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Ion-irradiation-induced athermal annealing of helium bubbles in SiC

Wei Hua [a], Shu-De Yao [a,*], N. David Theodore [b], Xue-Mei Wang [c], Wei-Kan Chu [c], Michael Martin [d], Lin Shao [d]

[a] State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, PR China
[b] Advanced Products Research and Development Laboratory, Freescale Semiconductor Inc., Tempe, AZ 85284, USA
[c] Texas Center for Superconductivity and Department of Physics, University of Houston, Houston, TX 77204, USA
[d] Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843, USA

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ABSTRACT

We have compared the microstructural evolution of helium bubbles under ion irradiation and high temperature annealing. 4H–SiC was irradiated first by 140 keV He ions to a fluence of 1.0×10^{17} cm^{-2} and then annealed at 1200 K for 30 min. Then, the samples were either irradiated by 2 MeV He ions to a fluence of 3.0×10^{16} cm^{-2} at room temperature or annealed additionally at 1200 K for 30 min. Before and after 2 MeV He ion irradiation, significant microstructural changes were observed, similar to effects of high temperature annealing. Thus, the study provides evidence of ion-irradiation-induced athermal annealing on defect Ostwald ripening process and bubble evolution. Possible mechanisms are discussed.

1. Introduction

Silicon carbide (SiC) has very unique electronic, mechanical and thermal properties and has applications in a wide range of fields [1,2]. Radiation effects in SiC have been studied for decades [1–7], driven by the need for doping in microelectronic device fabrication and for radiation simulation of structural components in nuclear engineering applications. Previous studies have obtained a comprehensive knowledge of ion stopping, damage cascade formation, amorphization, defect recovery and defect clustering [1–7]. For its application in a fusion reactor [8–10], material response upon He ion irradiation needs to be further studied. Due to low solid solubility of He atoms in SiC matrix, He atoms prefer to agglomerate to form bubbles. The bubble formation is facilitated by the presence of irradiation induced vacancy type defects. The geometry changes of bubbles is governed by factors such as He pressure, void size, and annealing conditions [11]. The changes can be caused by atomic migration on the bubble internal surfaces and by bulk diffusion of point defects [11].

The present work is aimed to study the role of ion irradiation on bubble evolution. For this purpose, low energy He ion irradiation followed by high temperature annealing is chosen to create He bubbles in SiC. Then the sample undergoes either an additional annealing at the same temperature for the same time or a high energy He ion irradiation at room temperature. Comparison is made to explore ion-irradiation-induced athermal annealing effects.

* Corresponding author.
E-mail address: sdyao@pku.edu.cn (S.-D. Yao).

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2. Experimental procedures

Single-crystalline 4H–SiC (0 0 0 1) wafers (from Cree Res. Inc.) were first irradiated with 140 keV He^+ ions at room temperature to a fluence of 1.0×10^{17} cm^{-2}. After irradiation, samples were annealed in a vacuum furnace at 1200 K for 30 min or 1 h (which consisted of two steps of 30 min annealing). A hot zone annealing approach was used for sample annealing in which the sample is pushed into the heated zone when desired temperature is reached. Sample with 140 keV He ion irradiation and annealing at 1200 K for 30 min were irradiated by 2 MeV He^+ ions at room temperature to a fluence of 3.0×10^{16} cm^{-2}. The beam current of the 2 MeV ion irradiation is around 100 nA, which caused negligible beam heating (<20 °C). Cross-sectional transmission electron microscopy (TEM) was used to characterize the structure of the samples. TEM specimens were prepared by using a conventional focus-ion-beam method by using a 25 keV Ga ion beam. A detailed description of this method can be found in Ref. [12].

3. Results and discussion

Fig. 1a shows the damage and He distribution caused by 1.0×10^{17} cm^{-2} 140 keV He ion irradiation. Fig. 1b compares the nuclear and electronic stopping powers for the same ion irradiation. All data were obtained by using SRIM (stopping and range in matter) code [13]. The calculation has used threshold displacement energies of 20 and 35 eV for C and Si, respectively. The displacement per atom (DPA) is peaked at a depth of 600 nm. The maximum DPA value is about 4.2, which is larger than DPA

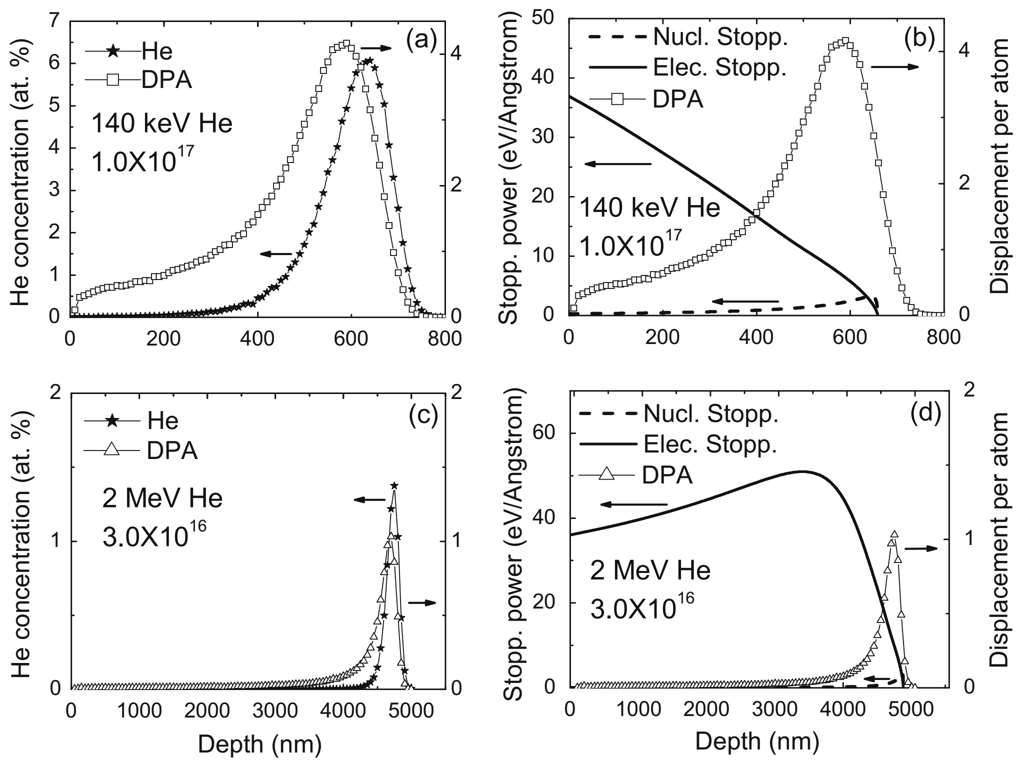

Fig. 1. (a) Depth distributions of damage in DPA (right ordinate) and He concentration (left ordinate) for 1×10^{17} cm^{-2} 140 keV He ion irradiation; (b) depth distribution of nuclear and electronic stopping powers (left ordinate) and damage in DPA (right ordinate) for 1×10^{17} cm^{-2} 140 keV He ion irradiation; (c) depth distributions of damage in DPA (right ordinate) and He concentration (left ordinate) for 3×10^{16} cm^{-2} 2 MeV He ion irradiation; and (d) depth distribution of nuclear and electronic stopping powers (left ordinate) and damage in DPA (right ordinate) for 3×10^{16} cm^{-2} 2 MeV He ion irradiation. All data are obtained by using SRIM code [13].

reported before to induce amorphization [14,15]. According to recent studies on Al-irradiated 4H–SiC, full amorphization occurs when DPA is greater than ~0.5 for ion irradiation at 350 K and ~0.2 at 250 K [14]. However, RBS channeling analysis of the as-irradiated sample in the present study shows a buried region with a peak displacement ratio of 85%. Therefore, complete amorphization is not reached. It is worthy to point out that numerous studies suggested that threshold DPA values for amorphization are a strong function of implanted species, ion energy and irradiation temperatures [3,7]. The absence of amorphization after the high fluence 140 keV ion irradiation is believed to be due to dynamic point defect recombination, which is significant for light ion irradiation. The projected range of He ions is about 630 nm, which is slightly deeper than DPA peak.

Fig. 1c shows the damage and He distribution caused by 3.0×10^{16} cm^{-2}, 2 MeV He ions. Fig. 1d compares the depth distributions of nuclear and electronic stopping powers and damage for the same ions. The projected range of 2 MeV He ions are ~5 μm. In the present work to study the effect of 2 MeV ion irradiation on damage caused by 140 keV He ions, we can neglect He interactions between two He irradiations due to large separation distance between projected ends of range of each irradiation. 140 keV He ion irradiation creates a damage peak at 600 nm, which is near the surface and located in the region dominated by electronic stopping of 2 MeV He ions, as shown in Fig. 1d.

Fig. 2a shows the TEM image of SiC after 140 keV He ion irradiation and annealing at 1200 K for 30 min. The annealing temperate was selected to be high enough to induce crystallization (>1173 K), but low enough to minimize He release from the surface [16]. In a manner similar to threshold DPA for amorphization, there is a wide range of crystallization temperatures reported in literature, with complexity caused by detailed ion irradiation

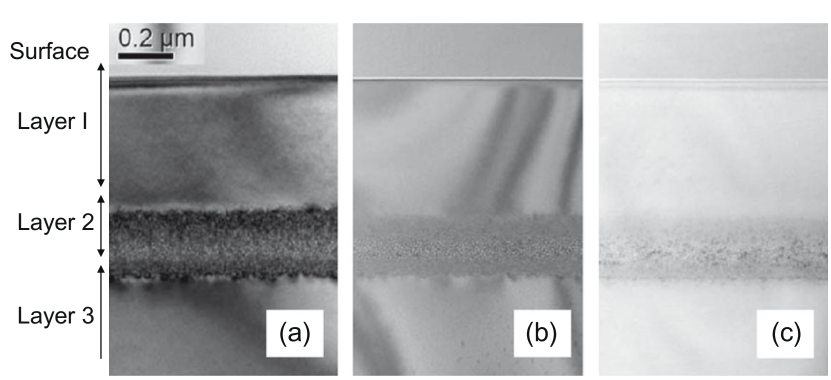

Fig. 2. Cross-sectional TEM micrographs of SiC after (a) 140 keV He ion irradiation followed by 1200 K annealing for 30 min; (b) 140 keV He ion irradiation followed by 1200 K annealing for 1 h; (c) 140 keV He ion irradiation followed by 1200 K annealing for 30 min and 2 MeV He ion irradiation.