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Thermal sensitivity from current-voltage-measurement temperature characteristics in Au/*n*-GaAs Schottky contacts

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Abstract: We have measured the current–voltage-temperature (I-V-T) characteristics of the Au/n-GaAs/In Schottky barrier diodes (SBDs) to introduce their thermal sensitivity mechanism. The forward bias voltage variation with temperature (thermal sensitivity) of this SBDs has been studied at different constant current levels. The diode showed high and decisive thermal sensitivity up to a current level of 0.10 pA. The bias voltage-temperature (V-T) curves of the SBD have showed an excellent linear behavior at all current levels. The slope $\mathrm{d}V/\mathrm{d}T = \alpha$ or the thermal sensitivity coefficient α from the V-T curves decreased from 3.42 mV/K at 0.10 pA to 1.31 mV/K at 10 mA with increasing current level. Furthermore, the α versus current graph of the diode has given a straight line from 0.10 pA to 10 mA whose intercept α_0 and slope $d\alpha/dI$ values have been obtained as 2.65 mV/K and -0.081 mV/(AK). The linearity of the voltage vs temperature and the α vs current graphs is a very crucial key factor of a good thermal sensor in the thermal sensitivity.

Keywords: Schottky diodes, temperature sensor, thermal sensitivity, thermionic emission, GaAs semiconductor

1. Introduction

Metal-semiconductor (MS) Schottky contacts (SCs) allow the current to flow in forward biased direction after a given specific voltage (threshold voltage) but rectify the current in the opposite reverse biased direction. The MS Schottky barrier diodes (SBDs) have a wide application field in electronic devices and in high frequency and microwave applications. The MS contacts are generally used as both ohmic and Schottky contact in electronic device fabrication [1–4]. The SCs are often used in high frequency circuits, low noise amplification, microwave and optical signal detection in circuit applications. Besides these applications, the SCs based on different Semiconductor materials were also used as a temperature sensing element in various low and high temperature applications. That is, a MS SC can also be used as a thermal sensing probe in temperature measurements [1–10]. In contrast to the p-n junction and semiconductor transistors, a change in the state of the SC immediately affects its parameters when a SBD is in direct contact with environment, namely gas, pressure and temperature. That is, the thermal sensing devices capable of operating under low and high temperature, high radiation, and corrosive environment provide important information about the temperature variation at the desired locations in the applications such as automotive industries, aerospace systems, industrial

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turbines, deep-well drilling telemetric systems and cement industries [5–15]. In integrated thermal sensing units, the cryogenic temperature sensor is used as an important device [10–15].

A number of works were made on the performance of a MS SC in temperature sensing, using the variations of forward bias voltage drop across the SC with temperature [5–16]. Brezeanu et al. [5] have designed a temperature probe with a 4H-SiC SC which can sense temperature having sensitivity from 1.3 mV/K to 2.8 mV/K, over a wide temperature range from 20℃ to 400℃. Guo et al. [7] used an Al_2O_3 based a-IGZO (amorphous indium-gallium-zinc-oxide) SDs as a temperature sensor, and reported that the thermal sensitivity of the sensor was 0.81 mV/℃, 1.37 mV/℃ and 1.59 mV/℃ at the forward bias current density levels of 10^{-5} A/cm^2, 10^{-4} A/cm^2 and 10^{-3} A/cm^2, respectively. Moreover, the forward voltage-temperature (V-T) measurements have been carried out thermally annealed and un-annealed W/n-GaAs SBDs by Marcano et al. [8] in the temperature range of 140K to 363 K and in the current range of 2.5 pA to 500 pA. They [8] have obtained the thermal-sensitivity coefficient ($\mathrm{d}V/\mathrm{d}T$) = α values of -2.31 mV/K and -2.59 mV/K, at 100 pA for thermally annealed and un-annealed SBDs, respectively. Filonov [9] found a α value of 2 mV/^{o}C for Pd/GaAs structures with 0.32 mm^2 SC area for I=10 mA and n_0 = (1-3)x10^{16} cm^{-3}.

Kumar et al. [10] inspected the thermal sensitivity variation trend of Ni/4H-nSiC temperature sensors depending on the metal contact diameter, [10] measured the thermal sensitivities in the current range from 50 pA to 1 μ A and in the temperature range of 273 K to 473 K in step of 25 K. Again, in a later article, Kumar et al. [11] introduced a study on highly sensitive and circular shaped Ni/4H-nSiC temperature sensors of area 3.140 mm^2 fabricated and characterized in temperature range of 233 K to 473 K and in forward current from 10 pA to 5 nA, and reported that the highest value of absolute thermal sensitivity for the SB diode is 3.425 mV/K at 10 pA. Benedetto et al. [12] analyzed the performances of di-vanadium Pentoxide/4H polytype of silicon carbide (V_2O_5/4H-SiC) temperature sensors in the temperature and current range between 147.22 and 396.75 K and 1 μA and 1 mA, respectively. Rao et al. [13] revealed from the thermal sensing measurements of a 4H-SiC SBDs that the forward bias voltage showed a linear dependence on the temperature with the sensitivity of 1.86 mV/K at 16 μA and 1.18 mV/K at 80 μA.

Draghici et al. [14] reported the temperature sensing element of Ni/4H-SiC SBDs with sensitivities over 2 mV/℃ and excellent linearity which allows operation at temperatures up to 400 ℃. Their diode temperature sensitivities were between 1.8 mV/℃ and 2.54 mV/℃, for the current levels in the range 100 nA to 100 μA [14]. Pascu et al. [15] introduced temperature-sensing element of the annealed (750 ℃) and non-annealed Ni/4H-SiC SBDs over 60-700 K. The high-performance temperature sensors in dual 4H-SiC Junction BDs and SBDs were made by Min et al. [16] over 298-573 K. Their dual JBS diodes showed the higher peak sensitivity of 4.32 mV/K compared to the 2.85 mV/K of the SBD at a forward current ratio (I_{D2}/I_{D1}) of 25 [16]. Li et al. [17, 18] fabricated the NiN/GaN and Ni/GaN SBDs, and reported from their temperature-dependent I-V characteristics that the NiN-SBDs have better thermal stability than that of the Ni-SBDs owing to the suppression of interface reaction between Ni and GaN, and therefore, that the thermal stability of the GaN diode with NiN (nickel nitride) anode has temperature sensing application with the sensitivity of about 1.3 mV/K. Again, in their other work, Li et al. [19] fabricated TiN/GaN SBDs with different SC diameters to investigate the temperature sensing mechanism over a temperature range of 25-200 ℃, and found that the thermal sensitivity increased with the increasing SC diameter and obtained the highest sensitivity of 1.22 mV/K for SD with 300-μm-diameter at current level of 20 mA. In addition to works above, it has been stated by Perez et al. [20] that the biased voltage of a SBD at a given bias current level can be used as a thermos-sensitive parameter to perform temperature measurements on a monolithic integration of SBDs, and that the bias voltage versus temperature plot for a bias current of 2.5 A/cm^2 had a linear variation range with a sensitivity of -1.6 mV/K in 300-440 K [20]. Moreover, the thermal sensitivity for Ni/4H-*n*-SiC SBD was reported to vary from 3.11 mV/K at 1 nA to 3.32 mV/K at 5 pA by Kumar et al. [21].

We have measured the current-voltage (I-V) characteristics of the Au/*n*-GaAs/In SBDs in temperature range of 350 K down to 20 K by steps of 5 K. We have characterized the thermal sensitivity or cryogenic temperature behavior of the Au/*n*-GaAs/In SBDs as a temperature sensor and have operated from low current of 0.10 pA to 10 mA which have covered a broad thermal sensing range. From the applicability point of view, the thermal sensitivity study of the SBDs in low current levels is very important. Thermal-sensing applications require a strongly linear forward voltage - temperature dependence [5–15]. To the best of our knowledge, no such a study has been reported so far regarding this kind of sensitivity variation for Au/n-GaAs/In SBDs over a wide temperature and current range.

2. Experimental procedure

The Si doped *n*-type GaAs layer with 1x10^{16} cm^{-3} concentration density was grown by Molecular Beam Epitaxy (MBE) in a VG VAOH system. Detailed information about the epitaxy growth on the *n*-type GaAs substrate can be found in ref. [22]. The chemically ultrasonic cleaning procedure was applied trichloroethylene, acetone and methanol for 5 min to *n*-type MBE-GaAs samples. Then, the semiconductor sample was immersed to 5% diluted HCl for 30 sec. After this step it was washed with DI water. Indium ohmic contact was evaporated at 8x10^{-7} Torr, and then the *n*-type MBE-GaAs/In samples were annealed at 450 ^{o}C in dry nitrogen flow for 5 min for the ohmic contact formation. Finally, Au Schottky contacts with 0.5 mm diameter were carried out in 8x10^{-7} Torr. The schematic cross-section of MS Schottky diode is given in Figure 1. The I-V characteristics were measured by Keithley 6515 and 2400 current-voltage source and electrometer, respectively. Cooling of samples was provided by closed cycle He cryostat. The sample temperature was measured by Lakeshore 330 temperature controller and stability was better than 0.02 K during each sampling.

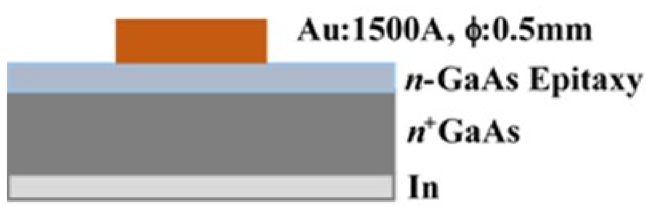

Figure 1. Schematic cross-section of metal-semiconductor Schottky diode.

3. Result and discussion

It was reported that the maximum current sensitivity to temperature changes can be observed in the Schottky contacts where a thermionic emission (TE) takes place [7–11]. Therefore, we should first look at whether the current flow through the Au/*n*-GaAs/In SBDs obeys to TE model. The current transport expression with voltage through a SB diode in the standard TE model is given by [2–4]

$$I = AA^{*}T^{2}exp\left(-\frac{\mathrm{e}\Phi_{b}\left(V\right)}{kT}\right)\left[exp\left(\frac{eV}{kT}\right)-1\right], \quad (3.1)$$

in expression above, A, A^*, V and $\Phi_b(V)$ terms represent, respectively, the diode area, Richardson constant for n-type GaAs (8.16 $\mathrm{Acm}^{-2}\mathrm{K}^{-2}$), the forward bias voltage and the bias-dependent SBH, respectively. The $\Phi_b(V)$ can be obtained as follows [2–4]:

$$\Phi_b(V) = \Phi_b(0) - \left(1 - \frac{1}{n}\right) V, \tag{3.2}$$

$$\beta = \left(1 - \frac{1}{n}\right), \Phi_b(V) = \Phi_b(0) - \beta V, (1-\beta) = \frac{1}{n} \tag{3.3}$$

$$I = AA^*T^2 exp\left(-\frac{\mathrm{e}\Phi_b(0) + \beta eV}{kT}\right)\left[exp\left(\frac{eV}{kT}\right) - 1\right] \tag{3.4}$$

$$I = AA^*T^2 exp\left(-\frac{\mathrm{e}\Phi_{b0}}{kT}\right) exp\left(-\frac{\beta eV}{kT}\right)\left[exp\left(\frac{eV}{kT}\right) - 1\right] \tag{3.5}$$

where I_0 and Φ_{b0} are the saturation current and zero bias SBH, and from eqn.(3.5) I_0 is given by

$$I_0 = AA^*T^2 exp\left(-\frac{\Phi_{b0}}{kT}\right). \tag{3.6}$$

From Equation (3.6), $\Phi_{b0} = \Phi_b(0)$ is written as

$$\Phi_{b0} = \frac{kT}{q} ln\left(\frac{I_0}{\mathrm{A}A^*T^2}\right) \tag{3.7}$$

Thus, the TE current expression can be written as

$$I = I_0 exp\left(-\frac{\beta eV}{kT}\right) exp\left(\frac{eV}{kT}\right)\left[1 - exp\left(-\frac{eV}{kT}\right)\right]$$

$$I = I_0 exp\left(\frac{eV(1-\beta)}{kT}\right)\left[1 - exp\left(-\frac{eV}{kT}\right)\right]$$

$$I = I_0 exp\left(\frac{eV}{nkT}\right)\left[1 - exp\left(-\frac{eV}{kT}\right)\right], \tag{3.8}$$

where

$$(1-\beta) = \frac{1}{n}$$

and for $qV > 3kT$ from Equation (3.8), ideality factor n and forward bias voltage are given by

$$n = \frac{q}{kT}\frac{dV}{d(lnI)} \tag{3.9}$$

$$V = n\frac{kT}{q} ln\left(\frac{I}{\mathrm{A}A^*T^2}\right) + n\Phi_{b0} \tag{3.10}$$

$$\alpha = \frac{dV}{dT} = \frac{nk}{q}\left[ln\left(\frac{I}{\mathrm{A}A^{*}T^{2}}\right) - 2\right]. \tag{3.11}$$

Figure 2 displays the temperature-induced I-V curves of one from the Au/n-GaAs/In SBDs. It can be seen from the figure that the linear portion of the curve where TE current is dominant still occupies more than six decades in current at 350 K, with an ideality factor of 1.026. The linear part in the I-V curves increases with decreasing temperature from 350 K to 120 K. It can be said that the TE fitting curves obey the experimental data quite well at high temperatures or in the high current region at low temperatures.

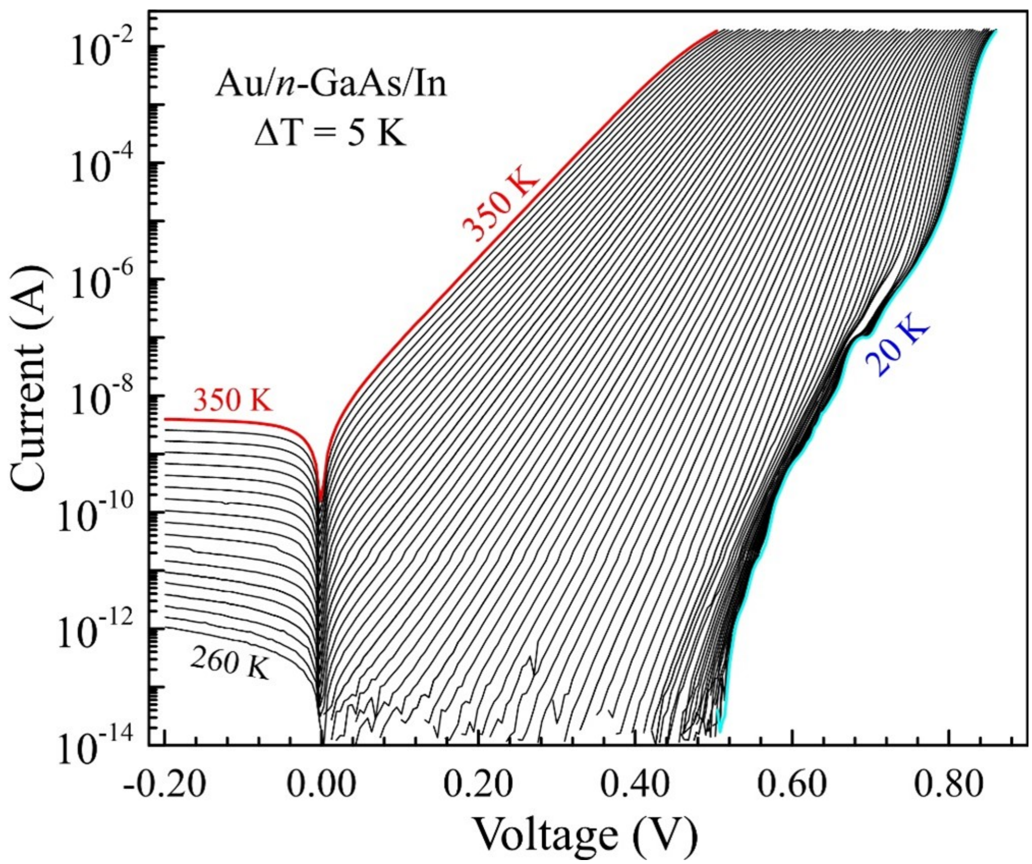

Figure 2. Dependence of the I-V data on measurement temperature in the Au/n-GaAs/In diode

Some researchers [5–21] reported from the experimental thermal sensitivity studies that the maximum current sensitivity depending on temperature can be observed in the Schottky contacts where a TE takes place. Therefore, we first looked at whether the current flow through the Au/n-GaAs Schottky contact corresponds to TE. Furthermore, the bias voltage in the forward bias I-V characteristics depends explicitly on barrier height and thus ideality factor. That is, the bias voltage dependent of the SBH in the intimate SBDs will also affect its thermal sensitivity. Therefore, the dependence of the bias voltage on the temperature and current in the SBDs are important factors in thermal sensitivity studies. A systematic study of the variation of these parameters with temperature is required to get a relevant explanation about measured thermal sensitivity trend in the fabricated SBD. The forward bias current flow through the diode should obey TE law and should show an ideal exponential type curve [22–30]. The ideality factor value ranges from 1.026 at 350 K to 1.064 at 120 K, and the values of the ideality factor close to one are evidence that the current fits the TE model [22–35].

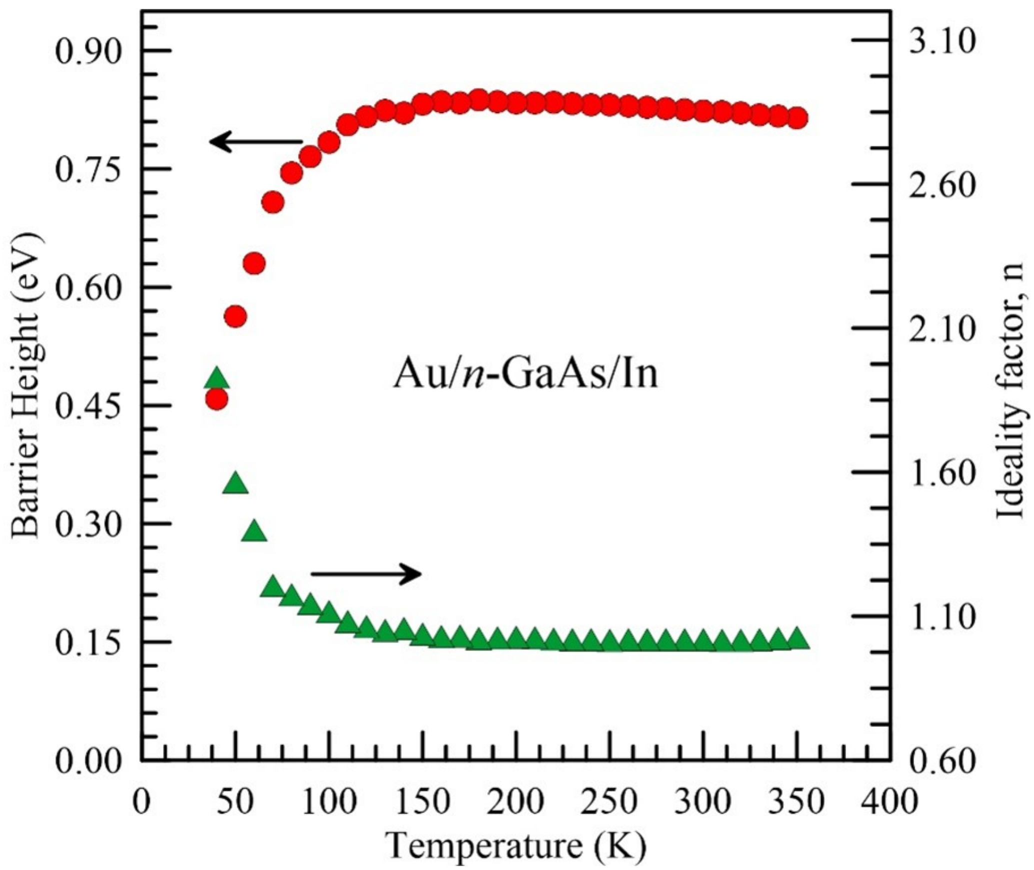

Figure 3. Dependence of barrier height and ideality factor characteristics on measurement temperature in the Au/n-GaAs/In diode

The dependence of barrier height Φ_{b0} and ideality factor n on measurement temperature was given in Figure 3 for the Au/n-GaAs/In diode. The Φ_{b0} taken the values of 0.815 eV, 0.824 eV and 0.458 eV at 350 K, 300 K and 40 K. It can be seen from Figure 3 that the Φ_{b0} value decreased while n value increased from 120 K down to 40 K. These low and high barrier height values are evidence that there exist inhomogeneities in barrier height formation at the Au/n-GaAs lateral interface. The SBH in the MS Schottky contacts has been reported to depend sharply on the interface atomic structure at epitaxial MS interfaces. In such cases, the current across the MS contact is greatly influenced by the presence of the SBH inhomogeneity [35–40]. Some researchers have considered the presence of locally non-uniform regions or patches with relatively lower or higher barriers [41–45]. Thus, they have suggested that the abnormal behaviors at low temperature can rather be adequately explained using a barrier potential fluctuation model based on spatially inhomogeneous BHs at the MS interface. Thus, it is reasonably assumed that the I-V characteristics are dominated by the current flow through the low-SBH patches because the overall current across the SBD arises from low barrier height regions which are interspersed within a uniform higher barrier height region [45–56]. That is, as the temperature is decreasing, electrons loose thermal energy, and the current preferentially flows through areas with smaller barrier height with decreasing temperature due to the BH inhomogeneity [45–56].

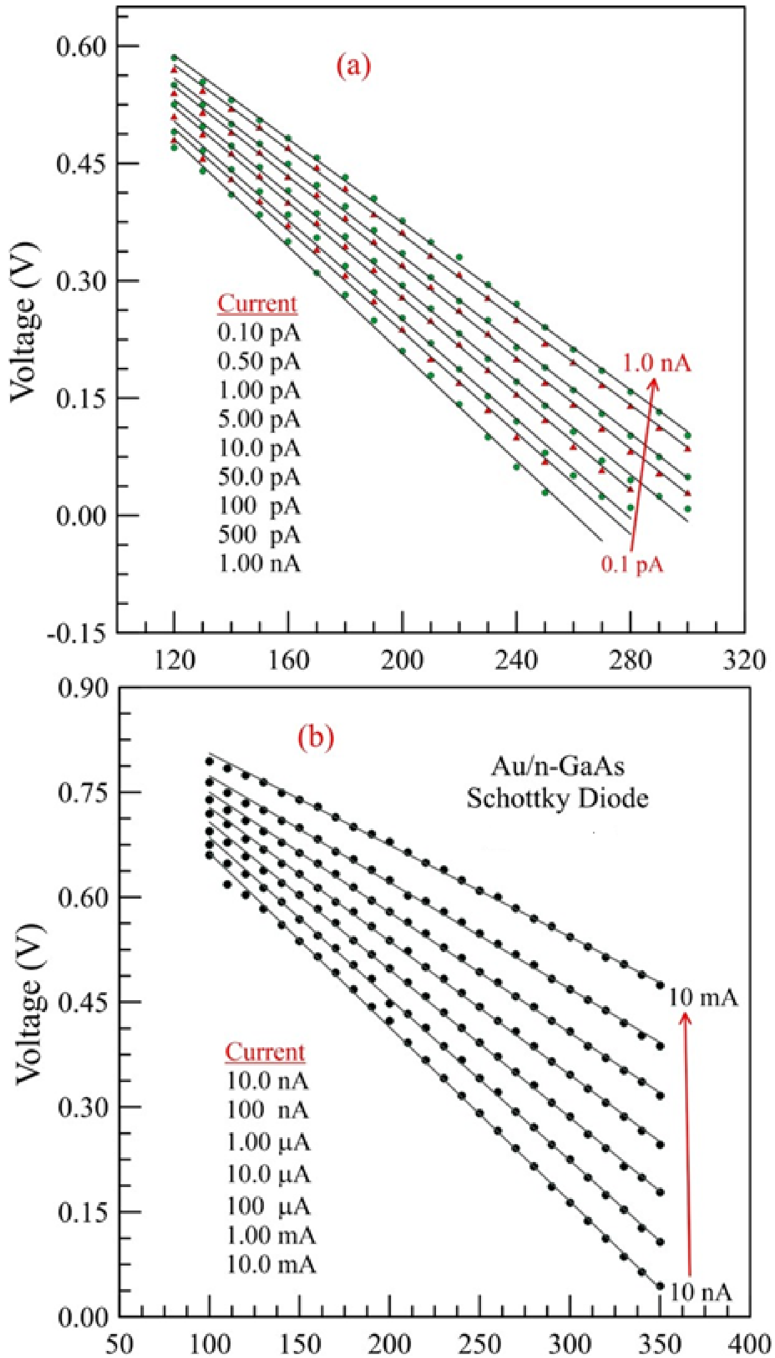

Figure 4. Dependence of the forward biased voltage on measurement temperature in Au/*n*-GaAs/In diode at different constant currents, (a) 0.10 pA to 1.0 nA, and (b) 10 nA to 10 mA

Figure 4 represents the dependence of the forward biased voltage on measurement temperature in Au/*n*-GaAs/In diode, (a) 0.10 pA to 1.0 nA, and (b) 10 nA to 10 mA. The V-T curve at each current level in Figure 4 (a) and (b) given a straight line. The linearity in the thermal sensitivity plots is a key factor of a good thermal sensor. Paying attention to Figure 4 (a) and (b), the V-T graph at each current level continues linearly down to approximately 120 K. The thermal sensitivity coefficient defined as the slope of V-T curve depends on the Φ_{b0} and n values. It can be noticed that these two parameters have a very low temperature dependence. The situation is clearly seen from Figure 3. The Φ_{b0} value decreased while n value increased from 120 K down to 40 K. The series resistance of the diode causes the V-T curves to deviate from the linearity at high voltages. We can state that the series resistance restricts the linearity of the V-T characteristics for higher bias current level. This is more evident at higher current levels in Figure 4 (b), for example, at 0.75 V for the current level of 10 mA. The thermal sensitivity coefficient values $\boldsymbol{\alpha} = (\mathrm{d}V/\mathrm{d}T)$ corresponding to constant current values for the Au/n-GaAs/In SBD are given in Table 1. The slope $\mathrm{d}V/\mathrm{d}T = \alpha$ or the thermal sensitivity coefficient α from V-T curves increased with decreasing current level and it ranged from 3.42 mV/K at 0.10 pA to 1.31 mV/K at 10 mA. Furthermore, we have also obtained a value of $\alpha = 2.67$ mV/K at the current level of 1.0 nA.

Table 1. The thermal sensitivity coefficients, $\alpha = (dV/dT)$, corresponding to constant current values in the Au/n-GaAs/In SBD. These values have been obtained from the V-T curves in Figure 4 (a) and (b).

Current	$(\mathrm{d}V/\mathrm{d}T)$(mV/K)
0.10 pA	3.42
0.50 pA	3.24
1.00 pA	3.17
5.00 pA	3.06
10.0 pA	2.99
50.0 pA	2.90
100 pA	2.84
500 pA	2.72
1.00 nA	2.67
10.0 nA	2.50
100 nA	2.31
1.00 μA	2.11
10.0 μA	1.91
100 μA	1.72
1.00 mA	1.53
10.0 mA	1.31

It has been seen that the sensitivity for SiC SBDs [5] has varied from 1.3 mV/K from 010 mA to 2.8 mV/K at 0.10 nA with the forward current in 300 K to 400 K range. Marcano et al. [8] obtained α values of 2.31 mV/K and 2.59 mV/K, at 100 pA for thermally 750 ℃ annealed and un-annealed W/n-GaAs SBDs, respectively, in the measurement temperature range of 140-363 K. Filonov [9] reported a thermal sensitivity coefficient of $\alpha = 2$ mV/^{o}C at I=10 mA for Pd/GaAs structures.

The thermal sensitivity α versus forward current plot of the diode is given in Figure 5. The thermal

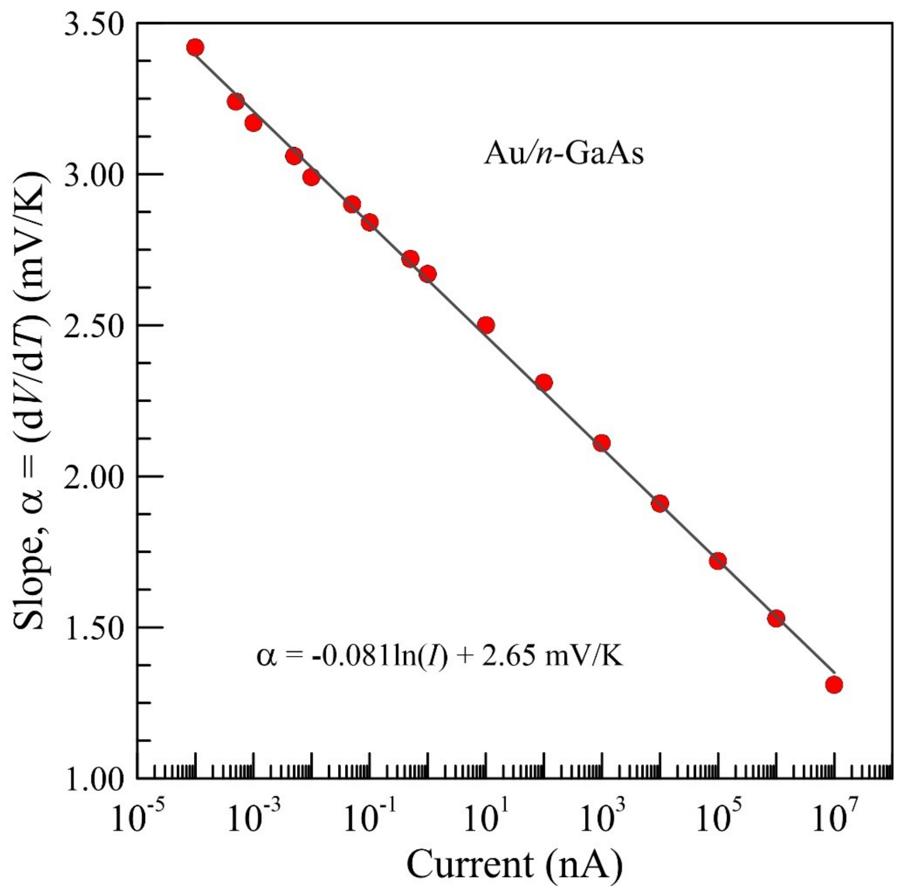

Figure 5. Dependence of the thermal sensitivity α on current level in the Au/n-GaAs/In diode

sensitivity of the Au/n-GaAs/In diode as a function of forward current level is expressed theoretically by Equation (3.11). That is, the thermal sensitivity has followed Equation (3.11) because the current across the diode obeys the TE model down to about 120 K. The experimental data in the graph have been fitted Equation (3.11). It has been clearly depicted that thermal sensitivities linearly have varied with logarithmic value of the current. The intercept and slope values of the straight line in Figure 5 have been obtained as 2.65 mV/K and -0.081 mV/(AK) for the diode, respectively.

4. Conclusion

It has been seen that the current flow through the fabricated Schottky contact obeys to TE model with the ideality factor values ranging from 1.026 at 350 K to 1.064 at 120 K. This is an important property in the experimental thermal sensitivity studies for the fact that the maximum current sensitivity depending on temperature can be observed in the Schottky contacts. The forward biased voltage versus measurement temperature curve at each current level for the Au/n-GaAs/In diode has given a straight line in the current range of 0.10 pA to 10 mA. The linearity in the thermal sensitivity is a key factor of a good thermal sensor. The thermal sensitivity coefficient α from V-T curves increased with decreasing current level and ranged from 3.42 mV/K at 0.10 pA to 1.31 mV/K at 10 mA. Furthermore, we have also obtained a value of α = 2.67 mV/K at the current level of 1.0 nA.

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