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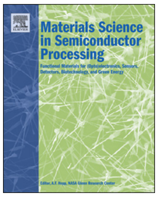

Influence of the Germanium content on the amorphization of silicon–germanium alloys during ion implantation

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ABSTRACT

We have studied by transmission electron microscopy the amorphization of silicon–germanium (SiGe) alloys by Ge^+ implantation. We show that when implanted with the same amorphization dose, the resulting amorphous layers get narrower when the Ge content increases. The experimental results can be simulated using the critical damage energy density model assuming that the amorphization threshold rises linearly with the Ge content from 3 eV/at for pure Si to 5 eV/at for pure Ge. These results and simulations are needed to optimize the fabrication of highly doped regions in SiGe alloys.

1. Introduction

Silicon–germanium (SiGe) alloys are being integrated by microelectronics industries as channel materials for optimized p-type Metal-Oxide-Semiconductor (PMOS) devices owing to the much better hole mobility they offer as compared to Si. As in Si, highly p-doped source and drain regions can be fabricated following three process steps: (1) preamorphization of the SiGe crystal by Ge implantation, (2) low energy B^+ implantation and (3) Solid Phase Epitaxial Regrowth (SPER) of the amorphous layer at low temperature i.e., typically in the 500–600 °C range [1].

Moreover, future planar MOS devices below the current nodes (typically below 22 nm) will be built on Silicon-On-Insulator (SOI) wafers, the traditional thin Si top layer being possibly replaced by a SiGe alloy (SGOI wafers). The successful implementation of the same sequence of process steps to form highly B-doped regions in SOI and SGOI wafers requires that the top crystalline region is not fully amorphized by the Ge implantation so that some thin crystalline layer remains close to the box to provide a seed to the defect-free SPER of the amorphous layer during annealing. An additional advantage of this approach is that the End-Of-Range (EOR) defects, which inevitably form below the original crystalline/amorphous interface during annealing [2] and which affect dopant diffusion and degrade the electrical characteristics of the device, will form in smaller densities and will dissolve faster than in the bulk because of the capability of the Si/SiO_2 interface to recombine Si interstitials [3].

Thus, the optimal use of the pre-amorphization technique requires that models exist to predict the depth at which the Si and SiGe layers are amorphized by any given Ge implantation. At the moment, such a model exists for pure Si and Ge and it has been integrated into modern process simulators. But the effect of adding Ge to Si, i.e. forming a SiGe alloy, onto the efficiency of the damage generation and amorphization processes is, at best, controversial.

On one hand, T. E. Haynes and O. W. Holland [4] reported that, for (Si^+, 80–90KeV) implantations at room temperature, the amount of ion-induced damage increases with the Ge content at a “larger rate than expected from calculations”. They suggested that increasing the Ge fraction progressively reduces the mobility of primary defects within the collision cascades. A. N. Larsen et al.

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[5,6] studied the damage produced by implanting relaxed n-type $Si_{1-x}Ge_x$ alloys at room temperature with 2 MeV Si^+ as a function of the Ge content. The ion doses were ranging from 10^{10} to 2×10^{15} cm^{-2}. An enhanced level of damage and a strong decrease in the critical dose for the formation of a buried amorphous layer were observed when increasing the Ge content. More recently, G. Impellizzeri et al. [7] reported a higher damage rate in Ge than in Si, when investigating the implantation of germanium at different energies and doses. They attributed this effect to both the higher stopping power of Ge atoms and a reduced mobility of the defects within the collision cascades. Similarly, R. Kögler et al. [8] reported that, for a given set of implantation conditions, the amorphization threshold decreases and the extension of the buried amorphous layer increases when the Ge content increases. This time, the authors suggested that during annealing the recombination of vacancies and interstitials is relatively inefficient and that the widely used "+1 model" [9] describing the ion-induced damage in Si is not valid for SiGe alloys.

On the other hand, R. Wittmann et al. [10] reported that while the implantation profiles in Ge are shallower than in Si, due to the larger nuclear and electronic stopping powers of Ge atoms, damage production is less efficient, because the displacement energy of atoms is larger (30 eV) and that the energy transfers from the ions to the primary recoils are smaller than in Si. Finally, our own works [11–13] have shown that, for a large variety of implantation conditions, the width of the generated amorphous layers decreases, i.e. the "amorphization threshold" increases when switching from silicon to germanium.

Actually, this confusion arises because the different techniques used to characterize the "damage" created by ion implantation are sensitive to different types of disorder and that, consequently, the terminology used to qualify the observed "damage" differs from one author to the next. The goal of this work is to clarify the situation by firstly providing robust experimental results about the amorphization efficiency of Ge implantation into SiGe alloys of various Ge contents. These data, obtained by Transmission Electron Microscopy (TEM), will be tested against the Critical Damage Energy Density (CDED) model already used to predict the amorphization kinetics of both Si and Ge for a large variety of experimental, industry relevant, conditions.

2. Experimental details

By using an Epi Centura RP-CVD tool from Applied Materials, relaxed $Si_{1-x}Ge_x$ alloy layers (about 1 μm thick) of various Ge contents ($x=0$; 0.2; 0.35; 0.5 and 1) were grown by Chemical Vapor Deposition (CVD), via a compositionally graded buffer layer, in which the Ge is incorporated into the sample at an increasing rate of 10% Ge/μm. The virtual substrates were deposited on 200 mm slightly p-type doped Si(001) substrates. Dichlorosilane and germane diluted at 2% in hydrogen were used as the silicon and the germanium gaseous precursors. The growth pressure was fixed to 20 Torr for all the samples. Details on the growth kinetics in RP-CVD in the temperature range used to grow the SiGe virtual substrates can be found in Refs. [14,15]. The pre-amophization was performed by a Ge^+ 35 keV implantation with a dose of 1.10^{15} cm^{-2} and at room temperature. Samples were then prepared by mechanical polishing and subsequent argon ion thinning until electron transparency and ready for cross-sectional imaging. Low beam densities were used for ion thinning while keeping the sample at low temperature to prevent the regrowth of the amorphous layers which are a possible artifact for Ge-rich layers.

3. Results and discussions

Fig. 1 presents a set of bright-field XTEM images obtained from the five samples of increasing Ge content. In all samples, the Ge^+ implantation has resulted in the formation of a continuous amorphous layer extending from the surface and toward a depth which decreases from 57 nm to 47 nm (+/−3 nm) when the Ge content increases from 0 to 1. The amorphous nature of the upper layer can be easily demonstrated by electron diffraction. At this point, several would claim that the "amorphization efficiency" decreases when increasing the Ge content in SiGe layers. We prefer to remain factual and state that the width of the amorphous layers generated by some given Ge implantation decreases when increasing the Ge content.

Fig. 2 shows the damage energy distributions, i.e. the energy transferred by the incident ion and the recoiling atoms to the target through nuclear collisions at each depth, obtained for a 35 keV Ge^+ implantation into $Si_{1-x}Ge_x$ alloys of different compositions. These profiles have been obtained by Monte Carlo simulation of the slowing down process of the ions using displacement energies of 15 eV and 30 eV for Si and Ge, respectively [16]. This damage energy is proportional to the number of Frenkel's pairs generated in the crystal by the implantation. It is noticeable that the maximum of this damage energy shifts toward the surface while its amplitude increases with increase in the Ge content in the target. This characteristic results from both the increased stopping power of the

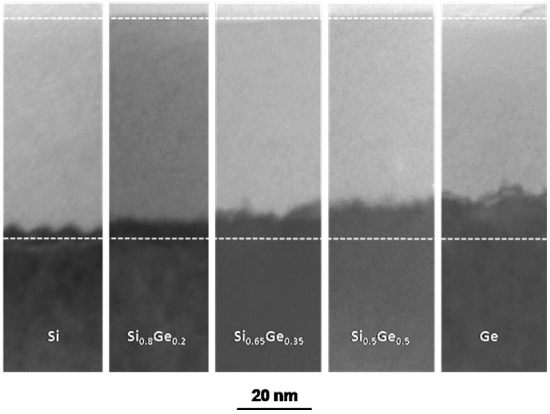

Fig. 1. Set of XTEM images showing the amorphous layers created by a 35 keV 1.10^{15} cm^{-2} Ge^+ implantation at RT in $Si_{1-x}Ge_x$ alloys of increasing Ge content. The upper dotted line delineates the surface, and the lower one is to help visualize the shift of the c/a interface.