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On analysis of current-voltage characteristics in an inhomogeneous Al/4H-SiC junction structure

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Abstract – In this paper, the current-voltage (I-V) measurements of an Al/4H-SiC Schottky device are characterized as a function of the temperature in 60-300 K temperature range. The series resistance values are calculated to be 12.5 Ω at 300 K from Cheung functions. The experimental parameters such as the ideality factor and apparent barrier height show resolute temperature dependent. These inhomogeneous characteristics observed for Al/4H-SiC are related to Schottky barrier anomalities. Thus, it may be commented that the temperature dependent electrical characteristics of an Al/4H-SiC Schottky sample can be characterized on the basis of the thermionic emission theory.

Keywords - 4H-Sic, Schottky Diodes, Schottky Barrier Inhomogeneities, Ideality Factor, Barrier Height

I. INTRODUCTION

The interface layer between the metal and semiconductor affects the stability, reliability and performance of the diode. The composition, quality and non-stoichiometric structure of the interface and the position of electrical charges in the interface are known as interface states. The interface states cause Schottky barrier anomalies in barrier and influence the other all barrier parameters such as ideality factor and barrier height.

A contact structure which does not have an interface with an abrupt junction has ideal conditions and its current mechanism is governed by thermionic emission. Under these conditions, it is expected that ideality factor is 1 and the barrier height is constant. However, the current transport mechanism under non-ideal conditions cannot be described by the thermionic emission theory. The measured I-V curves demonstrate that there are excess currents, which arise from some current transport mechanisms such as thermionic-field emission and field emission as well as thermionic emission current in the barrier [1-9]. These current transport mechanisms can flow through the junction and depend on characteristic parameters such as the temperature of the device, the concentration of dopants, the applied bias, the properties of barrier and interface. As a consequence of these effects, ideality factor deviates from one and the barrier height is not constant over a broad temperature [1,2,7-18].

The effects of the non-homogeneous dielectric interface layer are introduced generally within ideality factor. The reason that is bigger than 1 is attributed to factors such as generation-recombination currents in the depletion region [1], tunnelling currents in highly doped semiconductors

[1], interface states at a thin layer between the metal and semiconductor [19-21], image-force lowering of the Schottky barrier in an electric field at the interface [5].

SiC belongs to IV-IV group in the periodic table and it is an indirect wide band-gap semiconductor material. Due to some useful capabilities existing potentially of the electronic devices based on SiC such as high electron saturation drift velocity, a high thermal conductivity, a wide band-gap of 2.9 eV and large breakdown electric field, these devices have special importance technologically [22-24]. In addition, due to these excellent structural capabilities of SiC such as the large Si-C bonding energy, resistant to chemical attacks and radiation effects and its stability at high temperatures, it has been an attractive material for high power-high voltage switching applications, high power microwave applications, high radiation environments, high temperature electronics, high corrosion and high frequencies device applications [25-27].

In recently, the materials based on SiC Schottky rectifiers have been the charming electronic devices and they have been carried out a lot of works over their electrical transport properties. Moreover, in the literature, it is seen frequently that the researches connected with SiC Schottky rectifiers have concentrated on 4H-SiC [28-33] by comparison the other SiC based materials such as 6H-SiC.

So far, in the literature, it is seen that the separate metals such as tungsten (W) [34], titanium (Ti) [35-39], nickel (Ni) [35,37,40,41], molybdenum (Mo) [42,43] the have been used to fabricate Schottky contacts with 4H-SiC. As our knowledge, Al as a refractory metal on 4H-SiC was carried out in limited number [44,45]. In this study was carried out an analysis over I-V-T measurements of an Au/4H-SiC Schottky diode fabricated. Moreover, this paper relates to the behavior of the interface states in Au/4H-SiC and is analyzed the behaviors of the Schottky barrier inhomogeneities in this sample.

Experimental Details

In this study, the n-type 4H-SiC bulk wafer material which is one-side polished used for Schottky diodes was purchased from commercially available Cree Research Inc. This wafer has <0001> crystalline orientation with carrier concentration of $1.0x10^{17}$ cm^{-3}. It may get damaged due to mechanical polishing with diamond paste in decreasing grid sizes, the surface and subsurface of SiC and this result may cause in a specular surface on the macroscopic scale [46]. Thus, after annealing at 1100 ^{0}C in 30 min under Ar:%10H_2 gas flow, its surface in order to reconstruct atomically flat 4H-SiC was subjected to wet KOH etching.

Before the metallization deposition procedure, 4H-SiC wafers to remove the organic and inorganic contamination from the sample surface were exposed to classical Si cleaning process well known as RCA1 and RCA2. The ohmic contact operation on back of 4H-SiC sample was realized by thermal evaporation of Ni at $8x10^{-8}$ Torr base pressure, and afterwards it was exposed to the annealing process at 950 ^{0}C temperature for 10 min under a N_2 gas flow. Schottky metallization process onto the other surface of the sample was made by thermal evaporation operation of Al at $2x10^{-8}$ Torr base pressure. The current-voltage (I-V) measurements against the temperature for the 4H-SiC diodes were performed using a closed cycle He cryostat with 10 K temperature steps at 60-300 K temperature range stabilized in 50 mK with a LakeShore 330 temperature controller for measurements. The voltage for measurements was applied to sample with 5 mV steps driven from a Keithley 2400, and in result, the current was measured from a Keithley 6514 electrometer.

II. Materials and Method

According to the thermionic emission theory, the relation between the applied bias and thermionic emission current for is given as follows [47],

$$I = Io[exp(q(V - IRs)/nkT)] \quad (1.a)$$

with

$$Io = AA * Texp(-q\phi/kT) \quad (1.b)$$

where T is the absolute temperature, k is the Boltzmann constant, q is the electronic charge, V is the applied voltage, n is the ideality factor, Rs is the series resistance, ϕ is the apparent barrier height, A is the diode area and A* is the Richardson constant.

Figure 1 presents the forward bias I-V characteristics of the Au/4H-SiC Schottky sample and it is seen that the measurements depend on the temperature with 30 K temperature steps over the 60-300 K temperature range and between 0 V and 1.5 V voltage values. In Fig. 1, it may be expressed that I-V characteristics of Al/4H-SiC have high rectification ratio and large thermionic emission region for all temperatures.

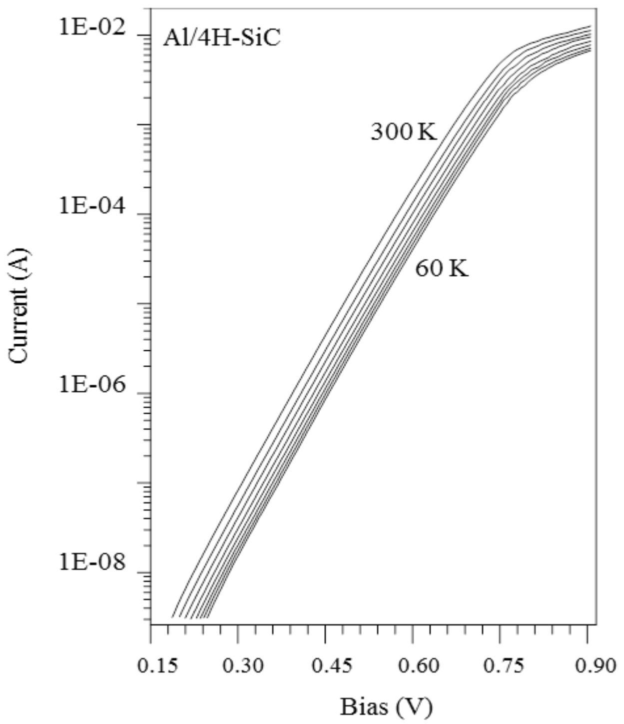

Figure 1. Semi-logarithmic forward bias current-voltage characteristics of an Al/4H-SiC Schottky barrier diode. Temperature step is 30 K. A temperature stability less than 50 mK is provided for all measurements.

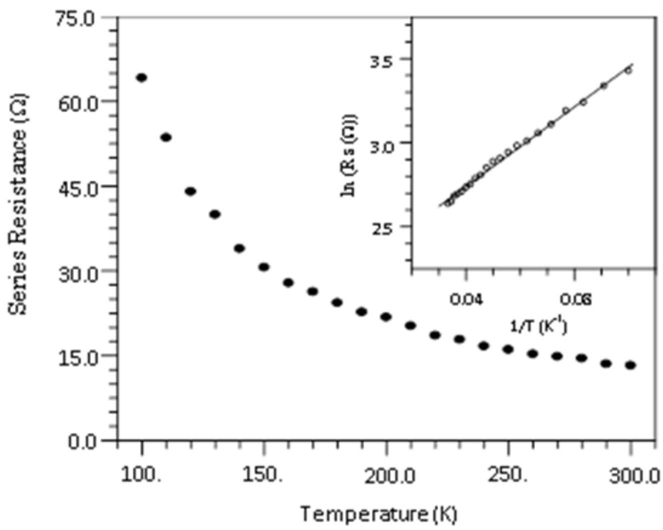

Figure 2. The series resistance values calculated for 100-300 K temperature range from Cheung functions of Au/4H-SiC. In the inset, the plot of $\ln(R_s)$ versus 1/T for this sample is presented.

The series resistance effect in Schottky diodes always exists and it gets effective with increasing forward bias. In addition, it has an effect which limits the current. Cheung functions [48] in order to calculate the series resistance values of Schottky diodes, are preferred frequently in the literature. The variation versus temperature of series resistance values of Al/4H-SiC are presented in Figure 2 and they increase from 12.5 Ω to 65.3 Ω with the temperature which goes from 300 K to 100 K. Moreover, in the inset of this figure is presented the $\ln(R_S)$ versus 1/T plot. It is expressed that the variation with temperature of the series resistance is due to the lack of free carrier concentration at low temperatures and the increase in ideality factor [14].

The bulk resistance in semiconductors is related to by the following equation [49],

$$1/Rs \propto \sigma = Cexp(-Ea/kT) \quad (2)$$

where Ea is the activation energy and C is a constant. Al/4H-SiC has an activation energy value of Ea:23.15 meV, calculated using Eq. (2) from the inset of Fig. 2.

From Eq. (1.a) for forward bias I-V curves, the ideality factor and apparent barrier height values may be written through the Eqs. (3.a) and (3.b)

$$n = q/kT \;\; dV/(d(lnI)) \quad (3.a)$$

$$\phi = -kT/q \; ln(Io/(AA*T2)) \quad (3.b)$$

The values of n and ϕ, from Eqs. (3.a) and (3.b) were calculated as 1.28 and 0.99 eV at 300 K and as 1.75 and 0.87 eV at 150 K, respectively. Fig. 3 and Fig. 4 show the plots of ϕ and n values versus temperature in 100-300 K temperature range. ϕvalues decrease while n increases swiftly with the temperature. On the other hand, in the literature, the relation with temperature of energy band gap of 4H-SiC, it is given as [50].

$$Eg = 3.19 - 3.3x10\text{-}4(T\text{-}300) \quad (4)$$

The values of Eg is depicted addition to ϕ values at 100-300 K temperature range in Fig.3 for Al/4H-SiC sample. In an ideal Schottky contact, the barrier height should increase essentially with temperature due to variation of band gap [46]. In the literature, these anomalities observed for the values of ϕ in Fig.3 and n in Fig. 4 are related to Schottky barrier inhomegeneities [7-18].

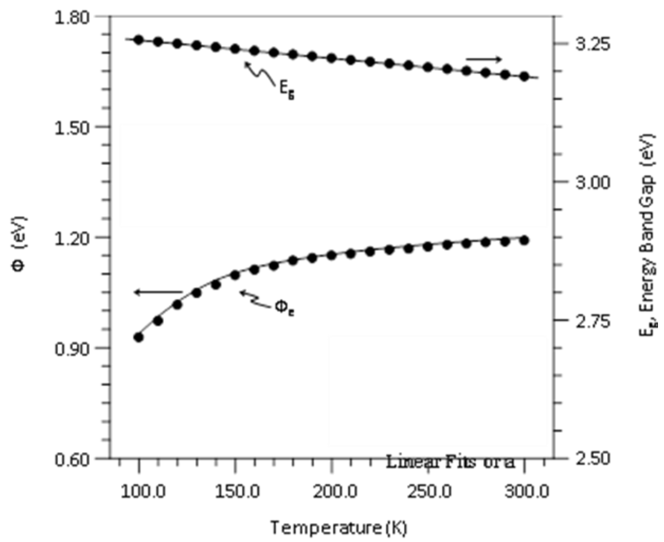

Figure 3. Temperature dependence of ϕ_e and E_g energy band gap values calculated for temperature range of 100-300 K from I-V data,

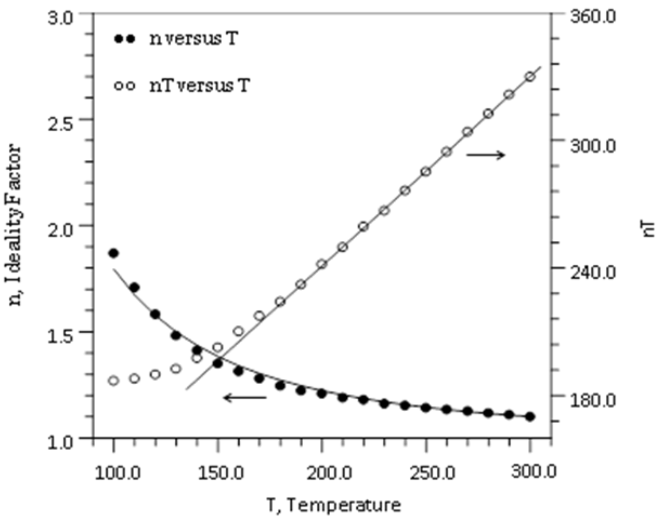

Figure 4. The plots of n versus T and nT versus T in 100-300 K temperature range. In addition, a discrete linear fit is carried out for the variation of nT versus T.

Furthermore, the plot of nT versus n is the one from possibilities determining the current transportation mechanism in a Schottky sample. According to this consideration, the relationship with temperature of nT is expressed as,

$$nT = noT + To \tag{5}$$

From Eq. (5), the phenomenon which explains this relation is generally known as To effect. According to the plot of nT versus T, in case of the slope of this plot should have a value which is no=1, the conduction mechanism of diode is through the thermionic emission. But, when no is not close to 1, it may be explained that the conduction mechanism is through of the thermionic-field emission or field emission. From Fig. 4, no and To values were calculated as no:0.94 and To:41.68 K, respectively. In addition, the nT values for a wide temperature range in Fig. 4 are the linear and it deviates in low temperatures.

As seen in Figs. 3 and 4, at low temperatures, a resolute decrease in the apparent barrier height and increase in the ideality factor are related to the causations such as interfacial reactions, anomality thickness and composition of the interface layer, abnormality of interfacial charges, interface roughness, inhomogeneous doping, structural defects in the semiconductor, diffusion or interdiffusion of the metal contaminations applied on semiconductor substrate and existence of a thin insulating oxide layer in the junction [10,11]. In the literature, even in the most carefully processed samples, it is expressed that the fluctuations in barrier heights are unavoidable [51].

III. CONCLUSION

The current transport properties of an Al/4H-SiC Schottky sample have been characterized by means of I-V measurements in 60-300 K temperature range. The series resistance values were calculated to be 12.5 Ω at 300 K to be 65.3 Ω at 100 K by using Cheung functions. It was seen that the barrier height values decrease and ideality factor values increase as a function of temperature. These abnormalities calculated for the ideality factor and barrier height of I-V data were attributed to Schottky barrier anomalities existing in its barrier structure. The value of To as a result of the curve of experimental nT versus T was obtained to be To:41,68 K.

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