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CURRENT –VOLTAGE-TEMPERATURE (I-V-T) CHARACTERISTICS OF CR/4H-SIC SCHOTTKY DIODES

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Abstract:

This paper reports temperature dependent current-voltage (IV) characteristics of Cr/n-type 4H-SiC Schottky diode within the temperature range of 300-500K. The main diode parameters like barrier height and ideality factor were found to be strongly dependent on temperature. It has been found that with the increase in temperature ideality factor decreases and barrier height increases and the conventional activation energy plot deviates from linearity. According to the thermionic emission theory the slope of the conventional Richardson plot $\ln(I_0/T^2)$ versus 1000/T should give the barrier height. However experimental data don't correlate with the straight line of linearly fitted curve. These discrepancies from ideal thermionic emission theory are attributed to the in homogeneities of the Schottky barrier which persist at metal/semiconductor interface. This behavior has been interpreted on the basis of standard thermionic emission theory and Gaussian distribution which yields mean barrier height of 1.05eV and standard deviation of 0.128eV. Furthermore the modified Richardson plot resulted in mean barrier height of 1.25eV and Richardson constant A^* of 138Acm^{-2}K^{-2}. Thus it can been concluded that the temperature dependence of forward I-V characteristics of n-type Cr/4H-SiC contacts can be effectively elucidated on the basis of TE theory with Gaussian distribution of the barrier height.

Keywords: - Schottky barrier diodes, Silicon Carbide, barrier inhomogeneities, temperature dependence, thermionic emission, Gaussian distribution.

I. INTRODUCTION

Silicon Carbide is an attractive material for high power and high temperature applications because of its remarkable electrical properties. In recent years a lot of advancement has been accomplished in SiC power semiconductor devices [1-5]. A significant work has been done in the development of SiC electronic devices specially Schottky contacts due to their technological importance. Although SiC Schottky diodes are now readily available in the market, yet studies related to their properties and applications is a topic of current research [6-15]. Many investigators have investigated/ examined the properties of SiC Schottky diodes on both 4H and 6H-SiC. But out of these two polytypes, 4H-SiC is getting more preference due to high electron mobility and more isotropic nature of many of its electrical properties [15].

Several studies relating to electrical transport in SiC Schottky contacts have been carried out during the last decades. Still current transport and temperature dependence of the SBH in SiC SBDs is a topic of interest. The I-V-T analysis of Schottky diodes using ideal TE theory reveals s anomalous behavior such as decrease in barrier height, increase in ideality factor with decreasing temperature. These deviations are generally interpreted by the presence of in-homogeneities at the interface which might be due to several physical reasons like inhomogeneity in doping concentration, high interface state density due to interface contamination, surface defects etc [16,17-18]. In literature mainly two approaches are proposed to explain experimental data and model the I-V-T characteristics of inhomogeneous Schottky barrier diodes. These are based on models proposed by Tung [17] and Werner and Gutler [18]. These two approaches have been successfully used for the interpretation of experimental results on various practical SiC Schottky diodes [6, 11, 12, 19, and 20].

For explaining deviations from ideality, Tung assumed in his model the presence of locally non-uniform regions or patches with relatively lower or higher barriers with respect to average barrier height. Whereas according to Werner's model, barrier height is supposed to be distributed according to Gaussian function which will usually lead to an apparent barrier height that is both temperature and bias dependent. In this paper forward I-V characteristics of Cr/ 4H-SiC SBD's have been analyzed on the basis of thermionic emission theory with Gaussian distribution of barrier heights to yield information pertinent to Schottky diode parameters and their dependence on temperature.

II. FABRICATION AND CHARACTERIZATION

The starting material used for the fabrication of Schottky diodes was n-type 4H-SiC (0001), 8^0 off Si face epiwafer purchased from Cree Inc. The substrate was n+-type with a donor concentration of 1×10^{18}cm-3 with lightly doped ($N_D=9\times10^{14}$ cm-3) n-type epi-layer having specific resistivity of 0.020Ωcm. Prior to metal deposition for making Schottky and ohmic contacts the samples were degreased in organic solvents like acetone, trichloroethylene and methanol successively. Immediately prior to placing the samples in a vacuum chamber, they were immersed in 10% HF for 20 s at room temperature followed by rinsing in DI water and blow drying. Then, Nickel back-side ohmic contact was deposited and annealed in N_2

atmosphere at 900°C for 10 min. Guard ring was realized by standard lithography processes. Schottky contact was formed using Cr on 4H–SiC epilayer was done by e-beam metallization process at a pressure ranging between1×10^{-6} to 1×10^{-7}Torr having thickness of 1500A^0. The contact metal had circular geometry with diameter of 1mm. Structure of the diode is shown in fig.1 The barrier height of each of the fabricated contacts was determined by(1) determining saturation current from measured current-voltage characteristics (I-V method).The I–V measurements of the diodes were performed on a probe station equipped with Keithley 236.

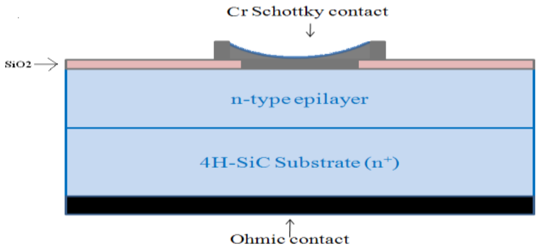

Fig. 1. Schematic crossection of metal/4H-SiC Schottky diodes.

III. RESULTS AND DISCUSSION

III.1 *I-V-T characteristics of Cr/4H-SiC Schottky diodes*

I-V-T analysis is used to identify different conduction mechanisms in current transport phenomenon taking place in Schottky diodes. If current is assumed to be due to thermionic emission then relation between applied voltage and current can be given as [20-21]

$$I = I_0 \exp(\frac{qV}{nkT})[1-\exp(\frac{-qV}{kT})] \qquad (1)$$

For V>3kT, $I = I_0 \exp(\frac{qV}{nkT})$

where T is the temperature in K, q is the electronic charge, k is the Boltzmann constant and I_0 is reverse saturation current which can be given as:

$$I_0 = AA^*T^2 \exp(\frac{-q\phi_b}{kT}) \qquad (2)$$

A is the effective diode area, A^* is effective Richardson constant which is 146Acm^{-2}K^{-2} for 4H-SiC [22] and ϕ_b is zero bias barrier height, n is the ideality factor which measures deviation of practical diodes from ideal thermionic emission theory. Fig. (2) shows forward I-V characteristics of Cr/4H-SiC SBD's measured in temperature range of 300-480K.

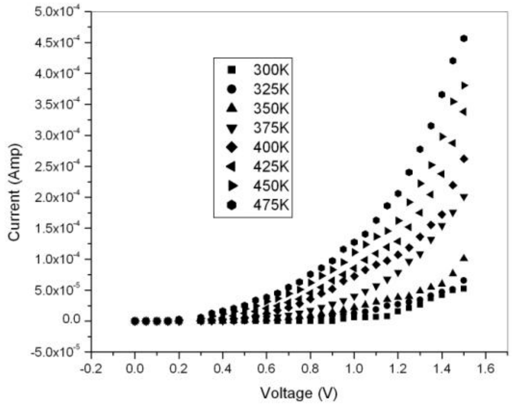

Fig. 2. Experimental forward I-V characteristics of Cr/4H-SiC SBD's measured at different temperatures.

Using these characteristics ideality factor and barrier height are calculated from equation (3).

Fig. (3) plots experimental values of ideality factor and barrier height as a function of temperature. This figure shows that barrier height decreases and ideality factor increases with the decreases in temperature.

$$\phi_b = \frac{kT}{q}\ln\left(\frac{AA^{*}T^{2}}{I}\right) \qquad (3)$$

Barrier height can also be calculated by using the Arrhenius or Richardson plot of the saturation current. Natural logarithm of equation (2) will yield:

$$\ln\left(\frac{I_0}{T^{2}}\right) = \ln(AA^{*}) - \frac{q\phi_b}{kT} \qquad (4)$$

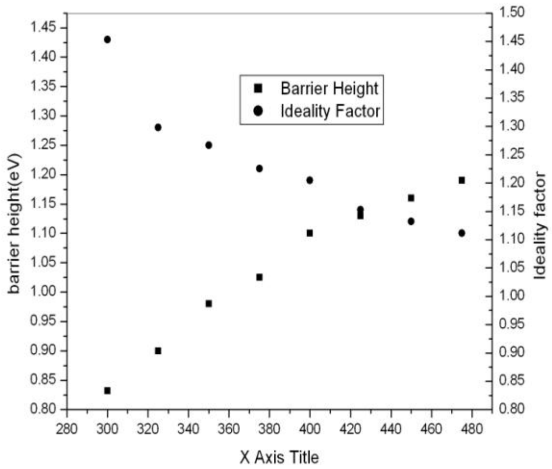

Fig. 3. SBH and ideality factor as a function of temperature.

Plot of $\ln(I_0/T^2)$ versus q/kT should give a straight line whose slope and intercept will give barrier height and Richardson constant respectively. Fig. (4) shows the conventional activation energy $\ln(I_0/T^2)$ versus 1000/T plot. It can be seen that curve strongly deviates from linearity. The discrepancies from classical thermionic emission theory observed in our Cr/4H-SiC Schottky diode such as increase in barrier height with the increase in temperature and non-linearity of activation energy plot can be cured by considering spatial inhomogeneity of SBH. The spatial inhomogeneity is generally illustrated by some distributed functions, among them Gaussian distribution is most successfully used to explain the non-ideal behavior of Schottky diodes.

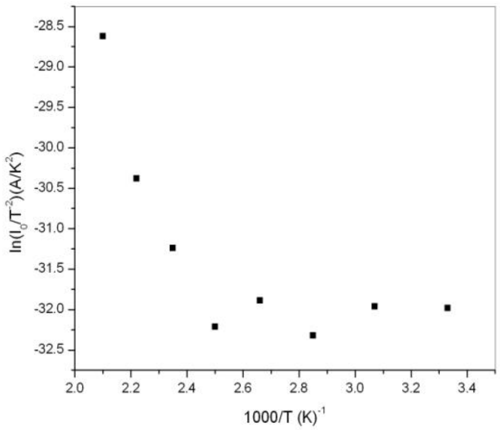

Fig. 4. Conventional activation energy plot of Cr/4H-SiC diode.

III.2 Gaussian distribution of barrier heights

To explain the anomalies observed in our Schottky diodes, we have considered inhomogeneous barriers, which consist of various patches of relatively higher or lower barrier height with respect to a mean barrier height. Now using this assumption, temperature dependence of barrier height can be attributed to inhomogeneous barrier height. Since current transport across the metal/semiconductor interface is a temperature activated process, so at low temperature electrons will be able to overcome only lower barriers and current transport mechanism will be dominated by flow of current through the patches of lower barrier height and having large value of ideality factor. In other words with the increase of temperature more electrons have sufficient energy to surmount the higher barriers. Therefore dominant barrier height will increase with the increase of temperature.

Here, barrier height inhomogeneity have been modeled with a spatial distribution of the band bending ϕ_b at m/s interface of Schottky contacts using Gaussian distribution $P(\phi_b)$ with a standard deviation δ_s and mean value of barrier height $\overline{\phi_b}$ which is expressed as:

$$P(\phi_b) = \frac{1}{\delta_s\sqrt{2\pi}}\exp[\frac{-(\phi_b-\overline{\phi_b})^2}{2\delta_s^2}] \qquad (5)$$

The total current across a Schottky diode containing barrier inhomogeneities can be written as:

$$I(V) = \int_{-\infty}^{+\infty} I(\phi_b,V)P(\phi_b)d\phi_b \qquad (6)$$

Where I (ϕ_b,V) is the amount of current for a barrier height of ϕ_b at a voltage V based on ideal thermionic theory and $P(\phi_b)$ is the normalized distribution function which gives the probability of occurrence of barrier height. Now using equs. (5) and (6) current of the Schottky diode with modified barrier will be:

$$I(V) = AA^*T^2\exp[(\frac{-q}{kT})(\overline{\phi_b}-\frac{q\delta_s^2}{2kT})]\times\exp(\frac{qV}{n_{ap}kT})[1-\exp(\frac{-qV}{kT})] \qquad (7)$$

Comparison of equation (1) and (7) gives expression for apparent barrier height as a function of temperature and mean barrier height which is given in equ. (8)

$$\phi_{ap} = \overline{\phi_b} - \frac{q\delta_s^2}{2kT} \qquad (8)$$

According to equ. (8) the plot of ϕ_{ap} versus q/2kT should be a straight line with intercept giving mean barrier height $\overline{\phi_b}$ and slope determining standard deviation δ_s. Using barrier height obtained from I-V measurements, ϕ_{ap} versus q/2kT plot has been plotted as shown in fig. (5). It is apparent that the data fit adequately with a straight line and intercept and slope of this linearly fitted straight line yield mean barrier height of 1.05eV and standard deviation of 0.128eV. As stated earlier that conventional energy plot of Cr/4H-SiC SBDs deviates from linearity. To explain this discrepancy equ. (4) can be rewritten and yield equ.(9).

$$\ln(\frac{I_0}{T^2})-(\frac{q^2\delta_s^2}{2k^2T^2})=\ln(AA^*)-\frac{q\overline{\phi_b}}{kT} \qquad (9)$$

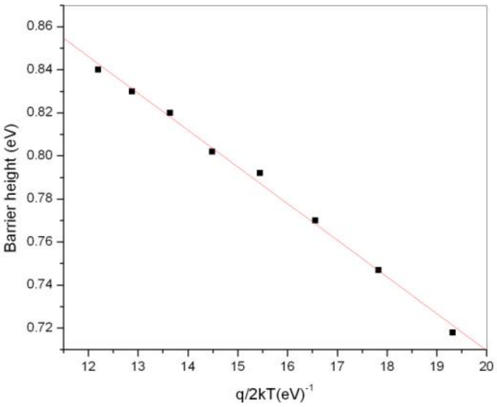

Fig. 5. ϕ_{ap} versus q/2kT plot.

Based on the equ. (9) the modified activation energy plot of $\ln(I_0/T^2)$-$q^2\delta_s{}^2/2kT$ versus q/kT has been plotted. This plot takes into account the deviations of the barrier height and must give a straight line whose slope and y-axis intercept yields mean barrier height and Richardson constant respectively. Fig. 6. Shows the modified activation plot which is reasonably linear and from the slope and intercept of fitted straight line barrier height and Richardson were found to be 1.25eV and 138 Acm^{-2}K^{-2}respectively and this value is in close agreement with the theoretical value of 146 Acm^{-2}K^{-2} for 4H-SiC.

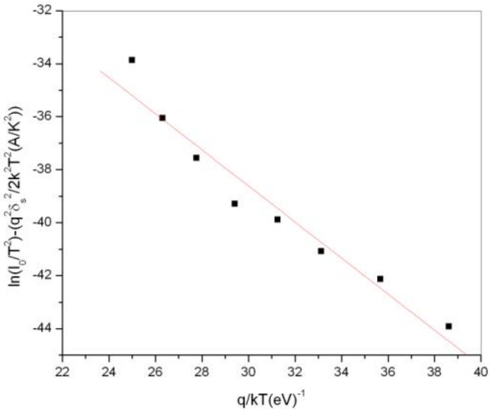

Fig. 6. Modified Richardson $\ln(I_0/T^2)$-($q^2\delta_s{}^2/2k^2T^2$)versus q/kT plot for Cr/4H-SiC Schottky diode.

IV. CONCLUSION

In this paper the I-V characteristics of n-type Cr/4H-SiC Schottky diodes were measured in the temperature range of 300-480K. The electrical parameters of the diode such as ideality factor and barrier height were found to be strongly temperature dependent. The departures from the classical thermionic emission theory were illustrated by assuming the presence of barrier inhomogeneities at m/s interface and modeling them with a Gaussian distribution. Using the ϕ_{ap} versus q/2kT plot, the mean value and standard deviation of the Gaussian distribution of barrier heights were determined to be 1.05eV and 0.128eV respectively. The activation energy plot was seen to deviate from linearity but the modified Richardson plot which considers the Gaussian distribution of the barrier heights fitted nicely with a straight line. The mean barrier height and the Richardson constant from the modified Richardson plot were found to be 1.25eV and 138 $Acm^{-2}K^{-2}$. The linearity of the modified activation energy plot and the nearness of the calculated Richardson constant to its theoretical value verify the success of the Gaussian distribution in explaining temperature dependence of I-V characteristics of Cr/4H-SiC Schottky diodes.

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