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Discontinuous tracks in relaxed SiGe alloy layers: Formation and thermal evolution

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Abstract

Strain-relaxed epitaxial $Si_{1-x}Ge_x$ alloy layers partially doped with arsenic were irradiated with U^{238} ions of energy 0.8–2.7 GeV in the electronic stopping regime. Using transmission electron microscopy, clear evidence is found that in some of the $Si_{1-x}Ge_x$ alloy layers latent tracks are created. Depending on the composition of the $Si_{1-x}Ge_x$ alloy and on the doping level of As, the tracks exhibit a more or less discontinuous character. Larger GeAs precipitations are observed in supersaturated alloy layers. We also find indications that the velocity of the projectile ions plays an important role. Additional thermal treatment results in gradual annealing of track-related defects at low temperature (200–400 °C) and in the formation of GeAs precipitates at high (850 °C) temperature.

Keywords: Tracks; Swift heavy ions; SiGe alloys; TEM

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1. Introduction

By passing through the solids, swift heavy ions (SHI) may produce cylindrical zones of physical, chemical, and structural modifications, so-called ion tracks [1,2]. Depending on the type of solid and on the irradiation conditions, tracks consist of homogeneous cylinders of amorphized matter or just discontinuous strings of more or less complex defects. Semiconductors are easily damaged by average-energy ions up to amorphization in the nuclear stopping (S_n) process [3,4], but, display an unexpectedly low sensitivity to the electronic stopping (S_e). Moreover, for single crystals of group IV (Si, Ge, diamond) materials, efficient defect annealing or S_e-induced recrystallization has been reported [5–7]. The situation is different for the case of low-energy C_{60} clusters: amorphous tracks are observed in Si [8,9], Ge [10] and GaAs [11], irradiated with 20–40 MeV clusters. Discontinuous tracks are formed in single-crystalline SiGe alloy layers irradiated with 0.7–2.7 GeV U^{238} ions ($S_e \sim 33-34\,keV/nm$) as it has been recently evidenced in our study [12–14]. In the present work, the results of track formation in SiGe alloys are shortly reviewed and new results on thermal stability of the track-related defects are presented.

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Dislocation-free, strain-relaxed, epitaxial SiGe layers of 2 μm thickness and of different composition were grown on (0 0 1) silicon wafers by means of molecular-beam epitaxy (MBE) in a VG Semicon V80 system using the approach developed in [15]. Several samples were in situ (during MBE growth) implanted with 1 keV As^+ at two different depth intervals (20–80 nm and 180–280 nm) to concentrations of about $1.1 \times 10^{21}\,cm^{-2}$, which exceeds the solid solubility limit of As in a $Si_{0.5}Ge_{0.5}$ alloy by about a factor of ten. The SiGe layers were then irradiated with U^{238} ions of different energies: 2.64 GeV (4.27×10^7 m/s), 1.36 GeV (3.31×10^7 m/s), and 0.8 GeV (2.52×10^7 m/s). A fluence of $(1–5) \times 10^{10}\,cm^{-2}$ was applied at a beam flux of around $2 \times 10^8\,cm^{-2}\,s^{-1}$. According to TRIM95 [16], the S_e values for these ions in $Si_{0.5}Ge_{0.5}$ vary only by about 3% (between 32.4 and 33.5 kev/nm), whereas their velocity changes by a factor of almost two. One set of samples was then annealed in a thermal furnace at 150–900 °C for 10 min in pure N_2 atmosphere. The samples were investigated by means of transmission electron microscopy (TEM) with a Philips CM20 microscope operating at 200 kV. For TEM imaging, the samples were prepared in plan-view (PVTEM) as well as in cross-section (XTEM) geometry using the standard procedure of successive mechanical polishing and ion-beam milling at room temperature.

2. Velocity effect [14]

Fig. 1 shows bright-field PVTEM images of samples irradiated at three different ion velocities. They exhibit black dot-like defects of an average size of ~3–10 nm. Both the density and the morphology of the spots strongly depend on the velocity of projectiles. In the sample irradiated at highest beam energy (2.64 GeV), less than $2 \times 10^9\,cm^{-2}$ dots are produced (Fig. 1a). In the TEM-imaged 0.5-μm surface layer, the dots are randomly distributed. The dot density increases drastically to about $5 \times 10^{10}\,cm^{-2}$ and further up to about $7 \times 10^{10}\,cm^{-2}$ (Fig. 1b) when the energy of the U ions decreases to 1.36 GeV and to 0.8 GeV, respectively. At the same time, there is a tendency of the dots to form rows. A discontinuous sequence of defects aligned along the ion trajectory is a typical observation at the initial stage of track formation close to the threshold [17]. From the TEM data, we find about $6.5 \times 10^9\,cm^{-2}$ dotted tracks which contain ca. 40% of the total number of dots. The samples exposed to the 0.8 GeV U^{238} ions show about $1.3 \times 10^{10}\,cm^{-2}$ uniting more than 70% of the individual dots (Fig. 1b). Clear evidence is found that a large number of the dots in the tracks are double-arc features ascribed to dislocation loops (DLs) (see arrows in Fig. 1c). The size of the DLs varies between 5–10 nm. Their density is estimated to be approximately $1–2 \times 10^{10}\,cm^{-2}$, i.e., about 20–40% of all dots are DLs; the other 80–60% of the dots are established to be clusters of point defects. Finally, no indication for amorphization in tracks is found.

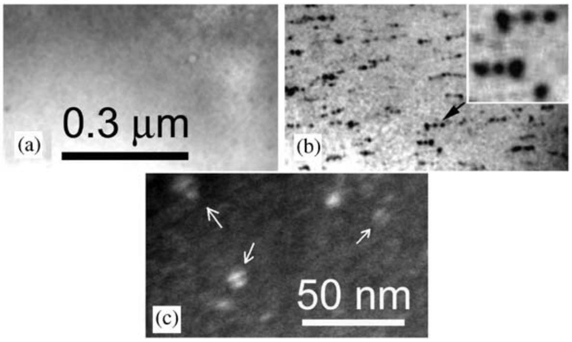

Fig. 1. PVTEM images of $Si_{0.5}Ge_{0.5}$ irradiated with U^{238} ions of energy (a) 2.64 GeV and (b,c) 0.8 GeV. (a,b)—bright field and (c)—dark-field weak beam TEM images.

3. Composition effect [13]

In bulk single-crystalline Si wafers and also in MBE-grown layers of $Si_{1-x}Ge_x$ with $x<0.1$, we did not find any indications of extended defects induced by U^{238} irradiation. In the $Si_{1-x}Ge_x$ alloy of composition $x = 0.2$, a small number ($<10^9\,cm^{-2}$) of black dots are identified with sizes between 3 and 10 nm. When x is increased, the dot density becomes larger, reaching 1.5×10^{10} dots/cm^2 for $x = 0.3$ and a maximum value of about