Investigation of temperature dependent barrier height of Au/ZnO/Si schottky diodes

M Asghar¹, K Mahmood¹, S Rabia¹, Samaa BM¹, M Y Shahid¹ and M A Hasan²
¹Department of Physics, The Islamia University of Bahawalpur, Pakistan
²Department of Electrical and Computer Engineering, UNC-Charlotte, NC, USA

E-mail: mhashmi@iub.edu.pk

Abstract. In this study, temperature dependent current-voltage (I-V) measurements have been performed to investigate the inhomogeneity in the temperature dependent barrier heights of Au/ZnO/Si Schottky barrier diode in the temperature range 150 – 400K. The room temperature values for ideality factor and barrier height were found to be 2.9 and 0.60 eV respectively indicating the inhomogeneity in the barrier heights of grown samples. The Richardson plot and ideality factor verses barrier height graph were also drawn to verified the discontinuity between Au and ZnO. This barrier height inhomogeneity was explained by applying Gaussian distribution model. The extrapolation of the linear Φ_{ap} (n) plot to n = 1 has given a homogeneous barrier height of approximately 1.1 eV. Φ_{ap} versus 1/T plot was drawn to obtain the values of mean barrier height for Au/ZnO/Si Schottky diode (1.1 eV) and standard deviation(δ_s) (0.02 V) at zero bais.

1. Introduction
ZnO is a material of interest among the research community due to its wide band gap of 3.37 eV and large exciton binding energy (60 meV) at room temperature [1, 2]. In order to utilized ZnO in practice applications, metal contacts are neccessory. Therefore the study of characteristics parameters such as barrier height and ideality factor of metal-semiconductor Schottky diodes has fudamental importance. The performance and relaibility of these devices especially depend on the formation of insulator layer between metal and semiconductor interface, inhomogenities of Schottky barrier contacts and series resistance of diode [3]. Generally Schottky contacts show temperature dependent behavior as evidenced by the parameters such as ideality factor, barrier height and series resistance [4]. It is observed in the literature that I-V characteristics normally deviate from the ideal thermionic model because both, ideality factor and barrier height showed strong temperature dependence behavior [5-7]. This abnormal behavior of Schottky diodsp was attributed to series resistance and inhomogeneties between metal and semiconductor [8, 9]. Different models have been employed to understand the abnormal behavior but the subject is still under hot debate. Therefore the study of Schottky contacts of different metals on ZnO is an active area of research and needs to be further investigated.

In this study temperature dependence I-V measurements have been performed on Au/ZnO/Si Schottky diodes in the temperature range of 150 to 400 K to investigate the discontinuity present between Au and ZnO. The ideality factor, series resistance and barrier height show strong dependence of temperature. There was also correlation between ideality factor and barrier height which showed the inhomogenity in the barrier height. The inhomogenity in barrier height was explained using Gaussian distribution model of barrier heights.
2. Experimental
ZnO layers were grown on 3 inch diameter p-type silicon (001) wafer \(N_A \sim 1.2 \times 10^{15} \text{ cm}^{-3}\) by means of Molecular Beam Epitaxy (MBE). The ZnO was grown under following conditions: the substrate temperature was set at 703 K while oxygen was supplied from an RF atomic source and Zn was evaporated from -Zn-Knudsen cell maintained at 562 K filled with Zn beads having a purity of 99.9999%. The pressure of the chamber during the growth was \(\sim 1 \times 10^{-4} \text{ mbar}\) mainly due to the pressure required to operate the oxygen RF atomic source and growth time was 7 hours. The oxygen RF atomic source was operated at 300W. For electrical measurements, gold Schottky contacts with diameter 78 mm\(^2\) were fabricated by electron beam evaporation. I-V measurements of Schottky diodes were carried out by the following equipment (manufacturer): DLTS (DLS-83D Hungry)

3. Results and Discussion
Fig. 1 shows the semi-logarithmic forward biased I-V characteristic of the Au/ZnO/Si Schottky barrier diodes in the temperature range 150 to 400 K. Current in the Schottky barrier diode due to the thermionic emission, neglecting series resistance is given as [10],

\[
I = I_S \left[ \exp \left( \frac{qV}{n kT} \right) - 1 \right] \tag{1}
\]

Where \(n\) is the ideality factor and \(I_S\) is the reverse saturation current given by the relation,

\[
I_S = A A^* T^2 \exp \left[ -\frac{q \phi_B}{kT} \right] \tag{2}
\]

Where \(A\) is the contact area, \(A^*\) is the Richardson constant and its value is 32 AK\(^{-2}\) cm\(^2\) for ZnO [11]. \(T\) is temperature in Kelvin, \(k\) is the Boltzmann’s constant \((k=1.38 \times 10^{-23} \text{ J/K or } 8.617 \times 10^{-5} \text{eV/K})\), \(q\) is the electric charge and \(\phi_B\) is the barrier height

![Figure 1. Semi-logarithm I-V plot of Au/ZnO/Si Schottky diodes at different temperatures.](image)

The value of barrier height and ideality factor was determined from the slope of semi-logarithm forward biased I-V characteristics (shown in fig. 1) using following equations.

\[
n = \frac{q}{kT \times \text{slope}} \tag{3}
\]

\[
\phi_B(I_{V=0}) = \frac{kT}{q} \ln \left( \frac{AA^*T^2}{I_S} \right) \tag{4}
\]
The ideality factor and barrier height shows a strong dependence of temperature as shown in Fig. 2. The ideality factor decreases and barrier height increases with temperature. Room temperature $n$ and $\Phi_B$ values are found to be 2.9 and 0.60 eV respectively. The value of ideality factor attributed to interface states between gold and ZnO, image force lowering and barrier height inhomogeneity [12]. Such results have been already published by many researchers [13]. Such temperature dependence is an obvious disagreement with the reported negative temperature coefficient of the Schottky barrier height. The reason of this disagreement may be the barrier height inhomogeneity.

The barrier height inhomogenity can be also determined by plotting the graph between ideality factor and barrier height. Fig. 3 shows a plot of experimental BH and ideality factor. Fig. 3 demonstrated a linear relationship between experimental BH and ideality factor and is explained by lateral inhomogenities of BH in the schottky diode. The extrapolation of experimental BH verses ideality...
factor plot of \( n=1 \) has given homogenous barrier height of 1.1 eV. Therefore decreases of ideality factor and increases of barrier height at high temperature clearly demonstrated that there is discontinuity at Au/ZnO interface.

This barrier height inhomogeneity can be explained by using Gaussian distribution model of barrier height. According to this model the expression of barrier height can be written as \([14-16]\)

\[
\Phi_{ap} = \Phi_{bo} - q\delta_s^2/2kT 
\]

where \( \Phi_{ap} \) is the apparent BH which can be measured experimentally, \( \Phi_{bo} \) is the mean BH and \( \delta_s \) is the standard deviation of the BH distribution. The standard deviation is the measure of barrier height inhomogeneity.

The temperature dependence of \( \delta_s \) is usually small and can be neglected. In this model the observed variation of ideality factor with temperature is given by \([17]\)

\[
1/n_{ap} - 1 = -\rho_1 + q\rho_2/2kT 
\]

where \( n_{ap} \) is the apparent ideality factor and \( \rho_1 \) and \( \rho_2 \) are voltage coefficients which may depend on temperature and they quantify the voltage deformation of the BH distribution.

![Figure 4. Zero bias apparent barrier height verses1/2kT curves of Au/ZnO/Si Schottky diodes according to the Gaussian barrier height](image)

The linear relationship between barrier height and 1/2kT shows an agreement with current model that confirmed the discontinuity at metal and semiconductor interface. The fig shows a plot between \( \Phi_{ap} \) and 1/2kT for Au/ZnO Schottky diode [18]. The intercept and slope of this plot gives the mean barrier height and the zero-biais standard deviation with values 1.1 eV and 0.02 eV respectively.
Figure 5. Zero bias ideality factor versus 1/2kT curves of Au/ZnO/Si Schottky diodes according to the Gaussian barrier height

Again, the plot of $n_{ap}$ versus 1/2kT is a straight line that gives voltage coefficients $\rho_1$ and $\rho_2$ from the intercept and slope, respectively (shown in fig. 5). The values of $\rho_1 = 0.55$ and $\rho_2 = -0.006$ V were obtained from the experimental $n_{ap}$ versus 1/2kT plot (Fig. 5). As the inhomogeneity of the interface is depend upon the value of $\delta_s$. The lower value of $\delta_s$ corresponds to more homogeneous barrier heights.

4. Conclusion
In this study, temperature dependent current-voltage (I-V) measurements have been performed to investigate the inhomogeneity in the temperature dependent barrier heights of Au/ZnO/Si Schottky barrier diode in the range 150–400K. The room temperature values for ideality factor and barrier height found to be 2.9 and 0.60 eV respectively indicating the inhomogeneity in the barrier heights of grown samples. This barrier height inhomogeneity was explained by applying Gaussian distribution model.

5. References
[1] Asghar M, Mahmood K, Ali A, Hasan M-A, Raja M Y A, Hussain I, Willander M 2011 ECS transactions 35 (6) 149-154
[2] Asghar M, Mahmood K, Ferguson I.T, Yasin R, Tsu R, Xie Y-H 2013 Semicond. Sci. Technol. 28 105019
[3] Asghar M, Mahmood K, Faisal F, Hasan M-A 2013 J. Phys: Conf. Ser. 439 012030
[4] Durmus A A, Ali K, Ahmet F Ö 2012 Microelectronic Eng. B. 98 6-11
[5] Jiang Y.L, Ru G.P, Lu F, Qu X.P, Li B. Z, Li W, Li A. Z 2002 Chin. Phys. Lett. 19 553–556.
[6] Chand S, Kumar J1997 J. Appl. Phys. 82 5005–5010
[7] Tung R. T, Levi A.F.J, Sullivan J. P, Schrey F 1991 Phys. Rev. Lett. 66 72–75
[8] Tung R. T 1992 Phys. Rev. B 45 13509–13523
[9] Potzger K, Shengqiang Z.J, Grenzer M.H, Fassbender 2008 J Appl. Phys. Lett. 92 182504
[10] Tneh S.S, Hassan Z, Saw K.G, Yam F.K, Hassan H.A 2010 Physica B 405 2045
[11] Asghar M, Mahmood K, and Hasan M A 2012 Key Eng. Mat. 511-512 132-136
[12] Wenksten H V, Kaidashev E M, Lorentz M, Hochmuth H, Biehne G, Lenzer J, Gottsealach V, Pickenhain R and Grundmann M 2004 Appl. Phys. Lett. 84 79
[13] Shawn C, Bernard J R and Kristin M P 2008 Appl. Phys. Lett. 92 012103
[14] Aydo gan S, Cinar K, Asıl H, Coskun C and Türüt A 2009 J. Alloy. Comp. 476 913
[15] Coskun C, Gedik N and Bale E 2006 Semicond. Sci. Technol. 21 1656–1660
[16] Dhananjaya, Nagarajua J and Krupanidhi S B 2007 Physics B 391 344
[17] Padovani F A and Summer G 1965 Appl. Phys. A 36 3744
[18] Altindal S, Karadeniz S, Tugluogiu N and Tataroglu A 2003 Solid-state Electronics 471847 1854