SIMS Round-Robin Study of Depth Profiling of Boron Implants in Silicon

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A round-robin study is performed concerning with depth profiling of boron implanted in silicon using secondary ion mass spectrometry (SIMS). Relative sensitivity factors (RSFs) are derived by 18 participants using various types of SIMS instrument. Obtained RSF values agree with a deviation of within 11 % for the boron doses of $3x10^{14}$ - $3x10^{16}$ ions/cm^2 (for B^+ and BSi^-). However, RSFs for $1x10^{17}$ ions/cm^2 deviate due to the matrix effect of high boron concentration. Measurement conditions and the calculation method of RSF are shown to be crucial to quantify boron profiles in a high concentration range.

1. Introduction

Depth profiling is the most common measurement mode in dynamic secondary ion mass spectrometry (SIMS) and widely used in evaluating microelectronics materials. To establish standard protocols in SIMS depth profiling, however, more knowledge is needed about fundamentals of ionization and sputtering as well as instrumental aspects. So far, several round-robin tests were performed to assess boron profiles,[1,2] but they did not cover a wide range of ion dose. Therefore, a round-robin study was organized among Japanese SIMS users to evaluate the problems of the quantification of boron (B) implanted in silicon (Si) specimens with a wide range of ion dose. In the previous study[3], we reported the results of the reproducibility of depth profiles and the linearity of the ion intensity.

For higher B doses (over $1x10^{16}$ ions/cm^2), the peak concentration of implanted B is over $1x10^{21}$ atoms/cm^3. Therefore, the profiles of B and Si distort due to a matrix effect. These distortions affect the quantification for higher dose specimens.

In this study, we report the behavior of B and Si in higher dose specimens and discuss the problems of the quantification for B implanted in Si from the results of this round-robin test.

2. Experimental

Specimens for this round-robin were five Si wafers implanted with $^{11}B^+$ at 50 keV using AMT PI-9500 (xR) ion implanter (Applied Materials Inc.). The B doses were $3x10^{14}$ (Sp1), $1x10^{15}$ (Sp2), $1x10^{16}$ (Sp3), $3x10^{16}$ (Sp4) and $1x10^{17}$ (Sp5) ions/cm^2.

Eighteen laboratories participated in the test. The SIMS instruments used were double-focusing ion microscopes (CAMECA IMS 3f, 4f, 5f and 6f); double-focusing scanning ion microprobes (HITACHI IMA-3 and Kratos S 1030); and quadrupole-based scanning ion microprobes (ATOMIKA SIMS 4000 and Physical Electronics PHI 6650).

B profiles were acquired using O_2^+ primary ion beam for $^{11}B^+$, $^{27}BO^+$ (positive secondary ions) and using Cs^+ for $^{39}BSi^-$, $^{11}B^-$ (negative secondary ions). The matrix ions (^{30}Si, $^{60}Si_2$, etc.) were alternately monitored with those boron-related ions. Stylus profilometers were used to measure the crater depth eroded by SIMS primary ion beam in order to convert the sputtering time into the real depth scale.

Relative sensitivity factor (RSF) was derived from measured depth profiles in two ways. One is using average matrix intensity [Eq. (1)] for normalization, and the other is point-by-point matrix intensity [Eq. (2)]:

$$RSF_{AV} = \Phi \Big/ \left(\sum_{k=1}^{N} \frac{I_k^B - I_{BG}^B}{I_{AV}^{Si}} \Delta Z \right), \qquad (1)$$

$$RSF_{pp} = \Phi \Big/ \left(\sum_{k=1}^{N} \frac{I_k^B - I_{BG}^B}{I_k^{Si}} \Delta Z \right), \qquad (2)$$

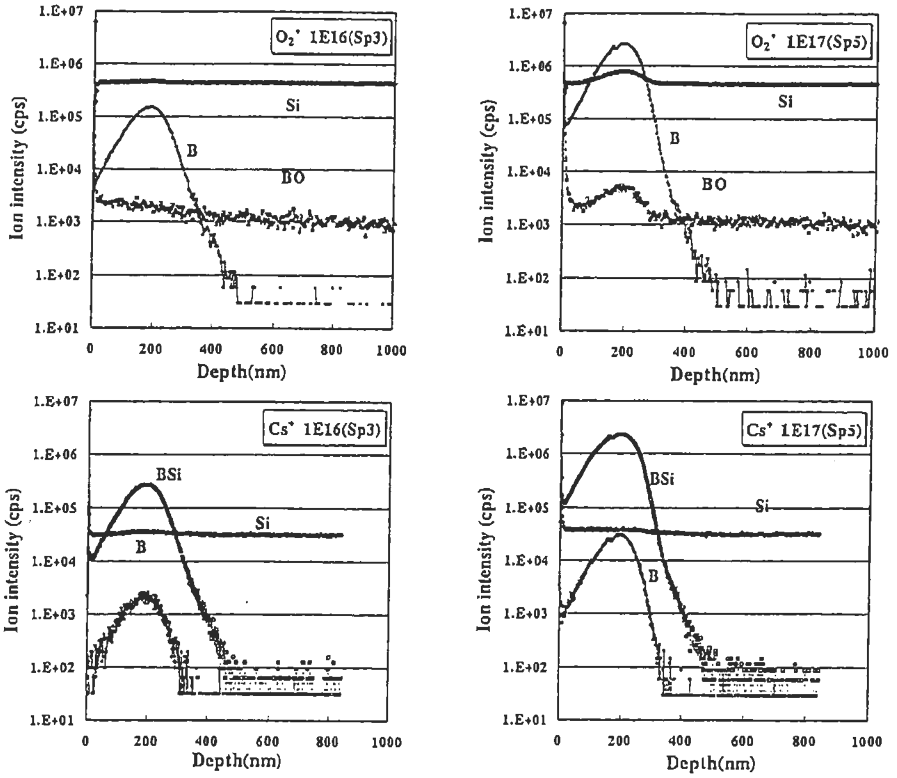

Fig. 1 Depth profiles of boron and silicon for Sp3 and Sp5. (Impact angle:60deg)

$\Delta Z = Z/N$,

where, Φ is the implanted B dose, I^B_k and I^{Si}_k are the B and Si intensities at *k*th cycle, I^B_{BG} is the background B intensity, I^{Si}_{AV} is the average Si intensity obtained at a stable intensity region, N is the total measurement cycle, and Z is the total depth measured by stylus profilometer.

3. Results and Discussion

RSFs and their relative standard deviations (RSDs) obtained in the present round-robin are listed in Table 1.[3] These RSF values are the averages of all participants and normalized to those of Sp3. RSDs of B^+ and BSi^- for Sp1-Sp4 ($\leq$ 3x10^{16} ions/cm^2) are within 11%, while that for Sp5 is much larger. The RSFs of B^+ and B^- decrease with the increase in B dose.

Table 1 RSFs normalized to Sp3's and their RSDs(%).

	Sp1(3E14)	Sp2(1E15)	Sp3(1E16)	Sp4(3E16)	Sp5(1E17)
B^+	1.04 (5.1)	1.07 (8.1)	1.00 (0)	0.97 (8.4)	0.86 (21.7)
BO^+			1.00 (0)	1.03 (24.1)	1.04 (32.6)
BSi^-	1.06 (11.3)	1.05 (10.7)	1.00 (0)	1.04 (7.4)	1.08 (15.6)
B^-	1.05 (4.6)	1.01 (4.9)	1.00 (0)	0.95 (5.7)	0.80 (12.9)

The RSF value relates both SIMS and stylus measurements. The stylus profilometry round-robin test performed in conjunction with the SIMS round-robin showed that the reproducibility of stylus measurements is around 2%.[4] Therefore, the decreasing RSFs are thought to be mainly influenced by variation in (relative) secondary ion intensities.

Figure 1 shows typical depth profiles of B and Si for Sp3 and Sp5. Si profiles exhibit no particular features up to 1x10^{16} ions/cm^2 (Sp3). However, the change of Si intensity appears at around the B peak concentration in the 1x10^{17} ions/cm^2 profiles (Sp5). This change is caused by the matrix effect of B, and can be recognized even in the 3x10^{16} ions/cm^2 profile (Sp4). The B ion intensity also changed in these specimens.[3]

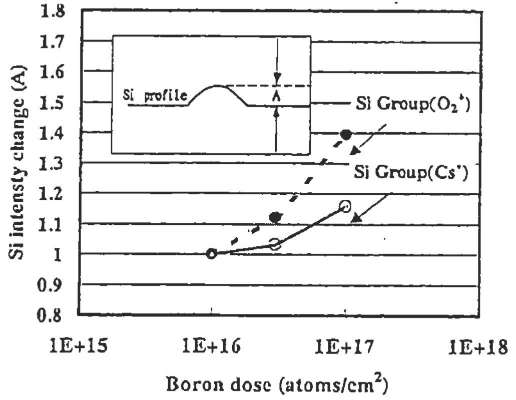

Fig. 2 Dependence of Si intensity change on the implanted B dose.

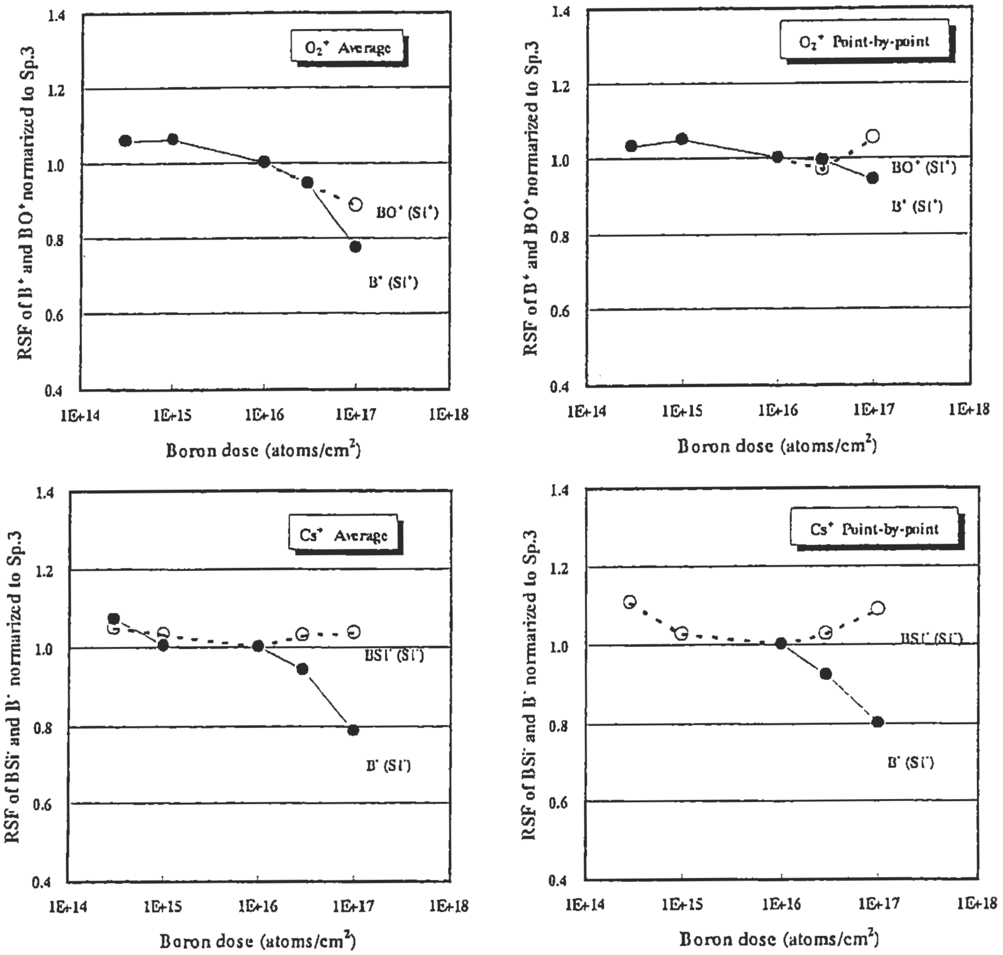

Fig. 3 Dependence of RSF on the implanted B dose for average matrix intensity and point-by-point normalization methods.

The magnitude of changes in Si intensity around the B peak is shown in Figure 2 for various detection modes. This change is largest for the 1x10^{17} (Sp5) data under O_2^+ bombardment.

When intensity changes occur, as in the present case, the normalization method (i.e., to use average matrix intensity or point-by-point matrix intensity) directly influences quantitative results and their accuracy. RSF values obtained using average matrix intensity and point-by-point normalization are compared in Figure 3. Those data having an obvious problem in measurements were excluded. Under the O_2^+ primary ion/B^+ detection mode, the point-by-point normalization method gives a constant RSF, even for higher doses. Therefore, it is necessary to take into consideration matrix-ion intensity change and normalization method as well as B ion intensity change in the quantification of high B concentrations (~1x10^{21}atoms/cm^3).

To analyze the behavior of B and Si intensity change in the high B concentration region, we investigated primary-ion impact-angle dependence of B and Si intensity changes. The impact-angle of primary ions changes the surface concentration of primary ion species, and therefore, largely influences secondary ion yields. Figure 4 shows Si intensity change around the B profile peak with respect to the primary impact angle.

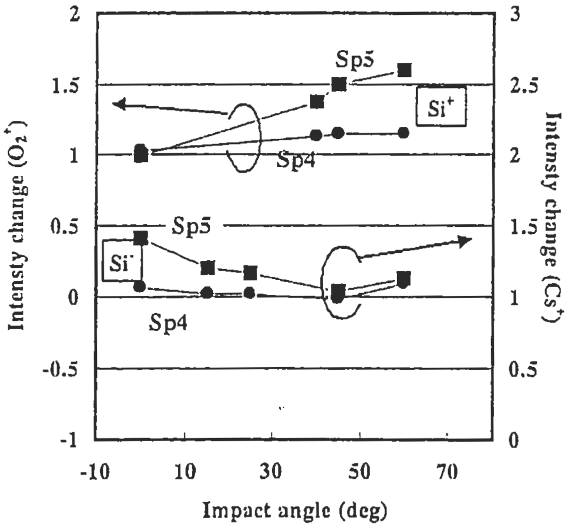

Fig. 4 Dependence of Si peak intensity change on the impact angle of primary ion.

found in the Si^+ intensity change under O_2^+ bombardment. This change increases for larger impact angle (at an oblique incidence). The decrease of Si^+ yield change at smaller impact angle may be due to the high oxygen concentration of bombarded surface, which saturates ion yields and thus masks the matrix effect of B.

Under Cs^+ bombardment, on the other hand, the intensity changes show a reverse tendency with respect to O_2^+ bombardment. This behavior is not well understood at present, and requires further investigations.

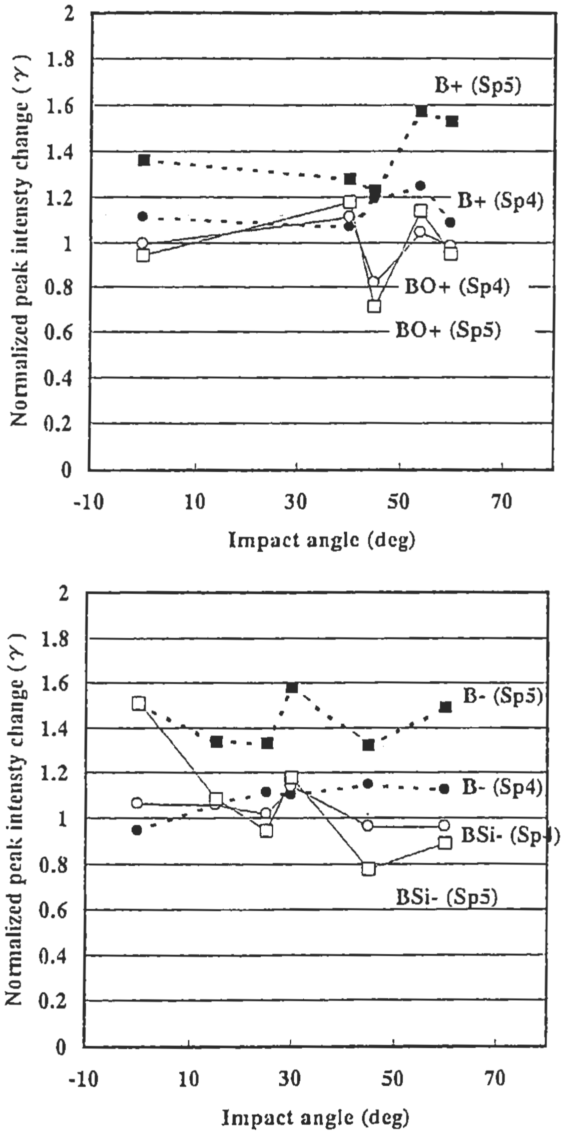

Fig. 5 Dependence of boron peak intensity change on the impact angle of primary ion.

Normalized B peak intensity change (γ^m_n) is defined as follows

$$\gamma^m_n = (I^m_n / I^m_{Sp3}) \cdot (\Phi_{Sp3} / \Phi_n), \qquad (3)$$

where, m denotes B^+, B^-, BO^+ and BSi^-, and n denotes Sp4 and Sp5. The data are normalized to those of Sp3 ($1x10^{16}$ ions/cm^2). Figure 5 shows the impact-angle dependence of γ^m_n. Although the data points at each angle are too few to discuss details, B^+ and B^- intensity changes are independent of impact angle and increase with the increase in ion dose (for $3x10^{16}$ and $1x10^{17}$ ions/cm^2). Molecular ions, BO^+ and BSi^-, seem to show an independent of impact-angle and ion dose.

4. Conclusion

In the present round-robin test, the following results were obtained. For high dose specimens such as $3x10^{16}$- $1x10^{17}$ ions/cm^2, B and Si yield changed because of a matrix effect, influencing RSF values and quantitative results. These yield changes were found to exhibit primary-ion impact-angle dependence, although detailed analysis could not be done because of small numbers of data. For quantification of high B concentration, it is necessary to select optimum conditions, such as an impact angle, B and matrix ion species, and a normalization method.

5. References

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