Current dependence of ideality factor of silicon diodes

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The current dependence of ideality factor (n) is studied from the forward characteristics of different batches of silicon diodes. It is found that n is highly current dependent. The measurements on different silicon diodes reveal that n is different for different diodes, current remaining unchanged. The current dependence of sensitivity (dV_f/dT) and that of crossover temperature (T^*) are understood by taking the current dependence of n into account.

It is well known that the ideality factor (n) is voltage-dependent and generally, determined from the I–V characteristics of p–n junction. The relation of current and voltage is described by the simple equation[1,2]

$$I = I_0 \left[\exp\left(\frac{eV}{nkT} \right) - 1 \right], \tag{1}$$

where I_0 is the reverse saturation current and k is the Boltzmann constant. For a large forward bias voltage, diffusion dominates and $n \sim 1$, whereas for low forward bias voltage $n \sim 2$ as recombination dominates. Even higher value of n is expected because of the lateral inhomogeneities of the barrier height and the contribution of series resistance[3]. Also, depending on concentration profile, the value of n varies from one batch to the next for the same variety of diodes[3]. In order to study the current dependence of n, we have carried out the electrical measurements on different silicon diodes, viz. 1N4007, 1N4003 and a cryogenic silicon diode supplied by Cryo Industries of America[4]. Hereafter, the cryogenic diode is referred to as cryo diode.

The measurements were carried out from 10 to 300 K using an automated setup built around a Leybold closed-cycle refrigerator. The experimental details are given elsewhere[5,6]. The epoxy encapsulation of the diodes was ground flat on one side and fixed to the sample site with GE7031 varnish. Cigarette paper fixed with GE7031 varnish provided the required electrical isolation. The electrical leads (insulated copper wires) are thermally anchored to the cold parts in order to reduce the stray thermal emf. The usual four probe electrical connections are made to the sample. A stable constant current was provided to the diode from Keithley model 224/2243 programmable current source. The forward voltage was measured using a Keithley model 182 digital voltmeter. The diodes are operated at a constant current ranging from 10 nA to 100 mA while the voltage variation with temperature is monitored. This amount of current corresponds to a value below the knee in the $V_f - I$ characteristic of the diode in the entire temperature range studied. The temperature of the sample site is controlled using a calibrated type D silicon diode thermometer in conjunction with a Leybold model LTC60 temperature controller. The temperature is determined using the same silicon diode thermometer. This has a standard measurement accuracy of ± 1% or better. A typical temperature resolution of 50 mK and voltage resolution of 100 μV were obtained.

The temperature dependence of the forward voltage of a 1N4007 Si diode with various current values (10 nA–200 μA) is shown in Figure 1. It is observed that the forward voltage V_f for a particular current value increases linearly with decreasing temperature, increases rapidly below certain temperature T^* and then gradually with further reduction in temperature as in case of commercially available diodes. This is due to the neutralization of impurities and the 'freeze out' of carriers. T^* is seen to shift to lower temperatures by decreasing the current, thereby improving the linear region with lower current[7,8]. It is a great advantage in diode thermometry.

The linear variation can be understood either by the theory of Sah, Noyce and Shockley (SNS) for generation–recombination current[9] or by the theory of Shockley for diffusion current[2,10]. In order to ensure the applicability of the above theories, it is necessary to know the approximate value of n that can be determined quite easily from the I–V characteristics of the diode. The value of $n = 1.7$ was found to give a relatively good fit to the I–V data at 298 K for all the diode studied (not shown here). In this context, it is worth pointing out that n value close to 2 has also been found in the same current range[3,11]. For 1N4007 and 1N4003, the I–V curve fits reasonably up to current value 100 mA, whereas it deviates for cryo diode beyond 1 mA. The deviation is due to the voltage drop across the device series resistance which is found to be 3.9 Ω. As the value of n is close to 2 and the effect of recombination dominates at low temperature[1], we have used the SNS theory to analyse the data. According to the theory of SNS, the forward voltage (V_f) is shown to be related to the absolute temperature and the forward current I as

$$V_f = \frac{nE_g}{2} - \frac{nk_BT}{e} \left[\log Q + \tfrac{5}{2} \log T - \log I \right], \tag{2}$$

with $Q = 2(2\pi m^* k_B/\hbar^2)^{3/2} A k_B/\tau_0 \varepsilon$, where E_g is the band gap, e the electronic charge, k_B the Boltzmann constant, A the cross sectional area of the diode, τ_0 the average carrier life time in the recombination region, ε the electric field in the recombination region and m^* the effective mass of the electron. It is noted from eq. (2) that at 0 K

$$V_f = \frac{nE_g}{2}. \tag{3}$$

Thus, it is expected that the extrapolation of V_f–T curve to zero temperature would give $nE_g/2$ value for different currents and hence, the ideality factor n.

In order to study the current dependence of n, we have extrapolated the linear region (30–300 K) of all the V_f–T curves of an 1N4007 Si diode to 0 K as shown in Figure 2. The $nE_g/2$ for a current of 10 nA was found to be 1.16 V and was changed to 1.17515 V for a current of 100 µA for an 1N4007 Si diode. The behaviour of 1N4003 silicon diode (not shown here) is very similar to that of 1N4007, whereas the V_f–T curves with different current of cryo diode are different, as shown in Figure 3. In this case it is noted that $nE_g/2$ changed from 1.06 V for a current of 10 nA to

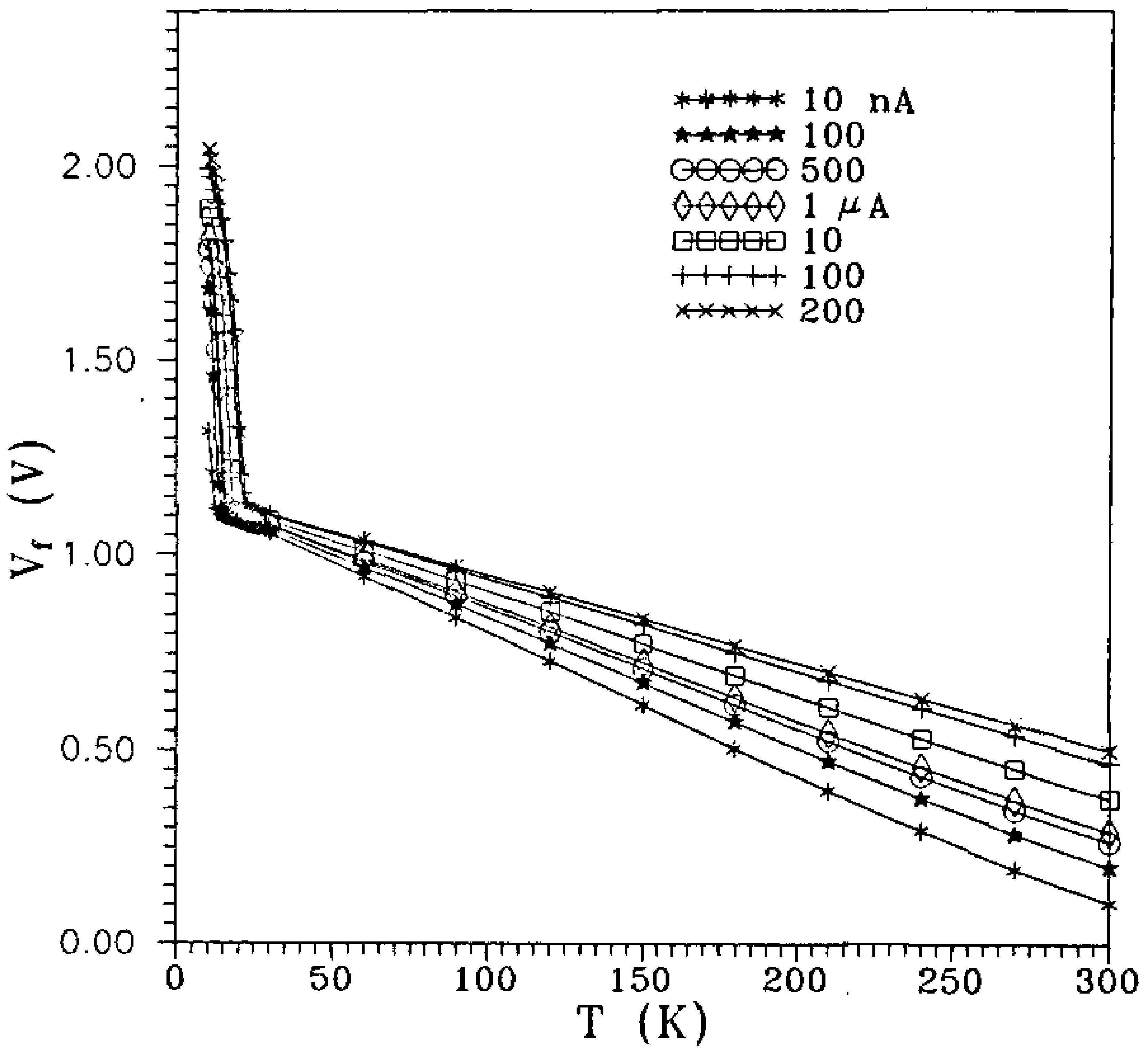

Figure 1. V_f–T characteristic of an 1N4007 silicon diode for different currents in the temperature range 10–300 K.

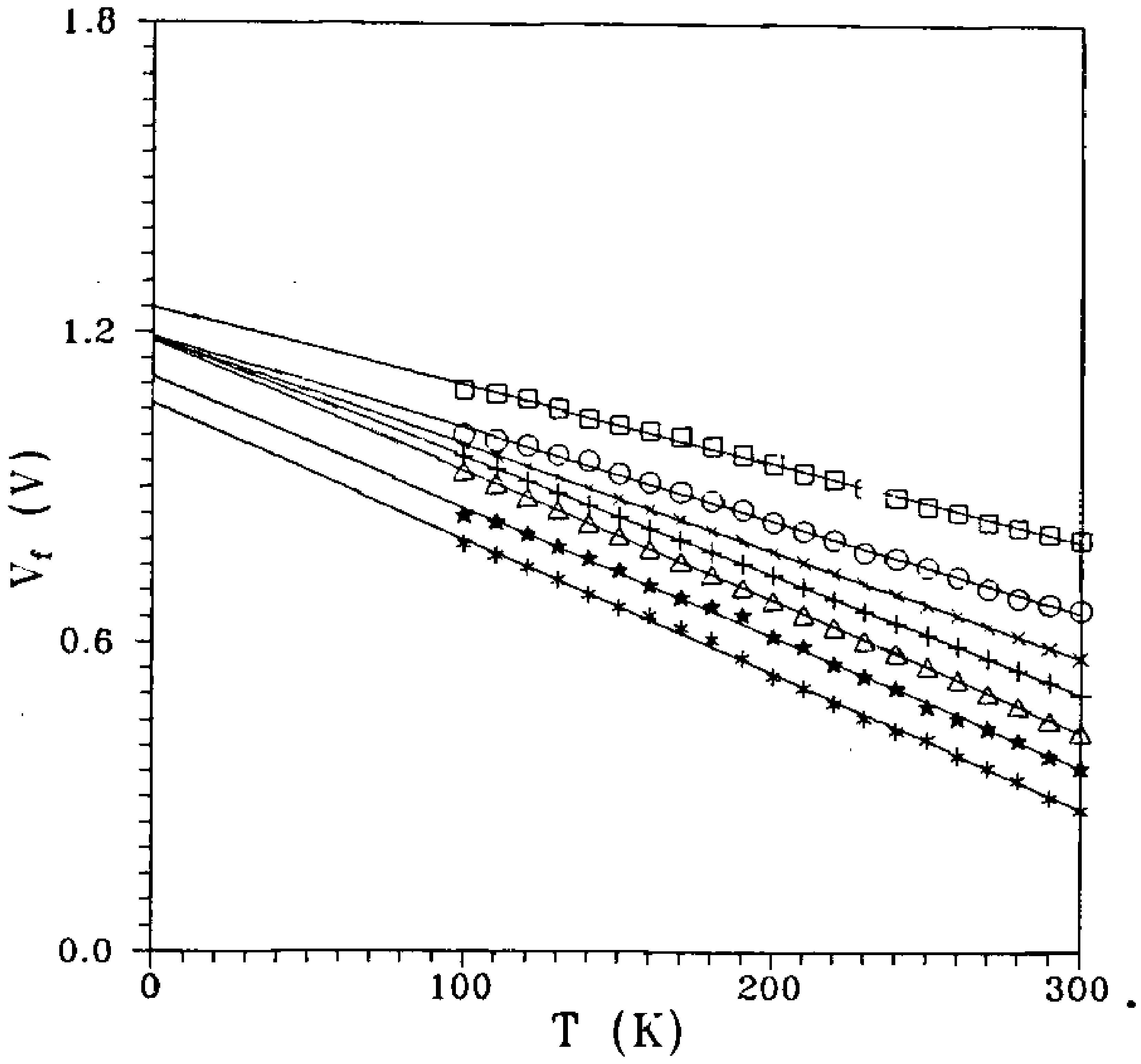

Figure 3. The least-square fit V_f–T curves of a cryo diode for 10 nA (lowest curve), 100 nA, 1 µA, 10 µA, 100 µA, 1 mA, 10 mA and 100 mA (topmost curve) in the temperature range 100–300 K. All the curves are extrapolated to 0 K.

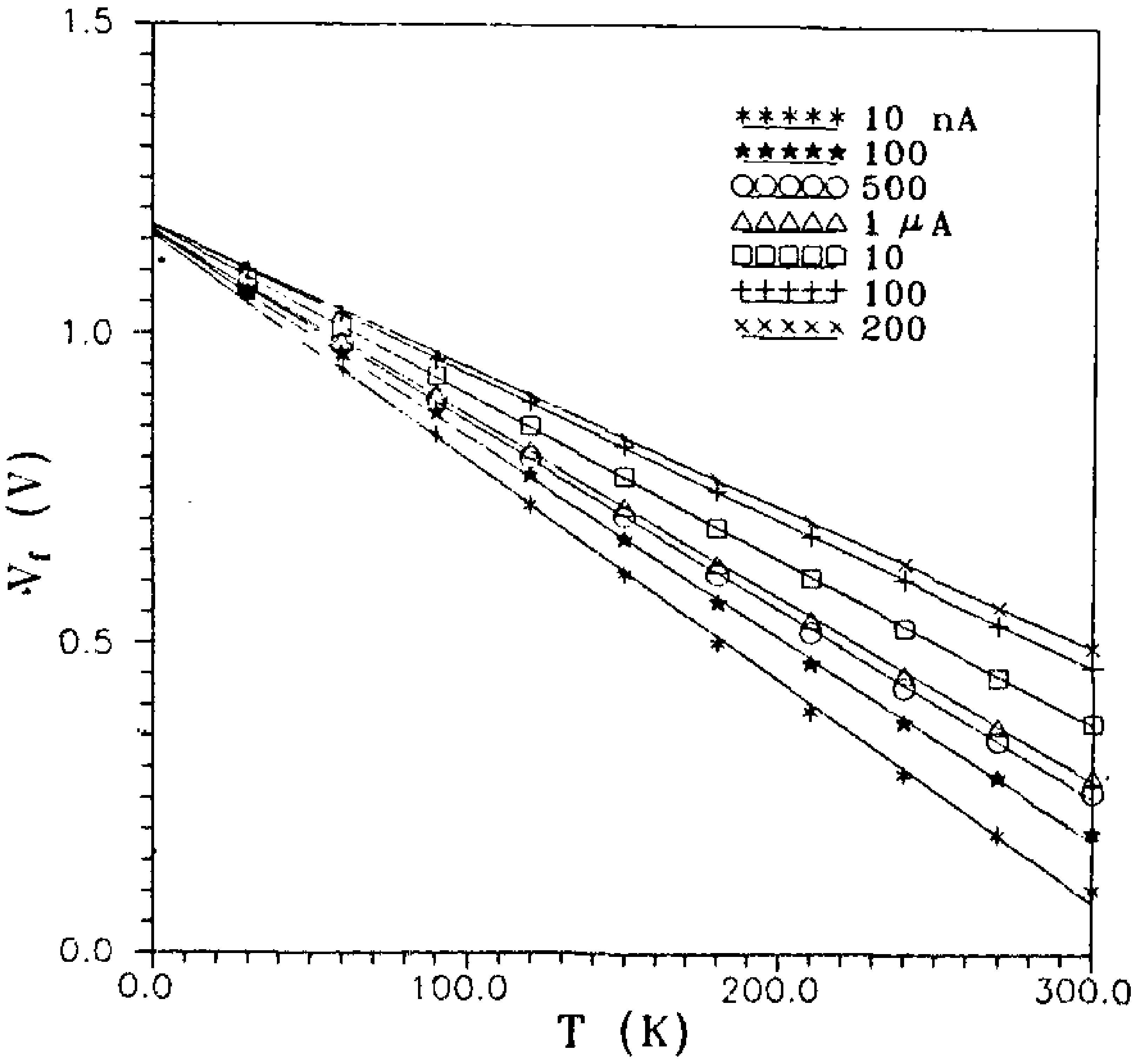

Figure 2. Same as Figure 1 in the temperature range 30–300 K. All the curves are extrapolated to 0 K.

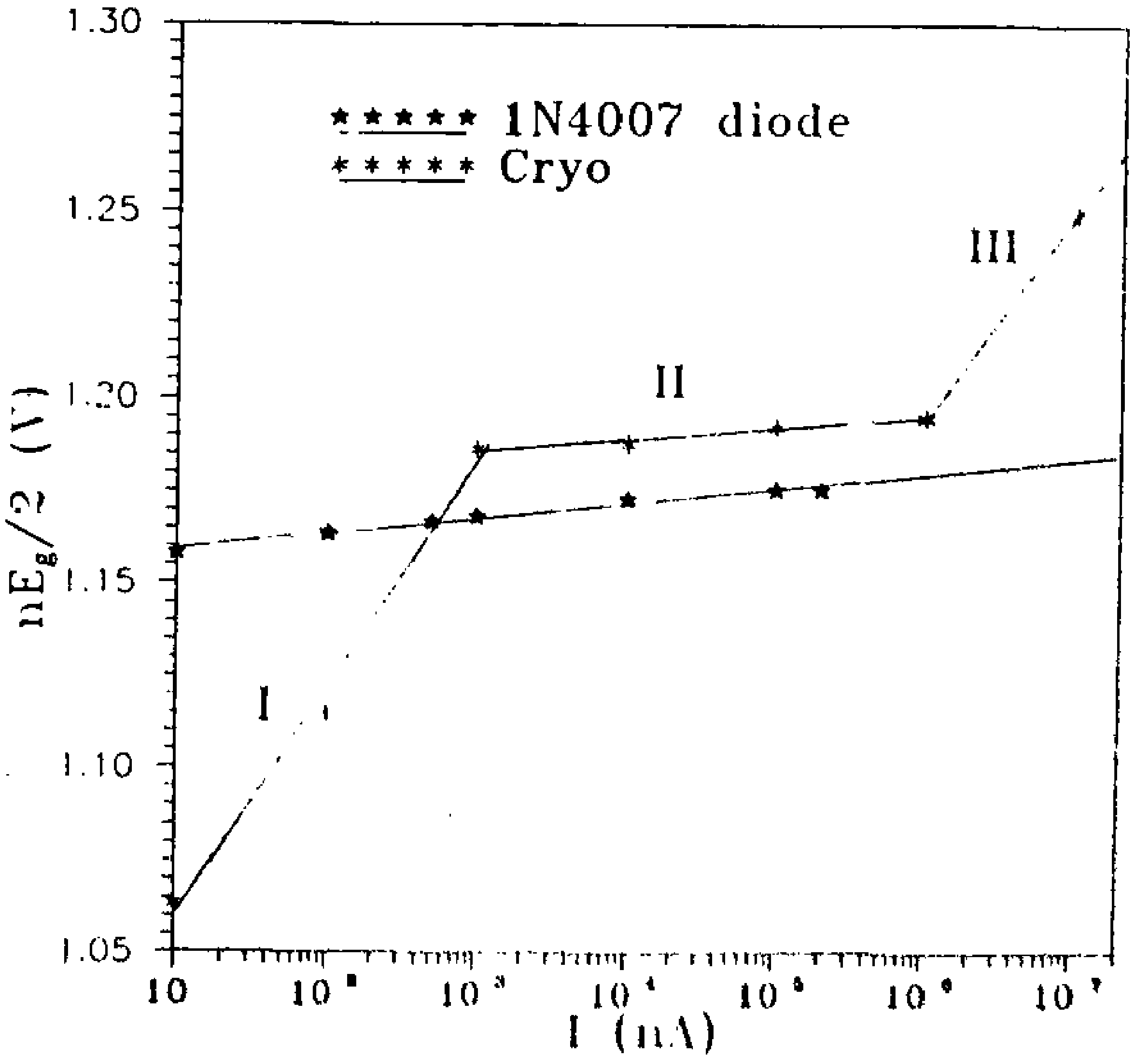

Figure 4. Current dependence of ideality factor for different silicon diodes.

1.19 V for a current of 100 μA. We have plotted $nE_g/2$ versus $\ln I$ instead of n, as $E_g/2$ is independent of current and shown in Figure 4 for different silicon diodes. It can be noted that in case of 1N4007 Si diode, the variation is almost logarithmic with current, whereas in case of cryo diode the variation is different in different current regime. In the low (regime I) and high (regime III) regime, the slope of variation is faster and the slopes are almost same. In regime II, the variation is slow and the slope is the same as in the case of 1N4007 Si diode. The different variations for different diodes are expected to be due the different concentration profiles[3] and the fast variation in regime III is expected to be due to the contribution of series resistance. In order to confirm the variation of n, we consider the variation of sensitivity and T^* with respect to current. From eq. (1), the sensitivity ($\mathrm{d}V_f/\mathrm{d}T$) is given by

$$\frac{\mathrm{d}V_f}{n\,\mathrm{d}T} = -\frac{k_B}{e}\left[\log Q + \left(1 + \tfrac{5}{2}\log T\right) - \log I\right]. \qquad (4)$$

Here, we have neglected the temperature dependence of E_g. It is noted from eq. (4) that $\mathrm{d}V_f/n\,\mathrm{d}T$ is logarithmic in I. If n is independent of current, the sensitivity should vary as $\ln I$. It is observed that the forward voltage for all current values is almost linear for temperatures above T^*. The sensitivity was found out by least-square-fit procedure in the temperature range 60–300 K for 1N4007 Si diode. The temperature dependence of the forward

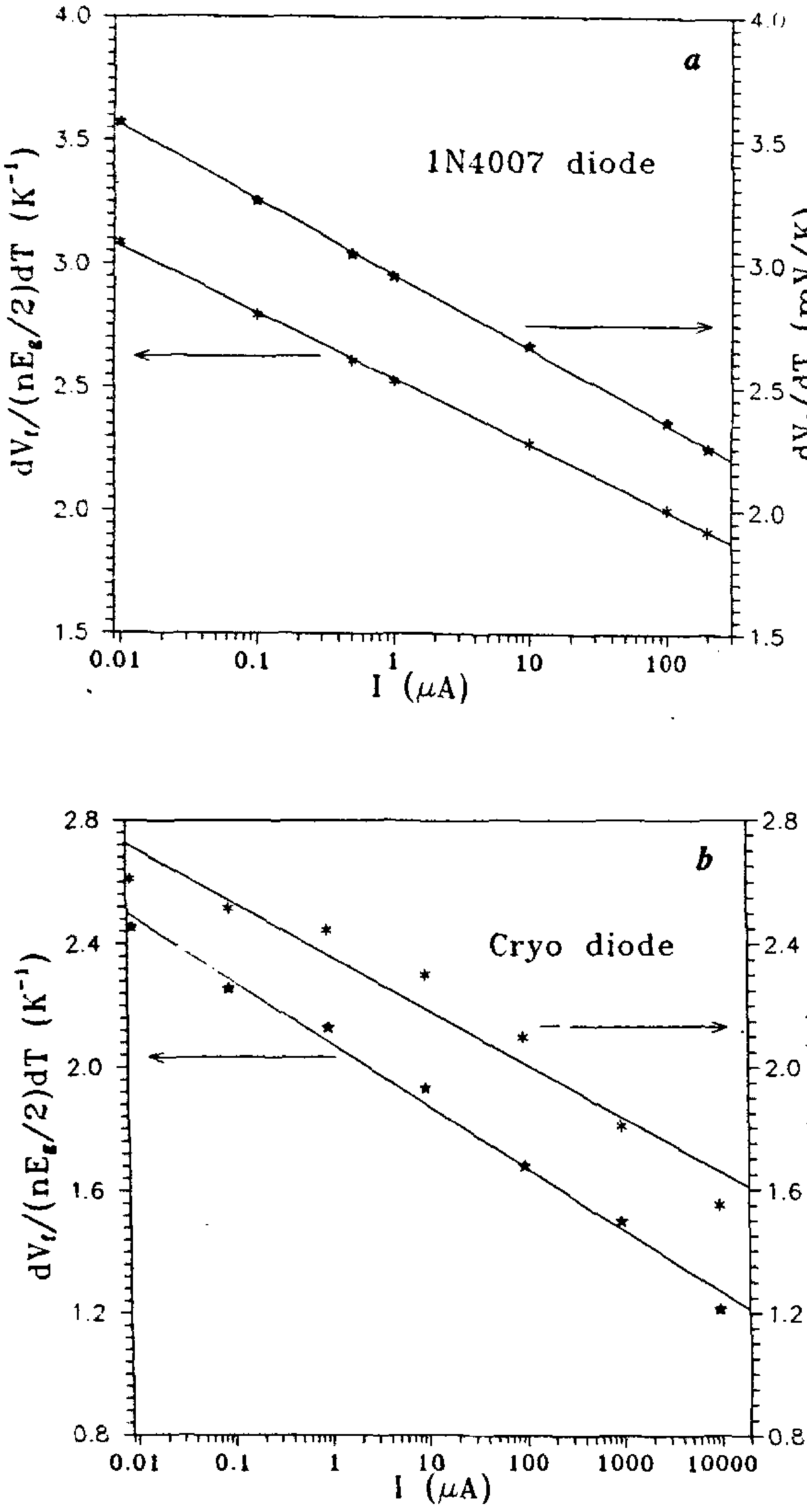

Figure 5. Current dependence of the sensitivity of (*a*) 1N4007 Si and (*b*) cryo diode.

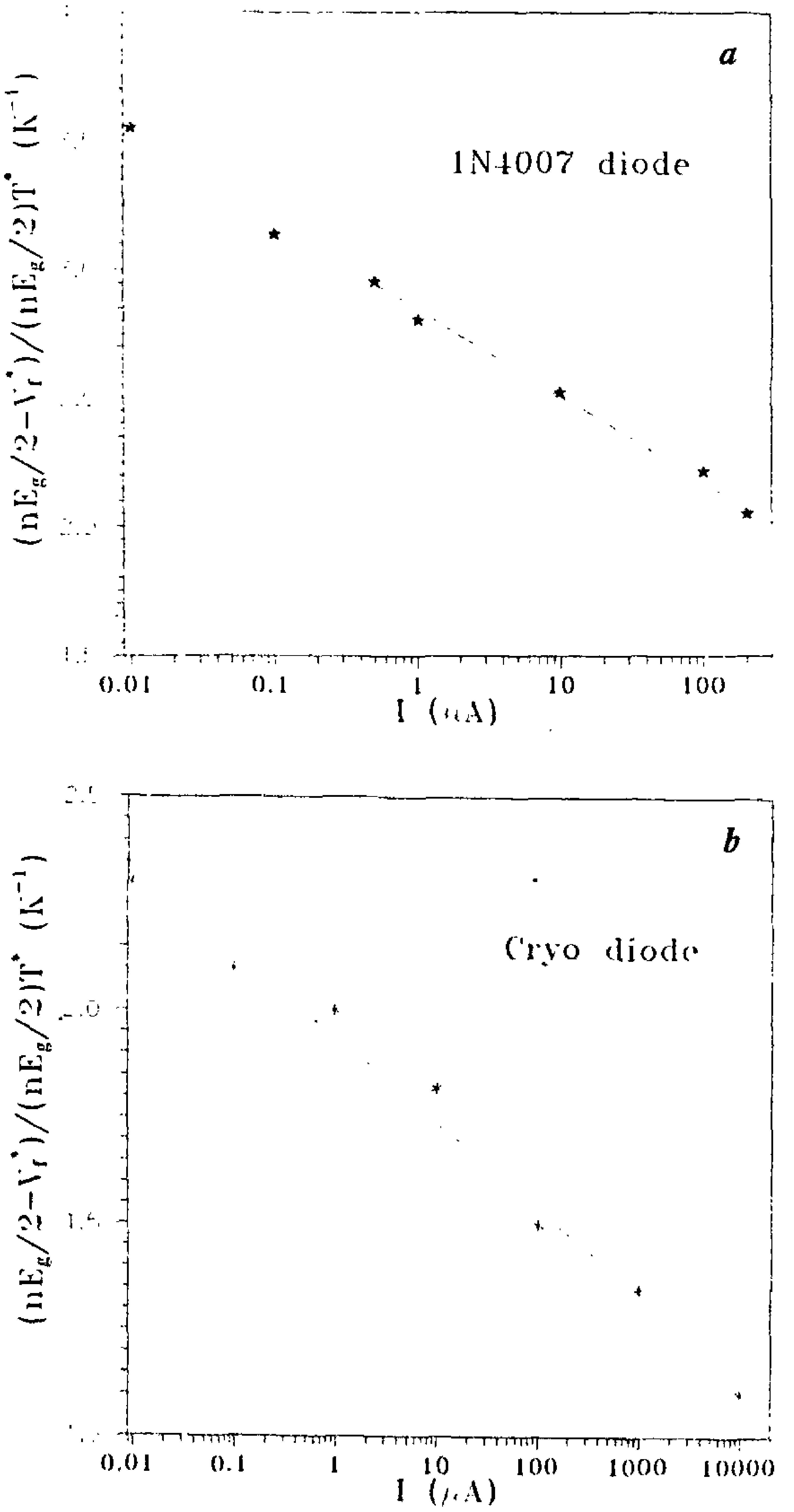

Figure 6. Current dependence of T^* for (*a*) 1N4007 Si and (*b*) cryo diode.

voltage was found to change from -2.4 mV/K to -3.5 mV/K in case of 1N4007 Si diode when the current was changed from 200 μA to 10 nA. The current dependence of the sensitivity and $[dV/(nE_g/2)\,dT]$ as $E_g/2$ is independent of current, are shown in Figure 5. As for 1N4007 Si diode, the change of $nE_g/2$ is little with respect to current, both the quantities seem to vary linearly (Figure 5 *a*). Of course, the match is excellent in the latter case. Similarly, in case of the Cryo diode (Figure 5 *b*), it is noticed from the (dV_f/dT) vs $\ln I$ that the data points are quite away from a straight line, whereas when plotted as $[dV_f/(nE_g/2)dT]$, the data points fit reasonably to a straight line as expected from eq. (4).

In order to test the T^* dependence of the current, we define V_f^* as the voltage that corresponds to T^*. At $T = T^*$, eq. (2) becomes

$$\frac{nE_g/2 - V_f^*}{nT^*} = \frac{k_B}{e}\left[\log Q + \tfrac{5}{2}\log T^* - \log I\right]. \qquad (5)$$

Eq. (5) implies that the quantity in the left hand side is logarithmic in I. The procedure to obtain T^* is described in ref. 7. In order to verify experimentally, we have plotted $(nE_g/2 - V_f^*/(nE_g/2)T^*)$ vs $\ln I$ for 1N4007 Si diode and cryo diode (Figure 6). Interestingly, the variation is found to be linear for both the diodes. Similar investigations on different diodes of the same batches confirm the result qualitatively.

The most interesting feature associated with the forward characteristics that the band gap can be determined by extrapolating V_f–T curve to 0 K (ref. 10). In the case of 1N4007 Si diode, though $nE_g/2$ varies logarithmically with current, the slope is too small, i.e. all the V_f–T curves meet almost at a point to give the value of $E_g = 1.17$ eV. But, in case of cryo diode, the slope is different in different current regime. It is noted from Figure 4 that in regime II, the slope is of the same order of magnitude as in the case of 1N4007 Si diode and can be used for the determination of the band gap. Following this procedure, the value of E_g for silicon is found to be 1.189 eV, which is very close to the earlier reported value[10] and within 2% that obtained for 1N4007 diode.

In conclusion, the current dependence of ideality factor (n) is found to be different for different silicon diodes. The current dependence of sensitivity (dV_f/dT) and that of crossover temperature (T^*) are understood by taking the current dependence of n into account. The procedure for the determination of the band gap is also presented.

1. Sze, S. M., *Semiconductor Devices: Physics and Technology*, John Wiley, New York, 1985.
2. Sze, S. M., *Physics of Semiconductor Devices*, John Wiley, New York, 1981.
3. Martil, I. and Gonzalez Diaz, G., *Eur. J. Phys.*, 1991, **12**, 149–152.
4. Cryo Industries of America, Inc., Atkinson, USA.
5. Nanda, K. K. and Ota, S. B., preprint (IP/BBSR/93-68).
6. Ota, S. B. and Nanda, K. K., 14th National System Conference – Agra (India), 1995, pp. 741–743.
7. Ota, S. B. and Nanda, K. K., *Rev. Sci. Instrum.*, 1994, **65**, 3189–3190.
8. Nanda, K. K. and Sarangi, S. N., *Rev. Sci. Instrum.*, 1997, **68**, 2904–2908.
9. Sah, C. T., Noyce, R. N. and Shockley, W., *Proc. IRE*, 1957, **45**, 1228–1243.
10. Kirkup, L. and Placido, F., *Am. J. Phys.*, 1986, **54**, 918–920.
11. Krause, J. K. and Dodrill, B. C., *Rev. Sci. Instrum.*, 1986, **57**, 661–665.

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CD4 positive T-cells produce cytotoxic factor in cases of dengue haemorrhagic fever

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During dengue virus infection of mice and man, an unique cytokine, cytotoxic factor (CF), is produced which reproduces various pathological lesions in mice that are seen in human cases of dengue fever (DF) and dengue haemorrhagic fever (DHF). The present study was undertaken on 15 cases of DF/DHF and 5 normal healthy control individuals to find out the cell responsible for the production of the human cytotoxic factor (hCF). Peripheral blood mononuclear cells (PBMC) or their enriched subpopulations of monocytes, B- or T-cells were cultured for 24 h and the culture supernatants were assayed for the presence of hCF by ELISA, dot blot and cytotoxicity assay. The findings showed that hCF was produced by T-cells and not by the monocytes or B-cells. Pretreatment of the T-cells with anti-CD4 antibody abrogated the production of hCF while anti-CD8 antibody had no effect. Presence of hCF-specific mRNA was found by Northern hybridization in the CD4 positive T-cells only of the cases and not in the CD8 positive T-cells, B-cells or monocytes, thus confirming, for the first time, production of hCF by CD4 positive T-cells.

THE cytotoxic factor is a unique cytokine that is produced in mouse (mCF) and man (hCF) during dengue virus infection only[1-3]. The amino terminal sequence of mCF has no homology with any known protein or cytokine as shown by matching at the data base till 1996. mCF