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Barrier characteristics of gold Schottky contacts on moderately doped n-InP based on temperature dependent *I–V* and *C–V* measurements

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ABSTRACT

The temperature dependences of current–voltage (*I–V*) and capacitance–voltage (*C–V*) characteristics of the gold Schottky contacts on moderately doped n-InP (Au/MD n-InP) Schottky barrier diodes (SBDs) have been systematically investigated in the temperature range of 60–300 K. The main diode parameters, ideality factor (n) and zero-bias barrier height (apparent barrier height) (Φ_{b0}^{i}) were found to be strongly temperature dependent and while the Φ_{b0}^{i} decreases, the n and the (Φ_{b}^{C}) increase with decreasing temperature. According to Thermionic Emission (*TE*) theory, the slope of the conventional Richardson plot [$In(J_0/T^2)$ vs. $1000/T$] should give the barrier height. However, the experimental data obtained do not correlate well with a straight line below 160 K. This behaviour has been interpreted on the basis of standard *TE* theory and the assumption of a Gaussian distribution of the barrier heights due to barrier inhomogeneities that persist at the metal-semiconductor interface. The linearity of the apparent barrier height (Φ_{b0}^{i}) vs. $1/(2kT)$ plot that yields a mean barrier height ($\overline{\Phi}_{b0}^{i}$) of 0.526 eV and a standard deviation (σ_{s0}) of 0.06 eV, was interpreted as an evidence to apply the Gaussian distribution of the barrier height. Furthermore, modified Richardson plot [$In(J_0/T^2) - (q^2\sigma_{s0}^2/2\,k^2T^2)$ vs. $1/T$] has a good linearity over the investigated temperature range and gives the $\overline{\Phi}_{b0}^{i}$ and the Richardson constant (A^*) values as 0.532 eV and 15.90 $AK^{-2}cm^{-2}$, respectively. The mean barrier heights obtained from both plots are appropriate with each other and the value of A^* obtained from the modified Richardson plot is close to the theoretical value of 9.4 $AK^{-2}cm^{-2}$ for n-InP. From the *C–V* characteristics, measured at 1 MHz, the capacitance was determined to increase with increasing temperature. *C–V* measurements have resulted in higher barrier heights than those obtained from *I–V* measurements. The discrepancy between Schottky barrier heights (SBHs) obtained from *I–V* and *C–V* measurements was also interpreted. As a result, it can be concluded that the temperature dependent characteristic parameters for Au/MD n-InP SBDs can be successfully explained on the basis of *TE* mechanism with Gaussian distribution of the barrier heights.

1. Introduction

The metal-semiconductor (MS) structures are of important applications in the electronics industry. These applications consist of microwave field effect transistors, radio-frequency detectors, phototransistors, heterojunction bipolar transistors, quantum confinement devices and space solar cell [1–3]. The performance and reliability of a Schottky contact is highly influenced by the interface quality between the deposited metal and the semiconductor surface. In order to understand the conduction mechanism of the Schottky barrier diodes (SBDs), many attempts have been made. Generally, the SBD parameters are determined over a wide range of temperatures and doping concentrations in order to understand the nature of the barrier and the conduction mechanism.

The analysis of the current–voltage (*I–V*) characteristics of Schottky barriers on the basis of thermionic emission diffusion (*TED*) theory reveals an abnormal decrease of the barrier height (BH) and increase of the ideality factor with decreasing temperature [1–4]. Also, the ideality factor has been found to increase with increasing carrier concentration, while BH obtained by the *I–V* measurements decreases with increasing doping level [1]. Explanation of the possible origin of such anomalies have been proposed by taking into account the interface state density distribution [5], quantum-mechanical tunnelling [1,6,7], image-force lowering [1] and most recently the lateral distribution of BH inhomogeneities [2,8,9]. In addition, a Gaussian distribution of the BH over the contact area has been assumed to describe the inhomogeneities as an other way too [2,10].

Indium Phosphide (InP) being one of the III–V compound semiconductors is a promising material for high-speed electrical and optoelectronic devices due to its large direct band gap, high electron mobility, high saturation velocity and breakdown voltage

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which are very important in electronic devices [11,12]. But, due to the large reverse leakage current for metal/n-InP structures it is difficult to obtain a Schottky barrier height (SBH) greater than 0.5 eV [1,12–18]. Thus, the use of n-InP has been hindered in this area. However, low BH Schottky diodes of n-InP seem to be a good candidate for the application of zero-bias Schottky detector diodes [12].

Newman et al. [14] have studied the electrical transport characteristics of nine metals on n-GaAs and n-InP as a function of doping level on (1 1 0) surfaces. Furthermore, Horváth et al. [15] have presented experimental results obtained on n-type InP using various Schottky metal on untreated and/or HF, HF + Na_2S and HCl treated surface. Most of studies have been done on n-InP wafers with unintentionally doped or with low doping level [11–18].

In this study, the current–voltage (*I–V*) and capacitance–voltage (*C–V*) measurements of the gold Schottky contacts on moderately doped n-InP (Au/MD n-InP) SBDs have been made over the temperature range of 60–300 K. The resultant temperature dependent barrier characteristics of the diodes have been interpreted on the basis of the existence of Gaussian distribution of the barrier height.

2. Experimental details

SBDs were fabricated on moderately S-doped n-type InP (100) substrate with doping agent concentration of 1.2×10^{16} cm^{-3}. The substrate was sequentially cleaned with trichloroethylene, acetone, and methanol and then rinsed in deionised water. The native oxide on the surface was etched in sequence with acid solutions (H_2SO_4:H_2O_2:H_2O = 3:1:1) for 60 seconds, and (HF (49%):H_2O = 1:1) for another 60 s. After a rinse in deionised water a blow-dry with nitrogen. Low resistance Ohmic contact on the back side of the sample was formed by evaporating of Au:Ge eutectic alloy (88% Au:12% Ge) at a pressure of 2×10^{-6} mbar, followed by annealing at 300 °C for 5 min in nitrogen atmosphere. Then, the above procedures were also used to clean the front surface. Finally, circular dots with a diameter of approximately 1 mm of Au were then evaporated through a molybdenum mask at a pressure of 2×10^{-6} mbar to form the Schottky barriers.

I–V and *C–V* measurements of the devices were made using a computer controlled Keithley 487 picoammeter/voltage source and an HP 4192 A LF impedance analyser, respectively over the temperature range of 60–300 K and in dark. The measurements below room temperature were performed by mounting the device onto the specially designed cold finger of ARS HC-2 closed-cycle helium cryostat. The device temperature was controlled within an accuracy of ±0.1 K by a Lake Shore 331 model temperature controller.

3. Results and discussion

3.1. The current–voltage characteristics as function of temperature

The current density (*J*) through a SBD at a forward bias (*V*), according to thermionic emission (*TE*) theory, is given by [19,20]

$$J = J_0 \exp\left(\frac{qV_d}{nkT}\right)\left[1 - \exp\left(-\frac{qV_d}{kT}\right)\right] \quad (1)$$

where $V_d = (V - IR_s)$ is the diode voltage, J_0 is the reverse saturation current density derived from the straight line intercept of $In(J)$ at zero-bias and is given by

$$J_0 = A^* T^2 \exp\left(-\frac{q\Phi_{b0}^{j}}{kT}\right). \quad (2)$$

Where q is the electronic charge, V is the definite forward bias voltage, A^* is the effective Richardson constant, k is the Boltzmann constant, T is the absolute temperature, Φ_{b0}^{j} is the zero-bias current-barrier height (apparent barrier height) and n is the ideality factor. From Eq. (1), the ideality factor n can be written as

$$n = \frac{q}{kT}\left(\frac{dV}{dIn(J)}\right). \quad (3)$$

Fig. 1 shows forward bias semi-logarithmic $J - V$ characteristics of an Au/MD n-InP SBD in the temperature range of 60–300 K. The values of Φ_{b0}^{j} and n determined from the intercept and the slopes of the forward bias $In(J)$ versus voltage (V) plot according to *TE* theory are shown in Figs. 2 and 3 as a function of temperature, respectively. Richardson constant of electrons in n-type InP was calculated as $A^* = 120m_e^*/m_0 = 9.4\ AK^{-2}cm^{-2}$, where $m_e^*(= 0.078m_0)$ is the effective mass for electrons [21]. The experimental values of the Φ_{b0}^{j} and n range from 0.194 eV and 2.895 at 60 K to 0.465 eV and 1.029 at 300 K, respectively. The values of the Φ_{b0}^{j} are the effective values and do not take into account the image-force lowering. This value is comparable with those of obtained by Szydlo and Oliver [22] and Benamara et al. [23], which are equal to about 0.46 eV, 0.441 eV, respectively and that found by Shi et al. [24], which is 0.51 eV, for Au/n-InP contacts. The series resistance R_S varies between 3 and 5 Ω, and is almost independent of temperature. As seen in Figs. 2 and 3, both of the n and Φ_{b0}^{j} are strongly dependent on temperature and the changes are more pronounced below 160 K. Such a behaviour of the ideality factor has been attributed to the particular distribution of the interface states. Since current transport across the metal-semiconductor interface is controlled by temperature, electrons at low temperature pass over the lower barriers and therefore current will flow through patches of the lower SBH and results in a larger ideality factor. In other words, more electrons have sufficient energy to overcome the higher barrier.

To determine the BH in another way, the Richardson plot is drawn. Eq. (2) can be rewritten as

$$In\left(\frac{J_0}{T^2}\right) = InA^* - \frac{q\Phi_{b0}^{j}}{kT}. \quad (4)$$

Fig. 4 shows the conventional Richardson plot. The experimental data show a bowing at low temperature and it appears a straight line above 160 K. Φ_{b0}^{j} obtained from the slope of this straight line yields to be 0.30 eV. Similarly, the value of A^* obtained from the intercept at the ordinate is equal to 1.70×10^{-2} $AK^{-2}cm^{-2}$, which is lower than the known value of 9.4 $AK^{-2}cm^{-2}$

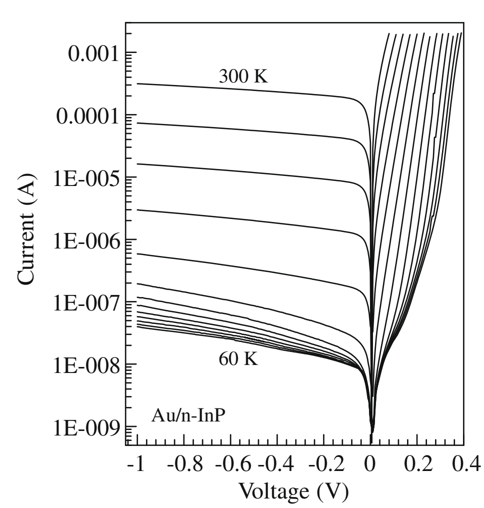

Fig. 1. Semi-logarithmic reverse and forward bias current–voltage characteristics of an Au/MD n-InP Schottky barrier diode at various temperatures.