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Role of electronic and nuclear energy losses in swift heavy ion beam induced epitaxial crystallization of a buried Si_3N_4 layer

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Abstract

This paper reports on swift heavy ion beam induced epitaxial crystallization of a buried Si_3N_4 layer. Transmission electron microscopy and selected area diffraction patterns are used to study the epitaxial growth of the buried Si_3N_4 layer. We observe good epitaxial crystallization at 150 °C and 200 °C, respectively, for 70 MeV Si and 100 MeV Ag ions at an ion fluence of 1×10^{14} ions cm^{-2}. The fact that recrystallization is achieved at a lower temperature for Si ions is attributed to the higher ratio (one order of magnitude) of the electronic to nuclear energy loss values compared to that of Ag ions. The possible role of the electronic and nuclear energy loss processes in the mechanism of recrystallization has also been discussed.

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Keywords: Ion beam induced epitaxial crystallization; Swift heavy ions; Transmission electron microscopy

1. Introduction

Ion beam induced epitaxial crystallization (IBIEC) is a promising tool to achieve solid phase epitaxial growth in silicon and other materials at considerably lower target temperatures [1–7]. IBIEC has unique characteristics such as low processing temperature, layer-by-layer crystallization and dynamic defect annealing. In most of the existing reports, for low to medium energy IBIEC, recrystallization has been mainly ascribed to the migration and recombination of defects (at the amorphous/crystalline (a/c) interface) created by the elastic collisions between ions and target atoms [1–3]. However, Nakata had first pointed out about the possible role of inelastic scattering processes in IBIEC [3] of Si. We have comprehensively shown in our recent works that swift heavy ions (SHI) induce recrystallization in Si and Si_3N_4, where inelastic scattering process plays a dominant role [6,7].

In this paper, we show that swift heavy ion beam induced epitaxial crystallization (SHIBIEC) of a buried Si_3N_4 layer is observed to occur at temperatures as low as 150 °C and 200 °C corresponding to 70 MeV Si^{5+} and 100 MeV Ag^{8+} ions, respectively, at a fluence of 1×10^{14} ions cm^{-2}. The buried Si_3N_4 layer was produced by high current density (30–40 μA cm^{-2}) N-ion implantation at 300 °C. Such high current density implants leads to rise in the sample temperature due to heating effect of the incident ion beam [8,9] to result in the recrystallization of the top Si layer [7]. It can be mentioned here that this is a typical silicon-on-insulator (SOI) structure consisting of an almost defect-free Si layer at the top, a buried silicon nitride dielectric layer and two high-quality abrupt interfaces of the buried insulating layer with the top as well as the substrate Si. Such SOI structures are known to offer the possibility of producing integrated circuits of high packing density, low power consumption and high speed [10].

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We have demonstrated the possible role of electronic (S_e) and nuclear energy loss (S_n) processes in the mechanism of achieving hetero-epitaxy by swift heavy ions. The fact that recrystallization of the buried Si_3N_4 layer is achieved at a relatively lower temperature for Si ions is attributed to the higher ratio (one order of magnitude) of the electronic to nuclear energy loss values compared to that of Ag ions. Systematic transmission electron microscopy (TEM) and selected area diffraction (SAD) patterns have been used to examine the microstructure formed in the buried layer.

2. Experimental

Ultrasonically cleaned Si(1 0 0) substrates were implanted with 100 keV N^+ ions (at an incidence angle of 7° from the normal) at an elevated temperature of 300 °C up to the fluence of 8×10^{17} ions cm^{-2} under a vacuum of 4×10^{-7} mbar. Current during the implantation was quite high ∼30–40 μA over a scanned beam area of 1×1 cm^2. Monte Carlo SRIM-2003 [11] calculation reveals that these N ions have a projected range of 245 nm and are expected to form a buried Si_3N_4 layer [12].

The N-implanted samples were irradiated by 70 MeV Si^{5+} and 100 MeV Ag^{8+} ions at normal incidence under a vacuum of 9×10^{-7} mbar and using a constant fluence of 1×10^{14} ions cm^{-2} at different temperatures, viz. room temperature (RT), 150 °C, 200 °C, 250 °C and 300 °C. The flux during Si-ion irradiation was always kept low (<10^{10} ions cm^{-2} s^{-1}) to avoid any additional sample heating. Uniform sample irradiation was achieved under secondary electron suppressed geometry by using a 1×1 cm^2 scanned beam.

Table 1
Values of S_e, S_n and their ratios in Si and Si_3N_4 for Si and Ag ions

Layer	Ion species	Energy (MeV)	S_e (keV nm^{-1})	S_n (keV nm^{-1})	S_e/S_n
Si	Si	70	2.8	0.002	1067
Si_3N_4	Si	70	4.5	0.004	1115
Si	Ag	100	10.5	0.06	175
Si_3N_4	Ag	100	17.9	0.09	199

The range of the projectile ions and the energy deposited by them were calculated by SRIM-2003 code. The corresponding S_e and S_n values of Si and Ag ions in Si and Si_3N_4 are given in Table 1. These values are accurate within 15% in terms of the experimental values. Table 1 also shows the (S_e/S_n) ratio in the respective layers. It can be mentioned here that for both Si and Ag ions, the implanted species would penetrate deep (≈16 and 21 μm, respectively) into the Si substrate.

Microstructure and crystalline quality of the N-implanted and post-implantation SHI irradiated samples were studied by cross-sectional TEM (XTEM) and SAD measurements. TEM samples were prepared by a standard preparation technique, which included dimpling and subsequent 3 keV Ar^+ ion milling at low incident angles. TEM measurements were performed using a high-resolution JEOL-2010 UHR microscope operated at 200 keV. We also performed the Rutherford backscattering spectrometric measurements to measure the composition of the samples.

3. Results and discussion

Fig. 1(a) demonstrates a low magnification bright field XTEM image obtained from an as-implanted sample. The presence of the implanted layer is clear in the Si substrate. The measured projected range of the N ions from this image matches very well with that calculated from SRIM-2003 simulation. The crystallinity of each layer was checked by collecting the respective SAD patterns from three distinct regions (as marked in Fig. 1(a)), which are presented in Fig. 1(b). The SAD patterns indicate that the implanted layer is amorphous, while the top Si layer and the substrate Si are crystalline. In order to get a better insight about the nature of the a/c interfaces, we present the high-resolution TEM (HRTEM) images in Fig. 1(c) corresponding to the

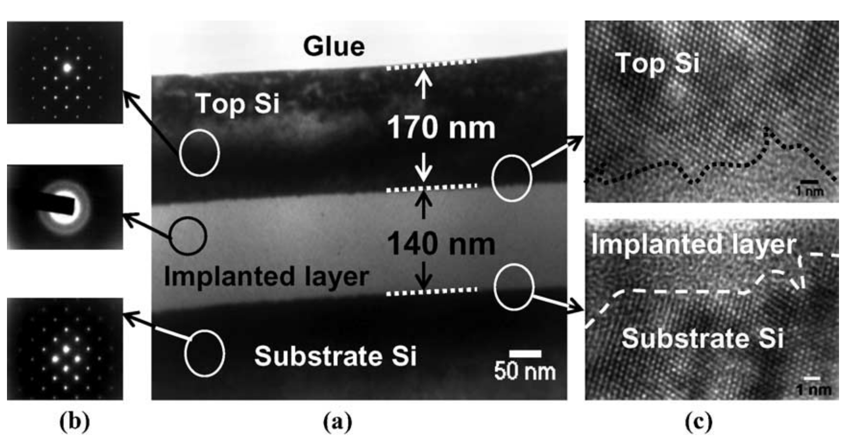

Fig. 1. Bright field XTEM micrographs obtained from an as-implanted sample: (a) low magnification image showing three distinct regions, (b) SAD patterns obtained from the three marked regions, (c) HRTEM images obtained from the marked interfaces.