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J.Phy.Ast.

Print-ISSN: 2320-6756
Online-ISSN: 2320-6764

Journal of
Physics & Astronomy

WWW.MEHTAPRESS.COM

Full Paper

Calibration of GaAlAs semiconductor diode around 15 K

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PACS Number(s): 73.40.Kp, 73.43.Fj, 83.30.-z

Received: January 13, 2013
Accepted: February 20, 2013

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Abstract

The forward voltage of GaAlAs semiconductor diode has been measured around 15 K for current values between 10 nA and 450 μA. The forward voltage as a function of temperature is least-squares fitted up to 3rd order and the coefficients are given. Only the 1st order least-squares fitting has high temperature roots between 40 - 55 K. The 2nd order least-squares fitting has no high temperature roots. The 1st and 2nd order least-squares fitting are of similar character.

Key Words

Semiconductor; Temperature sensors; GaAlAs.

The measurement of temperature using diodes is based on the observation that the voltage across the forward-biased diode increases with decrease in temperature[1-5]. Si and GaAlAs are most commonly used semiconductor diodes for temperature measurement[6-8]. 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 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[9]. Whereas for cryogenic silicon diode the bend occurs between 25-30 K[10]. In case of GaAlAs diode the bend occurs between 25-50 K[11,12]. The diodes are generally operated with 10 μA of forward current. These diodes have been used in the temperature range 1.4 to 450 K with an accuracy of 50 mK. A temperature sensitivity of a few mV/K has been obtained at high temperatures (T>50 K). In the low temperature range (T<50 K), the sensitivity exceeds 100 mV/K. We note here that for diodes the forward current can be reduced by several orders of magnitude down to 10 nA without losing sensitivity.

The problem of magnetic field dependence of the forward characteristic was overcome with the GaAlAs diode, which is a direct band gap semiconductor. GaAs p-n junction has also recently been studied in the context of carrier transport using light modulated scanning tunneling spectroscopy[13] and ideality factor[14]. In certain possible applications of semiconductor diodes for temperature measurement a high precision in the measurement of temperature is needed. Such situations include the measurement of temperature drift curve in low temperature heat pulse calorimetry[15,16].

Earlier we reported the calibration of the GaAlAs semiconductor diode for current values between 10 nA and 450 μA and for temperatures between 50-300 K[17]. For temperatures below 50 K the sensitivity of GaAlAs diode increases by about two orders of magnitude. At the same time Joule power dissipation becomes important specially for temperatures below 4 K. If the diode characteristic remains monotonic below 10 K then it can be used in the ultra low temperature range (50 mK – 1 K) by reducing the current by several orders of magnitude. The temperature sensors which have been generally used in ultra low temperature are resistance thermometer such as germanium and Ru_2O, noise thermometry, magnetic susceptibility thermometers or Coulomb blockade thermometer. In view of this we give the calibration of the temperature dependence of forward voltage of GaAlAs diode for various current values between 10 nA and 450 μA and around 15 K from measurements between 10-50 K.

The measurements were carried out using a computer controlled four-probe setup built around a closed cycle refrigerator[9-11]. The diode in the CU package configuration is epoxied into a flat cylindrical disk and the sensor leads are thermally anchored to the same disk. The metal encapsulation of the diode was fixed o the sample space of the closed cycle helium refrigerator with 0.2mm thick indium foil and a thin layer of Apiezon-N grease by clamping with an aluminum disk with screws using moderate pressure. The leads were further anchored at the sample space to minimize any thermo-electromotive force developed. The temperature of the sample site was controlled using a calibrated type-D silicon diode thermometer in conjunction with a Leybold model LTC60 temperature controller (Leybold AG, Germany). Measurements were carried out between 10 K – 50 K, for forward current from 10 nA to 450 μA. The temperature increment was 2 K and the current increment was in 11 equal logarithmic steps. Each data point was obtained by averaging 50 reading. A constant current was provided to the GaAlAs diode from a Keithley (Keithley Instruments, USA) model 224/2243 programmable current source. The forward voltage was measured using a Keithley model 182 sensitive digital voltmeter.

First the temperature is determined using the calibrated voltage value of the GaAlAs diode for 10 μA of current, which was provided by the manufacturer. The measured voltage as a function of temperature, for various current values, was then least-squares fitted to the following polynomials:

$$V=\sum_{i=0}^{n} a_i T^i;\ n=1\text{-}3 \quad (1)$$

For the least squares fittings only 7 points were used for temperatures between 10-22 K. There are two coefficients for the 1st order least squares fitting 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 decrease as the corresponding values of the current is increased from 10 nA to 450 μA. The T_0 is 52.70 K and 42.32 K for 10 nA and 450 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 increase with increase in current. a_1 varies from -5.18×10^{-2} to -1.78×10^{-1} V/K as the current is increased from 10 nA to 450 μA. The coefficients a_0 represent the extrapolated voltage at zero temperature, which was found to vary from 2.73 V to 7.52 V as the current is increased from 10 nA to 450 μA.

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

Current	a_0	a_1	R^2	T_o (K)
10nA	2.73018	-5.18101×10^{-2}	0.99	52.70
30nA	3.06378	-6.27116×10^{-2}	0.99	48.86
100 nA	3.43547	-7.37544×10^{-2}	0.99	46.58
300 nA	3.79593	-8.37501×10^{-2}	1.00	45.33
1 μA	4.25260	-9.62701×10^{-2}	1.00	44.18
3 μA	4.71490	-1.08295×10^{-1}	1.00	44.00
10 μA	5.26455	-1.21727×10^{-1}	1.00	44.00
30 μA	5.86011	-1.37148×10^{-1}	1.00	42.80
100 μA	6.52018	-1.52076×10^{-1}	1.00	43.50
300 μA	7.22072	-1.69108×10^{-1}	1.00	43.00
450 μA	7.52067	-1.77730×10^{-1}	1.00	42.32

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 coefficients a_1 and a_2 are found to be negative and positive respectively. The R^2 of the least squares fitting was nearly 1.00. It is seen from TABLE 2 that there is no real roots and the fitted polynomials are of similar nature. The coefficient a_0 is found to vary from 3.22 V to 8.09 V as the current is increased from 10 nA to 450 μA. The coefficient a_2 which represents the deviation from linearity is found to be nearly constant (~2.0×10^{-3} V/K^2). In case of 3rd order least-squares fitting, there were no high temperature roots for all current values. The coefficients are given in TABLE 3. Therefore, we conclude that the fitted polynomials for different values of current are not of similar nature.

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

Current	a_0	a_1	a_2	R^2	T_0 (K)
10 nA	3.22296	-1.15293×10^{-1}	1.93667×10^{-3}	1.00	-
30 nA	3.59690	-1.31390×10^{-1}	2.09518×10^{-3}	1.00	-
100 nA	3.90296	-1.33979×10^{-1}	1.83726×10^{-3}	1.00	-
300 nA	4.22005	-1.38386×10^{-1}	1.66679×10^{-3}	1.00	-
1 μA	4.71798	-1.56223×10^{-1}	1.82899×10^{-3}	1.00	-
3 μA	5.20579	-1.71532×10^{-1}	1.92919×10^{-3}	1.00	-
10 μA	5.71791	-1.80132×10^{-1}	1.78175×10^{-3}	1.00	-
30 μA	6.41416	-2.08524×10^{-1}	2.17747×10^{-3}	1.00	-
100 μA	7.10746	-2.27733×10^{-1}	2.30805×10^{-3}	1.00	-
300 μA	7.85295	-2.50554×10^{-1}	2.48469×10^{-3}	1.00	-
450 μA	8.08877	-2.50916×10^{-1}	2.23267×10^{-3}	1.00	-

The forward voltage of GaAlAs semiconductor diode

TABLE 3 : The 3rd order least squares fitting of GaAlAs diode at 15 K

Current	a_0	a_1	a_2	a_3	R^2	T_0 (K)
10 nA	3.31301	-1.32700×10^{-1}	3.02272×10^{-3}	-2.19316×10^{-5}	1.00	88.87
30 nA	3.74230	-1.59496×10^{-1}	3.84878×10^{-3}	-3.54119×10^{-5}	1.00	64.16
100 nA	3.68249	-9.13613×10^{-1}	-8.21763×10^{-4}	5.36961×10^{-5}	1.00	-
300 nA	4.30257	-1.54338×10^{-1}	2.66204×10^{-3}	-2.00979×10^{-5}	1.00	64.98
1 μA	4.76764	-1.65822×10^{-1}	2.42790×10^{-3}	-1.20943×10^{-5}	1.00	107.10
3 μA	5.63664	-2.54817×10^{-1}	7.12560×10^{-3}	-1.04936×10^{-4}	1.00	40.68
10 μA	5.78643	-1.93376×10^{-1}	2.60809×10^{-3}	-1.66869×10^{-5}	1.00	59.49
30 μA	6.34306	-1.94780×10^{-1}	1.31995×10^{-3}	1.73166×10^{-5}	1.00	-
100 μA	7.16508	-2.38872×10^{-1}	3.00302×10^{-3}	-1.40343×10^{-5}	1.00	83.07
300 μA	8.46760	-3.69367×10^{-1}	9.89777×10^{-3}	-1.49699×10^{-4}	1.00	39.83
450 μA	8.75061	-3.78851×10^{-1}	1.02149×10^{-2}	-1.61193×10^{-4}	1.00	38.85

is measured at low temperatures. The data is obtained for current values between 10 nA and 450 μA and around 15 K. The voltage as a function of temperature is least-squares fitted to polynomials and the coefficients are given.

ACKNOWLEDGMENTS

The author is benefited from his visit to Europe in 1988-1992 for HTSC research, Xiamen, China during 1995 for statistical physics conference and New Orleans, USA during 2008 for APS March meeting. The author gratefully acknowledges maintenance members of the Institute of Physics.

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