



# Toward accurate in-depth profiling of As and P ultra-shallow implants by SIMS

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## Abstract

A new technique is proposed for the depth profiling of low energy As and P implants. We show that monitoring the monatomic negatively charged ions of As<sup>-</sup> and P<sup>-</sup>, using oxygen backfilling (flooding) in combination with low energy Cs<sup>+</sup> sputtering, improves the sensitivity of SIMS profiling and removes the variation of the ion yield at the native oxide/silicon interface.

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## 1. Introduction

There are a number of fundamental and instrumental limitations for the characterization of ultra-shallow implants by SIMS, that have already been identified (see for instance [1,2]). Some of these limitations are inherent to the sputtering process itself. The most noticeable effects that have received much attention are (1) the presence of a transient region, sometimes combined with sputtering through the native oxide/silicon interface and (2) the development of crater bottom roughening. These effects make it difficult to achieve accurate depth profile quantification, especially when the absolute implant dose value is considered. In order to reduce (but not eliminate) the transient region, it is necessary to lower the primary ion energy. However, low energy sputtering conditions could initiate more pronounced surface topography

development when used in combination with grazing incidence angles. In many cases, sample chamber gas flooding in combination with low energy oxygen sputtering minimizes roughening effects. This work presents, investigations into quantification issues of As<sup>-</sup> and P<sup>-</sup> shallow profiles, recorded under Cs bombardment. The experimental results show that appropriate oxygen flooding during depth profiling can be used to improve the profile quantification at the near-surface region.

## 2. Experimental

All SIMS analyses were carried out on the CAMECA IMS WF instrument using a 10–20 nA Cs<sup>+</sup> primary ion beam or a 30 nA O<sub>2</sub><sup>+</sup> primary beam, rastered over an area of 200 μm × 200 μm. The Cs<sup>+</sup> beam impact energy was varied from 250 to 500 and 300 eV was selected for the O<sub>2</sub><sup>+</sup> primary beam. The incidence angle was about 50° for the Cs<sup>+</sup> beam and

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44° for the  $O_2^+$  beam. Oxygen and argon backfilling at a pressure between  $1 \times 10^{-7}$  and  $1 \times 10^{-5}$  mbar was employed. Silicon wafers with As or P implants at 500 eV and 2 keV implant energy were analyzed. The implanted dose for all wafers was  $10^{15}$  atoms/cm<sup>2</sup>. As<sup>-</sup> and P<sup>-</sup> profiles were measured with a mass resolving power of 4500. Note that for this study, As<sup>-</sup> is preferred over AsSi<sup>-</sup> because, in the case of As analysis in SiGe layers or in Ge pre-amorphized Si substrates, AsSi<sup>-</sup> profiling would require either an impractically high mass resolution or applying the background subtraction technique—a source of analytical uncertainty [3]. Laser interferometer data were used for the depth scale calibration in silicon.

### 3. Results and discussion

A large number of analyses for P (500 eV), P (1 keV) and As (2 keV) implant profiles were recorded under Cs<sup>+</sup> bombardment with impact energies of 300 and 500 eV and for an incidence angle range of 45–52° [4]. All analyses cannot be shown in this paper, but typical examples are shown in Fig. 1 (As (2 keV) and P (1 keV) implants). The As<sup>-</sup> and P<sup>-</sup> profiles (measured along with Si<sup>-</sup> and O<sup>-</sup>), exhibit all the problems associated with the implantation peak shape distortion

already reported (e.g. [5]). In the near-surface region, a deviation of the measured profile from the theoretical profile is observed. The variation of the sputter rate in the near-surface region is responsible for a peak position shift and peak shape distortion, together with enhanced ion yields for As<sup>-</sup> and P<sup>-</sup> at the native oxide/silicon interface. Note that the position of the interfacial peak in As<sup>-</sup> and P<sup>-</sup> profiles is consistent with the first derivative curve peak of the O<sup>-</sup> profile (see Fig. 1), supporting this latter assumption.

Figs. 2 and 3 show the depth distribution of As<sup>-</sup>, P<sup>-</sup>, <sup>18</sup>O<sup>-</sup> and <sup>30</sup>Si<sup>-</sup> measured under Cs<sup>+</sup> bombardment at 500 eV (46°) for the P (1 keV) and As (2 keV) implants, respectively. For both implants, results for different oxygen pressures are presented. It can be seen that the interfacial peak for As<sup>-</sup> and P<sup>-</sup> disappeared when the oxygen-flooding pressure was higher than  $1 \times 10^{-7}$  mbar. The down slope of the different profiles does not show any evidence of depth resolution degradation due to roughening development while using oxygen flooding. This is supported by results (not shown) of depth profiles recorded with the same experimental conditions for a BN-delta layer in Si. However, direct roughness measurements of the crater bottom are required to infer this fact. In Fig. 3, a P<sup>+</sup> profile measured under O<sub>2</sub><sup>+</sup> bombardment is overlaid

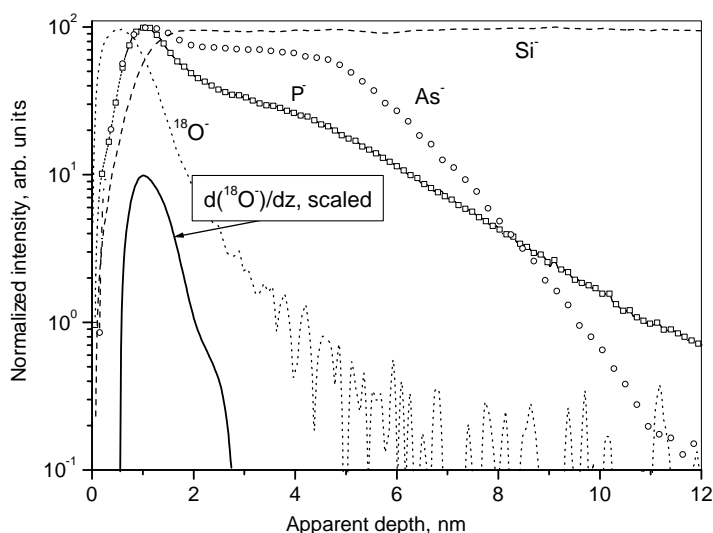


Fig. 1. Raw (normalized to 100%) SIMS depth profiles of 2 keV As implant, measured under Cs<sup>+</sup> of 300 eV impact energy and 48° impact angle sputtering conditions. <sup>30</sup>Si<sup>-</sup>, <sup>18</sup>O<sup>-</sup> and P<sup>-</sup> results for a P (1 keV) implant are shown for comparison. The first derivative (scaled) of the <sup>18</sup>O<sup>-</sup> profile is shown as well. Depth scale is not corrected.

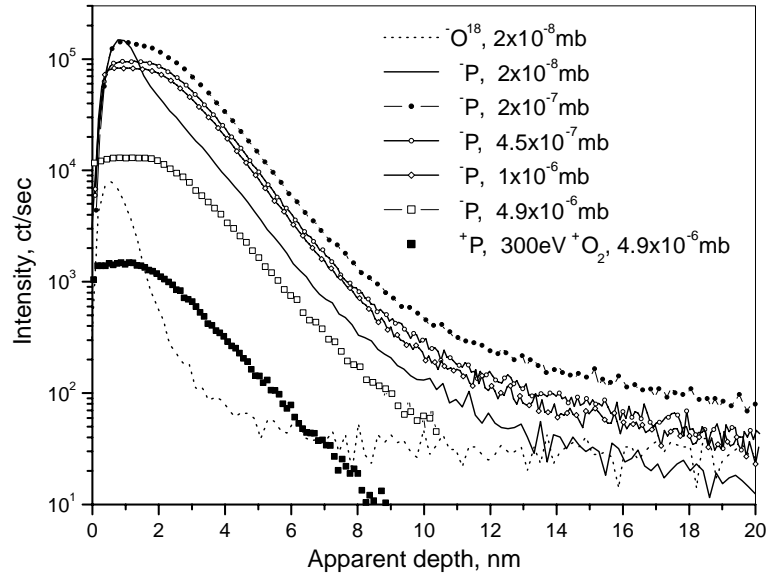


Fig. 2. Raw depth profiles of  $P^-$  and  $^{30}Si^-$  ions for the P (1 keV) implant, measured with different  $O_2$  backfilling pressures.  $P^+$  profile measured under  $O_2$  bombardment (300 eV,  $44^\circ$ ) is shown for comparison. Depth scale is not corrected.

for comparison. It shows that the present conditions ( $Cs^+$  + oxygen flooding) yield a profile shape very similar to the one obtained with  $O_2^+$ , but with a significant sensitivity improvement (one decade).

The relative variations of the ion yield of  $As^-$ ,  $P^-$  and  $Si^-$  as a function of the oxygen pressure are shown in Fig. 4. The ion yield for a species is defined as the total number of ions detected (i.e. integral of the

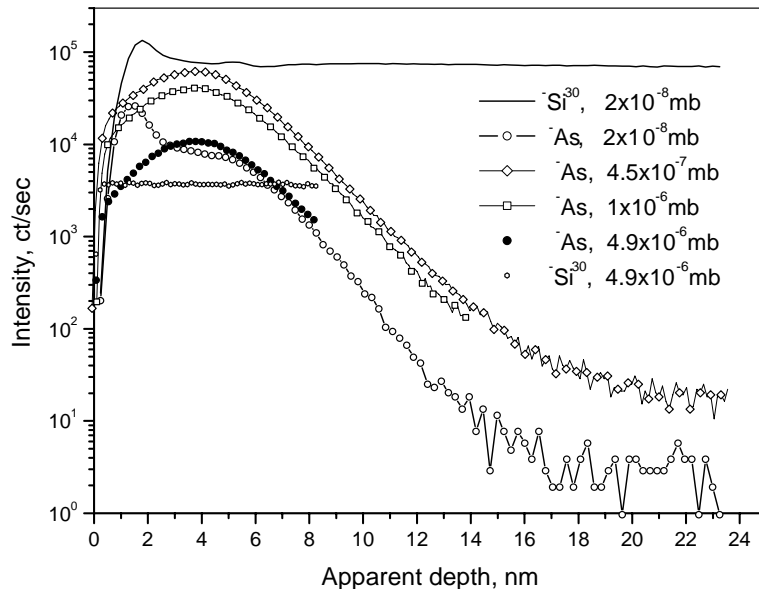


Fig. 3. Raw depth profiles of  $As^-$  and  $Si^-$  ions of the As (2 keV) implant measured with different  $O_2$  backfilling pressures. Depth scale is not corrected.

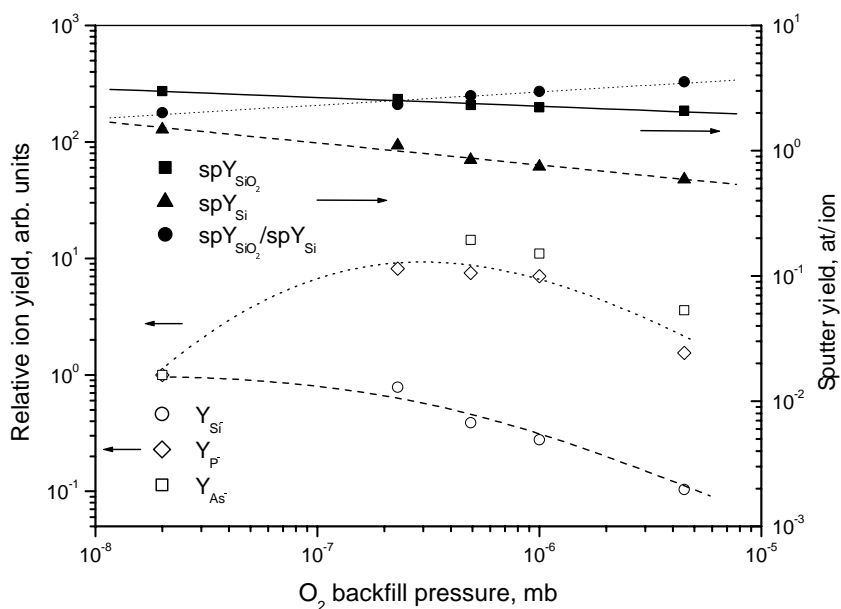


Fig. 4. Left axis: relative ion yield of  $P^-$ ,  $As^-$  and  $^{30}Si^-$  ions, measured with different  $O_2$  backfilling pressures. Right axis: absolute sputtering yields in Si and  $SiO_2$ .

profile, excluding the surface peak) divided by the total number sputtered atoms (i.e. implanted dose over the analyzed area). The ion yield values have been normalized to the ion yield measured under high vacuum conditions (no flooding).  $As^-$  and  $P^-$  ion yields pass through a maximum at a pressure of about  $5 \times 10^{-7}$  mbar. On the other hand, the  $Si^-$  intensity drops over the entire pressure range investigated. Thus, relatively light oxygen flooding conditions produce an ion yield gain of one decade along with the disappearance of the peak intensity at the interface of native oxide/silicon. This technique could be advantageously applied for SIMS shallow profiling with low energy  $Cs^+$  primary ions while analyzing  $P^-$  and  $As^-$  secondary ions.

Values of the  $SiO_2/Si$  sputter yield ratio, measured in the 6 nm thermal oxide layer, are reported in Fig. 4. In the first approach, a correction of the depth scale for such shallow implants could be performed, given the similarity of native oxide properties to the grown thermal oxide. However, achieving accurate depth scale calibration would first require investigations into roughness development under these present sputtering conditions. This in turn would require that sputtering rate variation be taken into account. There-

fore, no SR correction has been applied to the present data.

One expects to form more  $Cs-O$  interactions by raising the oxygen pressure in the analysis chamber. These interactions reduce the work function lowering effect of  $Cs$  and therefore decrease the yield of negative secondary ions. This assumption is consistent with what is observed for  $Si^-$ , but not for  $As^-$  and  $P^-$ . At this point of the study, no physical explanation can be proposed for the observed ion yield gain with the oxygen pressure, or for the suppression of the  $As^-$  and  $P^-$  peak at the native oxide/silicon interface.

#### 4. Conclusion

Peak intensities observed in  $As^-$  and  $P^-$  profiles at the native oxide/silicon interface, while sputtering with low energy  $Cs^+$  primary ions, can be completely eliminated by using the oxygen flooding technique (oxygen pressures of a few  $10^{-7}$  mbar). Moreover, the ion yields for  $As^-$  and  $P^-$  are improved by one decade. No evidence of depth resolution degradation over the first 20 nm has been observed while using oxygen flooding.

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