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Medium Energy Ion Spectroscopy of Ultra-Thin As^+ Implanted Layers: The Effect of Reversible Site Change of As Atoms

Zbigniew J. RADZIMSKI[a,c], Shin YOKOYAMA[a], Takeshi WATANABE[b], Kensaku ISHIBASHI[b] and Masataka. HIROSE[b]

[a]Research Center for Integrated Systems, Hiroshima University
[b]Department of Electrical Engineering, Hiroshima University
1-4-2 Kagamiyama, Higashi-Hiroshima 724, Japan

An arsenic atom displacement in As^+ ion implanted silicon has been observed during the measurement of Medium Energy (175keV) Ion Spectroscopy (MEIS). Arsenic atom sites are reversibly changed by He^+ ion beam irradiation in random and aligned conditions. This observation has become possible due to a high sensitivity of MEIS. Characterization of silicon surface damage and evaluation of implanted As concentration by using MEIS are also presented and discussed.

1. INTRODUCTION

Beam-induced atomic displacement has been observed by many characterization techniques and utilized for semiconductor processing[1-4]. It is generally assumed that no appreciable change in the crystal lattice arrangement occurs in channeling measurements in Rutherford Back Scattering Spectroscopy (RBS). However, it has been shown that the interaction of the analysis beam of MeV He^+ ions with doped As atoms results in kicking off 20-40% of As atoms from the substitutional lattice sites[3]. Such arsenic atom displacement has been observed during RBS measurements in random conditions. The effect was at least order of magnitude smaller than the case of the measurements in aligned conditions[3,4]. The atom displacement effects depend strongly on the beam energy and current as well as a sample temperature.

In this work we have found a reversible site change of As atoms during Medium Energy Ion Spectroscopy (MEIS) measurements performed in random and aligned conditions. The observation has become possible due to a high sensitivity of this technique. MEIS could become a strong candidate for evaluating defects and impurities in very shallow semiconductor regions. Hence, the other purpose of this work is to demonstrate the potentials of MEIS for more realistic characterization of implanted Si wafers. The arsenic concentration and the extent of damage for low-energy As implanted silicon are determined by MEIS.

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c)Present address: Analytical Instrumentation Facility, North Carolina State University, Raleigh, NC 27695-7917, USA

2. EXPERIMENTAL

The MEIS measurement system using a solid state detector has been developed by modifying an ion implanter[5]. Arsenic atoms were implanted into p-Si(110) at 14keV with different cumulative doses from 2.3×10^{12} to 5×10^{14} cm^{-2} at room temperature. The sample was tilted by 10° with respect to the As^+ ion beam. The backscattering spectra were measured in aligned and random conditions using a 175keV He^+ ion beam with a 1 mm diameter. The beam current was varied from 2 to 10nA to evaluate the influence of the He^+ ion beam intensity on the motion of As atoms in silicon lattice.

3. RESULTS AND DISCUSSION

The MEIS spectra collected in the channeling direction for a non-implanted Si wafer and those after each implantation step are compared in Fig. 1. A very good proportionality of the As peak counts with respect to the implant dose is obtained as illustrated in Fig. 2, where the net counts correspond to the integrated As signal intensity over the energy range from 100 to 145keV. The As signal level detected at a dose of 2.3×10^{12} cm^{-2} indicates a very high sensitivity of MEIS.
A clear peak at energies 85 to 95 keV as observed in Fig.1 shows the presence of the damaged layer even at a dose of 2.3×10^{12} cm^{-2}. The integrated signal corresponding to the damaged Si surface layer is also plotted as a function of the implantation dose in Fig. 2. At doses above 4.2×10^{13} cm^{-2} the damage signal tends to saturate, indicating that silicon amorphization threshold is located at $\sim 4.2 \times 10^{13}$ cm^{-2}. The portion of the As spectrum at a dose of $1 \times 10^{14} cm^{-2}$ measured in the aligned condition with a 10nA He^+ beam current is shown in Fig. 3a. A clear As peak at 132 keV and a low

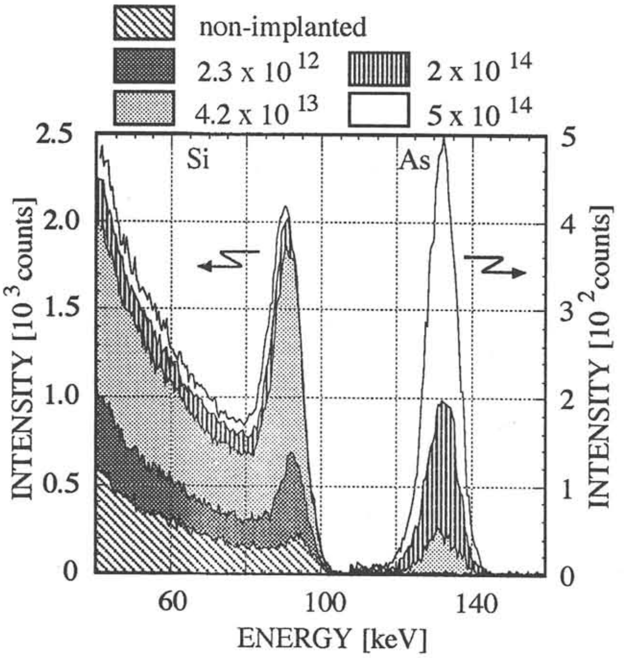

Fig. 1. The MEIS spectra of the As implanted Si (110) substrate. The spectra were taken after each implantation step with cummulative dose shown above.

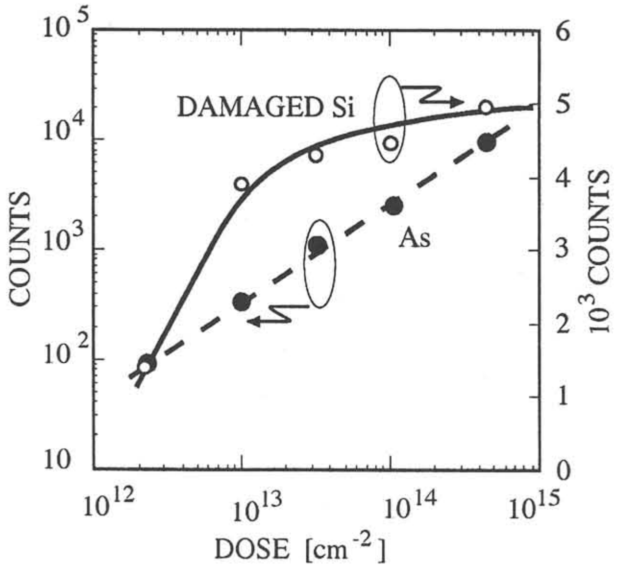

Fig. 2. Total integrated signal of As peak (broken line) and that of the damaged Si surface layer as a function of As cummulative dose.

background between 100 and 125 keV are observed. The spectrum measured in the random condition with the same beam current (Fig. 3b) shows an enhancement of the As background signal. Assuming that the total amount (100%) of As is detected in this configuration, then only 27% of total As can be measured in the aligned mode (Fig.3a). This indicates that approximately 73% of As reside in the substitutional sites of the Si crystal lattice or otherwise in the interstitial sites behind the

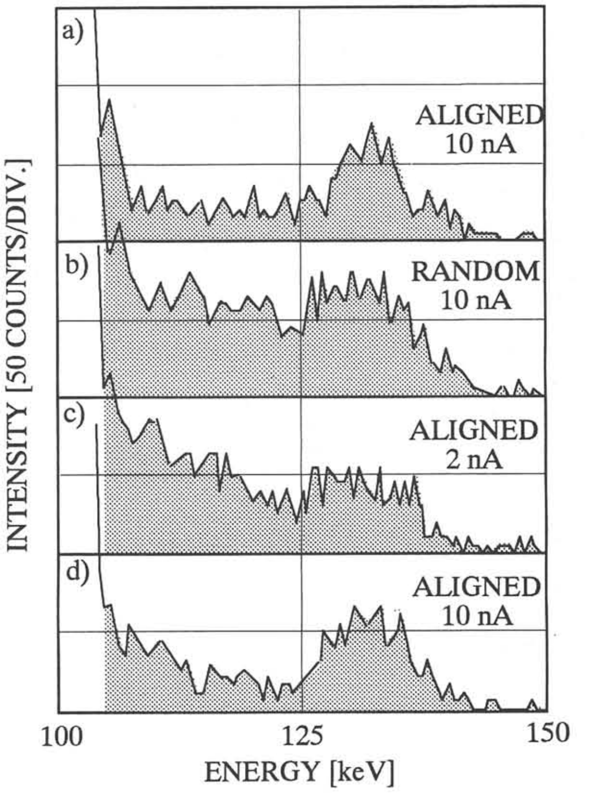

Fig. 3. The MEIS spectra of As part measured subsequently in the aligned and random conditions with low (2nA) and high (10nA) He^+ ion beam currents.

shadow cone regions. This interpretation is possible under the assumption that As atoms remain in stationary positions. However, the following experiment proves that this estimation might be inaccurate. In fact, when the spectrum is subsequently measured in the aligned mode with a 2nA beam current (Fig. 3c), 60% of the total As atoms are detected. This implies a 33% increase of detected As atoms when it is compared with the result of Fig. 3a (27%). This increase occurs mainly due to the increase of the background signal in the energy range from 105 to 125keV. This background signal corresponds to the As atoms being located at the interstitial positions which are not behind the shadow cone regions. When the beam current is again increased to 10 nA in the same aligned mode as in Fig. 3a, the amount of detected As atoms dropps to 39% of the result of Fig.3b (100%) presumably because interstitial As atoms are kicked back to the shadow cone regions by the aligned He^+ ion beam irradiation as discussed later. These variations in the integrated As signal intensity are summarized in Table 1, where the As content is normalized by the signal intensity detected at random conditions with a 10nA beam (Fig. 3b). The table shows that As atom displacement occurs in an approximately reversible way. Namely, the 10 nA aligned measurement (Figs. 3a and 3d) results in pushing interstitial As atoms to the shadow cone regions while the random measurement forces such As atoms to return to the interstitial sites.

Table 1. Arsenic amount as detected by MEIS at each step of aligned or random measurement. The As content is normalized with respect to the amount detected at the random condition with a 10nA beam current.

Beam current	10nA ↓↓↓	10nA ↘↘↘	2nA ↓↓↓	10nA ↓↓↓
Analysis mode	o o o o o o o o o o o o	o o o o o o o o o o o o	o o o o o o o o o o o o	o o o o o o o o o o o o
Arsenic content	27%	100%	60%	39%
Spectrum	Fig. 3a	Fig. 3b	Fig. 3c	Fig. 3d

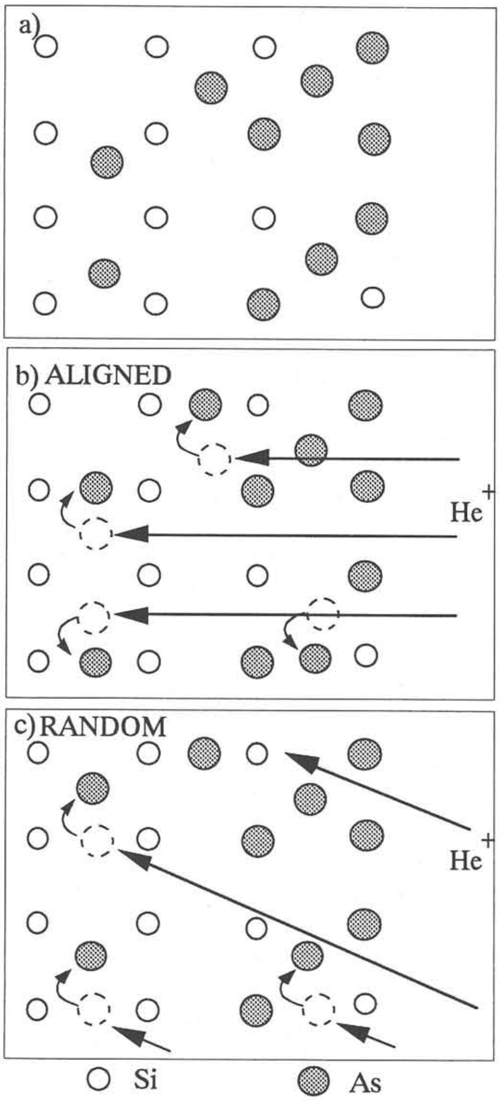

Fig. 4. The schematic illustration of As atom displacement by He$^+$ ion beam during MEIS measurements. (a) arsenic atom sites in as implanted sample, (b) arsenic atom movement during analysis in the aligned mode with a high beam current, (c) arsenic atom movement during analysis in the random mode.

A possible model of such arsenic atom displacement is schematically shown in Fig. 4. In as-implanted Si arsenic atoms reside in various interstitial and substitutional positions of silicon lattice. Most of them can be detected by He$^+$ beam in random conditions as shown in Fig. 4a which refers to the case of Fig. 3b. In the aligned condition the As atoms in substitutional sites as well as interstitial sites behind the shadow cone of silicon lattice cannot be detected. A smaller As signal detected in the aligned mode with a 10 nA beam (Fig. 3d) in comparison with an aligned 2 nA beam (Fig. 3c) implies that a fraction of As atoms is relocated by the aligned 10nA He$^+$ beam. It is likely that As atoms are kicked off from the interstitial positions to the shadow cone regions of the Si lattice as illustrated in Fig. 4b that refers to the case of Fig. 3d. From Table 1 and Figs. 3c and 3d it is shown that the difference between the number of As atoms detected by the 2 and 10 nA aligned beams is 21% which correspond to the relocated As atoms. It should be noted that this process is basically reversible, i.e. by changing the He$^+$ incident beam to the random direction a part of the As atoms are moved back to the interstitial positions as shown in Fig. 4c. In this case the random spectrum is again similar to that shown in Fig. 3b.
Rimini et al.[3)] have used a high energy ion beam (1.8 MeV) to move As atoms into interstitial positions, whereas no reversible effect has been observed.

4. SUMMARY

It is shown that the MEIS is very sensitive for probing low-dose As-implanted ultra-shallow regions and the induced damage. Because of the extremely high sensitivity a reversible As atom displacement induced by He$^+$ ion beam has been clearly observed. Our results indicate that a special care has to be paid during RBS and MEIS measurements to obtain a reliable information about the content of implanted impurity concentration and its profile. It is also shown that a very low level of surface damage can be detected by MEIS.

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