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the curve minimum position corresponds to true zero implantation angle, an offset of 0.02º was estimated for the tilt angles relative to the (100) plane. The arsenic SIMS profiles are shown in Fig. 2. Significant channeling reduction was observed at tilt angles of 0.25° and higher. As expected, very high energy profiles are found to be highly sensitive to the ion beam incident angle
profiles show some difference in channeling tails even for tilt angle variations as low as 0.04º. This drives higher requirements for the angle alignment and control during implantation relative to the wafer crystalline plane.

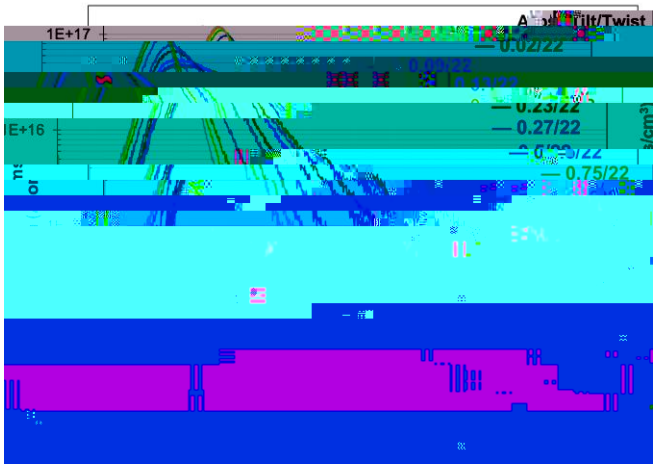

Fig. 2. SIMS profiles for As, 4.5MeV, $1x10^{13}$at/cm^2 for different implantation tilt angles, with a 22º twist angle.

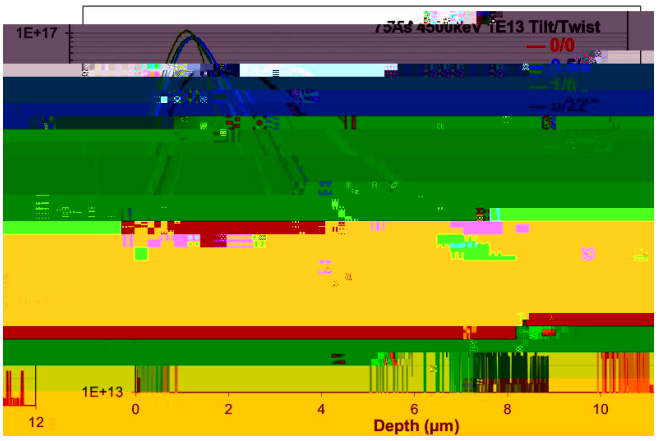

Fig. 3. SIMS profiles for As, 4.5MeV, $1x10^{13}$at/cm^2. Tilt angles 0, 0.5° and 1.0º. Comparison of 0º and 22º twist angles.

Arsenic SIMS profiles for twist angles of 0º and 22º are shown in Fig. 3. At zero twist angle the (004) planar channel is sufficiently deep that profiles for tilts 0.5º and 1.0º are very close. TW maps were measured for these wafers after implantation. As expected, the TW value was higher for 1.0º compared to 0.5º. This suggests that higher damage does not influence the arsenic profiles for this condition. The profile for tilt/twist=1º/0º is more channeled than for 0.5º/22º, indicating the significance of planar channeling for this . We also found that arsenic profiles did not show any dependence on the beam current during implantation for a 10X beam current change. Fig. 4 overlays arsenic SIMS profiles implanted at normal angle with energies of 1.9, 3.0, 4.5, and 8.0 MeV using multiply charged ions. All profiles show a deep channeling tail.

Experimental and modeled As profiles at 8.0 MeV are shown in Fig. 5. For non-channeling angles (5º/27º) the model demonstrates a good agreement with SIMS data but slightly overestimates channeling tail of a random direction implant. For zero tilt angle a good agreement with experimental data is observed for different ion doses of $2.5x10^{12}$, $5x10^{12}$, and $1x10^{13}$at/cm^2. All fits were achieved using the OVT model with the same input settings, which suggests negligible influence of damage and excellent angle control achieved on the implanter.

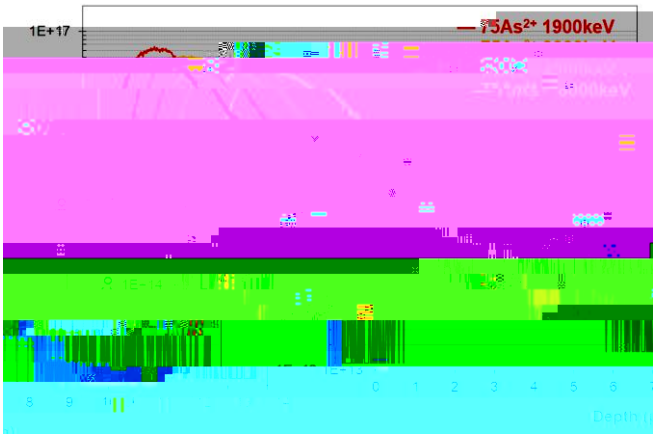

Fig. 4. SIMS profiles for As, $1x10^{13}$at/cm^2 implanted at energies of 1.9, 3.0, 4.5, and 8.0 MeV. 0º tilt and twist.

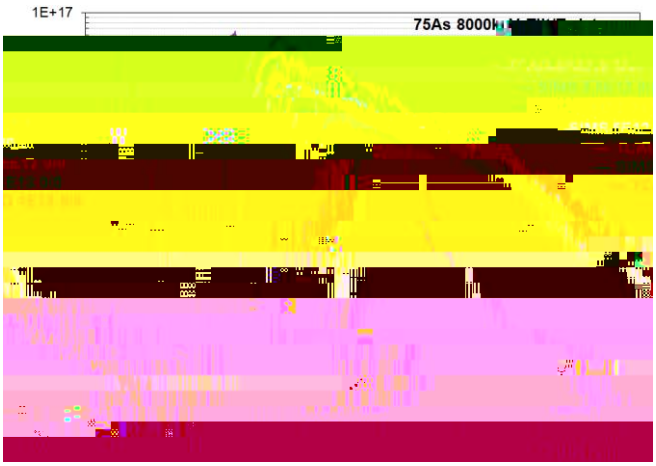

Fig. 5. Experimental and simulated profiles for As, 8MeV. Dose $2.5x10^{12}$, $5.0x10^{12}$, and $1.0x10^{13}$at/cm^2 (tilt/twist 0º/0º) and $5x10^{12}$at/cm^2 (tilt/twist 5º/27º).

B. Boron SIMS Profiles and TCAD Modeling

In Fig. 6 boron experimental and modeled profiles are shown for a non-channeling implantation angle. Similar to arsenic, the simulated profiles agree well with experimental data except that TCAD slightly overestimates the channeling tail of all three implants. Changing default model parameters did not result in improved profile fits.

Normal implantation angle SIMS and TCAD profiles are shown in Fig. 7. Generally good agreement is seen between experimental data and simulated profiles using default model parameters. Interestingly, 3.6 MeV and 5.0 MeV agree better than 2.0 MeV, where the channeling concentration peak on the SIMS profile is significantly higher than on the TCAD-simulated profile. The only way found to make the TCAD channeled peak higher than non-channeled peak was to increase the Debye temperature. With a higher Debye

Fig. 11. Experimental and simulated profiles for phosphorus, 6.0 MeV. Tilt/twist angle 0º/0º. TCAD modeling with different electronic stopping power (LSS.pre).

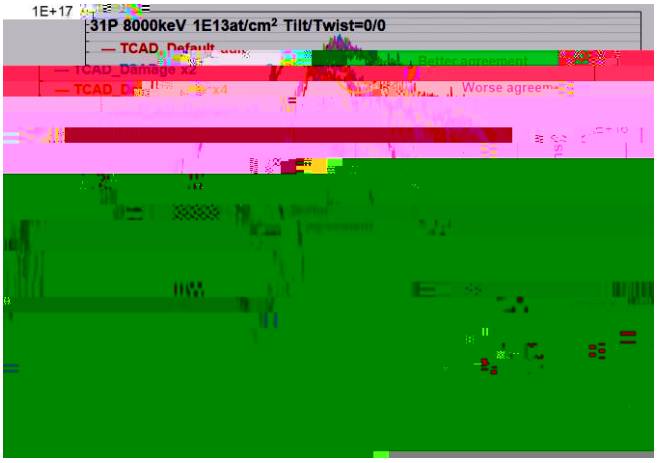

Fig. 12. Experimental and simulated profiles for phosphorus, 8.0 MeV. Tilt/twist angle 0º/0º; TCAD modeling with different implantation damage.

Fig. 13. P and As 8.0 MeV SIMS and TCAD profiles comparison. Tilt/twist angle 0º/0º. Default TCAD parameters.

For P 6.0 MeV implants, (Fig. 11) the profile peak position cannot be fit with the default TCAD parameters. The electronic stopping power in TCAD has to be reduced by ~8% to fit the SIMS peak position. This was not observed for other energies; all other phosphorus profiles fit with the