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Electrical measurements of n-type 4H- silicon carbide metal contacts

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ABSTRACT

Silicon Carbide (SiC) is an attractive wide bandgap semiconductor for high temperature, high power or high frequency applications. In this work , we study metal contacts on single crystal silicon carbide(Polytype 4H SiC). The polytype 4H SiC exhibits high electron mobility and low mobility anisotropy compared to other SiC polytypes. Contacts are prepared by evaporating metals of different work functions on n type 4H SiC. The electrical characteristics of the junctions obtained are determined as a function of temperature. Analysis of the current-voltage characteristics gives information on the nature of the contact (Ohmic type or Schottky barrier rectifying type), capacitance-voltage measurements gives information about the barrier height, doping concentration as well as the distribution of shallow and deep levels near the surface of the contact.

Key words: Experimental results in semiconductor physics, SiC-metal contact, Wide bandgap semiconductor, Barrier height.

INTRODUCTION

Silicon carbide

Silicon Carbide (SiC) has been known for many years as an attractive semiconductor for electronic devices operating at high temperature[1,2], high power or high frequency[3]. This is due to its unique physical and electronic properties. SiC is a wide bandgap semiconductor with high breakdown electric field, good coefficient of thermal conductivity and high saturated carrier drift velocity. The main obstacle to the development of SiC was the lack of a reproducible process for growing semiconductor quality crystal[4]. Two growth processes have been adopted. The first, in 1983, was a method for obtaining large-area 3C SiC film by heteroepitaxial growth of silicon carbide on silicon by chemical vapor deposition[5]. The second, in 1987, was by the modified sublimation process for SiC crystal growth[6]. This later growth method made silicon carbide wafers commercially available. The commercial availability of single crystal wafers in the early 1990s from CREE Research[7] initiated a significant growth in device research, with strong activities in Europe, Japan and United States.Many different "polytypes" of crystalline silicon carbide (SiC) are known. These polytypes of SiC differ from one another only in the stacking sequence of double layers of silicon and carbon atoms[8]. Each double layer consists of a plane of closed-packed silicon atoms over a plane of closed-packed carbon atoms; one silicon atom lies directly over each carbon atom in a double layer. Each successive double layer is stacked on the previous double layer in a closed packed arrangement that allows for only three possible relative positions for the double layers. These positions are normally labeled A, B and C. Depending on the stacking sequence, various crystalline structures (i.e. cubic, hexagonal or rhombohedral) are produced. The stacking direction is the c-axis in the hexagonal frame of reference .The more common SiC polytypes are listed in Table1. Several ways of designating the various structures are shown in this Table[8]. The most common is the Ramsdell notation which is a number followed by a letter. The number is the number of the double layers in stacking repeat sequence and the letter designates the structure. The hexagonal and rhombohedral polytypes are collectively referred to as á-SiC while the cubic polytype 3C is referred to as â-SiC. Polytypes of practical importance are 3C SiC, the only cubic polytype, and the hexagonal polytypes 6H SiC and 4H SiC.

The physical properties of these polytypes and properties of silicon important for electron device operation have been reported in references[9-12].Many devices have been demonstrated in Sic, from simple Schottky barrier rectifiers [13-18] to high voltage, high current p-n junction diodes[19, 20], and to complex structures as pnpn- based bipolar power devices[21, 22]. The recently demonstrated reliable high current density switching ability of high density, The recently demonstrated reliable high current density switching ability of high density,high voltage gate turn-off thyristors shows that SiC pnpn-based bipolar power devices are very attractive for high temperature and high power switching applications[22].

Table 1. Selected SiC polytypes

	Ramsdell Notation	Stacking Sequence
Cubic or	3C	ABCABC…
beta Alpha	2H	AB/AB/…
	4H	ABAC/ABAC/…
	6H	ABCACB/A BCACB/…

Metal semiconductor contacts

The first practical semiconductor device was the metal-semiconductor diode. Recently , modern semiconductor and vacuum technology has been employed to fabricate reproducible metal-semiconductor contacts so that it is now possible to obtain both rectifying and nonrectifying metal-semiconductor junctions.

Fig.1. shows the energy-band diagram incorporating the Schottky effect for a metal on n-type semiconductor for a forward biased junction (the applied voltage V from the metal to the semiconductor is greater than zero). The built-in potential V_{bi} (V_b at V=0) for the n-type semiconductor is given by

$$V_{bi} = \varphi_{bn} - V_n \quad ....(1)$$

where ϕ_{bn} is the barrier height of a real metal-semiconductor contact and V_n is the potential difference between the Fermi level and the bottom of the conduction band can be deduced from the doping concentration[30].

$$V_n = \frac{kT}{q} \ln \frac{N_C}{N_D} \quad ...(2)$$

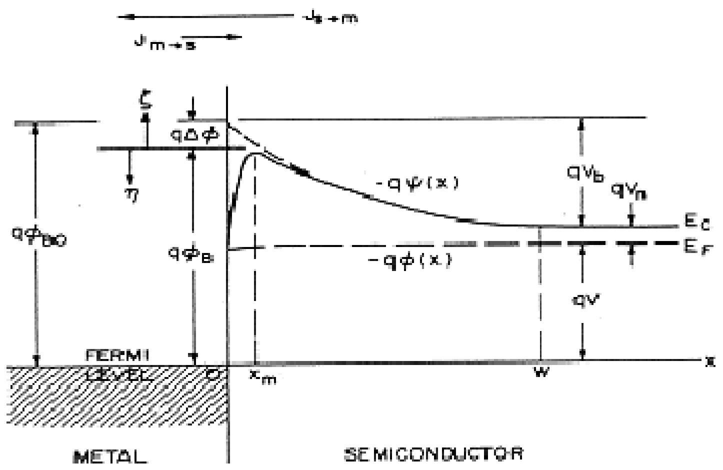

Fig. 1: Energy band diagram incorporating Schottky barrier lowering

where N_D is the doping concentration and N_C is the effective density of states in the conduction band. Similar results can be given for p-type semiconductors. In the following discussion, we concentrate on n-type semiconductors. Under the abrupt and depletion approximations the $r=qN_D$ for $x<W$, where W is the depletion width, the results for the metal-semiconductor barrier is similar to those of the one sided abrupt p^+-n junction and we obtain.

$$W = \sqrt{\frac{2\varepsilon_s}{qN_D}\left(V_{bi} - V - \frac{kT}{q}\right)} \quad ...(3)$$

The junction capacitance C can be obtained from the charge Q stored in the space charge region,

$$Q = qWAN_D \quad ...(4)$$

$$C = \frac{\partial Q}{\partial V} \quad ...(5)$$

where A is the junction area. Combining (3), (4) and (5) we get

$$C = \frac{\varepsilon_S A}{W} \quad ...(6)$$

Taking into account the voltage dependence of W, (6) can be arranged as

$$\frac{1}{C^2} = \frac{2}{q\varepsilon_s N_D A^2}\left(V_{bi} - V - \frac{kT}{q}\right) \quad ...(7)$$

or

$$-\frac{d(1/C^2)}{dV} = \frac{2}{q\varepsilon_s N_D A^2} \quad ...(8)$$

IF N_D is constant throughout the depletion region, one should obtain a straight line by plotting $1/C^2$ versus V. If V is not a constant, the differential capacitance method can be used to determine the doping profile from (8)[30].

The current transport in metal-semiconductor contacts is mainly due to majority carriers.

The current-voltage characteristics of a Schottky barrier rectifier is usually expressed by

$$I = I_S\left[\exp\left(\frac{qV}{nkT} - 1\right)\right] \quad ...(9)$$

with

$$I_S = AR^*T^2 \exp\left[\left(-\frac{q\varphi_B}{kT}\right)\right] \quad ...(10)$$

where R* is the Richardson constant. The ideality factor n in (9) is equal to unity when thermionic emission over the barrier dominates other transport mechanisms. Referring to Fig. 1, due to image-force induced lowering of the potential energy for charge carrier emission when an electric field is applied the barrier height is lowered by

$$\Delta\phi = \sqrt{\frac{qE_{max}}{4\pi\varepsilon_S}} \quad ...(11)$$

According to (10) and (11) $\ln I_s$ varies linearly with $E_{max}^{1/2}$ or with $V^{1/2}$, V being the reverse voltage, as a result of Schottky barrier lowering.

Contact fabrication

Silicon carbide requires special cleaning method. We followed a Huang clean method[14] consisting of 10-min. dip in $NH_4OH:H_2O_2:H_2O$:1:1:5 followed by 10-min. dip in $HCl:H_2O_2:H_2O$:1:1:5 solution at 70°C.

Metal evaporation was carried out at a pressure of 10^{-5} torr. The purity of the evaporated metal was about 99.99%. Contact pattern definition is performed using a suitable mask containing circular holes of diameters 1 and 1.7 mm.The back contact was made by evaporating silver on the whole

Table 2. Summaries the obtained results

n -type 4H SiC	
Wafer Thickness (μm)	372
Resistivity ρ (Ω.cm)	0.093
Mobility (cm^2/V.s)	680
Doping concentration (cm^{-3})	9.8×10^{16}
$V_{n,p}$ (eV) (Refer to Figure. 1)	0.15
Built-in voltageV_{bi} Au contact(V)	1.8
Barrier height of Au contact (eV)	1.95

back surface of the wafer to provide a more effective contact.

The vacuum system is an Edward 306. The temperature required for evaporation is produced by resistive heating. The source material is supported by a molybdenum boat,which has a high melting point(2617 °C).A substrate holder is also installed about 20-cm from the evaporating boat.A built-in shutter is also used to control the deposition of metal onto the silicon carbide wafer.

Equipment to test the fabricated schottky rectifier

Ohmic contacts are made to SiC by evaporating silver film on the back surface of the wafer.For measuring small currents, a good electrical contact in every part in the circuit is an important issue. The current noise from the outside environment must also be minimized.

A design of our homemade probe is shown in Fig. 2, where the connection force is provided by a flexible spring. In an early version of this design, the whole device was made from copper. After using the probe several times at high temperature, the copper needle movement through its guiding hole became difficult. In this case, it was not easy to release the sample under the needle tip resulting in serious damage to the whole sample. This problem has been solved by replacing the upper part of the probe by another made from Teflon as shown in Fig. 2.

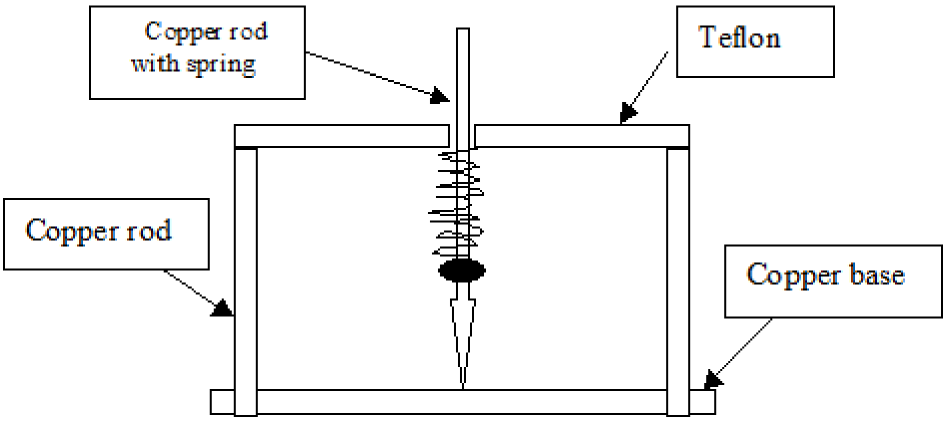

Fig. 2: Schematic illustration of the measuring probe

Capacitance-voltage measurements

Depletion layer capacitance measurements give information about fixed impurity and defect centers in the semiconductor as well as the metal to semiconductor barrier height. All C-V measurements were performed at room temperature for reverse bias in the range 0-10 V using the Fluke PM6306 programmable automatic RLC meter. The capacitance C is then plotted as $1/C^2$ versus voltage. From the C-V measurements the doping concentration and the built-in potential V_{bi} can be obtained. Knowing the doping concentration, the difference in the energy between the bottom of the conduction band in an n-type material and the Fermi level qV_n (or qV_p) can be determined, from which the value of the barrier height can be obtained.

The C-V characteristics in the reverse bias are found to follow the depletion layer capacitance theory for Schottky barriers as outlined in Section 3 as shown in Fig. 3 .From this Figure it is clear that the plots of $1/C^2$, the effect of deep donors was observed in 4H n-type sample since deviation from linearity of $1/C^2$ versus V was found for a reverse voltage higher than 7 V.

Current-voltage characteristics

I-V measurements were performed at

different temperatures ranging between 290-500K for both forward and reverse bias. I-V measurements were carried out using Programmable *hp* 4140B pico Amber METER and DC Voltage Source. Measurements were done under vacuum in a Heraeus furnace type VT 5042 EKP. The I-V measurements as a function of temperature give insight on the effect of the oxide layer, the Schottky barrier lowering effect, the non-ideal back contact effect, and surface states for both the forward and reverse characteristics.

Fig.4 report typical I-V characteristics at different temperatures. Rectification is clear for Au contacts to 4H SiC. With increasing temperature the turn on voltage tends to decrease slightly. It should be noted that the non ideal back contact results in a greater turn on voltage. This is due to the fact that

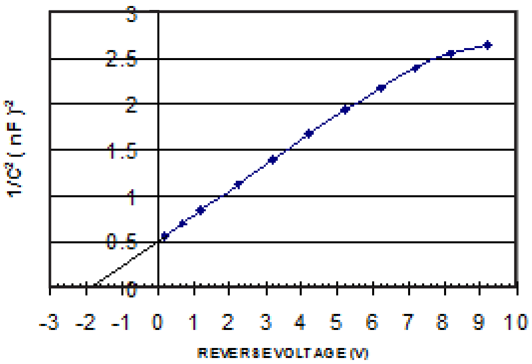

Fig. 3: The reciprocal of the square of the capacitance versus the reverse bias for n-4H SiC-Au contact. Diode diameter = 1 mm. The built-in voltage V_{bi} is found from the intercept with the voltage axis to be about 1.8 V

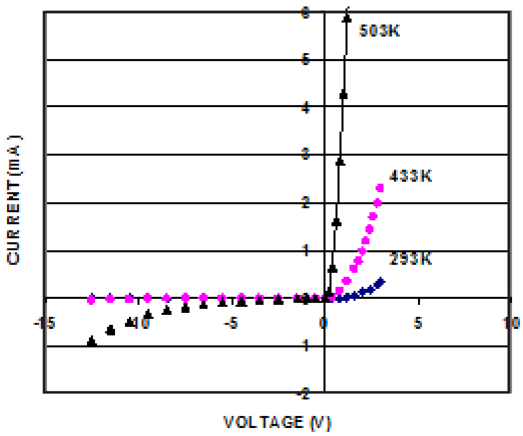

Fig. 4: Typical current-voltage characteristics with the temperature as a parameter of the n-4H SiC-Au contact

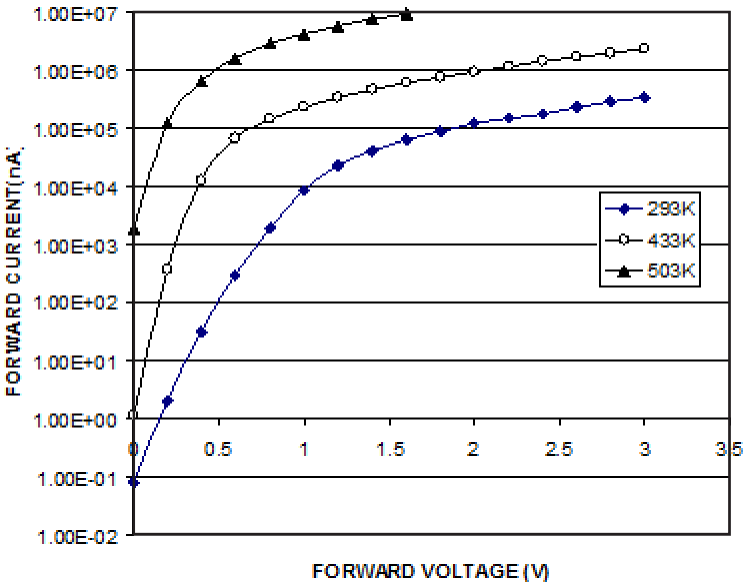

Fig. 5: Semi-logarithmic plot of the forward current-voltage characteristics of the n- 4H SiC-Au contact with the temperature as a parameter

the back contact formed by silver evaporation may not be ohmic; rather it acts somewhat as a blocking contact.

Fig. 5 shows the forward I-V characteristics on a semi-logarithmic plot. The plots do not form straight lines over the whole range of voltage. The value of the ideality factor n is calculated from the slopes of the graphs using equation (9). For lower bias voltages the ideality factor was found to have a value of n greater than 2. For large bias voltage the ideality factor had very large values. Such a behavior is commonly associated with series resistance. the whole range of voltage. The value of the ideality factor n is calculated from the slopes of the graphs using equation (9). For lower bias voltages the ideality factor was found to have a value of n greater than 2.. For large bias voltage the ideality factor had very large values. Such a behavior is commonly associated with series resistance. Despite the removal of the oxide layer and other contaminants from the surface of the wafer by etching and degreasing processes, the SiC wafer can be rapidly covered by a thin oxide layer 10-20 Angstroms on exposure to air.The surface also absorbs the atmospheric gases and undoubtedly had a large density of surface states whose concentration was further by metal induced gap states evaporation of the Schottky contact.

From the foregoing discussion it is apparent that the actual values of n cannot be used directly for the interpretation of the current flow mechanisms. In the devices fabricated for the study

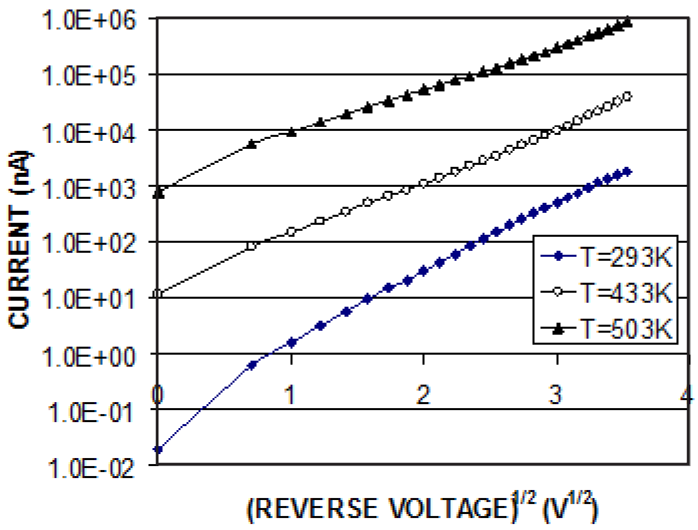

Fig. 6: Current versus the square root of the reverse voltage for the n- 4H SiC-Au contact

reported here, both the Schottky contact and the so-called ohmic contact contribute to this deviation of n from the ideal value of unity corresponding to dominating thermionic emission mechanism. Thus in view of the above results, the I-V character rustics of our diodes could not be used for the determination of the barrier height. Fig.6 shows the I-V characteristics in the reverse bias. The current is observed to increase with increasing temperature. This can be explained by carrier generation in the depletion region; most of the electron-hole pairs generated are separated by the high field in the depletion region and are then collected by the electrodes giving higher saturation currents. Another possibility is the excitation of electrons from the metal into the semiconductor which increases with temperature as given by equation (10). The reverse current is plotted against the square root of the voltage on a semi-logarithmic plot in Figure.6. The plots become linear after about 1 V. For voltages in excess of 1 V the field becomes high enough for the Schottky lowering effect to assert itself. At high fields the Schottky barrier is considerably lowered according to equation (11). Another interpretation is in terms of the generation current which is proportional to the width of the space charge region W, while W varies as $V^{1/2}$ as given by equation (3).

Conclusion

In this work , we study metal contacts on single crystal silicon carbide. The polytype of our choice is the 4H SiC supplied by CREE Research, Inc. in the form of single-crystal wafers. Contacts are prepared by evaporating metals of different work functions on n type 4H SiC. With the Huang clean given to the SiC wafers[14] we could indeed obtain ohmic and rectifying silicon carbide junctions.

Ohmic contacts to n-type 4H SiC was realized by evaporating silver to the backside of the wafer. This ohmic contact largely affected the forward biased characteristics. However, its effects on the reverse biased characteristics were negligible as it is in this case forward biased leading to small series resistance.

The electrical characteristics of the obtained junctions were determined as a function of temperature. Analysis of the current-voltage characteristics gives information on the nature of the contact (ohmic type or Schottky barrier rectifying type), current conduction mechanisms, barrier height, etc. On the other hand, capacitance-voltage measurements yield information about the barrier height, doping concentration as well as the distribution of shallow and deep levels near the surface of the contact.The work carried out here can be extended to the case of epitaxial silicon carbide wafers with more confidence. The epitaxial wafers are more expensive than the substrate wafers used in the present work (at least four times more expensive).

With epitaxial wafers one can obtain more reliable ohmic contacts allowing for better interpretation of forward I-V characteristics.

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