Electrical characteristics of Al/n-type GaAs Schottky barrier diodes at room temperature

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The current–voltage (I–V) characteristics of metal–semiconductor Al/n-GaAs (MS) Schottky diodes were measured at room temperature (300 K). In addition, capacitance–voltage–frequency (C–V–f) characteristics are investigated by considering the interface states (Nss) at frequency 1 MHz. SBD parameters such as ideality factor n, the series resistance (R_s) determined from Cheung's functions and Schottky barrier height, Φ_{bo}, are investigated as functions of temperature. Ideality factor, barrier height and series resistance values were found as 2.93-3.51, 0.58–1.47 eV and 0.80-0.59Ω, respectively. The diode shows non-ideal I–V behaviour with an ideality factor greater than unity. Furthermore, the energy distribution of interface state density was determined from the forward bias I–V characteristics by taking into account the bias dependence of the effective barrier height. The results show the presence of thin interfacial layer between the metal and semiconductor. The interface distribution profile (Nss) as a function of (E_c-E_{SS}) was extracted from the forward-bias I–V measurements by taking into account the bias dependence of the effective barrier height and series resistance (Rs) for the Schottky diodes. The value of N_{SS} obtained $1.92x10^{13}(eV)^{-1}cm^{-2}$.

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1. Introduction

The electrical properties of metal–semiconductor (MS), metal–insulator–semiconductor (MIS) Schottky diodes have been investigated because of their importance in electronic device applications [1–3]. GaAs is an important semiconductor used for optoelectronics, fast computers, and microwave applications. The metal-semiconductor field effect-transistor (MESFET) containing a Schottky barrier gate is one of the main components in GaAs integrated circuits [4–6] Gallium arsenide is one of the most popular semiconductors that has intrinsic electrical properties superior to silicon, such as a direct energy gap, higher electron mobility, a high breakdown voltage, chemical inertness, mechanical stability, and lower power dissipation. These advantages of gallium arsenide make it attractive for optoelectronic devices, discrete microwave devices and/or large-scale integrated electronic devices. Due to the technological importance of GaAs SBDs, a full understanding of the nature of the electrical characteristics of SBDs in the system is of great interest.

In the study, the I–V characteristics of Al Schottky contacts on an n-GaAs substrate were measured at room temperature. Electrical parameters such as ideality factor, barrier height, series resistance and Richardson constant were extracted from forward bias I-V measurements. Thus, we examined the electronic properties of main parameters obtained from current–voltage (I–V) and capacitance–voltage (C–V) measurements and interface state density distribution properties of interface states of Al/n-GaAs SBD.

2. Experimental procedures

The semiconductor substrates used were n-type GaAs single crystals, with a (100) surface orientation, 300 μm thick and 2 mm in diameter. Before the fabrication, the n-GaAs wafers were chemically cleaned by methanol and acetone and then rinsed in de-ionised water. For the oxide present on the semiconductor, the samples were etched by H_2O:HCl(1:1) solution. Then rinsed de-ionised water and finally samples were blown dry with nitrogen gas. After cleaning, for ohmic contact fabrication the samples were placed into the electron beam deposition system. Immediately after surface cleaning, ohmic contacts of low resistance on the backside of the samples were formed by evaporating Ni (10nm)-AuGe 200nm-Au 300nm thick followed by a temperature treatment at 450 C^0 for 5 min in N_2 atmosphere. After that rectifier Schottky contacts were formed on the other faces by evaporating 150nm thick Al. The evaporation process was carried out in a vacuum of 5.1×10^{-6} Torr. The native oxide on the front surface of n-GaAs was removed using HF:H_2O (1:10) solution and de-ionised water for 30 s. Preceding each cleaning step, the wafer was rinsed thoroughly in de-ionized water of resistivity of 18 MΩ cm.

The temperature dependence of current–voltage measurements were performed by the use of a Keithley 220 programmable constant current source, a Keithley 614 electrometer using a temperature-controlled Janes vpf-475 cryostat, which enables us to make measurements at room temperature. The sample temperature was always monitored by using a copper-constantan thermocouple close to the sample and measured with a dmm/scanner Keithley model 199 and a Lake Shore model 321 auto-tuning temperature controllers with sensitivity better than ±0.1K. All measurements were carried out with the help of a microcomputer through an IEEE-488 ac/dc converter card.

3. Results and discussion

We analyze the experimental I–V characteristics by the forward bias thermionic emission (TE) theory given as follows [1-3]

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

where Io is the saturation current derived from the straight line intercept of lnI at V = 0 and is given by

$$I_0 = AA^{*}T^2 \exp\left(-\frac{q\phi_{B0}}{kT}\right) \tag{2}$$

where q is the electron charge, V is the definite forward-bias voltage, A is the effective diode area, k is the Boltzmann constant, T is the absolute temperature, A^* is the effective Richardson constant and equals 8.16 Acm^{-2} K^{-2} for n-type GaAs [7-8], where Φ_{bo}(I-V) is the barrier height at zero bias (which is defined by Eq. (2)), and n is called the ideality factor, which is defined as:

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

Fig. 1 shows the experimental semilog-forward and reverse-bias characteristics of the Al/n-GaAs SBD. The values of the barrier height Φ_{b0} and the ideality factor n of the Al/n-GaAs SBD were calculated as 0.58 eV from the extrapolated experimental saturation current, I_0= 2.26× 10^{-6}A, and n=1.76 from the slope of the linear region of the semilog-forward bias I–V characteristics indicating that the effect of series resistance in this region was not important, respectively [6-7].

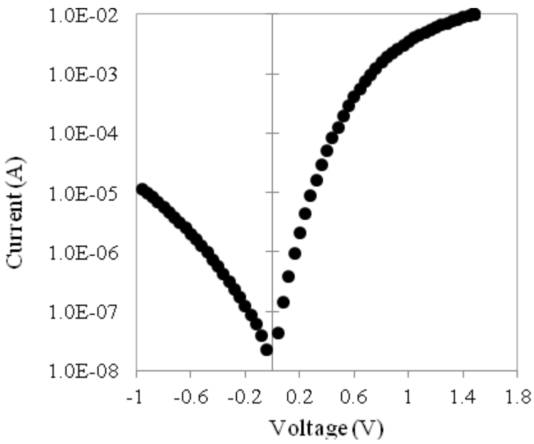

Fig. 1. The experimental forward and reverse current–voltage characteristics of the Al/n-GaAs Schottky barrier diode at room temperature.

Moreover, at high currents there is forever a deviation which has been clearly shown to depend on parameters such as the interfacial layer thickness, the interface states density and series resistance, as one would expected [9]. Furthermore, ideality factor and the series resistance were evaluated using a method developed by Cheung et al. [5]. The Cheung method is achieved by using the functions.

$$\frac{dV}{d(\ln I)} = IR_s + n\left(\frac{kT}{q}\right) \tag{4}$$

$$H(I) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{I_0}{AA^{*}T^2}\right) \tag{5}$$

$$H(I) = IR_s + n\phi_b \tag{6}$$

Eq. (4) should give a straight line for the data in the downward-curvature region of the forward bias I–V characteristics, where Φ_b is the BH obtained from data of downward curvature region in the forward bias I–V characteristics. The value of n calculated from the slope of the linear portion of the I–V characteristics especially includes the effect of the interfacial parameters such as R_S. The values of n obtained from the vertical axis intercepts of H(I)–I and dV/dln(I)–I curves and the values of R_s from their slopes were found as 2.93-3.51 and 0.80-0.59 Ω, respectively. Thus, it can clearly be seen that there is relatively difference between the values of n obtained from the downward curvature regions of forward bias I–V plots and from the linear regions of the same characteristics. The reason of this difference can be attributed to the existence of effects such as the series resistance and the bias dependence of the Schottky barrier height according to the voltage drop across the interfacial layer and change of the interface states with bias in this concave region of the I–V plot.

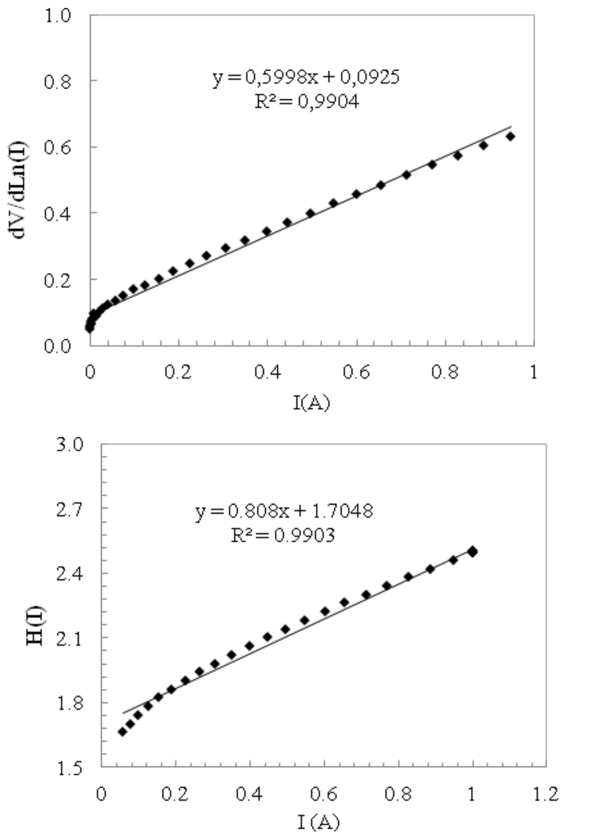

Fig. 2. The experimental H(I) vs. I and dV/dln(I) vs. I plots for the Al/n-GaAs Schottky barrier diode at room temperatures.

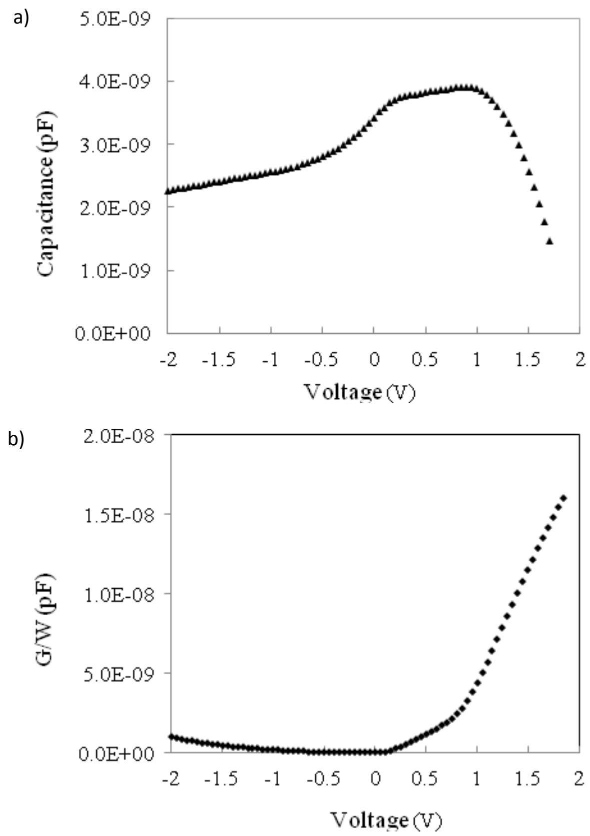

Fig. 3. (a) The experimental capacitance–voltage, and (b) conductance–voltage characteristics of the Al/n-GaAs Schottky barrier diode in the frequency 1 MHz at room temperatures.

Fig. 3 shows the C–V and G/W-V characteristics at room temperature (T=300 K) measured at frequency of 1 MHz. As can be seen in Fig. 3(a), C–V characteristic in the idealized SBDs case shows an increase in capacitance with increasing forward voltage, and the C–V characteristic has an anomalous peak. In Schottky diodes, the depletion layer capacitance can be expressed as

$$\frac{\partial C^{-2}}{\partial V} = \frac{2}{q\varepsilon_s A^2 N_A} \quad (7)$$

or

$$C_2 = \frac{1}{n_{cv}} = \frac{2}{q\varepsilon_s N_D\left(\frac{\partial C^2}{\partial V}\right)} \quad (8)$$

where A is the area of the diode, ε_s the dielectric constant of the GaAs , q is the electronic charge and N_D is the donor concentration. The diffusion potential or built-in potential is usually measured by extrapolating $1/C^2$–V plot to the V-axis (See Fig. 4). The barrier height, Φ_{b0} (CV), from C–V measurement is defined by

$$\phi_{b0}(C-V) = V_d + E_F - \Delta\phi_B \quad (9)$$

where $\Delta\Phi_B$ is the image force correction and E_F is the Fermi energy. According to Eq. (9), the measured barrier height Φ_{b0}(C-V) is 1.42 eV and the donor concentration is determined to be 9.45×10^{17} cm^{-3}. The difference between barrier heights obtained from I-V and C-V measurements is mainly due to inhomogeneities.

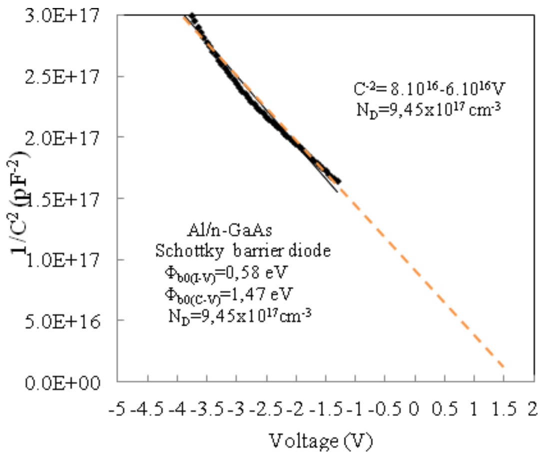

Fig. 4. C^{-2}–V characteristics of the Al/n-GaAs Schottky barrier diode in the frequency 1MHz at room temperature.

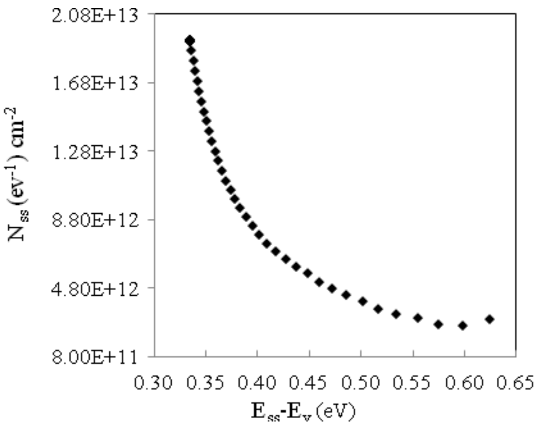

Fig. 5. Density of interface states N_{SS} as a functions of E_{SS}–E_V obtained from the I–V measurements at room temperature.

The interface state energy distribution curve of the Al/n-GaAs SBD is given in Fig. 5. For an MS diode having interface states in equilibrium with the semiconductor, the ideality factor, n becomes greater than unity as proposed by Card and Rhoderick [2] and is given by

$$N_{ss}(V)=\frac{1}{q}\left[\frac{\varepsilon_i}{\delta}(n(V)-1)-\frac{\varepsilon_s}{W_d}\right] \qquad (10)$$

where W_d is the interfacial insulator layer thickness, N_{SS} is the density of interface states, ε_i is the permittivities of the interfacial layer, and W_d is the thickness of insulator layer. The interfacial insulator layer thickness (W_d=9.3×10^{-6} cm) was obtained from high-frequency (1 MHz) C–V characteristic using the equation for insulator layer capacitance ($C=C_{ox}=\varepsilon' A/\delta$), and ε_0 is the permittivity of free space. Furthermore, in n-type semiconductors, the energy of the interface states with respect to the top of the conduction band at the surface of the semiconductor is given by [10-15]

$$E_c - E_{ss} = q(\phi_e - V) \qquad (11)$$

where V is the applied voltage drop across the depletion layer and Φ_e is the effective barrier height. The relationship between effective barrier height, applied voltage V and the ideality factor n in given by:

$$\phi_e = \phi_{b0} + (1 - 1/n(V)) \qquad (12)$$

The interface state density (N_{SS}) values obtained decrease with applied voltages. This confirms that the density of interface states changes with bias and each of applied biases corresponds to a position inside the GaAs gap. The value of N_{SS} obtained by using the I–V measurements range from 2x10^{13}(eV)$^{-1}$cm^{-2} in (E_C-0.33) eV.

4. Conclusion

The electrical characteristics of Al/n-GaAs Schottky diode has been studied using I-V and C-V measurements at room temperature. SBD parameters such as ideality factor n, the series resistance (R_S) determined from Cheung's functions and Schottky barrier height, Φ_{bo}, are investigated as functions of temperature. Ideality factor, series resistance and barrier height values were found as 2.93-3.51 and 0.80-0.59 Ω and 0.58–1.47 eV, respectively. The ideality factor (n) values obtained from I–V characteristics are higher than unity, and this is attributed to the presence of a thin insulating layer between the metal and semiconductor. In particular, the values obtained from the C–V measurements are higher than derived from the I–V measurements as expected. The difference between barrier heights obtained from I–V and C–V measurements is mainly due to inhomogeneities. The interface states and interfacial insulator layer at the MS interface play an important role in the determination of the characteristic parameters of the devices.

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