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Study of SiGe Alloys with Different Germanium Concentrations Implanted with Mn and As Ions

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Abstract. In this work we studied the structural properties of SiGe alloys with different Ge molar compositions co-implanted with manganese and arsenic ions. The ions were implanted at room temperature to fluences of 1×10^{15}, 5×10^{15} and 1×10^{16} cm^{-2} and energies of 170 keV (Mn) and 200 keV (As) in order to achieve the overlap of the implanted profiles. The alloys were studied with Rutherford Backscattering/Channeling spectrometry (RBS/C) and X-ray Diffraction (XRD) techniques. After implantation the implanted region (150 nm) turns into amorphous according with RBS/C. The evolution of the lattice parameter was studied using XRD. The annealing at 550ºC induces the recrystallization of the amorphous layer for the sample implanted with the lower fluence and the full recovery is complete after annealing at 700ºC. The samples implanted with higher fluences did not reveal any noticeable recovery. The Mn and As profiles do not exhibit significant changes during the annealing at 550^{o}C.

Introduction

The strained GeSi alloys have an enormous potential on the development of new electronic semiconductor heterostructures [1]. On the other hand, magnetic nanoclusters embedded in semiconductor materials have a large interest for spintronic applications. Recent work has demonstrated the magnetic behaviour of MnAs nanoparticles in Si with a transition temperature above room temperature [2]. The possibility to produce such new structures in GeSi alloys is very interesting and challenging. One of the routes to produce the nanoparticles is using ion implantation. However, to promote the activation of the implanted ions, it is necessary to remove the implantation damage.

In this work we studied the damage recovery in SiGe alloys with different molar concentrations of Ge implanted with Mn and As ions at room temperature. The energy of the ions was chosen to obtain one and the same projected range.

Experimental Details

SiGe single crystals with a nominal composition of 0.4, 2.5 and 4.0 at.% Ge were implanted with Mn (170 keV) and As (200 keV) ions at room temperature. The implantation energy was chosen to obtain an overlap of the depth profiles. The implantation fluences were equal to 1×10^{15}, 5×10^{15} and 1×10^{16} cm^{-2}. After implantation the samples were annealed in vacuum in a tubular furnace for 10 min, 1 h and 2 h at 550 and 700ºC.

X-ray diffraction (XRD) characterization was performed using a Bruker-AXS D8Discover with the Cu $K_{\alpha1}$ line. A Göbel mirror, a 2-bounce Ge(220) monochromator and a divergence slit of 0.05 mm width and 2 mm height was used in order to collimate the beam to a divergence of 7 arcsec. Symmetric (004) θ-2θ scans were acquired with a point detector positioned 300 mm away from the sample and operating with an acquiring time of 10 s per omega step (0.005º). Rutherford

Backscattering/Channeling (RBS/C) studies were performed with a 0.2 × 0.6 mm^2 collimated beam of 2 MeV He^+ ions. The backscattered particles were detected at 140^o with respect to the incoming beam direction using a silicon surface barrier detector with a resolution of 15 keV located in the standard IBM geometry.

Results and Discussion

Figure 1a shows the θ-2θ scans of the as-grown samples. The measured lattice parameters perpendicular to the surface are 5.4319 Å, 5.4367 Å and 5.4401 Å. According to the Vegard's law, we determine the germanium concentration to be 0.39 %, 2.51 % and 4.00 %, respectively. The presence of germanium increases the structure factor, which implies a higher reflectivity, and so the curves are normalized in order to see only the shift in 2θ. Figure 1b presents the θ-2θ scans of the as-implanted samples. The effect of the implantation damage is clearly visible on the lower angle side, and no changes were found in the lattice parameter perpendicular to the surface.

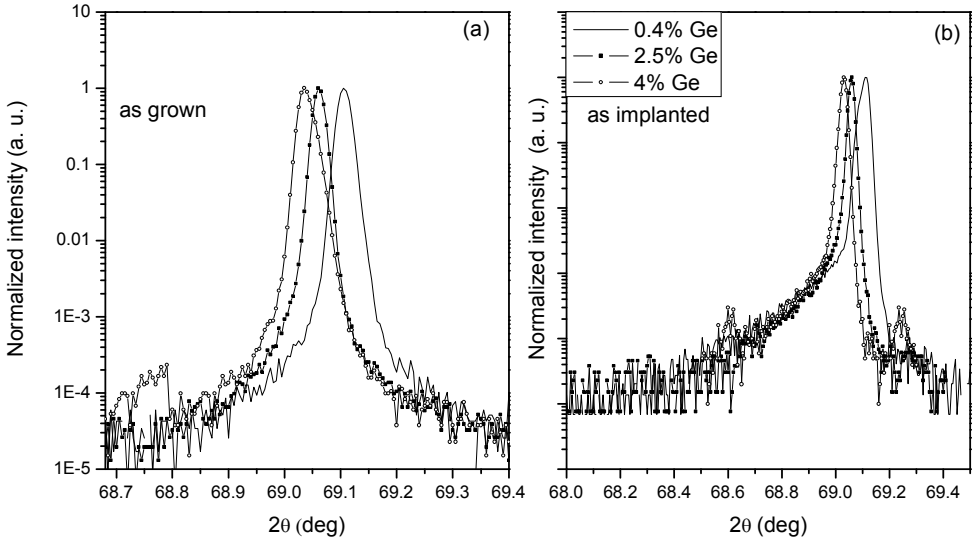

Figure 1- θ-2θ scans of the as-grown samples (a) and of the as-implanted ones (b).

Figure 2 shows the random and aligned RBS spectra before and after implantation for the 0.4 % Ge alloy. The simulation of the as-implanted random spectra using the NDF code [3] is represented by the continuous curve. The best fit gives a germanium concentration of 0.38 %. Concentrations of 2.46 % and 3.98 % were obtained for the other two samples, which agree well with the XRD results. The presence of the implanted ions is shown by the peaks appearing at 1514 keV (Mn) and 1598 keV (As) (figure 2). The implantation fluence obtained from the fit is 8 × 10^{14} cm^{-2}, about 25 % below the expected value (1 × 10^{15} cm^{-2}). For the other samples the results (not shown) give a value 5 % lower than the nominal. Before implantation the value of the minimum

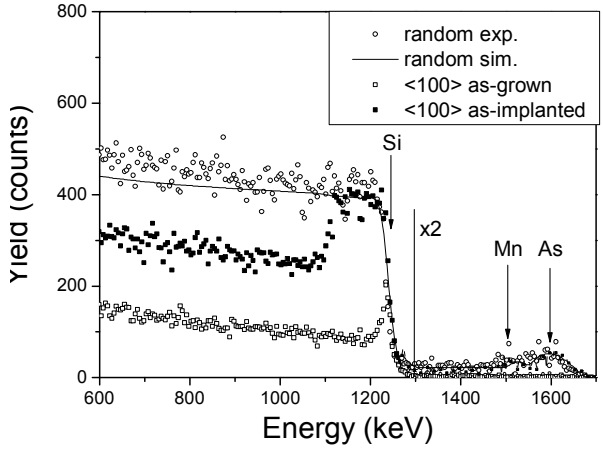

Figure 2: (a) Random and <100> aligned RBS spectra before and after implantation for the sample with 0.4 % Ge. The continuous line is the result of the simulation. The depth scale is in nanometres.

yield (the ratio between the ordinates of the aligned and the random spectra just behind the surface peak) was 0.11 %. This low value is an evidence of the good crystalline quality of the samples. After implantation the implanted region becomes fully disordered, which is visible by the overlap of the random and aligned spectra in this region (figure 2). This result is expected since covalent semiconductors reveal low resistance to irradiation [4,5]. Silicon is easily amorphized for implantation fluences above 10^{14} cm^{-2} of medium/high atomic number elements [6].

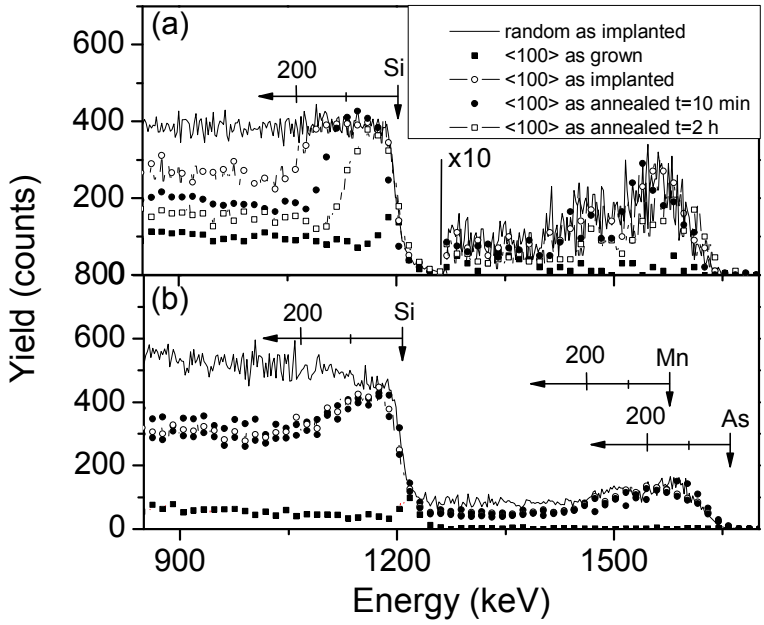

Figure 3: Random and aligned RBS spectra after implantation and annealing at 550^{o}C for the samples: (a) 0.4 % Ge, implanted with 8×10^{14} cm^{-2} of Mn and As; (b) 4 % Ge, implanted with 4.7×10^{15} cm^{-2} of Mn and As. The depth scale is in nanometres.

Since studies of amorphous silicon indicate that recrystallization starts for temperatures above 550^{o}C, we annealed the samples at this temperature. Figures 3a, 3b show the comparison between the <100> aligned spectra with the random spectrum of the implanted samples after each annealing

step at 550ºC. The arrows indicate the backscattering energy for each of the elements for their location at the sample surface. The inset depth scales show the profile of the implanted ions and the evolution of the amorphous layer thickness. For the 0.4 % Ge alloy (figure 3a), the thickness of the amorphous layer decreases with the annealing. A layer-by-layer regrowth process occurs. For the samples implanted with the highest fluences the thickness of the damage region remains unchanged. The Mn and As profiles do not reveal significant changes during the annealing.

The XRD results after annealing at 550ºC (not shown) also indicate a slight decrease of the damage tail for the sample implanted with the lowest fluence in agreement with the channelling measurements. For the highest fluence no changes were observed.

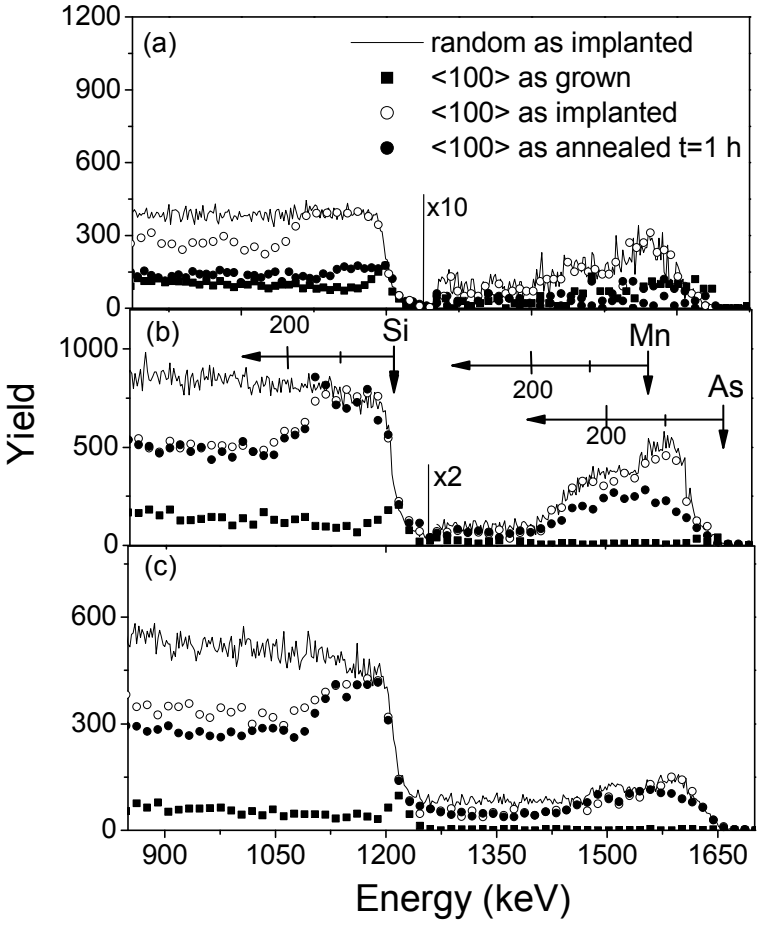

Figure 4: Random and aligned RBS spectra after implantation and annealing at 700°C for the samples: (a) 0.4 % Ge, implanted with 8×10^{14} cm^{-2} of Mn and As; (b) 2.5 % Ge, implanted with 9.5×10^{15} cm^{-2} of Mn and As; (c) 4 % Ge, implanted with 4.7×10^{15} cm^{-2} of Mn and As. The depth scale is in nanometres.

To study the influence of the annealing temperature, we annealed the samples at 700ºC. Figure 4 shows the comparison between the random and the <100> aligned spectra after annealing for the 0.4 % Ge, 2.5 % Ge and 4 % Ge. At this temperature the 0.4 % Ge sample nearly reaches the crystal quality of its virgin state. This recovery effect was not observed in the other samples. Comparing the random spectra of the three germanium molar compositions one can note that As diffuses more strongly than Mn does, particularly for the highest fluence, but we could not conclude if As is lost through the surface or diffuses deeper inside the crystal.

Conclusions

SiGe alloys with different compositions (0.4, 2.5 and 4 % of Ge) were implanted with Mn and As ions. After implantation all the samples show a complete lack of crystalline order in the implanted region. The samples implanted with a fluence of 8×10^{14} cm^{-2} reveal a layer-by-layer regrowth process during the annealing at 550°C. The complete recovery of the damage was achieved after annealing at 700°C for 1 h. The samples implanted with fluences above 5×10^{15} cm^{-2} do not show any recrystallization of the damage region. During the annealing at 700°C a pronounced change of the As profile was observed for the higher fluences suggesting a strong diffusion.

Acknowledgments

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