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Determination of the lateral barrier height of inhomogeneous Au/n-type InP/In Schottky barrier diodes

F E Cimilli, M Sağlam and A Türüt

Faculty of Sciences and Arts, Department of Physics, Atatürk University, 25240 Erzurum, Turkey

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Abstract
We have identically prepared Au/n-InP/In Schottky barrier diodes (SBDs). The barrier height for the Au/n-InP/In SBDs from the current–voltage characteristics has varied from 0.557 eV to 0.615 eV, and the ideality factor n from 1.002 to 1.087. We have determined a lateral homogeneous barrier height value of approximately 0.597 eV for the Au/n-InP/In SBD from the experimental linear relationship between barrier heights and ideality factors. The barrier height value obtained from the reverse bias C^{-2}–V characteristics has varied from 0.512 eV to 0.572 eV and statistical analysis yields the mean $\Phi(C\text{–}V) = 0.562 \pm 0.004$ eV. A doping density of about $(2.90 \pm 0.05) \times 10^{15}$ cm^{-3} has been determined from the reverse bias C^{-2}–V characteristics.

1. Introduction

Schottky barrier diodes (SBDs) are of the most simple of MS contact devices [1–7]. Although Schottky interfaces have been well studied for over 50 years, it is only in the past decade that inhomogeneous contact has been considered as an explanation for voltage-dependent barrier height [8–21]. The barrier height (BH) is likely to be a function of the interface atomic structure, and the atomic inhomogeneities at a metal–semiconductor (MS) interface which are caused by grain boundaries, multiple phases, facets, defects, a mixture of different phases etc [10–16]. There has developed the idea that non-ideal behaviour in the SBDs could be quantitatively explained by assuming specific distribution of nanometre-scale interfacial patches (small regions) with lower BH than the junction's main BH [22, 23]. In such cases, the current across the MS contact may be greatly influenced by the presence of the BH inhomogeneity [14–22]. Some authors have been able to account for much of the observed nonideal behaviour by assuming certain distributions of microscopic barrier heights for the different diodes [21–30]. Tung and co-workers [22, 23] have modelled imperfect Schottky contacts by assuming lateral variations of the barrier height. They found larger ideality factors and smaller effective barrier heights when they increased the inhomogeneity of barriers. Thus, it has been pointed out that the BH inhomogeneity model would also explain the linear relationship between effective BHs and ideality factors that is often observed on sets of identically prepared diodes [10, 21–30].

Our purpose is to determine laterally homogeneous BH of Au/n-InP/In Schottky barrier diodes (SBDs) with the help of the linear relationship between effective BHs and ideality factors which is theoretically [22, 23] and experimentally [25–30] confirmed. For this purpose, Au/n-InP/In SBDs (25 dots) with a doping density of about $(2.90 \pm 0.05) \times 10^{15}$ cm^{-3} have been prepared and used in the linear region with large BHs and low patch density below $n \cong 1.1$ in the effective BHs versus ideality factors plot [23–30]. As is well known, the homogeneity or uniformity of the Schottky BH is an issue with important implications on the theory of Schottky BH formation and important ramifications for the operation of Schottky barrier diodes and contacts [22, 23]. In the literature, a BH value of 0.79 eV has been reported for Au/p-InP Schottky diodes [31]. Researchers [21, 32] have reported different BH values for Au/n-InP Schottky diodes at room temperature—Cetin and Ayyildiz [21] have obtained a value of 0.51 eV, while Newman *et al* [32] has found a value of 0.42 eV and some researchers have also given values of 0.47 eV [33] and 0.49 eV [34]. Therefore, it can become a measure for future studies in this area that the lateral homogeneous BH for the MS Schottky diodes has been determined. Furthermore, such determination is also important to distinguish from each other the BH values of Au/p-type InP and Au/n-type InP Schottky diodes. Moreover, as mentioned in [25], the homogeneous

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BHs rather than effective BHs of individual contacts or mean values should be used to discuss theories on the physical mechanism that determine the BHs of the MS contacts. Thus, provided the semiconductor substrate is well characterized then the homogeneous Schottky BH may be obtained from the I–V characteristics of even one contact [25].

2. Experimental procedure

The used n-type InP wafer (Si doped) was (1 0 0) oriented with a free carrier concentration of $(2.90 \pm 0.05) \times 10^{15}$ cm^{-3} at room temperature. The wafer was degreased consecutively in trichloroethylene, acetone and methanol for 3 min. The degreased wafer was etched with H_2SO_4:H_2O_2:H_2O (5:1:1) for 1 min to remove the surface damages and undesirable impurities. Indium was evaporated on the back side of the n-InP for the ohmic contact and the n-InP/In structure was annealed at 350 °C for 2 min in a N_2 atmosphere. Schottky contacts were formed on the front face of the n-InP as dots with a diameter of about 1 mm by evaporation of Au. The current–voltage (I–V) and capacitance–voltage (C–V) characteristics were measured using a Keithley 487 Picoammeter/Voltage Source and a HP model 4192A *LF* impedance analyser, respectively, at room temperature and in the dark.

3. Results and discussion

When a nearly ideal SBD is considered, it is assumed that the forward bias current of the device is due to thermionic emission current and can be expressed as [1]

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

where

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

is the saturation current density, Φ_{eff} is the zero bias effective barrier height, A^* is the effective Richardson constant and equals 9.4 A cm^{-2} K^{-2} for n-type InP, A the diode area, n is an ideality factor and is a measure of the conformity of the diode to pure thermionic emission, and if n is equal to 1, pure thermionic emission occurs. However, n has usually a value greater than unity. It is obtained from the slope of the straight line region of the forward bias ln I–V characteristics through the relation

$$n = \frac{q}{kT}\frac{\mathrm{d}V}{\mathrm{d}(\ln I)}. \tag{3}$$

25 dots (Schottky contacts) for the Au/n-InP/In were fabricated on the same n-type InP semiconductor substrate by evaporation of Au. Figure 1 shows the dark forward and reverse I–V characteristics of the Au/n-InP/In SBDs, respectively. The barrier height for the Au/n-InP/In SBDs from the current–voltage characteristics has varied from 0.557 eV to 0.615 eV, and the ideality factor n from 1.002 to 1.087. Statistical analysis yields the mean effective SBH = 0.584 ± 0.004 eV and the mean ideality factor = 1.041 ± 0.010 for the Au/n-InP/In SBDs. As seen, the experimental effective BHs and ideality factors obtained from the current–voltage (I–V) characteristics can differ from diode to diode even if they were identically prepared on the same sample.

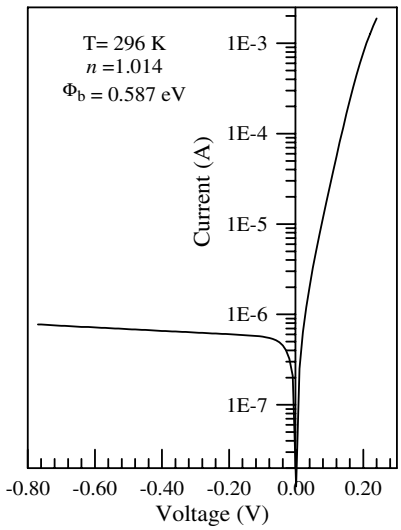


Figure 1. Forward and reverse bias current versus voltage characteristics of one of the 25 Au/n-InP/In Schottky barrier diodes at room temperature.

Furthermore, the slight non-saturating behaviour observed as a function of bias in the experimental reverse bias branch in figure 1 may be explained in terms of the spatial inhomogeneity of Schottky barrier height (SBH) [22, 23]. This bias-dependence of the SBH is frequently observed experimentally; however; in many cases the observed voltage dependence of the barrier height in the reverse characteristics exceeds the expected result based on image force lowering. The existence of SBH inhomogeneity offers a natural explanation for the experimentally observed soft reverse characteristics [22, 23]. For the inhomogeneous MS contacts, the reverse current may be dominated by the current which flows through the low-SBH patches controlled by the potential at the saddle point. Increase in the reverse bias drops the potential at the saddle point, hence the reverse current increases with increasing reverse bias and does not saturate [22, 23].

Larger ideality factors are attributed to secondary mechanisms at the interface [1, 8–18, 22, 23]. For example, interface defects may lead to a lateral inhomogeneous distribution of barrier heights at the interface which then results in larger ideality factors, and the charge transport across the interface only is no longer due to thermionic emission [1, 21–26]. Ideality factors between 1.01 and 1.02 can be expected due to image force lowering of the Schottky barrier at the interface. We have obtained an ideality factor value of 1.008 for the Au/n-InP/In SBDs with the mean effective BH of 0.584 eV that we have formed from n-InP with free carrier concentration of $(2.90 \pm 0.05) \times 10^{15}$ cm^{-3} at room temperature. As seen from the explanations above, the inhomogeneities may play an important role and have to be considered in the evaluation of experimental I–V characteristics. The high values of n can be attributed to the presence of a wide distribution of low-SBH patches caused by lateral barrier inhomogeneity. As can be seen from figure 2, the BHs become smaller as the ideality factors increase. That is, there is a linear relationship between experimental effective BHs and ideality factors of Schottky contacts. This finding

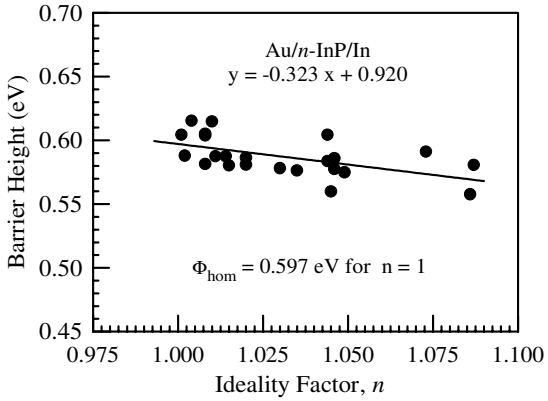


Figure 2. Experimental barrier height versus ideality factor plot of Au/n-InP/In Schottky barrier diodes at room temperature.

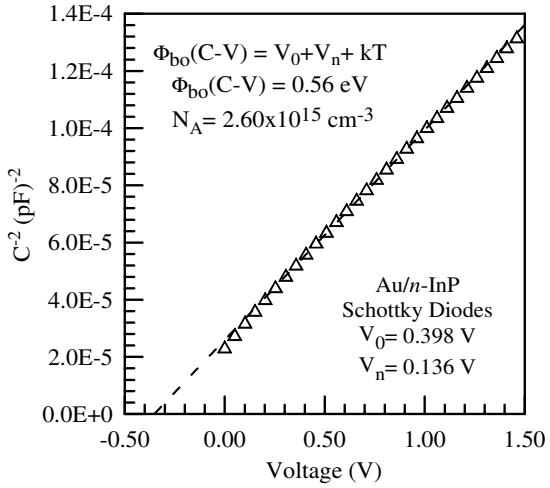


Figure 3. The room temperature reverse bias C^{-2}–V characteristic of one of the Au/n-InP/In SBDs at 500 kHz.

may be attributed to lateral barrier inhomogeneities in Schottky diodes [21–30]. It has been mentioned that higher ideality factors among identically prepared diodes were often found to accompany lower observed BHs. A laterally homogeneous BH value of approximately 0.597 eV for the Au/n-InP/In SBDs was obtained from the linear relationship between experimental effective BHs and ideality factors in figure 2. The homogeneous BH of 0.597 eV and mean effective BH of 0.584 eV that we have experimentally found are in close agreement with the mean value of 0.60 eV obtained from the temperature dependence I–V characteristics of Au/n-InP/In diodes by Cetin and Ayyildiz [21]. The straight line of the experimental effective BHs versus ideality factors plot that corresponds to the region with large BHs and low patch density below $n \cong 1.1$ [24–30] was extrapolated to $n = 1$ for determining the laterally homogeneous BH.

The depletion layer capacitance of Schottky diodes, C, can be expressed as [1]

$$C^{-2} = 2(V_0 + V)/q\varepsilon_s A^2 N_d, \tag{4}$$

where A is the area of the diode, V_0 is the diffusion potential at zero bias and is determined from the extrapolation of the linear C^{-2}–V plot to the V axis, ε_s is the dielectric constant of the semiconductor, N_d is the acceptor concentration of the n-type semiconductor substrate. Figure 3 shows the reverse bias C^{-2}–V characteristic of one of the devices at 500 kHz and 300 K. The BH and carrier concentration values for each diode were extracted from its reverse bias C^{-2}–V characteristic. The barrier height value obtained from the reverse bias C^{-2}–V characteristics has varied from 0.512 eV to 0.572 eV and statistical analysis yields the mean $\Phi(C$–$V) = 0.562 \pm 0.004$ eV. A doping density of about $(2.90 \pm 0.05) \times 10^{15}$ cm^{-3} has been determined from the reverse bias C^{-2}–V characteristics.

As can be seen from the obtained BH values, a mean effective $\Phi(I$–$V) = 0.584 \pm 0.004$ eV was obtained from the statistical analysis yield for our Au/n-InP/In SBDs. It has been said that the mean $\Phi(C$–$V) = 0.562 \pm 0.004$ eV from C–V characteristics is in close agreement with the mean effective $\Phi(I$–$V) = 0.584 \pm 0.004$ eV from I–V characteristics within the limits of experimental error. The BH value of approximately 0.597 eV obtained from the linear relationship between experimental effective BHs and ideality factors is an expected BH value for a lateral homogeneous Au/n-InP/In SBD. That is, this value should represent the barrier height of an ideal Au/n-InP/In Schottky contact, i.e. the highest value of the barrier height distribution in which small patches of the lower barrier are embedded. The mean effective $\Phi(I$–$V) = 0.584 \pm 0.004$ eV is a mean of the experimental BH values. As known, the BH measured by C–V is always close to the weighted arithmetic average of the BHs in the inhomogeneous MS contact [23]. Therefore, the mean $\Phi(C$–$V) = 0.562 \pm 0.004$ eV should be compared with the mean effective $\Phi(I$–$V) = 0.584 \pm 0.004$ eV. Furthermore, the current in the I–V measurement is dominated by the current which flows through the region of low Schottky BH (SBH). Since the low SBH patch is pinched off, the effective SBH of the patch is the potential at the saddle point. It should be noted that since the low-SBH patches are more effectively pinched-off when the semiconductor doping is low, the discrepancies between $\Phi(C$–$V)$ and $\Phi(I$–$V)$ should be less at lower doping levels ($(2.90 \pm 0.05) \times 10^{15}$ cm^{-3} in the considered InP sample). This trend is, indeed, observed experimentally [22, 23].

In conclusion, the data on the Au/n-InP/In samples allow meaningful extrapolation to $n = 1$ to determine the laterally homogeneous BH. A laterally homogeneous BH value of approximately 0.597 eV for the Au/n-InP/In SBDs was obtained from the linear relationship between experimental effective BHs and ideality factors that can be explained by lateral inhomogeneities. The statistical analysis yields the mean effective SBH $= 0.584 \pm 0.004$ eV and the mean ideality factor $= 1.041 \pm 0.010$ for the Au/n-InP/In SBDs from the I–V characteristics and the mean $\Phi(C$–$V) = 0.562 \pm 0.004$ eV from the C–V characteristics.

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