

Ranges and Moments of Depth Distributions of Boron and Phosphorus Implanted into Silicon in the Energy Range 1.7 - 5.0 MeV with an Eaton NV-GSD/VHE Implanter

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Abstract—High energy implantation of dopant atoms is used to form buried layers of high conductivity in silicon. These layers have many potential applications, including triple wells for FLASH memory devices, buried layers for CCD devices, and damage induced gettering regions in all devices. In order to make optimum use of very high energy dopant implants, the depth and profile shape characteristics of these implants need to be determined. This paper presents the results of depth profiling by SIMS of implants of boron and phosphorus in silicon. The implants were done on an Eaton NV-GSD/VHE mechanically scanned implanter with energies of 1.7-3.0 MeV for boron and 3-5 MeV for phosphorus, doses of $1 \times 10^{13}/\text{cm}^2$ to $1 \times 10^{15}/\text{cm}^2$, and tilt/twist orientations of $0^\circ/0^\circ$, $5.2^\circ/16.7^\circ$, and $7^\circ/27^\circ$. The four central moments of the depth distributions, as well as the peak depth have been calculated for each of the profiles. The projected ranges of all these implants are underestimated by TRIM92 calculations.

I. INTRODUCTION

The ability to alter the conductivity of regions that are micrometers below the silicon surface by high energy implants has created many opportunities for device and circuit improvements [1]. Very high energy implants have been used to improve device isolation and increase circuit density [2], and to enhance impurity gettering [3]. High dose, very high energy buried layers are being investigated as a low cost replacement of both p- and n-type epitaxial layers. For very high energy implants to be successfully implemented in a manufacturing environment, sufficient beam currents must be available for economical throughputs. Additionally, the presence of low energy contaminants in a very high energy ion beam may affect the devices so as to cancel out the intended benefits from using a very high energy implant. Thus it is critical that the ion beams have high energy purity as well as economically viable beam currents.

In this paper, we report the statistical moments of very high energy implants of boron and phosphorus performed on an Eaton NV-GSD/VHE implanter. The velocity filtering inherent in the linear accelerator of this implanter ensures a beam free of energy contamination under almost all operating conditions.

II. EXPERIMENTAL

A dose, energy, and wafer orientation matrix for both boron and phosphorus implants into bare silicon wafers was performed. The boron implant energies were 1.7, 2.3, and 3.0 MeV, and all were done using the B^{++} ion. The beam current was 150 particle microamperes (μA) for the lower energies, and 115 μA for the highest energy. Phosphorus implants at 3.0 and 3.5 MeV were done by implanting P^{++} at 500 μA , and P^{+++} for 4.0, 4.5, and 5.0 MeV, with a beam current of 90 μA . Implants were made at doses of $1 \times 10^{13}/\text{cm}^2$ to $2 \times 10^{14}/\text{cm}^2$ and wafer orientations of 0° tilt, 5.2° , 16.7° (tilt, rotation) and 7° , 27° (tilt, rotation) for both species and all energies investigated. All implants were performed with wafers mounted on pedestals with active cooling to maintain temperatures under 50°C . For selected energies and wafer orientations, implants were made at doses of $1 \times 10^{15}/\text{cm}^2$ to $1 \times 10^{16}/\text{cm}^2$.

The implant profiles were measured using secondary ion mass spectrometry (SIMS) using a CAMECA sector magnet instrument. Oxygen primary ions and positive secondary ions were used to profile boron, while cesium primary ions and negative secondary ions were used to profile the phosphorus implants.

The as-implanted profiles were modeled as Pearson IV distributions, and the best fit of the four statistical moments (range, straggle, skewness, and kurtosis) for each distribution was determined. The results were compared with the statistical moments of identical implants simulated with TRIM version 92.12 [4].

III. RESULTS

A. Boron Implant Profiles

The boron implant profiles obtained at various energies with a 5° nominal tilt and doses of $1 \times 10^{14}/\text{cm}^2$ and $1 \times 10^{13}/\text{cm}^2$ are shown in Figs. 1 and 2, respectively. The logarithmic plot in Fig. 1 shows the clean shape of the profiles, indicating both a lack of low energy contamination, and minimal channeling

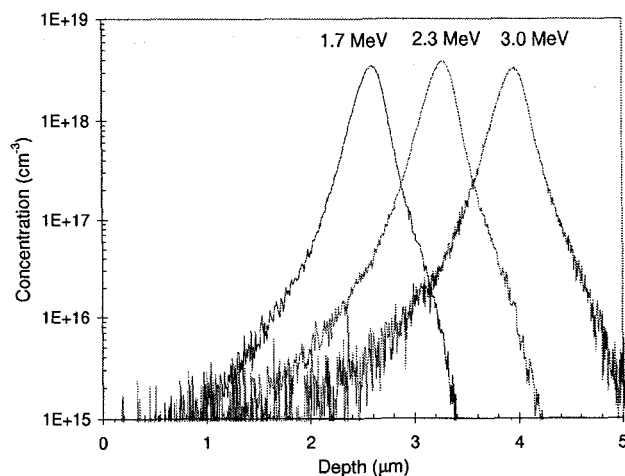


Fig. 1. As-implanted profiles of boron implants at a dose of $1 \times 10^{14}/\text{cm}^2$, a 5° tilt, and a 17° rotation.

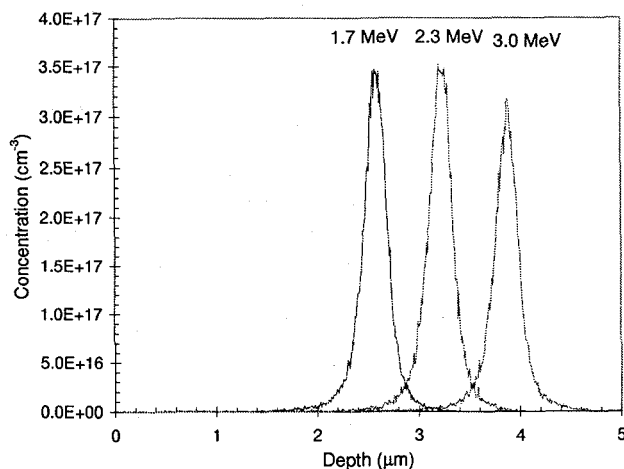


Fig. 2. As-implanted profiles of boron implants at a dose of $1 \times 10^{13}/\text{cm}^2$, a 5° tilt, and a 17° rotation.

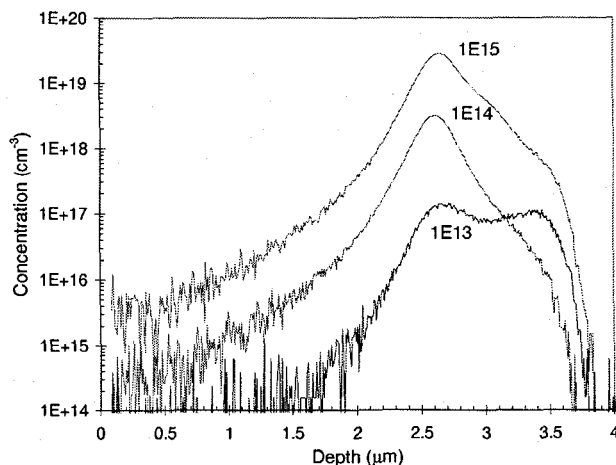


Fig. 3. As-implanted profiles of boron implants at an energy of 1.7 MeV and a 0° tilt, showing strong channeling effects.

from this “random equivalent” wafer orientation. The linear plot in Fig. 2 shows how the position of a high energy boron profile is a strong function of the implant energy.

A dramatic example of channeling effects is shown in Fig. 3. The figure is a logarithmic plot of various doses of 1.7 MeV boron implants done at 0° tilt. For the $1 \times 10^{13}/\text{cm}^2$ dose, the channeled portion is nearly as large as the unchanneled portion. Based on the profile shape, we estimate that the misorientation between the ion beam and the [001] axial channel for this implant was $\leq 0.1^\circ$. Since the amount of dopant in the channeling “tail” of this implant is higher than that for the $1 \times 10^{14}/\text{cm}^2$ implant, the large differences in the profile shapes in Fig. 3 are attributed to random variations in the crystal cut orientation of the sample wafers. These variations are typically $\pm 0.5^\circ$, much larger than the error in the wafer positioning mechanism of the implanter. Amorphization effects would not be expected for boron under these implant conditions, and in any case could not explain a larger channeling tail for a smaller dose.

The differences in the profiles in Fig. 3 suggest the extreme sensitivity of very high energy boron implants to slight ($\leq 0.5^\circ$) changes in wafer orientation in the vicinity of a major channel. To prevent this sensitivity from causing significant process variations, implant conditions that do not result in any area of the wafer being exposed to a major axial or planar channel should be selected. If resist sidewall shadowing is an issue, and implants must be made at 0° , then the possible variation in depth profile shown here should be considered in device design.

B. Phosphorus Implant Profiles

Phosphorus implant profiles for 3.0 MeV and 5.0 MeV implants at a nominal tilt of 5° and various doses are shown in Figs. 4 and 5. As is the case with boron, the profiles are free of energy contamination effects for depths below the main peak. Above the peak, there is little channeling observed because of the wafer orientation for these implants. The curves in Fig. 4 show the reproducibility of these clean profiles over a wide range of doses.

Implant profiles for phosphorus done at various energies with a 5° nominal tilt and a dose of $1 \times 10^{14}/\text{cm}^2$ are shown in Fig. 6. The idealized shape of the profiles is evident from the figure. The shift in the position of the profile with changes in energy is much lower than for boron, suggesting that large changes in phosphorus implant energy are required to shift the location of a phosphorus buried layer.

Because of its higher susceptibility to electronic stopping, the sensitivity of the channeling tail of a phosphorus profile to wafer orientation (Fig. 7) is lower than for boron. Nevertheless, the effect of [001] axial channeling from 0° tilt implants can be clearly distinguished.

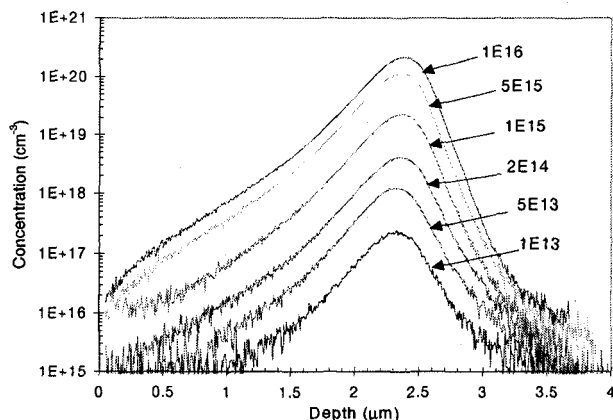


Fig. 4. As-implanted profiles of phosphorus implants at an energy of 3.0 MeV, a 5° tilt, and a 17° rotation.

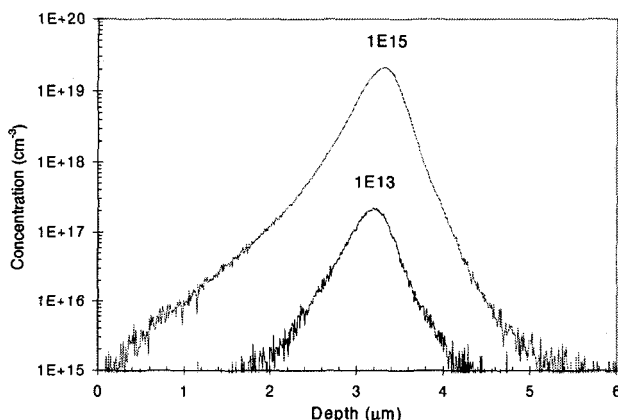


Fig. 5. As-implanted profiles of phosphorus implants at an energy of 5.0 MeV, a 5° tilt, and a 17° rotation.

IV. DISCUSSION

A. Profile Shapes

These implant profiles agree fairly well with theoretical predictions or descriptions such as Monte Carlo TRIM (Tables 1 and 2). There is no evidence of any incorrect energy presence in the depth distributions (for phosphorus or for boron). Both species exhibit backscattering of energetic atoms from stationary Si host atoms, which results in the strong negative third moment (skewness) of the profiles. The effect is greater for boron because the mass difference between boron and Si is large (lighter boron), while it is similar for phosphorus.

Implants made at 0° tilt (nominally "channeled") result in enough channeling to cause the depth of the profile peak to be measurably deeper than an "unchanneled" implant. Channeling also changes the shape of the distribution to a positive third moment from the negative third moment observed for the randomly aligned condition. This effect is considerably greater for boron than for phosphorus, because the smaller size of the boron ion means that more boron ions will be channeled. Additionally, the electronic stopping for

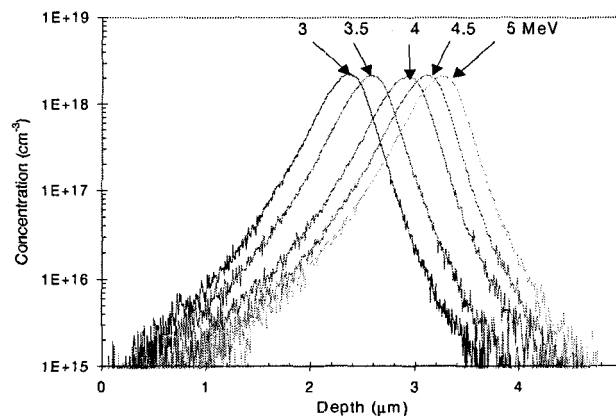


Fig. 6. As-implanted profiles of phosphorus implants at a dose of $1 \times 10^{14}/\text{cm}^2$, a 7° tilt, and a 27° rotation.

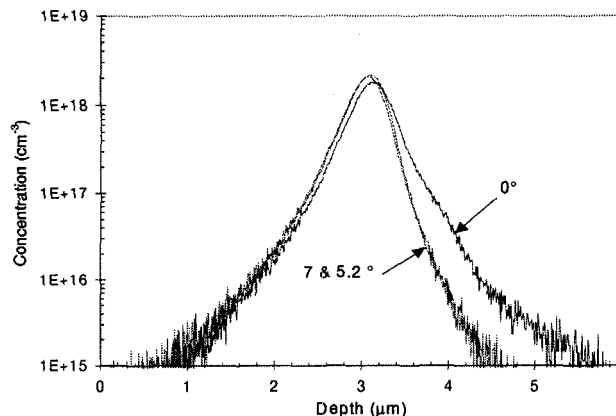


Fig. 7. As-implanted profiles of phosphorus implants at a dose of $1 \times 10^{14}/\text{cm}^2$, and an energy of 4.5 MeV. The curves for the 5° and 7° "random equivalent" orientations are identical to within the error of the SIMS measurement.

phosphorus is higher than that for boron, implying that phosphorus ions that do channel will not travel as far. As a result, more boron ions are channeled and go deeper, so the channeling shoulder or tail is higher in density and larger in depth. For phosphorus, fewer ions are channeled, and channel less deeply, so the channeling tail is shallower and of less density.

The peak implant depths are about the same for 1.7 MeV boron and 4.0 MeV phosphorus ($\sim 2.5 \mu\text{m}$). For the dose series at 3.0 MeV for phosphorus, the peak width increases with increasing dose. For all of these profiles, the magnitude of fourth moment (kurtosis) is large, both theoretically and experimentally. A kurtosis of 3 is considered small, 10 is large, and anything greater than about 50 is effectively infinity.

B. Comparisons of Experimental and Calculated Ranges and Moments of the Depth Distributions

Exact comparisons cannot be made between TRIM calculations and experimental measurements for implants

TABLE I
COMPARISON OF TRIM92 AND EXPERIMENTAL RANGE AND SHAPE PARAMETERS
FOR MEV B IMPLANTS INTO Si DETERMINED FROM PEARSON IV FITTING

Energy MeV	Dose cm ⁻²	Angle degrees	R _m μm	R _p μm	ΔR _p μm	γ ₁	β ₂
1.7	TRIM	7	2.580	2.475	0.168	-2.92	21
1.7	1.0x10 ¹³	7,27	2.587	2.560	0.175	-1.28	∞
1.7	1.0x10 ¹⁴	7,27	2.610	2.579	0.178	-1.40	∞
2.3	TRIM	7	3.160	3.061	0.174	-3.14	25
2.3	1.0x10 ¹³	7,27	3.238	3.211	0.185	-0.78	∞
2.3	1.0x10 ¹⁴	7,27	3.285	3.242	0.181	-1.47	∞
3.0	TRIM	7	3.850	3.754	0.184	-3.83	40
3.0	1.0x10 ¹³	7,27	3.868	3.860	0.187	-0.55	∞
3.0	1.0x10 ¹⁴	7,27	3.862	3.830	0.186	-1.29	∞
1.7	1.0x10 ¹⁴	0;0	2.600	2.619	0.201	0.84	∞
2.3	1.0x10 ¹⁴	0;0	3.298	3.356	0.262	1.81	∞
3.0	1.0x10 ¹⁴	0;0	3.904	4.030	0.324	2.58	∞

TABLE II
COMPARISON OF TRIM92 AND EXPERIMENTAL RANGE AND SHAPE PARAMETERS
FOR MEV P IMPLANTS INTO Si DETERMINED FROM PEARSON IV FITTING

Energy MeV	Dose cm ⁻²	Angle degrees	R _m μm	R _p μm	ΔR _p μm	γ ₁	β ₂
3.0	TRIM	5	2.260	2.154	0.222	-1.88	10
3.0	1.0x10 ¹³	5,17	2.323	2.250	0.265	-1.44	∞
3.0	5.0x10 ¹³	0,0	2.399	2.420	0.345	0.69	∞
3.0	5.0x10 ¹³	5,17	2.334	2.258	0.285	-2.07	∞
3.0	2.0x10 ¹⁴	5,17	2.369	2.226	0.305	-2.66	∞
3.0	1.0x10 ¹⁵	5,17	2.363	2.264	0.272	-2.10	∞
3.0	5.0x10 ¹⁵	5,17	2.365	2.272	0.311	-2.11	∞
3.0	1.0x10 ¹⁶	5,17	2.413	2.298	0.287	-1.96	22
4.0	TRIM	7	2.650	2.523	0.232	-2.02	11
4.0	1.0x10 ¹⁴	7,27	2.908	2.839	0.285	-1.83	∞
5.0	TRIM	7	3.000	2.874	0.233	-1.99	11
5.0	1.0x10 ¹⁴	7,27	3.248	3.177	0.289	-1.45	21

made in crystalline silicon, because TRIM assumes that the target matrix is amorphous. Channeling that results from scattering into <110> channels especially (~37° away), but also into the <100> axis that is just a few degrees away, before the lattice is effectively amorphized by the implant dose (if the dose is high enough and the temperature low enough to cause amorphization) produces a channeling tail (as is seen for phosphorus) or shoulder (as is seen for boron) in crystalline Si. Since it assumes a fully amorphized substrate, TRIM gives results that are independent of dose. It must also be understood that R_p, which TRIM calculates, is not the peak depth; the peak depth is the mode depth (R_m). The value of R_p cannot be determined without applying a curve fitting program and a formulation like Pearson IV to determine the four moments of a modified Gaussian profile (a profile with a non zero value of third moment or skewness).

For boron profiles (table 1), the TRIM calculations for R_p differ from the experimental results by -3%, -5%, and -3%, for 1.7, 2.3, and 3.0 MeV implants respectively, all of which are within experimental error. Therefore, we can say that TRIM and our experiments agree within the experimental

error of 5%. The experimental values of R_p for the "channeled" profiles are consistently greater than those for the corresponding random equivalent ones, by 2%, 4%, and 5%. The experimental values of ΔR_p for the "channeled" profiles are consistently greater than those for the corresponding random equivalent ones, by 49%, 43%, and 73%. These are significant amounts. The values of skewness for these same profiles changes from -1.3 to -1.5 to positive 0.8, 1.8, and 2.6. This result is caused by the "shoulder" on the channeled profiles that is caused by channeling. This shoulder causes the profiles to change from a negative to positive skewness, which can easily be seen by "eye" in the profiles.

TRIM calculations of phosphorus profiles (table 2) have R_p values that differ from the experimental results (Pearson IV determined values of R_p) by +10 to +23%, which is a much bigger discrepancy than for boron. TRIM calculations for ΔR_p differ from the experimental results by -15 to -25%, which is not as good as the fit for boron. TRIM underestimates the magnitude of ΔR_p. While a channeling tail is evident on the phosphorus profiles at 0° tilt, the third moment is not changed from strong negative to strong positive as it was for boron.

V. CONCLUSION

The as-implanted profiles of phosphorus and boron from the Eaton NV-GSD/VHE implanter, obtained with production compatible beam currents, are consistently free of any traces of energy contamination. Channeling effects are minimal at the recommended tilt and rotation settings of 5°, 17° for both species. For implants done at 0° tilt, channeling effects are severe for boron, and quite noticeable for phosphorus. These observations were consistent for all doses and energies investigated in this work. 0° tilt implants are thus undesirable from a process consistency standpoint.

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