Current mode atomic force microscopy study of Si films grown 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. An 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> preferential orientation of the Si film appears. It is shown that the Si films with different growth orientations on 6H-SiC(0001) have two types of distinctive crystalline grain structures: quasi-spherical grains with a general size of 20μm, and columnar grains with a typical size of 7×20μm. 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, Si(110)/6H-SiC(0001) heterostructure is more suitable to prepare the Si/SiC devices with better electrical properties.

Keywords: Si/6H-SiC heterostructure; Electrical properties; Current mode AFM; Chemical vapor deposition

1. Introduction

With a wide bandgap of 3.25–2.2eV, SiC has attracted much attention because of its wide applications for 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

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The infrared region of the optical spectrum. This essentially limits its applications for detection of visible and infrared light\textsuperscript{[5]}. 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\textsuperscript{[6, 7]}. At present, the SiC-based Si/SiC heterostructure is comparatively less studied\textsuperscript{[8-11]}, and the studies just focused on using Si/SiC heterostructure to improve the performance of the SiC SBD\textsuperscript{[9]}, or using Si/SiC heterostructure to solve the problem of SiC/SiO\textsubscript{2} interface defect states in SiC MOSFET\textsuperscript{[10, 11]}, the non-UV photoelectric applications of the Si/SiC heterostructure are rarely reported.

In our previous work, it was found that the Si films on SiC substrates always have a polycrystalline structure with multiple preferential orientations at different growth temperatures\textsuperscript{[12, 13]}. Preferential growth orientation of $\langle 111 \rangle$ can be achieved in a temperature range of 825–1000°C, the $\langle 110 \rangle$ preferential orientation of the Si film appears when the growth temperature increases to 1050°C\textsuperscript{[11]}. However, the local electrical properties of the epitaxial Si films with different orientations on SiC have not been investigated, which are closely related to the carrier transportation and recombination, and determine some important parameters of the heterostructure devices such as the reverse leakage current and conducted current. By exploring the local electrical properties of the epitaxial Si films, the relations between the current distribution and the crystalline structure of the 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 the current flowing across in the direction of the film thickness\textsuperscript{[14-16]}. With applying the voltage, the local current through the Si/SiC heterostructure can be measured by C-AFM with the topographic scan.

In this paper, the 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.
2. Experimental

The n-type isotype Si/SiC heterostructure was prepared on 6H-SiC(0001) substrate by LPCVD. An n-type doped (doping concentration of \(\sim 10^{17} \text{cm}^{-3}\)) 6H-SiC wafer with a thickness of 300\(\mu\)m was purchased from II-VI Inc.. The Si films were grown on 6H-SiC substrates at 750°C~1050°C. Silane (SiH₄) and hydrogen (H₂) are 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 H₂ atmosphere at 1050°C for 10min. The growth pressure is maintained at 300Pa during the Si/SiC heterostructure growth. In the present work, we describe results of local topography and electrical measurements with C-AFM on Si/SiC heterostructure. A bias voltage between the substrate and the conducting cantilever (which is grounded) was 1.5V during all imaging experiments, and the scheme of the experimental setup for C-AFM measurements is shown in Fig. 1. The crystal structure of the Si films was determined using a Rigaku SmartLab high-resolution X-ray diffractometer (XRD) with Cu Kα radiation (\(\lambda=1.5406\text{Å}\)). The heterostructure interface was investigated by cross-sectional TEM (JEM-3010).

3. 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. 2(a). 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 0.38–0.60\(\mu\)m shows irregular heterogeneous diffraction contrast, which suggests the existence of some structural defects such as grain boundaries, stacking faults and twins in the film. And these defects could lead to the differences of the current distributions. The SAED patterns at the Si/6H-SiC interface corresponding to Si[-110]SiC[-12-10] zone axes are shown in Fig. 2(b). The diffraction spots can be categorized into two sets. One has a hexagonal close-packed structure with a lattice constant of 3.08Å, which is identical with the corresponding lattice constant of the 6H-SiC. The other belongs to the Si film with a face-centered cubic structure and \(<111>\) growth orientation. SAED patterns confirm that the Si film has epitaxial connection with the 6H-SiC substrate and the orientation relationship of Si/6H-SiC heterostructure.
is Si(111)/6H-SiC(0001). Fig. 2(c) is a low magnification cross-sectional TEM image of the Si/6H-SiC(0001) heterostructure grown at 1050°C. The Si/SiC heterostructure has a sharp interface and consists of columnar grains. SAED patterns at the Si/6H-SiC interface corresponding to Si[001]/SiC[1-100] zone axes in Fig. 2(d) clearly show the FCC-on-HCP orientation relationship of Si(110)/6H-SiC(0001), confirming the epitaxial growth of the Si films with [110] growth orientation.

Figure 3 shows the XRD θ-2θ scans for Si/SiC(0001) heterostructures prepared at 900°C and 1050°C, respectively. As shown in Fig. 3(a), apart from the SiC(0006) reflection of the substrate, only the Si(111) reflection was observed. No trace of the Si(220) reflection was detected. When the Si was grown at 1050°C the diffraction pattern was different. Figure 3(b) shows the prominent presence of the Si(220) reflection. The intensity of the Si(111) reflection, on the other hand, is much reduced. It is shown that when the Si was deposited at the lower temperatures of 900°C, the Si film is <111> oriented, but when the Si layer was grown at 1050°C, it is mainly <110> oriented, which agrees with the SAED characterizations.

The surface morphologies of the Si/6H-SiC(0001) heterostructures were carefully examined using AFM, as shown in Fig. 4. The grain growth mode is observed in Si layers deposited on 6H-SiC(0001) substrate with different temperatures. Crystalline grain with a lateral size of 1~3 μm slightly stick out of the Si surface. And the presence of these grains is due to the large lattice mismatch of the Si/SiC heterostructure. Fig. 5(a) shows C-AFM measurements of the Si(111)/6H-SiC(0001) heterostructure with applying positive 1.5V at the 6H-SiC substrate. The heterogeneous current distributions indicate quasi-spherical grains with a typical size of 20μm present in the Si(111)/6H-SiC(0001) heterostructure. Compared with the grain size of 1~3μm observed in Fig. 4(a), it is deduced that the crystalline grains have been coalesced. This is consistent with the TEM observations. The electrical properties are greatly influenced by the coalesced grains. There are obvious positive current of up to 4nA at the boundaries of the coalesced grains and negative current of about 15nA on the coalesced grains. Fig. 5(c) shows the C-AFM images of Si(110)/6H-SiC(0001) heterostructure grown at 1050°C. The sample consists of columnar grains with a typical size of 7×20μm. 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 distributions are more uniform. It is demonstrated that the Si(110)/6H-SiC(0001) heterostructure with a low current fluctuation is more suitable to prepare the Si/SiC devices with better electrical properties.

4. Conclusions

In this article, 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 Si/SiC heterojunctions. An 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> preferential orientation of the Si film appears. It is shown that the Si films with different growth orientations on 6H-SiC(0001) have two types of distinctive crystalline grain structures: quasi-spherical grains with a general size of 20μm, and columnar grains with a typical size of 7×20μm. 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 more suitable to prepare the Si/SiC devices with better electrical properties.

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Fig. 1 Si/6H-SiC heterostructure and scheme of the C-AFM experiments.
Fig. 2 Low magnification cross-sectional TEM image and the SAED patterns of Si/6H-SiC(0001) interface. (a, b) Si/SiC heterostructure grown at 900°C, (c, d) Si/SiC heterostructure grown at 1050°C. The SAED patterns at the Si/6H-SiC interface corresponding to Si[-110]SiC[-12-10] and Si[001]SiC[1-100] zone axes, respectively.
Fig. 3 X-ray specular 0-20 scans for Si/SiC(0001) heterostructures with the Si layer grown at (a) 900°C, (b) 1050°C
Fig. 4 AFM images of Si/SiC(0001) heterostructures with the Si layer grown at (a) 900°C, (b) 1050°C
Fig. 5 C-AFM images of Si/SiC(0001) heterostructures with the Si layer grown at (a, b) 900°C, (c, d) 1050°C