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Barrier Height Tuning in Ti/4H-SiC Schottky diodes

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Abstract

In this work, we investigated the effects of annealing temperature and metal thickness on the Schottky barrier height in state-of-the-art Ti/4H-SiC rectifiers. By varying these two parameters, a controlled lowering of the Schottky barrier height has been obtained, thus giving the possibility to improve the efficiency of device in terms of power consumption.

1. Introduction

Nowadays, wide-band gap semiconductors are considered at the base of the next generation of power electronics devices [1]. Specifically, devices based on hexagonal polytype of silicon carbide (4H-SiC), such as Schottky barrier diodes (SBDs) and metal-oxide-semiconductor field effect transistors (MOSFETs), have reached a mature technological level with superior performance in high power, high frequency and high temperature applications if compared with the Si-based technology counterpart [2].

Particularly, a recent development of the 4H-SiC SBDs consists in embedding p-type regions within an n-type Schottky area to create the so-called junction barrier Schottky (JBS) rectifiers. This approach allows to gain advantages in terms of faster switching, lower leakage current and hard breakdown [3]. As for the SBDs, also for the JBS diodes the interface between metal and n-type epitaxial 4H-SiC layer plays an important role with the Schottky barrier height Φ_B, formed when metal and semiconductor are put in intimate contact, governing the forward voltage drop and the reverse leakage current. Peculiarity of an ideal Schottky contact is featuring a barrier height independent of temperature, voltage and measurement method, with the Φ_B value close to that predicted by the Schottky-Mott rule [4]. In real cases, a more complex situation occurs, with the presence of many variables involved in the contact formation, one above all the choice of the metal and its evolution in the contact formation. In this respect, in the last two decades several studies have investigated the electrical properties of various metallization schemes for Schottky contacts to 4H-SiC, with particular attention to the barrier height value and the current transport mechanisms through the metal/semiconductor interfaces [5,6,7,8]. However, some technological issues are still open and deserve further investigation. As matter of fact, a full understanding of the physics governing the contact is still missing, with the research on this system scientifically open and pushed by industrial requirements. For example, the possibility to control and lower the Schottky barrier height is an important point for a power consumption reduction of the device [9,10].

Currently, one of the most used metal as Schottky barrier for the 4H-SiC-based rectifiers is Ti [11], which typically gives barrier height values in the order of 1.25eV.

In this work, we explored the possibility to control the Schottky barrier properties in state-of-the-art Ti/4H-SC diodes, by varying either the post-annealing conditions or the metal thickness.

2. Experimental details

The semiconductor material used in our investigation was a commercial n-type 4H-SiC epitaxial layer (9.5 µm-thick with nitrogen doping concentration of $N_D=8\times10^{15}cm^{-3}$) grown onto a heavily doped 4H-SiC (0001) substrate. On these samples, JBS devices were fabricated with the p^+-type regions defined by Al-ion-implantation with an almost flat doping profile within a depth of 400 nm. The electrical activation of the dopant was obtained with a thermal process at 1650°C, thus allowing the formation of good Ohmic contacts [12].

The Schottky contacts were fabricated by deposition of Ti-metal layer with two different thickness, i.e. 80 nm (considered as reference) and 10 nm. As part of the deposition process, a thick layer of AlSiCu, treated at 475°C, was finally deposited on the Ti Schottky barrier metal-layer in order to lower the series resistance of the device during electrical probing.

The wafers were then cut in pieces, with the samples with 80nm-thick Ti-layer subjected to thermal annealing treatments in N_2 for 10 min at three different temperatures (600, 700 and 800°C), while the samples with 10nm-thick Ti-layer were unannealed and labelled as-deposited version. For comparison, also unannealed samples with 80nm-thick Ti-layer were preserved.

The key-electrical parameters (ideality factor n, and Schottky barrier height Φ_B), which describe the Schottky behavior of the metal/semiconductor interface, were derived by means of current-voltage (I–V) measurements performed in a Karl-Suss MicroTec probe station equipped with a parameter analyzer. These measurements were carried out on sets of several equivalent JBS diodes differing in the thermal annealing temperature or in Ti-layer thickness. The analysis of these large sets of samples allowed also evaluating the uniformity of the Schottky barrier over extended region of the wafer.

3. Results and Discussion

A schematic view of the complex layout of a JBS device is shown in Fig. 1. The p^+-type implanted regions, with the Ohmic contact above, are illustrated in the epitaxial drift layer. The Ti/4H-SiC Schottky contacts, subject of the characterization presented in this work, are located in between the p-regions.

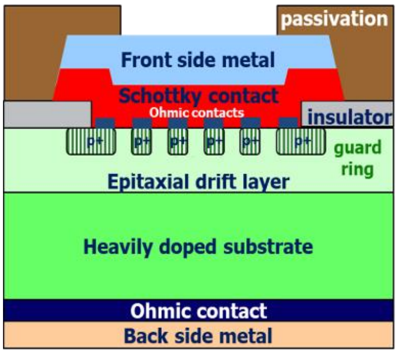

Fig.1: Schematic of a JBS device. The interface under investigation is the Schottky contact between "front-side metal" (Ti) and "epitaxial drift layer" (4H-SiC).

The Ti/4H-SiC contact was electrically studied, with the I-V characteristics of the as-deposited and the annealed 80nm-thick-Ti/4H-SiC tested diodes, reported in Fig.2. These characteristics were analyzed by applying the thermionic emission theory, with the I-V relationship expressed as follows [13]:

$$I = AA^{*}T^{2}\exp\left[\left(-\frac{q\phi_B}{kT}\right)\right] exp\left[\left(-\frac{qV_F}{nkT}\right)-1\right]$$
(1)

where A is the device area, A^* is the effective Richardson constant of 4H-SiC (146 $A\cdot cm^{-2}\cdot K^{-2}$) [14], k is the Boltzmann's constant, q is the elementary charge, V_F is the forward voltage applied across the metal/semiconductor interface and T is the absolute temperature.

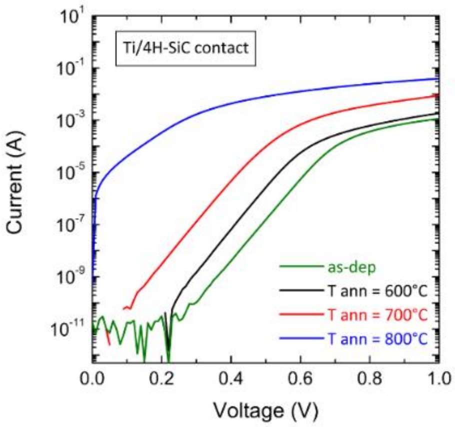

Fig.2: I-V characteristics of the as-deposited Ti/4H-SiC contact and the annealed at three different temperatures (600, 700 and 800°C).

The parameters that describe the electrical behavior of the contact, i.e., the barrier height Φ_B and the ideality factor n, were derived by analyzing the linear region of the current-voltage (I-V) characteristics in a semilog scale. Evidently, the forward I-V curves for samples annealed up to 700 °C present a wide linearity region over several decades. Above a certain bias (0.6-0.8V), the I-V curves start to bend, due to the dominant contribution of the series resistance. In addition, after annealing process up to 700 °C, the forward I-V curves of the Ti/4H-SiC diodes exhibit a negative shift with respect to the as-deposited case, suggesting a reduction of the barrier height, while a degradation of the Schottky contact is obtained for sample annealed at 800 °C. Quantitatively, concerning the ideality factor n, it remains constant with a value of 1.08 for the as-deposited and thermal annealed samples at 600 and 700 °C, confirming that thermionic emission is the best model to describe the transport. For the barrier height Φ_B, we observed a reduction of its value from 1.21 eV (derived for the as-deposited sample) down to 1.15 eV and 1.04 eV for the sample annealed at 600 °C et 700 °C, respectively.

To evaluate the process uniformity, a statistical distribution of the barrier heights was built from forward I-V characterization on a set of equivalent diodes fabricated on an extended region of the wafer. This was performed in the as-deposited and annealed (at 600 and 700 °C) version of the 80nm-Ti layer samples. These statistical distributions are shown in Fig.3. Notably, barrier heights distribution can be assimilated to a symmetric profile with narrow distributions of the Φ_B values, indicating a good reproducibility of the Ti-barrier formation process. Specifically, in the as-deposited contact, distribution of the measured barrier heights shows a barrier value peaked at 1.21 eV (Fig. 3a) with a dispersion of 0.01 eV. On the other hand, with the annealing treatment at 600 (Fig. 3b) and 700°C (Fig.3c), the barrier heights distribution is centered at 1.18 and 1.03 eV, while the dipersions are 0.06 and 0.04 eV, respectively. These results demonstrate that the annelaing tretment at 700°C gives the best trade-off between contact uniformity and barrier height reduction.

However, in our contacts a certain degree of local inhomogeneity of the barrier at a nanometric scale cannot be ruled out. In fact, such an inhomogeneity, has been often observed in 4H-SiC-based diodes [8,14] and has been explained by means of the Tung's model [15]. Different nanoscale techniques are used to directly visualize the barrier inhomogeneity, such as ballistic electron emission microscopy (BEEM) [16] or conductive atomic force microscopy (C-AFM) in ultrathin metal contacts [17]. However, these techniques require appropriate experimental set-up and specific sample preparation. Another common method to get insight on the

Schottky barrier homogeneity is carrying out a current–voltage-temperature (I-V-T) characterization [14]. In our case, preliminary I-V-T measurements indicated a slight temperature dependence of both the ideality factor and of the Schottky barrier height, thus suggesting the presence of an inhomogeneous barrier as described in the Tung's model. However, an extended electrical characterization as a function of the temperature and in several devices will be needed in order to give a quantitative description of this aspect.

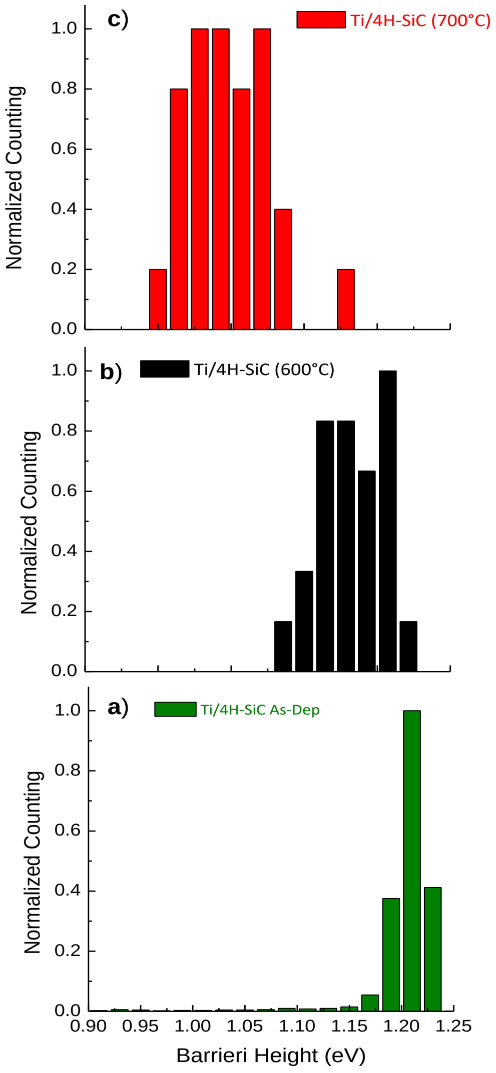

Fig.3: Statistical distribution of the barrier height of Ti/4H-SiC contact in the as-deposited case (a) and after 600 °C (b) and 700 °C (c) thermal treatment.

In order to evaluate the effect of the metal layer thickness reduction, the same kind of analysis was carried out on the as-deposited versions of the 10nm-thick and 80nm-thick Ti layer samples. Fig. 4 shows the forward I-V characteristics of the Ti/4H SiC for diode with the two Ti-layer thicknesses, i.e. 10 and 80 nm. The plot clearly shows the strong dependence of the barrier height Φ_B on the Ti-thickness. In particular, for 10 nm-thick-Ti Schottky barrier, the forward I-V curves of the Ti/4H-SiC diodes exhibit a negative shift with respect to the Ti(80nm)/4H-SiC as-deposited case, suggesting a strong reduction of the barrier height with the reduction of the metal thickness.

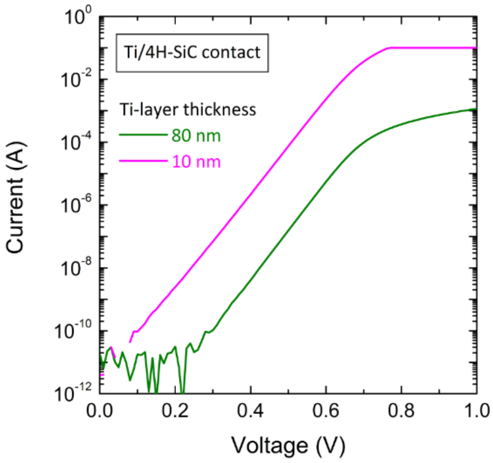

Fig.4: I-V characteristics of as-deposited Ti/4H-SiC contact with Ti-layer of 10 nm- or 80 nm-thick.

Regarding the uniformity of the Schottky barrier height over extended regions of the wafer, for both cases, Ti(80nm)/ and Ti(10nm)/4H-SiC contacts, in Fig.5 we observed a narrow distribution of Φ_B, centered at 0.95 eV for the devices with thinner Ti-layer, while a distribution peaked at e 1.21 eV was obtained for the contact with 80 nm-thick Ti-layer.

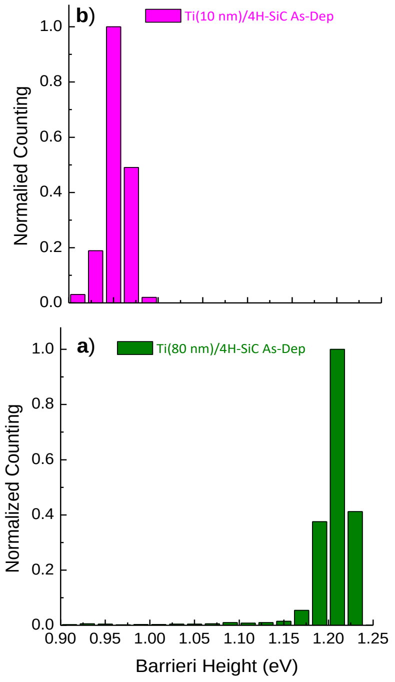

Fig.5: Statistical distribution of the barrier height of Ti/4H-SiC contact with 10 nm- or 80nm -thick metal layer.

A possible origin of the barrier height reduction, observed in the sample with thinner Ti-layer, could be the Al diffusion into the Ti layer up to the interface, leading to the formation an alloyed interface with a lower Φ_B. In fact, while the 80 nm Ti layer is thick enough to prevent that Al reaches the interface with SiC epilayer, the thinner 10nm Ti layer can be completely penetrated by the diffusion Al during the annealing treatment at 475 °C. This hypothesis will be object of future investigations by means of high-resolution microstructural and chemical analyses of the interface region.

4. Conclusion

In this paper, the effect of annealing temperature and metal thickness on the Ti/4H-SiC Schottky barrier was monitored in state-of-the-art diodes.

From the experimental values of the barrier height Φ_B, the ideality factor n and from their statistical dispersion, it was possible to conclude that annealing treatments at 700 °C of a 80nm Ti barrier is the most promising contact for practical applications.

On the other hand, by varying the Ti thickness can enable to control the Al diffusion through the Ti-layer and, ultimately, to tailor the Schottky barrier by the formation of different alloyes intererfaced.

These results pave the way for defining an industrial process to fabricate high performance SiC rectifiers with a lower power consumption.

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