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ORIGINAL PAPER

Analysis of dopant distribution profiles of very high energy implants

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Abstract
This paper presents SIMS data and analysis for dopant profiles of arsenic and boron implanted in silicon at energies up to 15 MeV. Arsenic and boron are widely used for very high energy implants into and adjacent to the photodiode region of CMOS image sensors to improve quantum efficiency and isolation. To avoid lateral shifts, shadowing effects, reduce implant damage, and to use channeling to increase ion penetration depth, the majority of high energy implants are performed at normal incidence or low beam tilt angles. Precise alignment and control of ion beam angles are, therefore, extremely important.

Introduction

Technology advances in products such as CMOS image sensors, discrete power devices, and analog devices for automotive applications have increased the required implantation energies into the range of 4–8 MeV and above. Characterization of the ion stopping and channeling behavior of common dopants into silicon at these energies are, therefore, important. A shortage of reference data especially for high energy arsenic was another motivation for this work [1].

We present experimental results for very high energy ion implantations of arsenic and boron from Axcelis' Purion™ XE-series implanters, which are based on an RF-linear accelerator architecture and have several modifications, which were developed to extend the maximum ion energies [1, 2]. In many cases, high energy ions are implanted at a normal angle to the crystalline substrate to minimize shadowing effects for structures with high aspect ratios and/or to use channeling effects to form deeper layers. This makes these implants very sensitive to beam angle alignment and control [3].

Materials and methods

SIMS analysis of profiles was performed on (100) Si wafers implanted with MeV-range energies using singly or multiply charged ions of ^{75}As and ^{11}B. Certified wafers with a slice angle offset of $<0.05°$ from ⟨001⟩ were used. Wafers from the same ingot were used for each test. The surface angle offset of the wafers was verified and accounted for using the V-curve method of Therma-Wave (TW) modulated reflectance measurement [4]. All implantations were performed on Axcelis' Purion XE-series high-energy implanters. The implanted dose was 1×10^{13} at/cm^2 for most test samples to provide reliable SIMS measurement with low background noise and minimize damage accumulation effects on dopant profiles. A dose dependance test was run with dose variation from 1×10^{12} to 1×10^{14} at/cm^2.

Results and discussion

High-energy arsenic profiles implanted at a beam incident angle normal to the (100) silicon wafer plane are presented in Fig. 1a. The ion energy was varied from 4 to 14 MeV with a 2 MeV increment step. All profiles show a deep channeling tail with penetration depths of 10–16 µm for corresponding energies of 4–14 MeV.

Arsenic profile comparisons for normal and low tilt angle (0.5°) for the energy range 4–10 MeV are shown in Fig. 1b. Increasing the tilt angle to 0.5° results in a significant profile tail reduction due to the significant reduction in axial channeling. Table 1 compares the shifts in depth of the leading and trailing edges of the profiles for the tilts of 0° and 0.5° at the same energies at the concentration level of 1×10^{15} at/cm^3. For the leading edge of the profile, closest to the wafer surface, the depth difference between zero and 0.5° tilt angle is about 0.3–0.4 µm and generally increases with ion energy. But for the profile trailing edge, the depth difference

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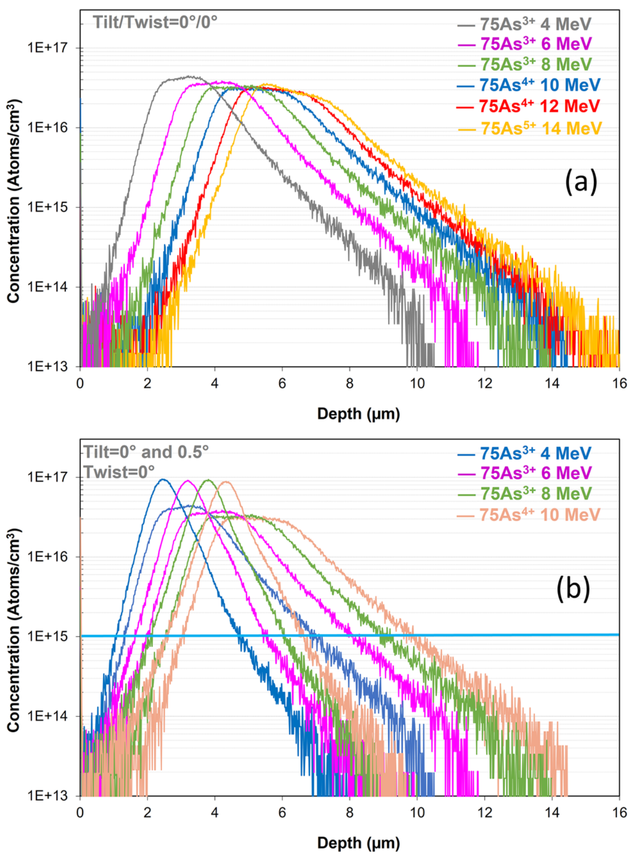

Fig. 1 High-energy arsenic SIMS profiles implanted with beam energies 4–14 MeV. Implanted dose 1×10^{13} at/cm.^{2} **a** tilt/twist = 0°/0°, and **b** tilt = 0° (flat top profiles) or 0.5° (higher peak profiles)

Table 1 Depth differences between the leading (surface) and trailing edges of profiles at 0° and 0.5° beam angles measured at 1×10^{15} at/cm^3 concentration as a function of implantation energy

Energy (MeV)	Profile position difference (µm)	
	Leading	Trailing
4	0.30	2.08
6	0.39	2.57
8	0.42	2.98
10	0.41	3.29

The corresponding SIMS profiles are shown in Fig. 1b

exceeds 2 µm and increases significantly with ion energy, reaching 3.3 µm for 10 MeV. This demonstrates the advantage of using a 0° tilt angle for deep-layer formation with arsenic implantation even though it is highly sensitive to tilt and difficult to control repeatably. Since the critical angle for ion channeling is proportional to $(Z/E)^{1/2}$, where Z is atomic number and E is ion energy [5], the large dechanneling effect observed in Fig. 1b is expected due to the high energies of these implants.

Arsenic and boron SIMS profiles as a function of tilt angle are shown in Fig. 2a and b, respectively. For the arsenic profiles, the tilt angle was increased from 0° to 0.3° in 0.05° increments. The arsenic energy was 8 MeV and the twist angle was 0°. Profiles at tilt/twist 0.5°/0° and 7.0°/23° are shown for reference and comparison in Fig. 2a. Implantation at tilt/twist = 7.0°/23° can be considered fully non-channeled. These arsenic profiles demonstrate high sensitivity to tilt, note that the channeling tail reduction is noticeable even for a 0.05° tilt angle difference. The changes in profile shape with small changes in tilt angle need to be accounted for in process and device technology simulations. Additionally, a very high degree of implanter angle control is required to achieve reproducible results for high-energy implants at low tilt angles.

Figure 2b shows 3.6 MeV boron profiles with a tilt variation from − 0.2° to 0.2° at 0° twist with the same increment of 0.05°. Unlike the arsenic profiles in Fig. 2a, the boron profiles do not exhibit a significant change of the profiles leading and trailing edge positions with tilt angle in the range of ± 0.2°. Major profile differences were observed only for the amplitude ratio between the channeled and

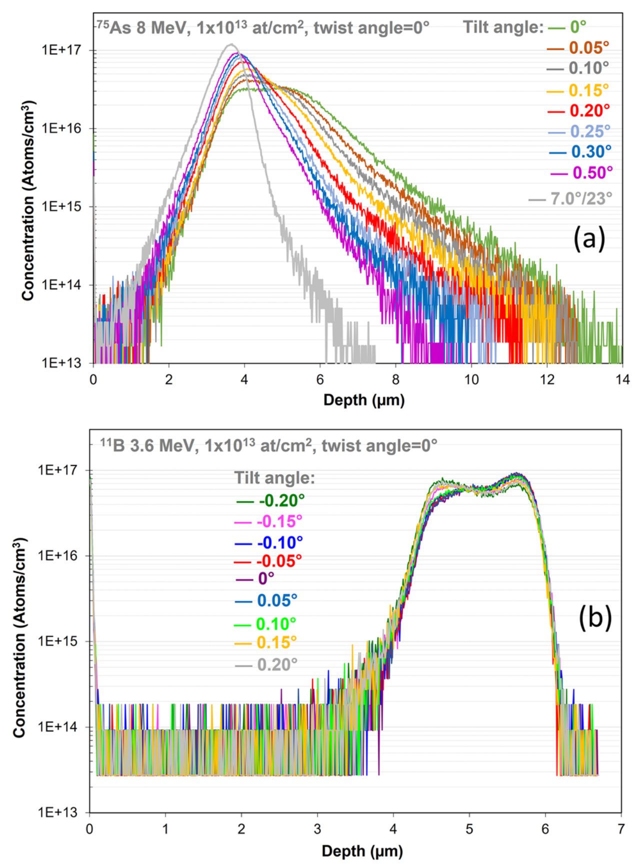

Fig. 2 SIMS profiles for different implantation tilt angles with 0.05° angle increment. Implanted dose 1×10^{13} at/cm^2, 0° twist angle. **a** Arsenic 8 MeV, and **b** boron 3.6 MeV

non-channeled profile peaks. As expected, boron profiles implanted at the same tilt absolute values are well matched, which confirm accurate beam angle alignment to the (100) wafer plane.

To investigate the influence of damage accumulation rate on implanted profiles, wafers were implanted with 4.5 MeV arsenic ions using ~ 10 × different beam currents of 8 pμA and 80 pμA. Tilt angles were 0° and 1.0°. The results (Fig. 3a) demonstrate that arsenic profiles are insensitive to beam current differences during implantation for both normal and low tilt beam angles.

In the previous results [1], it was reported a significant effect of the twist angle on arsenic channeling profiles. In this paper, we did further investigation of this effect at a higher arsenic energy of 8 MeV.

Arsenic SIMS profiles at 8 MeV with tilt angles of 0°, 0.5°, and 1° and twist angles of 0° and 22° are shown in Fig. 3b. Note that for the non-zero tilt angles, the 0° twist profiles are grouped together, and the 22° twist profiles form a separate group. The profile for tilt/twist = 1°/0° is more channeled than for 0.5°/22°, indicating the

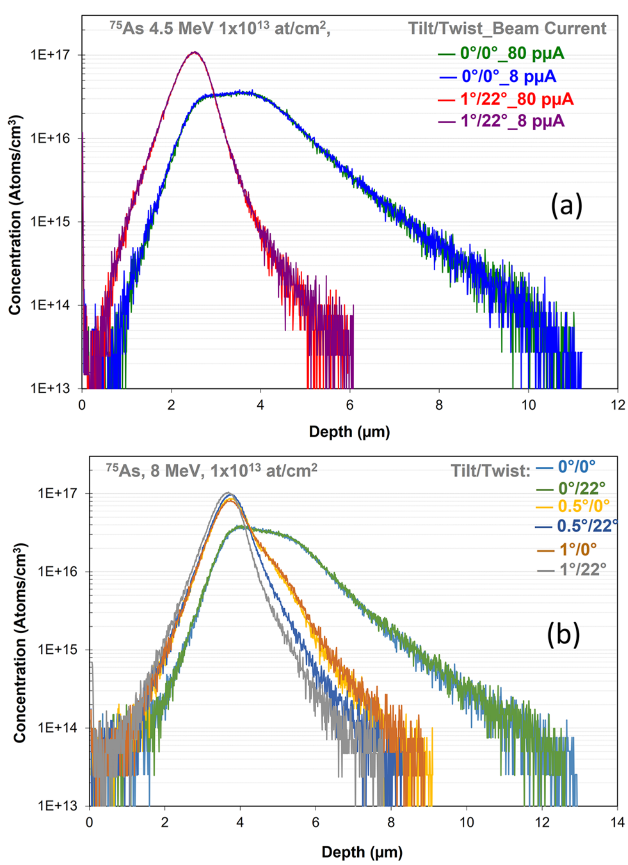

Fig. 3 As SIMS profiles comparison for axial and planar channeling conditions implanted at 4.5 MeV with 10 × beam current difference (**a**) and implanted at 8 MeV with tilt/twist angles of 0° and 22° (**b**). Dose is 1×10^{13} at/cm^2

significance of planar channeling for this condition even at tilt angles ≤ 1.0°. The 0° twist profiles are more channeled because of the (220) planar channel. At the 8 MeV energy, the critical angles for the ⟨001⟩ axial channel and the (110) planar channels are so small that twist angle, not tilt angle, is the dominant variable in determining the position of the channeling tail for tilt angles from 0.5° to 1.0°. This is an interesting result that we believe has not been reported before. No differences were observed between 0° and 22° twist for the profiles implanted at 0° tilt, as expected.

For implantations with incidence near but not at the ⟨001⟩ axial channel, wafer twist angle is important because the resulting profile is a combination of both ⟨001⟩ axial channeling and (220) planar channeling. Comparing SIMS profiles from 0° and 22° twist angles at low tilts shows a significant, non-linear contribution of planar channeling that affects the arsenic profile shape.

Arsenic profiles at 0° tilt as a function of implanted dose are shown in Fig. 4 for ion energies of 8 and 15 MeV. For doses ≥ 1×10^{13} at/cm^2, the arsenic concentration in the tail does not increase with the implanted dose, and profile tails are very close for the 1×10^{13} and 1×10^{14} at/cm^2 profiles. This effect was observed for both considered energies and indicates damage accumulation and channeling suppression for doses ≥ 1×10^{13} at/cm^2. This effect was similar for both energies, despite the ions being spread out over a larger depth at 15 MeV.

Conclusions

We analyzed SIMS profiles of arsenic and boron ions in silicon implanted on Axcelis' Purion XE-series implanters with energies up to 15 MeV. By careful control of the ion beam parameters and the wafer crystal cut offset, we demonstrated that both species and especially arsenic are extremely sensitive to tilt and twist angle. For energies > ~4.0 MeV, better than 0.05° beam angle control is required to control channeling effects.

We further investigated the (220) planar channeling effect reported earlier [1], which causes an arsenic implant at tilt/twist = 1.0°/0.0° to be more channeled than at 0.5°/22° and confirmed similar behavior for arsenic ions with a higher energy of 8 MeV. Finally, 0° implants at doses greater than 1×10^{13} at/cm^2 showed a saturation of the channeling tail, indicating significant damage accumulation at depths of several microns into the silicon.

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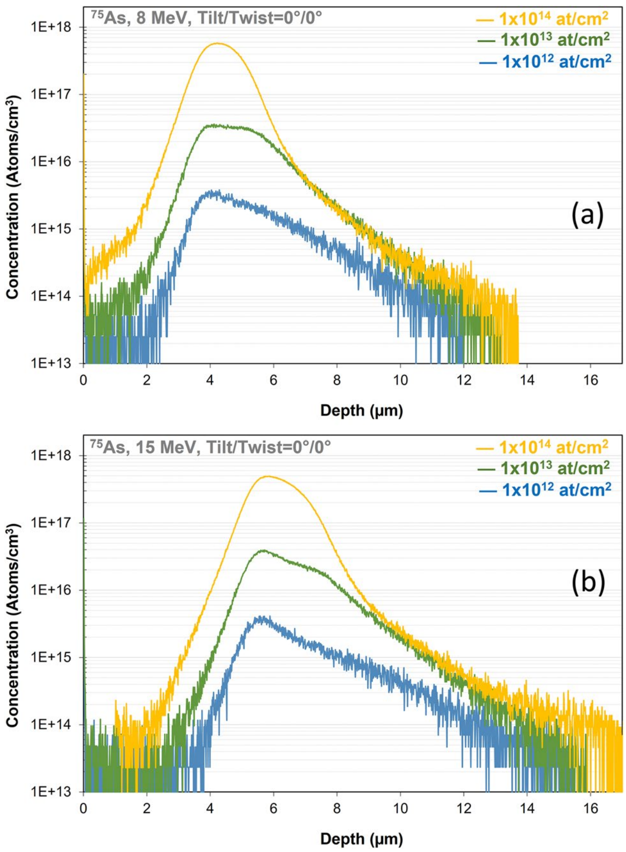

Fig. 4 ⟨100⟩ Channeling As profiles implanted at doses, 1×10^{12}, 1×10^{13}, and 1×10^{14} at/cm^2. Tilt/twist angle 0°/0°. Implant energy 8 MeV (**a**) and 15 MeV (**b**)

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest No funds, grants, or other support was received.

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