Low-temperature epitaxial growth of β-SiC by multiple-energy ion implantation

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A cubic silicon carbide (β-SiC) buried layer was synthesized in Si(111) using a combination of multienergy carbon ion implantation at room temperature and post-thermal annealing. The crystal structure and the crystalline quality of the β-SiC layer was identified by x-ray diffraction in the θ–2θ mode and was examined by pole figure measurement of x-ray diffraction. Interestingly, by using the multienergy implantation technique, the β-SiC buried layer showed epitaxial growth at annealing temperatures as low as 400 °C. At an annealing temperature of 800 °C, the x-ray pole figures show that the β-SiC buried layer has a near-perfect epitaxial relationship with the silicon substrate. [S0163-1829(98)02843-4]

Silicon carbide is a promising candidate material for device applications due to its outstanding properties such as wide band gap, high-temperature stability and high thermal conductivity, radiation hardness and chemical inertness, etc.[1,2] Considerable effort has been devoted to developing and improving methods to produce silicon carbide with high purity and good crystalline quality. Among these methods, high-dose carbon implantation into silicon in combination with subsequent or *in situ* thermal annealing, namely, ion beam synthesis (IBS), has been proven a powerful means of synthesizing polycrystalline or epitaxial β-SiC in silicon.[3,4] In accordance with the previous studies, the key factor that determines the crystalline quality of the β-SiC layer by IBS is the annealing temperature.[5] It seems to be clear from the published results to date that annealing temperatures between $\approx$850 and 900 °C are needed to crystallize the implanted Si-C layer and transform the disordered Si-C bonds into the ordered β-SiC structure.[6,7] However, other authors demonstrate that much higher annealing temperatures, e.g., 1000,[8] 1250,[9] and 1405 °C (Ref. 10) are demanded to achieve crystalline silicon carbide layer in silicon. It has been reported also that other conditions like the implantation temperature[11] and the implanted carbon dose[9] might have some influence on the growth of the buried silicon carbide layer. Therefore, more systematic work is required for successful application of IBS to synthesize SiC.[5]

Recently, a multienergy ion implantation approach has been proposed to produce thick silicon carbide layer in silicon, and to modify its composition profile.[12] By selecting carefully the implantation energy and dose of carbon ions, a rectangular carbon concentration profile can be achieved for the buried β-SiC layer using this approach.[12] It is therefore applicable in device fabrications now that the β-SiC layer is able to grow epitaxially at low annealing temperatures.

We report, in this paper, the epitaxial growth of the β-SiC buried layer in silicon at low annealing temperatures by using this multienergy ion implantation technique.

A silicon wafer of (111) orientation was used as a substrate for multienergy carbon ion implantation. Using TRIM simulation, three different energies, i.e., 160, 100, and 60 keV, and three corresponding doses, i.e., 1×10^{18}, 9×10^{17}, and 5.3×10^{17} C^+/cm^2, were selected for the implantation. The beam current density of the carbon ions was controlled in the range of 9–12 $\mu A/cm^2$, which results in a target temperature of about 335–365 °C due to the beam heating effect. The implanted samples were then annealed in argon flux at temperatures from 400–1200 °C for 10 h to allow the growth of crystalline silicon carbide. After annealing, all samples were analyzed by x-ray diffraction in the θ–2θ mode to identify the structure and by the pole figure measurement of the x-ray diffraction to examine the crystalline quality of the SiC buried layer.

X-ray diffraction analysis in the θ–2θ configuration was carried out using a precise x-ray diffractometer with a resolution of 0.002°. The x-ray-diffraction pattern was obtained using a step of 0.02° with Cu $K\alpha1$. The Cu $K\alpha2$ was filtered by a monochromator. Figure 1 shows the diffraction pattern

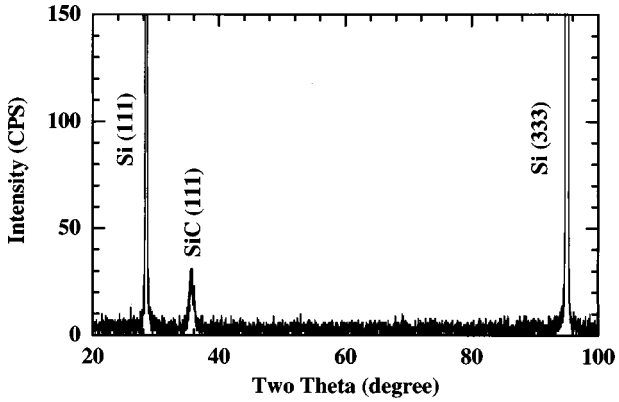

FIG. 1. The x-ray-diffraction pattern of the β-SiC buried layer formed after 10 h annealing at 800 °C, showing clearly the β-SiC (111) peak.

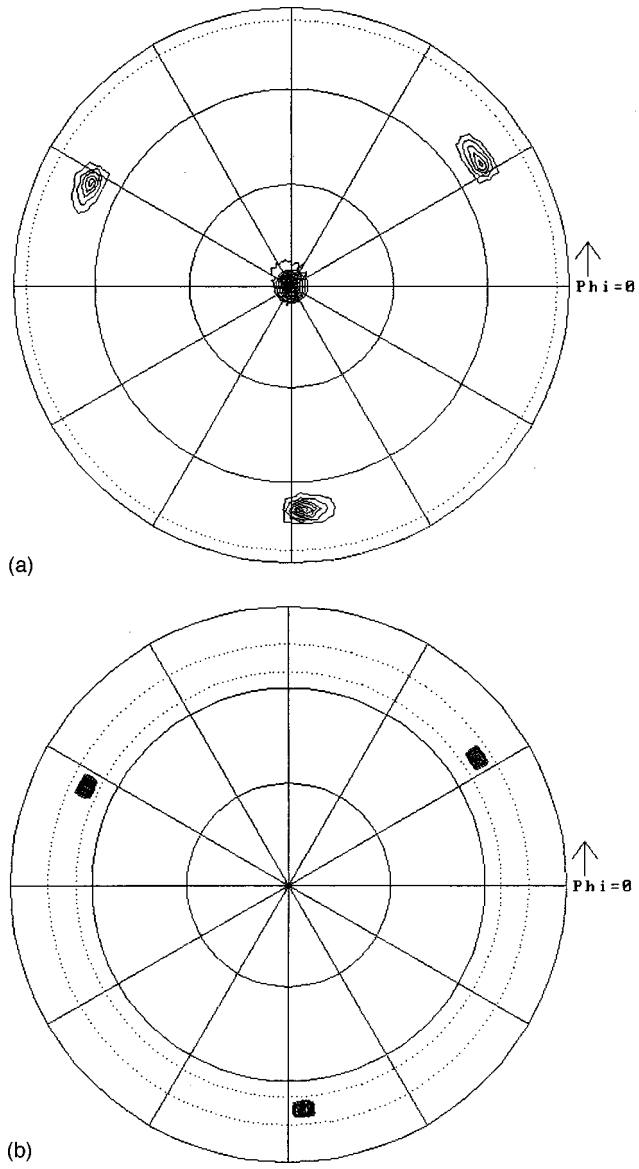

FIG. 2. The (111) pole figures of (a) the β-SiC buried layer and (b) the silicon substrate after 10 h annealing at 800 °C. The contour lines show the diffraction intensity divided into 10 segments. The dashed circles show the range of the tilt angle.

of the sample annealed at 800 °C. One can see clearly from the figure the (111) diffraction peak of β-SiC at about $2\theta = 35.6°$. This suggests that crystalline β-SiC was formed in the sample. It is also noticed that other diffraction peaks of β-SiC, e.g., (200) at about $2\theta = 41.4°$ and (220) at about $2\theta = 60.0°$, were not observed in this diffraction pattern. This suggests that the β-SiC layers probably grow epitaxially.

The crystalline quality of the β-SiC buried layer was then examined by pole figure measurement of the x-ray diffraction with a Philips X'pert four-circle x-ray diffractometer. To investigate the orientation relationship with the substrate, three pole figures, i.e., (111), (200), and (220), were measured by fixing the detector at 2θ positions of 35.6766°, 41.4302°, and 60.0315°, respectively. The pole figures were obtained by scanning the tilt angle, i.e., χ from 0°–85°, and the azimuth rotation angle φ from 0°–360°. For comparison, the (111) pole of the silicon substrate was also obtained in a χ range of 65.53°–75.53° by fixing the detector at 2θ of

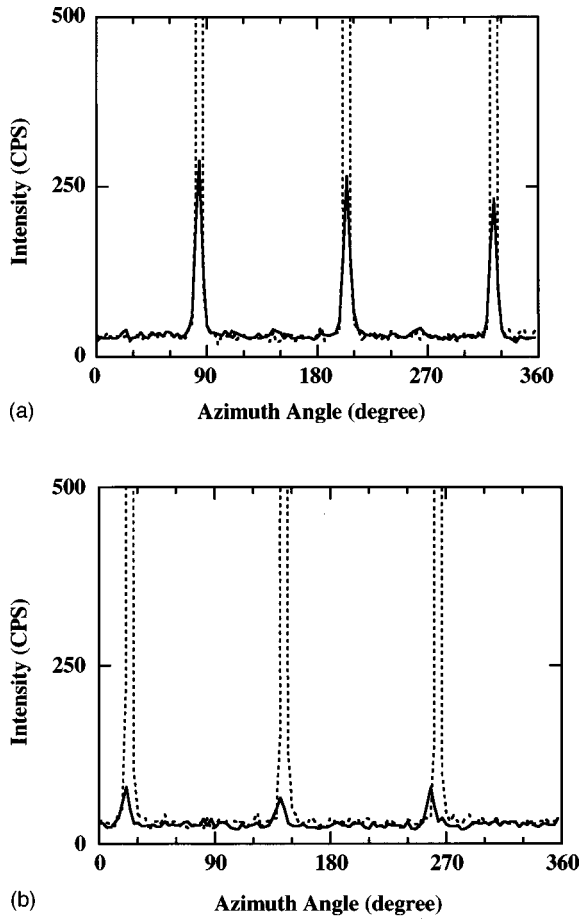

FIG. 3. The φ scan of (111) and (200) poles of the β-SiC and (111) and (400) poles of the silicon substrate annealed at 400 °C: (a) (111) and (b) (200) or (400). The solid and dotted lines stand for the data of the β-SiC and the substrate, respectively.

28.4651°. Figures 2(a) and 2(b) show, respectively, the (111) pole figures of the β-SiC and the substrate after 10 h annealing at 800 °C. It is noticed that the {111} β-SiC peaks show exactly the symmetrical points of (111) of the cubic structure where the angle between {111} is about $\chi = 70.53°$. The {111} β-SiC and Si peaks differ only in their width and intensity, but locate at the same χ and φ positions. This suggests that the β-SiC be well aligned to the silicon substrate. The x-ray (200) and (220) pole figures were also measured for the β-SiC layer. In the two figures, the {200} and {220} peaks locate also at the exact positions of the symmetrical points of (200) and (220) of the cubic structure where the angles between (111) and (200), (111) and (220) are about $\chi = 54.74°$ and 35.26°, respectively. It is therefore concluded that the β-SiC layer has a near-perfect orientation relationship with the substrate, i.e., $(111)_{\beta\text{-SiC}} // (111)_{\text{Si}}, [110]_{\beta\text{-SiC}} // [110]_{\text{Si}}$.

This orientation relationship was also observed at low temperatures, e.g., 400 °C. The (111) and (200) poles of the β-SiC and the (111) and (400) poles of the substrate were also measured for the sample annealed at 400 °C. Figures 3(a) and 3(b) show the comparison of the φ scans from 0–360° at the tilt angles of $\chi = 70.53°$ and 54.74° for (111), (200), or (400), respectively. It is seen that the {111} and {200} peaks of the β-SiC and {111} and {400} peaks of the substrate locate at almost the same φ positions, although their intensity is sharply different. These results confirm

that the orientation of the major portion of the β-SiC is in strong coincidence with the substrate orientation: $(111)_{\beta\text{-SiC}}//(111)_{\text{Si}}$ and $[110]_{\beta\text{-SiC}}//[110]_{\text{Si}}$.

In conclusion, epitaxial growth of crystalline β-SiC buried layer was achieved by a multienergy implantation technique. The annealing temperature necessary for the epitaxial growth was found to be as low as 400 °C. In the sample annealed at 800 °C, the β-SiC layer has a near-perfect orientation relationship with the substrate.

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