Strained SiC:Ge Layers in 4H SiC formed by Ge Implantation

M.W. Dashiell, G. Xuan, Xin Zhang, E. Ansorge and J. Kolodzey

Department of Electrical and Computer Engineering
University of Delaware
Newark, DE 19716

ABSTRACT

The ion implantation of germanium into 4H-SiC at 1000 ^{o}C resulted in crystalline SiC:Ge layers that are coherently strained to the (0001) oriented 4H-SiC substrates. Germanium implantation energies of 140 keV and 50 keV were chosen to form approximately 100nm thick step-like SiC:Ge layers with Ge atomic fractions ranging from 0.0007 to 0.006. High-resolution x-ray diffraction (HRXRD) and reciprocal space mapping reveal a high-quality, compressively strained SiC:Ge layer. High-temperature annealing resulted in partial relaxation of the macroscopic layer strain, however the SiC:Ge layer remained strained with a coherent interface for annealing up to at least 1650^{o}C.

Because Ge is a group-IV atom like Si and C, its incorporation into the lattice is expected to act as an isoelectronic impurity, rather than a charged donor or acceptor. Thus, high-quality, SiC:Ge layers have the potential for bandgap and strain engineered electronics such as SiC-based high electron mobility transistors (HEMTs) for RF-power electronics. Currently there is no established heterojunction pair in SiC material technology for fabricating HEMTs and other heterojunction devices.

INTRODUCTION

Silicon carbide is an important wide bandgap semiconductor whose intrinsic properties make it suitable for high-temperature and high-power microwave devices [1-2]. Unlike III-V wide bandgap materials however, the lack of a well developed SiC-based heterostructure system limits the ultimate performance of SiC devices compared to nitride based high bandgap devices such as the AlGaN/GaN high-electron-mobility-transistor (HEMT). Recently there have been a number of investigations of the material and structural characteristics of semiconductor SiC after implanting Ge ions into the SiC crystal. Depending on the implantation and post-implant conditions, the resulting layer may exhibit one or more of the following: (1) amorphization due to heavy radiation damage, (2) re-crystallization into one of several different SiC polytypes, or (3) phase separation of Ge nanocrystals embedded within the SiC lattice [3-4]. There has been little experimental work to date however on the use of Ge ion-implantation to form a dilute substitutional SiC:Ge alloy as discussed in [5]. Although the group IV elements such as Ge are immiscible in crystalline SiC under equilibrium conditions, the addition of a few atomic percent Ge to form a metastable alloy would offer additional flexibility for high-bandgap SiC electronics by introducing a new group IV material for enabling heterostructure concepts.

In this paper we present high-resolution x-ray diffraction measurements of pseudomorphic SiC:Ge layers synthesized on the technologically relevant 4H-SiC substrate.

Dilute Ge contents (on the order of 1 percent) were chosen so that layer strains were not so large as to prevent the formation of coherent interfaces. Metastable SiC:Ge layers were formed with coherent interfaces to the SiC substrate by Ge ion implantation at elevated temperatures. Although ion implantation may not be the optimal growth technique to form thin epitaxial layers, it is a reasonable technique to incorporate immiscible atoms into a host lattice at concentrations far in excess of their solubility limit. We note that ion-implantation/solid phase epitaxy was one of the early synthesis techniques which lead to the considerable international research effort on metastable $Si_{1-x-y}Ge_xC_y$ alloys on Si substrates (in this case C was the immiscible atom)[6].

EXPERIMENTAL

Silicon carbide (0001) wafers (4H-SiC, ρ=0.059Ωcm) from Cree Research were implanted at 1000^{o}C using 140keV and 50keV Ge^+ ions. The implantation conditions formed a step-like Ge profile starting at the surface and extending ~130 nm into the substrate, predicted from SRIM (Stopping and Range of Ions in Matter) simulations as in Figure 1. This profile was confirmed with Rutherford Backscattering Spectrometry (RBS). The HRXRD spectra were measured with a Phillip's X'Pert diffractometer equipped with a four-crystal Ge (220) monochromator and Ge channel-cut analyzer on the primary and detector optical arms respectively Annealing experiments were performed under Ar purge, in a closed tube furnace for 10 minutes, not including the ramp up/cool down cycle.

Figure 2 displays the symmetric (0004) HRXRD spectra from SiC:Ge samples with Ge concentrations ranging from approximately 0.07 to 0.6 atomic percent (the implant doses are given in the figure caption). The spectra of figure 2 reveal well resolved low-angle diffraction features relative to the (0004) 4H-SiC substrate peak. The lowest-angle/maximum-intensity SiC:Ge-related diffraction peak of each spectrum is interpreted as the Bragg reflection from a compressively strained SiC:Ge layer having perpendicular lattice plane spacing (i.e. along the c-axis) greater than that of the SiC substrate. The oscillations between the substrate and the lowest

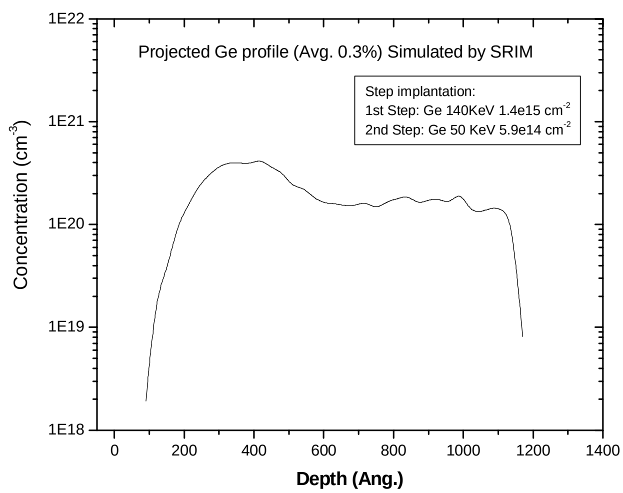


Figure 1. Projected Ge implant profile from SRIM. Average Ge content is 0.35 atomic percent.

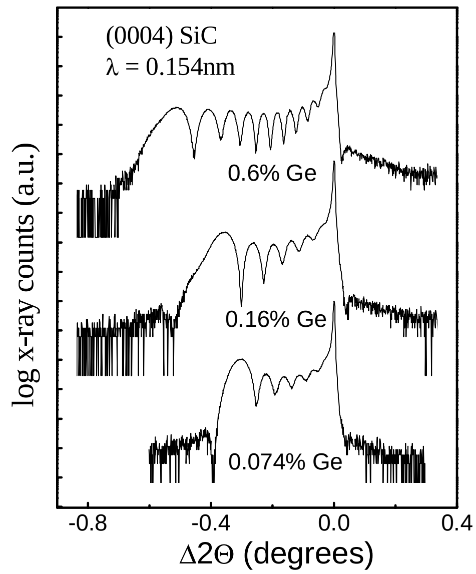


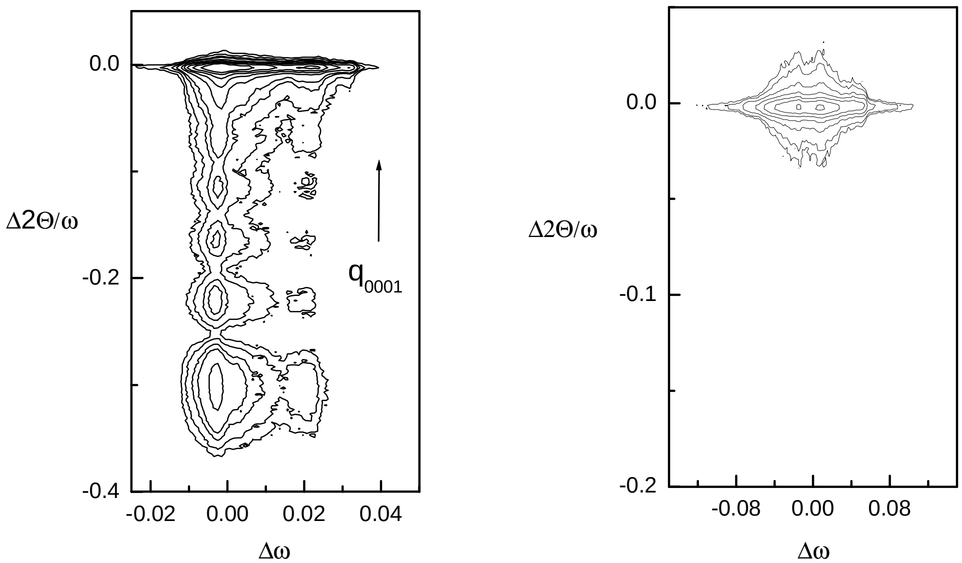
Figure 2. HRXRD spectra of the (0004) reflections of SiC:Ge layers for the following implant doses of 140keV and 50keV Ge^+ respectively: from bottom spectra (i) $0.3\times10^{15}cm^{-2}$ and $0.15\times10^{15}cm^{-2}$, (ii) $0.7\times10^{15}cm^{-2}$ and $0.3\times10^{15}cm^{-2}$, (iii) $2.6\times10^{15}cm^{2}$ and $1.2\times10^{15}cm^{-2}$. The horizontal axis is rescaled so that the 4H-SiC substrate reflection is shown at zero degrees.

angle peaks are interpreted as the Pendellösung (thickness) fringes due to the finite thickness of a strained SiC:Ge layer. Thickness fringes, predicted from the dynamical theory of x-ray scattering, indicate good crystalline quality and a coherent interface [7]. These fringes have not been previously observed in implanted SiC samples presumably due to a heavily lattice damage[8,9]. The fringe period ($\Delta\Theta$)is related to the strained layer thickness (t), x-ray wavelength (λ) and the Bragg angle (Θ_B) by equation 1.

$$t = \frac{\lambda \sin \Theta_B}{\Delta\Theta \sin 2\Theta_B} \quad (1)$$

The fringe spacing taken from the spectra of figure 2 give a strained layer thickness of 140 ± 20nm, in good agreement with the calculated SRIM Ge depth profile and RBS measurement, indicating that the x-ray features correspond to the entire SiC:Ge layer. Pendellosung fringes are attributed to the coherent interface between the 4H-SiC and strained SiC:Ge layer.

X-ray reciprocal space maps (RSMs) were taken to check for broadening of the x-ray scattering vector due to the implantation of Ge. Figure 3 displays the high-resolution x-ray RSMs of (a) the as-implanted ($T_{implant}$=1000 °C, 0.074% Ge) SiC:Ge layer and the (b) unimplanted 4H-SiC substrate as a comparison. The distinct Pendellosung fringes of the SiC:Ge layer are evident in figure 3a and are aligned with the (0001) scattering vector. The axes are scaled so that the 4H-SiC substrate peak is observed at the origin of the contour plots. No evidence of broadening of the x-ray diffraction peaks associated with the SiC:Ge layer is observed in the ω-scan compared to the 4H-SiC substrate. Qualitatively, the RSM's suggest that



(a) (b)

Figure 3. High resolution x-ray reciprocal space maps about the (0004) reflections of (a) SiC:Ge/SiC heterostructure with 0.074% Ge and (b) the 4H-SiC substrate prior to implantation. The iso-intensity contours of each plot are drawn on logarithmic scales with the same total range (30-24000 counts/second). Figure 3a show the Pendellosung fringes of the SiC:Ge layer; the layer features are aligned with the 0001 lattice vector. Compared to the starting substrate the SiC:Ge layer features are not observably broader than those of the starting substrate.

the structural quality of the implanted SiC:Ge layers are the same as the starting substrate. Figure 3b shows the RSM of the substrate prior to implantation, showing the x-ray features which are characteristic of the commercially available substrate.

The thermal stability of the implanted SiC:Ge layer (~0.3% Ge) was investigated using HRXRD measurements for samples annealed for 10 minutes at T_A=1250^{o}C and 1650^{o}C. The HRXRD spectra of SiC:Ge (0.3% Ge) after annealing is shown in Fig. 4. After annealing at 1250^{o}C, the maximum perpendicular layer strain decreases from $\varepsilon_{\perp,max}$ of 0.0089 to 0.0028, while the period of the thickness fringes observed in both the (000.4 and 000.12) reflections remains unchanged. Further increase of T_A to 1650^{o}C, does not significantly change the HRXRD spectra; illustrating that the strain and strained-layer thickness remains unchanged. The spectra from Fig 4 indicate that strained SiC:Ge layer is metastable after implantation, however upon annealing the compressive strain relaxes to a magnitude that is stable up to at least 1650^{o}C, while the thickness fringes indicate that the interface quality is unchanged . This was not the case for compressive strains previously reported for ion-implanted GaAs, Si and SiC crystals where post-implant annealing removed all residual macroscopic strains observable with HRXRD [8,10,11].

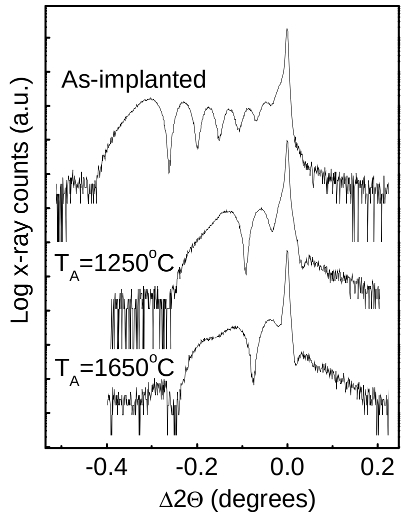


Figure 4. (0004) HRXRD spectra of SiC:Ge samples (Ge=0.3%) as-implanted, and after 10 minute furnace anneals at 1250°C, and 1650°C.

CONCLUSION

In conclusion, ion implantation of 0.07-0.6 atomic percent of Ge into 4H-SiC at 1000°C forms a strained crystalline layer on the 4H-SiC substrate. High resolution x-ray diffraction indicates good crystalline quality, with no degradation of the layer compared to the starting substrate. Upon high temperature annealing, the strain partially relaxed to a magnitude that is stable to at least 1650°C. X-ray diffraction revealed that the layer remained compressively strained to the SiC substrate under all conditions. These results illustrate the potential for new SiC based heterojunction and strain engineered band structures for SiC semiconductor electronics using metastable strained SiC:Ge layers.

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