Sub-nm depth resolution in sputter depth profiling by low energy ion bombardment *

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The sputter damage profile of a Si(100) by low energy O\(^+\) and Ar\(^+\) ion bombardment with various incident angles was measured by using medium energy ion scattering spectroscopy. It was observed that the damaged Si surface layer could be minimized down to 0.5−0.6 nm with grazing incident angle of 80° for 500 eV Ar\(^+\) and O\(^+\) ion bombardment. The SIMS depth resolution for a GaAs delta layer in Si and a multiple boron nitride delta layer in Si with low O\(^+\) ion bombardment was sub-nm, which is in good agreement with the measured damaged layer thickness. [DOI: 10.1380/ejssnt.2004.24]

Keywords: Damage profile; Depth resolution; Delta layer

I. INTRODUCTION

With the rapid scale reduction of semiconductor devices, nm scale characterization of ultrathin film and dopant distribution becomes more critical. Sputter depth profiling by secondary ion mass spectrometry (SIMS) and Auger electron spectroscopy (AES) have been widely used in semiconductor industries due to its high sensitivity and depth resolution [1]. However, the depth resolution of conventional SIMS and AES using several keV ion beam sputtering is not good enough for ultra shallow junctions. Recently, low energy primary ion beam has been used to improve the depth resolution and to reduce the surface transient effect. The ultimate limit for the depth resolution depends on how surface damage and transient width can be minimized during sputtering. Even though low energy ion sputtering has been used frequently to improve the depth resolution of ultra shallow junction, the surface damage effects caused by low energy ion sputtering was not studied so far because of the difficulties in measuring the damage profiles caused by low energy sputtering.

For a quantitative measurement of a damaged layer, surface and subsurface analysis tools with much better depth resolution and quantification capabilities are required. Medium energy ion scattering spectroscopy (MEIS) has been successful in obtaining the surface composition and structure, almost nondestructively and quantitatively, with less than 1.0 nm depth resolution [2-4].

The sputter damage profile of a Si(100) by 500 eV O\(^+\) and Ar\(^+\) ion bombardment with various incident angles was measured using MEIS. The SIMS depth resolution, estimated with trailing edge decay length for a GaAs delta layer in Si and a multiple boron nitride (BN) delta layer with spacing of 5 nm were sub-nm, which is in good agreement with the measured damaged layer thickness.

II. EXPERIMENTS AND SIMULATION

For damage profile measurements, a MEIS analysis system was used. A clean Si(100) surface was obtained by flashing up to 1150°C after etching with dilute HF. For low energy ion bombardment, 500 eV O\(^+\) and Ar\(^+\) were used. The current density was around 0.5 µAcm\(^-2\), which is measured by a Faraday cup moved to the sample position. During the ion beam sputtering, the pressure of the etching chamber is 2×10\(^-3\) Pa. The MEIS analysis was carried out with 100 keV H\(^+\) ion incident along the [111] direction and exiting along the [001] direction with the scattering angle of 125°. Details of the MEIS techniques and the system used in this experiment are given elsewhere [5, 6]. The reduction of the surface damaged layer thickness by the low energy sputtering was also observed by SIMS depth profiling. The Si thin films with a Ga delta layer 10 nm beneath the surface and a multiple BN delta layer with spacing of 5 nm were used. In the case of Ga delta layer, the specimen was bombarded by O\(^+\) ions, and the incident ion impact energy was varied from 8.0 keV to 0.65 keV with accompanying changes in the ion incident angle from 39° to 75°. The SIMS depth resolution was estimated with trailing edge decay lengths of 69Ga\(^+\) ion profiles. The SIMS analysis was performed by Cameca-IMA 4f. In the case of a BN delta layer, the specimen was bombarded by 500 eV O\(^+\) ions, and the ion incident angle was 46°. The SIMS depth resolution was estimated with the leading and trailing edge decay lengths of B\(^+\) ion profiles. The SIMS analysis was performed by Cameca-IMA 6f.

III. RESULTS AND DISCUSSION

The dose dependence of the sputter damage on a clean Si(100) surface under normal incidence of 500 eV O\(^+\) ion is shown in Fig. 1. A crystalline Si(100) surface peak

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FIG. 1: MEIS energy spectra of a Si(100) surface for various doses of 500 eV O$_2^+$ ions with surface normal incidence. For comparison, the clean Si(100) surface peak was indicated.

FIG. 2: MEIS energy spectra of a Si(100) at the steady state after 500 eV O$_2^+$ ion bombardment with various incident angles. For comparison, the clean Si(100) surface peak was indicated.

corresponding to zero ion dose is also shown. Because of the double alignment measurement condition, only atoms in the amorphous layers, that is, the surface damaged layers are measured. As the O$_2^+$ ion dose increases, the surface damaged layer becomes thicker and the Si surface is oxidized. After the ion doses of $\sim 2.0 \times 10^{16}$ O$_2^+$ ions cm$^{-2}$, the Si surface reaches the steady state with a 7.9 nm Si surface damaged layer and 3.0 nm oxide layer. Because the formation of the 7.9 nm surface damaged layer on Si(001) under 500 eV O$_2^+$ ion bombardment at normal incidence is not appropriate for shallow junction profiling, possible further decrease in the damaged layer was explored by changing the incident angle. The incident angle dependence of the MEIS damage profiles by 500 eV O$_2^+$ ion bombardment is shown in Fig. 2. All the MEIS spectra were obtained after the saturation ion dose. The surface peak of a clean Si(100) is also shown for comparison with that of the glancing angle of 80$^\circ$. As the incident angle varies from surface normal to glancing angle, the damaged layers become thinner. The damaged layer thickness, measured from the Si peak, is reduced from 7.9 nm at the surface normal to 0.6 nm at the glancing angle of 80$^\circ$. Therefore the sputter damage effect in the sputter depth profiling can be confined to a couple of atomic layers in the surface by low energy ion sputtering with the grazing incident angle. Since Ar$^+$ ion bombardment is commonly used in AES and XPS depth profiling, the surface sputter damaged layer formation under Ar$^+$ ion bombardment was also studied. The saturation damage

FIG. 3: MEIS energy spectra of a Si(100) at the steady state after 500 eV Ar$^+$ ion bombardment with various incident angles.

FIG. 4: SIMS depth profiling of a Si(10 nm)/SiGaAs(1 nm)/Si(50 nm)/Si(100) for various O$_2^+$ ion energies. The incident angles are determined by the incident energy and bias voltage, and are 39$^\circ$ for 8.0 keV, 42$^\circ$ for 5.5 keV, 52$^\circ$ for 3.0 keV, 57$^\circ$ for 2.5 keV, 64$^\circ$ for 2.0 keV and 75$^\circ$ for 0.65 keV.
FIG. 5: SIMS depth profiling of a multiple BN delta layer with spacing of 5nm for 500 eV O\textsuperscript{2+} ion energies with the incident angles of 46°.

Profiles for 500 eV Ar\textsuperscript{+} ion bombardment with various incident angles are shown in Fig. 3. For 500 eV Ar\textsuperscript{+} ion bombardment, the damaged layer thickness is reduced from 5.1 nm at the surface normal to 0.5 nm at the glancing angle of 80°. In our previous surface sputter damage study for a Si(100) under 3 keV Ar\textsuperscript{+} bombardment [4], we had reported the surface sputter damaged layer thickness to be 14.2 nm at the surface normal and 4.8 nm at the incident angle of 80°, respectively. This shows that low energy sputtering significantly reduces the damaged depth. The damage layer thickness for Ar\textsuperscript{+} ion sputtering is thinner than that of O\textsuperscript{2+}. The swelling of implanted layer due to oxide formation might be responsible to the apparent thicker damaged layer in the O\textsuperscript{2+} bombardment [7]. In the case of O\textsuperscript{2+} bombardment, the surface was fully or partially oxidized by incorporated oxygen atoms depending on the incident angle as shown in Fig. 2. However, in the case of Ar\textsuperscript{+} ion bombardment, the implanted Ar atoms are easily ejected into the vacuum. For normal incidence, the total number of oxygen atoms calculated from the oxygen MEIS peak is $1.2 \times 10^{14}$ O atoms cm\textsuperscript{-2} for O and $2.4 \times 10^{12}$ Ar atoms cm\textsuperscript{-2} for Ar. Figure 3 also shows the peak of implanted primary Ar atoms as well as Si(100) damage profiles. In-depth concentration profiles of Ar can be calculated from this distribution. The maximum atomic concentration of Ar is about 6% at the depth of about 2nm for the normal incidence, but is not detected for the glancing incident angle of 80°. Details about in-depth distribution of Ar atoms can be seen elsewhere [8]. The reduction in the surface damaged layer by low energy sputtering with grazing incident angle was confirmed with SIMS depth profiling as shown in Figs. 4 and 5. The incident ion impact energy was varied from 8.0 keV to 0.65 keV. To compare with MEIS experimental results, the trailing edge decay lengths of \textsuperscript{69}Ga\textsuperscript{+} profiles were estimated [9, 10], as given in Fig. 4. The experimental result for 8.0 keV shows a very long Ga tail with the trailing edge decay length of 5.9 nm. With the decrease of the ion energy, the SIMS depth resolution is improved quite significantly. The ion energy dependence shows that the error in determinations of shallow junction depths can be as large as 30 nm under conventional SIMS analysis conditions. For the ion energy of 650 eV, the trailing edge decay length decreases down to 0.9 nm. According to the MEIS results in Fig. 2, the surface damaged layer in Si(001) is 0.6 nm for 500 eV O\textsuperscript{2+} ions with the glancing incident angle of 80°, which is in a good agreement with the estimated SIMS depth resolution. Fig.5 (a) shows the SIMS depth profile of B\textsuperscript{+} for a multiple BN delta layer with spacing of 5nm [12] with a CAMECA-6f by 500 eV O\textsuperscript{2+} ions at the incident angle of 46° from surface normal. Here the nominal thickness of BN delta layer is 0.05 nm, which actually corresponds to 0.37 nm monolayer (ML) coverage and the thickness of BN delta layer should be one ML thick by definition. The leading edge and the trailing edge decay length is about 0.05 nm and 0.8 nm, respectively, which is not significantly degraded in each delta layer. This indicates that the surface topographic development is negligible under the sputtering conditions. Therefore, in this multiplayer thin film, the physical process is expected to mainly contribute to the depth resolution of B delta layer. Dynamic Monte Carlo (MC) simulation [11] has been carried out to compare with experimental results. The calculation results were obtained with partial sputtering yield of B in a multiple BN delta layer with spacing of 5nm. In the calculation, the concentration of

**FIG. 6:** Calculated results of SIMS depth profiling of a multiple BN delta layer with spacing of 5nm for 500 eV O\textsuperscript{2+} ion energies with the incident angles of 46° and 80°.
BN delta layer is 100 at% within 0.27 nm, but in experiment the concentration of BN delta layer is low enough to avoid the matrix effects. Therefore the simulation results cannot be compared with experimental results quantitatively, but can be compared qualitatively. The simulation result is in a good agreement with experimental result in leading edge and peak position as shown in Fig.5 (b). The trailing edge decay length at the incident angle of 46° and 80° is about 2.3 nm and 1.4 nm, respectively. Differences between experiment and MC result exist in the trailing edge decay length because of different parameters such as the concentration of BN delta layer thickness, ionization probability. In Fig. 6, MC results show clearly the ion incident angle effect, that is, the depth resolution at the incident angle of 80° is quite improved compared with that at the incident angle of 46°. The peak of B profile at the incident angle of 46° is shifted to the surface side compared with that at the incident angle of 80°. The peak shift of delta layer is attributed to the atomic mixing of delta layer into the damaged layer caused by the penetration depth of primary ion beam. Considering that the damaged layer thickness in our experiment is 0.6 nm at the glancing angle of 80°, the depth profile obtained at the incident angle of 80° is close to the true profile. Therefore, to achieve the ultimate SIMS depth resolution with low energy ions, the glancing incident angle should be utilized together.

IV. SUMMARY

The damage profile of a Si(100) surface after 500 eV O$_2^+$ and Ar$^+$ bombardment was measured with MEIS as a function of the incident angle. The sputtered damaged layer thickness is reduced significantly down to sub-nm as the incident angle increases from the surface normal to the glancing angle. The sputter damaged layer thickness of a Si(100) by 500 eV O$_2^+$ and Ar$^+$ ion bombardment could be minimized to 0.5 nm for the glancing incident angle of 80°. The sub-nm sputter damaged layer thickness is also confirmed by the low energy SIMS depth profiling of a Ga delta layer in Si and a multiple BN delta layer with spacing of 5 nm. Thus we clearly confirmed that the sub-nm depth resolution is possible by low energy ion sputtering with the glancing incident angle in practical sputter depth profiling.

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