Research of Current Mode Atomic Force Microscopy (C-AFM) for Si/SiC Heterostructures on 6H-SiC(0001)

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Abstract: Si/SiC heterostructures with different growth temperatures were prepared on 6H-SiC(0001) by LPCVD. Current mode atomic force microscopy and transmission electron microscopy were employed to investigate the electrical properties and crystalline structure of Si/SiC heterostructures. Face-centered cubic (FCC) on hexagonal close-packing (HCP) epitaxy of the Si(111)/SiC(0001) heterostructure was realized at 900°C. As the growth temperature increases to 1050°C, the <110> preferred orientation of the Si film is observed. The Si films on 6H-SiC(0001) with different growth orientations consist of different distinctive crystalline grains: quasi-spherical grains with a general size of 20 μm, and columnar grains with a typical size of 7 μm×20 μm. The electrical properties are greatly influenced by the grain structures. The Si film with <110> orientation on SiC(0001) consists of columnar grains, which is more suitable for the fabrication of Si/SiC devices due to its low current fluctuation and relatively uniform current distribution.

Key words: Si/6H-SiC heterostructure; electrical properties; current mode AFM; chemical vapor deposition


With a wide band-gap of 3.25 eV–2.2 eV, SiC has attracted much attention because of its wide applications in various optoelectronic and electronic devices[1–4]. However, due to its wide bandgap, SiC is not sensitive to long-wavelength light ranging from most of the visible to the infrared regions of the optical spectrum. This essentially limits its applications for detection of visible and infrared light. A promising way to solve this problem is to adopt a Si/SiC heterostructure, in which Si is used as a non-UV light absorption layer[5,6]. At present, SiC-based Si/SiC heterostructures are comparatively less studied[7–9], and the research is mainly focused on using Si/SiC heterostructures to improve the performance of the SiC SBD[7] or on using Si/SiC heterostructures to solve the problem of SiC/SiO₂ interfacial defect states in SiC MOSFET[8–9]. However, the non-UV photoelectric applications of Si/SiC heterostructures are rarely reported.

In our previous work, it was found that the Si films on SiC substrates always have a polycrystalline structure with multiple preferred orientations at different growth temperatures[10–11]. Hetero-epitaxy with a preferred orientation of <111> can be realized at 825°C–1000°C; the <110> preferred orientation of the Si film is observed when the growth temperature increases...
to 1050°C. However, the electrical properties of epitaxial Si films with different orientations on SiC have not been investigated, which are closely related to the carrier’s transportation and recombination and determine some important properties of hetero-devices such as reverse leakage current and forward current. By exploring the local electrical properties of epitaxial Si films, the relationship between the current distribution and the crystalline structure of a Si/SiC heterostructure can be revealed and the device performance can be optimized. Current mode atomic force microscopy (C-AFM) is a powerful method for characterizing local electrical properties of the semiconductor thin films. This method can probe the overall microstructure of the thin film since the voltage is applied between the sample stage and the C-AFM cantilever to induce current flowing across in the direction of the film’s thickness [12−14]. Applying the voltage, the local current through the Si/SiC heterostructure can be measured by C-AFM with the topographic scan.

In this paper, Si/SiC heterostructures with different growth temperatures were prepared on 6H-SiC(0001) by low-pressure chemical vapor deposition (LPCVD). C-AFM, transmission electron microscopy (TEM), and X-ray diffraction (XRD) were employed to investigate the Si/SiC heterojunctions.

1 Experimental

An n-type isotype Si/SiC heterostructure was prepared on 6H-SiC(0001) substrate by LPCVD. An n-type doped (doping concentration of $10^{17}$ cm$^{-3}$) 6H-SiC wafer with a thickness of 300 μm was purchased from II-VI Inc. The Si films were grown on 6H-SiC substrates at 750°C−1100°C. Silane (SiH$_4$) and hydrogen (H$_2$) were used as a silicon source and a carrier, respectively. Prior to deposition, the 6H-SiC substrates were cleaned using the standard RCA method, and then treated in a H$_2$ atmosphere at 1050°C for 10 min.

The growth pressure is maintained at 300 Pa during the Si/SiC heterostructure growth. In the present work, we describe the results of local topology and electrical measurements with C-AFM (Veeco, NanoScope IIIa) on a Si/SiC heterostructure. A bias voltage between the substrate and the conducting cantilever (which is grounded) was 1.5 V during all imaging experiments. The crystal structure of the Si films was determined using a high-resolution XRD (Rigaku, SmartLab) with Cu K$_α$ radiation (λ = 1.5406 Å). The heterostructure interface was investigated by cross-sectional TEM (JEOL, JEM-3010).

2 Results and Discussion

The low magnification cross-sectional TEM bright-field image of the Si thin film grown on 6H-SiC(0001) at 900°C is shown in Fig.1a. In this image, the lower part belongs to the 6H-SiC substrate, while the upper part represents the Si thin film. Near-spherical grains running across the entire Si film and the coalescence of these grains are observed. The Si film with an inhomogeneous thickness of 0.38 μm−0.60 μm shows irregular heterogeneous diffraction contrast, which demonstrates existence of structural defects such as grain boundaries, stacking faults, and twins in the film. The SAED patterns at the Si/6H-SiC interface corresponding to Si[-110]/SiC[-12-10] zone axes are shown in Fig.1b. The diffraction spots can be categorized into two sets. One has a hexagonal close-packed (HCP) structure with a lattice constant of 3.08 Å, which is identical with the lattice constant of the 6H-SiC. The other belongs to the Si thin film with a face-centered cubic (FCC) structure and <111> growth orientation. SAED patterns confirm that the Si film has epitaxial connection with the 6H-SiC substrate and the out-plane orientation relationship is Si(111)/6H-SiC(0001). Fig.1c shows the low-magnification cross-sectional TEM image of the Si/6H-SiC(0001) heterostructure grown at
1050°C. The Si/SiC heterostructure exhibits a sharp interface and consists of columnar grains. SAED patterns at the Si/6H-SiC interface (Fig.1d) corresponding to Si[001]/SiC[1-100] zone axes clearly show the FCC-on-HCP orientation relationship of Si(110)/6H-SiC(0001), confirming the epitaxial growth of the Si films with [110] orientation.

Fig. 1 TEM image and the SAED patterns of Si/6H-SiC(0001) heterostructure with different growth temperature

Fig. 2 shows the XRD θ-2θ scans for Si/SiC (0001) heterostructures prepared at 900°C and 1050°C. Apart from the SiC(0006) reflection of the substrate, only Si(111) reflection is observed in Fig.2a. When the growth temperature increases to 1050°C, Si(220) reflection appears and becomes the main diffraction peak, as shown in Fig.2b. The lattice mismatch of the Si/SiC heterostructure...
erostructure with the different preferred orientations has been studied elsewhere\textsuperscript{[10−11]}.
It was found that the lattice mismatch for $\langle 111 \rangle$ and $\langle 110 \rangle$ orientations is less than 2\% in the domain matching (DM) mode\textsuperscript{[11]}, which is more stable than the other orientations. This is why these two orientations are preferred at 825°C–1100°C. Due to the higher relaxation energy of the Si(220)/SiC(0001) interface, Si film with $\langle 110 \rangle$ preferred orientation can be fabricated at higher temperature (above 1050°C). Furthermore, the morphology of the grains is related to the preferred orientation and thermodynamic factors such as the temperature gradient along the growth orientation.

The surface morphologies of Si/6H-SiC(0001) heterostructures are characterized by AFM, as shown in Fig.3a and Fig.3b. Crystalline grain with a lateral size of 1 μm–3 μm slightly stick out of the Si surface. And the presence of these

Fig. 3  AFM images of the Si/6H-SiC(0001) heterostructures fabricated at different temperature and schematic diagram of the C-AFM characterization
grains is due to the large lattice mismatch of the Si/SiC heterostructure. The local topography and electrical properties of the Si/SiC heterostructure are characterized by C-AFM. The bias voltage between the substrate and the conducting cantilever was 1.5 V during all imaging experiments (Fig. 3c). Fig. 3d shows C-AFM images of the Si(111)/6H-SiC(0001) heterostructure fabricated at 900°C. The heterogeneous current distribution indicates quasi-spherical grains with a typical size of 20 μm present in the Si (111) film. Compared with the grain size of 1–3 μm observed in Fig. 3a, it is deduced that the quasi-spherical crystalline grains have coalesced. This is consistent with the TEM observations (Fig. 1a and Fig. 1c). The electrical properties are obviously influenced by the coalesced grains. There is a positive current of up to 4 nA at the boundaries of the coalesced grains and a negative current of ~15 nA on the grains. Fig. 3e shows the C-AFM image of the Si(110)/6H-SiC(0001) heterostructure grown at 1050°C. The sample consists of columnar grains with a typical size of 7 μm×20 μm. Compared with the Si(111)/6H-SiC(0001) heterostructure, the positive current at the grain boundaries and the negative current on the coalesced grains are relatively low, and the current distribution is more uniform. It is demonstrated that the Si(110)/6H-SiC(0001) heterostructure with lower current fluctuation is more suitable to fabricate the Si/SiC devices with better electrical properties.

3 Conclusion

Si/SiC heterojunctions with different growth temperatures were prepared on 6H-SiC(0001) by LPCVD. C-AFM and TEM were employed to investigate the electrical properties and crystalline structure of the Si/SiC heterojunctions. A FCC-on-HCP parallel epitaxy is achieved for the Si(111)/SiC(0001) heterostructure with a growth temperature of 900°C. As the growth temperature increases to 1050°C, the <110> preferred orientation of the Si film is observed. The Si films with different growth orientations on 6H-SiC(0001) consist of two distinctive crystalline grains: quasi-spherical grains with a general size of 20 μm, and columnar grains with a typical size of 7 μm×20 μm. The electrical properties are greatly influenced by the grain structures. The Si film with <110> orientation on SiC(0001) consists of columnar grains. With a low current fluctuation and relatively uniform current distributions, it is suitable to be used in preparing Si/SiC devices with better electrical properties.

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