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Damage characteristics of low-temperature BSi molecular ion implantation in silicon

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Abstract

This study investigates the damage characteristics of BSi molecular ions implanted into silicon at liquid nitrogen temperature (LT) and room temperature (RT). ⟨1 0 0⟩ single-crystal silicon specimens tilted 7° were implanted with 77 keV BSi molecular ions for various ion fluences (1×10^{13}–2×10^{15} cm^{-2}) and then rapid thermal annealed at 1050 °C for 25 s in nitrogen ambient. The SRIM Monte-Carlo computer code was adopted to calculate theoretical damage depth profiles. Raman scattering spectroscopy (RSS) was employed to experimentally characterize damage behavior. It is found that the existence of crystalline and amorphous phases in the specimens can be clearly identified by the longitudinal and transverse optical phonon Raman peaks, respectively, in terms of peak intensity, peak position, area under the peak, and full-width at half-maximum (FWHM) of the peak. The as-implanted results reveal that LT leads to a greater amount of implantation-induced damage than RT does. However, the as-annealed results show that the amount of residual damage in the LT specimen is only slightly smaller than it is in the RT specimen.

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1. Introduction

In recent decades, ion implantation has been well-received as a novel technique in controlling the doping of materials in the near-surface region. Lately, molecular ion implantation [1,2] has attracted increasing attention because of its remarkable feasibility in fabricating shallow junctions in order to meet the needs of modern device technologies. Among many viable techniques, BSi molecular ion implantation has gained plentiful interests on account of its desirable advantages [1–4] including: (a) a greatly reduced energy partitioning factor for boron in BSi (0.28) which substantially lowers the effective boron implantation energy thus benefiting shallow junction fabrication; (b) a greatly amplified beam transport gain for BSi molecular ions (6.7) which considerably enlarges the extracted ion current due to the space-charge effect [5]; (c) significantly enhanced amorphization of the target material due to the presence of the Si constituent in BSi which reduces the channeling of boron atoms in the target material; (d) the incorporation of silicon atoms into the silicon target material (due to the additional Si implantation) without causing any undesired chemical, electrical, or physical effects; and (e) a high rate of Si solubility in the silicon target material.

The major parameters in leading device performance (such as sheet resistance and junction depth [6]) are closely related to the characteristics of radiation damage. Furthermore, radiation damage induced by ion implantation is strongly dependent on substrate temperature, since the occurrence of *in situ* annealing during ion implantation (e.g. out-of-diffusion vacancies, collisions with already-displaced atoms, recombination of vacancies and interstitials) [7,8] may significantly affect radiation damage. Hence, a thorough investigation of the substrate-temperature

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dependence of radiation damage induced by BSi molecular ion implantation, especially at low temperature, is crucial. Unfortunately, to the best of our knowledge, very few research studies on this subject have been conducted. It is therefore the intent of this study to investigate the damage characteristics of 77 keV BSi molecular ion implantation into silicon at liquid nitrogen temperature (LT) and room temperature (RT). In particular, Raman scattering spectroscopy (RSS) is adopted in this study to characterize radiation damage because it is a highly effective detection method in distinguishing between crystalline and disorder structures [9,10]. Additionally, the effects of substrate temperature on threshold ion fluence in achieving amorphization are examined. Variations of damage behavior with ion fluences and rapid thermal annealing (RTA) treatments are also studied in depth.

2. Experimental details

In this study, all the specimens were 2 cm × 2 cm squares prepared from Czochralski-grown phosphorous-doped ⟨100⟩ silicon wafers with a resistivity of 1–10 Ω cm and were deliberately clamped on to a target holder in order to ensure good thermal contact. The implantation of 77 keV BSi molecular ions into silicon specimens was performed using a NEC 9SDH-2 3 MV tandem accelerator. The ion fluenes under investigation ranged from 1×10^{13} to $2\times10^{15}\ \text{cm}^{-2}$. The implanted area on the specimen was 1.5 cm in diameter and the ion beam current was measured directly from the specimen. A copper grid was employed to minimize interference from secondary electrons in charge integration when determining ion fluence. For the liquid-nitrogen-temperature implantations, the specimens were cooled by a flux of liquid nitrogen passing beneath the target holder while the temperature was monitored by a thermocouple placed on the backside of the target holder. The specimens were not cooled during the room-temperature implantations. The normal direction of the specimen was tilted 7° away from the incident-ion beam axis in order to lessen the channeling effect and the incident-ion beam current was maintained at approximately 30–50 nA so as to prevent the specimen from overheating. In addition, the as-implanted specimens were chemically cleaned and one-step annealed in dry nitrogen for 25 s at a temperature of 1050 °C in a Heatpulse 610i RTA system and are hereafter referred to as the as-annealed specimens.

All of the non-implanted, as-implanted, and as-annealed specimens were measured using Raman scattering spectroscopy in order to determine damage characteristics. In this study, Raman spectra of the specimens were recorded at room temperature using a micro-Raman spectrometer together with a tripe grating monochromator (TRIAX 550) in backscattering geometry. An argon laser beam with a single-line wavelength of 514.5 nm was utilized to project onto the specimens and make a spot size of 1–2 μm in diameter. The laser power was maintained as low as 1–2 mW in order to minimize heating in the specimens. A thermoelectrically-cooled charge-coupled device (CCD 3000) detection system was employed to probe the scattered light after its passing through the monochromator. The scattered light was integrated for 180 s with a step size of $1.2\ \text{cm}^{-1}$ in wavenumber.

3. Results and discussion

Fig. 1 displays the SRIM [11] Monte-Carlo simulation of the depth profiles of boron atoms and total defects (interstitials plus vacancies) of the 77 keV BSi implant at an ion fluence of $5\times10^{14}\ \text{cm}^{-2}$. Since SRIM is only applicable for monomer ion implantation, this study approximates the 77 keV BSi implant by a linear superposition of the 21.4 keV B and 55.6 keV Si implants. All the required input data for SRIM computations are obtained from [12]. In Fig. 1, it is obvious that the depth profile of total defects lies closer to the specimen surface and is more highly skewed compared to that of boron atoms. The projected range and longitudinal range straggling of ion-implanted boron in silicon are 79.5 and 29.4 nm, respectively. The calculated threshold ion fluence $\Phi_{\text{th}}^{\text{calc}}$ that initiates amorphization [13] is defined as the ion fluence at which the concentration of total defects equals the atomic number density of silicon ($4.98\times10^{22}\ \text{cm}^{-3}$ [12]) and is thus given by $1.96\times10^{14}\ \text{cm}^{-2}$. Take the ion fluence of $5\times10^{14}\ \text{cm}^{-2}$ for example. The amorphous layer ranges from $x = 3.2$ nm to $x = 106.9$ nm. That is, the thickness of the amorphous layer is 103.7 nm. Notably, the optical penetration depth of the 514.5 nm argon laser light in silicon at RT is approximately 1000 nm [14–16] which is greater than the implanted layer. Therefore, the detection signals obtained from Raman scattering spectroscopy include information regarding the entire implanted layer as well as the bulk silicon to some extent.

Fig. 2 illustrates the representative as-implanted Raman spectra (intensity I versus wavenumber k) of the 77 keV BSi implants at LT and RT with various ion fluences. The

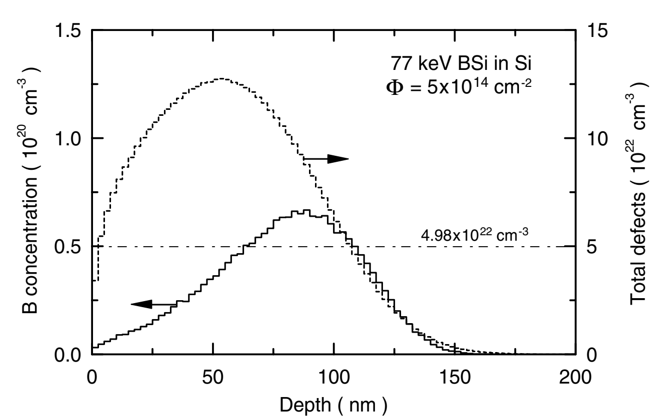

Fig. 1. SRIM-calculated depth profiles of boron atoms and total defects in the as-implanted specimen under 77 keV BSi molecular ion implantation with an ion fluence of $5\times10^{14}\ \text{cm}^{-2}$. The atomic number density of silicon is also indicated in the figure.