IP/BBSR/94-21
May 1994

The Temperature Dependence of the Forward Characteristics of 1N4007 Silicon Diode

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Abstract:

The temperature dependence of the forward voltage of 1N4007 Si-diode is reported in the temperature range 10−300K. The forward voltage for a current of 200μA was found to vary linearly at a rate of −2.4mV/K for temperatures above 60K. This temperature dependence of the forward voltage was found to change to −3.6mV/K when the current was changed to 10nA. It is observed that the forward voltage for a current of 200μA, first increased rapidly below a temperature (T^*) of about 21K and then gradually with further reduction in temperature. Moreover, T^* was found to reduce linearly with ln(I).

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The forward voltage of a semiconductor diode is known to increase by decreasing the temperature[1]. This characteristic has therefore found application in the measurement of temperature. Semiconductor diode exclusively made for sensing temperature are now-a-days available commercially[2]. These sensors can provide accuracy of 50mK and costs several orders of magnitude more than the diodes available for general electronic application. The later can also be used for sensing temperature[3,4]. Here, the temperature dependence of the forward voltage of 1N4007 Si-diode is reported.

The measurements were carried out from 10−300K using an automated setup built around a Leybold closed cycle refrigerator[5]. The encapsulation of the 1N4007 silicon diode was ground flat on one side and fixed to the sample site with GE7031 varnish. 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, typically 10 nA−200μA, while the voltage variation with temperature is monitored. This amount of current corresponds to a value below the knee in the V−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[6]. This has a standard measurement accuracy of ±1K at 2 to 100K, ±1% of the display value where T>100K. Measurement was carried out in two sets one from 10−27K in 1K step and the other from 30−300K in 30K step. Each data point was obtained by averaging 500 samples. This gave a typical temperature resolution of 50mK and voltage resolution of 100μV.

The forward voltage for a current of 200μA was found to vary linearly at a rate of −2.4mV/K for temperatures above 60K. This temperature dependence of the forward voltage was found to change to −3.6mV/K when the current was changed to 10nA. The

linear variation is understood by the theory of Sah, Noyce and Shockley[1] where the forward voltage(V_f) is shown to be related to the absolute temperature(T) and forward current(I) as follows:

$$V_f=(nk_BT/e)\ln(I/I_s+1)$$

where I_s is reverse saturation current, e is the electron charge and k_B is the Boltzmann constant. n is a parameter depending on the material, temperature and current level and typically has a value between 1 and 2. The observed increase in $|dV_f/dT|$ with decrease in forward current is also apparent Eq.1.

It was also observed that the forward voltage first increased rapidly below a certain temperature T^* and then gradually with further reduction in temperature. T^* was obtained using an extrapolation procedure as follows. The high temperature region of the V_f-T characteristic is linearly extrapolated to low temperatures. The region of maximum increase of forward voltage at low temperatures is also linearly extrapolated to high temperatures. The point of intersection of these two extrapolations is defined as T^*. T^* obtained in this manner is given in table–I for the measurements made on four diodes. It is seen that T^* is about 21K for a current of 200 μA. Moreover, T^* shifted to nearly 11K when the current was reduced to 10 nA. It was also found that T^* varies linearly with ln(I). This is shown in Fig.2. The suppression of the rapid increase of the forward voltage at low temperatures is accompanied by the increase in the temperature range over which the temperature dependence of the forward voltage is linear.

One of the main problems faced in diode thermometry is the loss of linearity at low temperatures. The observed improvement in the linearity with lower current is of advantage in diode thermometry, whose applicability is limited due to lack of reliable interpoation formula. In addition, the self heating in the diode is also reduced.

This work is supported by DST project no.SBR-49.

References:

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/6/ Leybold model LTC60 operating instructions AG, Germany.

Figure Captions:

Fig.1: The temperature dependence of forward voltage of 1N4007 Si-diode. Measurement was carried out with 10nA (lower most curve), 100nA, 500nA, 1μA, 10μA, 100μA and 200μA (upper most curve). The extrapolation procedure was used to obtain T^* is also shown (T^*=17.5K for 10μA). T^* is seen to shift to lower temperatures by decreasing the current.

Fig.2: T^* as a function of current for the 1N4007 diode results shown in fig.1. T^* is found to reduce lineraly with ln(I). The solid line is the least squares fitted line given by T^*=0.932 ln(I)+28.3.

Fig

le I: The forward characteristics of 1N4007 Si diode.

ode	dV_f/dT at 200 μA 60–300K	dV_f/dT at 10 nA 60–300K	V_f at 60K 200μA	V_f at 60K 10nA	T^* 200μA	T^* 10 nA
1	−2.38mV/K	−3.57mV/K	1.0457	0.9531	20.5K	~11K
2	−2.35mV/K	−3.54mV/K	1.0410	0.9518	20.5K	~11.0K
3	−2.37mV/K	−3.59mV/K	1.0410	0.9475	21.5K	13.5K
4	−2.25mV/K	−3.55mV/K	1.0396	0.9475	21.0K	~10.5K

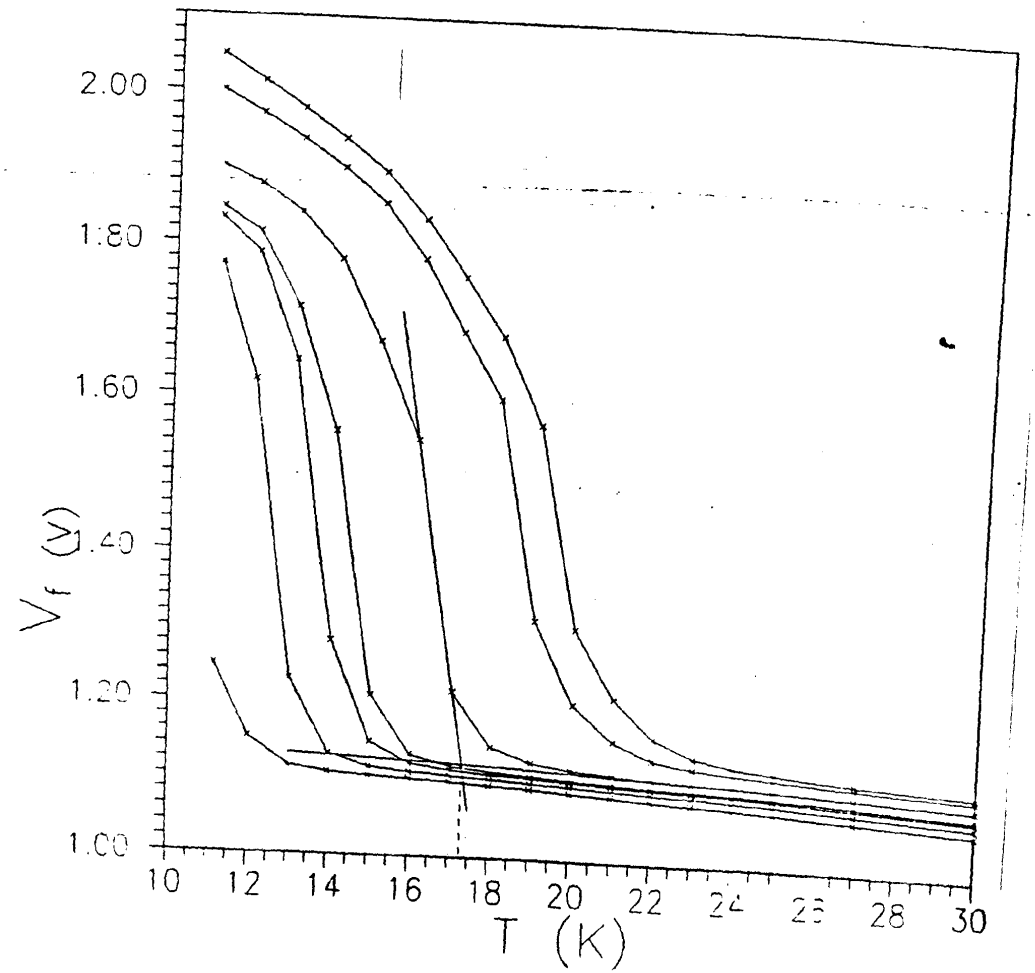
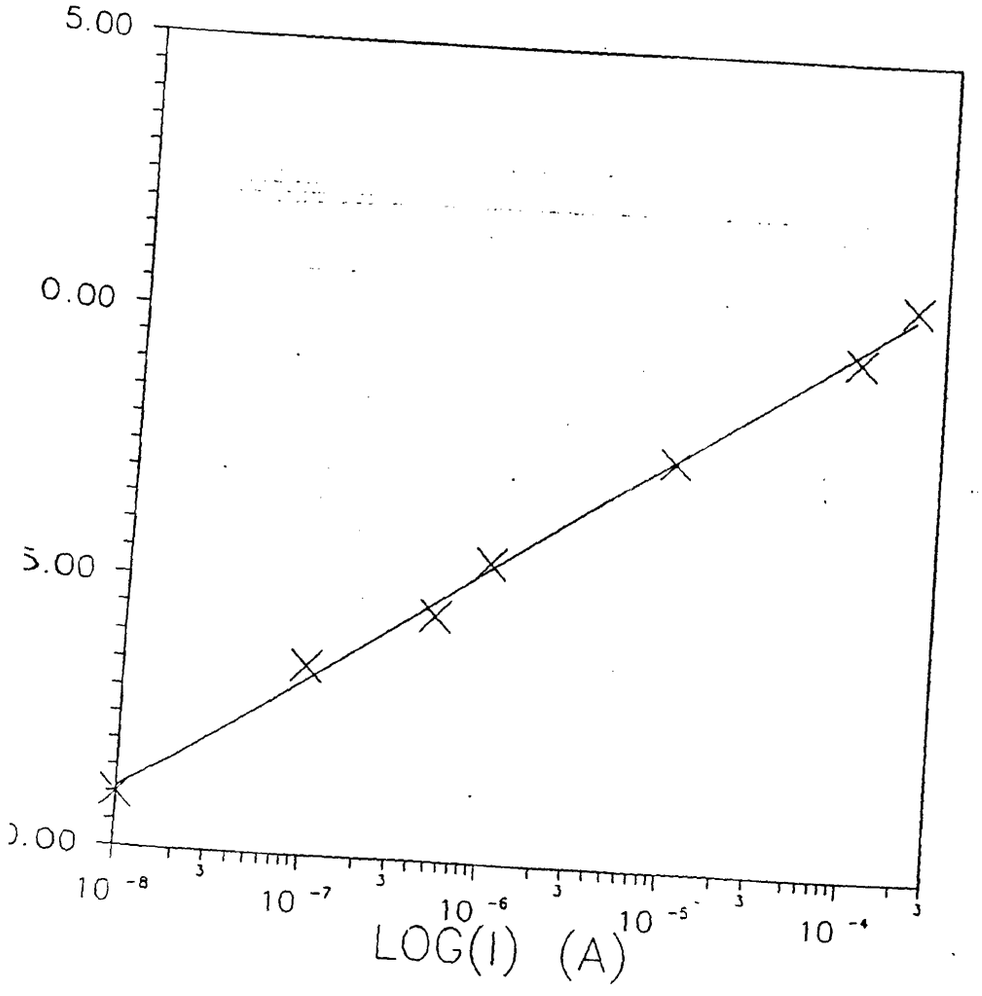


Fig 2



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