Nuclear Instruments and Methods in Physics Research B 368 (2016) 86–89

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Influence of hydrogen fluence on surface blistering of H and He co-implanted Ge

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ARTICLE INFO

Article history:
Received 15 October 2015
Received in revised form 12 December 2015
Accepted 15 December 2015
Available online 23 December 2015

Keywords:
Germanium
Hydrogen and helium
Ion implantation
Blistering
Implantation-induced defect

ABSTRACT

The effect of hydrogen fluence on surface blistering of H and He co-implanted Ge is investigated using atom force microscope, X-ray diffraction and transmission electron microscopy. With a fixed He, we find that for $1 \times 10^{16}\,\mathrm{cm}^{-2}$ H implantation fluence, only a few small dome-shaped blisters appear, for $3 \times 10^{16}\,\mathrm{cm}^{-2}$ H implantation fluence, large blisters as well as craters are formed, while for $5 \times 10^{16}\,\mathrm{cm}^{-2}$ H implantation fluence, no blisters can be observed. The strain evolution and platelet forming tendency are found to be relevant for the different blistering phenomenon. The weak blistering phenomenon for $1 \times 10^{16}\,\mathrm{cm}^{-2}$ H implantation fluence may be attributed to less “free” H for the building up of internal pressure of platelets and the sustained growth of platelets. While the absence of blistering phenomenon for $5 \times 10^{16}\,\mathrm{cm}^{-2}$ H implantation fluence is likely due to the retarded relief of the decreased uniform compressive stress throughout the damage region.

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1. Introduction

Implantation of light ions, such as H and He, into semiconductor materials can lead to blistering and exfoliation of the surface. The Smart-Cut technology mainly based on ion implantation was first developed by Bruel to achieve a cost-effective process for high quality silicon on insulator wafers [1]. Agarwal et al. discovered that co-implantation of H and He ions into silicon allowed blistering at considerably lower total fluence than H alone [2]. From then on, a number of studies have been performed to elucidate the underlying mechanism [3–8]. In general, this effect has been attributed to a synergy between the passivation of the internal surface of the crack by H and the efficient crack pressurization by He. However, the effect of H–He co-implantation on blistering of Ge is seldom reported [5,7], though Ge has been reconsidered as a potential channel material for the future CMOS technology due to its higher carrier mobility [9,10]. In this work, we systematically study the dependence of the Ge blistering phenomenon on H ion implantation fluence during H–He co-implantation process, and interpret the underlying mechanism based on the experimental results.

2. Experimental

N-type (100) germanium wafers were sequentially implanted with H and He. The energy of H and He ions was 30 keV and 50 keV, respectively, which was chosen so that both ions had similar depth profiles. The fluence of H was varied from 1×10^{16}, 3×10^{16} to $5 \times 10^{16}\,\mathrm{cm}^{-2}$, and the fluence of He was kept at $1 \times 10^{16}\,\mathrm{cm}^{-2}$ (In the following, they were named as 1H1He, 3H1He, and 5H1He, respectively, for clarity). The wafer holder was kept near room temperature and tilted 7° off the direction of the beam to minimize the ion channeling effects. All implanted samples were annealed at various temperatures from 200 to 500 °C in the flowing ambient of N_2 gas for 30 min.

Atom force microscopy (AFM) in contact mode was utilized to characterize the surface morphology of the implanted Ge after annealing at different temperatures. The strain evolution in the implanted Ge during annealing process was characterized by a Philips X'Pert MRD X-ray diffraction (XRD). The microstructure evolution of the implantation-induced defects underneath the sample surface was observed by transmission electron microscopy (TEM) using a FEI Tecnai G2 F20 S-TWIN microscope with an accelerating voltage of 200 kV.

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http://dx.doi.org/10.1016/j.nimb.2015.12.030
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3. Results and discussion

3.1. Surface morphology

Fig. 1 shows the surface blistering phenomenon by AFM images from 1H1He, 3H1He and 5H1He after annealing at 500 °C. It clearly shows that the blistering phenomenon originating from H and He sequentially being implanted into Ge depends strongly on the H ion fluence. For $1 \times 10^{16}\,cm^{-2}$ H implantation fluence, a few tiny dome-shaped blisters with a diameter generally less than 1 μm and height less than 10 nm appear. When the H fluence increases to $3 \times 10^{16}\,cm^{-2}$, not only large blisters, but also craters are formed. The depth of the craters is around 300 nm, which coincides with the depth of implantation-induced damage, as simulated by SRIM program [11]. However, the surface blistering phenomenon is totally suppressed, and no optically visible blister is found on the surface of the sample implanted with $5 \times 10^{16}\,cm^{-2}$.

3.2. XRD measurements

Fig. 2 displays the XRD curves from 1H1He, 3H1He and 5H1He prior to the annealing process. The fringe pattern indicates a tensile strain gradient in the direction normal to the surface of Gaussian-like shape [12,13], which is induced by the changes of lattice structure during ion implantation. The maximum strains given by the position of the last fringe away from the Bragg peak for 1H1He, 3H1He and 5H1He are 0.63%, 0.86% and 0.68%, respectively [12]. For low H fluence up to $3 \times 10^{16}\,cm^{-2}$, the maximum strain increases with the H does. However, the maximum strain shrinks when the H fluence increases to $5 \times 10^{16}\,cm^{-2}$, indicating a decrease in the average compressive stress in the damage region. In addition, the intensity of the fringe pattern decreases and the fringe spacing becomes shorter with the increasing of H fluence. The attenuation of the fringe pattern is ascribed to higher level of lattice damage [14]. The reduction in the fringe spacing represents the expansion of the strain profile, which is related to the broader distribution with the increasing of H fluence as well as a synergy effect on H and He co-implantation induced defects.

Fig. 3(a–c) shows the XRD curves of strain evolution from 1H1He, 3H1He and 5H1He after annealing at various temperatures from 200 to 500 °C. Slight differences can be observed in the diffraction patterns after annealing at 200 °C, indicating that the evolution of microstructure is negligible up to 200 °C. When annealed at 300 °C and above, the strain relaxation for all the samples with different H implantation fluence evolves in a significantly different way. For $1 \times 10^{16}\,cm^{-2}$ H implantation fluence, the fringe pattern gradually attenuates, corresponding to a restricted evolution of microstructure defects. And the fringe pattern preserves up to 400 °C, indicating the retention of strain induced by the implantation. However, the situation has changed significantly when the H implantation fluence increases to $3 \times 10^{16}\,cm^{-2}$, the fringe pattern vanishes when annealed at 300 °C and above. In contrast, for $5 \times 10^{16}\,cm^{-2}$ H implantation fluence, the fringe spacing always exists even the temperature approaches 500 °C, platelets as well as cracks may have formed but are not able to strongly deform the crystalline planes.

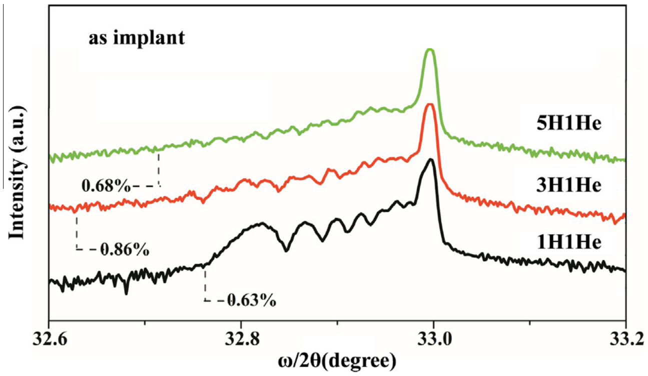

Fig. 2. X-ray measurements of three as-implanted samples.

3.3. TEM results

Fig. 4(a–c) shows a set of XTEM observations of 1H1He, 3H1He and 5H1He after annealing at 300 °C for 30 min. A damage band could be observed ranging from about 200 to 400 nm below the surface. It is made up of a few tiny spherical bubbles, with diameters less than 10 nm, which is common in helium implanted germanium samples [15], and of defect clusters with few tens of nanometers. It is obvious that with the increasing of hydrogen implantation fluence, the width of the damage region becomes broader and moves toward the surface, which is consistent with XRD results.

High resolution XTEM images of the damaged regions are shown in Fig. 5(a–c), which shows the formation of platelets (Annotations are added to these images to show the location of platelets). Most of the platelets, filled with hydrogen and helium molecules, are aligned parallel to the sample surface in the (1 0 0) plane. Histograms of platelet population distribution deduced from XTEM images are also shown in the bottom panel. For 1H1He sample, only a few platelets can be found in the damage layer. While the other two samples are significantly different—more platelets as well as micro-cracks with an average size ranging from 10 to 50 nm can be observed in the damage region. For 3H1He sample, most of the platelets are found relatively in more abundance within a narrow range of about 100 nm in the middle of the damage layer, where the implanted H and He ions mostly overlapped.

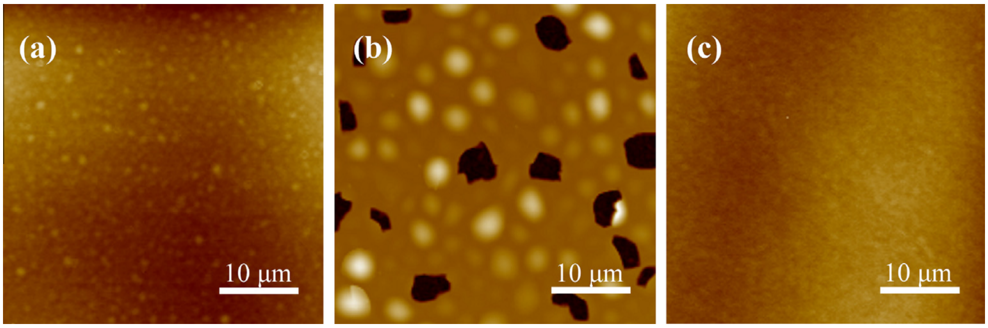

Fig. 1. AFM images of surface blistering of H and He co-implanted Ge samples annealed at 500 °C for 30 min: (a) 1H1He, (b) 3H1He and (c) 5H1He.

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