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Nuclear Instruments and Methods in Physics Research B 266 (2008) 2466–2469

NIM B
Beam Interactions with Materials & Atoms

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A systematic study on analysis-induced radiation damage in silicon during channeling Rutherford backscattering spectrometry analysis

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Available online 7 March 2008

Abstract

Channeling Rutherford backscattering spectrometry (RBS) is an essential analysis technique in materials science. However, the accuracy of RBS can be significantly affected by disorders in materials induced by the analyzing ion beam even under channeling mode. We have studied RBS analysis-induced radiation damage in silicon. A 140-keV H^+ ion beam was incident along $\langle 100 \rangle$ Si axis at room temperature to a fluence ranging from 1.6×10^{16} cm^{-2} to 7.0×10^{16} cm^{-2}. The evolution of the aligned yields versus fluences has been examined and found to agree well with a model proposed by us.

PACS: 61.05.Np; 61.85.+p; 61.80.Jh

Keywords: Rutherford backscattering spectrometry; Ion beam analysis; Dechanneling; Displacements

1. Introduction

Rutherford backscattering spectrometry (RBS) under channeling mode is a powerful tool to characterize defect densities and structures in the near surface region of monocrystalline thin layers [1]. However, radiation damage can be unintentionally introduced during RBS by the analyzing beam itself. Consequently, attention should be paid in selecting RBS analysis parameters, particularly the total charge collection on one analyzing spot, to minimize radiation damage. The damage accumulation induced by RBS analysis has been noticed as issues in many previous studies. As an example, one study has shown that the energetic analyzing ions can significantly change the substitutional ratio of dopants due to defects created by the analyzing beam [2]. Currently, there is no established model to quantitatively describe the phenomena. In this paper, we reported our experimental studies on damage accumulation in silicon caused by an aligned H ion beam along $\langle 100 \rangle$ crystallographic axis. Moreover, we proposed a systematic approach to model beam-induced damage during RBS. The modeling can be applied to describe general substrates. We select silicon as model materials in this study because of its importance in semiconductor industry.

2. Theory

RBS is based on the well known channeling effect [1]: when the ion beam is aligned within a crystallographic axis or a planar symmetry direction, a significant fraction of the incident ions have trajectories guided between the atomic rows called the “channels”. The ion beam can be separated into two components: a channeled component and a dechanneled component. The channeled component will not have close encounters with lattice atoms. Once close encounters occur, they become dechanneled. Channeled component does not cause damage in the crystal before

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doi:10.1016/j.nimb.2008.03.025

becoming dechanneled. For the channeled component, its energy loss mechanisms are dominated by collisions with target electrons. For the dechanneled component, it is responsible for significant displacement creation owing to its high possibility to have close encounters with lattice atoms. The transition from being channeled to being dechanneled, however, can be enhanced if displacements exist in the channels. The enhanced dechanneling in defective crystals creates more displacements. And these displacements further enhance dechanneling. Therefore, radiation damaging is accelerated in this manner with increasing beam fluences.

In RBS spectra, the dechanneling component, $\chi_R(z)$, can not be directly measured. Its value, at depth z, is given by

$$\chi_R(z) = \chi_V(z) + [1-\chi_V(z)]\left[1-\exp\left(-\int_0^z \sigma_D n_D(z')\,dz'\right)\right], \quad (1)$$

where $\chi_V(z)$ is the normalized aligned yield for a virgin crystal at depth z, $n_D(z)$ is the concentration of displacements at depth z and σ_D is the dechanneling cross section. σ_D can be estimated by [3]

$$\sigma_D = \frac{\pi}{2}\frac{Z_1 Z_2 e^2 d}{E}, \quad (2)$$

where d is the atomic distance along an axial direction and E is the incident energy. Eq. (1) was extracted based on a single scattering mechanism, which is valid under the condition that the density of displacements is relatively low. If we further assume that displacements created by the analyzing beam are randomly distributed, the measured aligned yield, $\chi_D(z)$, can be expressed by [3]

$$\chi_D(z) = \chi_R(z) + [1-\chi_R(z)]\frac{n_D(z)}{n}, \quad (3)$$

where n is the atomic density of the crystal.

We here propose to calculate n_D by using the following formula:

$$n_D(z) = \chi_R(z)\phi\frac{\alpha S_n(z)}{2E_d}. \quad (4)$$

The above equation is based on the Kichin–Pease formulation of the displacements creation [3]. $S_n(z)$ is the depth dependent nuclear stopping power, α is a constant between 0.5 and 1 ($\alpha = 1$ in this study), ϕ is the beam fluency and E_d is the displacement energy required to displace an atom from its lattice site. A well established value of E_d is 14 eV in Si [3].

Our approach is based on a double iterative process. Briefly, final beam fluence is divided into many small fluences, and the substrate is divided into many thin slabs. At each slab, the dechanneling component, contributed by all slabs at a shallower depth is calculated by using Eq. (1) and converted into displacements in the slab by using Eq. (4). After calculation for one small fluence, the newly-created displacements are added to previously existing displacements and used to start iteration for the next fluence; calculations are continued until the total fluence equals the experiment value.

Starting from the lowest fluence, we begin the iteration process at the surface (depth $z = 0$), by assuming $\chi_R(0) = \chi_V(0)$. In order to calculate Eq. (4), $S_n(Z)$ from the stopping and range of ions in matter (SRIM) code is used [4].

3. Experimental procedure

The procedure described above is used to discuss RBS spectra obtained from a ⟨100⟩ monocrystalline Si. The sample was irradiated at room temperature with a 140-keV H^+ ion beam to a fluence up to $7 \times 10^{16}\,\mathrm{cm}^{-2}$. The beam was aligned along Si ⟨100⟩ axis during the irradiation. After irradiation with different fluences, a quick channeling RBS spectra was obtained by using the same beam but with a very small charge collection. The sample alignment was realized by using a 4-axis goniometer with a resolution of 0.01°. A surface barrier detector was placed at an angle of 170° away from the beam incident direction.

4. Results and discussion

Fig. 1 shows RBS spectra obtained from Si after irradiation with different fluencies. Each curve in Fig. 1 is obtained by using the same analyzing fluence. The analyzing fluence is much less than irradiation fluences. Channel numbers of raw RBS spectra have been converted to Si depths. For the convenience of discussion, we have removed the C signals in the raw spectra, and spectra were reconstructed by using an interpolation between points immediately before and after C signals. As shown in Fig. 1, RBS yields are increasing with enhanced irradiation fluences, which provides clear evidence that damage is gradually accumulated in Si by irradiation.

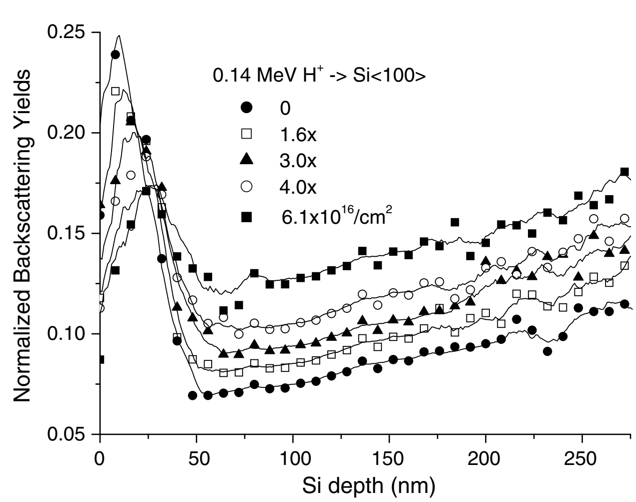

Fig. 1. RBS spectra obtained from Si after irradiation with 140-keV H^+ ions at different fluences.