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Analysis of current–voltage–temperature characteristics and T_0 anomaly in Cr/*n*-GaAs Schottky diodes fabricated by magnetron sputtering technique

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ABSTRACT

We have fabricated two groups of Cr/*n*-GaAs Schottky diodes (SDs) by magnetron sputtering technique to determine whether T_0 anomaly varies in similarly fabricated SDs or not. Firstly, the first group diodes were inserted into a vacuum chamber to form the Schottky contacts, then the second group diodes which are held in the clean room medium for 3 h before Schottky metal deposition. The current–voltage (*I–V*) characteristics of three diodes (the dots of the sample CrD1) from the first group and two diodes (the dots of the sample CrD2) from the second group were measured in temperature range of 60–320 K. The barrier heights increased with increasing temperature in range of 60–160 K, and did not changed in range of 160–320 K. Ideality factory value decreased with increasing temperature in range of 60–160 K and changed between 1.05 and 1.10 in range of 160–320 K. T_0 anomaly values were calculated from straight lines fitted to *nT'–T* plots. The fits to the experimental values of *nT–T* plots are parallel to the ideal Schottky contact line, especially for the dots (Schottky diodes) of the sample CrD1. T_0 anomaly values for the dots of the sample CrD1 were obtained as 13.9, 11.20 and 13.31 K; and the values of 19.74 and 19.20 K was obtained for the dots of the sample CrD2. It has been concluded that the T_0 anomaly values for the similarly fabricated diodes (the dots of the sample CrD1 or the CrD2) are almost very close to each other within the margins of experimental error.

1. Introduction

Schottky diodes (SDs) are the basis of large number of compound semiconductor electronic devices, including microwave diodes, field-effect transistors (FETs), solar cells, photo-detectors [1–3]. Owing to recent developments in GaAs devices, much information is available about metal contacts on Gallium Arsenide. The stability and reproducibility of contact properties and the formation of a high-quality Schottky barrier height (SBH) are essential prerequisites for device development [3–7]. Choosing semiconductor and fabricating methods must be in good agreement for having electrical properties in maximum performance. Magnetron sputtering is a promising technique that allows deposition of films with good electrical properties at low temperatures [7–9].

However, analysis of the *I–V* characteristics of the SDs at room temperature only does not give detailed information about their conduction process or the nature of barrier formation at the metal–semiconductor (MS) interface. The temperature dependence of the *I–V* characteristics allows us to understand different aspects of conduction mechanisms [10–25]. Specifically, it is shown that leakages, edge-related currents, greater-than-unity ideality factors, T_0 anomaly and other dependences of ideality factor on temperature, soft reverse characteristics and the dependence of the measurement technique are all natural results of SBH inhomogeneity [3–6,10–21].

Analysis of the *I–V* characteristics of SDs based on thermionic emission theory usually reveals an abnormal decrease in the SBH and an increase in the ideality factor *n* with a decrease in temperature [3–20]. The decrease in the SBH at low temperatures leads to nonlinearity in the activation energy $\ln(I_0/T^2)$ versus $1/T$ plot. These findings have been satisfactorily explained recently by incorporating the concept of barrier inhomogeneities and introducing a thermionic emission mechanism [15–35]. T_0 anomaly may be a parameter to show us temperature dependence of Schottky barrier and ideality factor. Tung et al. [4–6] indicated that T_0 effect may be explained by SBH inhomogeneity model. Furthermore, it has been reported in some experimental results that the plots of the inverse slope of the *I–V* plot versus *kT* in which the ideality factor has a $[1+(T_0/T)]$ behavior at low temperatures and a more ideal behavior, $n = 1.00$ at high temperature ranges [3–6,10–21]. It has been shown in some studies that all of the electrical anomalies in the

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SDs may be attributed to the presence of the SBH inhomogeneity [25–36].

In the present study, it has been investigated the temperature-dependent current–voltage (I–V) characteristics of Cr/n-GaAs SDs fabricated by magnetron sputtering technique. It has been studied on two group diodes to explain whether T_0 anomaly changes in identically prepared SDs. One of them (the CrD1) was immediately inserted into a vacuum chamber. The other (the CrD2) was held in the clean room medium for 3 h before Schottky metal deposition, then, was inserted into the vacuum chamber. This process was made to determine whether the characteristic diode parameters of the dots the first group or the dots the second group may be different from each other or not. The I–V measurements of the Cr/n-GaAs SDs were made in the temperature range 60–320 K. Furthermore, to the best of our knowledge, the temperature dependent I–V characteristics in Cr/n-GaAs SDs fabricated by magnetron sputtering and vacuum deposition technique have been not given over a wide temperature range of 60–320 K in literature so far; and it has been also not reported whether T_0 anomaly varies in these kinds of similarly fabricated SDs (the dots of the sample CrD1 or CrD2) or not; where the sample CrD1 should be differently treated from the sample CrD2 because the CrD2 was held in the clean room medium for 3 h before Schottky metal deposition. Moreover, the straight line fitted to the experimental values for the T_0 effect should be parallel to and near that of ideal Schottky contact behavior [2,5,6,19–22], therefore, the experimental I–V data almost should be independent of the sample temperature and quite well obey the traditional thermionic emission. Own our diodes are fabricated by magnetron sputtering technique, and their I–V characteristics are nearly ideal.

2. Experimental procedure

The Cr/n-GaAs/In SDs have been prepared using cleaned and polished n-GaAs (as received from the manufacturer) with [1 0 0] orientation and 7.3×10^{15} cm^{-3} carrier concentrations. Before making contacts, the n-GaAs wafer was cleaned in $5H_2SO_4 + H_2O_2 + H_2O$ [37,38] solution for 1.0 min to remove the surface damage layer and undesirable impurities and then in $H_2O + HCl$ solution followed by a rinse in deionized water of 18 MΩ. The wafer has been dried with high-purity nitrogen and after the etching process inserted into the deposition chamber immediately. For ohmic contacts, indium was evaporated on the back of the wafer in a vacuum-coating unit of 10^{-6} Torr. Then, low resistance ohmic contacts were formed by thermal annealing at 380 °C for 3 min in flowing N_2 in a quartz tube furnace. After thermal annealing, the ohmicity of In for the chosen GaAs material was checked before study, and it showed an ohmic characteristic with a contact resistivity of 2×10^{-2} Ω. Then the wafer was cut into pieces of 5 mm × 5 mm. One of them was immediately inserted into a vacuum chamber of 10^{-6} Torr to form the Schottky contacts. This sample was called CrD1. The Schottky contacts have been formed by dc magnetron sputtering Cr as dots with diameter of about 1.5 mm on the front surface of the n-GaAs. Then, the second piece with ohmic contact exposed to clean room air for 3 h was inserted into the vacuum chamber to form the Schottky contacts. The same dc magnetron sputtering process was also carried out for this piece called CrD2. The thickness of Cr was approximately 50 nm. The temperature dependence of the I–V characteristics were measured in the temperature range of 60–320 K using a Leybold Heraeus closed-cycle helium cryostat that enables us to make measurements in the temperature range of 10–340 K, and a computerized Keithley 487 Picoammeter/Voltage Source in dark conditions. The sample temperature was always monitored by a copper-constantan thermocouple and a Windaus MD850 electronic thermometer with sensitivity better than ±0.1 K.

3. Results and discussions

We analyzed the I–V characteristics of three dots of the CrD1 and two dots of the CrD2 using thermionic emission (TE) current equation. The TE equation at forward-bias ($V \geq 3kT$) is given by

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

where I_0 is saturation current and it is defined by

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

where A is diode area, A^* is the effective Richardson constant of 8.16 A cm^{-2} K^{-2} for n-type GaAs, T is temperature in Kelvin, k is Boltzmann constant and q is electronic charge and Φ_{b0} is the zero bias barrier height (BH). We can write an equation for ideality factor n from Eq. (1):

$$n = \frac{q}{kT}\left(\frac{dV}{d\ln I}\right). \tag{3}$$

The forward current–voltage (I–V) characteristics of one of the dots of the CrD1 and CrD2 SDs in the temperature range of 60–320 K are given in Figs. 1 and 2, respectively. The CrD2 SDs were inserted into a vacuum chamber after the CrD1 SDs were fabricated, thereby it was held in the clean room medium for 3 h before Schottky metal deposition. It is well known that the semiconductor surfaces are easily oxidized when it is left in air for extended periods of time [1,2,20] and thus, a very thin interfacial native oxide layer forms on its surface, which plays an important role in the formation of the SBH and other characteristics parameters of the devices. Therefore, the characteristic diode parameters of two groups may be different from each other. The experimental values of the barrier height Φ_{b0} and the ideality factor n for the device were determined from intercept and slope of the linear portion of the forward-bias I–V plot at each temperature using Eqs. (2) and (3), respectively.

The values of the barrier height, ideality factor and series resistance R_s were extracted by fitting I–V data over the whole bias

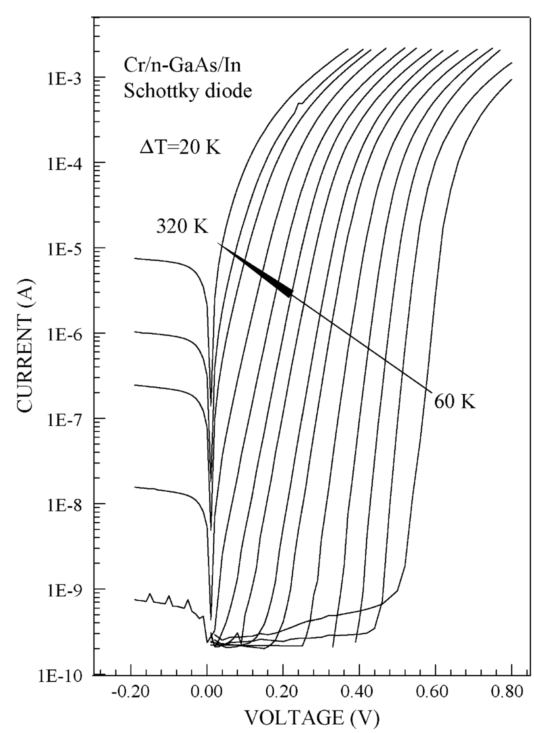

Fig. 1. Current–voltage characteristics in the range of 60–320 K of one of similarly fabricated three dots of the sample CrD1.

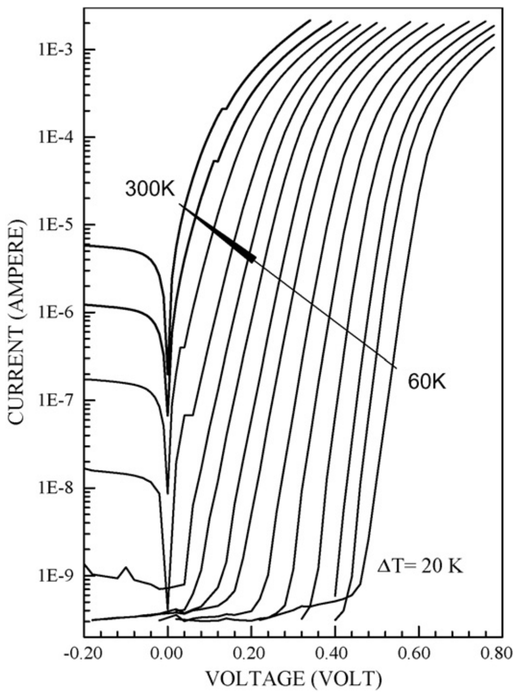

Fig. 2. Current–voltage characteristics in the range of 60–320 K of one of similarly fabricated two dots of the sample CrD2.

region with Eq. (1) at 320, 300 and 280 K because the ln *I* versus *V* curves are not exactly linear at these temperatures, assuming that the transport mechanism is established via the thermionic emission. The temperature-dependent Φ_{b0} and *n* plots are given in Fig. 3 for one of the CrD1 Schottky diodes (dots) and Fig. 4 for one of the CrD2 Schottky diodes, respectively.

The Φ_{b0} values of the CrD1 samples change between 0.60 and 0.62 eV and that the ideality factor *n* values change between 1.05 and 1.10 with a decreasing in temperature in the range of 160–320 K. That is, Φ_{b0} and *n* values for three dots mostly do not change in 160–320 K ranges. For temperatures for below 160 K, the ideality factor *n* reached the value of 1.90 at 60 K by increasing with a decrease in temperature, and Φ_{b0} value decreased with a decreasing in temperature and become 0.40 eV at 60 K. For the dots of the CrD2 sample, the ideality factor *n* reached the value of 1.90 at 60 K by increasing with a decreasing in temperature from 200 K down to 60 K, and Φ_{b0} value decreased with a decreasing in temperature and become 0.42 eV at 60 K. Because of temperature-activated process, the current transport will be dominated by current flowing through of the lower SBH and a larger ideality factor at low temperatures [4–6,16–24]. That is, more electrons have sufficient energy to overcome the higher barrier when temperature increases and then Φ_{b0} increases with temperature and bias voltage.

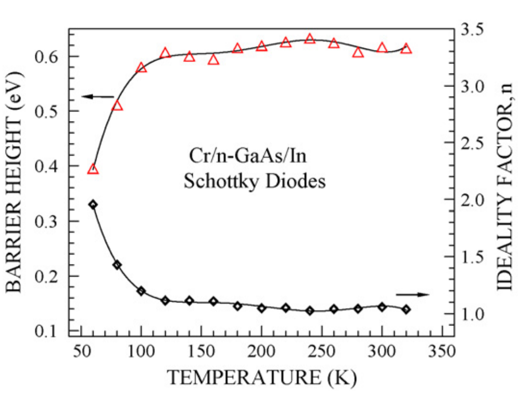

Fig. 3. Temperature dependence plot of barrier height and ideality factor in range of 60–320 K of one of similarly fabricated three dots of the sample CrD1.

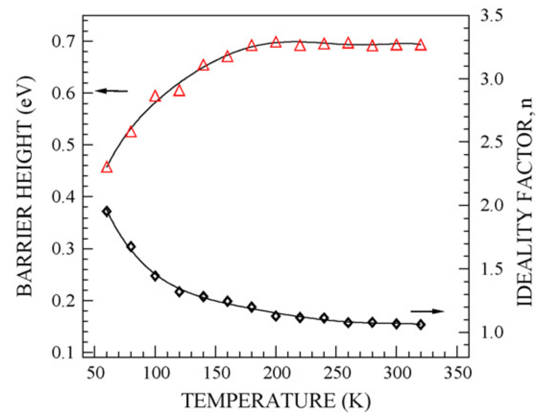

Fig. 4. Temperature dependence plots of barrier height and ideality factor in range of 60–320 K of one of similarly fabricated two dots of the sample CrD2.

It has been reported by some authors [7–9] that the diode sputtering introduces donor-type defects in Si, GaAs and InP although the sputtering supplies the good adherence of these contacts and plays an important role in the preparation of clean surfaces. Again, it has been reported that the decrease of the barrier height for an *n*-type and the corresponding increase of the barrier height for a *p*-type can be related to the presence of sputter-induced positively charged donor-like damage centers in the interface region of the semiconductor substrate [7–9]. Waldrop [39] and Myburg et al. [40] reported values of 0.77 and 0.80 eV for the evaporated Cr/*n*-GaAs SDs, respectively. We obtained values of 0.62 and 0.67 eV for the CrD1 and CrD2 Cr/*n*-GaAs SDs at 300 K, respectively. Thus, the decrease of the barrier height for the samples can be attributed to the presence of the sputter-induced donor-like damage centers.

Fig. 5 show *n*T versus *T* plot for one of the CrD1 Schottky diodes and Fig. 6 for one of the CrD2 Schottky diodes (dots), respectively. Demonstration of T_0 effect is usually accomplished by plotting *nkT* (the inverse slope of an *I*–*V* curve) against *kT* and observing a straight line. T_0 anomaly shows temperature dependence of ideality factor that becomes one of significant characteristics of the SDs, and it is a parameter which is independent of temperature and voltage over a wide range of temperatures. If T_0 value is near to $T_0 = 0$ of ideal Schottky value, diode has a homogeneous BH. A

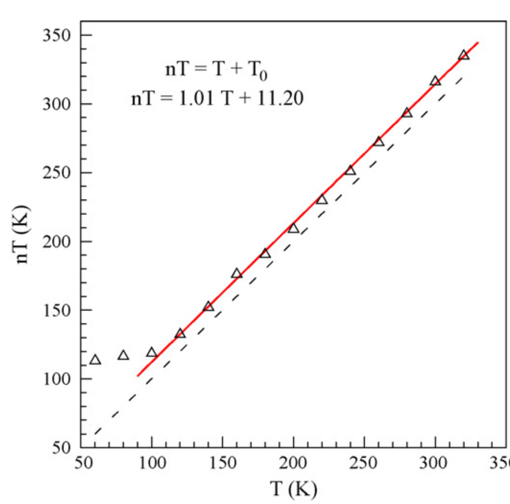

Fig. 5. *n*T vs. *T* plots in range of 60–320 K of one of similarly fabricated three dots of the sample CrD1.

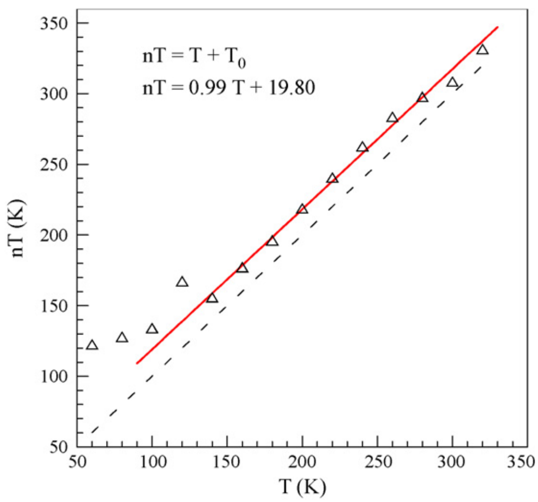

Fig. 6. *nT* vs. *T* plots in range of 60–320 K of one of similarly fabricated two dots of the sample CrD2.

diode is said to display the T_0 effect if its junction current may be expressed as [2–6]

$$I_{T0} = AA^*T^2 \exp\left(\frac{-e\Phi}{kT}\right)\left[\exp\left(\frac{eV}{k[T+T_0]}\right)-1\right] \quad (4)$$

The straight line fitted to the experimental values for the T_0 effect should be parallel to that of ideal Schottky contact behavior [2,5,6,19–22,28–36]. The straight lines fitted to the experimental values are drawn parallel to that of the ideal Schottky contact behavior (dashed lines) to illustrate deviation from Eqs. (1) and (4). T_0 anomaly values for the similarly prepared dots (Schottky diodes) of the sample CrD1 were obtained as 13.90, 11.20 and 13.31 K; and values of 19.74 and 19.20 K was obtained for the similarly prepared two dots (Schottky diodes) of the sample CrD2. Thus, it can be concluded that the CrD1 SDs (the dots) fabricated in the same conditions almost have the same T_0 value, as 13.9, 11.20 and 13.31 K. Likely, the T_0 values of the identically prepared dots of the CrD2, which held in the clean room medium for 3 h before Schottky metal deposition, also are the same as 19.74 and 19.20 K. As can be seen, T_0 anomaly values for the dots of the sample CrD1 are very close to each other within the margins of experimental error, the same can be also said for the dots of the sample CrD2. Average deviation for T_0 values of the dots of the sample CrD1 is found as 1.07 K, and thus the statistical analysis yields a mean values of 12.80 ± 1.07 K; these values for the dots of the sample CrD2 are 0.27 and 19.47 ± 0.27 K. The fact that the values T0 of the dots of the CrD2 differ from those of the CrD1 may be ascribed to the very thin interfacial native oxide layer on surface of the CrD2. Hardikar et al. [41] obtained a value of 17.1 ± 1.2 K for Au/*n*-GaAs SDs. Dio et al. [42] obtained T_0 values of 61 and 104 K for the Ti/*n*-GaAs Schottky diodes prepared by the ion beam sputtering. Small deviations from *nT*–*T* lines (from Eqs. (1) and (4)), especially, for the dots of the sample CrD2 at low temperatures may attribute to current transportation mechanism controlled by low-SBH regions at low temperature ranges. This is explainable in terms of SBH inhomogeneity. However, as mentioned in Refs. [2,4,5], the T_0 effect is evidently not an intrinsic property of ideal Schottky barriers but an artifact introduced by the fabrication process and so the experimental results imply a very special sort of temperature dependence of ideality factor *n*. Furthermore, Tung [4,5] have indicated that the measured T_0 anomaly can be varied significantly among similarly fabricated diodes, and the proposal that T_0 varies locally in a large diode are suggestive that the T_0 anomaly is not directly related to the formation mechanism of the Schottky barrier height.

4. Conclusions

The *I*–*V*–*T* characteristics of Cr/*n*-GaAs SDs fabricated by magnetron sputtering technique have been measured in the range of 60–320 K. The barrier height values increased with increasing temperature in range of 60–160 K and unchanged in range of 160–320 K. Ideality factor values decreased with increasing temperature in range of 60–160 K and almost unchanged in range of 160–320 K. The deviation in range of 60–160 K is attributed to current transportation mechanism in inhomogeneous SBH model at low temperatures. The straight line fits to the experimental values of *nT*–*T* plots are parallel to that of the ideal Schottky contact behavior, especially for the dots of the sample CrD1. When considering only the sample CrD1 or the sample CrD2, it has been concluded that the T_0 anomaly values for the similarly fabricated diodes almost are very close to each other within the margins of experimental error. That is, the CrD1 SDs (the dots) fabricated in the same conditions almost have the same T_0 value, as 13.9, 11.20 and 13.31 K. Likely, the T_0 values of the identically prepared dots of the CrD2, which held in the clean room medium for 3 h, approximately is the same as 19.74 and 19.20 K. Moreover, it can be said that the experimental *I*–*V* data are almost independent of the sample temperature and quite well obey the traditional TE model above 160 K.

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