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Analysis on Capacitance-Voltage Characteristics of an Al/4H-SiC Schottky Diode

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Abstract – In this paper, an Al/4H-SiC Schottky junction structure has been fabricated by using of thermal method and the C-V measurements of this sample were characterized as a function of the temperature. From C-V data, the net ionized state density and the barrier height values have calculated and its barrier height values were determined to be 1.81 eV at 300 K and 1.93 eV at 8 K. In result, it was seen that C-V barrier height values have increased with the temperature. The effect of image force lowering mechanism which cause Schottky barrier inhomogeneities in Al/4H-SiC is investigated using C-V measurements. In addition, in Al/4H-SiC was observed that the image force-lowering values increase with decreasing temperature.

Keywords – 4H-SiC, Schottky Diodes, Schottky Barrier İnhomogeneities, Barrier Height, Image-Force Lowering

I. INTRODUCTION

So far, Schottky rectifies based on SiC have been the charming electronic devices of last decades and over their electrical transport properties have been realized a lot of works. However, the current transport characteristics of SiC is still as a topic. In the literature, it is determined frequently that the researches based on SiC Schottky rectifiers have majored on 4H-SiC [1-4] and 6H-SiC [5-7]. Moreover, 4H-SiC is more preferred rather than the 6H-SiC which is the other, due to the isotropic nature of many of its electrical properties together with which the electron mobility than the other [8].

Compared to that of traditional Si semiconductor structure, SiC has the superior advantages due to its electrical, chemical, thermal and mechanical properties and SiC is considered as a semiconductor material that will supply of silicon power technology into smart power. Resultantly, SiC material structure have received much special attention and have become a quickly developing semiconductor material. In today, the studies over electrical, optical properties and device applications of SiC keep increasing such as main work topics and in the electronic materials based on SiC Schottky diode become great and significant advances. In result, in the fabrication of electronic devices such as thyristors, metal-oxide-semiconductor field effect transistors (MOSFETS), pin diodes, insulated gate bipolar transistors (IGBTS), SiC are preferred sufficiently [1-4,8].

Despite some inert physical advantages of SiC such as a wide band gap, high thermal conductivity, high electron saturation drift velocity, large breakdown electric field; SiC has a low crystal quality comparatively with silicon in industrial applications. In addition, the doping inhomogeneities, dopant clustering contaminations, defects, dislocations, comets, micropipes and inclusions of different polytypes in the epitaxial layers existing in SiC and/or even in the other some semiconductors are responsible for Schottky barrier inhomogeneities and these effects affect device performance [9,10]. Besides, Schottky barrier anomalities can influence Schottky barrier height value of I-V measurements due to poor Schottky interface quality of diode in barrier. In result, the value of C-V barrier height is to be more than the value deduced from I-V data. This discrepancy has been attributed to the existence of Schottky barrier anomalities and due to the quality of the metal/semiconductor interface, the electrical behaviors of a SiC Schottky contact are strongly influenced.

In this study is carried out an analysis over C-V-T measurements of an Al/4H-SiC Schottky diode fabricated. Moreover, this paper relates to the behavior of the interface states in Al/4H-SiC and is analyzed the behaviors of the image force lowering effects from the causations of the Schottky barrier inhomogeneities in this sample.

II. MATERIALS AND METHOD

The n-type 4H-SiC bulk wafer material used for Schottky diodes in this study was purchased from commercially available Cree Research Inc. The wafer is one side polished, heavily doped with $Nd=5x10^{18}$ cm^{-3} concentration value and it has <0001> crystalline orientation. Due to mechanical polish using diamond paste with decreasing grit sizes, the surface and subsurface of SiC damage and it results in a specular surface on the macroscopic scale [11]. Thus, to reconstruct atomically flat 4H-SiC surface due to the mechanical polish process was subjected to wet KOH etching after annealing at 1100 ^{0}C in 30 min under Ar:%10H_2 gas flow.

Prior the metallization deposition procedure to sample, 4H-SiC wafers was exposed to well known a Si cleaning process named as RCA cleaning method (10 min boiling in $NH_3+H_2O_2+6H_2O$ following to $HCI+H_2O_2+6H_2O$ for boiling 10 min at 60 ^{0}C) to remove the organic and inorganic dirtinesses from over its sample surface. The metallization for ohmic contact on back of 4H-SiC sample was made by thermal evaporation of Ni at $8x10^{-8}$ Torr base pressure following the annealing process at 950 ^{0}C temperature for 10 min under a N_2 gas flow. Schottky metallization operation onto the other surface of the sample was performed by thermal evaporation of Au at $2x10^{-8}$ Torr base pressure using a molybdenum shadow mask having circular dots with 0.5 mm diameter.

C-V-T measurements of the 4H-SiC diodes were made using a closed cycle He cryostat with 10 K temperature steps at 10-300 K temperature range and in 8 K additionally. While the temperature was stabilized in 50 mK with a LakeShore 330 temperature controller, the voltage to sample was applied with 10 mV voltage steps which vary from -1.5 V to 0.5 V driven from a Keithley 6514 electrometer. In result, the capacitance was measured from a Boonton 72B capacitance meter under 1 MHz constant frequency using an automated measurement system [12].

III. RESULTS AND DİSCUSSİONS

The depletion layer capacitance of a Schottky junction for the ideal cases varies with the voltage as [13],

$$C^{-2} = \frac{2(V_0 + V)}{q\varepsilon_s A^2 (N_d - N_a)} \tag{1}$$

where A is the area of the diode, q is the electron charge, ε_s is the dielectric constant of semiconductor which is 9.7 for 4H-SiC, V is the magnitude of bias which apply to the diode, V_0 is the diffusion potential at zero bias obtained from the extrapolation to voltage axis of a linear C^{-2}-V variation, $N_d - N_a$ is the net ionized state density for a n-type 4H-SiC.

The C-V measurements dependent to the temperature were performed to observe the behaviors of depletion layer and the other C-V characteristics such as the Schottky barrier height

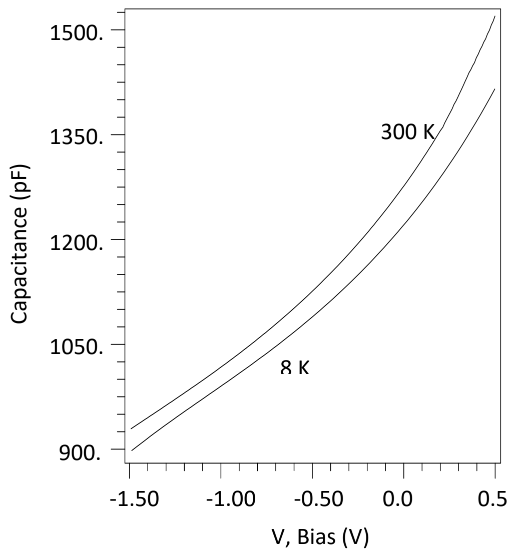

Figure 1. C-V curves measured in 300 K and in 8 K of Au/4H-SiC.

and carrier concentration with the temperature in Au/4H-SiC. Fig. 1 shows C-V measurements from 0.5 V to -1.5 V in 300 K and in 8 K of Au/4H-SiC.

In Fig. 1, the capacitance values are high for two measurement temperature. It implies that our sample may have high doping concentration.

The interface states in the C-V measurements of Schottky diodes can follow ac. signal and they may cause the excess capacitance at sufficiently low frequencies. However, when high frequencies such as 1 MHz can be carried out to Schottky devices, the interface states can follow negligibly small ac. signal. Fonash [14], the slope of C^{-2}-V for high frequencies have determined as,

$$\frac{dC^{-2}}{dV} = -\frac{2}{q\varepsilon_s A^2 (N_d - N_a)} \tag{2}$$

In Schottky junctions, it is reported that electrically active traps in depletion layer cause the excess capacitance. In examples of 6H-SiC and 4H-SiC were expressed that the deep trap levels from their DLTS measurements are active at different temperatures [15]. In some diodes where the deep trap levels are very active, it was seen that $N_d - N_a$ net ionized state density values and C-V or C^{-2}-V measurements freeze out quickly. However, due to the resolute behaviors relatively with temperature of $N_d - N_a$ values in Table I and characteristic linear variations of C^{-2}-V-T; it may be noted that the deep levels is not very active in our Au/4H-SiC diode.

Table I. N_d-N_a net ionized state density and V_0 diffusion potential values dependent to the temperature calculated using Eq. (2).

T (K)	N_d-N_a (10^{19} cm^{-3})	Vo (eV)	T (K)	N_d-N_a (10^{19} cm^{-3})	Vo (eV)
300	1.078	1.760	140	1.085	1.872
290	1.081	1.763	130	1.085	1.879
280	1.086	1.775	120	1.088	1.885
270	1.086	1.782	110	1.089	1.890
260	1.083	1.790	100	1.087	1.897
250	1.081	1.798	90	1.084	1.902
240	1.081	1.804	80	1.083	1.902
230	1.081	1.812	70	1.083	1.912
220	1.082	1.819	60	1.087	1.911

The ϕ_b barrier height values from C-V measurements by neglecting the image-force lowering effect can be determined by equation written as,

$$\phi_b = V_0 + \frac{kT}{q} + V_n \tag{3}$$

where V_n is the energy level difference between the minimum edge of the conduction band and the Fermi level in the neutral region of a n-type semiconductor expressed by equation $V_n = (kT/q)\ln(N_c/N_d - N_a)$. N_c in V_n eqution is known as the electron density or effective density of states in the conduction band of a n-type 4H-SiC determined by $N_c = 2(2\pi m_e^* kT/h^2)^{3/2}$ where m_e^* is the effective mass of the electrons.

The ϕ_b barrier height values which neglects the image-force lowering effect for Au/n-type 4H-SiC may be deduced using Eq. (3) by knowing the N_c and $N_d - N_a$ concentration values from its C-V measurements and it was calculated to be 1.81 eV at 300 K and 1.93 eV at 8 K. In the literature, ϕ_b value from C-V data was reported to be 1.7 eV at 300 K [16] for Au/4H-SiC and in result, it may be noted that the ϕ_b barrier height value calculated in 300 K in this research are some high from its literature value. This result is a state which may take place for C-V measurements owing to the behavior of barrier and depletion layer. In addition, due to the temperature dependence of energy band gap of 4H-SiC has not been published yet; it is reported that energy band gap equation expressed in Eq. (7) of 6H-SiC may be used instead.

$$E_g(T) = 3.19 - 3.3x10^{-4}(T - 300) \tag{4}$$

In the literature is reported generally that the barrier height values of C-V-T measurements are higher from I-V-T barrier heights [17,18]. This difference originates from natural structure of the barrier and separate measurement techniques of I-V and C-V. Song et al. [19] noted that the differences between I-V and C-V Schottky barrier heights arise from barrier anomalies in the interface oxide layer composition, non-uniformity of the interfacial layer thickness and distributions of interfacial charges. In C-V measurements, the edge of the depletion region is only modulated and is not sensitive to potential fluctuations of the junction. In addition, ϕ_b barrier height values of I-V-T measurements are restricted effectively with the temperature owing to the interface structure. The most of currents at lower temperatures flows with the low barrier regions to be reversely in high temperatures. In result, barrier height of I-V-T measurements are very lower from barrier height of C-V-T measurements.

The ϕ_b barrier height in Eq. (3) due to the image force lowering effect can be rewritten by,

$$\phi_b = V_0 + \frac{kT}{q} + V_n - (\Delta\phi_b)_{img.} . \quad (5)$$

The image force lowering is the other one of the barrier height differences in I-V and C-V measurements and from causations of the barrier anomalies additionally to the tunneling currents in Schottky barrier. $(\Delta\phi_b)_{img.}$ barrier reduction in barrier height due to the image-force lowering effect is calculated from

$$(\Delta\phi_b)_{img.} = \left(\frac{q^3(N_d - N_a)}{8\pi^2\varepsilon^3}\right)\left(\phi_b - V - \frac{kT}{q} - V_n\right)^{1/4} . \quad (6)$$

$(\Delta\phi_b)_{img.}$ reduction at V=0 was calculated to be 198 meV in 300 K and to be 204 meV in 8 K using Eq. (10).

IV. CONCLUSION

In this study were discussed C-V-T properties of a n-type Al/4H-SiC Schottky contact in low temperatures such as 8-300 K temperature range. It was determined that the Al/4H-SiC has a high doping concentration from its resolute C^{-2}-V_r-T variations. The image-force lowering effect from causations of Schottky barrier anomalies existing in nature of barrier were investigated using C-V data. It was seen that the field emission have been dominated for lower temperatures and 170 K, thermoionic-field emission in nearly 180-220 K temperature range, thermoionic emission in 230-300 K temperature range in Al/4H-SiC. The image force lowering effect increasing with field emission and thermoionic-field emission demonstrate that Schottky barrier anomalies in low temperatures are effective in Al/4H-SiC.

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