Effect of Barrier Metal Based on Titanium or Molybdenum in Characteristics of 4H-SiC Schottky Diodes

[1, 2] M. Ben Karoui, [1] K. Shili, [1, *] R. Gharbi, [1] M. Fathallah, [3] S. Ferrero, [3] C. F. Pirri

[1] Laboratoire des Semi-conducteurs et Dispositifs Electroniques. (LSDE-C3S)
Ecole Supérieure des Sciences et Techniques de Tunis
05 Av. Taha Hussein 1008, Montfleury, University of Tunis, Tunisia
[2] Centre des Recherches et des Technologies de l'Energie. Technopole Borj Cédria B. P N°95- 2050
Hammam Lif- Tunisia
[3] Politecnico di Torino, 24 c.so Duca Degli Abruzzi, 10129 Torino, Italy
Tel.: (216)71496066. fax: (216)71391166
[*] E-mail: rached.gharbi@esstt.rnu.tn

Abstract: The electrical properties were extracted by I-V and C-V analysis, performed from 10 K to 450 K. When the annealing temperature varied to 400 °C, the Schottky barrier height (SBH) increased from 0.85 Ev to 1.20 eV in Ti/4H-SiC whereas in the Mo/4H-SiC the SBH varied from 1.04 eV to 1.10 eV. Deformation of J-V-T characteristics was observed in two types of devices when the temperature decreases from 300 K to 10 K. The electrical properties and the stability of the devices have been correlated to the fabrication processes and to the metal/semiconductor interfaces. Mo-based contacts show better behaviour in forward polarization when compared to the Ti-based Schottky contacts, with ideality factors close to the unity even after the annealing process. However, Mo-based contacts show leakage currents higher than that measured on the more optimized Ti-based Schottky. *Copyright © 2014 IFSA Publishing, S. L.*

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1. Introduction

Wide band gap semiconductor materials having high breakdown electric field are needed for high-power semiconductor devices. The silicon carbide (SiC) material is a candidate to replace the silicon material in realizing electronic components due to its interest physical properties. It is a semiconductor material with interesting properties such as wide band gap and high breakdown field, the saturation electronic drift velocity and the thermal conductivity [1, 2].

These factors makes SiC a good candidate for the fabrication of high – power and high –frequency electronic devices, with lower power losses and smaller size than their Si or GaAs counterparts.

The metal-semiconductor (MS) contact on SiC is important in the fabrication of Schottky diode not only because they are unavoidable, but also because the associated Schottky barriers to electronic

transport across the metal-semiconductor interface can be tuned by judicious choice of materials and processing techniques [3]. In this work, we compare two types of diodes fabricated using molybdenum (Mo) or titanium (Ti) Schottky contacts.

2. Experimental Details

Schottky barrier formation on 4H-SiC epilayer was obtained by thermal evaporation. We have used Molybdenum (Mo) or Titanium (Ti), with or without thermal annealing in controlled atmosphere. Ohmic contact formation was made on the back of the wafer by a sequential evaporation of titanium, nickel have been used and silver or titanium and aluminium (Table 1).

In the first type of diodes, we employed SiCrystal wafers having an n doped bulk substrate (Nd+ = 1×10^{18} cm^{-3}, thickness 350 µm) and an n doped epilayer (Nd- = 7×10^{15} cm^{-3}, 5 µm thick) (Fig. 1 (a)). The average junction depth was 0.5 µm. In the second type of diodes we used Cree wafers having a n type substrate (Nd+ = 1×10^{19} cm^{-3}, thickness 300 µm) and an n doped epilayer (Nd-=4.8×10^{15} cm^{-3}, 7 µm thick) (Fig. 1b)).
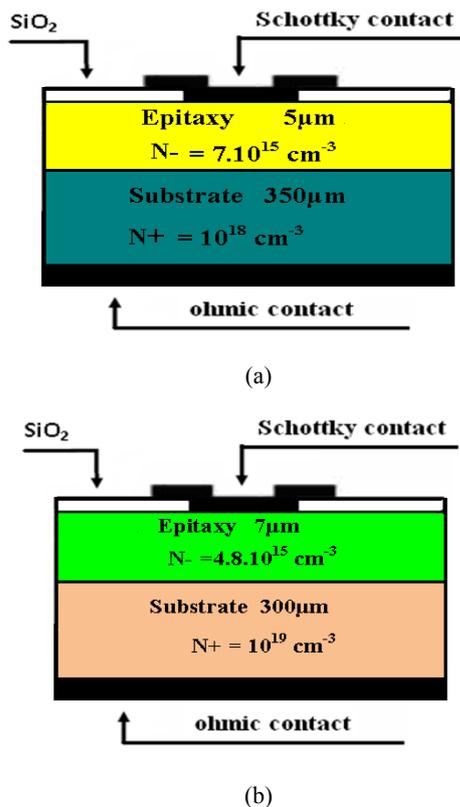

(a)

(b)

Fig. 1. Structure of studied Schottky contact realized using Mo (a) and Ti (b).

On the wafer backside, a phosphorus ion implantation has been performed with the aim to fabricate an n+ doped superficial layer. This process is necessary in order to lower the contact resistance of the ohmic contact, even without the need of a post metallization annealing. A rapid thermal annealing (RTA) process has been performed in order to obtain a good recovery of the lattice damage induced by ion implantation [4].

A silicon dioxide layer was grown on the wafer front side by low temperature oxidation, using Tetra Ethyl OxySilane (TEOS). The oxide layer was then patterned using standard optical lithography and buffered HF wet etching in order to fabricate the diode oxide termination.

Schottky contacts deposition was performed using an e-beam evaporator and the contacts were annealed by means of a RTA process at 400 °C. Ar inert atmosphere was used during the annealing. The SBD active area was 1 mm^2. For the entire set of samples, the process was completed after the high temperature annealing with the deposition of the ohmic contact on the wafer backside. For this purpose Ti/Al or Ti/Ni/Ag metallization have been used. The studied structures were given in Table 1.

The electrical properties were extracted by I-V and C-V analysis, performed from 10 K to 460 K using a cryogenic system. We are used the electrometer Keithly 6517 to measure I-V characteristics and impedance meter analyzer HP 4192A LF to acquire the C-V measurements at the frequency of 1 MHz and at ambient temperature.

3. Results and Discussions

Figs. 2 and 3 give respectively the forward density of current J versus voltage V for Ti/4H-SiC and Mo/4H-SiC. In the thermoinic emission theory, the current through a homogeneous SBD at a forward bias *V* is described:

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

With the saturation current I_s defined by:

$$I_S = AA^* \exp\left(-\frac{q\Phi_0}{kT} \right), \qquad (2)$$

where A is the diode area, k is the Boltzmann constant, A* is the modified Richardson constant and T is the temperature. Starting from these basic equations, a method used by Ben Karoui et al. [5] to extract the parameters of the SBDs, namely the zero bias SBH (Φ_0), the ideality factor (n) and the series resistance (R$_s$) associated with the bulk material in the semiconductor and the back ohmic contact. In the process of these extractions, the theoretical value of the Richardson constant (A*), for 4H-SiC, was taken as equal to 146 A cm^{-2} K^{-2} [6].
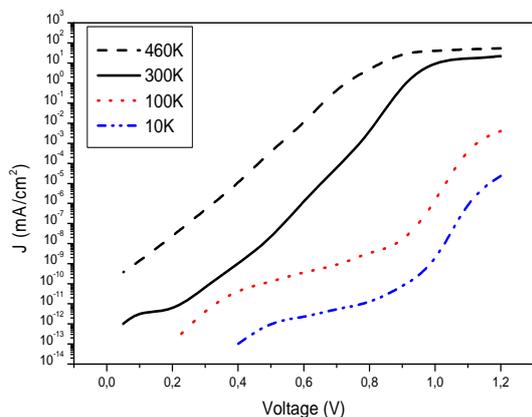
Fig. 2. J-V characteristics under temperature variations of Ti/4H-SiC diode.
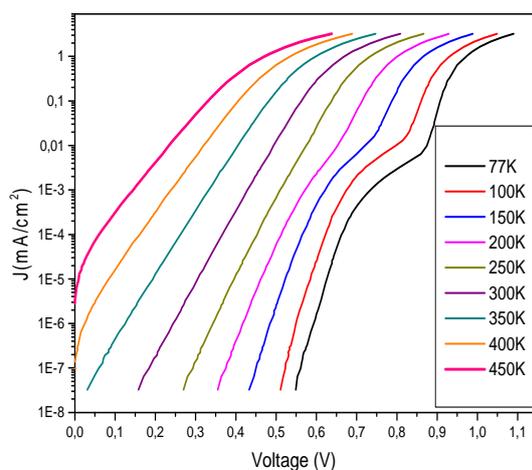

Fig. 3. Evolution of J-V characteristics under temperature of Mo/4H-SiC diode.

It has to be noted in this respect that there is a wealth of methods that can be used to extract the ideality factor in a diode or a solar cell [7–9]. These methods have their advantages as well as their limits. The method we have used follows a generalized approach in extracting parameters such as the barrier height and the ideality factor by considering the whole range of the experimental data (forward and reverse parts of the *I–V* curve). It uses a least-squares method that unambiguously allows the determination of these parameters with good accuracy; it works even in the absence of a linear part in the *I–V* curve and in situations where other currents such as within the TED theory.

In Table 1 we presented the Schottky barrier height (SBH) values using I-V and C-V methods [10]. The Φ_0^{I-V} values increased from 0.85 eV to 1.21 eV in Ti/4H-SiC whereas in the Mo/4H-SiC the SBH varied from 1.04 eV to 1.10 eV when the annealing temperature varied to 400 °C. The difference shown in barrier height values determined by I-V and C-V methods (Table 1) have be explained by the existence of barrier height inhomogeneities as mentioned by Sullivan et al.[11]. They demonstrated that if the barrier height follows some statistical distribution, the SBH value extracted from C-V measurements is the arithmetic mean of the barrier height distribution (the capacitance of the Schottky contact comes from the modulation of the total space-charge as a function of bias). On the other hand, the SBH obtained from I-V measurements is well below the value extracted from C-V analysis and is dominated by the current flow through regions of lower SBH.

In Ti/4H-SiC structure annealed at 400 °C, we observed a good agreement between the barrier height extracted from C-V and I-V measurements and it can be explained with the presence of a homogeneous metal/semiconductor interface. Whereas in the Mo/4H-SiC diode the difference between two measured barrier is about 0.19 eV. The increase of annealing temperature to 600 °C reduces the difference to 0.11 eV [12].

The Mo-based contacts show better behaviour in forward polarization when compared to the Ti- based Schottky contacts, with ideality factors close to the unity even after the annealing process. However, Mo-based contacts show leakage currents higher than that measured on the more optimized Ti-based Schottky diodes as given in Table 1.

Table 1. Electrical parameters of the fabricated Schottky diodes: barrier height (Φ_0), ideality factor (n) and reverse saturation current I_s determined at 600 V.

Schottky contact (Thickness, [nm])	Annealing (T [°C])	Ohmic contact	Φ_0^{I-V} [eV]	Φ_0^{C-V} [eV]	n	I_s @ 600V [µA]
Ti (100)/Al(3000)	No Ann.	Ti/Ni/Ag	0,85	0,92	1,07	100
Ti(100)/Al(3000)	400	Ti/Ni/Ag	1,21	1,23	1,02	30
Mo (100)	No Ann.	Ti/Al	1,04	1,08	1,04	170
Mo (100)/Al(3000)	400	Ti/Al	1,10	1,21	1,07	1000

In the temperature range 300 K-450 K the logarithmic J-V characteristics for two types of diode shows a linear behaviour over several orders of magnitude improving the thermionic emission theory in forward conduction. But when the temperature decreases from 300 K to 10 K a deformation of

J-V characteristics was observed and a second linear region in the logarithmic J-V curve was shown in Figs. 4 and 5 for two types of diodes. This behaviour was observed a first by Defives and al. for Ti/4H-SiC diode [13] and an electrical model for two parallel SBH was proposed. In our previous work [5], we are studied this phenomena in Ti/4H-SiC diode. A critical modification was observed in Mo/4H-SiC diode under 300 K showing another SBH2 for high part of the graph with ideality factor n_2 in parallel with SBH1 having an ideality factor n_1.
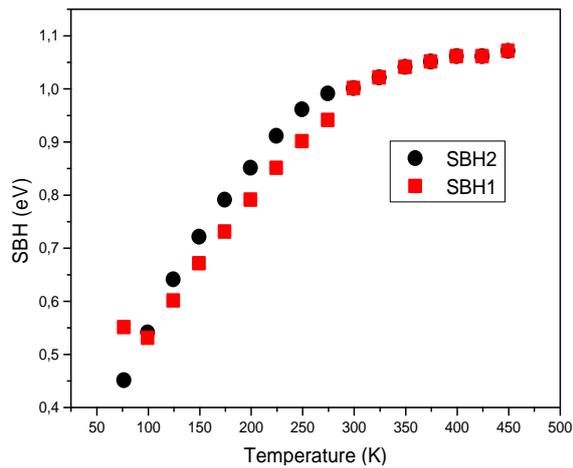
Fig. 4. Two barrier height values versus temperature deduced from Mo/4H-SiC characteristics.
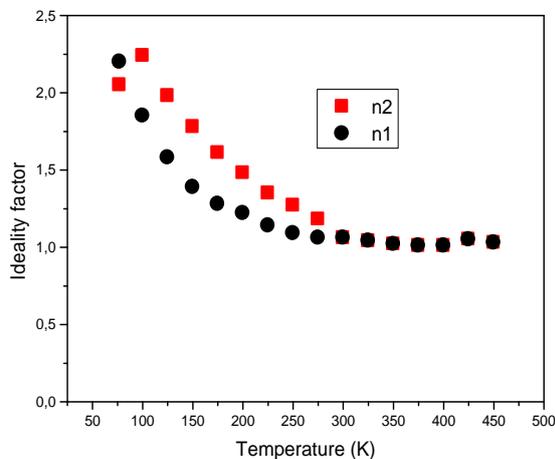
Fig. 5. Evolution of ideality factor n versus temperature for two SBH in Mo/4H-SiC.

The evolution of SBH2 (Fig. 4) is important when the temperature decreases varying from 0.99 eV at 275 K to 0.45 eV at 77 K. Whereas the ideality factor n_2 (Fig. 5) increases from 1.18 at 275 to 2.24 at 100 K. The in homogeneity of the barrier height is may be a primary reason for the observation of large ideality factors at low temperature. The Richardson plot is obtained from equation (2):

$$\ln\left(\frac{J_s}{T^2}\right) = \ln A^* - \frac{q\Phi_0}{kT} \qquad (3)$$

Fig. 6 shoes the Richardson plot of the saturation current density obtained from J-V curves for both barriers SBH1 and SBH2 for two Schottky diodes.

For a temperature independent SBH, one should obtain the SBH from the linear slope of the curve $\ln(J_s/T^2)$ versus 1000/T, according to Eq. 3. The non-linearity of the curve confirms that it is impossible to extrapolate a constant SBH value and confirms the deviations from ideality and barrier inhomogeneities.
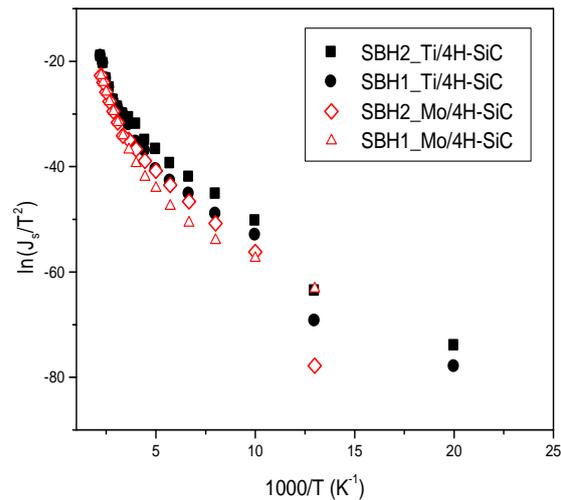

Fig. 6. Richardson plot of Mo/4H-SiC and Ti/4H-SiC Schottky diodes.

Many hypotheses in literature are found and two models were given: The first proposes an analytical model to explain temperature dependence of SBH by built-in potential fluctuations, assuming a Gaussian distribution of the band bending at the metal-semiconductor interface. The second proposes another approach which takes into account also interactions between regions with different SBHs [14, 15].
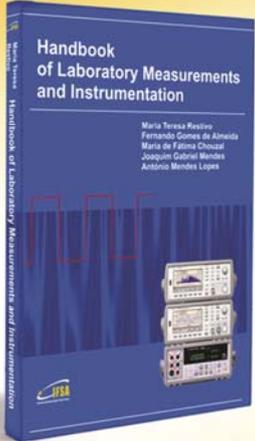
4. Conclusions

Different Schottky and ohmic contacts on 4H-SiC were studied to fabricate Schottky barrier diodes (SBDs) for high power applications. Ti and Mo Schottky contacts annealed at 400 °C can be considered as promising candidates for the fabrication of SBDs able to operate at high temperature with low power losses. Mo-based contacts show leakage currents higher than that measured on the more optimized Ti- based SBDs. Mo-based contacts show better behaviour in forward polarization when compared to the Ti-based Schottky contacts, with ideality factors close to the unity even after the annealing process. The non-linear Richardson plot of saturation current indicates that

Ti-SiC and Mo-SiC is a non-uniform Schottky contact at low temperature.

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