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Temperature dependence of current–voltage characteristics of Au/*n*-GaAs epitaxial Schottky diode

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Abstract. The influence of temperature on current–voltage (*I–V*) characteristics of Au/*n*-GaAs Schottky diode formed on *n*-GaAs epitaxial layer grown by metal organic chemical vapour deposition technique has been investigated. The dopant concentration in the epitaxial layer is 1×10^{16} cm^{-3}. The change in various parameters of the diode like Schottky barrier height (SBH), ideality factor and reverse breakdown voltage as a function of temperature in the range 80–300 K is presented. The variation of apparent Schottky barrier height and ideality factor with temperature has been explained considering lateral inhomogeneities in the Schottky barrier height in nanometer scale lengths at the metal–semiconductor interface.

Keywords. Schottky barrier height; metal–semiconductor interface; current–voltage characteristics; thermionic emission; ideality factor; lateral inhomogeneities in SBH.

1. Introduction

Understanding the mechanisms giving rise to the apparent Schottky barrier height (SBH) of metal–semiconductor (MS) contacts is still an unsolved problem despite decades of intensive investigations (Bardeen 1947; Spicer *et al* 1980; Tersoff 1984, 1987; Rhoderick and Williams 1988; Hubers and Roser 1998). Several theoretical models have been developed with the pinning of the Fermi level by electronic states being the most favoured one. According to this model the Fermi level is pinned either by the metal induced gap states (MIGS) (Tersoff 1984, 1987) or defect states at the interface (Bardeen 1947). The dependence of SBH on temperature can give insight into the physical mechanism of Fermi level pinning at the MS interface (Revva *et al* 1993; Hubers and Roser 1998). When the Fermi level is pinned by MIGS, the temperature dependence of the barrier height is governed by the temperature dependence of the band gap. However, if the Fermi level is pinned by the interface defects, their ionization entropy would control the temperature dependence of the barrier height. The measurements of the temperature evolution of barrier height allow one to distinguish between both the pinning mechanisms (Aboelfotoh and Tu 1986; Aboelfotoh 1991).

But in these Fermi level pinning models no direct account is taken of the possible existence of laterally extended SBH inhomogeneities (Tung *et al* 1991; Palm *et al* 1993). The investigation of the electrical properties of MS contact is usually performed with current–voltage (*I–V*) and capacitance–voltage (*C–V*) measurements. These methods yield only an integral information over the entire contact area. The interpretation of electrical data of real MS contacts has implicitly assumed uniformity of SBH at MS interface. Recent experimental investigations, however, reveal nonuniformities of the local SBH on a nanometer length scale (Talin *et al* 1994; Olbrich *et al* 1997, 1998). In a recent model of potential pinch-off effect in MS contacts, Tung has modeled the influence of mesoscopic SBH inhomogeneities on macroscopic properties like the integral SBH (Tung 1991, 1992). Assuming the lateral variations in local SBH in nanometer scale lengths he explained the variations of apparent barrier height (Φ_B) and ideality factor (n) with temperature.

We report here the temperature variation of SBH, Φ_B and ideality factor, n, for Au/*n*-GaAs epitaxial Schottky diode in the range 80–300 K. We have observed a strong dependence of these quantities on temperature which has been explained using the lateral SBH inhomogeneities model.

2. Experimental

The *n*-GaAs epitaxial layer was deposited over SI–GaAs by metal organic chemical vapour deposition (MOCVD) technique. The temperature during the growth was 400°C and the growth rate was 4 μm/h. The Si dopant concentration

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in the epitaxial layer was 1×10^{16} cm^{-3} as confirmed by Hall measurements. Prior to ohmic and Schottky contact deposition, the sample was thoroughly cleaned and etched. The sample was dipped in methanol, trichloroethylene and acetone sequentially for 5 min each for the removal of organic impurities from the surface of the sample. It was then dipped in HCl for 1 min to remove the native oxide layer from the surface. Then the sample was inserted in a cryopump operated vacuum deposition chamber where a 2 mm diameter Au : Ge (88 : 12) contact of 100 nm thickness was deposited for making the ohmic contact. Afterwards the sample was annealed at 430°C for 5 min in Argon atmosphere. After this the sample was again loaded in the deposition chamber for Au Schottky contact fabrication. The Au Schottky contact was 2 mm in diameter and 100 nm in thickness and it was on the same side as the ohmic contact. The base pressure of the chamber during the entire deposition process was 2×10^{-7} mbar.

For current–voltage (*I–V*) measurements, the Au/*n*-GaAs epitaxial Schottky diode was loaded in a variable temperature cryostat where the temperature of the diode could be varied in the range 80–300 K. The temperature was controlled by a Lakeshore temperature controller (model DRC-93CA) using a PT100 sensor and a heater and the temperature stability was within ± 0·2 K. The *I–V* characteristics at various temperatures was recorded utilizing Keithley's voltage source (model 230) and digital multimeter (model 2001).

3. Results and discussion

The current flow through a Schottky contact can be described by thermionic emission theory (Sze 1981; Rhoderick and Williams 1988) and the *I–V* relationship is given by

$$I = I_S[\exp(qV/nkT) - 1], \tag{1}$$

where q is the electronic charge, k the Boltzmann constant, V the applied voltage and n the ideality factor. The reverse saturation current I_S is given by

$$I_S = AA^{**}T^2 \exp(-q\Phi_B/kT), \tag{2}$$

where A is the diode area, A^{**} the effective Richardson constant and taken as 10 A/cm^2 K^2, and Φ_B the apparent barrier height.

Figure 1 shows the *I–V* characteristics of Au/*n*-GaAs epitaxial Schottky diode measured at various temperatures ranging from 80–300 K. The slopes of the linear portions of these curves were calculated and the ideality factors determined using the relation:

$$n = \frac{1}{2\cdot 3026 \times kT/q \times d(\log I)/dV}. \tag{3}$$

The intercept on y-axis was used to determine the value of I_S and using this value the apparent barrier height can be computed with the help of (2).

The dependence of apparent barrier height and ideality factor on temperature is shown in figure 2. It has been observed that the ideality factor increases with decrease in temperature and its value increases from 1·9 at 300 K to 4·7 at 80 K. On the other hand, the apparent barrier height decreases with decrease in temperature and its value at 300 K is 0·82 eV which becomes 0·36 eV at 80 K.

The reverse saturation current density J_S is obtained by dividing reverse saturation current I_S by geometrical area of Schottky contact. The variation of J_S, along with n and Φ_B, with respect to temperature is shown in table 1. The J_S decreases sharply with decrease in temperature. At 300 K its value is $8\cdot 1 \times 10^{-9}$ A cm^{-2}. This value matches well with the values of J_S reported by other authors (Borrego *et al* 1977; Hubers and Roser 1998). Hence the leakage current in the fabricated Schottky diode is of low value which is indicative of its good quality.

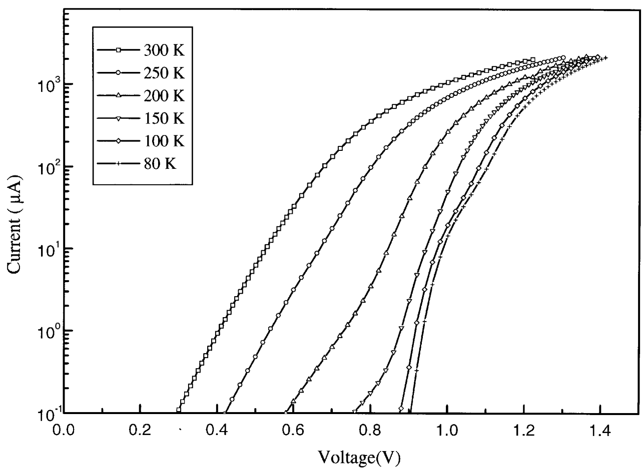

Figure 1. Current–voltage characteristics for Au/*n*-GaAs epitaxial Schottky diode at different temperatures in the range 80–300 K.

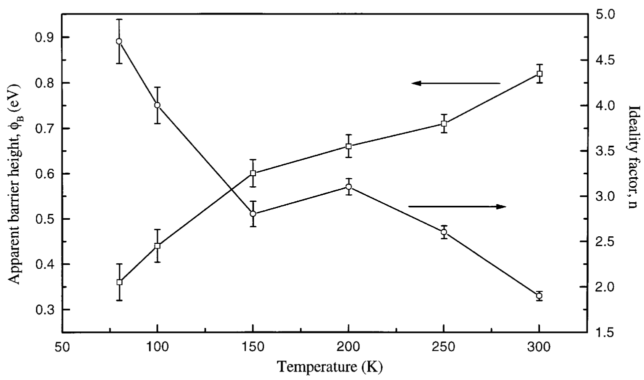

Figure 2. Variation of apparent barrier height, Φ_B and ideality factor, n with temperature for Au/*n*-GaAs Schottky diode.

Table 1. Variation of ideality factor n, SBH Φ_B, reverse saturation current density, J_S and breakdown voltage, V_{BD} with temperature.

Temperature (K)	Ideality factor	SBH (eV)	J_S (A cm^{-2})	V_{BD} (V)
80	4·7	0·36	$5·3 \times 10^{-18}$	9.0
100	4·0	0·44	$7·2 \times 10^{-17}$	9·2
150	2·8	0·60	$1·5 \times 10^{-16}$	10·2
200	3·1	0·66	$4·6 \times 10^{-11}$	11·6
250	2·6	0·71	$1·7 \times 10^{-9}$	12·5
300	1·9	0·82	$8·1 \times 10^{-9}$	13·0

Various factors may be responsible for these large variations observed in ideality factor and apparent barrier height with temperature. Some authors have explained these variations by using Fermi level pinning at the MS interface. The Fermi level pinning may occur either by metal induced gap states (Tersoff 1984, 1987) or the interface defects (Bardeen 1947). The dependence of SBH on temperature can give an insight into the physical mechanism of the Fermi level pinning in MS contacts. But in our case the variation in SBH with temperature could not be explained with the Fermi level pinning either by metal induced gap states (MIGS) or defect states. If the Fermi level pinning is due to MIGS, then the temperature dependence of SBH is governed by the temperature dependence of the band gap. In this case the value of temperature coefficient of SBH should be equal to 0·2 meV/K (Hubers and Roser 1998). In our case its value is about 2 meV/K, and hence MIGS model cannot explain this large temperature coefficient of SBH. Now if the Fermi level pinning is assumed to be due to the defect states, then their ionization entropy would control the temperature dependence of SBH. The ionization entropy of the interface defects depends weakly on temperature and hence the temperature coefficient of SBH in this case should be nearly zero (Revva *et al* 1993). But in our case its value is quite high i.e. 2 meV/K. So both the Fermi level pinning models are unable to explain the observed large variations in SBH with temperature. Hence we turn towards lateral SBH inhomogeneities model as proposed by Tung (1991, 1992) and Werner and Guttler (1991). This model explains well the dependence of SBH and ideality factor on temperature by considering the SBH inhomogeneities at the MS interface in nanometer length scales. The electron transport at inhomogeneous MS junctions has been treated by parallel conduction model. The current is assumed to be a sum of the currents flowing in all the individual patches (I_i) each with its own area (A_i) and SBH (Φ_i):

$$I(V) = \Sigma I_i = A^* T^2[\exp(qV/kT) - 1]\Sigma\exp(- q\Phi_i/kT)A_i. \quad (4)$$

Here the current transport will be dominated by the low barrier height regions. In fact, utilizing ballistic electron

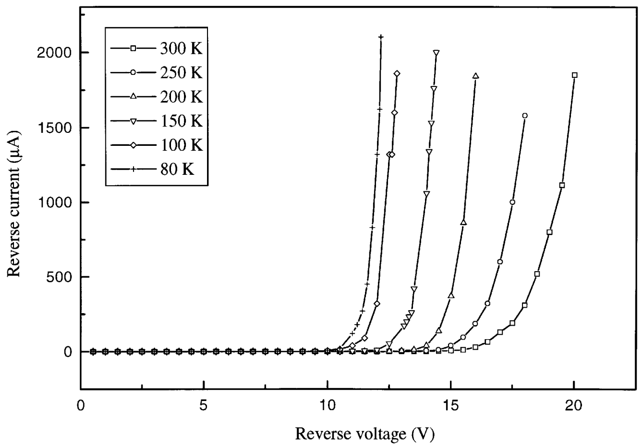

Figure 3. Reverse current–voltage characteristics for Au/*n*-GaAs epitaxial Schottky diode at different temperatures in the range 80–300 K.

emission microscopy (BEEM) technique it has been shown that SBH varies laterally in various MS contacts (Talin *et al* 1994; Olbrich *et al* 1997, 1998). Dobrocka and Osvald (1994) simulated the effect of temperature on apparent barrier height and ideality factor assuming the inhomogeneity of the local SBH. They assumed a Gaussian type of distribution function for SBH variations. The dependence of apparent barrier height and ideality factor on temperature for various standard deviations, s, of the distribution function were evaluated. According to them for the largest standard deviation, the temperature dependence is also the strongest. In fact from 300 K to 80 K, the value of ideality factor increases by a factor of 2 while the barrier height decreases by about 2 times.

We have deposited the Au having purity of 99·95% over *n*-GaAs by resistive heating evaporation method to obtain the Schottky structure. It is expected in this case that the polycrystalline MS interface will be formed which have large lateral variations in the local SBH. These may be due to the presence of interface roughness and interface defects. The value of ideality factor increases from 1·9 at 300 K to 4·7 at 80 K. Also at 300 K the value of apparent barrier height is 0·82 eV which decreases with decrease in temperature and at 80 K its value goes down to 0·37 eV. These variations in ideality factor and apparent barrier height with temperature are consistent with

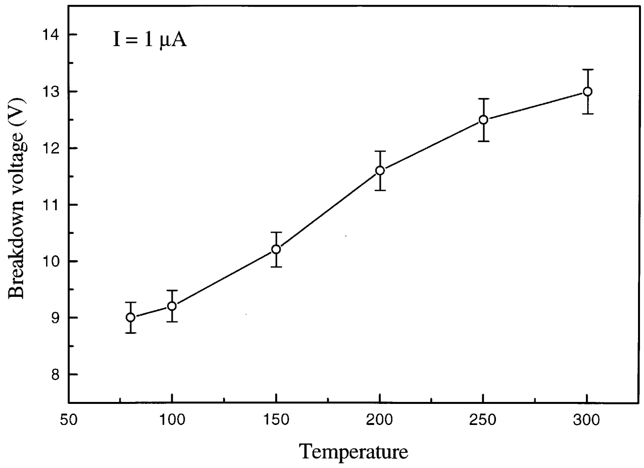

Figure 4. Breakdown voltage, V_{BD} versus temperature for Au/*n*-GaAs Schottky diode.

the results of numerical simulations of Dobrocka and Osvald (1994) who have assumed inhomogeneous SBH at the MS interface.

Now let us consider the reverse *I*–*V* behaviour. The reverse *I*–*V* characteristics at various temperatures are shown in figure 3. The reverse current is small (a few μA) up to a reverse voltage of about 10 V. Then it increases sharply after a certain voltage, called as breakdown voltage, V_{BD}. The breakdown voltage, V_{BD} is defined as the voltage in reverse bias case at which the reverse current becomes equal to 1 μA. The breakdown voltage increases linearly with increase in temperature. It increases from a value of 9 V at 80 K to 13 V at 300 K as shown in figure 4. Hence the breakdown voltage has positive temperature coefficient which is indicative of avalanche multiplication as the mechanism responsible for junction breakdown in this Schottky diode (Sze 1981).

4. Conclusions

Au/*n*-GaAs Schottky diodes are fabricated by deposition of Au on *n*-GaAs epitaxial layer in a clean vacuum environment created by a cryopump. The variation of apparent Schottky barrier height, ideality factor, reverse saturation current density and reverse breakdown voltage of these Schottky diodes with temperature has been investigated. The temperature dependence of Schottky barrier height and ideality factor can be explained as due to lateral inhomogeneities in local SBH in nanometer dimensions. The reverse breakdown voltage has a positive temperature coefficient which indicates that avalanche multiplication is the mechanism responsible for junction breakdown.

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