Ion Channeling in Si & SiC: A historical review

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1. Early days: Channeling as an anomaly (60's & 70's)
2. Channeling comes to ion implantation as a problem (80's &90's)
3. Countermeasures to ion channeling (80's)
4. Other additions to ion implantation aiding channeling (80's &90's)
5. Process issues for Direct Ion Channeling
    1. Alignment, 2. Temperature, 3. Divergence.
6. Direct Ion Channeling in SiC.
7. Summary & Acknowledgments

1. Early days: Channeling as an anomaly (60's & 70's)

Channeling was "discovered" in computer studies of neutron damage in metals in 1960.

Cu lattice atoms
(R= closest approach at 1 keV)

Channeled from other directions

Channeled 1 keV Cu atoms

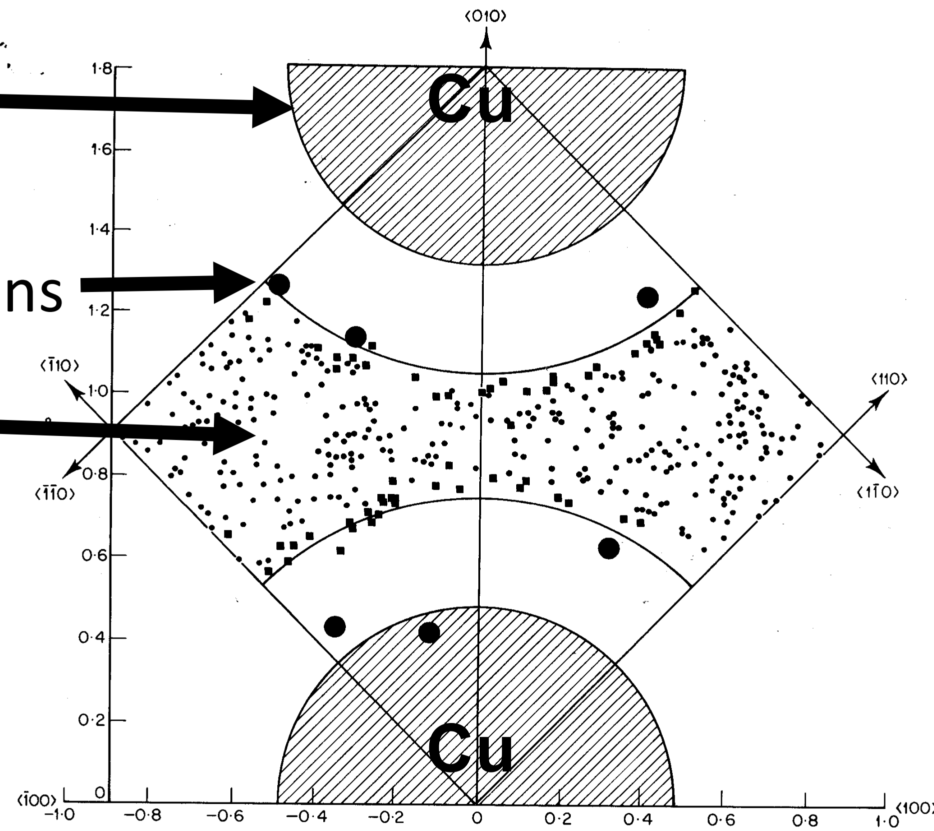
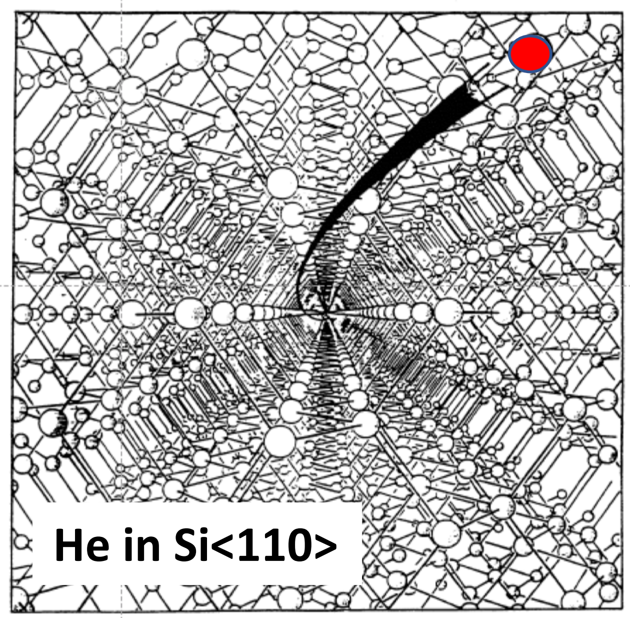


Fig.5.35 View of a {001} face of f.c.c. Copper showing points at which ⟨001⟩ channelled 1 keV Cu primaries enter the channels. The larger filled circles show the entry points of primaries which become channelled in other directions. The shaded circles show the location of target atoms, their radii represent the distance of closest approach in a head on collision at 1 keV. The larger radii circles represent the impact parameter for transfer of 10 eV at 1 keV. A truncated Bohr potential in a static lattice is assumed. (viz. Ref. 5.28)

M.T. Robinson, G. Oen, Phys Rev (1963)

Some Images of Channeling



Source: W. Brandt, Scientific American (March, 1968)

Note: This famous image is not a good model for channeling.

Channeling trajectories depend on many correlated collisions in crystals, not just open space.

Local Models for Channeling

Channeling comes to ion implantation as a problem (80's &90's)

Ion implantation came to IC's in ≈1975.
Mainstream by 1980 for MOS (Vth)
& by 1982 for Bipolar (Base widths).

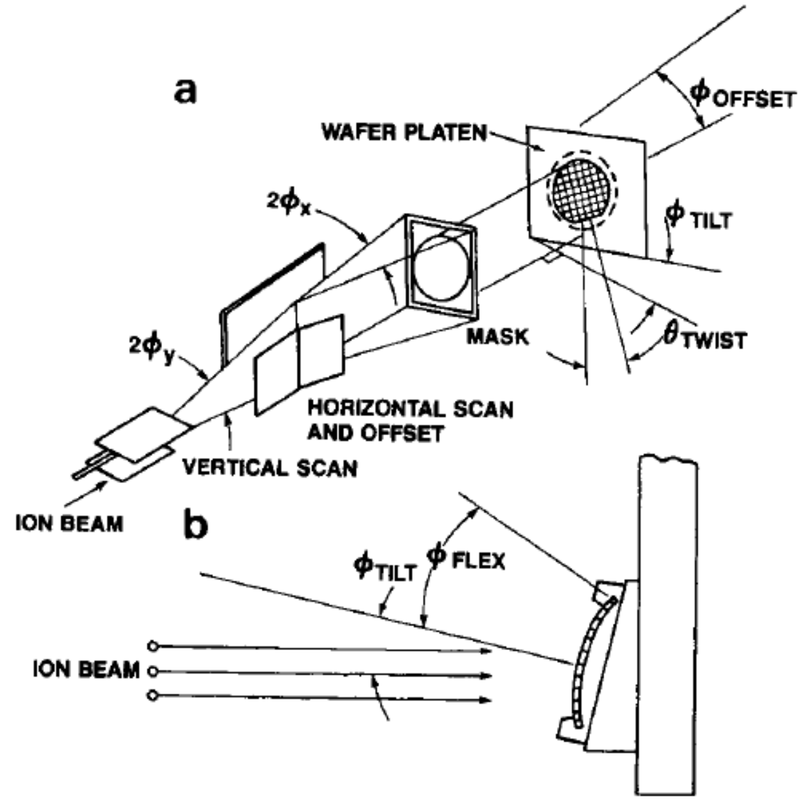


Fig. 1. (a) Angular parameters for an electrostatic-scan system. (b) Wafer flexing over a heat-sink pad is shown for the case of a wedge clamp on a spinning disk mechanical-scan system. Wafer flexing over a hemispherical heat-sink is also incorporated into some electrostatic scan systems.

Most implant designs were not ready.

Typical ion scan angles were ± 2°.

Hints for Fig. 1

a: Extrion DF-4.
b: Nova NV-10-80

Sheet resistance (ρ / Xj) is a sensitive measure of junction depth variations.

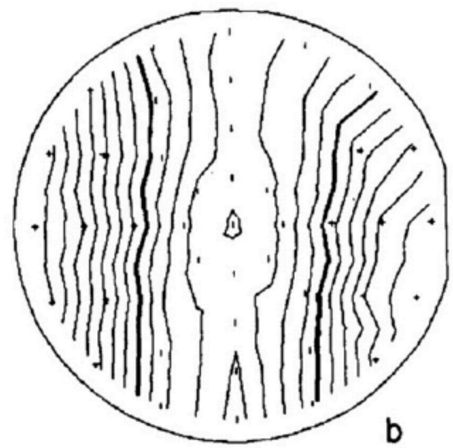
Sheet resistance was sold as a "dose" monitor.
Why are these "physicists" talking about "channeling" ?

Axial Channeling

a

Figure 2. Sheet resistance contour map for axial channeling of 80 keV B ions in a 100mm Si(100) wafer implanted on a mechanical scanned disk with 0° tilt and a center to edge wafer flex of ≈2°. The ion dose was $7x10^{13}$ B/cm^2 and the contour intervals above and below the R_{sheet} average (dark line) is 1% [4].

Planar Channeling



b

Figure 3. Sheet resistance contours for planar channeling of 50 keV B ions along (220) planes in a 100mm Si(100) wafer implanted on a mechanical scanned disk with 7° tilt and a center to edge wafer flex of ≈2°. The fast scan ion path (due to disk spin) was left to right. The wafer twist angle was 90°. The ion dose was $9x10^{13}$ B/cm^2 and the contour intervals above and below the R_{sheet} average (dark line) is 1% [4].

a: Extrion 160-10.
b: Nova NV-10-80

Sheet resistance (ρ / Xj) is a sensitive measure of junction depth variations.

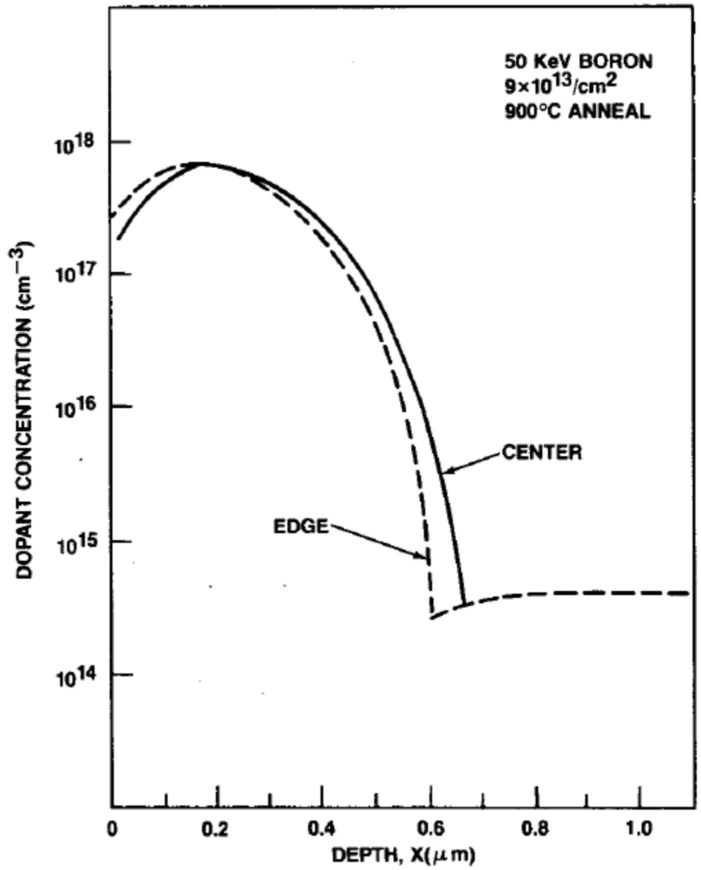


Fig. 5. Spreading resistance profiles of 50 keV B implanted with a mechanical scan system with a 2° wafer flex after a short anneal at 900°C. The junction depth at the center of a wafer similar to the one shown in fig. 4a is ~10% deeper than regions near the edge of the wafer.

IWJT25

Countermeasures to ion channeling (80's)

Tilt & twist angles

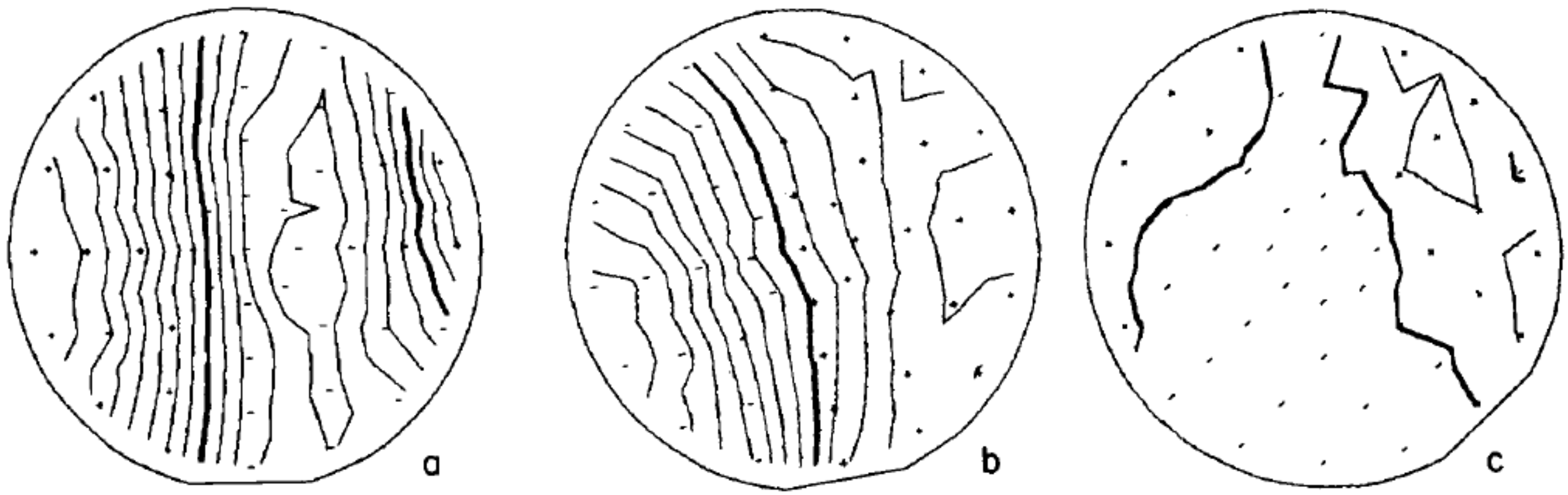
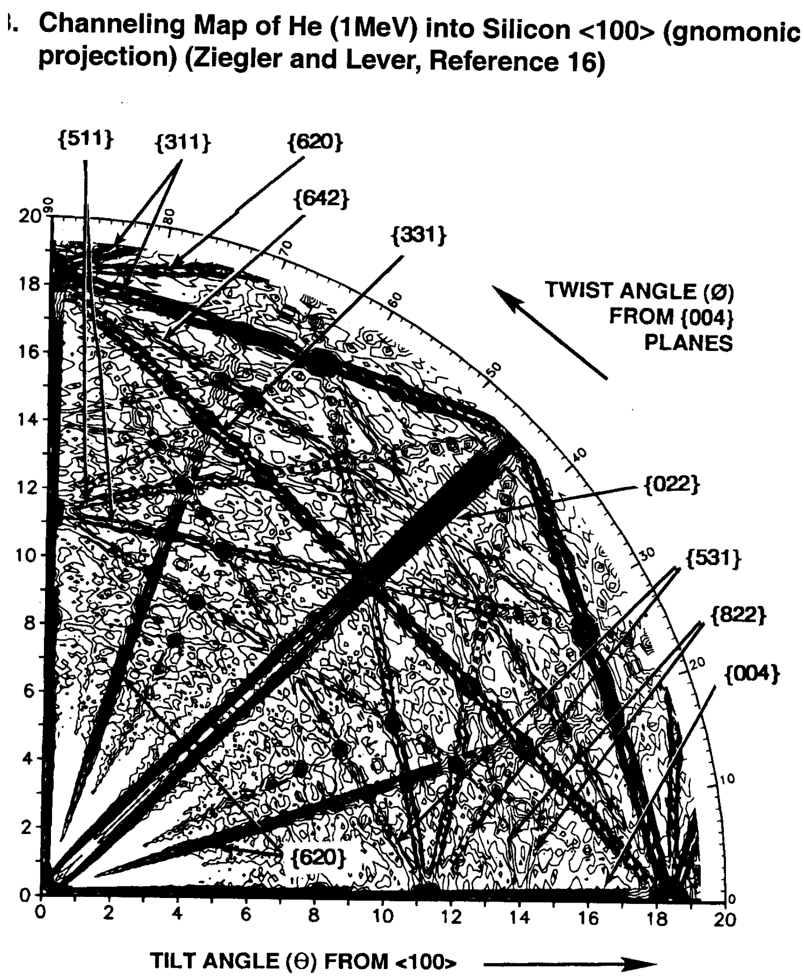
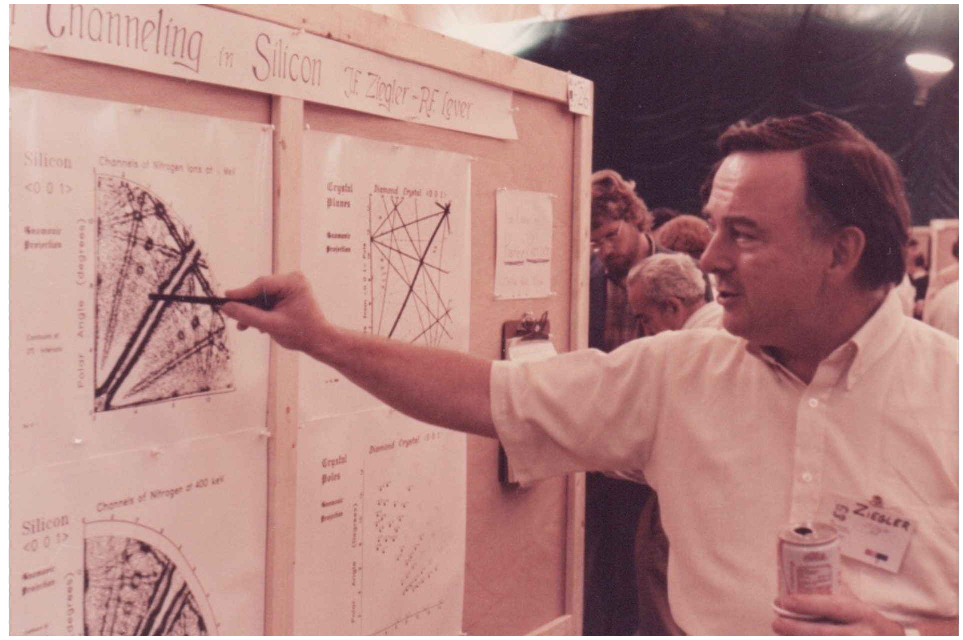


Figure 6. Sheet resistance contour lines at 1% around an average (dark lines) for 50 keV B implant at a dose of 7x1013 B/cm^2 with a mechanical disk scan with a tilt of 7° and wafer flex of 2°, with wafer twist of 0° (a), 10° (b) and 45° (c). The sheet resistance (and junction depth variation) reduced from 4.3% (a), to 3.7% (b) and 0.65% (c).

What tilt & twist avoids channeling ?



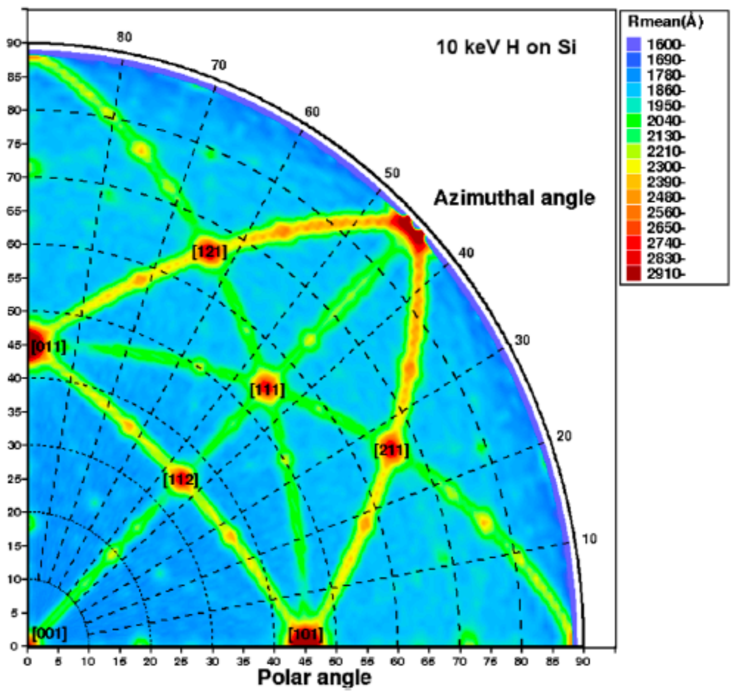


Jim Ziegler (IBM/YKT) first shows channel maps for 1 MeV He^{+}

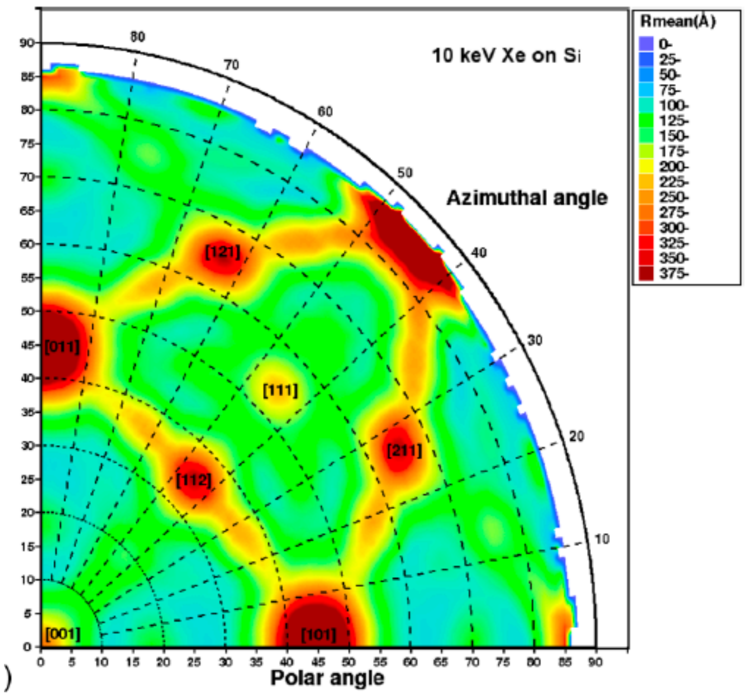
IIET84 (Smuggler's Notch, VT,USA)

Yes, but it gets tricky for heavy ions and low energies.

10 keV H^+ in Si



10 keV Xe^+ in Si



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PHYSICAL REVIEW B **94**, 214109 (2016)

Large fraction of crystal directions leads to ion channeling

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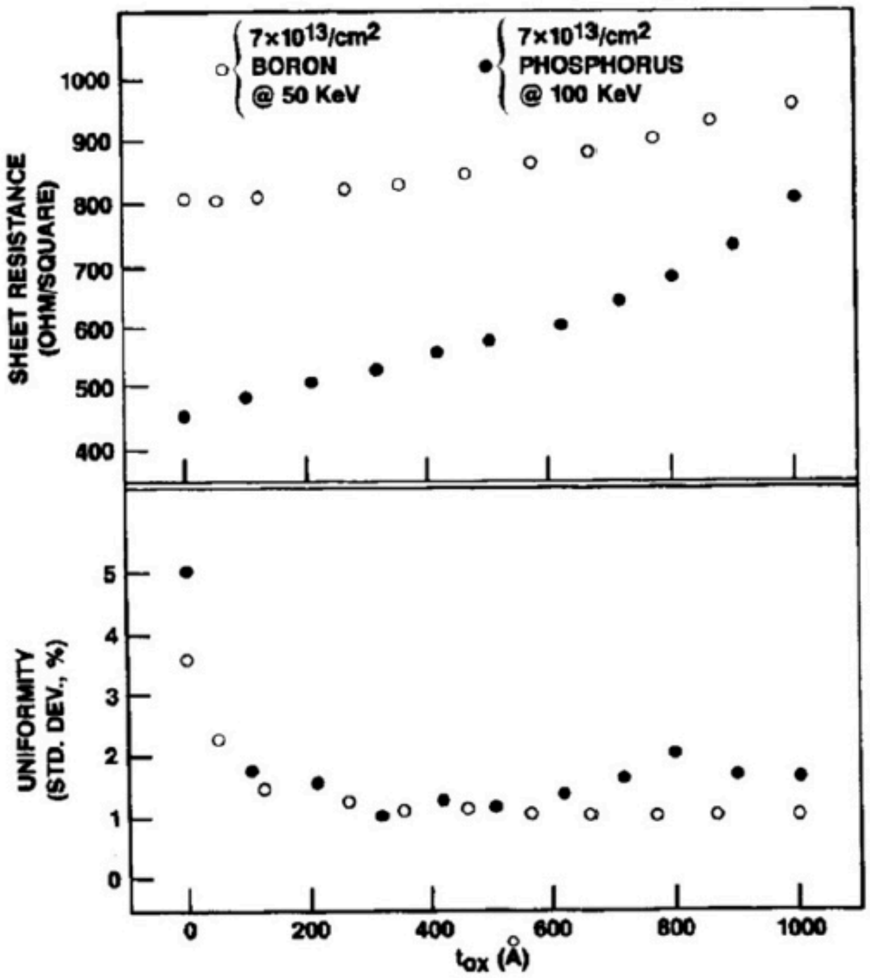
How about scattering ions into various directions ?

Add amorphous scattering layers: thermal oxides (SiO_2) or surface amorphization (Ge^+ on Si).



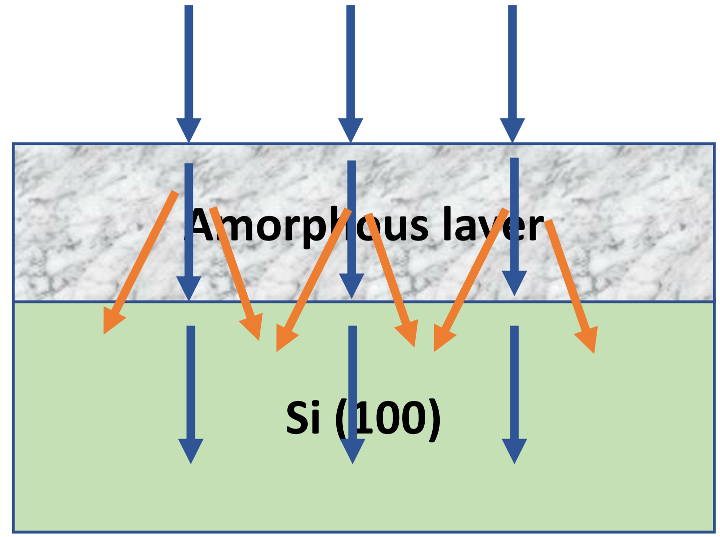


Figure 7. Average sheet resistance values (upper) and percent uniformity (lower) verses screen oxide thickness for implants of 50 keV B and 100 keV P at a dose of $7x10^{13}$ ions/cm^2 with a wafer tilt of 7°, twist angle 0° (planar channeling) and annealed at 900 C for 30 min with electrostatic scanning with a wafer flex of 2°. Note strong decrease in R_{sheet} (and junction depth) variation for a screen oxide of greater than 100 Å for both B and P ions.

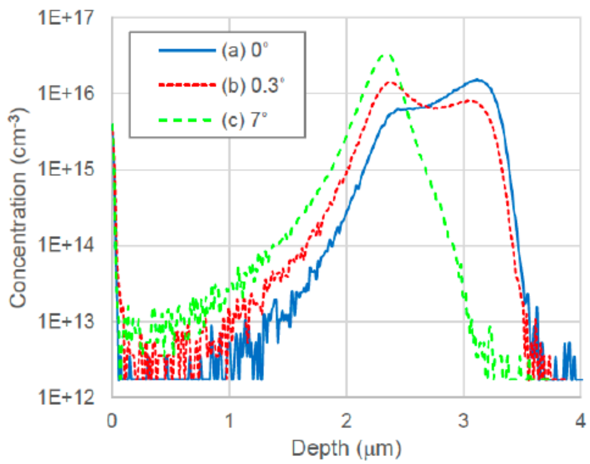
Other additions to ion implantation aiding channeling (80's &90's)

1. **Precision goniometers (later 80's)**
   Many medium current ion implanters fitted with accurate wafer tilt & twist orientation for under-gate "quad" implants at ≈45^{o} beam incidence angles.
2. **Availability of Monte Carlo calculation methods for crystalline solids.**
   MARLOWE, IMSIL, Crystal-TRIM, etc.
3. **MeV dopant implanters for Retrograde wells, buried layers, etc.**
   Tandem and LINAC accelerators starting at ≈1 MeV and now 10-15 MeV.
4. **Improved understanding for control of beam space charge & ion optics.**
   Improved controls on beam divergence.
5. **General implementation of parallel scanning of dopants on 300mm wafers.**
   Improved dopant angle and dose control.

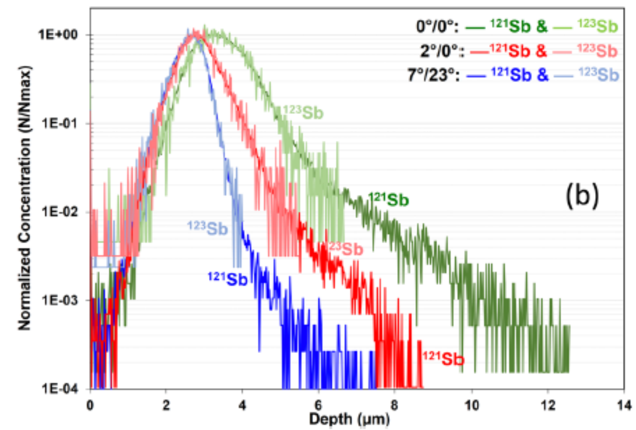
6. **New markets for deep implants (2000's to 2020's)**
   a. **CMOS Image Sensors (CIS).**
   b. **Vertical Power Devices (Si, SiC).**

7. **Use of <u>Direct Ion Channeling</u> for deep implants.**

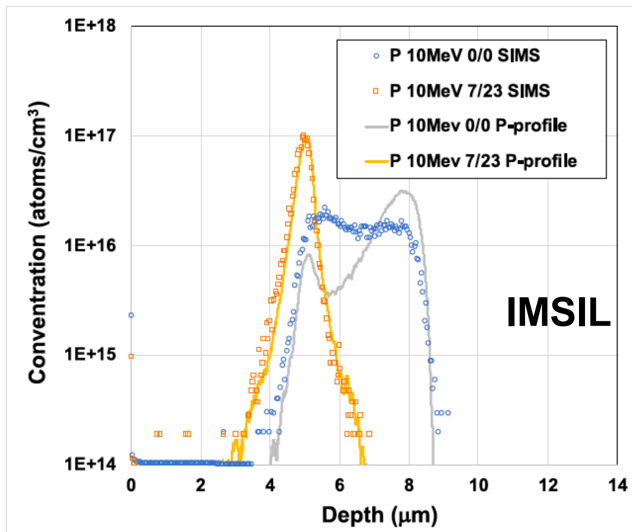
Direct Ion Channeling Examples in Si:



1.5 MeV B, 1e13 B/cm², 300 K
M. Sano et al. (SMIT) IIT22.



7 MeV Sb, 1e13 Sb/cm²
S. Kondratenko et al. (ACLS) IIT24.



10 MeV P, 5e12 P/cm²
M. Current et al. (SMIT) IWJT23.

Direct Ion Channeling Process Effects in Si: Orientation

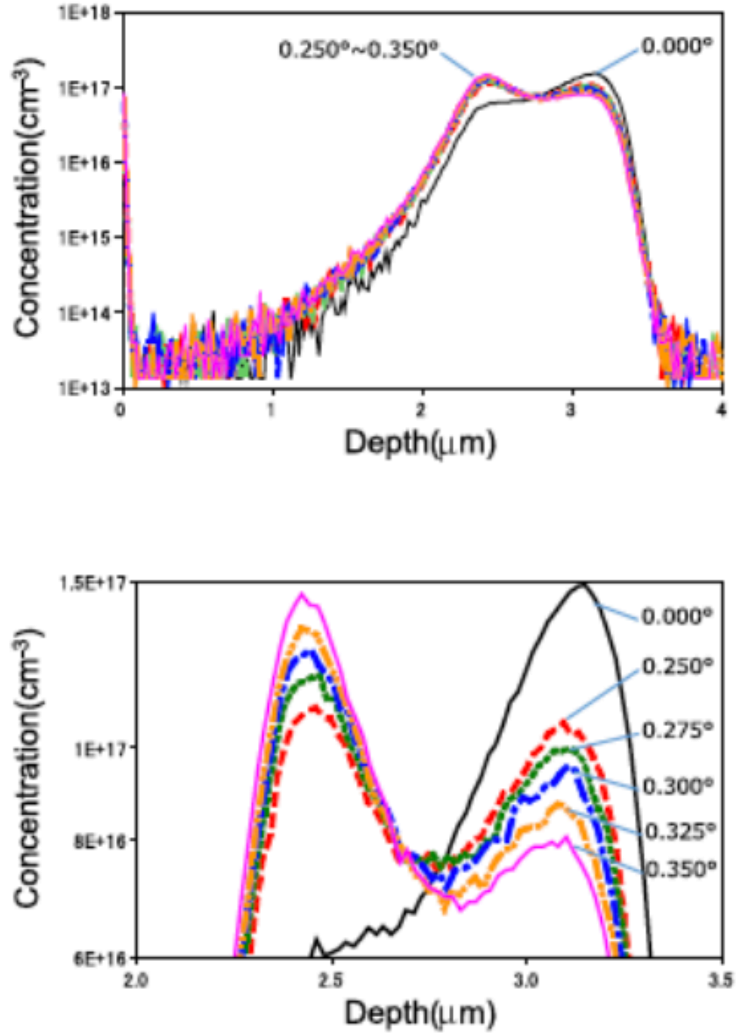


Figure 15. 1.5 MeV B SIMS profiles at a dose of 1e13 B/cm^2 at a beam current of 50 uA at tilt angles of 0° to 0.35° in 0.025° increments. The lower graph is an expanded scale detailed plot of the SIMS profile peaks [15].

Orientation accuracy to within 0.2 degrees matters.

Direct Ion Channeling Process Effects in Si: Temperature

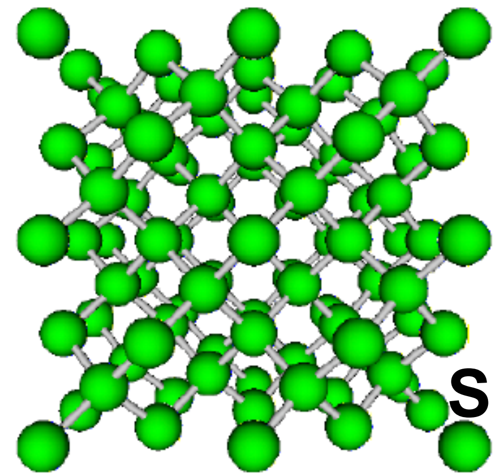
RMS vibration amplitudes for Si atoms:

0.083 Å at 300 K
0.125 Å at 723 K.

Si(100) axial channel diameter (at 0 K):

2.716 Å.

T_{Debye} = 490 K



Si (100)

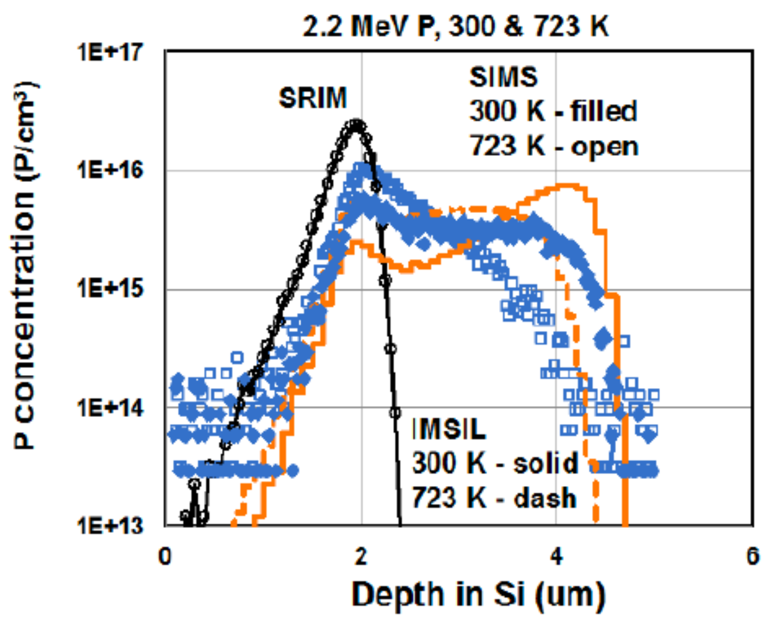


Figure 13. 2.2 MeV axial channeled P at wafer temperatures of 300 and 723 K and a dose of 1e12 P/cm^2; SIMS (symbols), IMSIL (histograms) and SRIM (open circles) for amorphous Si (no channeling) [14].

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Direct Ion Channeling Process Effects in Si: Divergence

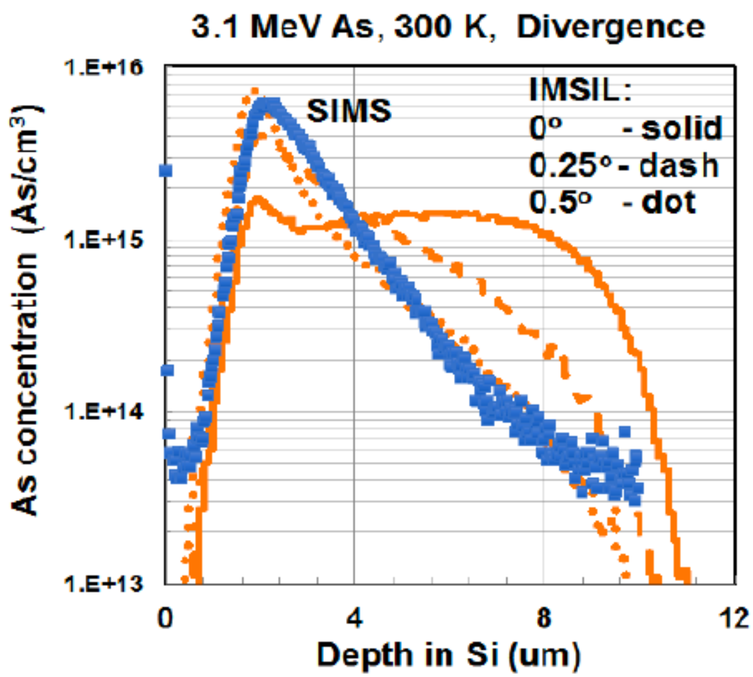


Figure 16. 3.1 MeV As axial channeled profile at a dose of 1e12 As/cm^2; SIMS (symbols), IMSIL (histograms) at divergences of 0°, 0.25° and 0.5° [14].

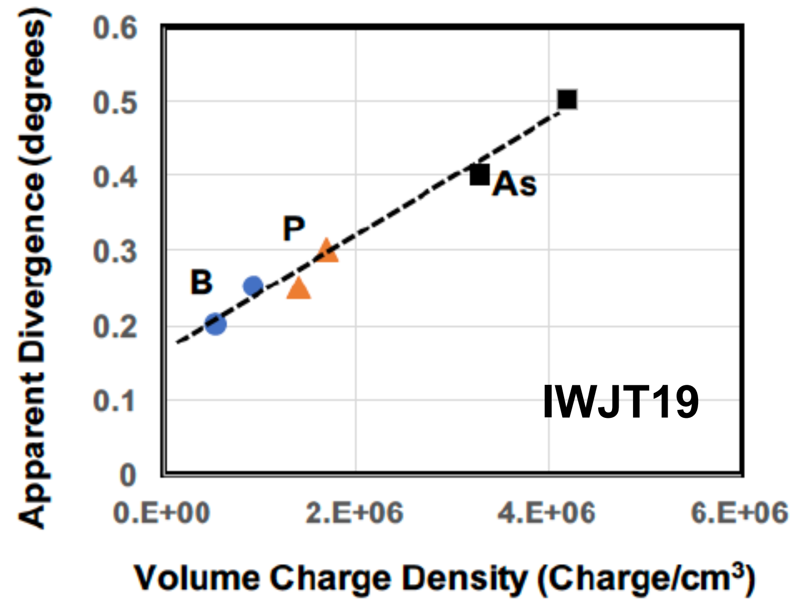


Figure 17. Apparent dopant ion beam divergence angles vs. volume charge density (charge/cm^3) in an ion energy range of 0.8 to 3.1 MeV, as judged by SIMS profile shape and location relative to IMSIL calculated profiles [16].

Direct Ion Channeling in SiC

Advantages of Direct Ion Channeling for SiC: (many deep non-axial channels)

1. Deep profiles at lower ion energies than Random.
2. Lower damage implants at lower temperatures than Random.
3. Tighter control of lateral profiles than Random.

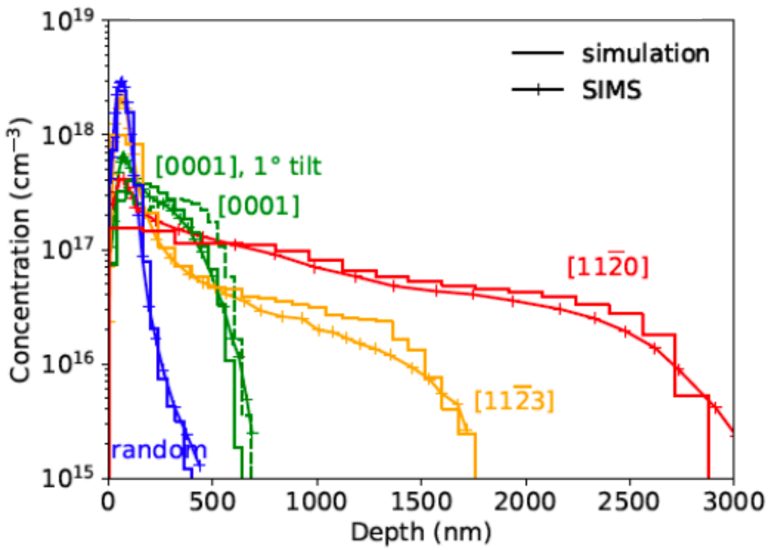


Figure 18. 60 keV Al in 4H-SiC at a dose of 2e13 Al/cm^2 for random and 3 crystal aligned directions for SIMS (solid lines with crosses) and IMSIL calculations (histograms) [17].

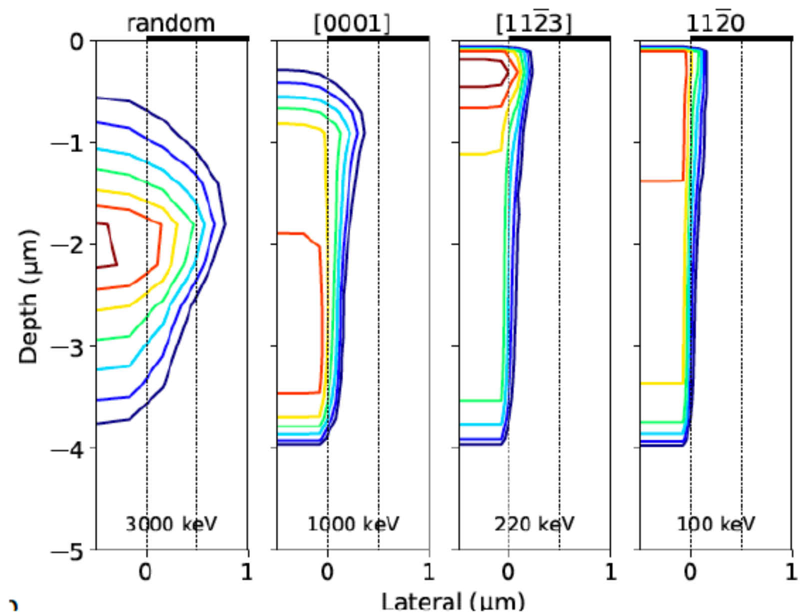


Figure 19. Al 2D-profiles for al in 4H-SiC calculated by IMSIL for a channeled depth of ≈4 um for random and aligned incidence Al along various crystal directions for Al ion energies from 100 keV to 3 MeV [17].

Process Effects of Direct Ion Channeling in SiC: Orientation

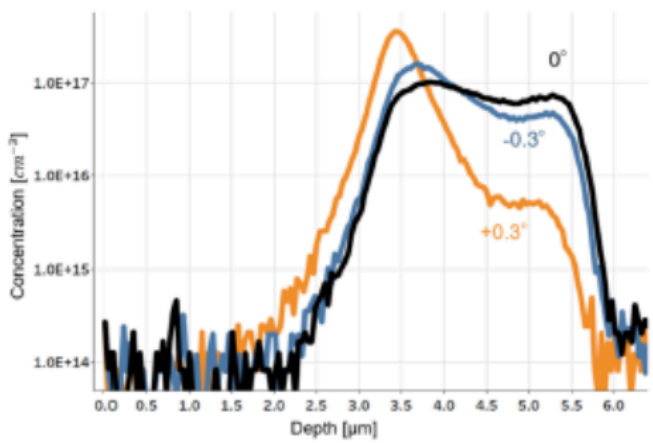


Figure 20. 9.6 MeV P SIMS profiles channeled along a [0001] axial channel, with a measured beam divergence of <0.1 degrees, with a 4°-off axis cut SiC wafer at a dose of 2e13 P/cm² at tilt angles of 0 and ±0.3 degrees [10].

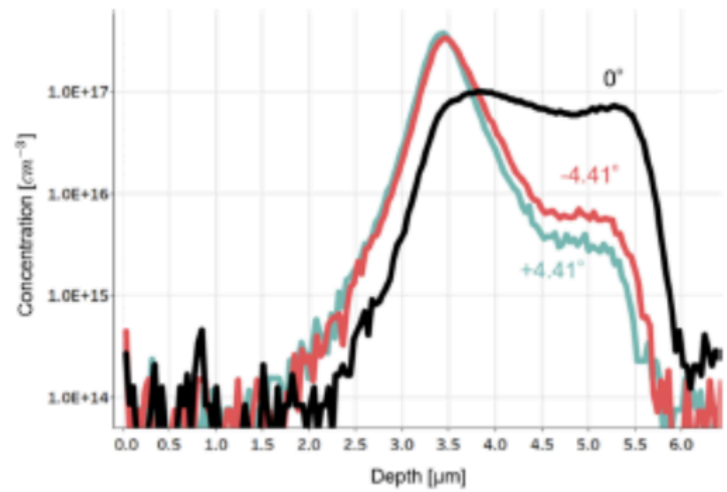
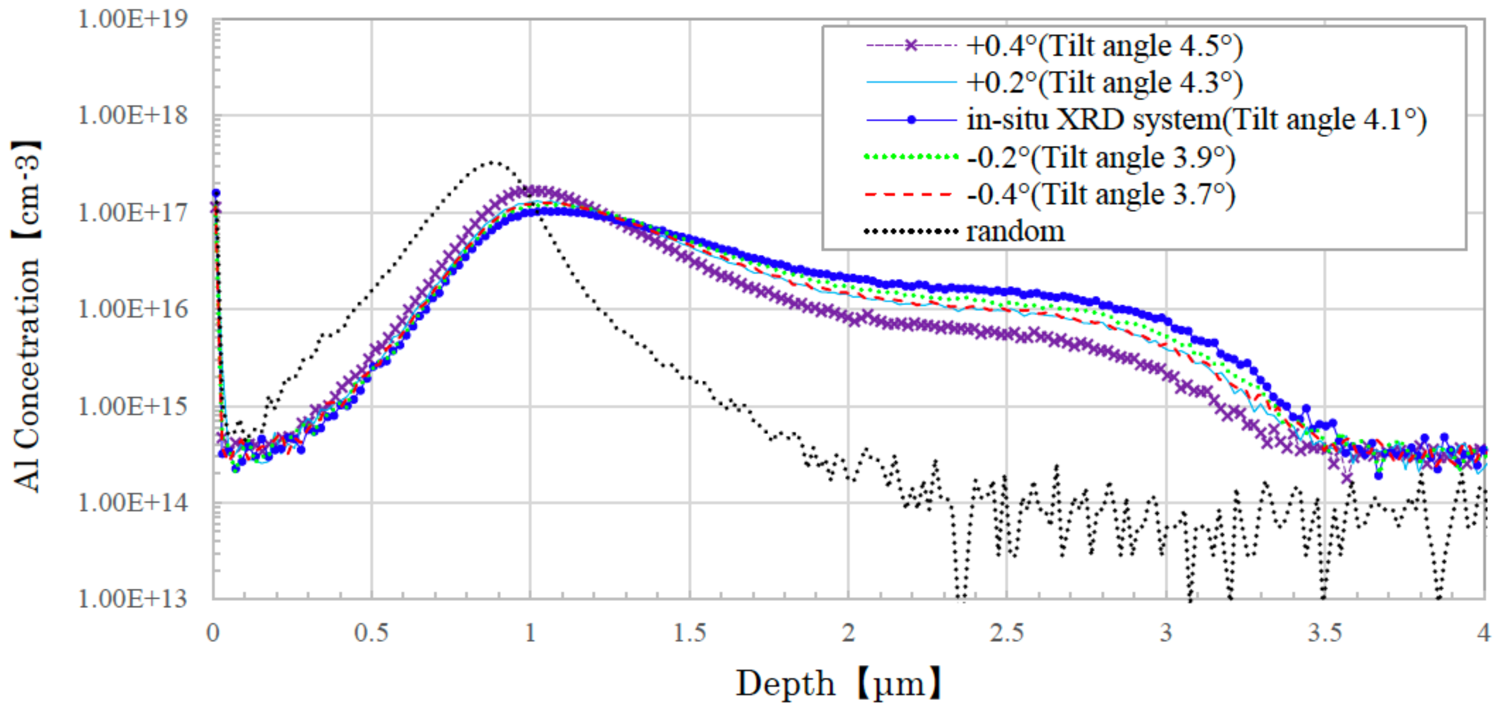


Figure 21. 9.6 MeV P SIMS profiles channeled along a [0001] axial channel, with a measured beam divergence of <0.1 degrees, with a 4°-off axis cut SiC wafer at a dose of 2e13 P/cm² at twist angles of 0 and ±4.41 degrees [10].

9.6 MeV P, 2e13 B/cm², Divergence <0.1°

A. Ohno et al. (SMIT) IIT24.

Al^{+3} Direct Ion Channeling in 4H-SiC (with in-situ XRD wafer orientation)



Direct channeling of 960 keV Al^{+3} in n-type 4H-SiC (0001), 1e13 Al/cm^2

Y. Hirai et al. (Nissin Ion) IIT24.

Summary & Acknowledgements

Over the 65 years since the discovery of ion channeling effects in solids, “channeling” has progressed from a curious "**anomaly**" to decades as a "**problem**" to be avoided, driving many improvements in process procedures and implant tool design.

Spurred by the **expanding markets** for **deep ion implants** for **CMOS Image Sensors, CIS** (in Si) and **power devices** (in SiC), numerous implant tool options for **direct ion channeling** implantation are available across 300mm wafers, with dopant ion energies well into the MeV range.

No doubt, much is still to be learned about ion channeling in Si and SiC.

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Throughout my 45-year direct contact with ion channeling issues, I have been aided by answers to my many questions and extended discussions with many teachers and friends, in particular, **James Ziegler** (IBM), **Ken Purser** (General Ionex), **Gerhard Hobler** (TU Wein) and **Werner Schustereder** (Infineon).

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