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Electrical Characterization of Mo-Carbide Schottky Contacts on 4H-SiC

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Abstract. In this work, the electrical properties of Mo_2C/4H-SiC Schottky contacts were studied at different annealing temperatures. In particular, the Schottky barrier height was derived by current-voltage measurements on as-deposited and 400 °C and 700 °C-annealed contacts. The Schottky barrier height was comparable for the as-deposited and 400°C-annealed Mo_2C/4H-SiC contact (0.94 and 0.96 eV, respectively), while it increased (1.07 eV) for the 700 °C-annealed Mo_2C/4H-SiC one. For the sample annealed at 700°C, the electrical characterization of the diodes was combined with the study of the surface and interface electrical properties, by Kelvin-probe force microscopy (KPFM) and frequency dependent capacitance-voltage measurements (C-f-V) and discussed assuming a Mo/4H-SiC Schottky contact (Φ_B =1.39 eV) as a reference. The KPFM measurements revealed a similar value of the surface potential, thus suggesting that the work function of the metal is the same in both cases. On the other hand, a higher density of interface state was obtained by C-f-V for the Mo_2C/4H-SiC system. This latter can explain the reduction of the Schottky barrier height observed for this system.

Introduction

The Schottky-barrier diode (SBD) on 4H-SiC is a well-established technology, currently employed in several power electronics applications within the medium-to-high voltage range [1]. Although the advantages (namely fast switching, low forward voltage drop, high temperature operations) of using 4H-SiC-SBD are undoubted, further technological optimizations are still necessary to fully exploit the potential of 4H-SiC [2]. To this end, various approaches have been explored to improve the properties of the metal/4H-SiC interface, which underpins the performance of the SBDs, with particular attention to the metal choice and its interaction with 4H-SiC during thermal annealing for the Schottky contact formation [3]. In recent years, molybdenum (Mo) has attracted interest due to its good thermal stability and ability to form contacts with low Schottky barrier height, which is beneficial for minimizing the conduction power losses [4]. However, a wide variability in the Schottky barrier height has been observed in Mo/4H-SiC Schottky contacts, depending on several factors, such as surface passivation treatments [5], temperature of the metal deposition [6] and metal stack composition [7], with the Φ_B varying between 1.0 and 1.5 eV. Recently, we investigated Mo/4H-SiC Schottky contact subjected to annealing treatments up to 950 °C, observing a reduction of the Φ_B from 1.42 eV to 1.29 eV upon annealing at 950 °C, without any evidence of interface reaction between metal and semiconductor [8]. In that case, the reduction of Φ_B was associated with

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the enlargement and preferential orientation of the metal grains, as demonstrated by X-Ray Diffraction (XRD) and Transmission Electron Microscopy (TEM) [8]. Nevertheless, based on the ternary phase diagram of the Mo-Si-C system, solid-state reactions can occur between Mo and both silicon (Si) and carbon (C), leading to the formation of carbides and silicides. This tendency opens the possibility to further explore and tune the Schottky barrier properties to 4H-SiC, potentially broadening the range of achievable Φ_B values. As an example, Mo-based contacts containing C have been recently investigated, either deposited in laminated layers or obtained from Mo-C alloyed targets [7,9], demonstrating stable electrical characteristics even at high annealing temperature. However, the origin of this electrical behavior is not fully clear yet.
In this paper, the behavior of the Schottky barrier height Φ_B in Mo-carbide/4H-SiC contacts was investigated, as a function of the annealing temperature. The electrical characterization of the diodes was combined with the study of the surface and interface electrical properties, by Kelvin-probe force microscopy (KPFM) and frequency dependent capacitance-voltage (C-V-f) measurements, to get information on the surface potential and the energy of interface state density (N_{SS}). While similar values of surface potential were found for the Mo_2C and Mo/4H-SiC contacts, the higher level of N_{SS} in the Mo_2C/4H-SiC can explain the reduction of the Schottky barrier in this contact compared to a Mo/4H-SiC one.

Experimental Details

The starting material for this study consisted in a 4H-SiC epitaxial layer with a n-type doping concentration of 1.5×10^{16} cm^{-3} grown onto a n^+-doped substrate. Schottky diodes were fabricated starting from the deposition of a large-area back-side Ohmic contact by sputtering 100 nm-thick Ni layer, followed by a rapid thermal annealing (RTA) treatment in a furnace at 950 °C in N_2 for 60 s [10]. Then, for the front-side Schottky contact, 100 nm-thick film was sputtered from a Mo_2C target. The contact pads were defined by optical photolithography and lift-off processing steps. Rapid thermal annealing (RTA) treatments were carried out in a furnace for 10 min in N_2 atmosphere at temperatures of 400 °C and 700 °C. For comparison, 80 nm-thick Mo/4H-SiC contacts were fabricated in the same manner. The electrical characteristics of a set of contacts were investigated by means of current-voltage (I-V) and capacitance-frequency-voltage (C-f-V) measurements in a Karl-Suss MicroTec probe station equipped with a parameter analyzer. Kelvin Probe Force Microscopy (KPFM) measurements were carried out in PeakForce Tapping Mode Amplitude Modulation (AM)-KPFM with a Dimension Icon system by Bruker. Silicon tips with a triangular geometry (nominal radius of 5 nm) were employed to evaluate the variation of the surface potential of the contact.

Results and Discussion

Firstly, we investigated the electrical characteristics under forward bias for a set of as-deposited, 400 °C and 700 °C annealed Mo_2C/4H-SiC contacts. The related current density-voltage (J-V) curves are reported in Figs.1a, 1b and 1c, respectively.

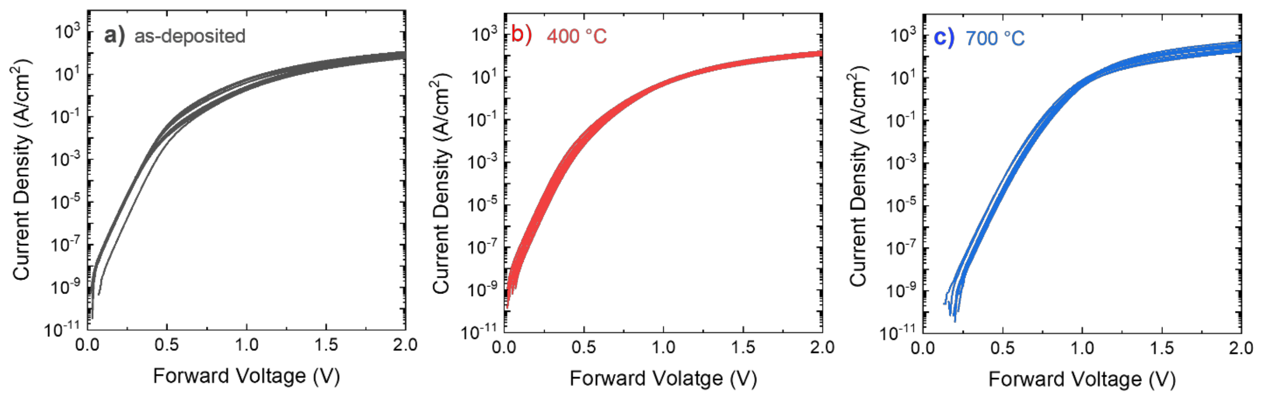

Fig. 1. Forward J-V curves of the a) as-deposited, b) 400 °C and c) 700 °C-annealed Mo_2C/4H-SiC Schottky contacts.

The J–V characteristics exhibited good reproducibility, with the 700 °C-annealed sample showing a more extended linear region. The Schottky barrier height values, extrapolated from a fit of the linear part of the J-V curves, according to the thermionic emission (TE) model [11], are reported in Fig.2. As one can see, the as-deposited and 400 °C-annealed Mo_2C/4H-SiC contact showed similar barrier height, with $\Phi_B = 0.94 \pm 0.02$ eV and $\Phi_B = 0.96 \pm 0.04$ eV, respectively. After thermal treatment at 700 °C, the barrier increased up to 1.07 ± 0.04 eV.

To understand the origin of the barrier reduction, we investigated the surface potential, which is linked to the work-function of the contact material. The surface potential mapping was performed by KPFM, carried out on both the Mo (reference) and Mo_2C contacts. Specifically, 4H-SiC was employed as a reference to evaluate the variation on the surface potential of the contact material with respect to the semiconductor. Figs. 3a and 3b show the histograms of surface potential values extracted from the KPFM maps.

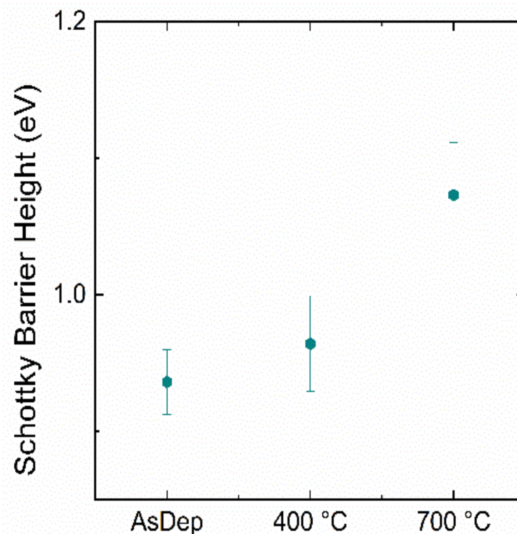

Fig. 2. Schottky barrier height (Φ_B) for the as-deposited and annealed Mo_2C/4H-SiC contacts.

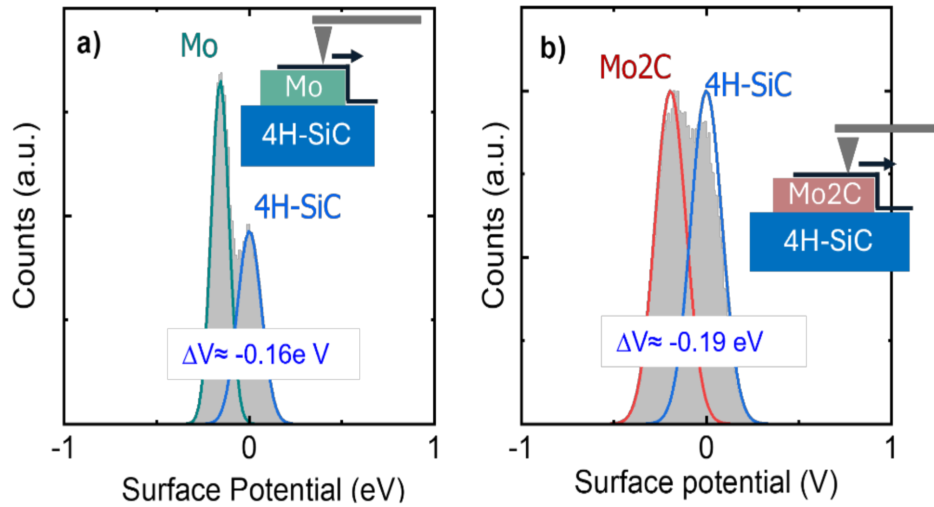

Fig. 3. Histograms of the KPFM surface potential values associated to the maps for a) Mo/4H-SiC and b) Mo_2C/4H-SiC contacts. 4H-SiC was taken as reference.

These surface potential distributions were fitted by Gaussian functions to derive the peak corresponding to the average surface potential values. Noteworthy, a surface potential variation of 0.16 eV was observed for Mo and 4H-SiC while is of 0.19 eV for Mo_2C and 4H-SiC one. This corresponds to very similar surface potential values for Mo and Mo_2C, differing by only ~0.03 eV. Such a small variation alone cannot account for the difference observed in the Schottky barrier height between the two contacts. Hence, we extended the investigation to the interface electrical properties by a C-f-V study [12]. This technique enables the evaluation of the density of interface states (N_{SS}) in Schottky diodes from capacitance measurements as function of the frequency (f) and forward bias (V). In fact, at low frequencies, the measured capacitance contains contributions from both the space-charge region (C_{SC}) and the interface states (C_{SS}), whereas at high frequencies only the space-charge capacitance contributes [13]. This can be expressed according to the following eqs.1 and 2, where the total capacitance is given by a parallel of C_{SC} and C_{SS} at low frequencies whereas the total capacitance can be approximated to only C_{SC} at high frequencies [14]:

$$C_{lf} = C_{sc} + C_{SS} \text{ (at low frequency)} \tag{1}$$

$$C_{hf} \approx C_{sc} \text{ (at high frequency)} \tag{2}$$

From the difference between the two cases, C_{SS} is derived. This term is proportional to the N_{SS}, as given in eq.3 [15]:

$$C_{SS} = qAN_{SS}\frac{\arctan(\omega\tau)}{\omega\tau} \tag{3}$$

with ω=2πf (f varying between 1 kHz and 1MHz), q the elementary charge, A the device area, and τ a time parameter depending on the thermal velocity of carriers, the cross-section of interface states and the doping concentration.

The N_{SS} derived according to eq.3, results of 2.2×10^{10} $eV^{-1}cm^{-2}$ for Mo/4H-SiC contact and of 9.5×10^{13} $eV^{-1}cm^{-2}$ for Mo_2C/4H-SiC. This high difference in the density of interface state can be at the base of the reduction of the Schottky barrier occurred in Mo_2C contacts.

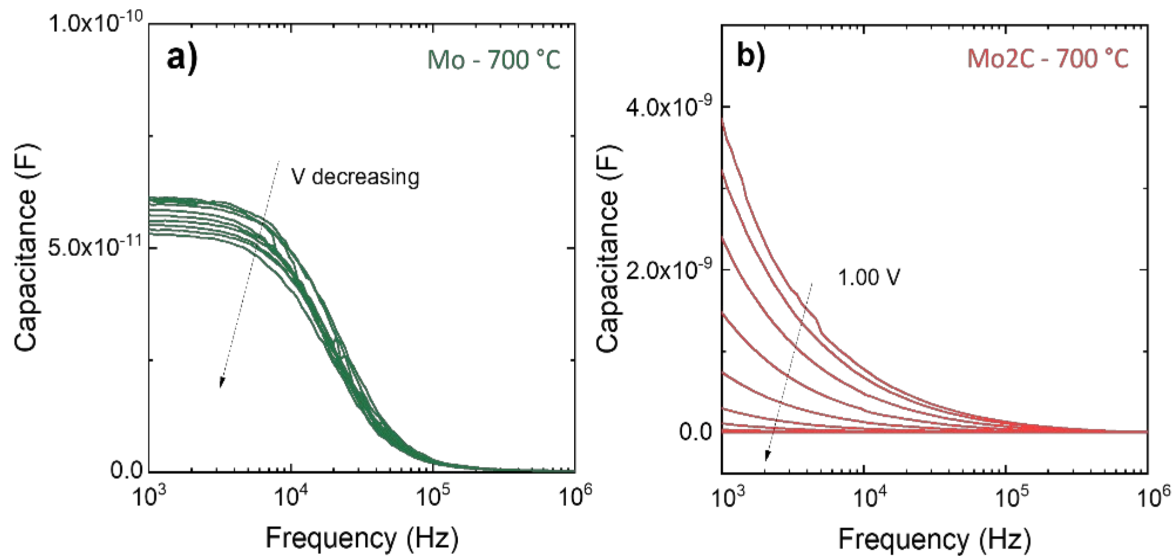

Fig. 4. C–*f*–V characteristics for 700 °C annealed Mo and Mo_2C/4H-SiC contacts.

Summary

The electrical characterization of Mo_2C/4H-SiC Schottky contacts demonstrated a Schottky barrier height around 0.95 eV for the as-deposited and 400 °C-annealed contact and of 1.07 eV for the 700 °C-annealed contact, the latter exhibiting a more extended linear region. The Mo_2C/4H-SiC contact properties were compared with those of a reference Mo/4H-SiC contact, fabricated under same processing conditions, with surface and interface electrical properties investigated by Kelvin-probe force microscopy and capacitance-frequency-voltage study, respectively. The study indicated comparable surface potential values (derived by Kelvin-probe force microscopy) for the two systems, whereas a higher density of interface state was extracted for the Mo_2C/4H-SiC contact. This latter finding accounts for the reduction in Schottky barrier height observed in the Mo_2C/4H-Si contact.

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