Electrical and optical properties of Ge–implanted 4H–SiC

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The structural, electronic, and optical properties of single crystalline *n*-type 4H–SiC implanted with Ge atoms have been investigated through x-ray diffraction (XRD), Rutherford backscattering spectroscopy (RBS), Raman spectroscopy, and sheet resistivity measurements. Ge atoms are implanted under the conditions of a 300 keV ion beam energy with a dose of $2\times10^{16}\,\mathrm{cm}^{-2}$. X-ray diffraction of the Ge-implanted sample showed broadening of the Bragg peaks. A shoulder on the (0004) reflection indicated an increase in the lattice constant corresponding to substitutional Ge and implantation induced lattice damage, which was repaired through thermal annealing at 1000 °C. The diffraction pattern after annealing indicated improved crystal structure and a peak shift to a lower reflection angle of 35.2°. The composition of Ge detected through XRD was reasonably consistent with RBS measurements that indicated 1.2% Ge in a 1600-Å-thick layer near the SiC surface. Raman spectroscopy also showed fundamental differences in the spectra obtained for the Ge-implanted SiC (SiC:Ge) compared to a pure sample of SiC. Sheet resistivity measurements indicate a higher conductivity in the Ge implant by a factor of 1.94 compared to unimplanted SiC. These results have demonstrated the possibility of substitutional implantation of Ge atoms into the crystalline lattice of 4H–SiC substrates. The change in composition and properties may have numerous electronic device applications including high power, high temperature, optoelectronic, as well as high frequency device structures.
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The single crystalline SiC substrate investigated for the Ge implantation is *n*-type nitrogen doped to $2.5\times10^{18}\,\mathrm{cm}^{-3}$, is 421.6 μm thick, and is from Cree Research, Inc. The sample was cleaned prior to implantation and analysis with a standard chemical rinse of methanol, acetone, and deionized water. The SiC substrate was ion implanted uniformly with Ge atoms from a hot filament electron bombardment ion source with an ion mass spectrometer for a period of 2000 s. The ion energy during the implant was 300 keV and the fluence was $2\times10^{16}\,\mathrm{cm}^{-2}$. The ion current was 1.5 μA, providing a current density of about 1 $\mu\mathrm{A/cm}^2$. It is estimated that the SiC substrate reached a steady state temperature of 50 °C during the implantation process. Post implantation annealing was performed with an AG Associates Heatpulse 610 rapid thermal annealer (RTA) with forming gas ambient consisting of 85% H_2 and 15% N_2. Experimental characterization of the SiC and SiC:Ge samples was carried out with x-ray diffraction (XRD), Rutherford backscattering spectroscopy (RBS), Raman spectroscopy, and sheet resistivity measurements.

XRD measurements were made with a Philips X-pert diffractometer utilizing the Cu $K_{\alpha1}$ wavelength in the symmetrical Bragg configuration at low resolution as described previously.[1] XRD results of the pure SiC and SiC:Ge-implanted samples have indicated distinct differences in the region representing the (0004) Bragg reflection ($2\theta=35.7°$) of the hexagonal 4H–SiC. The XRD data of the 4H–SiC and Ge-implanted 4H–SiC (SiC:Ge) is similar for the two samples including an intense x-ray peak at 35.695°. This peak is associated with the (0004) plane of 4H–SiC, which has also demonstrated strong reflection characteristics in XRD analysis by other researchers.[2] For the as-implanted SiC:Ge sample the XRD plot of Fig. 1 shows a subtle feature near 35.2°. Analysis of this feature indicates a defective 4H–SiC layer with slight compressive strain induced by the Ge in the lattice. For the SiC:Ge sample annealed at 1000 °C for a period of 1 min, the x-ray pattern of Fig. 1 shows a sharpened peak centered around 35.695°, indicating an improved

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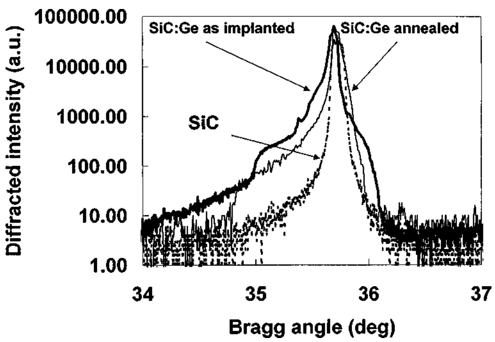

FIG. 1. Bragg (0004) reflections comparing (a) SiC:Ge as-implanted sample (thick solid line), (b) pure SiC (dashed line), and (c) SiC:Ge sample after RTA anneal at 1000 for 1 min, which indicated improved crystallinity of the annealed SiC:Ge compared to as-implanted sample.

SiC:Ge layer with fewer defects. The shift toward the direction of 35.2° indicates a substitutional Ge content of about 4% applying Vegard's law. This value of Ge concentration is somewhat larger than that obtained from RBS, which indicates a Ge content of approximately 1.2%.

Rutherford backscattering spectroscopy data with 2 MeV He^+ ions was obtained for the pure SiC and SiC:Ge samples along with theoretical results from Rutherford Universal Manipulation Program (RUMP) simulations.[3] Fitting the experimental RBS data to RUMP simulations was carried out iteratively for the purposes of determining the content of Ge atoms in the SiC:Ge layer as well as the layer thickness of SiC:Ge on the surface of the 4H–SiC, both of which are important for determining the electrical and optical properties. RBS results for the pure SiC, as-implanted SiC:Ge, and SiC:Ge annealed at 1000 °C, are given in Fig. 2. The Ge concentration and SiC:Ge layer thickness were determined to be 1.2% and 1600 Å, respectively, as indicated by RUMP simulation results shown in Fig. 2(b). These results closely match the experimental data obtained by RBS, as well as calculations performed with TRIM based on the implant conditions. There was no detectable change in the RBS data taken on the annealed SiC:Ge compared to the as-implanted sample [see Fig. 2(c)].

Raman spectra for pure and Ge ion-implanted SiC are illustrated in Fig. 3 which were obtained with incident polarized laser light having a wavelength of 785 nm. Figure 3 shows three different spectra having varied sample properties. The spectra for pure 4H–SiC has distinct Raman peaks at 205, 770, and 970 cm^{-1}. These well-defined bands are also strongly evident in the Ge-implanted SiC:Ge sample and they are believed to be associated with Si and C vibrational modes. Similar Raman spectra have also been reported for Si and C solid state structures previously.[4] The two other spectra in the figure are for the SiC:Ge sample after an RTA cycle at 800 °C for 1 min, and the other after annealing the SiC:Ge at 1000 °C for 1 min. The Raman spectrum of the as-implanted SiC:Ge sample prior to RTA annealing were badly distorted by broadening and band amplification across the entire region of interest (possibly due to fluorescence of the damaged material surface), and was not included here. Annealing with the RTA did have a strong influence on the resultant Raman spectra and the degree of fluorescence observed in the SiC:Ge sample, illustrated by the noticeably large differences in the Raman spectra shown in Fig. 3. The

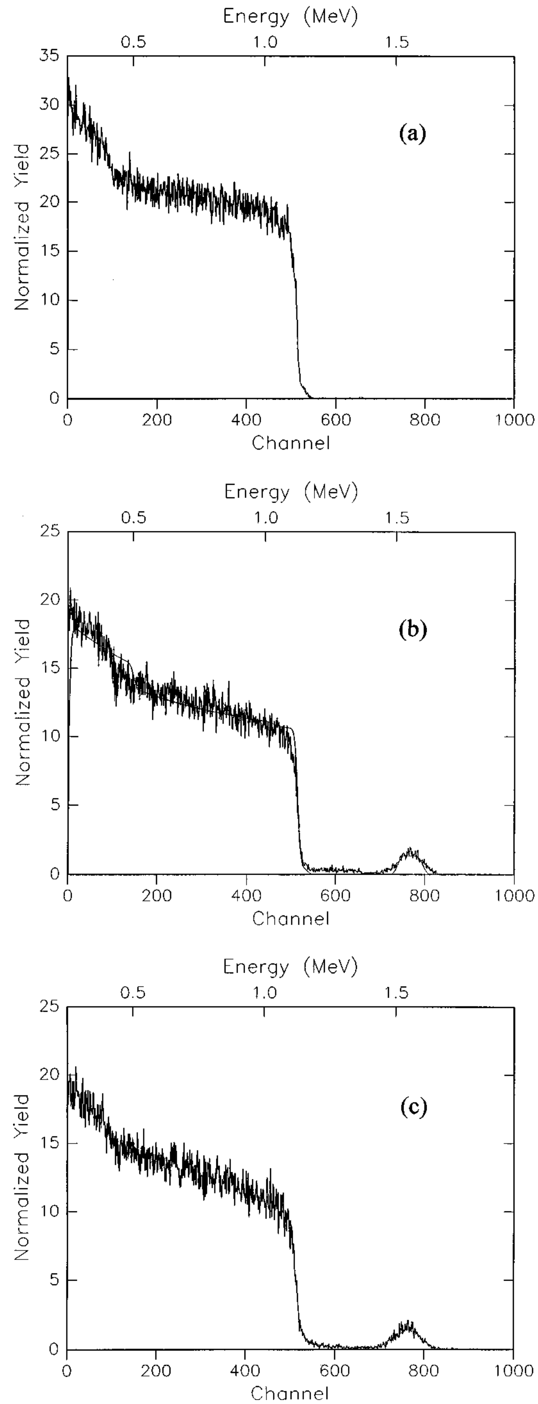

FIG. 2. (a) 2 MeV He^+ ion backscattering spectroscopy of pure SiC substrate prior to Ge implantation showing scattering from Si near 1.2 MeV and C near 0.4 MeV. (b) 2 MeV He^+ ion backscattering spectroscopy of Ge implanted SiC:Ge showing the Ge peak near 1.6 MeV. (c) 2 MeV He^+ ion backscattering spectroscopy of SiC:Ge after RTA annealing. The spectra relative ion intensity remain unchanged after annealing compared to the as-implanted SiC:Ge.

reduction of the fluorescence effect is believed to be attributable to thermally repairing crystalline damage induced by the ion implantation process itself. The repairing of implantation induced crystalline damage through high temperature annealing in SiC has been well documented.[5,6] Without additional experiments, though, it is difficult to determine the degree to which lattice damage has been sufficiently repaired and can be neglected, as well as the point at which optimal Ge substitutional implantation has occurred.

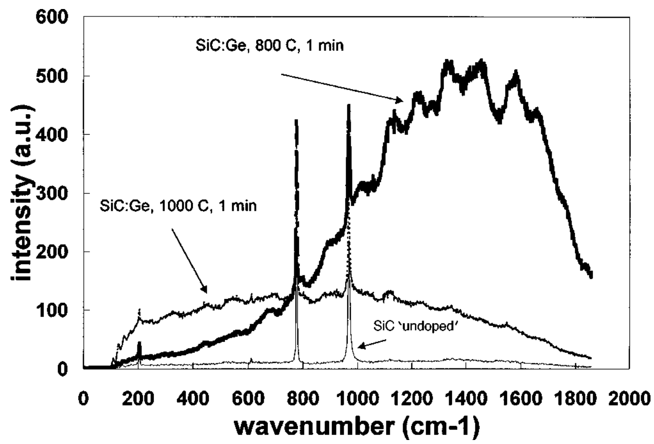

FIG. 3. Raman spectra of (a) SiC:Ge after 800 °C 1 min RTA anneal, (b) pure SiC, and (c) SiC:Ge after 1000 °C 1 min anneal. Measurements show large amplitude Raman signal in most of the spectra for the sample annealed at 800 °C probably due to implantation induced defects, which is greatly reduced after the 1000 °C RTA anneal. The pure SiC sample show distinct peaks at 205, 770, and 970 cm^{-1}.

The sheet resistivity of the SiC:Ge sample was determined qualitatively by four point–probe measurements. The four point–probe measurements were performed in two different spatial regions of the SiC:Ge sample and compared to results obtained on a pure SiC sample. The measurements were made on the SiC:Ge sample just after Ge implantation and prior to annealing. For the pure SiC and the SiC:Ge, the apparatus indicted an average sheet resistance of 584.75 and 301.35 Ω/□, respectively, indicating the conductivity of the Ge-implanted material is nearly twice that of SiC.

The substitutional implantation of Ge in SiC may play an important role in the electronic and optical properties required for several electronic device applications including those of high power, high frequency, and optoelectronics. The experimental observations to date on the ion-implanted SiC:Ge sample investigated here include fundamental differences compared to those of pure SiC. For example, our measurements have shown that the x-ray diffraction pattern near the (0004) reflection in ion-implanted SiC:Ge is significantly modified in comparison to that of the pure sample of 4H–SiC. The altered x-ray pattern is believed to be caused by the implantation of substitutional Ge atoms and the subsequent introduction of strain into the SiC lattice. The affect of thermal annealing at 1000 °C for 1 min has resulted in improved crystallinity compared to the as-implanted sample and the shift near the (0004) reflection toward 35.2 deg is still evident. However, additional measurement with annealed samples will be required in order to separate the affects of substitutional Ge implantation and implantation induced crystalline damage. RBS measurements taken immediately after ion implantation of Ge indicate a shallow layer of approximately 1600 Å containing 1.2% Ge atoms, which are not altered by the RTA annealing that was performed. Raman spectroscopy has revealed surface damage in the as implanted SiC:Ge, but there is also strong evidence that lattice damage, as indicated by fluorescence in the Raman spectra, is greatly reduced by thermally annealing the material after implantation. Finally, the as-implanted SiC:Ge sample has been shown to have a surface conductivity nearly twice that of SiC. This result was determined from standard four point–probe resistivity measurements.

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