

The distribution of barrier heights in Au/n-Si Schottky barrier diodes from I - V - T measurements

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The forward bias current-voltage (I - V) characteristics of Au/n-Si(111) Schottky barrier diodes (SBDs) with native interfacial insulator layer have been investigated in the wide temperature range of 80-400 K. Their analysis on the basis of the standard thermionic emission (TE) mechanism reveals an abnormal decrease of the zero-bias barrier height (Φ_B) and increase of ideality factor (n) with decrease in temperature and nonlinearity in the activation energy plot. Such behavior of Φ_{B0} and n are attributed the barrier inhomogeneities by assuming a Gaussian distribution (GD) of barrier heights (BHs) at metal/semiconductor (M/S) interface. The experimental Φ_B vs $q/2kT$ plot show that an existence of a double GD having mean BHs and standard deviations 0.747 eV and 0.081 V (between 80 and 200 K) and 1.203 eV and 0.146 V (between 230 and 400 K), respectively. Thus, the modified $\ln(I_0/T^2) - q^2 \sigma_0^2 / 2k^2 T^2$ vs q/kT plot gives Φ_B and A^* as 0.682 eV and $3.14 \text{ A cm}^{-2} \text{ K}^{-2}$ (between 80 and 200 K) and 1.199 eV and $110.16 \text{ A cm}^{-2} \text{ K}^{-2}$ (between 230 and 400 K), respectively, without using the temperature coefficient of the BH. This value of the Richardson constant $110.16 \text{ A/cm}^2 \text{ K}^2$ is close to the theoretical value of $120 \text{ A K}^{-2} \text{ cm}^{-2}$ for n-type Si. Hence, it has been concluded that the temperature dependence of the forward bias I - V characteristics of the Au/n-Si(111) SBDs can be successfully explained on the basis of TE mechanism with a double GD of the BHs.

(Received October 04, 2009; accepted April 11, 2010)

Keywords: Au/n-Si(111) Schottky barrier diodes, I - V - T characteristic, Barrier inhomogeneity, Double Gaussian distribution, Modified Richardson plot

1. Introduction

Unless specially fabricated of SBD, a thin native interfacial layer is formed at M/S interface. The existence such SiO_2 , SnO_2 , TiO_2 and Si_3N_4 insulator layer, R_s and N_{ss} transforms the SBD into a MIS type SBD and its I - V characteristics considerably deviate from the expected ideal cases [1-10]. Therefore, to determine the main electrical parameters, difficulties will arise. Also, especially at room temperature or narrow range of temperature, it is not possible to get detailed information on their I - V mechanisms or barrier formation at the M/S interface. However, the temperature dependence of the I - V characteristics in the wide temperature range allows us to understand different aspects of conduction mechanisms and device characteristics [11]. The non-linearity behavior of activation energy plot at low temperatures in some studies has been successfully explained on the basis of TE mechanism with GD [12-15] and it has been widely accepted to correlate the experimental data [15-18]. In generally the forward bias I - V characteristics are linear in the semi-logarithmic scale at intermediate bias voltages, but deviate considerably from linearity due to the effect of R_s of the devices when the applied voltage is sufficiently large [16,17]. Recently, it has been pointed out that the barrier height is inhomogeneous at M/S interface [3,19]. It may contain patches with low barrier height. The total current is the sum of the currents through all of these patches and the current through the whole junction area [20,21].

In this study, the I - V characteristics of Au/n-Si(111) SBDs have been investigated in the wide temperature range of 80-400 K. The experimental data show an abnormal decrease of Φ_B and increase of n with decreasing temperature, and these changes become effective especially at low temperatures. Such behavior of Φ_B and increase of n were interpreted by assuming double-Gaussian spatial distribution of BHs.

2. Experimental procedure

The Au/n-Si(111) SBDs were fabricated on 2 inch (5.08 cm) diameter n-type (P doped) epilayer silicon wafer with (111) surface orientation, $0.7 \text{ } \Omega\text{-cm}$ resistivity and $350 \mu\text{m}$ thickness. For the fabrication a process, Si wafer was decreased in organic solvent of CHCl_3 , CH_3COCH_3 and CH_3OH consecutively and then etched in a sequence of H_2SO_4 and H_2O , %20 HF, a solution of $6\text{HNO}_3:1\text{HF}:35\text{H}_2\text{O}$, %20 HF and finally quenched in deionized water for a prolonged time. Preceding each cleaning step, the wafer was rinsed thoroughly in deionized water of resistivity of $18 \text{ M}\Omega\text{-cm}$. After this cleaning process, high purity (99.999 %) Au with a thickness of about $1500 \text{ } \text{\AA}$ were thermally evaporated onto whole back side of Si wafer at a pressure about 10^{-6} Torr in high vacuum system. In order to perform a low resistivity ohmic backcontact, Si wafer was sintered at $500 \text{ } ^\circ\text{C}$ for 3 min in N_2 atmosphere. After that $\sim 1500 \text{ } \text{\AA}$ thick high purity Au (%99,999) dots of 1 mm diameter were evaporated onto front of Si wafer in high vacuum

system and at same pressure. In this way, the fabrication process of Au/n-Si(111) SBDs was completed. The temperature dependence of I - V measurements were performed by the use of a Keithley 2400 sourcemeter, a Keithley 614 electrometer in the temperature range of 80-400 K using a temperature-controlled Janes vpf-475 cryostat with a Lake Shore model 321 auto-tuning temperature controllers in a vacuum of 5×10^{-4} Torr which enables us to make measurements in the temperature range of 77-450 K. All measurements were carried out with the help of a microcomputer through an IEEE-488 ac/dc converter card.

3. Results and discussion

When a MS Schottky barrier diode with a series resistance (R_s), the relation between the applied forward bias voltage ($V \geq 3kT/q$), and the current I can be expressed as [1]

$$I = I_o \exp\left(\frac{q(V - IR_s)}{nkT}\right) \left[1 - \exp\left(\frac{-q(V - IR_s)}{nkT}\right)\right] \quad (1)$$

where the term of IR_s is voltage drop across the R_s and I_o is the reverse saturation current and it can be derived from the straight-line intercept of the I axis ($\ln I$) at zero bias and is given by

$$I_o = AA^* T^2 \exp(-q\Phi_{Bo}/kT) \quad (2)$$

where A^* and T are the effective Richardson constant and equals to $120 \text{ A/cm}^2 \text{ K}^2$ for n -type Si [1], temperature in K, respectively. Fig.1. shows the $\ln I$ - V characteristics of Au/n-Si (111) SBD at various temperatures. The n and Φ_{Bo} were obtained from Eq(1) and (2), respectively and shown in Fig. 2 (a) and (b). At low temperatures (80-200 K) (Fig.2 (b)), at the variation of Φ_{Bo} with temperature is faster than at high temperatures (230-400 K). The high value of n has been attributed to an existence of SiO_2 , and particular distribution of N_{ss} [7, 9,22-28]. The nkT/q vs kT/q plot was drawn to obtain evidence of T_o effect (Fig. 3). As shown in Fig. 3, the value of n is closer to unity and this behaviour of n can be attributed to the presence of SBH inhomogeneity about some mean SBH. For the evaluation of the BH, one may also make use of the activation energy or Richardson plot of saturation current. Eq. (2) can be rewritten as

$$\ln\left(\frac{I_o}{T^2}\right) = \ln(AA^*) - \frac{q\Phi_{Bo}}{kT} \quad (3)$$

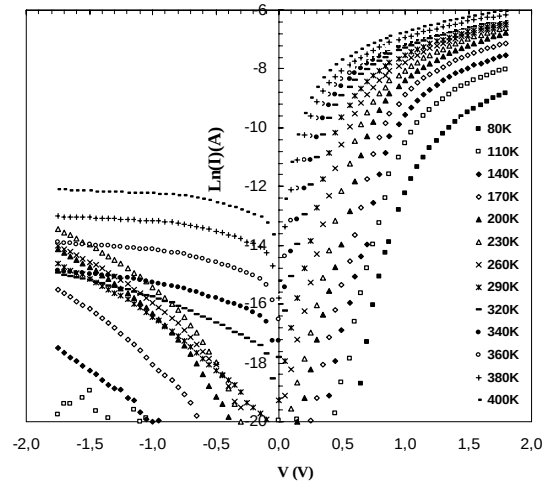


Fig. 1. The $\ln(I)$ vs V characteristics of the Au/n-Si (111) SBD at various temperatures.

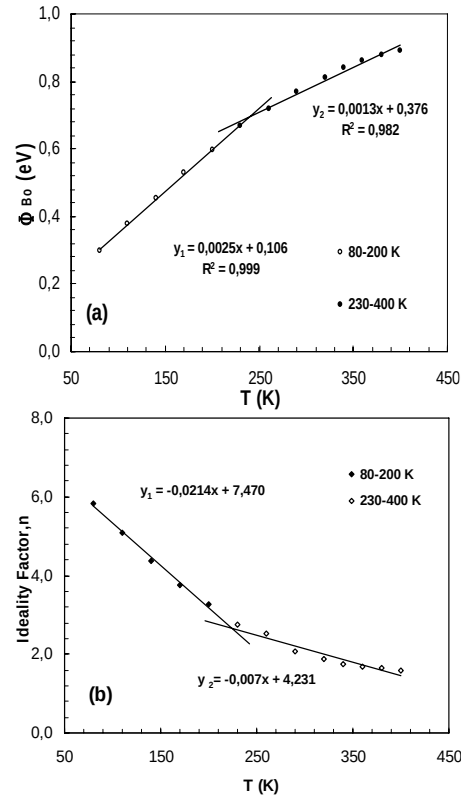


Fig. 2. The (a) Φ_{Bo} - T and (b) n - T plots for Au/n-Si (111) SBD and inserted fit correlation (R^2).

As shown in Fig. (4), the $\ln(I_o/T^2)$ vs q/kT plot has two linear regions with different slopes in low temperatures (80-200 K) and high temperatures (230-400 K) ranges. The E_a and A^* were obtained from the slope and intercept of these two straight lines as 0.108 eV and $5.26 \times 10^{-11} \text{ A/cm}^2 \text{ K}^2$ (80-200 K), and 0.355 eV and $1.15 \text{ A/cm}^2 \text{ K}^2$ (230-400 K), respectively. These A^* values for two temperature ranges are very much lower than the 120

$\text{A}/\text{cm}^2 \text{ K}^2$ for n-Si. The deviation in the A^* plots might be a result of the spatially inhomogeneous BHs and potential fluctuations at the interface, which consist of low and high barrier areas [13,18,24-27].

Φ_B vs n plot is shown in Fig.5. As shown in Fig. 5, there are two linear regions between Φ_B and n values of the Au/n-Si (111) SBD, which can be explained by the lateral inhomogeneities of the barrier heights [13,14,22]. In the first region (80-200 K), the extrapolation of the experimental Φ_{B0} vs n plot to $n=1$ has given the value of 0.85 eV, and in the second region (230-400 K) to $n=1$ has given the value of 0.985 eV, respectively.

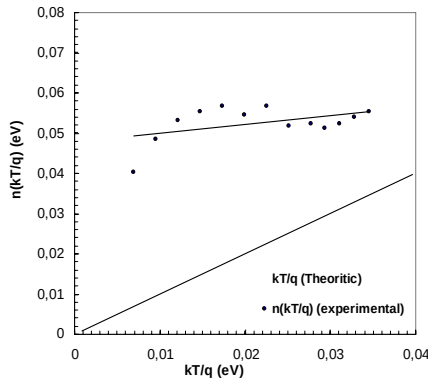


Fig. 3. The plot of nkT/q vs kT/q of the Au/n-Si (111) SBD.

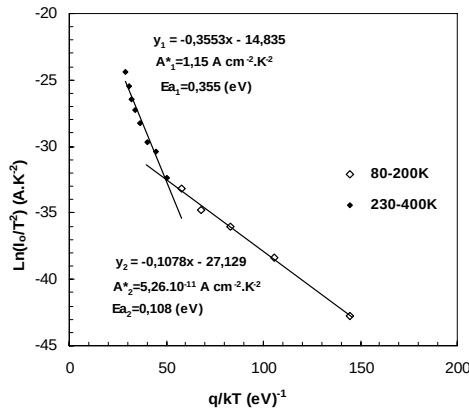


Fig. 4. Richardson plot of $\ln(I_o/T^2)$ vs q/kT for Au/n-Si (111) SBD.

The GD of the BHs and temperature dependent of the σ_s are given by [24-27], respectively.

$$\Phi_{B0} = \bar{\Phi}_{B0} - \frac{q\sigma_s^2}{2kT} \quad (4a)$$

and

$$\left(\frac{1}{n_{ap}} - 1\right) = -\rho_2 + \frac{q\rho_3}{2kT} \quad (4b)$$

where ρ_2 and ρ_3 quantities are the voltage coefficients. Both the Φ_B vs $q/2kT$ (Fig. 6(a)) and $(n^{-1}-1)$ vs $q/2kT$ (Fig. 6(b)) plots consist of two straight line with different slopes in low temperatures (80-200 K) and high temperatures (230-400 K) ranges. The observations in these figures indicated that the presence of two GD BHs in the contact area. The intercepts and slopes of these straight lines give two sets of values of Φ_B and σ_s as K 0.682 eV and 0.0067 V in the temperature range of 80-200 K (distribution 1), and as 1.199 eV and 0.0214 V in the temperature range in 230-400 (distribution 2). It was seen that value of $\sigma_s = 0.1503$ V is not small compared to the mean value of $\Phi_B = 1.199$ eV, and $\sigma_s = 0.0067$ V is not small compared to the mean value of $\Phi_B = 0.682$ eV, too, so it indicates the presence of the interface inhomogeneities. The existence of second GD at low temperatures may possibly arise due to some phase change taking place on cooling below a certain temperature. In addition, the $(n^{-1}-1)$ vs $q/2kT$ plot consists of two straight line with different slopes in low temperatures (80-200 K) and high temperatures (230-400 K) ranges. The intercept and slope of the straight lines of these plots give the voltage coefficient ρ_2 and ρ_3 , respectively. The of ρ_2 obtained from the intercepts of the experimental $(n^{-1}-1)$ vs $q/2kT$ plot (Fig.5(b)) are -0.634 in the temperature range of 80-200 K, and 0.0123 in the temperature range of 230-400 K, whereas the values of ρ_3 obtained from the slopes of these plots were found as -0.0029 V and -0.0264 V, respectively.

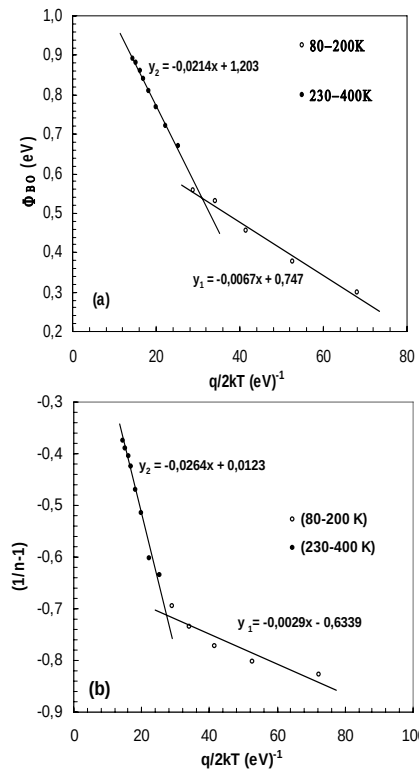


Fig. 5. The $\Phi_{B0}-q/(2kT)$ and $(n^{-1}-1)-q/(2kT)$ plots of Au/n-Si (111) SBD with two GD of BHs.

Using Φ_B in place of Φ_B in Eq.(2) according to GD of the BH, it can be rewritten as

$$\ln\left(\frac{I_0}{T^2}\right) - \left(\frac{q^2 \sigma_s^2}{2k^2 T^2}\right) = \ln(AA^*) - \frac{q\Phi_{B0}}{kT} \quad (5)$$

As shown in Fig. 6, there are two linear regions in low temperatures (80-200 K) and high temperatures (230-400 K) ranges and their slopes directly yielding the mean values Φ_{B0} and the intercept ($=\ln AA^*$) at the ordinate determining A^* values. From the straight line of these two regions, zero-bias mean BH was obtained $\Phi_B = 0.682$ eV (in the range of 80-200 K) and 1.199 eV (in the range of 230-400 K). These values show perfect agreement with the Φ_B obtained from the Φ_B versus $q/2kT$ plot in Fig. 6.

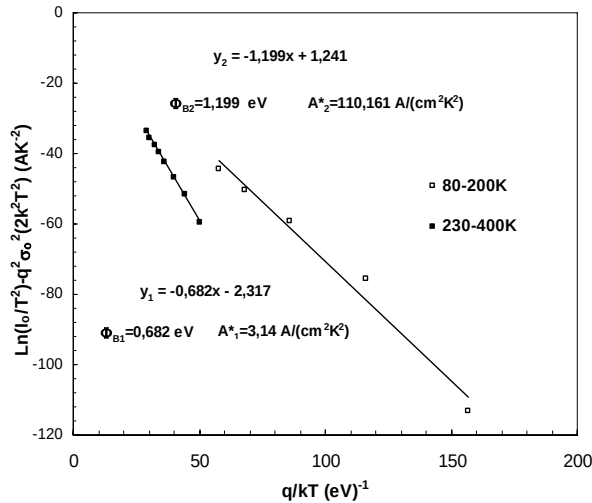


Fig. 6. Modified Richardson $\ln(I_0/T^2) - q^2 \sigma_s^2 / 2k^2 T^2$ vs q/kT plot for the Au/n-Si (111) Schottky diode according to Gaussian distribution of the barrier height.

As mentioned above, the intercepts at the ordinate give the Richardson constant A^* as 3.14 A/cm²K² (between 80 and 200 K) and 110.161 A/cm²K² (between 230 and 400 K). The Richardson constant value of 110.161 A/cm²K² is in very close agreement with 120 A/cm²K² for n-Si.

4. Conclusions

In this study, we investigated the BH inhomogeneties in Au/n-Si(111) SBDs with native interfacial insulator layer from the I-V characteristics in the wide temperature range of 80-400 K. While the n decreases, Φ_B increases with increasing temperature. Such behavior of Φ_B and n are attributed to SB inhomogeneties by assuming a GD of BHs due to BH inhomogeneties that prevail at M/S interface. The high value of n is attributed to the potential drop in the interfacial insulator layer and recombination through the interface states. In order to obtain evidence of

single or double GD of BHs, we have drawn the Φ_B vs $q/2kT$ plot and it show that an existence of a double GD having mean barrier heights and standard deviations 0.747 eV and 0.081 V (between 80 and 200 K) and 1.203 eV and 0.146 V (between 230 and 400 K), respectively. Thus, the modified $\ln(I_0/T^2) - q^2 \sigma_s^2 / 2k^2 T^2$ vs q/kT plot gives Φ_B and A^* as 0.682 eV and 3.14 A/cm²K² (80-200 K) and 1.199 eV and 110.16 A/cm²K² (230-400 K), respectively, without using the temperature coefficient of the BH. The value of $A^* = 110.16$ A/cm²K² is close to the theoretical value of 120 A/cm²K² for n-type Si. It can be concluded that the temperature dependence of the forward I-V characteristics of the Au/n-Si(111) SBDs can be successfully explained on the basis of TE mechanism with a double GD of the BHs.

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