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Temperature-Voltage characteristic of Si 1N4007 diode

Abstract

The forward voltage of Si 1N4007 diode has been measured in the temperature range 30-300 K and for current values between 10 nA and 200 μA. The forward voltage as a function of temperature is least-squares fitted and the coefficients are given. The 1st, 2nd and 3rd order least-squares fitting has high temperature root between 320 K and 500 K. The presence of high temperature root indicates that the fitted polynomials are of similar nature. The high temperature root is found to increase for the least squares fitted polynomials corresponding to higher current values.

Key Words

Semiconductor; Temperature sensor; Silicon.

The p-n junction forms the basic building block of modern semiconductor electronics and therefore has attracted a great deal of interest. Silicon is tetravalent and indirect band semiconductor. Pentavalent dopants such as As, Sb, P are e-donors and gives rise to n-type Si. On the other hand tetravalent dopants such as Al, Bo, Ge are e-acceptors and gives rise to p-type Si. The forward characteristic of a Si p-n junction (Si diode) can be understood in terms of transport in high electric field which exists at the 'depletion region' of the diode[1]. The dimension of depletion region at the p-n junction is expected to be ~μm which is much smaller than that of the bulk doped semiconductor. The measurement of low temperature using diodes[2-5] is based on the usual observation that the voltage across the forward-biased diode increases with decrease in temperature. Si and GaAlAs are most commonly used semiconductor diodes for temperature measurement. At low temperatures the forward voltage increases more rapidly as the temperature is reduced which gives rise to a bend in the temperature dependence of forward voltage. The bend at low temperature can be associated with the characteristic of 'bulk' Si in Si diode[6]. The temperature at which the bend occurs depends on the forward current and reduces by decreasing the current. For Si 1N4007 diode the bend occurs between 10-25 K[7]. Some reviews on low temperature measurement with diodes are given in references 8-12. Sometimes temperature measurement between 30-300 K in low temperature laboratories (e.g. Department of Physics, IIT, Madras) needs accuracy ~0.1 K with easily available temperature sensors such as 1N4007 Si diodes. In view of this the calibration of the temperature dependence of forwards voltage of Si 1N4007 diode for various current values between 10 nA and 200 μA and in the temperature range 30-300 K is reported here.

Electrical resistance measurement was carried out by an automated d.c. Four probe method. The setup is automated using GPIB-IEEE-488 interface and the instrument interface program is written in MSDOS GWBASIC in a 80386 PC. The setup is built around a Leybold closed cycle refrigerator. A calibrated type-D silicon diode thermometer was used as the sensor for a Leybold model LTC60 temperature controller to control and monitor the temperature of the sample holder. The temperature is determined using the same silicon diode thermometer. This has standard measurement accuracy of ±1 K at 2-100 K and ±1% of the display value where T>100 K. The current was varied in steps using Keithley model 224/2243 programmable current source. The dc voltage was measured using a Keithley model 182 sensitive digital voltmeter. The encapsulation of 1N4007 silicon diode was ground flat on one side and fixed to the sample site with GE7031 varnish. Measurements were carried from 30-300 K with temperature intervals of 30 K. Each data point was obtained by averaging 500 readings.

The forward current I_f is related to the forward voltage V_f in a p-n junction, as follows[13,14]:

$$I_f=\exp(qV_f/\eta kT) \quad (1)$$

where q is the electronic charge, k is the Boltzmann constant, T is the temperature, and η is the ideality factor. The Eq.1 gives rise to a linear temperature dependence of V_f, for a fixed value of current. For extended temperature range (~100 K) there is significant deviation of linearity. Therefore the semiconductor diodes need to be calibrated with respect to standard and interpolation data is made. In some situations a lower order polynomial covering a large temperature range is needed. The least-squares fitting provides such a polynomial. The measured voltage as a function of temperature, for various current values, was least-squares fitted to the following polynomials:

$$V=\sum_{i=0}^{n} a_i T^i;\ n=1\text{-}4 \quad (2)$$

For the 1st order least squares fitting, there are two coefficients, which are given in TABLE 1, for various values of current. The coefficient a_0 and a_1 are found to be positive and negative, respectively. The R^2 of the least squares fitting was nearly 1.00. There is high temperature root T_0, for the least squares fitting, which is found to increase as the corresponding values of the current is increased from 10 nA to 200 μA. The T_0 is 323.4 K and 503.1 K for 10 nA and 200 μA, respectively. The presence of the high temperature root indicates that the fitted polynomials are of similar character. In case of 1st order least squares fitting the coefficient a_1, represents the average sensitivity of the diode, which is found to decrease with increase in current. a_1 varies from -3.588×10^{-3} to -2.355×10^{-3} V/K as the current is increased from 10 nA to 200 μA. The coefficients a_0 represent the extrapolated voltage at zero temperature, which was nearly constant and have a value of 1.2 V. This is consistent with the band gap of Si at 4.2 K which has value of 1.2 eV[6].

TABLE 1 : The 1st order least squares fitting of Si diode

Current	a_0	a_1	R^2	T_o (K)
10nA	1.16026	-3.58763×10^{-3}	1.00	323.4
100 nA	1.16978	-3.29612×10^{-3}	1.00	354.9
500 nA	1.17421	-3.09998×10^{-3}	1.00	378.8
1 μA	1.17606	-3.01944×10^{-3}	1.00	389.5
10 μA	1.18174	-2.75679×10^{-3}	1.00	428.7
100 μA	1.18478	-2.46054×10^{-3}	1.00	481.5
200 μA	1.18485	-2.35526×10^{-3}	1.00	503.1

In case of the 2nd order least squares fitting, there are three coefficients, which are given in TABLE 2. The coefficient a_0 is found to be positive, whereas, the coefficient a_1 is found to be negative. The coefficient a_2 changes sign for current ~100 nA. The R^2 of the least squares fitting was nearly 1.00. It is seen from TABLE 2 that there is high temperature root T_0 for all values of current. The T_0 increased from 326.6 K to 477.3 K as the current is increased from 10 nA to 200 μA. The presence of the high temperature root indicates that the fitted polynomials are of similar character. Here, the coefficient a_2 represents the deviation from linearity. It is seen from TABLE 2 that, there is minimum deviation from linearity, for current of 100 nA. The reason for choosing the 30-300 K range is that for low currents (~10nA) the least squares fitting extends to ~30 K without systematic deviation. Moreover, the I-V characteristic changes significantly below 30 K.

TABLE 2 : The 2st order least squares fitting of Si diode

Current	a_0	a_1	a_2	R^2	T_0 (K)
10 nA	1.17237	-3.78943×10^{-3}	6.11501×10^{-7}	1.00	326.6
100 nA	1.17144	-3.32378×10^{-3}	8.38163×10^{-8}	1.00	355.7
500 nA	1.17077	-3.04267×10^{-3}	-1.73672×10^{-7}	1.00	376.7
1 μA	1.17064	-2.92916×10^{-3}	-2.73545×10^{-7}	1.00	385.8
10 μA	1.16979	-2.55772×10^{-3}	-6.03188×10^{-7}	1.00	416.5
100 μA	1.17039	-2.22083×10^{-3}	-7.26383×10^{-7}	1.00	458.4
200 μA	1.17146	-2.13210×10^{-3}	-6.76187×10^{-7}	1.00	477.3

The 3rd order least-square fitting is given in TABLE 3. It is seen that there is high temperature root T_0 for all values of current. In case of 4th order least-squares fitting (TABLE 4) there were no high temperature roots for all current values. Therefore, we conclude that the fitted polynomials for different values of current are not of similar nature.

TABLE 3 : The 3rd order least squares fitting of Si diode

Current	a_0	a_1	a_2	a_3	R^2	T_0 (K)
10 nA	1.14843	-3.08158×10^{-3}	-4.50433×10^{-6}	1.03349×10^{-8}	1.00	335.0
100 nA	1.15202	-2.74958×10^{-3}	-4.06606×10^{-6}	8.38348×10^{-9}	1.00	371.2
500 nA	1.15523	-2.58311×10^{-3}	-3.49505×10^{-6}	6.70977×10^{-9}	1.00	369.5
1 μA	1.15668	-2.51651×10^{-3}	-3.25579×10^{-6}	6.02448×10^{-9}	1.00	406.7
10 μA	1.16141	-2.30993×10^{-3}	-2.39397×10^{-6}	3.61759×10^{-9}	1.00	436.0
100 μA	1.16984	-2.20442×10^{-3}	-8.45001×10^{-7}	2.39623×10^{-10}	1.00	460.2
200 μA	1.17360	-2.19530×10^{-3}	-2.19506×10^{-7}	-9.22544×10^{-10}	1.00	469.2

In conclusion the forward voltage of Si 1N4007 diode is measured at low temperatures. The data is obtained for current values between 10 nA and 200 μA and in the temperature range 30 K to 300 K. The voltage as a function of temperature is least-squares fitted to polynomials. From the second order fitting it is found that there is minimum deviation from linearity, for current of 100 nA. There are high temperature roots for all current values, in case of 1st, 2nd and 3rd order least-squares fittings. There were no high temperature roots for all current values for 4th order fitted polynomials.

TABLE 4 : The 4th order least squares fitting of Si diode

Current	a_0	a_1	a_2	a_3	a_4	R^2	T_0(K)
10 nA	1.15090	-3.18728×10^{-3}	-3.21523×10^{-6}	4.46339×10^{-9}	8.89604×10^{-12}	1.00	335.9
100 nA	1.15566	-2.90553×10^{-3}	-2.16399×10^{-6}	-2.80145×10^{-10}	1.31266×10^{-11}	1.00	378.6
300 nA	1.16222	-2.88164×10^{-3}	1.46234×10^{-7}	-9.87597×10^{-9}	2.51301×10^{-11}	1.00	-
1 μA	1.16456	-2.85325×10^{-3}	8.51217×10^{-7}	-1.26816×10^{-8}	2.83413×10^{-11}	1.00	-
10 μA	1.16944	-2.65280×10^{-3}	1.78764×10^{-6}	-1.54281×10^{-8}	2.88558×10^{-11}	1.00	-
100 μA	1.17700	-2.51047×10^{-3}	2.88763×10^{-6}	-1.67608×10^{-8}	2.57567×10^{-11}	1.00	-
200 μA	1.18102	-2.51233×10^{-3}	3.64716×10^{-6}	-1.85337×10^{-8}	2.66820×10^{-10}	1.00	-

It is noted that the standard deviation (of the 500 measured voltage values) was found to vary from 4 μV to 0.3 mV which is identified as due to 1/f noise.

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