Characterization of Ultra-Shallow Implants Using Low-Energy Secondary Ion Mass Spectrometry: Surface Roughening under Cesium Bombardment

●Yuji Kataoka ●Mayumi Shigeno ●Yoko Tada
●Kazutoshi Yamazaki ●Masataka Kase

(Manuscript received January 15, 2002)

Surface roughening caused by low-energy Cs^+ bombardment was studied to obtain more reliable ultra-shallow arsenic depth profiles and to provide important information for the modeling and process control of advanced CMOS design. Ultra-shallow arsenic implantation distributions and narrowly spaced antimony delta markers in silicon were used to explore surface roughening caused by low-energy Cs^+ bombardment (0.25 to 1 keV) at impact angles between 0° (normal incidence) and 75°. The surface roughening was observed at oblique incidence. The roughening degraded the depth resolution and gave rise to a severe profile shift. In addition, another profile shift was observed at near normal incidence. This shift seems to be correlated to the amount of Cs accumulated in and on the sample. Impact angles of 45 to 50° (0.25 keV), 50 to 55° (0.5 keV), and 55 to 60° (1 keV) should be used to avoid the surface roughening and profile shift. The use of these conditions enables us to evaluate arsenic depth profiles more correctly and provide important information for forming reliable ultra-shallow junctions.

1. Introduction

Secondary ion mass spectrometry (SIMS) is an analytical technique based on the mass spectrometric analysis of elemental and molecular fragmentations that are sputtered from a surface being bombarded with energetic ions. SIMS is widely employed for dopant depth profiling in semiconductor layers and devices, providing accurate measurements of dopant distributions over concentrations from 1×10^{13} to 1×10^{21} cm^{-3}.

The continued reduction in the scaling of complimentary metal-oxide semiconductor (CMOS) devices requires the formation of ultra-shallow and very heavily doped junctions. Junction depths as shallow as about 20 nm are expected to be used in the production of 0.1 µm-generation devices. The scaling of shallow junctions has been performed by reducing the implant energy of ion implantation and increasing the dose to achieve a shallower, more abrupt profile with lower sheet resistance. SIMS is possibly still the most powerful characterization technique for profiling implants and measuring the junction depth and total dose. However, SIMS depth profiling of very shallow implants can be quite challenging since a major fraction of the profile can fall within the surface transient before the sputtering process achieves equilibrium.

Boron and arsenic, respectively, are the major p-type and n-type dopants currently used in CMOS processes. For boron depth profiling in Si, O_2^+ primary ions are commonly used to obtain a higher detection sensitivity. A number of studies have been done to reduce the transient effect and obtain more accurate boron depth profiles under O_2^+ bombardment. The depth resolution is known to be significantly improved by reducing the primary ion energy. Recent work has shown, however, that low-energy (sub-keV) O_2^+ bombardment of Si at oblique incidence gives rise to unfavorable artifacts; namely, rapidly forming ripples combined with long-term variations in the erosion rate.[1)-3)]

A quantitative study of dose accuracy with ultra-shallow arsenic implants was recently reported,[4)] but little work has been reported on arsenic depth profiling in Si. For arsenic depth profiling in Si, Cs^+ primary ions are commonly used at an impact angle of 60° to obtain a higher detection sensitivity. Other recent studies involving the use of oblique low-energy Cs^+ ions at impact angles between 50° and 80° do not consider the possibility of bombardment-induced ripple formation.

The aim of this study was to explore the Si surface roughening caused by low-energy Cs^+ bombardment in more detail to identify the optimum conditions for depth profiling ultra-shallow arsenic implants in Si. The study was done *in situ* by measuring the depth dependence of the depth resolution and *ex situ* by scanning electron microscopy (SEM) inspection of the roughness at the bottom of sputtered craters.

2. Experiments

Two types of samples were investigated. One type consisted of As^+-implanted silicon wafers with two types of doses: 5×10^{14} cm^{-2} at 1 keV and 1×10^{15} cm^{-2} at 5 keV. The other type was grown by MBE (Molecular Beam Epitaxy) on Si (100) and contained six Sb deltas with a spacing of 5 nm (Sb-6δ). After removing the native oxide from the substrate by an RCA-type HF dip and heating to 860°C in a vacuum, a 100 nm Si buffer layer was grown at 275°C. Then, six Sb delta layers containing nominally 5×10^{13} Sb atoms/cm^2 were grown with interlayer spacings of 5 nm.

An Atomika 4500 depth profiler was used for measurements in the negative SIMS mode. The Cs^+ primary ion energy ranged from 0.25 to 1 keV, and the beam current was from 25 to 35 nA. The raster scan area in the (x_0, y_0) plane normal to the beam axis was 500 µm × 500 µm. The nominal impact angle was varied between 0° (normal incidence) and 75°. Based on an analysis of the crater edge lengths in the x and y scan directions, the calculated impact angles turned out to be about 2° lower than the nominal values. As and Sb were detected as $AsSi^-$ and $SbSi^-$. Si^- and Si_2^- ions served as matrix reference species.

After depth profiling, the topography of the sputtered crater bottoms was explored using a Hitachi S5200 scanning electron microscope. A low-energy (2 keV) electron beam was chosen to obtain a high surface contrast.

3. Results and Discussion

Figure 1 shows the As depth profiles obtained from a 5 keV As implanted sample at 0.5 keV Cs^+ and various impact angles. The apparent depth scale was calibrated from the crater depth. As the figure shows, the peaks of the profiles are not observed at the same apparent depth. Furthermore,

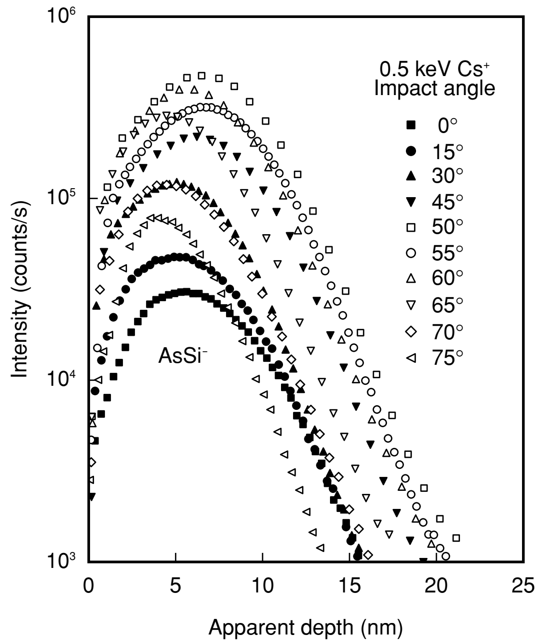


Figure 1
Raw SIMS depth profiles of an As implant in Si measured by Cs^+ bombardment at various impact angles.

the peaks appear at apparent depths significantly less than the mean projected range of 9 nm that was derived from high-resolution backscattering work[5] and TRIM simulations.[6] **Figure 2** shows the peak shift, which is the difference between the true and apparent peak positions, as a function of the impact angle. Figure 2 also shows the peak shift for a 1 keV implant with a mean projected range of 3.5 nm. The peak shift is distinctly larger for the higher-energy implantation distribution. It is likely that the ripple formation caused the peak shift and distorted the depth profiles.

To investigate the ripple formation in more detail, we considered the results obtained from the Sb-6δ sample. **Figure 3** shows Sb depth profiles for a 1 keV Cs^+ bombardment. The apparent depth scale was calibrated under the assumptions that 1) the erosion rate was constant throughout the profiling and 2) the last $SbSi^-$ peak was located at a depth of 30 nm. Contrary to the assumption that the depth resolution improves with increasing impact angle, at 1 keV, the maximum-to-minimum ratio of the $SbSi^-$ signal decreased at nominal impact angles above 65°. In fact, when the impact angle was increased to 70°, the delta layers became almost unidentifiable.

Inspection of the profiles shown in Figure 3 suggests that the width of the $SbSi^-$ peaks is not a very suitable parameter for quantifying the changes in resolution. Instead we define a resolution contrast R_c as:

$$R_c = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad , \qquad (1)$$

where $I_{\max}$ and $I_{\min}$ are the local signal maxima (peaks) and minima (valleys) in the $SbSi^-$ depth profile. **Figure 4** shows angular dependent results for three Cs^+ impact energies. The data relate to the 5th delta layer from the surface. This figure suggests that losses in depth resolution start at "critical" impact angles, θ_{cr}, of about 50° (0.25 keV), 55° (0.5 keV), and 60° (1 keV).

Figure 5 shows four SEM images of the crater bottoms produced during bombardment with 0.5 keV Cs^+. All images were taken at a crater depth of about 35 nm. Well-defined ripples are

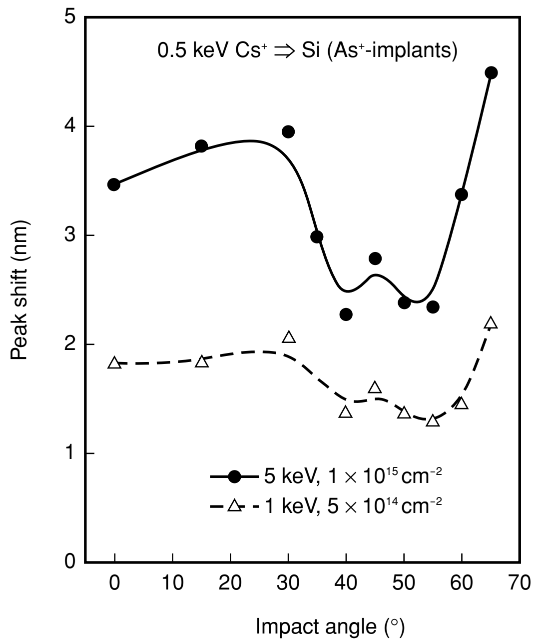


Figure 2
Peak shifts derived from measurements shown in Figure 1.

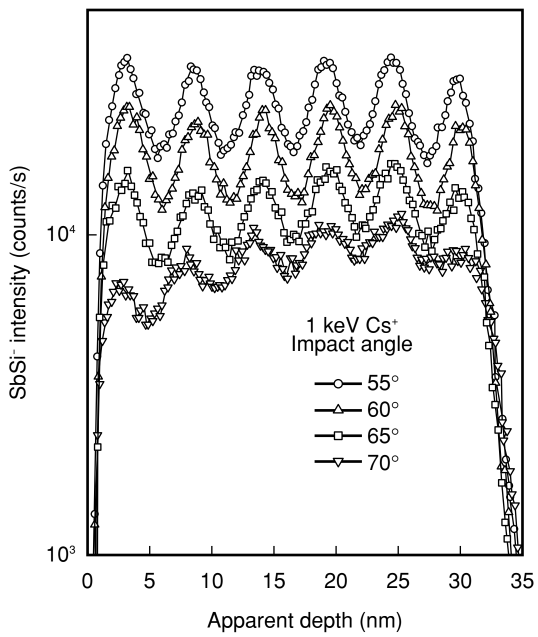


Figure 3
Depth profiles of Sb for 1 keV Cs^+ bombardment at various impact angles.

observed at impact angles above 55°. Under the quoted conditions, the mean ripple spacings or "wavelengths" are about 32 nm (55°), 16 nm (60°), 19 nm (65°), and 29 nm (70°). Although the ripple height cannot be deduced directly from the SEM images, the micrographs in Figure 5 suggest that the growth rate of ripples increases with the impact angle. This interpretation is in accordance with the results shown in Figures 3 and 4. Clearly, the rate of loss in contrast and therefore depth resolution is intimately related to the growth rate of ripples.

The results described here are qualitatively very similar to those reported for low-energy oxygen bombardment at oblique beam incidences.[1)-3)] Even though a large amount of work has been devoted to elucidating the mechanism of ripple formation under oxygen bombardment, a clear understanding of the observed phenomena has not yet been achieved. There appears to be some agreement with the idea that above a critical angle, the formation of a coherent oxide layer is no longer possible. Making an analogy with oxide formation, the new phase generated under low-energy Cs bombardment could be cesium silicide. As with an oxygen beam,[7)] the sputtering yield can be expected to be a crucial parameter. Much more work must be done to arrive at a reasonably detailed understanding of ripple formation on silicon bombarded with "reactive" primary ions.

Figure 6 shows the $SbSi^-$ peak shifts from the nominal depth as calculated from the $SbSi^-$ depth profiles shown in Figure 3. The peak shifts in this figure are all minimum at impact angles between 55° and 65°. We found that low-energy (sub-keV) Cs^+ bombardment gives rise to a peak shift not only at oblique incidences above θ_{cr}, but also at near normal incidence. The shift decreases with increasing impact angle up to 55 to 65°. Apparently, the amount of Cs that accumulates in and on the sample decreases as the angle increases. The peak shift at near normal incidence seems to be correlated to the amount of Cs. We obtained the same kind of results for 0.25 and 0.5 keV bombardments. The minimum peak shifts were observed at impact angles from 45 to 55° (0.25 keV) and 50 to 60° (0.5 keV).

To summarize the above results, impact angles from 45 to 50° (0.25 keV), 50 to 55° (0.5 keV), and 55 to 60° (1 keV) should be used to avoid

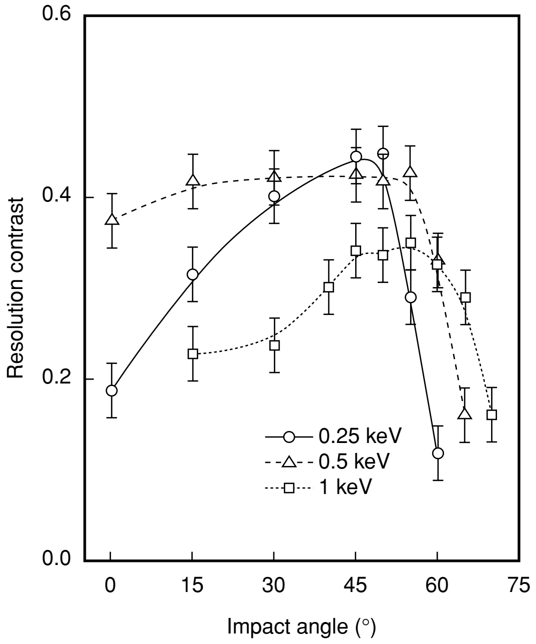


Figure 4
Resolution contrast R_c of Sb profile vs. nominal impact angle for three Cs^+ energies. R_c is defined in Eq. (1).

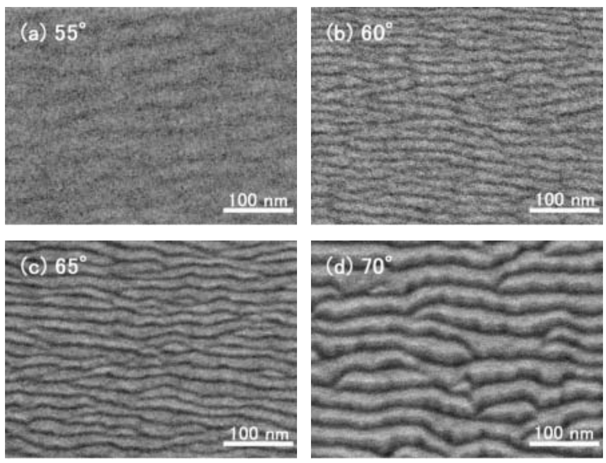


Figure 5
SEM images of the bottom of 35 nm craters produced by bombardment with 0.5 keV Cs^+ at various impact angles.

surface roughening and peak shifts and obtain more reliable depth profiles.

4. Conclusion

The surface roughening caused by low-energy Cs^+ bombardment was studied using As^+-implanted Si wafers and Si samples grown by MBE that contained six Sb delta layers. Losses in depth resolution and severe profile shifts were observed above critical Cs^+-bombardment impact angles of about 50° (0.25 keV), 55° (0.5 keV), and 60° (1 keV). SEM observations showed well-defined ripples above the critical impact angles. The SEM observations suggest that the ripple formation is responsible for the losses in depth resolution and the profile shift. In addition, another profile shift was observed at near normal incidence. This shift was caused by the amount of Cs that accumulated in and on the sample during the bombardment.

To avoid surface roughening and profile shifts, we should use impact angles from 45 to 50° (0.25 keV), 50 to 55° (0.5 keV), and 55 to 60° (1 keV). The use of these conditions will enable us to evaluate arsenic depth profiles more correctly and provide important information about forming reliable ultra-shallow junctions.

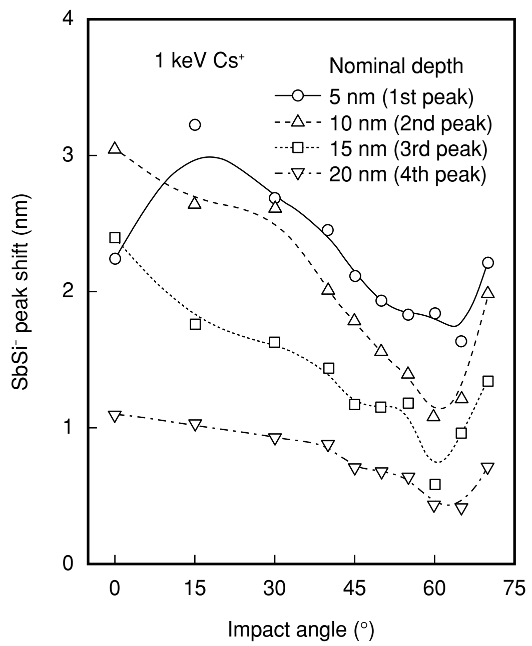


Figure 6
$SbSi^-$ peak shifts derived from measurements shown in Figure 3.

References

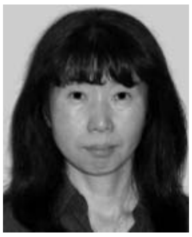
1) K. Wittmaack and S. F. Corcoran: Sources of error in quantitative depth profiling of shallow doping distributions by secondary-ion-mass spectrometry in combination with oxygen flooding. *Journal of Vacuum Science & Technology B*, **16**, 1, p.272-279 (1998).
2) Z. X. Jiang and P. F. A. Alkemade: Secondary ion mass spectrometry and atomic force spectroscopy studies of surface roughening, erosion rate change and depth resolution in Si during 1 keV 60° O_2^+ bombardment with oxygen flooding. *Journal of Vacuum Science & Technology B*, **16**, 4, p.1971-1982 (1998).
3) K. Wittmaack: Influence of the depth calibration procedure on the apparent shift of impurity depth profiles measured under conditions of long-term changes in erosion rate. *Journal of Vacuum Science & Technology B*, **18**, 1, p.1-6 (1998).
4) M. Tomita, C. Hongo, and A. Murakoshi: Native oxide effect on ultra-shallow arsenic profile in silicon. In Secondary Ion Mass Spectrometry SIMS XII, A. Benninghoven, P. Bertrand, H. N. Migeon, and H. W. Werner (eds), Elsevier, 2000, p.489-492.
5) S. Kalbitzer and H. Oetzmann: Ranges and range theories. *Radiation Effects,* **47**, p.57-71 (1980).
6) J. Ziegler: *http://www.SRIM.org*.
7) K. Wittmaack: Local SiO_2 formation in silicon bombarded with oxygen above the critical angle for beam-induced oxidation: new evidence from sputtering yield ratios and correlation with data obtained by other techniques. *Surface and Interface Analysis*, **29**, 10, p.721-725 (2000).

Yuji Kataoka received the B.S. degree in Applied Chemistry from Waseda University, Tokyo, Japan in 1984. He joined Fujitsu Laboratories Ltd., Kawasaki, Japan in 1984, where he has been engaged in materials characterization using Secondary Ion Mass Spectrometry.

Kazutoshi Yamazaki graduated from Hakodate Technical High School, Hakodate, Japan in 1983. He joined Fujitsu Laboratories Ltd., Kawasaki, Japan in 1983, where he has been engaged in materials characterization using Secondary Electron Microscopy and Auger Electron Microscopy.

Mayumi Shigeno received the B.S. degree in Chemistry from Gakushuin University, Tokyo, Japan in 1983. She joined Fujitsu Laboratories Ltd., Kawasaki, Japan in 1983, where she has been engaged in materials characterization using X-ray Photoelectron Spectroscopy and Secondary Ion Mass Spectrometry.

Masataka Kase received the B.S. and M.S. degrees in Physics from Ehime University, Matsuyama, Japan in 1984 and 1986, respectively. He joined Fujitsu Ltd., Kawasaki, Japan in 1986, where he has been engaged in development of FEOL (front end of line) processes for ULSI.



Yoko Tada received the B.S. degree in Physics from Toho University, Funabashi, Japan in 1986. She joined Fujitsu Laboratories Ltd., Kawasaki, Japan in 1986, where she has been engaged in materials characterization using Secondary Ion Mass Spectrometry.