Band Gap Energy in Silicon

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ABSTRACT

The band gap energy, E_g in silicon was found by exploiting the linear relationship between the temperature and voltage for the constant current in the temperature range of 275 K to 333 K. Within the precision of our experiment, the results obtained are in good agreement with the known value energy gap in silicon. The temperature dependence of E_g for silicon has also been studied.

I.   INTRODUCTION

The study of the band gap structure of a semiconductor is important since it is directly related to its electronic properties. As a consequence, it has attracted a considerable interest in undergraduate laboratories [1-3]. Several different methods have been discussed to determine the band gap energy of semiconductors [1-4]. A diode is also used as a temperature sensor [5], in which the linear relationship between the temperature, T and the forward voltage drop across the p-n junction, V is exploited.

It has been shown that with certain simplifications, the $T-V$ relationship for a diode can be written as [4]

$$T = \left(\frac{e}{kC}\right)V - \left(\frac{E_g}{kC}\right) \qquad (1)$$

where e is the charge of electron, k is Boltzmann constant, E_g is band gap energy and C is a function of I, the current through the diode. Therefore, if I is kept constant, then

$$T = aV + b \qquad (2)$$

where $a = \dfrac{e}{kC}$ and $b = \dfrac{-E_g}{kC}$

Hence

$$E_g = -\left(\frac{b}{a}\right)e \qquad (3)$$

Therefore, if we find constants a and b by experimentally measuring the temperature and voltage across the diode, we can find the band gap energy of a semiconductor, provided that E_g does not depend strongly on temperature. For silicon, the variation of E_g with temperature is weak [6] in the temperature range of our interest, 273 K to 335 K.

II.   EXPERIMENTAL DETAILS

Figure 1(a) shows the schematic diagram of the circuit used for $T-V$ data measurements for the base-collector junction of an npn transistor (MPS2222AG) while Fig. 1(b) depicts the use of a silicon
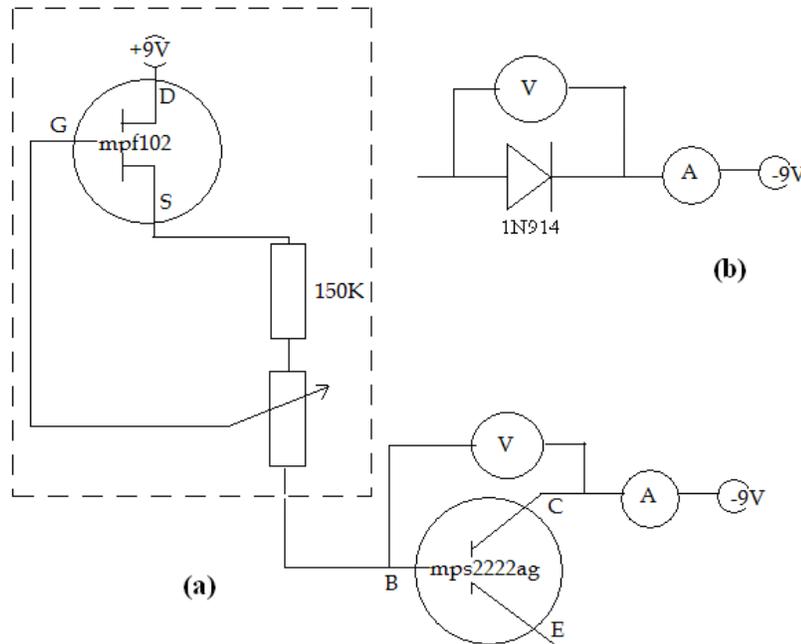
Figure 1. (a) The MPS2222AG Transistor and (b) the 1N914 Diode are at variable temperature. The MPF102 Transistor was used as a constant current source. The circuit for constant current source is shown in dotted box above. The gate-source bias voltage was adjusted by a 100-kΩ variable resistor to obtain a constant current of 10 μA.

diode (1N914). The current, I was kept constant using the circuit [7] shown in the dotted box in Figure 1(a). The variable resistor was adjusted to obtain 10 μA current. The whole circuit was powered by a constant voltage power supply (Elenco Precision, Model XP-660), keeping the voltage at approximately 9 V. The voltage drop across the pn-junction was measured by a digital voltmeter (Heath, Model SM2320), while the temperature was measured by a carefully calibrated AD-590 temperature sensor. Both diode and temperature sensors, were wrapped together in a thin plastic foil to insulate them electrically. The whole system was then placed in a de-ionized ice-water mixture (the ice was also made from de-ionized water) to obtain the temperature of 273 K.

The voltage readings were then taken for various temperatures while the system was heated slowly. The measurements were repeated several times to reduce the statistical errors.

III.   RESULTS

The $T-V$ curve for the silicon pn junction of transistor (MPS2222AG) in the temperature range of 273 K to 335 K is shown in Figure 2(a). The data exhibits a fairly good linear relationship between absolute temperature and the voltage drop across the pn junction in the temperature range of our interest, except at the higher end of temperature (see discussion). We also used a 1N914 silicon diode in place of the transistor (MPS2222AG) and repeated the experiment. The $T-V$ data for the silicon diode (1N914) is shown in Figure 2(b). The values of constants a and b of Eq. (2) were obtained by the least-squares fit of the data from 275 K to 330 K temperature. The value of E_g was then calculated from Eq. (3).

The uncertainties in results were found in the following way: Since the calculation of E_g depends on two variables, a and b, the uncertainty in E_g is written as
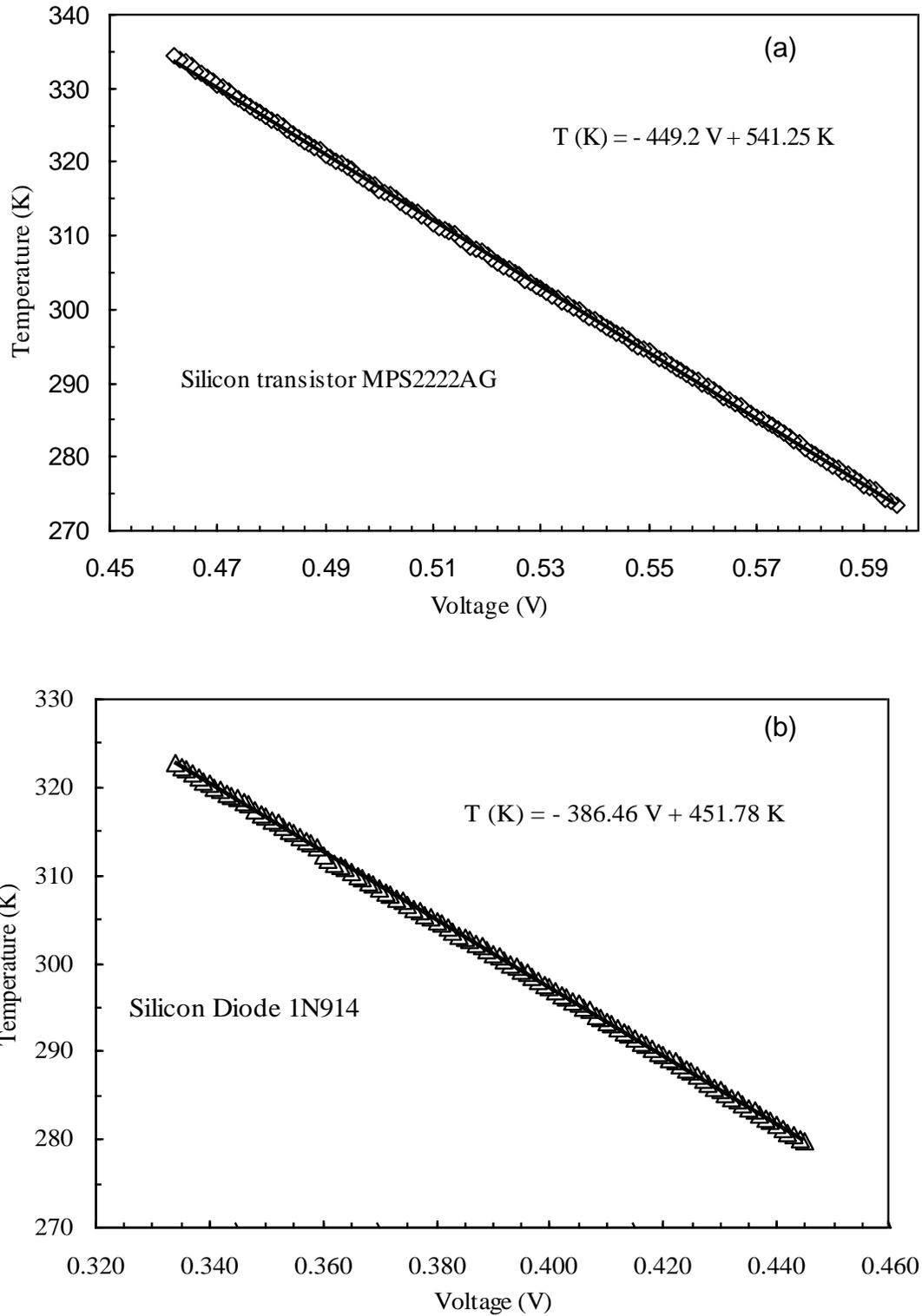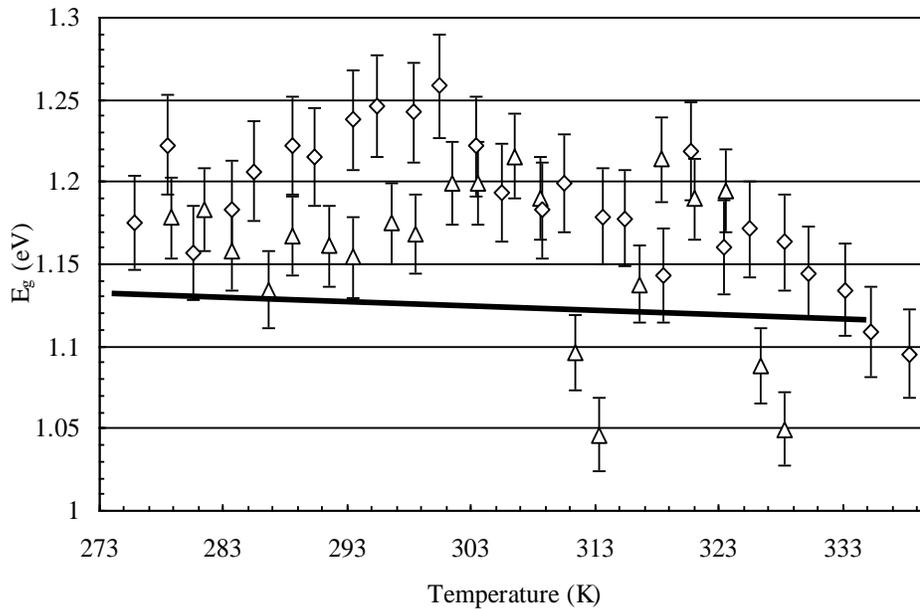
Figure 2. Temperature versus voltage graphs for the silicon (a) pn junction of npn transistor (MPS2222AG). The T-V curve becomes nonlinear above 330 K. (b) diode (1N914). Solid line is least-squares fit to the data.

Figure 3. The temperature dependence of the band gap energy in silicon. ◊ the pn junction of MPS2222AG npn transistor, △ 1N914 diode, and solid line represents the universal function taken from [6] for comparison

$$dE_g = \left(\frac{\partial E_g}{\partial b}\right)db + \left(\frac{\partial E_g}{\partial a}\right)da \,.$$

The maximum fractional error therefore is $\dfrac{dE_g}{E_g} = \varepsilon = \left|\dfrac{db}{b}\right| + \left|\dfrac{da}{a}\right|$, where da and db are standard deviations of the slope, a and y-intercept, b of straight line fit to $T-V$ data, respectively.

For the pn junction of the MPS2222AG transistor [see Fig. 2 (a)], a = -462.17 K/V, da = ±7.95 K/V, b = 547.40 K, and db = ±4.12 K, Therefore in the temperature range of 273 K to 330 K, the value of E_g is 1.20 eV with uncertainty of ± 2.47 %. Similarly for the 1N914 diode [see Fig. 2(b)], a = -393.538 K/V, da = ±6.3828 K/V, b = 454.18 K, and db = ±2.388 K. Hence in the temperature range of 278 K to 323 K, the value of E_g is 1.17 eV with uncertainty of about ±2.15%. The results are summarized in Table 1 and compared with known values of energy gap in silicon from different references.

For silicon the value of E_g is known within ±5% uncertainty and varies from 1.13 ±0.057 eV at 273 K to 1.11 ±0.056 eV at 330 K [6,8]. Therefore our results are in good agreement to the known values in literature [4,6,8], although the values obtained in here tend to be slightly higher (see discussion).

We have further analyzed our data to investigate the temperature dependence of E_g. The straight line was obtained by the least-squares fit of the $T-V$ data in small temperature intervals of ± 2.5 K, assuming that E_g of silicon remains constant in small temperature intervals. The results are shown in Figure 3.

IV.   DISCUSSION

a. Temperature – Voltage Curve

As shown in Figure 2 (a) $T-V$ curve deviates from a straight line towards higher temperature side (>330 K). Such non-linear behavior in $T-V$ curve was also observed in Germanium above 313 K [4].

	a (K/V)	b (K)	E_g (eV) 273 K to 330 K	E_g (eV) 288 K to 383 K [Ref. 4]	E_g (eV) 300 K [Ref. 6]
MPS2222AG	-462.17 ± 7.95	547.40 ± 4.12	1.20 ± 0.03	1.23	1.12
1N915	-393.54 ± 6.38	454.18 ± 2.39	1.17 ± 0.03		

Table 1. Linear regression coefficients a and b obtained from measured $T-V$ data, and E_g calculated from them. Last two columns are E_g values at given temperature from references [4] and [6] for comparison.

When deriving equation (2) using the Ideal Diode Equation [4,6]:

$$I = I_0[e^{V/kT} - 1] \qquad (4)$$

where I_0 is reverse saturation current, we assumed $e^{(eV/kT)} \gg 1$, to obtain

$$I = I_0 e^{V/kT} \qquad (5)$$

For a forward bias voltage of 0.4 V, taken at room temperature, we get

$$eV/kT = 0.4/0.025 = 16,$$

thus $e^{ev/kT} \approx 8.9E+6$. Therefore the approximation is generally justified at room temperature and below. But as temperature increases the exponential term decreases. This may cause a deviation from the linear behavior of $T-V$ data.

The reverse current I_0 depends strongly on temperature. It is proportional [6] to the Boltzmann factor $\exp(-E_g/kT)$ and to $T^{3+\gamma/2}$, where γ is a constant. Therefore,

$$I_0 = AT^{3+\gamma/2} \exp(-E_g/kT) \qquad (6)$$

Here the $T^{3+\gamma/2}$ dependence of I_0 is neglected as compared to its exponential dependence on T and thus

$$I_0 = B\exp(-E_g/kT) \qquad (7)$$

where $B = AT^{3+\gamma/2}$. Now combining Eq. (5) and Eq. (7), we get

$$I = B\exp(-E_g/kT + eV/kT) \qquad (8)$$

Since I is maintained constant in the experiment, therefore we can write Eq. (1) in which $C = \ln(I/B)$.

b. Values of E_g

But if $T^{3+\gamma/2}$ dependence is not ignored, then the so-called constant C is no more a constant and will depend on $\ln(T)$. That means the experimental slope of $T-V$ graph will be smaller and hence the value of E_g obtained here is expected to be slightly higher. Similar results are reported for silicon as well as for germanium in [4] (see Table 1). Also the contribution of $\ln(T)$ term will be larger towards higher temperature and this may also contribute in non-linear behavior of $T-V$ data at higher temperature.

c. Temperature Dependence of E_g

So for we have assumed that E_g of silicon is temperature independent which is not exactly true. As a matter of fact E_g does depend on the temperature, although weakly as described by a universal function [6] and is shown in Figure 3 (solid line). To investigate the temperature dependence of E_g, the straight line was obtained by the least square fit of the data in the temperature intervals of ±2.5 K, assuming

that E_g of silicon remains constant in small temperature intervals.

In the derivation of Eq. (2), the $T^{3+\gamma/2}$ term was neglected as compared to the exponential dependence of temperature. For a temperature change ± 2.5 K ($\Delta T = 5K$) at room temperature, the contribution of exponential term is almost ten times higher than that of the $T^{3+\gamma/2}$ term (Assuming $\gamma = 1$ for simplification). Therefore this assumption can also be justified in small temperature intervals.

As shown in Figure 3, the temperature dependence of E_g in silicon is weak and is consistent with the description of the universal function [6]. The value of E_g in silicon obtained in our experiments varies from about 1.18 eV at 275 K to 1.1 eV at 335 K. The data for npn-transistor (MPS2222AG) exhibits a small peak in E_g between the temperature range of about 290 K to 300 K (see Figure 3). We intend to offer no explanation for this behavior at this stage. Note that the data is more scattered towards higher temperature range as expected and is explained earlier. The temperature dependence of E_g given by universal function [6] is plotted in solid line varies in Figure 3 for comparison and it varies from 1.13 eV at 273 K to 1.11 eV at 330 K.

V.   CONCLUSION

The band gap energy, E_g of silicon and its temperature dependence in the temperature range of 273 K to 335 K was investigated. At 275 K temperature it is found to be 1.18 ± 0.03 eV and it weekly depends on the temperature. The data is in good agreement with the earlier known values in the literature [4,6,8].

ACKNOWLEDGEMENTS

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