Standardization of SIMS Shallow Junction Profiling with Multiple Delta-layer Thin Films

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For quantitative shallow junction SIMS depth profiling, the surface transient Si sputtering effect should be measured and calibrated. It is shown that the average Si sputtering yield with low energy Cs^+ ion bombardment in the surface 5 nm layer can be higher than that in the steady state by a factor of two. Secondary ionization probabilities also change significantly in the surface region. We report that multiple As delta-layered Si thin films characterized with HRTEM and MEIS can be used as a reference thin film for shallow junction SIMS depth profiling.

INTRODUCTION

Even though SIMS (Secondary Ion Mass Spectrometry) has been widely used for depth profiling analysis in semiconductor industries due to its excellent sensitivity and high depth resolution, the depth resolution of conventional SIMS using keV ions is not enough for shallow junction profiling. Even with the recent development of low energy SIMS for depth resolution improvement, additional problems come from the surface transient effects where the sputtering rate and the secondary ionization probability continuously change during SIMS profiling through shallow junctions[1 - 2]. For the quantitative measurement of the sputtering yield change in the transient region, multiple delta-layers with nm intervals can be used. Since Arsenic is a common dopant used in the fabrication of *n*-type silicon, multiple As delta-layered Si thin films were grown as reference materials. It was characterized with HRTEM (High Resolution Transmission Microscope) and MEIS (Medium Energy Ion Scattering Spectroscopy) to determine the thickness and the areal density of As in the delta layers. With multiple As delta-layered thin films, the change in the depth scale and the secondary ionization probability in low energy SIMS shallow junction depth profiling can be measured and calibrated.

EXPERIMENTAL

Multiple As delta-layered Si thin films were grown by ultra-high vacuum ion beam sputter deposition and characterized with HRTEM, MEIS, and SIMS. Multiple As delta-layered Si thin films were grown on *n*-type Si (100)wafers at room temperature by sputtering a Si wafer target with 1 keV Ar^+ ions. To minimize the As surface segregation during thin film growth, H atoms were continuously supplied to the thin film surface during growth to passivate the surface. To determine the amount of As and the thickness of one As delta layer, HRTEM and MEIS were used. The MEIS spectrum was taken with 100 keV H^+ ions. The H^+ beam was incident along the [111] direction and exited along [001] direction with the scattering angle of 125°. Details of the MEIS techniques and the system used in this experiment are given elsewhere[3-4]. For the analysis of the absolute areal density of As atoms for each layer with MEIS, the MEIS system calibration factor was determined using various standards such as Si(100) and Pt(111)surface peak, nm SiO_2 and Ta_2O_5 thin films on Si(100)[5]. For As SIMS profiling, 0.5 keV Cs^+ with 45° incidence angle and 0.25 keV Cs^+ with 50° incidence angle were used in an ION-TOF time-of-flight SIMS system and an ATOMIKA quadrupole-based SIMS system, respectively.

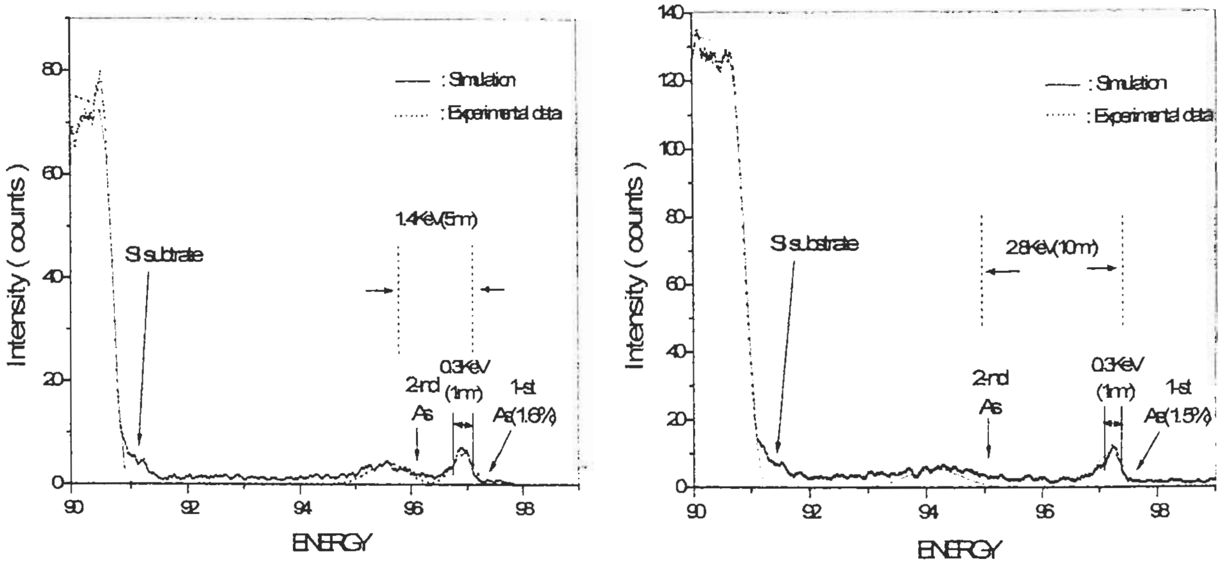

Figure (a)   Figure (b)

Fig. 1. MEIS spectra of a multiple As delta-layered Si thin film. 100 keV H⁺ ions were incident in the [111] direction and the ions scattered in the [001] direction were measured. The thin film specimen structure are (a) Si(100) / {Si(30 nm) /As(1 nm)} x 4 / Si(5 nm) / As(1 nm) and (b) Si(100) / {Si(90 nm) / As(1 nm)} x 4 / Si(10 nm) / As(1 nm).

RESULTS AND DISCUSSIONS

MEIS depth profiling and HRTEM analysis

MEIS measurements were carried out to analyze the thickness and composition of As delta layer. Figure 1 shows As delta-layer MEIS spectra for the first and second delta layers with intervals of 5 nm and 10 nm, respectively. The other As delta-layer peaks are overlapped with Si peaks and cannot be distinguished. The width of the As peak and the As areal density for each layer is estimated to be 1nm and $1.08\times10^{14}/cm^2$, respectively, from MEIS spectra analysis. The As concentration in a delta-layer is estimated to be ~1.5%. For the first peak, the thickness estimations is more reliable than other layers, since there is no electronic straggling effect. The second As delta-layer peak is broad due to the straggling effect of projectile ions[5].

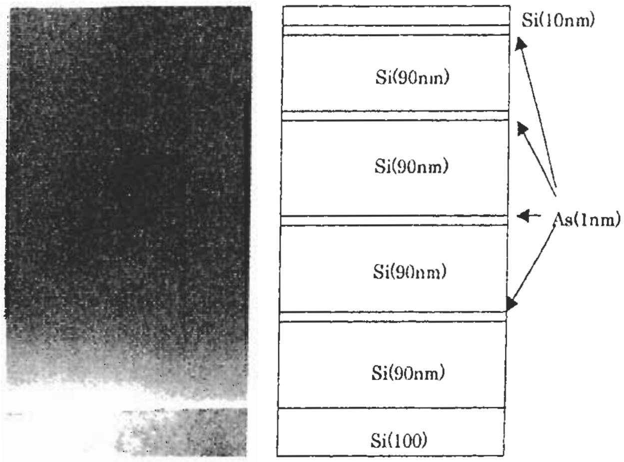

Fig. 2. Bright-field cross-section transmission TEM image of a multiple As delta-layered Si thin film.

Figure 2 is a bright-field cross-section transmission TEM image of a multiple As delta-layered Si thin film, which shows that Si layers are amorphous with the thickness of 90 nm and multiple As delta-layers are identically repeated. The determination of thickness of As delta layers with TEM seems to be not reliable. However, from the combined result of MEIS and TEM, we think the interval and the thickness of As delta-layers are identical within the uncertainty of ~ 10%. The SIMS profiles in Fig. 3 also show the reproducibility of As delta-layers, in consistent with MEIS and TEM results.

Low energy SIMS analysis of multiple As delta-layered Si thin films

A low energy SIMS profile of a multiple As delta-layered Si thin films with 5 nm intervals and 10 nm intervals is shown in Fig. 3. It was taken by a ION-TOF SIMS

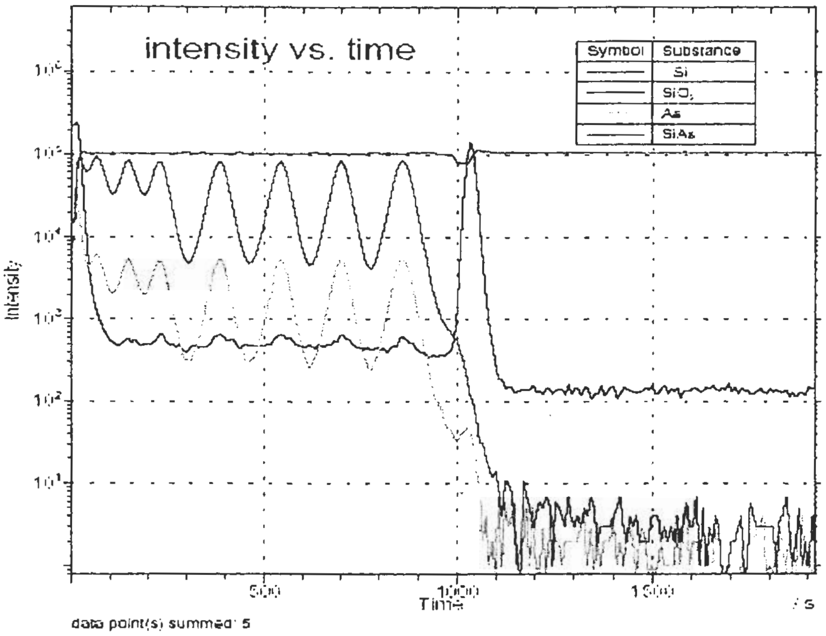

Fig. 3. Low energy SIMS depth profile of a multiple As delta-layered Si thin films taken with 15 keV Ga^+ primary ions for SIMS analysis and 0.5 keV Cs^+ ions with 45° incidence angle for sputtering.

system with 15 keV Ga^+ primary ions for SIMS analysis and 0.5 keV Cs^+ ions with 45° incidence angle for sputtering. The SIMS profiles in the shallow region show that the average Si sputtering yield in the first 5 nm region is 2 times higher than that in the steady state. It corresponds to a depth scale shift of 2.5 nm to the shallower direction. The trailing edge decay length estimated from the profiles [6-7] is 1.3 nm. The SIMS profiles also show that the secondary ionization probability changes significantly in the first 5 nm shallow region. For $SiAs^-$, the change is not significant but for As^-, the secondary ionization probability is 5 times higher in the first As delta layer. However, the Si profile does not show any change in the intensity from the beginning, which is consistent with the $SiAs^-$ profile.

Similar observations were made with another low en-

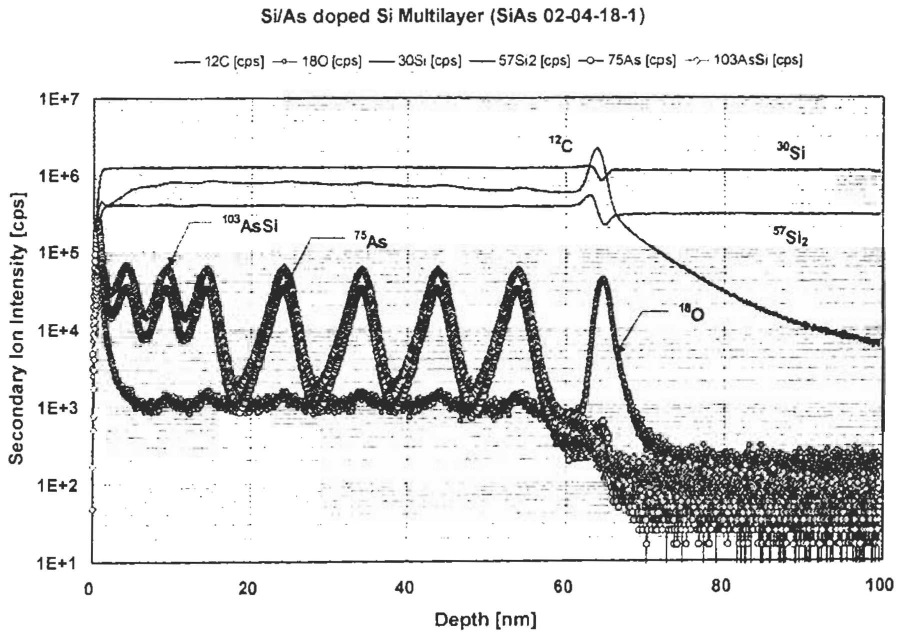

Fig. 4. Low energy SIMS depth profile of a multiple As delta-layered Si thin films taken with 0.25 keV Cs^+ ions with 50° incidence angle for sputtering.

ergy SIMS profiling analysis. In Fig. 4, a low energy SIMS depth profile of the same multiple As delta-layered Si thin films is shown, which was taken by a ATOMIKA SIMS system with 0.25 keV Cs^+ ions with 50° incidence angle. The SIMS profiles in the shallow region shows that the average Si sputtering yield in the first 5 nm region is 1.6 times higher than that in the steady state, which corresponds to a depth scale shift of 2.0 nm to the shallower direction. The trailing edge decay constant is 0.98 nm. The SIMS profiles also show that the secondary ionization probability changes significantly in the first 5 nm shallow region. For $SiAs^-$, the change is not significant but for As^-, the secondary ionization probability is 8 times higher in the first As delta layer. Again, the Si^- profile does not show any change in the intensity from the beginning like the $SiAs^-$ profile. The slightly improved trailing edge decay lengh of 0.98 nm can be mainly due to the lower Cs+ ion energy of 250 eV compared to 500 eV, considering the similar incidence angle.

The low energy SIMS profiles in Fig. 3 and Fig. 4 show that the leading edge decay constants are 1.2 nm for both profiles. It does not change with the Cs+ sputtering energy, while the trailing edge decay length decreases from 1.3 nm to 0.98 nm. It indicates that the distribution of As in the leading edge is not as abrupt as in the trailing edge due to the As surface segregation during thin film growth. The abruptness of the As delta layers in Si thin films should be improved further.

The measured SIMS depth profiles in Fig. 3 and Fig. 4 show clearly that the change of the surface transient sputtering effect is sensitively dependent on each analysis condition. The possibility of molecular interference between $^{75}As^-$ and $^{29}Si^{30}Si^{16}O^-$ can be excluded due to the absence of $^{75}As^-$ peak in the interface between the substrate and the multiple As delta-layered Si thin film, since the thin film were grown without removing the native oxide layer on the substrate.

CONCLUSIONS

It is reported that the surface transient Si sputtering effect can be measured and calibrated with multiple As delta-layered Si thin films as a reference thin film for shallow junction SIMS depth profiling. It was shown that the average Si sputtering yield with low energy Cs^+ ion bombardment in the surface 5 nm layer can be higher than that in the steady state by a factor of two. The secondary ionization yields also changes significantly in the surface region. The large change of the Si sputtering yield should be carefully calibrated for accurate shallow junction SIMS profiling.

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