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Effect of Implantation Temperature on the Layer Exfoliation of H-implanted Germanium

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This work describes the influence of implantation temperature on the layer exfoliation of the H-implanted Ge substrate. For the implantation at RT, post-implantation annealing showed large exfoliated regions over the sample surface. Two depths of the exfoliated regions were observed with average values of about 654 and 856 nm from the top of the H-implanted surface. In the H-implanted Ge at 300 °C, exfoliation occurred in the as-implanted state in the form of surface craters. The average depth of these craters was measured to be about 890 nm from the surface. Simulation results showed that the depth of the exfoliated regions was either located near to the damage peak or away from the H-peak depending upon the implantation temperature.

Keywords: Implantation, Ge, Exfoliation, Annealing.

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1. INTRODUCTION

The layer exfoliation of the semiconductors using hydrogen (H) implantation and direct wafer bonding technique has been used in the transfer of thin layers from the bulk substrate onto the foreign substrate [1-4]. This has been extensively used in the conventional semiconductors such as silicon and germanium, which has opened the gateway to silicon-on-insulator (SOI) and germanium-on-insulator (GeOI) technologies [5-7]. It is known that the H-implantation-induced defects in these conventional semiconductors are in the form of point defects and H-defect complexes [1, 3, 8]. These H-induced defects are located within the damage region close to the projected range of the hydrogen ions in the H-implanted material. During hydrogen implantation or after post-implantation annealing at elevated temperatures, these defects agglomerate to hydrogen filled extended defects such as nanocracks and microcracks [3, 8]. Such extended defects eventually responsible for the buckling of H-implanted material in the form of surface exfoliation/layer splitting [2, 8, 9].

However, the details of the layer splitting process of semiconductors such as silicon and germanium are still not been fully comprehended at the atomic level. In the case of Ge, most of the surface blistering/exfoliation investigations were carried out for the implantation at room temperature (RT) [9-11]. Albeit, the influence of implantation temperature on the layer exfoliation of Ge is not studied. Hence, in this work, the dependence of layer exfoliation of Ge at various hydrogen implantation temperatures has been discussed.

2. EXPERIMENTAL

n-type (100) Ge samples of size 1×1 cm^2 were implanted by 100 keV H^+ ions with a fluence of 1×10^{17} cm^{-2}. The H-implantation was carried out at sample holder temperatures of RT and 300 °C. During implantation, ion current density was kept at 10 μA·cm^{-2}. The hydrogen ion implantation was performed at the Low Energy Ion Beam Facility (LEIBF) of the Inter University Accelerator Centre (IUAC), New Delhi [12, 13]. During implantation, the sample surface normal was inclined at ~ 7 ° off relative to the incident ion beam in order to minimize channeling effects. After implantation, the samples were annealed in air ambient at various temperatures in the range of 300-600 °C. The samples were investigated in the as-implanted state and after post-implantation annealing using Nomarski optical microscope and atomic force microscopy (AFM).

3. RESULTS AND DISCUSSION

Ge samples implanted at RT showed surface exfoliation only after the post-implantation annealing at 500 °C for 30 min (see Fig. 1a). The exfoliated regions were extended over the large area of a few hundreds of micrometers. In addition, Fig. 1a also shows different small exfoliated regions within the largely exfoliated surface. This indicates that the exfoliated regions have different depths located near to the projected range ~ 705 nm of the 100 keV hydrogen ions in Ge (Stopping and Ranges of Ions in Matter (SRIM) simulations [14]) (see Fig. 2). Apart from this, isolated blisters of lateral size in the range of about 3-20 μm were also observed in these Ge samples implanted at RT (see Fig. 1a).

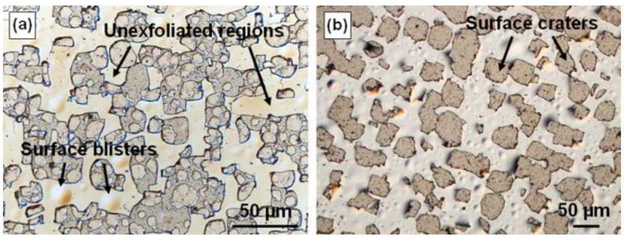

Fig. 1 – Nomarski optical images of the Ge samples: after post-implantation annealing at 500 °C for 30 min of the sample implanted at RT (a), sample in the as-implanted state for the implantation at 300 °C (b)

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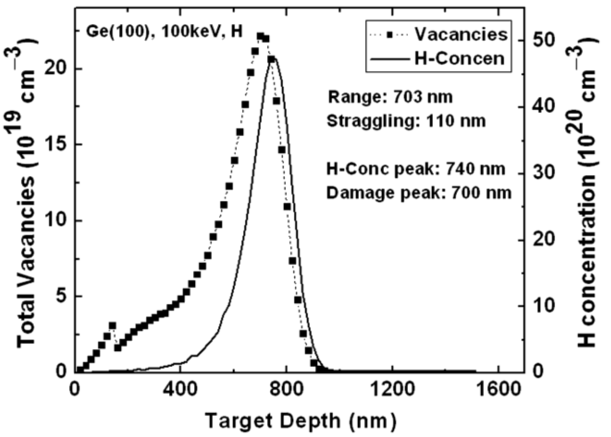

Fig. 2 – Depth profile of the implanted ions and number of vacancies produced for the energy of 100 keV hydrogen in Ge. The fluence of hydrogen ions was 1×10^{17} cm^{-2}. These simulations are done using SRIM 2008 [14]

On the other hand, exfoliation occurred in the as-implanted state in the form of surface craters for the Ge samples implanted at higher temperature of 300 °C (see Fig. 1b). The lateral size of the surface craters varied between 10-100 μm. In this case, Fig. 1b shows that the craters bottom region has no additional exfoliated regions. This reveals that the Ge samples implanted at higher temperature have reasonably good morphology of the exfoliated regions in comparison to the exfoliated surface of the Ge samples implanted at room temperature (see Fig. 1a and 1b).

In order to further investigate the surface morphology of the exfoliated regions at microscopic level, we have carried out AFM measurements in contact mode at the edge of the crater for the different scan area (see Fig. 3). In the case of H-implantation at RT, Fig. 3a clearly shows the formation of different exfoliated regions within the craters bottom from where further removal of the H-implanted surface occurred. Moreover, further measurements showed that the average value of the total depth of the exfoliated regions was ~ 856 nm from the top of the H-implanted Ge surface (see Fig. 3b). This value of the exfoliation depth matches well with the exfoliation depth of ~ 853 nm as predicted by Chien et al. in the investigation of surface blistering and exfoliation phenomena in molecular hydrogen implanted Ge samples [10]. They had done implantation at RT by 200 keV H_2^+ ions with a fluence of 2.5×10^{16} cm^2.

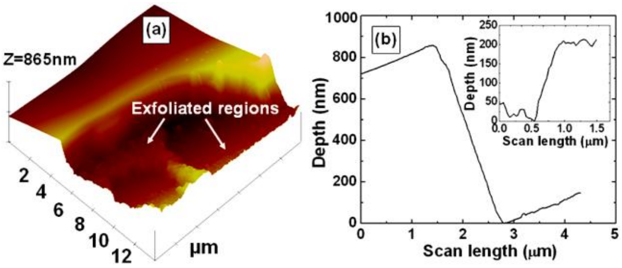

Fig. 3 – AFM images of the H-implanted Ge sample at RT after post-implantation annealing at 500 °C for 30 min: AFM at the edge of the surface crater (a), AFM sectional line scan at the edge of the surface crater (b). The inset picture of the Fig. 3b shows AFM sectional line scan at the crater bottom region

Further AFM investigation of the crater bottom shows that the average depth of the localized exfoliated regions within the crater bottom is ~ 202 nm (see inset picture of the Fig. 3b). This measurement was done from the top of the remaining exfoliated surface of the crater bottom. This means that in the case of Ge samples implanted at RT, surface exfoliation occurred from the two regions with average depth of ~ 856 nm and ~ (856-202) = 654 nm from the top of the implanted surface. Hence, the exfoliation depth of ~ 202 nm is actually responsible for the higher surface roughness of the craters bottom (exfoliated regions) in the Ge samples implanted at RT. However, in the case of Ge samples implanted 300 °C, AFM measurement showed average depth of the exfoliated regions ~ 890 nm from the top of the H-implanted surface (see Fig. 4). Since the exfoliation depth corresponds to the thickness of the transferred layer, hence, above results exhibit that in comparison to the H-implantation at RT, the thickness of the Ge layer transferred at 300 °C implantation temperature would be thicker.

Thus, in the case of H-implanted Ge samples at RT, the exfoliation depth either lies close to the damage concentration peak of 700 nm (SRIM simulations), or away from the H-concentration peak of 740 nm as predicted by the SRIM simulation code (see Fig. 2). However, for the implantation at 300 °C, the exfoliation depth is located toward the maximum depth away from the hydrogen concentration peak in the damage region. This shows that not only the exfoliation depth, but also the surface morphology of the H-implanted Ge samples depends significantly on the implantation temperature.

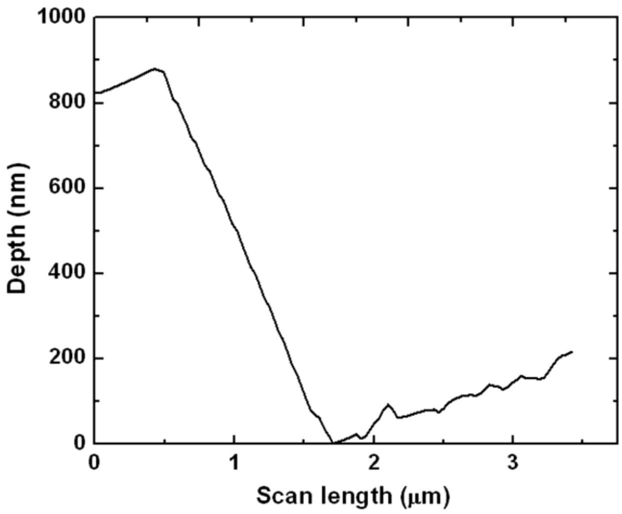

Fig. 4 – AFM sectional line scan at the edge of the surface crater in the as-implanted state of the Ge sample at 300 °C

The surface exfoliation of Ge samples is due to the formation of H-implantation-induced microstructural damage [9, 11]. In the case of H-implanted Ge samples at RT, it had been shown that the implantation-induced extended defects in the form of microcracks were formed in the damage band [11, 15]. The post-implantation annealing of the samples in the temperature about ≥ 400 °C results in the formation of surface blistering/exfoliation of the top H-implanted Ge surface [10]. On the other hand, in the H-implanted Ge samples at 300 °C, the implanted hydrogen may get sufficient diffusion activation energy in the presence of beam heating effects due to the higher ion current density of 10 μA·cm $^{-2}$. This could result in release of the implanted hydrogen from the H-passivated defects to show hydrogen agglomeration to molecular form. Thus, similar to the H-implanted Ge samples at RT, the molecular hydrogen could lead to the formation of overpressurized extended defects in the presence of higher implantation temperature of 300 °C. These overpressurized hydrogen induced microcracks may eventually result in buckling of the top H-implanted Ge surface in the as-implanted state (see Fig. 1b).

Further study of the H-implantation-induced microstructural damage is required especially for the implantation at higher temperature in order to comprehend the implantation temperature dependence of the layer exfoliation phenomenon in Ge.

4. CONCLUSIONS

The exfoliation of Ge samples is dependent upon the H-implantation temperature. The investigations showed that the hydrogen implantation at RT resulted surface buckling of the H-implanted surface in the form of exfoliated regions extended over the large regions. The exfoliated surface showed two values of the exfoliation depth with average values of ~ 856 nm and ~ 654 nm from the top of the H-implanted surface. For the hydrogen implantation at 300 °C, surface craters were formed in the as-implanted state. The average depth of these craters was measured to be ~ 890 nm from the H-implanted surface. The exfoliation depth was located either close to the damage concentration peak or away from the H-concentration peak for the implantation at RT. However, in Ge samples implanted at 300 °C, exfoliation depth was situated away from the H-concentration peak toward the deeper depth location.

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