Current-sensing AFM Study

Electric Conductance of Ultra-thin Cr Contacts on 6H-SiC(0001)

The easiest imaging mode for measuring the local conductivity of a sample is to combine the current measurements with contact mode Atomic Force Microscopy (AFM) imaging. Current-Sensing Atomic Force Microscopy (CS-AFM) is a powerful technique for electrical characterization of conductivity variation in resistive samples. It allows direct and simultaneous visualization of the topography and current distribution of a sample. In the studies presented in this report the CS-AFM technique has been implemented to study Cr contact formation on the 6H-SiC(0001). Silicon carbide SiC is a wide energy gap semiconductor whose unique properties such as the high melting point, high thermal conductivity or high critical breakdown electric field, offer a good basis for designing electronic components of important devices and make it be attractive for applications in optoelectronic, high-frequency, -power, -voltage, -temperature and -radiation hard microelectronics [1-3]. It is still difficult to prepare silicon carbide based components on an industrial scale. An improvement among others needs to overcome the difficulties in fully mastering the processes of defect-free surface preparation as well as the formation of metal-based contacts.

Motivation

Metal thin films deposited on single crystals of SiC have been studied for a number of metals [4]. Chromium, for its properties, is one of candidates for application to SiC-technology based electronic systems. Depending on the way of processing the surface and the way of metal thin film deposition, the Cr/SiC system can form a rectifying or ohmic contact whose quality is affected largely by the number of defects present at the interface. Although ohmic contacts on SiC have been investigated extensively [5], the mechanism of their formation has been a troublesome issue. The interfacial structures on the atomic scale responsible for forming the ohmic contacts have not been revealed. In our study we followed the growth process and the morphology changes of Cr thin films deposited from vapor
onto an atomically smooth 6H-SiC(0001) surface at room temperature (RT) in order to find out what kind of electrical contact is formed under these conditions.

We were interested how annealing changes the morphology of the Cr thin film and how it affects electrical properties of the contact. The influence of defects and an excess of carbon atoms introduced into the SiC surface by the Ar\(^+\) ion bombardment and vacuum annealing pretreatment was also the subject of our interest.

**Current-sensing Atomic Force Microscopy**

The CS-AFM technique needs cantilevers coated with a conducting film, which operate in the standard AFM contact mode [6]. Applying a voltage bias between the substrate and conducting cantilever generates a current flow. The current can be used to construct a spatially resolved conductivity image. The image is formed for a constant voltage bias and a constant cantilever load. The current image and sample topography are recorded simultaneously. Changing the bias voltage controls the contrast in the current image. Point current-voltage (I-V) characteristics can be measured during scanning the probed surface area for a programmed net of measurement points. CS-AFM allows current measurements in the range from hundreds of femto- to nearly microampere.

**Substrate Preparation and Measurement Details**

Samples, around 3x7 mm\(^2\) in size, were cut out of the nitrogen-doped n-type (resistivity 0.065 Ω⋅cm) 6H-SiC single crystal on-axis, (0001)-oriented Si-terminated wafers (Cree Research Inc.). The substrate surface was ex situ etched in the hydrogen flow tubular reactor to remove the randomly oriented scratches, arisen from the wafer polishing (fig. 1a). The etching procedure yielded an atomically smooth surface (fig.1b). Such prepared substrates were placed in the ultrahigh
vacuum (UHV) apparatus at an operating pressure of $\sim 1 \times 10^{-10}$ torr. In order to remove oxygen a thin layer of silicon was deposited on the surface prior to heating it up to 1000-1500 K. Low Energy Electron Diffraction (LEED) and Scanning Tunneling Microscopy (STM) were used to check out the cleanness of the surface. The surface was assumed clean when characteristic LEED and STM patterns of surface reconstruction [7] were obtained (fig.1c). Cr thin films were formed by UHV vapor deposition on the clean, carbon-excess and defective SiC surfaces. The excess of carbon and surface defects were introduced by $\text{Ar}^+$ ion bombardment. The Cr/6H-SiC interfaces were characterized in situ by CSAFM. The I-V characteristics were measured in the grid mode. The area of probed region was 1 $\mu\text{m}^2$ covered by 6400 measurement points.

**Morphology and Electric Conductance of the Contacts**

The growth of Cr on 6H-SiC(0001) at room temperature follows the Stranski-Krastanov growth mode. The investigation of the local tipsample conductance of the clean SiC surface and adlayer of the mean thickness less than 4.5 nm shows that the current image contrast of electric conduction is weak and strongly correlated with the surface topography. For the 4.5 nm and thicker layers, when the growing Cr islands start to contact each other forming a continuous grainy structured film, the local conductance pattern drastically alters. Insets in figure 2 show a current image for the forward and backward bias. The image is mosaic alike. Each domain has a different conductance. The tip-substrate current through a given grain passes a certain amount of grain boundaries of different conductivity. Different conductance magnitudes of the tip-substrate contact for every grain are imaged in the current patterns as domains. When the tip is in contact with two grains, the conductance of the tip-substrate contact is increased. The rise of the current for these areas is manifested in the current image as a narrow region separating the adjacent domains that emphasizes the “mosaic” contrast of the image.

The electric contact of the Cr-covered conducting tip and Cr/6H-SiC(0001) interface is typical of the rectifying contact. The measured $I-V$ characteristics are strongly asymmetric (fig. 2) due to the Schottky barrier on the semiconductor side, which causes the current blockade in the backward direction. Annealing the Cr/SiC contact at temperatures up to 1800 K leads to coalescence of grains and dissolution of Cr in the substrate. The dissolution essentially disturbs the rectifying character of the electric contact Cr/SiC (fig. 3).

The ion bombardment changes the surface topography. The roughness of the surface, as estimated by the RMS ripple parameter within the 1 $\mu\text{m}^2$ area frame, has decreased with increasing bombardment time. After a longer bombardment (20 min) the surface becomes amorphous and uniform. Contrary to the current image
formed by the conducting cantilever, it shows that the ion bombardment makes the local conductance of the surface highly heterogenic. The \textit{I-V} point characteristics taken after different bombardment times (fig. 4) shows that the conductance character of the contact between the conducting probe (Pt-Ir covered cantilever) and the 6H-SiC(0001) surface changes from the diode- to ohmic type. For short bombardment times (up to 7.5 min) the contact is rectifying. After a longer bombardment (15 min or more) it becomes almost ohmic. Further bombardment leads to a perfect ohmic contact. The Cr films deposited at RT onto the ion-bombarded surface reveal larger grains than in the case of the same thickness films deposited under unchanged conditions onto the non-modified surface (fig. 5). The electric contacts formed on the ion-bombardment-modified surfaces have an ohmic character. Short heating of such contacts at temperatures lower than 1000 K improves their uniformity and enhances the electric conductance.

To conclude, CS-AFM enables one to obtain essential information on the local character and uniformity of the electric contacts metal/semiconductor that is not accessible by other measurement techniques. Surface modification of SiC by ion bombardment opens the possibilities of creating electric ohmic contacts at considerably lower temperatures.

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**References:**


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