Optica Applicata, Vol. XXXIX, No. 4, 2009

Cr ohmic contact on an Ar^+ ion modified 6H-SiC(0001) surface

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Chromium layers were vapor deposited under ultrahigh vacuum onto samples cut out of a single crystal of 6H-SiC(0001) that were Ar^+ bombardment modified. The substrates and electrical contacts formed by the Cr adlayer were characterized *in situ* by current-sensing atomic force microscopy (CS-AFM) and X-ray photoelectron spectroscopy (XPS). Cr/SiC contacts reveal a good *I–V* characteristic linearity without the use of heavy impurity doping and high-temperature annealing.

Keywords: silicon carbide, chromium, electric contacts, AFM.

1. Introduction

Wide band-gap semiconductor silicon carbide (SiC) is suitable for high-power, high-frequency, and high-temperature electronic devices [1, 2]. Obtaining high quality electric contacts by metal deposition on the SiC substrate, that could be resistant to high temperature, oxidation and severe operating conditions, is of technological importance. Behavior of thin metal films deposited on the 6H-SiC(0001) has been investigated for a number of metals. The Schottky barrier height (SBH) at the metal/semiconductor interface determines the electrical behavior of the contact. Majority of metal layers as-deposited on SiC form the Schottky contact [3]. In order to obtain good ohmic contacts which are especially important for high power applications and outside communication to devices, lowering the SBH is necessary. Chromium metal, due to its properties such as the low electric resistivity and a strong resistance to oxidation at elevated temperatures, seems suitable in fabrication of electric contacts on SiC. The Cr layers as-deposited on the 6H-(0001)SiC at room temperature (RT) form a rectifying contact with the SBH in the range from 1.1 to 1.3 eV [4, 5]. In order to reduce the SBH, the metal/semiconductor interface has to heavily be doped with defects and/or impurities from the semiconductor side, which requires a high temperature treatment (1800–2200 K) [6]. Lowering the processing temperature should make Cr technologically more attractive.

It is well known that the chemical composition of the surface plays an essential role in the formation processes of the metal/semiconductor interface [3]. Preparation stage of semiconductor surface before the growth of metal films is critically important for the resulting contact properties. Several different SiC-surface preparation techniques have been developed, including oxidation [7], etching in H_2 [8], and ion bombardment. Surfaces modified by Ar^+ sputtering show considerable changes in conductance type of the metal/SiC contact [9]. In the present report discussed are results of our studies of electric contacts formation by chromium deposition on the 6H-SiC(0001) surface modified by Ar^+ bombardment. The results clearly indicate that the ohmic contact can be formed on the surface ion-bombarded prior to Cr deposition, which can be attained at a much lower temperature than that of forming such a contact on unpretreated surfaces.

2. Experimental details

Samples, around 10×12 mm^2 in size, were cut out of the nitrogen-doped *n*-type (resistivity 0.1 Ωcm) 6H-SiC single crystal on-axis, (0001) Si-face oriented wafer (Cree Research Inc.). Prior to placing under ultrahigh vacuum (UHV) conditions, the samples were degreased in acetone; next, were rinsed in distilled water. The substrate surface was modified through RT cycles of 1.2 keV Ar^+ bombardment at a current of 8 μA (flux density *ca.* 7×10^{-6} A/cm^2) and the pressure 1×10^{-5} torr Ar, lasting for 3 to 30 min. Cr/6H-SiC interfaces were formed and initially characterized in the UHV chamber at an operating pressure of 3×10^{-10} torr or lower. The chromium layers were deposited from an e-beam evaporator and the efficiency of the source was calibrated based on the measurements of the tree-dimensional Cr island growth rate [10].

The Cr/6H-SiC(0001) contacts were characterized *in situ*, by using the UHV current-sensing atomic force microscope (CS-AFM) operating in contact mode (Nanosensors-made Pt/Ir tip with the force constant 0.12 N/m). The surface morphology and topography were investigated with simultaneous measurement of the local changes in electric conductance of the system Cr-layers/6H-SiC(0001). Next, the behavior of the interface was investigated by measurement of $I-V$ characteristics in grid mode. The areas of the probed region ranged from 150×150 nm^2 to 3×3 μm^2 and were covered by 6400 measurement points. Additionally, the substrate and interface were analyzed by X-ray photoelectron spectroscopy (XPS) using Mg K_α radiation ($h\nu = 1253.6$ eV).

3. Results and discussion

The AFM topographies of as-prepared 6H-SiC(0001) surfaces exhibit numerous, randomly oriented scratches of up to 15 nm depth and 150 nm width, arisen during

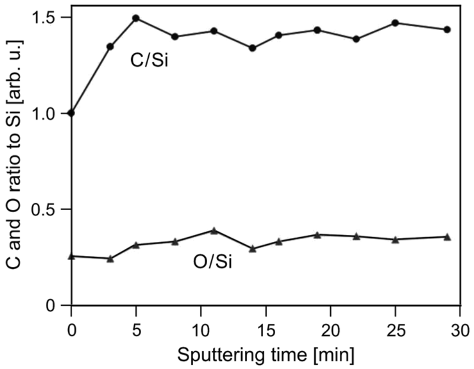

Fig. 1. Changes of chemical composition of the 6H-SiC(0001) surface as a function of Ar^+ sputtering time.

the original polishing process [8]. The residual contaminant of the as-prepared surface is oxygen. The XPS O-1*s* peak indicates an oxygen coverage of about one monolayer. The topographies reveal a smooth, uniform surface with steps of *ca.* 1.5-nm height. Ion bombardment resulted in an amorphous layer on the surface with a grainy structure [11]. Changes of the XPS peak areas show the C/Si ratio increasing with increasing Ar^+ bombardment time. The bombardment did not change the O/Si ratio (Fig. 1). C-enrichment advanced during the first 5 min of bombardment, as the Si should be preferentially removed from the surface under the sputter conditions. The C/Si ratio remained almost constant after further sputtering for up to 30 min, as the likelihood of C removal should rise with surface accumulation of the C. When the C/Si ratio reached 1.4, sputtering was not preferential any longer.

It results from comparison between the Si-2*p*, C-1*s* and O-1*s* XPS peaks of the as-prepared surface and those of the same surface after 30 minutes of ion

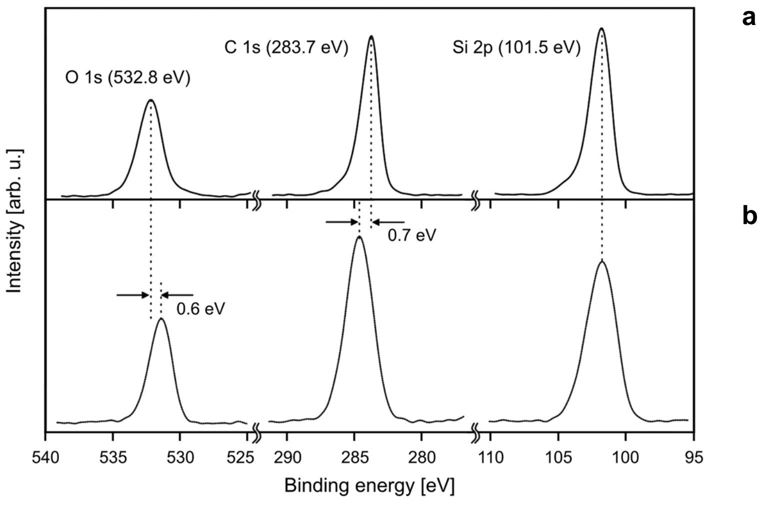

Fig. 2. The O-1*s*, C-1*s* and Si-2*p* peaks of the XPS spectra of (**a**) the as-prepared 6H-SiC(0001) surface and (**b**) the same surface after 30 minutes of sputtering (Ar^+ flux density ~7×10^{-6} A/cm^2).

bombardment (see Figs. 2**a** and 2**b**) that the bombardment does not change the binding energy (BE) of the Si-2*p* electrons. This is in contrast to the BE values of the C-1*s* and O-1*s* electrons, which are shifted by 0.7 eV toward the higher and 0.6 eV toward the lower energy, respectively. The full width at half-maximum (FWHM) of 1.80 eV of the Si-2*p* core level peak increases to 2.64 eV after bombardment. Likewise, the FWHM of C-1*s* peak broadens from 1.46 to 2.26 eV. The FWHM of O-1*s* peak changes insignificantly from 1.97 to 2.05 eV.

The C-shift can be due to an excess carbon present on the surface; we have found a similar effect upon high temperature graphitization of the sample. Surplus of carbon at the surface and subsurface layer favors C−C bond formation, which can cause the shift. The broadening of the peaks as well as the O-1*s* peak shift are also consequences of the surface and near-surface layer enrichment with carbon, which changes the chemical surrounding of the species.

Carbon enrichment and bombardment-induced point defects lower the Schottky barrier of the metal/SiC contact [9, 12]. Alteration of the $I-V$ characteristics from the diode- to ohmic-type was observed for electric contacts formed between the metal tip (AFM probe) and the 6H-SiC(0001) surfaces of different degree of surface modification by Ar^+ bombardment in our previous measurements [9]. Ar^+ modification of the SiC surface leads to the change in surface states of the semiconductor. Extra states arise as a result of the appearance of surface faults and the change in atomic concentration of the surface as well as due to the admixtures such as oxygen and carbon oxide with new donor levels. In the subsurface layer an electron-rich zone emerges, and the number of majority carriers at the surface exceeds that in bulk semiconductor. This leads to energy-band bending and, consequently, to the lowering of the Schottky barrier at the interface metal/semiconductor as observed via $I-V$ measurements.

For bombardment times up to 10 minutes, it was found that the tip/sample contact preserved its rectifying character and the $I-V$ characteristics were strongly nonlinear. For bombardment times longer than 20 minutes, the $I-V$ characteristics of the contact became linear.

In the case of these measurements, the Cr-layers were deposited onto two 6H-SiC(0001) samples whose surfaces were modified by ion bombardment. The first sample was sputtered for 10 minutes. The $I-V$ characteristics taken for it by using the metal tip of our AFM probe were nonlinear, of the diode type. The second sample was sputtered for 30 minutes. In this case, the $I-V$ characteristics were linear. For both samples, in the course of gradual Cr deposition the Cr-2*p* doublet peaks appeared with a BE of 574.7 eV for the Cr-$2p_{3/2}$. The split of the 2*p* doublet amounted to 9.3 eV. The Cr-$2p_{3/2}$ BE value was a little higher than the expected one. This could be due to oxygen present at the surface. During the growth of chromium the C-1*s* and Si-2*p* core-level peaks of the SiC substrate were slowly attenuated. Position of the peaks remained unchanged and their shape did not change significantly, indicating a negligible chemical interaction with the Cr deposit.

CS-AFM inspection of the interface formed by a Cr-layer on the first sample (the short bombardment time) reveals a grainy structure of the contact region.

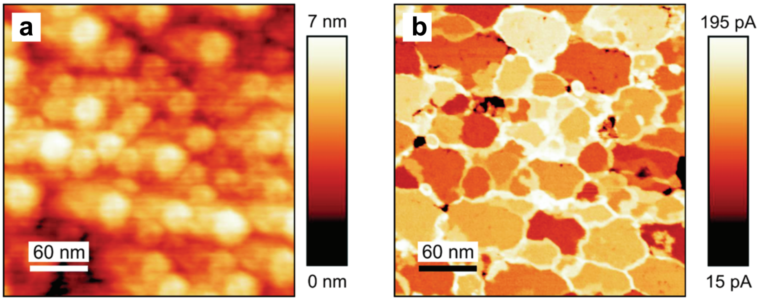

Fig. 3. AFM topography of a Cr layer of average thickness 5 nm, RT evaporated on the 6H-SiC(0001) surface modified by Ar^+ sputtering for 10 minutes (**a**). The current image of the same area obtained at the bias voltage $U = 0.17$ V (**b**).

Figures 3**a** and 3**b** show the topography of a 5 nm thick Cr-layer and the corresponding current image. From both the topography and the image it can be concluded that the adlayer consists of grains. Different conductance magnitudes of the Cr-grain/substrate contacts are imaged as domains of different contrast in the CS pattern. The measurements reveal that the nano-contacts formed by Cr grains have different $I-V$ characteristics.

Depending on the substrate region they are of either diode- or ohmic-type. This heterogeneity results from a non-uniform modification of the surface during ion bombardment. For certain surface regions, the Schottky barrier of the nano-contacts is high and the contacts formed on these areas have a diode-like character. For the others, where the barrier is low, the $I-V$ characteristics of nano-contacts exhibit a linear character. Typical $I-V$ characteristics of both types of the nano-contacts are

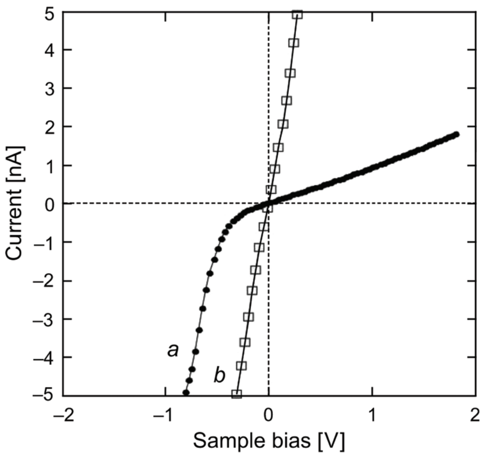

Fig. 4. Current–voltage characteristics of Cr/SiC nano-contacts formed on the Ar^+-modified substrate whose surface was sputtered for 10 minutes prior to Cr deposition. Contact formed by the whole Cr-layer is electrically non-uniform, depending on the surface area of the substrate it changes from the diode-type (*a*) to the linear one (*b*).

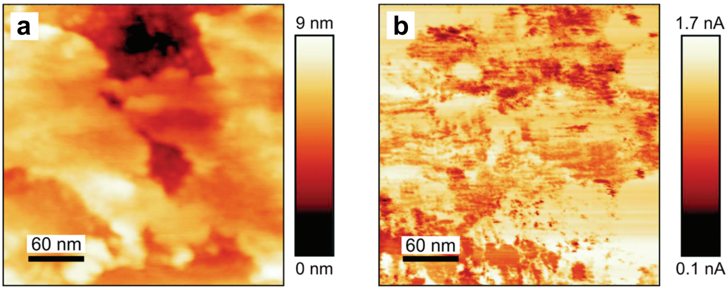

Fig. 5. AFM topography of a Cr layer of average thickness 5 nm, RT evaporated on the Ar^+-modified surface sputtered for 30 minutes (**a**), the corresponding current image obtained for the bias $U = 0.17$ V (**b**).

shown in Fig. 4. Electric contacts formed on the heterogeneously modified substrate are electrically non-uniform. Annealing at 1300 K improves the electrical homogeneity of the nano-contacts resulting in their uniform ohmic behavior. XPS spectra of the annealed contacts show the shift of the C-1*s* peak position to 283.1 eV. This would suggest formation of chromium-carbon compounds at the interface, taking into account that after chromium carbide formation on the graphitized SiC surface, the C-1*s* peak shifts from 284.6 eV (value characteristic of a strongly graphitized SiC surface) to 283.1 eV.

In the case of the second sample pretreated by 30-minute bombardment, the deposited Cr-layers do not display the grainy structure. The substrate surface after longer sputtering is much better wetted by chromium, and the chromium islands formed on the surface are much larger in size than those formed on the first sample (Fig. 5**a**). The current image is less differentiated and does not reveal separate Cr domains (Fig. 5**b**).

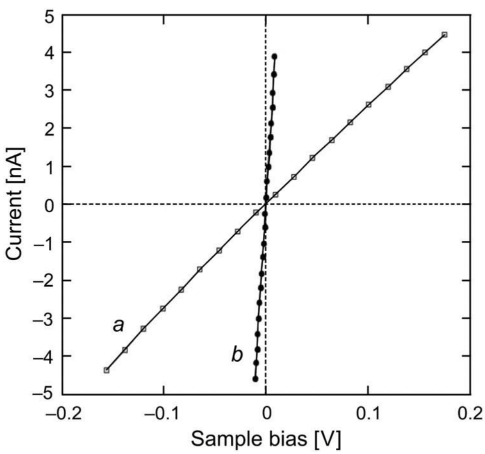

Fig. 6. Current–voltage characteristics of Cr/SiC contact on Ar^+-modified substrate sputtered for 30 minutes. The characteristics *a* and *b* were measured for different sites of the sample. The contact over the whole sample surface has linear characteristics of various conductance.

The whole surface of the sample has the same ohmic character of conductivity, but the electric contact is still non-uniform and the $I-V$ characteristics have different slopes at different surface sites, as shown in Fig. 6. After annealing at 1100 K, the contact becomes electrically uniform and the $I-V$ curves have the same slope in each region of the surface. Also in this case, the shift of the C-1*s* peak indicates that Cr–C bonds are formed at the interface. Formation of the carbide-like chromium-carbon compounds at the interface increases the charge carrier density at the interface and improves its electric conductivity.

4. Conclusions

Owing to the SiC-surface modification made by Ar^+ bombardment, the Cr/SiC ohmic contacts with linear characteristics have successfully been obtained without using the typical high-temperature processing. Reduction of the Schottky barrier height is attained due to carbon enrichment of the surface and the subsurface region. Annealing at 1100–1300 K improves the uniformity of the contact and increases the charge carrier density at the interface by formation of the Cr–C carbide-like species.

Acknowledgements – The authors would like to thank Ryszard Błaszczyszyn, Stanisław Surma, and SONEL S.A. Inc. for cooperation. This study was supported by the Marshal Office of the Lower Silesia Province under GRANT/II/49/2009, which is gratefully acknowledged.

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Received June 19, 2009
in revised form September 25, 2009