

Implant dose measurement and depth profiling of 10-keV implanted As by high-resolution RBS

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Implant dose and depth profile distribution of 10-keV arsenic (As) implanted silicon (Si) (projected range ~ 13 nm) at nominal doses between 1×10^{14} and 1×10^{16} cm⁻² have been characterized by high-resolution Rutherford backscattering spectrometry (HRBS). HRBS is a highly practical technique for such implanted samples because it provides quantitative and nondestructive measurements with a sub-nm depth resolution. A relationship between the nominal implant doses and peak area intensities of As on HRBS spectra is well fitted by a linear approximation with an error of $\sim 2\%$. As a result of measuring the same samples 3 times (at 1.5-year and 9-month intervals, respectively), the temporal repeatability of the slope of the linear approximation is good using the same detector (micro-channel plate and one-dimensional position sensitive detector), when one compensates the gain degradation of the detector by adjusting its bias. HRBS results also showed a segregation of As at the interface between the surface native SiO₂ and Si.

1. Introduction

Ion implantation is universally used in the fabrication of silicon metal-oxide semiconductor (MOS) devices. Along with the downscaling of MOS dimensions, it requires a very shallow ion implantation technique for a formation of the ultra shallow junctions. In development of such a device and process, it is a key point to measure the implant dose, the depth of the peak concentration, and depth profiles of the dopants, etc., with a high depth resolution.

High-resolution Rutherford backscattering spectrometry (HRBS) using a magnetic spectrometer is one of the useful techniques for such implanted samples. HRBS provides elemental depth profiles with a sub-nm depth resolution quantitatively [1-2], because the signal yields obtained in HRBS are essentially based on analytical cross-sections and they are not affected by matrix dependent effects as seen in secondary ion mass spectroscopy. However, from a practical point of view of applying HRBS to those implanted samples, it is important to realize its error or temporal repeatability, because they are key issues for the accuracy and reliability of the

measurement.

In this work, we have characterized 10-keV As implanted Si at a wide range of nominal doses between 1×10^{14} and 1×10^{16} cm⁻² using HRBS. We investigated the necessary total charge of incident ions to obtain the area intensity of As with a small error, and a relationship between the nominal dose and area intensity of As on HRBS spectrum. In order to study the temporal repeatability, we measured the same samples 3 times (at 1.5-year and 9-month intervals, respectively). Furthermore, the depth profiles were investigated by comparing with the results from TRIM Monte Carlo simulation [3].

2. Experimental

Silicon <100> wafers were implanted with 40-keV silicon ions (1×10^{15} cm⁻²) for pre-amorphization and then implanted with 10-keV As ions at 7° of tilt angle at nominal doses of 1×10^{14} , 1×10^{15} , 3×10^{15} and 1×10^{16} cm⁻².

HRBS 500 (Kobe Steel, Ltd.) [4] was used for HRBS measurements to obtain the As implant doses and depth profiles of those samples. A beam of 400 keV helium ions with ~ 40 nA was impinged on to the samples and

scattered ions at a scattering angle of 75° were energy analyzed by a 90-degree sector magnet. The scattering angle was chosen to fulfill the two following conditions. One is to separate As peak from Si on HRBS spectrum, and another is to obtain better depth resolution. After the sector magnet, the scattered ions are detected by a set of a micro-channel plate (MCP) and a one-dimensional position sensitive detector (BURLE Ind.). In order to prevent ion channeling, the incident angle (from the normal to the sample surface) was chosen to be 49° (random orientation), and the sample held on a 5-axis goniometer was rotated during the measurement.

In RBS the implant dose can be calculated directly from the area of the signals given by the total number of counts integrated over the region of interest on the spectrum. In HRBS it is necessary to take into consideration of detecting only one particular charge state ions and detection efficiency of the detector, then the area intensity A can be expressed as

$$A = Nt \frac{d\sigma}{d\Omega} \frac{\Omega Q}{\cos \alpha} \varepsilon \eta \quad (1)$$

where Nt is the number of implant atoms per unit area, $d\sigma/d\Omega$ the angular differential cross-section, Ω the acceptance solid angle of the spectrometer, α the incident angle, ε the fraction of single charged helium ions of all the scattered particles (He^+ , He^{2+} , He^0), and η the detection efficiency of the spectrometer. For obtaining a net area intensity of As, a proper coefficient that shall be multiplied to the background of the spectrum of the virgin silicon, was determined using Microsoft Excel's SOLVER function. The net area intensity of As was calculated by subtracting the background multiplied by the coefficient from As signals on each HRBS spectrum.

3. Results and discussions

To estimate the necessary total charge of incident ions Q for obtaining the As peak area intensity with a small error, we investigated an error defined by a standard deviation (σ) of area intensities of As of five HRBS spectra obtained with the same total charge Q . The results for the sample implanted at As dose of $1 \times 10^{16} \text{ cm}^{-2}$ with the total charge Q ranged between 2.5 and 50 μC are shown in Fig. 1. The figure also shows the As peak area A (right-hand scale) and its statistical error expressed by $A^{-1/2}$ for reference. It is found that the total charge Q of $\sim 5 \mu\text{C}$ is necessary to measure within 1 % of the error for

the sample implanted at $1 \times 10^{16} \text{ cm}^{-2}$. This amount of charge usually corresponds to ~ 2 minutes when the incident beam current is 40 nA.

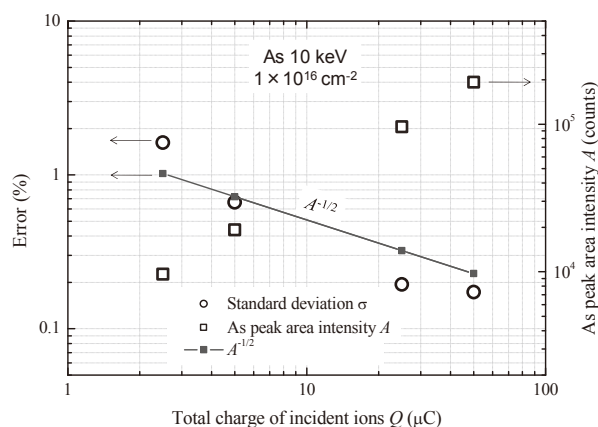


Fig. 1 Standard deviation σ (open circles) of As peak area intensities derived from five HRBS spectra as a function of the total charge of incident ions Q . The measurements were carried out for the same sample with the same total charge of incident ions. The sample is the one at As dose of $1 \times 10^{16} \text{ cm}^{-2}$. The right-hand scale denotes As peak area intensity A for open squares. The solid line is the statistical error of As peak area intensity expressed by $A^{-1/2}$.

In order to estimate accuracy and temporal repeatability of implanted dose measurement, we characterized 10-keV As implanted Si at a wide range of nominal doses (1×10^{14} , 1×10^{15} , 3×10^{15} , and $1 \times 10^{16} \text{ cm}^{-2}$). The measurements were carried out 3 times, on July 21 2005, January 20 2007, and November 1 2007. Table 1 shows the As peak area intensity for each sample and two kinds of differences. One is the difference of the maximum to minimum of the three results, and another is the one of the early two results. The results show that the former difference is larger than the latter one. It should be noted here that the early two results are obtained using the first MCP, and in the period between the second and third measurements the MCP was replaced by a new one. Thus it is inferred that the change of the value of the As peak area intensity is resulted by the replacement of MCP.

Table 1 As peak area intensity derived from HRBS spectrum.

Nominal As dose (cm^{-2})	Jul. 21 2005	Jan. 20 2007	Nov. 1 2007	Difference Max - Min	%	Difference @1st MCP	%
1×10^{14}	1.30E+04	1.38E+04	1.32E+04	8.28E+02	6.2%	8.28E+02	6.0%
1×10^{15}	1.02E+05	1.05E+05	1.16E+05	1.34E+04	12.5%	2.23E+03	2.1%
3×10^{15}	-	3.06E+05	3.40E+05	3.40E+04	10.5%	-	-
1×10^{16}	9.54E+05	9.64E+05	1.07E+06	1.20E+05	12.0%	9.32E+03	1.0%

A relationship between the nominal implant dose and the As peak area intensity for each measurement date (from data in Table 1) is shown in Fig. 2. In the figure, a linear approximation of those plots is shown by the solid line with its formula and error of its slope. The approximated line is well fitted with $\sim 2\%$ of its slope for each measurement. On the other hand, the absolute value of the slope changed from 9.6×10^{-11} to 1.1×10^{-10} (counts cm^2/atoms), which is corresponding to 11% difference, after the replacement of MCP as shown in Fig. 3. The change of the slope is thought to be caused by the individual difference of the detection efficiency of MCP because no other factors in Eq. (1) were changed. Fortunately, in usual sequence of estimating the areal density using the signal of substrate material, the individual change of the detection efficiency does not matter if one uses the same MCP. However, when one estimates the absolute areal density directly from the As peak area intensity, it is necessary to realize it. For the setup with the first MCP, the spectrometer efficiency η for single-charged helium ions with 300 – 400 keV is calculated from Eq. (1) to be $\sim 36\%$, where $\Omega = 0.6$ msr in the spectrometer and ε is assumed to be 75% [5]. It should be noted that the MCP bias was adjusted for each measurement, in order that the pulse height distribution of the MCP signals might be the same as the initial one in saturation mode.

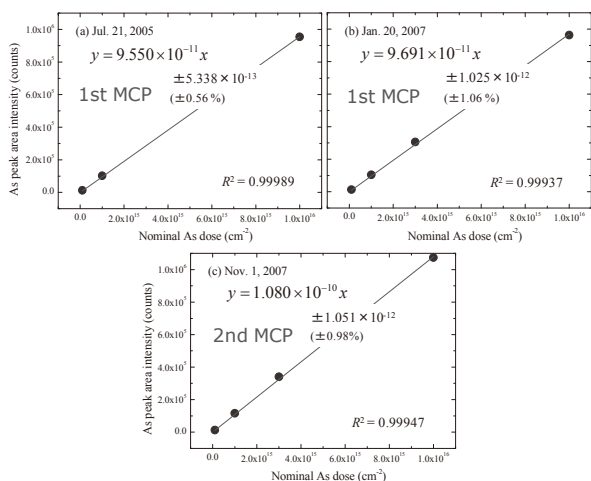


Fig. 2 As peak area intensity derived from HRBS spectrum as a function of nominal implant dose of As. The dates on which the data was obtained were (a) July 21 2005, (b) January 20 2007, and (c) November 1 2007, respectively.

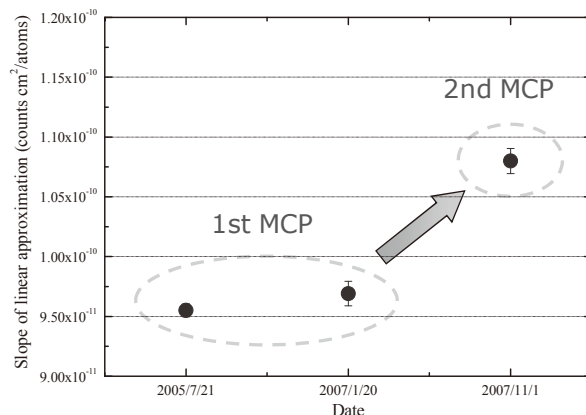


Fig. 3 Temporal change of slope of linear approximation of the nominal As dose vs. the As peak area intensity.

Figure 4 shows an example of As signals of HRBS spectrum for the sample implanted at $1 \times 10^{16} \text{ cm}^{-2}$ and its depth profile with a result of TRIM calculation for comparison. Note that the vertical scale for TRIM profile was normalized with the area of HRBS result. The results showed that the projected range is ~ 13 nm (almost likely to TRIM result), the peak concentration is $\sim 13\%$. It is also seen a segregation of As at a very surface region ($2 \sim 3$ nm) as is shown by markings in Fig. 4, which is corresponding to at the Si side of the interface between the native SiO_2 and Si substrate, supporting the observation of Berg et al. [6].

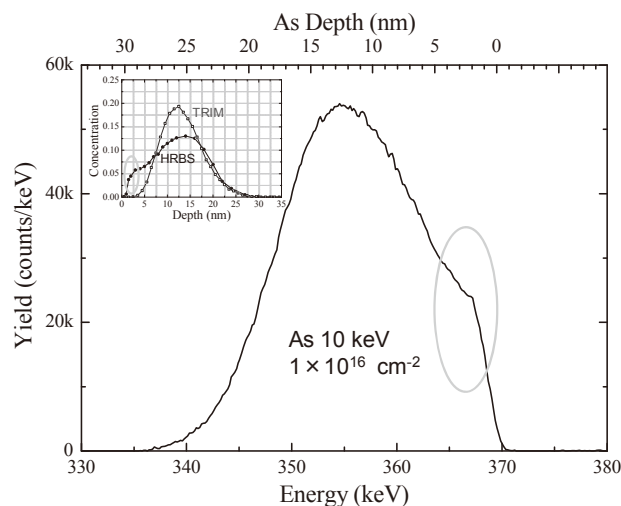


Fig. 4 Observed HRBS spectrum for the sample implanted at $1 \times 10^{16} \text{ cm}^{-2}$. The upper abscissa is the depth for As. The internal figure is the depth profile derived from the HRBS spectrum compared with the TRIM result. The vertical scale for TRIM profile was normalized with the area of HRBS result.

4. Conclusions

We have characterized 10-keV As implanted Si at a wide range of nominal doses between 1×10^{14} and 1×10^{16} cm^{-2} using HRBS. We presented the total charge of incident ions of $\sim 5 \mu\text{C}$ is necessary to measure within 1 % of the error for the sample implanted at 1×10^{16} cm^{-2} . We showed that once the relationship between As peak area intensity and nominal dose is obtained for one MCP, HRBS can provide an implant dose measurement with a high accuracy of ~ 2 %. Furthermore the segregation of dopant was observed and likely to be at the interface between SiO_2/Si . In conclusion, HRBS is a powerful analytical tool for the quantitative characterization of implant samples, for not only the implant dose measurement but depth profiling at the surface region.

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6. References

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