Comparison of Arsenic and Antimony Dopant Distribution Profiles of Very High Energy Implantations

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Abstract

This paper presents SIMS data and analysis of antimony dopant profiles in silicon implanted with an energy of 7.0 MeV at non-channeled random direction, axial [001] channeled, and planar (220) channeled implant conditions. The antimony ion energy was chosen to get distribution profiles similar to arsenic implanted at 4.5 MeV. Recently arsenic implantations with very high energies are widely used for power devices, whereas antimony implants at very high energies are relatively new and require further characterization. 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 tilt beam angles. Precise alignment and control of ion beam angles is therefore extremely important.

1. Introduction

Technology challenges associated with further integration and optimization of existing products and new developments such as BiCMOS, discrete power devices, and analog devices for automotive applications have increased the variety of implant species used in the MeV energy range. Characterization of the dopant distribution profiles in silicon at channeled and non-channeled implant conditions at these energies is therefore important. During epitaxial layer formation, the use of antimony implantation instead of arsenic provides benefits of auto-doping effect reduction and improves Ultra High Voltage (UHV) device performance [1]. For these applications antimony can be considered as substitute for arsenic to eliminate enhanced diffusion effects. It was demonstrated that highly doped Sb wells facilitate the fabrication of the steep doping profiles needed for high performance bipolar devices [2]. Sb can also be used to fabricate low-resistivity, shallow S/D extensions for nMOSFETs with excellent device characteristics [2].

Recently arsenic implantations with very high energies are widely used for power devices, whereas antimony implants with very high energies are relatively new and require further characterization. We present SIMS data and analysis of antimony dopant distribution profiles in silicon implanted with an energy of 7.0 MeV at different ion beam incident angles. The antimony ion energy was chosen to get distribution profiles similar to arsenic implanted at 4.5 MeV. In many cases high energy ions are implanted at a normal or low tilt 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].

For the experiments non-channeled, axial [001] channeled, and planar (220) channeled implant conditions were used. The implantations were performed on Axcelis' Purion^{TM} XEmax implanter, which is based on an RF-linear accelerator architecture and has several modifications, which were developed to extend the maximum ion energies up to 15 MeV [4].

2. Materials and Methods

SIMS analysis of dopant distribution profiles was performed on (100) Si-wafers implanted with MeV-range energies using multiply charged ions of As (4.5 MeV) and Sb (7.0 MeV). The implanted dose was 1E13 at/cm^2 to provide reliable SIMS measurement with low background noise and minimize damage accumulation effects on dopant profiles. Certified wafers with a slice angle offset of <0.05° from <001> were used. The crystal axis offset of the wafers was verified and accounted for using the TW V-curve method. The ion beam incident implant angles (tilt/twist) were 7°/23°, 2°/0°, and 0°/0° for non-channeled random direction, (220) planar channeled, and [001] axial channeled conditions, respectively. The AMU ratio of ~1.6 between ^{121}Sb and ^{75}As was used to choose antimony energy to create dopant profiles with close penetration depths for both Sb and As. The ion beam was tuned and optimized for implant of the ^{121}Sb isotope.

3. Results and Discussion

High energy antimony profiles for ^{121}Sb and ^{123}Sb isotopes implanted at different channeled conditions are presented in Fig. 1a. The ion energy was 7 MeV, implanted dose 1E13 at/cm^2. As expected, axial channeled profiles demonstrate the highest penetration depth in silicon up to ~12 µm. Increasing the tilt angle to 2° results in a significant profile tail reduction, down to ~8 µm due to the significant reduction in axial channeling. Non-channeled random direction profile shows penetration depth up to ~6 µm and demonstrates higher concentration gradient in the trailing edge of the profile compared to both, axial and planar, channeled conditions.

The summary of Sb profiles SIMS analysis is combined in Table 1. SIMS profiles showed that the largest implanted species was ^{121}Sb isotope, which the antimony ion beam was set up for during the implantations. At the same time, some energetic contamination profiles of ^{123}Sb were found, as is seen in Table 1. Even though, the amount of ^{123}Sb isotope in the total implanted dose is a relatively low value of ~3.2 % (compared with 42.8 % of ^{123}Sb natural abundance), there still can be a concern that ^{123}Sb isotope can modify the final dopant distribution profile due to energy or angular offset/difference between ^{121}Sb and ^{123}Sb isotope ion beams. Increasing AMU resolution for further reduction of ^{123}Sb isotope is not practical as results to a significant beam current loss and throughput reduction.

To analyze the distribution difference between ^{121}Sb and ^{123}Sb isotopes in silicon, SIMS profiles were plotted and overlayed using normalized N/N_{max} concentration scale (Fig. 1b). As it is seen in Fig. 1b, the concentration profiles ^{121}Sb and ^{123}Sb are well matched for all tested implant angle conditions. No profile difference observed, either energy or channeling difference related. All profiles are very close at the leading edge (closest to the wafers surface), trailing edge, and the tail.

Table 1. Summary of ^{121}Sb and ^{123}Sb SIMS profiles comparison with different channeled conditions. The corresponding SIMS profiles are shown in Fig. 1a.

Implant Angle, deg.		^{121}Sb			^{123}Sb		
Tilt	Twist	Dose, at/cm^2	Relative Dose, %	Rp, µm	Dose, at/cm^2	Relative Dose, %	Rp, µm
0	0	1.08E+13	96.84%	3.25	3.51E+11	3.16%	3.30
2	0	1.06E+13	96.79%	2.79	3.50E+11	3.21%	2.82
7	23	1.07E+13	96.85%	2.67	3.47E+11	3.15%	2.67

Considering a potential $^{31}P^{+}$ energetic contamination risk during $^{121}Sb^{++++}$ implants due to residual phosphorus deposition in the ion source and $^{31}P^{+}$ beam extracted with magnetic rigidity close to antimony beam, ^{31}P SIMS profiles were analyzed on the wafers implanted with antimony at different channeled conditions. 31P profiles are shown in Fig. 2. As it is seen in Fig.2, no energetic phosphorus contamination was detected.

Comparison of antimony and arsenic SIMS profiles implanted with the energies of 7 MeV and 4.5 MeV, respectively, presented in Fig. 3a. For more detailed comparison, the same profiles were overlaid and shown in Fig. 3b with a linear concentration scale. As it is seen in Fig. 3, Sb and As profiles with chosen energies has close positions for all three implant conditions, random direction, axial, and planar channel. The tail penetration depth is close for both antimony and arsenic profiles. 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], critical angles for 4.5 MeV arsenic and 7 MeV antimony should be very close.

Sb and As profiles for random direction and planar (220) channel are well agreed with a higher concentration gradient of the trailing edge of antimony profiles compared to arsenic. The largest difference between Sb and As profiles was observed for [001] axial channel condition. Arsenic profile has a significantly lower concentration peak of 4E16 at/cm^3 compared to the peak of 6E16 at/cm^3 for antimony. A lower concentration peak suggests more arsenic ions were channeled at 0° tilt angle and redistributed from the peak along the trailing edge of the profile. Less axial channeling was observed for heavier antimony ions Sb at the tilt angle 0°.

4. Conclusions

We analyzed SIMS profiles of antimony and arsenic ions in silicon implanted on Axcelis' Purion™ XEmax implanter with energy 7 MeV and 4.5 MeV, respectively. Three different channeled conditions were studied, [001] axial channel, (220) planar channel, and non-channeled random direction. ^{121}Sb profiles were analyzed for the presence of ^{123}Sb isotope and its effect on the profiles shape. No difference was found for the ^{121}Sb and ^{123}Sb profiles with a relative dose of ^{123}Sb isotope of ~3.2 %. The ratio of ~1.6 between Sb and As energies was chosen to form dopant profiles with close penetration depth for both Sb and As.

Acknowledgement

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Conflict of Interest Statement

No funds, grants, or other support was received.

Data Availability Statement

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

Reference

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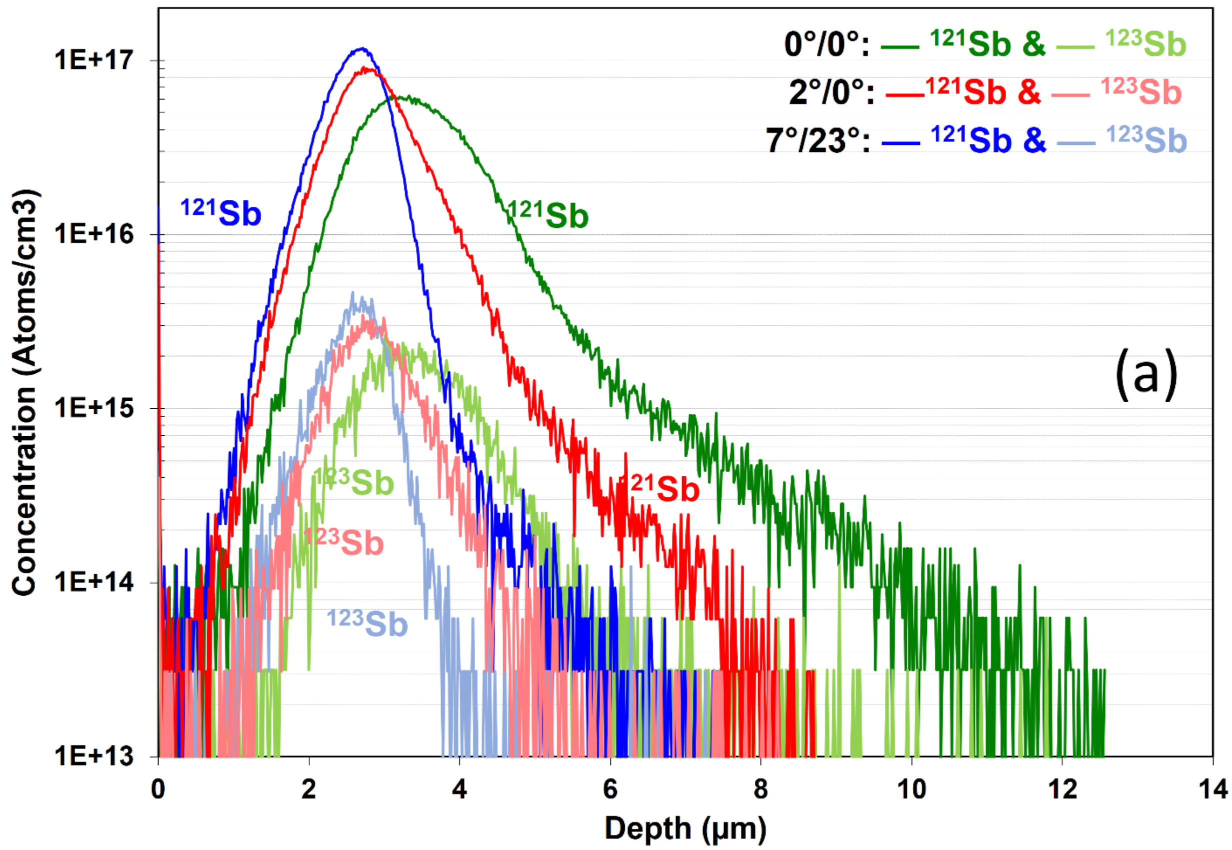
Figures Caption

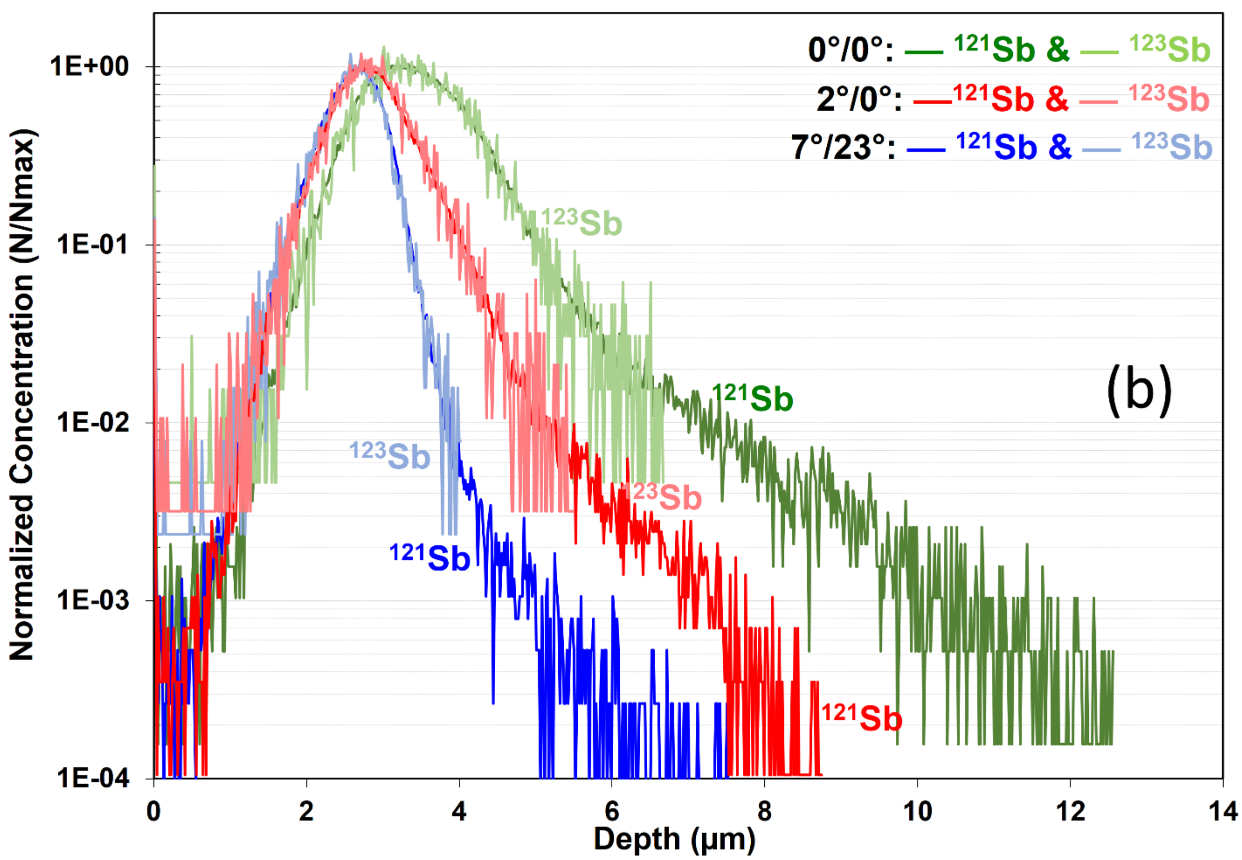
Fig. 1. ^{121}Sb and ^{123}Sb distribution profiles implanted at axial [001] channel (tilt/twist = 0°/0°), low tilt planar (220) channel (2°/0°), and non-channel random (7°/23°) condition. Implant energy, E = 7 MeV, Dose = $1x10^{13}$ at/cm^2. (a) concentration profiles, at/cm^3, (b) profiles overlay with normalized concentration scale, N/N_{max} .

Fig. 2. ^{31}P energetic contamination SIMS profiles analyzed in the wafers implanted with antimony at different beam angles. No energetic phosphorus contamination detected.

Fig. 3. Antimony and arsenic SIMS dopant profiles comparison. Random and channeled directions. Implanted dose 1E13 at/cm^2. (a) logarithmic and (b) linear concentration scale.



0°/0°: — 121Sb & — 123Sb
2°/0°: — 121Sb & — 123Sb
7°/23°: — 121Sb & — 123Sb
121Sb
121Sb
123Sb
123Sb
123Sb
121Sb
(a)
Concentration (Atoms/cm3)
1E+17
1E+16
1E+15
1E+14
1E+13
0
2
4
6
8
10
12
14
Depth (μm)



0°/0°: — 121Sb & — 123Sb
2°/0°: — 121Sb & — 123Sb
7°/23°: — 121Sb & — 123Sb
123Sb
121Sb
(b)
123Sb
123Sb
121Sb
121Sb
Normalized Concentration (N/Nmax)
1E+00
1E-01
1E-02
1E-03
1E-04
0
2
4
6
8
10
12
14
Depth (μm)

Fig. 1.

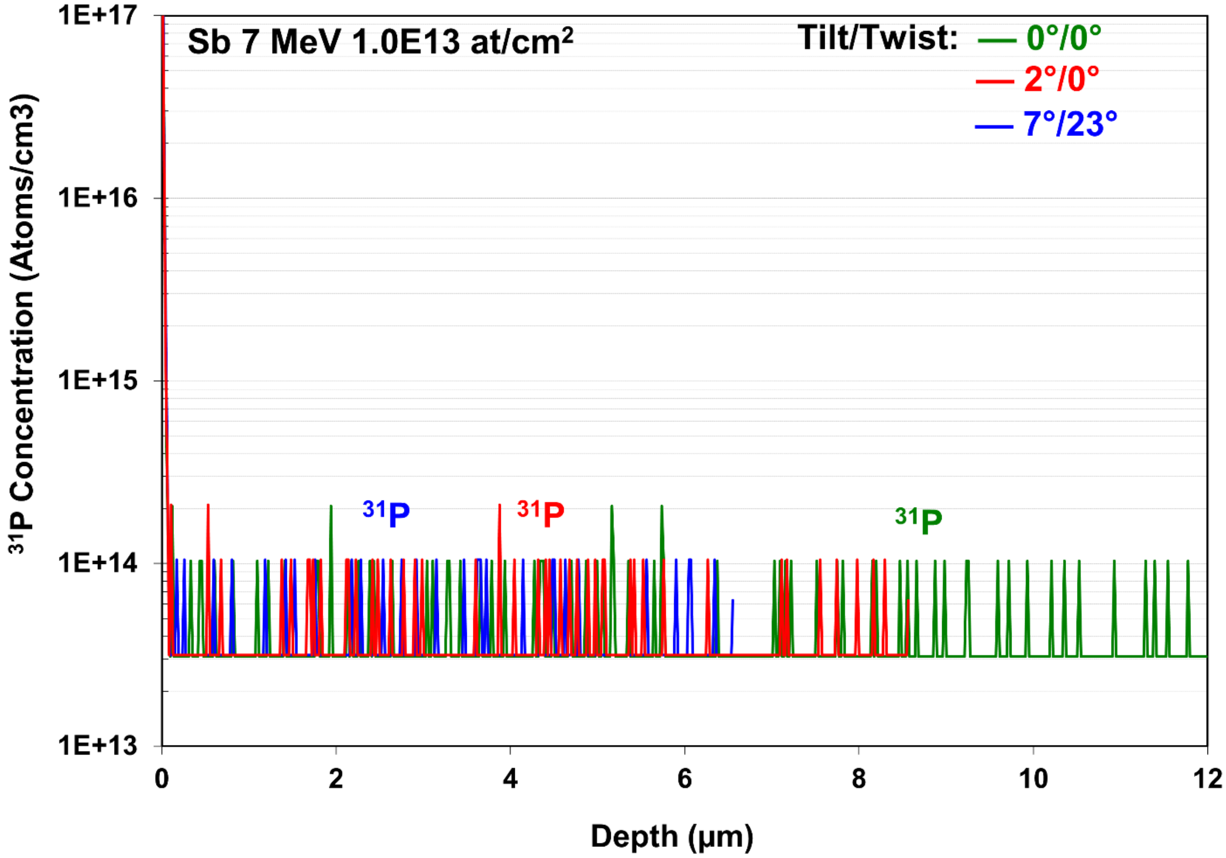
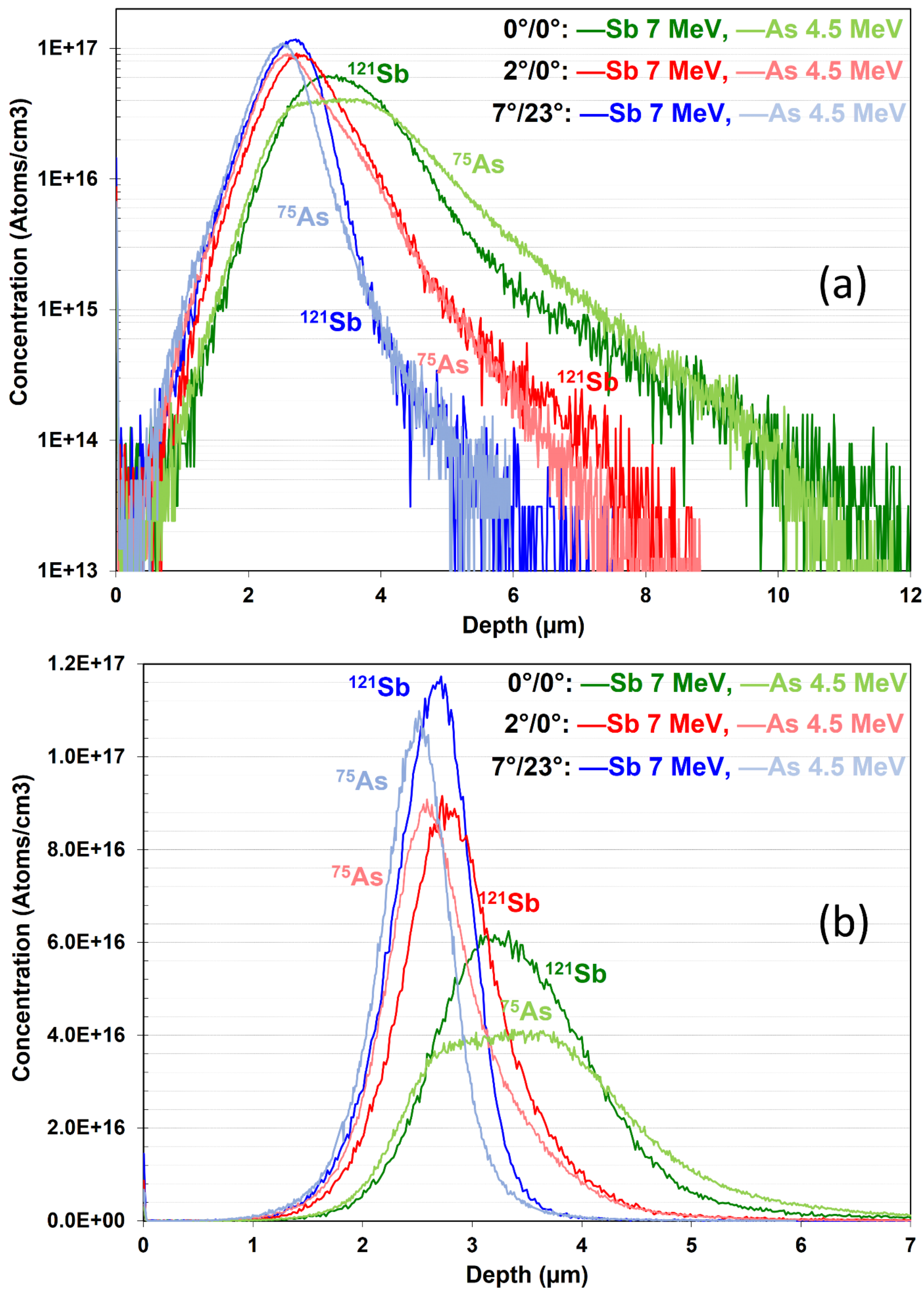

Sb 7 MeV 1.0E13 at/cm^2
Tilt/Twist:
0°/0°
2°/0°
7°/23°
^{31}P
^{31}P
^{31}P
^{31}P Concentration (Atoms/cm3)
1E+17
1E+16
1E+15
1E+14
1E+13
0
2
4
6
8
10
12
Depth (μm)

Fig. 2.



0°/0°: —Sb 7 MeV, —As 4.5 MeV
2°/0°: —Sb 7 MeV, —As 4.5 MeV
7°/23°: —Sb 7 MeV, —As 4.5 MeV
121Sb
75As
75As
121Sb
75As
121Sb
(a)
Concentration (Atoms/cm3)
1E+17
1E+16
1E+15
1E+14
1E+13
0
2
4
6
8
10
12
Depth (µm)
0°/0°: —Sb 7 MeV, —As 4.5 MeV
2°/0°: —Sb 7 MeV, —As 4.5 MeV
7°/23°: —Sb 7 MeV, —As 4.5 MeV
121Sb
75As
75As
121Sb
121Sb
75As
(b)
Concentration (Atoms/cm3)
1.2E+17
1.0E+17
8.0E+16
6.0E+16
4.0E+16
2.0E+16
0.0E+00
0
1
2
3
4
5
6
7
Depth (µm)

Fig. 3.