature rise caused by the diode current is negligibly small because of small power dissipation in the diode. There are initial drift, temperature change and variation of power supply in the differential amplifier. Among these drifting factors of the amplifer, temperature dependence of the circuit elements may be dominant as far as the characteristics of a pair of vacuum tubes are kept in balance with each other. According to Middlebrook[4], drifts caused by the circuit elements with temperature are less than 0.2 mV/°C in differential amplifiers so that this could be negligible amounts compared with the temperature coefficient of the probe (2.3 mV/°C).

The initial drift fades away in ten minutes after switch-in. When there is a drift caused by miscellaneous reasons, we can check and make calibration once in while

0°C reference voltage is also influenced by the change of the room temperature and the power supply variation, but before the measurement, it should be checked and calibrated by 0°C ice and water.

At this moment, it is hard to make the conclusion on the deterioration because the probe has not yet been tested long enough. We have put three probes into

4) R. D. Middlebrook, "Differential Amplifiers", John Wiley and Sons, 1963.

liquid air for 48 hours and also into boiling water for 4 hours. Then we have checked the forward bias voltage vs. current characteristics before and after the above trials, but we could not find any change among them. These lower and higher temperatures are beyond the limits of so-called storage temperatures. It seems, the diodes of the probes are considered to be strong against fairly severe temperature changes.

To transistorize the whole equipments in stead of vacuum tubes is desirable for handy use and is now under consideration.

If the special diode be developed for the purpose of electric thermometer, measurable range of temperature could be extended much more with good linearity. Moreover, we could make use of transistors for temperature sensitive elements with amplification ability[5] and could apply the forward bias voltage method to temperature control[6] in automatic control systems utilizing their linear characteristics successfully.

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5) A. G. McNamara, Rev. Sci. Instrum., vol. 33, No. 3, Mar., 1962.

6) J. E. Pallet, Electronic Eng., Jun., 1961.