Aspects of Highly-channeled MeV Implants of Dopants in Si(100)

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1. Introduction to dopant channeling
2. Experimental & modeling conditions
3. On-axis profiles; B, P, As
4. Implant temperature & beam divergence
5. Residual defects: PL/CL studies
6. Summary

1. Channeling of MeV Dopants in Si

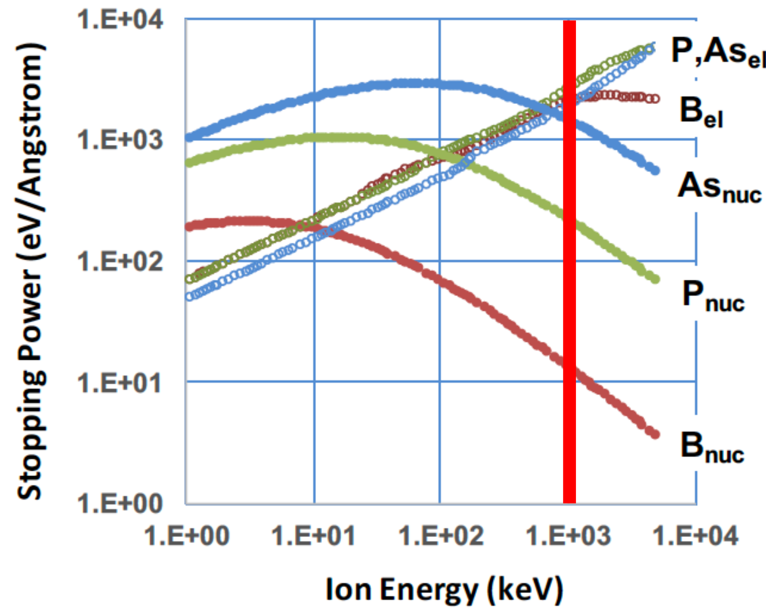
Ion stopping in solids: $S = S_{el} + S_{nuc}$

Electronic Stopping (S_{el}): Scattering of incoming ion electrons with loosely bound electrons in the solid.
Net effect: ion slowing down.

Nuclear Stopping (S_{nuc}): Scattering of incoming ion electrons with tightly bound (to the nucleus) core electrons.
Net effect: large angle scatter, defects.

Ion Channeling: Incoming ions avoid direct collisions with target core electrons by alignment of beam and crystal axis.
Net effect:

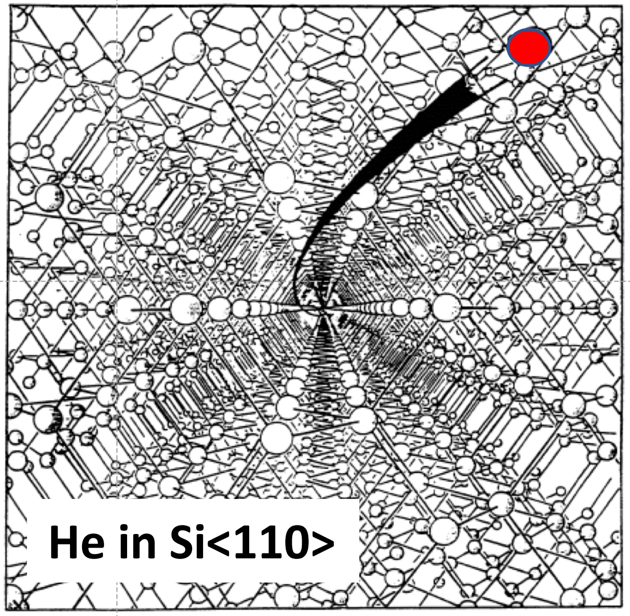
1. **some decrease in electronic stopping,**
2. **substantial decrease in nuclear stopping.**



For MeV B, S_{nuc} is ≈1% of total stopping, weak channeling impact on range.

For MeV P & As, S_{nuc} is a more substantial fraction of S, stronger impact on range.

Some Images of Channeling



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

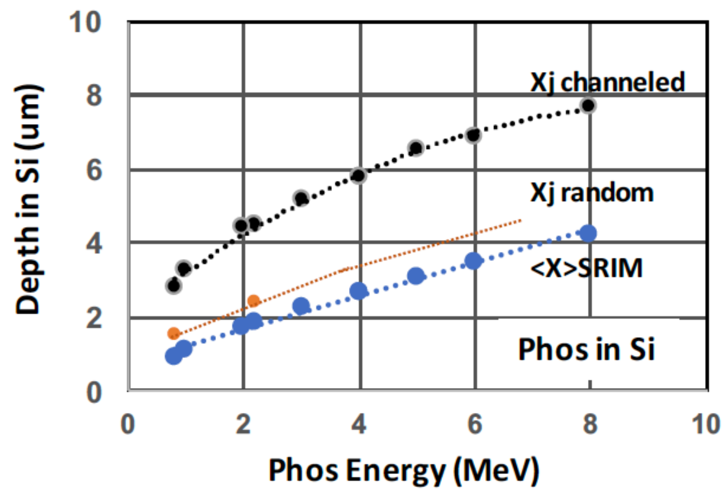
Note: This famous image is <u>not</u> a good model for channeling.

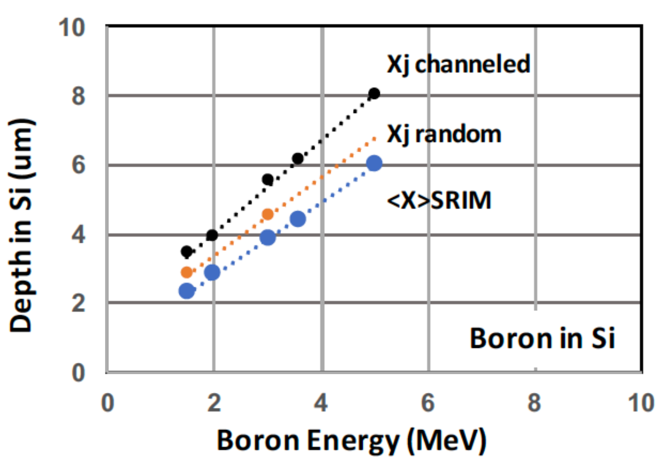
Channeling trajectories depend on many correlated collisions in crystals, not just open space.

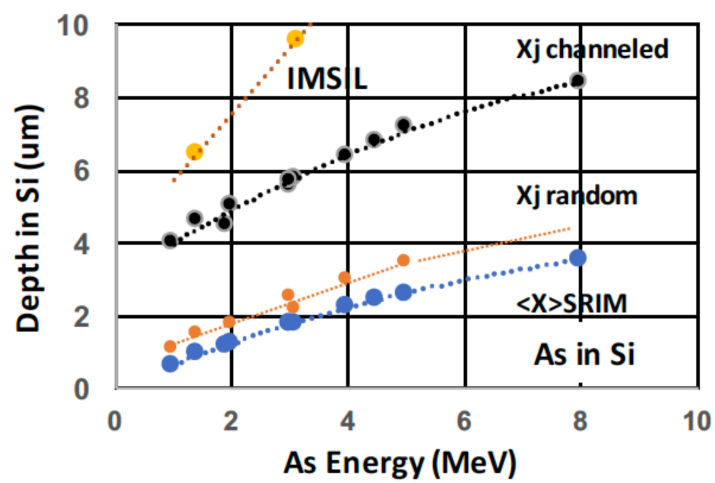
1. Channeling Effect on Range & X_j.

Although MeV B has a deep range in Si (light, fast ion), the proportional effect of channeling is small.

Channeling effects in P and As are proportionally larger.
Ideal (aligned, zero divergence) Xj depth for As can be substantially deeper still.







References: 1. M.I. Current et al., IIT18.
2. S.I. Kondratenko et al., IIT18

2. Experimental conditions: Ions & Energies

Ion.	Energy (MeV)	Beam current (e-uA)
^{11}B	1.5 ($^{11}B^{+}$)	78
	3.0 ($^{11}B^{2+}$)	63
^{31}P	0.8 ($^{31}P^{+}$)	50
	2.2 ($^{31}P^{2+}$)	100
^{75}As	1.4 ($^{75}As^{3+}$)	100
	3.1 ($^{75}As^{3+}$)	100

Wafer temperatures: 300 & 723 K. (25 & 450 C)

Highly-channeled MeV Dopant Profiles

What do you need?

1. **Uniform ion incidence angle over wafer.**
   parallel scanning, no-aberrations, uniform beam spot size, "no" beam divergence.

2. **Precise angular control on wafer alignment.**
   ≈0.1^{o} control on tilt and twist.

3. **Precise (<0.2^{o}) alignment of wafer surface and crystal axis.**
   x-ray diffraction alignment and wafer cutting.

   Note: Partially effective: "V-curve" alignment (with TW or Rs mapping) tests with wafers from same wafering cycle and then wafer positioning.

2. Experimental conditions: Implant tool

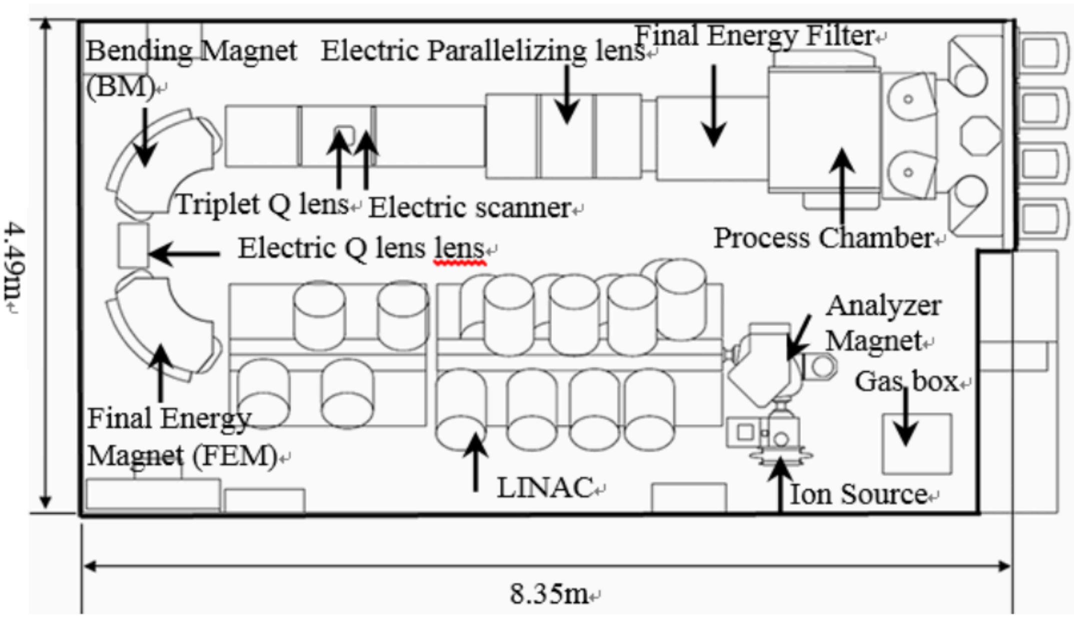
Sumitomo Heavy Industries
Ion Technology (SMIT): S-UHE

Accelerator: (Stage 1)
Multi-stage linear accelerator.
18 RF klystrons mixed with quads.
Max. energy 6.3 MeV (for As^{4+}).

Beam controls: (Stage 2)
Beam energy filter magnet.
Quad beam focus.
Electrostatic scanning.
Electric field parallelizing optics.
Final energy & neutral filter.

Precision wafer tilt & scanning.

S-UHE LINAC



2. Monte-Carlo Models

IMSIL: crystalline Si: (G. Hobler)

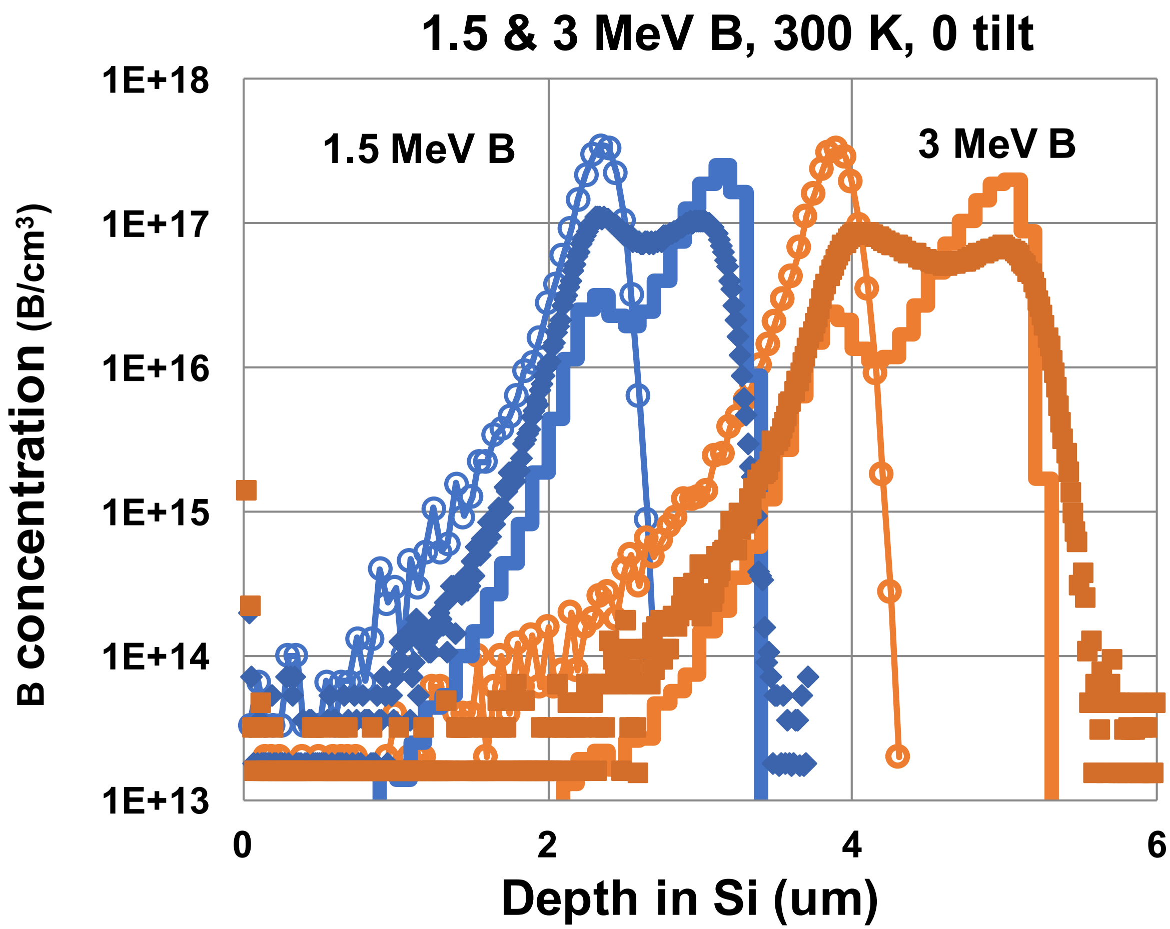
Damage: Kinchin-Pease, E_d =15 eV, recombination factors
Electronic stopping reduced for channeling conditions

Temperature: Debye, T_{Debye} = 490 K

Divergence: Gaussian angle distribution

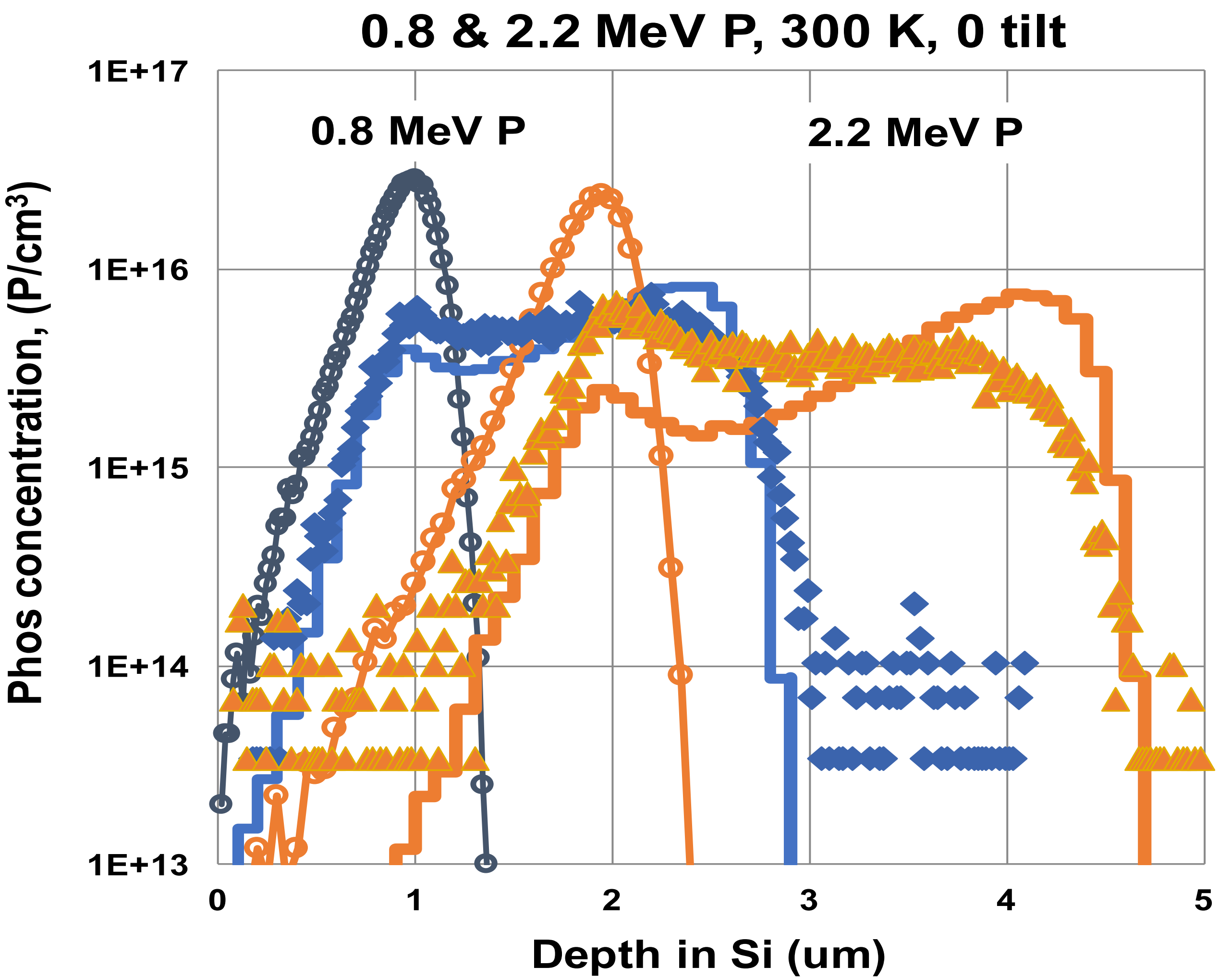
SRIM: amorphous Si. (J.F. Ziegler)

3. On-axis Profiles: Boron



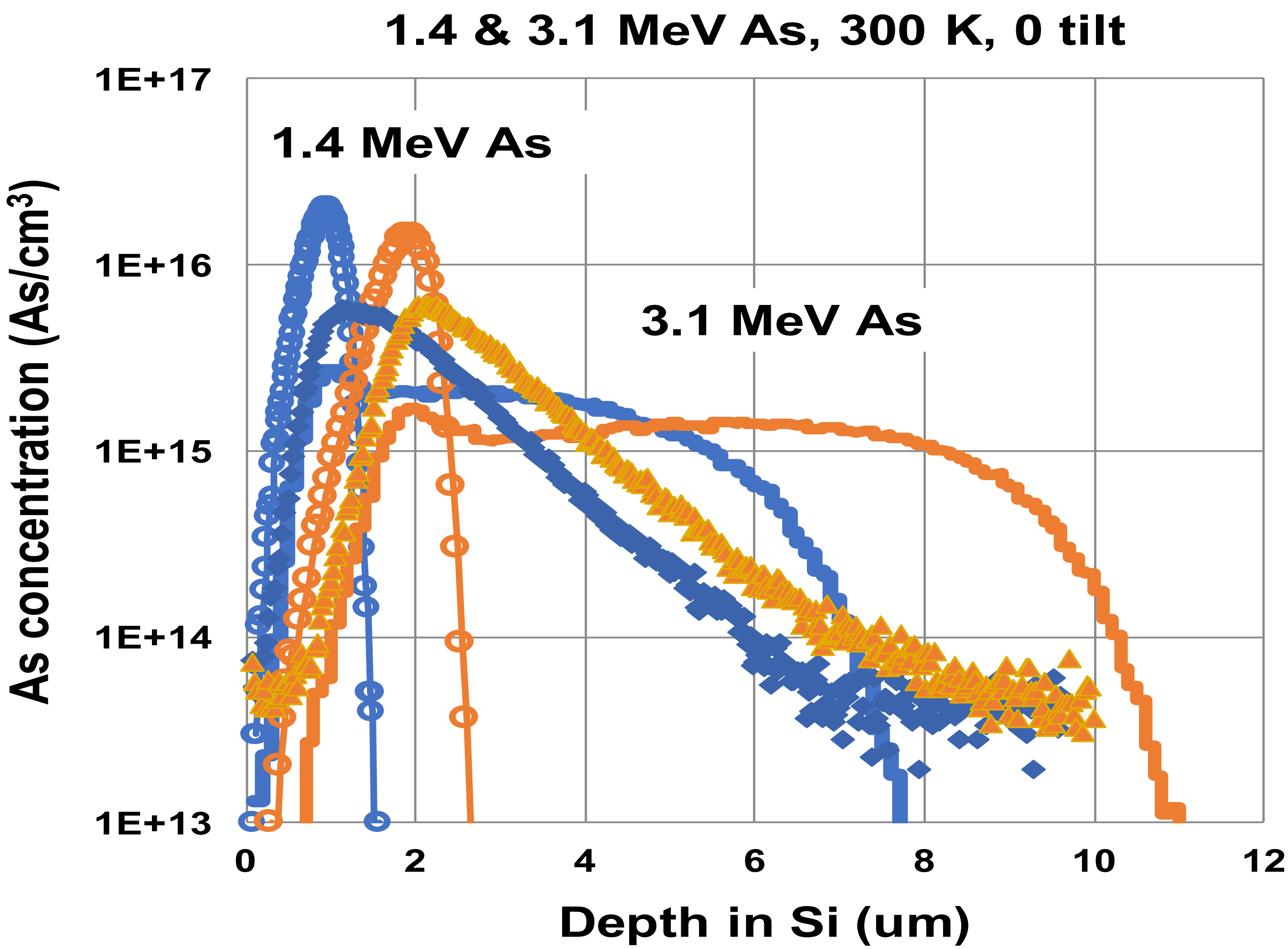
1.5 and 3 MeV Boron channeled profiles, SIMS (symbols), SRIM (open circles, amorphous Si), IMSIL (histograms). Dose = 1e13 B/cm^2.

3. On-axis Profiles: Phosphorus



0.8 and 2.2 MeV Phosphorous channeled profiles, SIMS (symbols), IMSIL (histograms), TRIM (open circles, amorphous Si). Dose = 1e12 P/cm^2.

3. On-axis Profiles: Arsenic



1.4 and 3.1 MeV Arsenic channeled profiles, SIMS (symbols), IMSIL (histograms), TRIM (open circles, amorphous Si). Dose = 1e12 As/cm^2.

4. Wafer Temperature effects:

RMS vibration amplitudes for Si atoms:

0.083 Å at 300 K

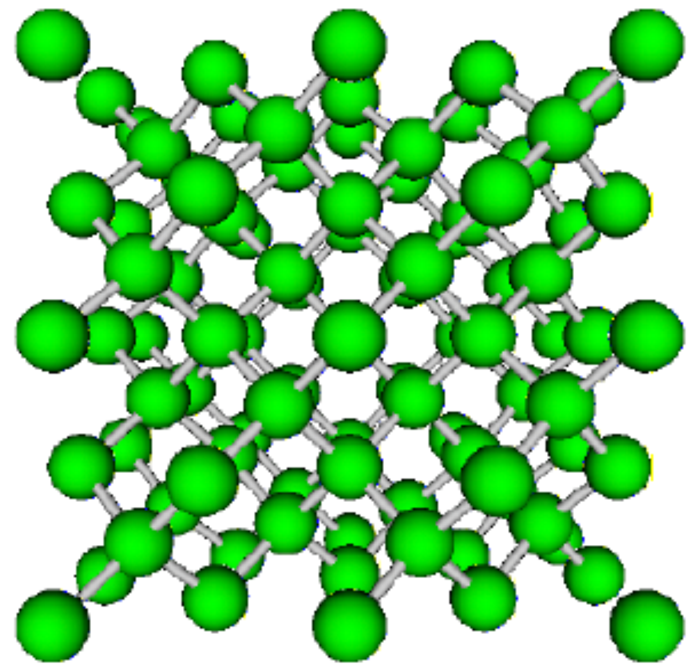
0.125 Å at 723 K.

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

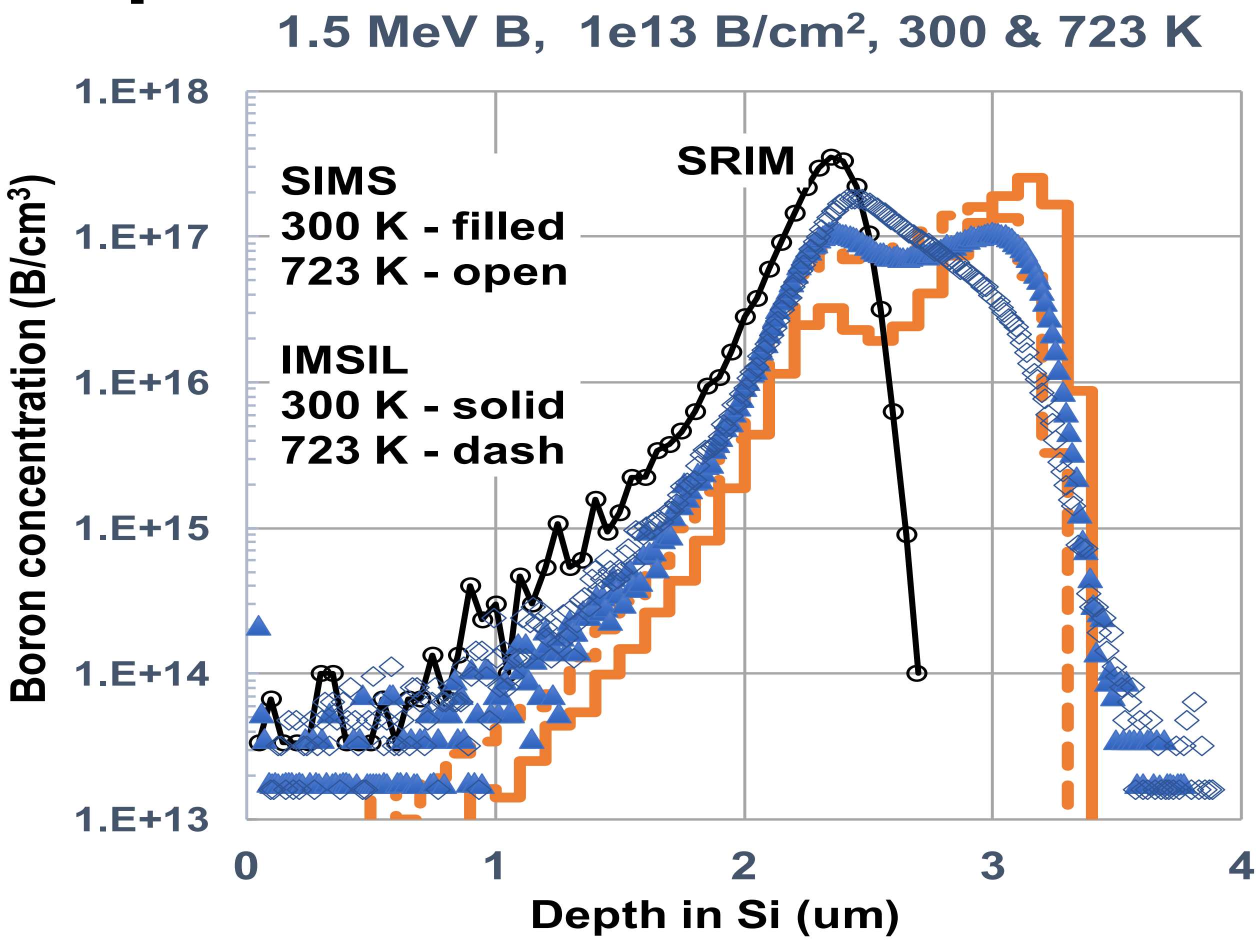
2.716 Å.

T_{Debye} = 490 K

Si (100)



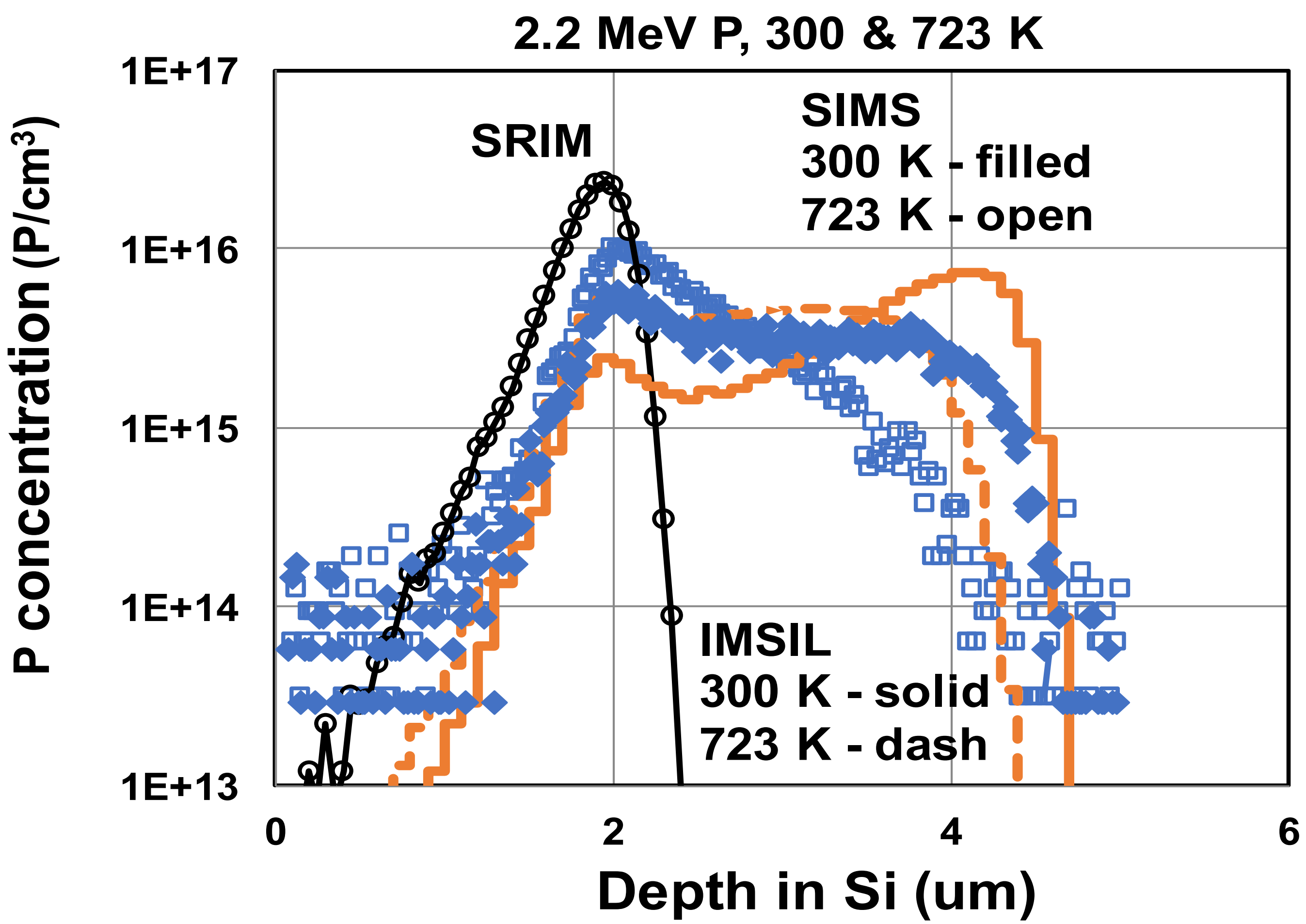
4. Temperature effects: Boron



1.5 MeV Boron channeled profiles at wafer temperatures of 300 and 723 K, SIMS (symbols), IMSIL (histograms) and SRIM (open circles) for amorphous Si target (no channeling). Dose = 1e13 B/cm^2.

M. Sano, H. Sasaki, Y. Kawasaki, M. Sugitani, "Change of depth profile for high temperature implantation in channeling condition", IIT18

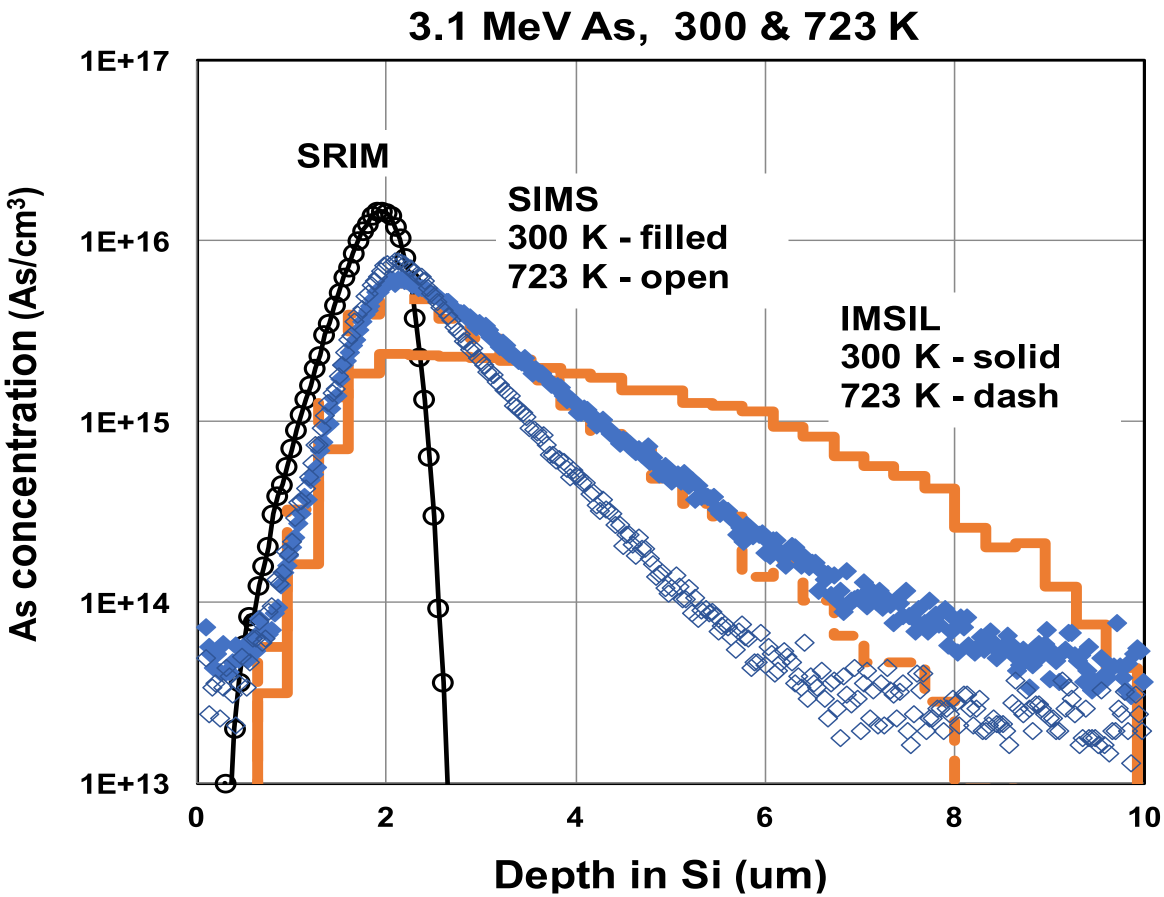
4. Temperature effects: Phosphorus



2.2 MeV Phosphorous channeled profiles at wafer temperatures of 300 and 723 K, SIMS (symbols), IMSIL (histograms), SRIM (open circles, amorphous Si). Dose = 1e12 P/cm^2.

M. Sano, H. Sasaki, Y. Kawasaki, M. Sugitani, "Change of depth profile for high temperature implantation in channeling condition", IIT18

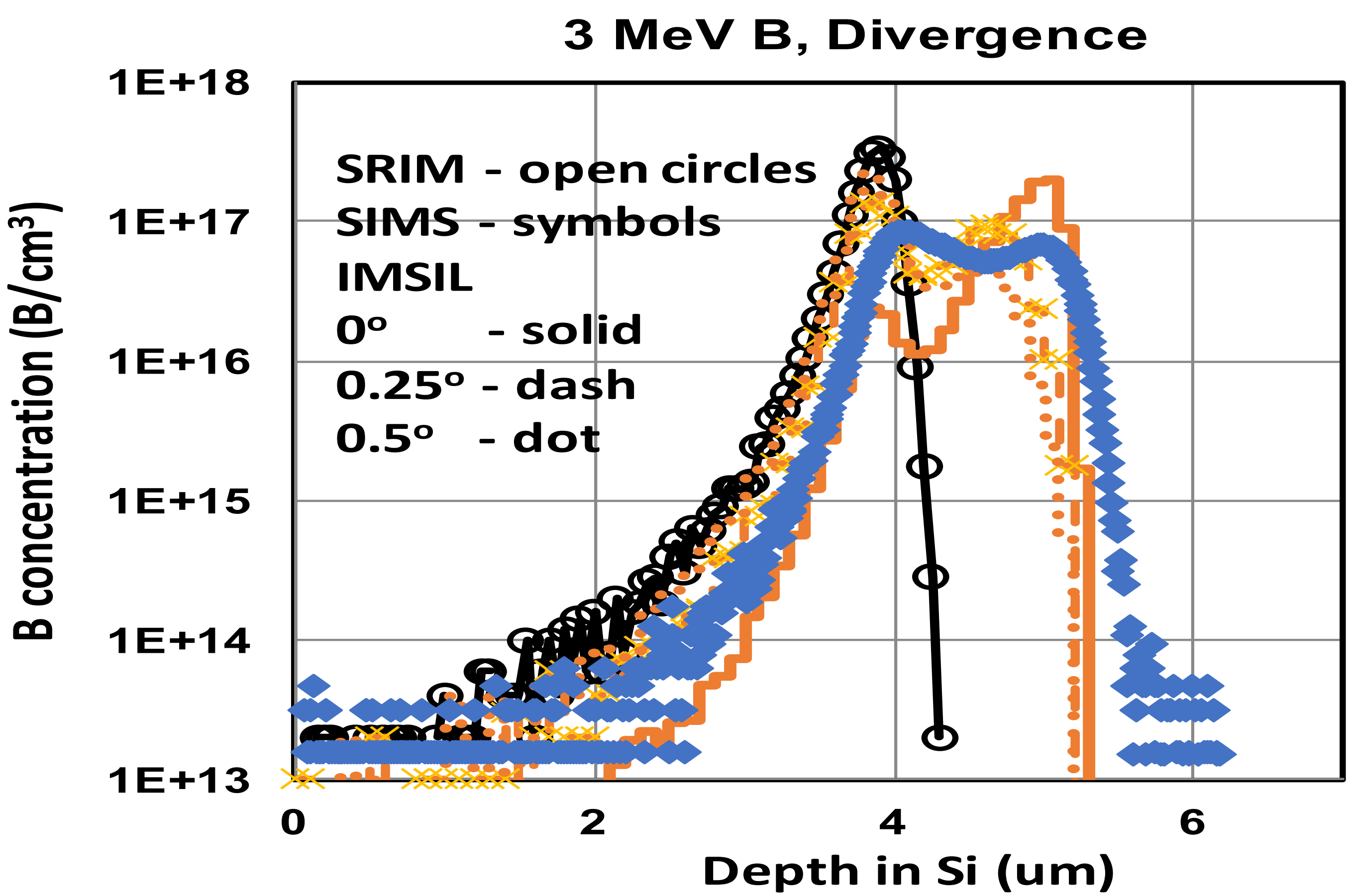
4. Temperature effects: Arsenic



3.1 MeV Arsenic channeled profiles at 300 and 723 K, SIMS (symbols), IMSIL (histograms), TRIM (open circles, amorphous Si). Dose = 1e12 As/cm^2.

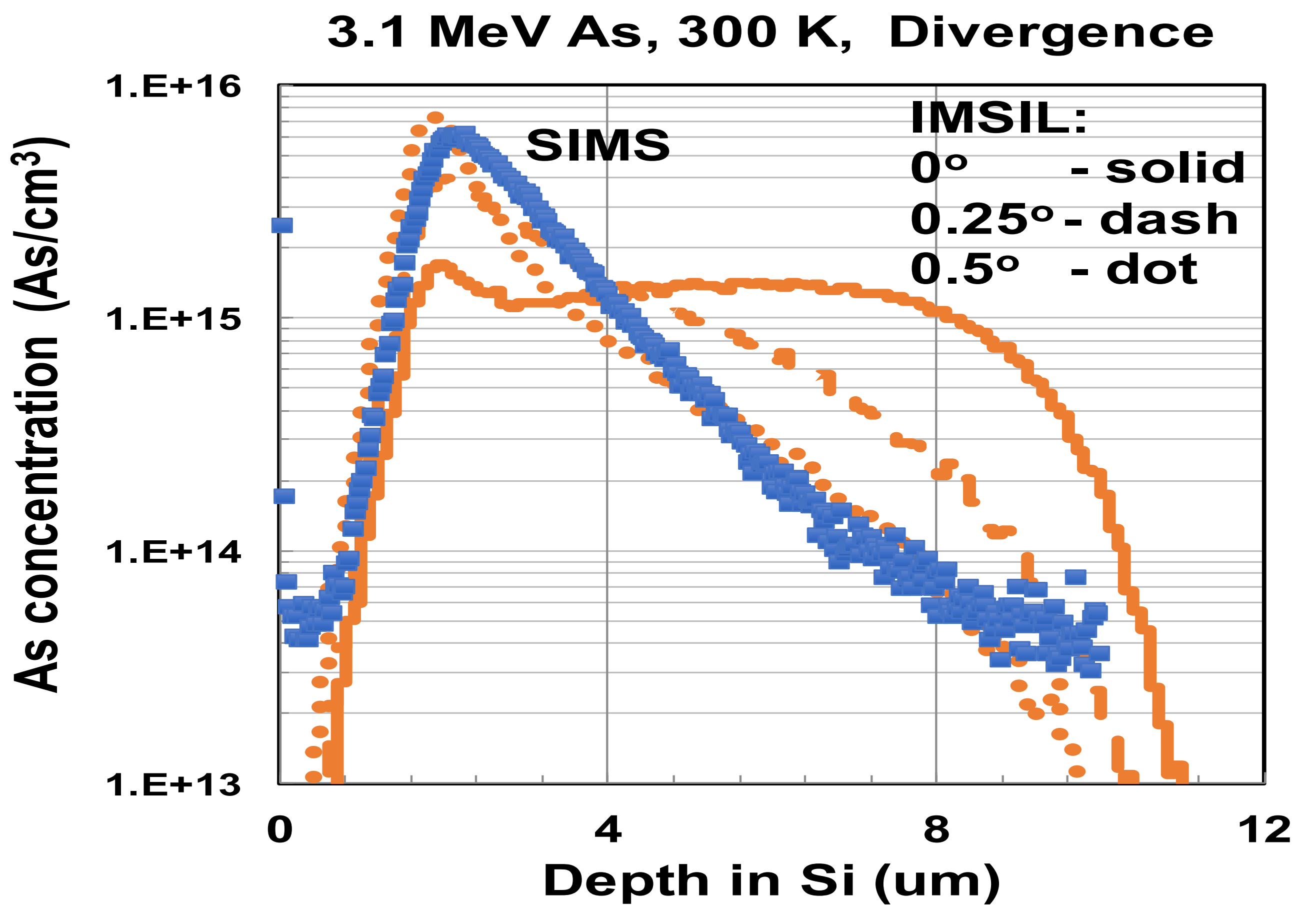
M. Sano, H. Sasaki, Y. Kawasaki, M. Sugitani, “Change of depth profile for high temperature implantation in channeling condition”, IIT18

4. Divergence effects: Boron



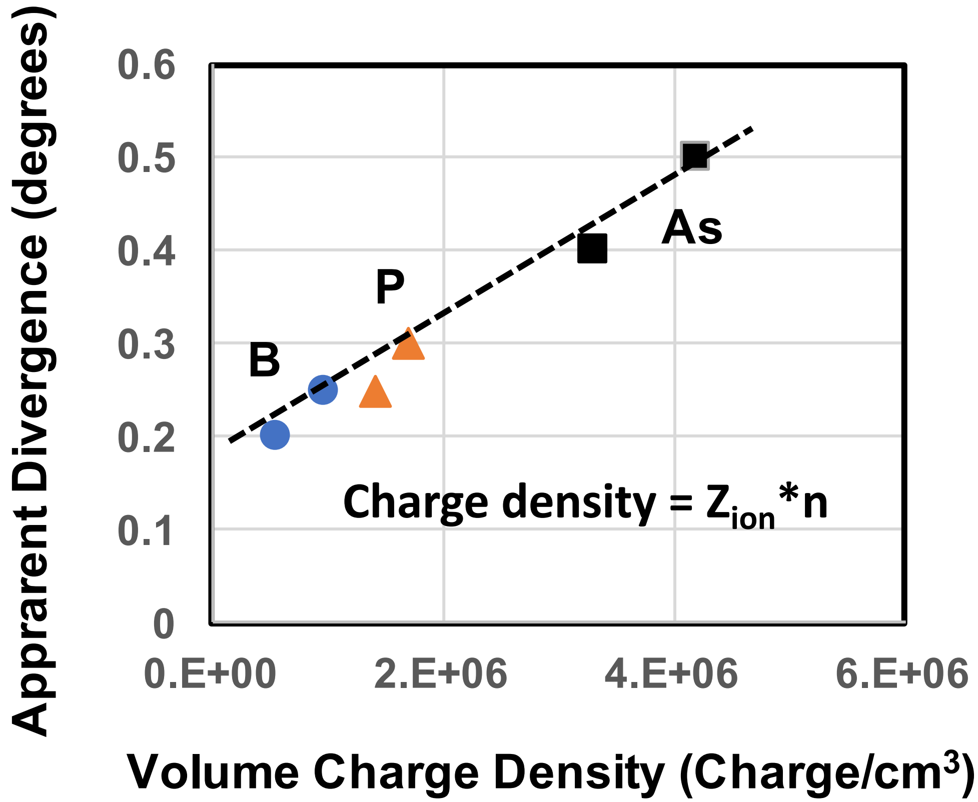
3 MeV Boron channeled profiles, SIMS (symbols), SRIM (open circles, amorphous Si), IMSIL (histograms). Dose = 1e13 B/cm^2.
IMSIL divergence modeled at 0, 0.25 and 0.5 degrees.

4. Divergence effects: Arsenic



3.1 MeV Arsenic channeled profiles, SIMS (symbols), SRIM (open circles, amorphous Si), IMSIL (histograms). Dose = 1e12 As/cm^2.
IMSIL divergence modeled at 0, 0.25 and 0.5 degrees

4. Divergence effects: Beam charge density



Apparent ion beam divergence angles, as judged by channeled profile shape and location, for B, P and As ions in the energy range of 0.8 to 3.1 MeV.

Beam Charge Density (ions/cm³):

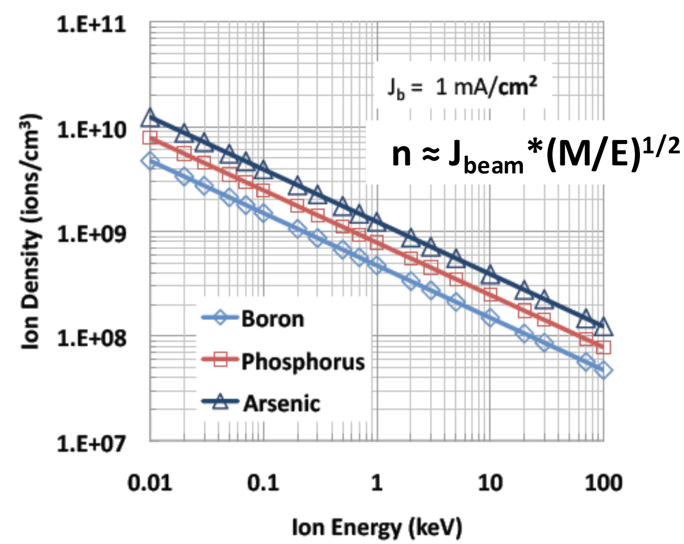
n_{beam} (ions/cm^3) = J_{beam} (mA/cm^2)/(e*Z*V_{ion})

= J_{beam}/ (e*Z*(2E/M)$^{1/2}$)

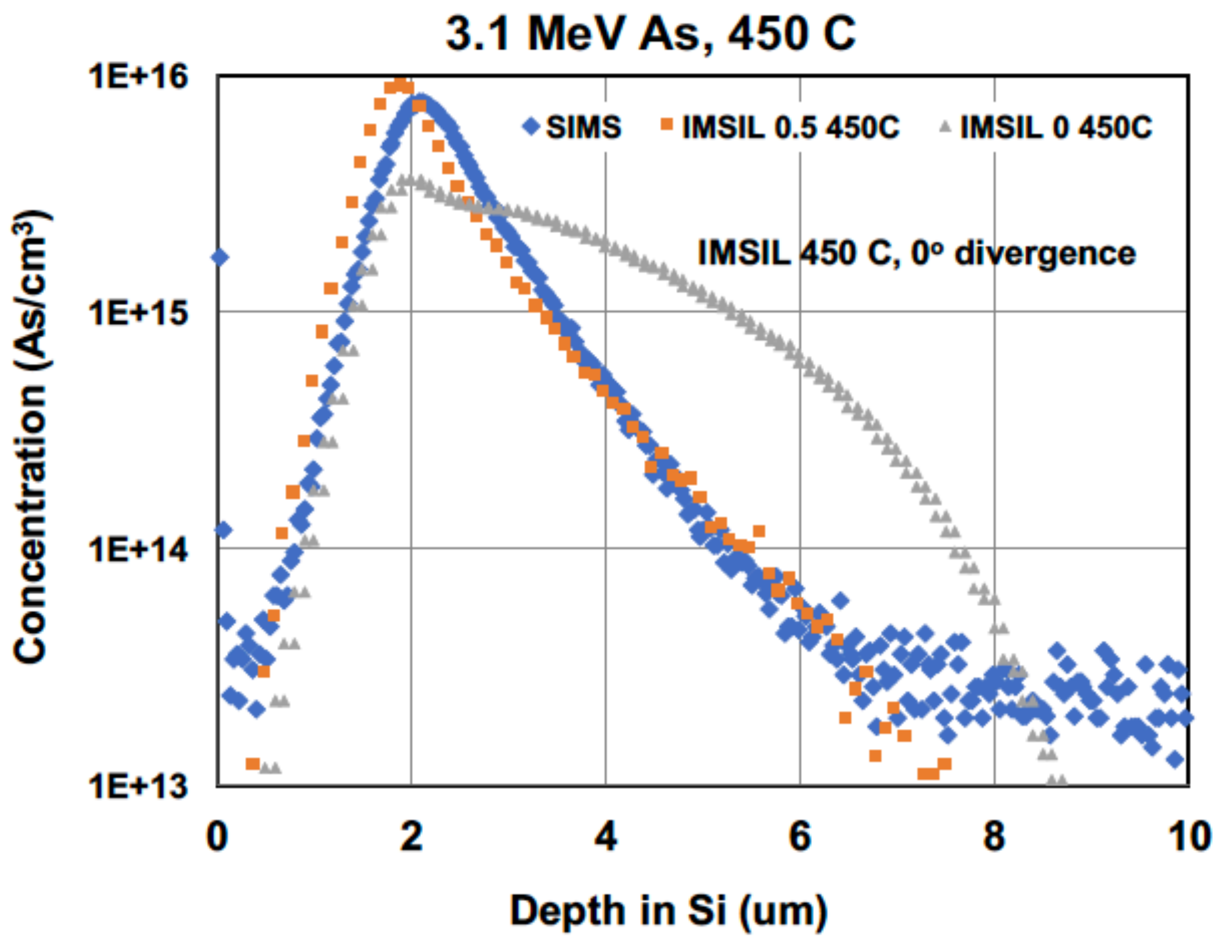
=1.43x10^8*(J_{beam}/Z)*(M(AMU)/E(keV)$^{1/2}$ (1)

where:

- e = electron charge
- Z = ion charge state
- V_{ion} = ion velocity
- E = ion kinetic energy = (1/2)*M*($V_{ion}{}^2$)
- M = ion mass.



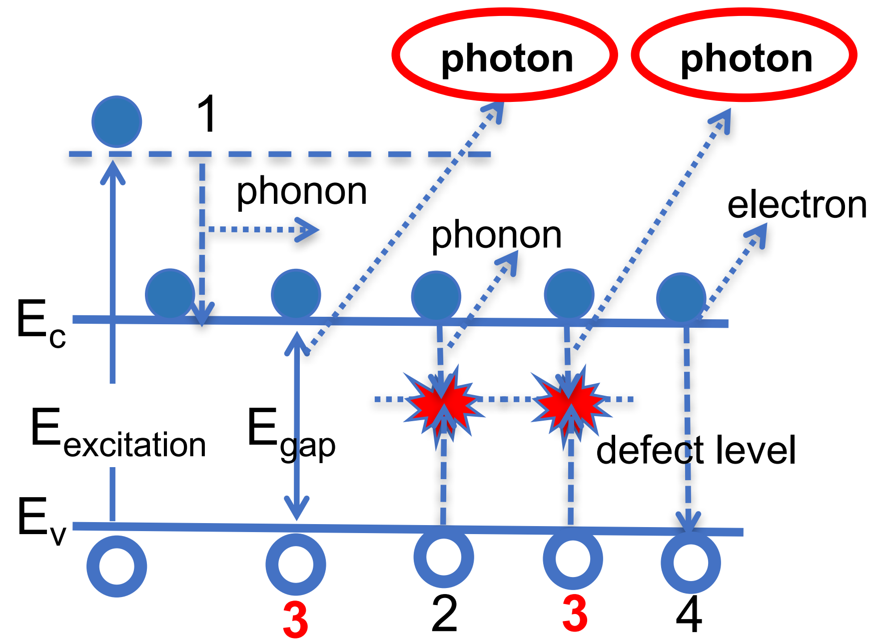
4. Divergence & Temperature Effects



3.1 MeV Arsenic channeled profiles at 450 C, SIMS (symbols), IMSIL (symbols). Dose = 1e12 As/cm^2. IMSIL divergence modeled at 0 and 0.5 degrees

5. Residual Defects: Implant Temperature Effects

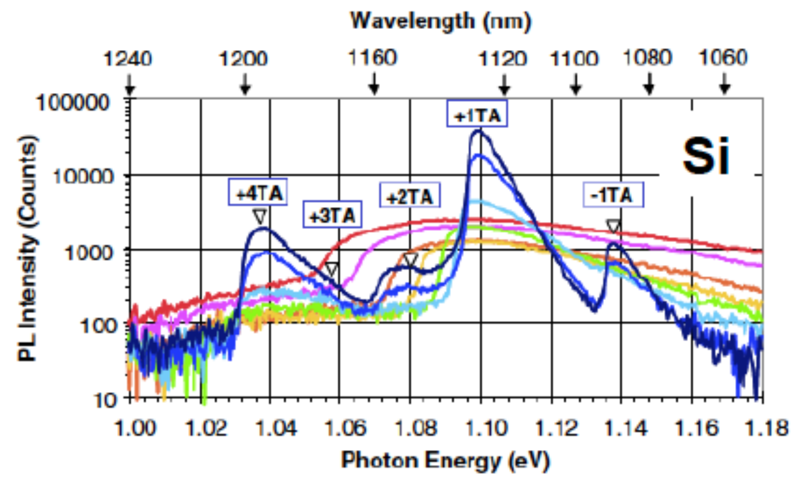
Luminescence Spectroscopy & Imaging



Transitions: Excitation ($E>E_{gap}$)
1.Fast relaxation (phonon)
2.SRH recombination (phonon)
3.Luminesence (photon)
4.Auger (electron)

Excitatons:
Electrons: cathodo-luminescense **(CL)**
Photons: photo-luminescense **(PL)**

Photons:
1. **Phonon-assisted: ≈1.1 eV**
2. **Defect related: <1.1 eV**



ECS Journal of Solid State Science and Technology, 4 (12) P456-P461 (2015)

Temperature Dependence of Photoluminescence Spectra from Crystalline Silicon

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[a] *WaferMasters, Inc., San Jose, California 95112, USA*
[b] *Kyoto Institute of Technology, Matsugasaki, Sakyo, Kyoto 606-8585, Japan*

5. PL Phonon-assisted Signals (≈1.1 eV)

Carrier generation by photons.

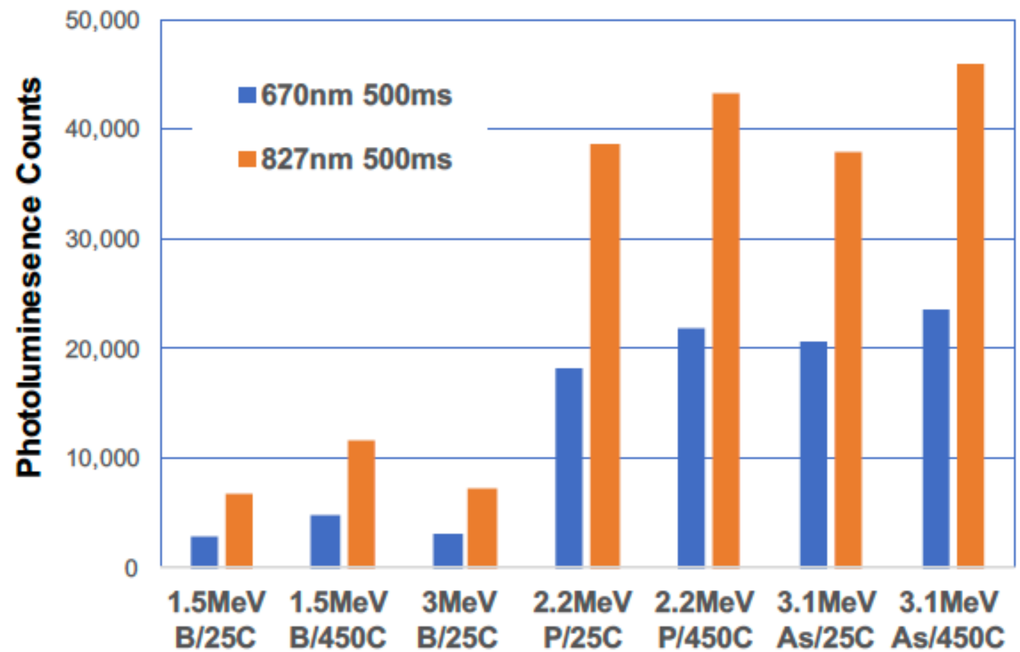
670 nm

827 nm

Full PL spectrum range.

(mostly 1.1 eV)

Room temperature (≈25 C).



<u>Upshot:</u>

1. **Strong defect recombination for B.**
2. **Less defect recombination for 450 C implants (all ions).**

Anneal: 950 C/ 3 min/ N_2 (O_2)

5. CL Spectra: Phonon (TO) & Defect Signals

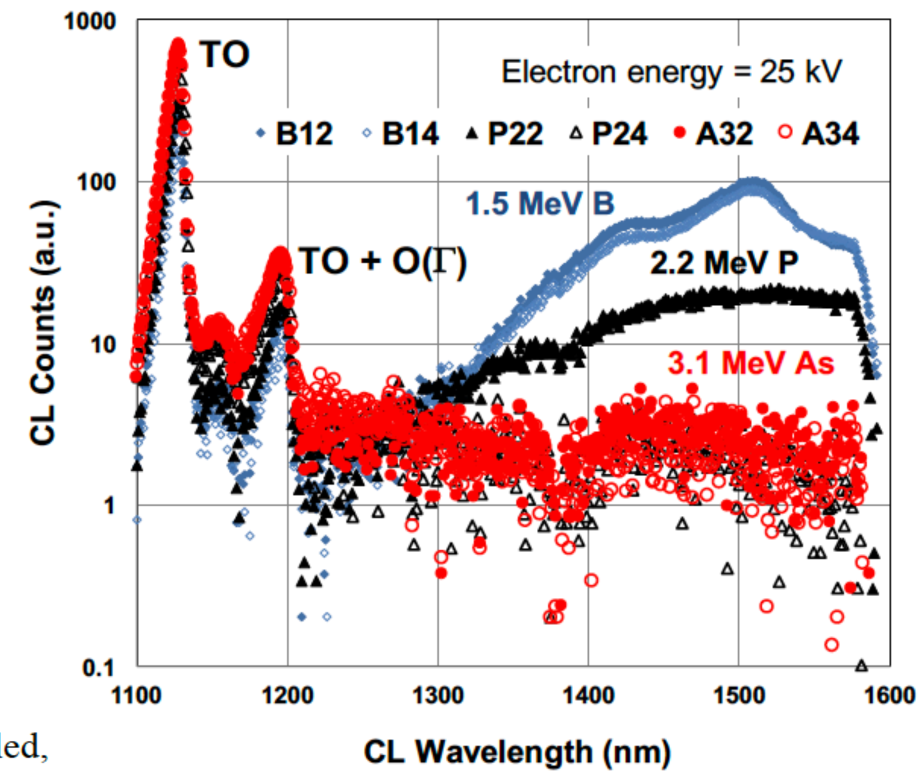
Electron carrier generation.

25 keV electrons;

50% stopping in 1.2-2.4 um

(carriers diffuse deeper before recombination).

Cryo samples: 35 K



Upshot:

1. **Strong defect effects for B.**
   No strong effect for 450 C implants.
2. **Lower defects for P (especially for 450 C).**
3. **Low defects for channeled As.**

Fig. 17. CL recombination spectra (at 35 K) for annealed, highly-channeled implants into Si with 1.5 MeV B (diamonds), 2.2 MeV P (triangles) and 3.1 MeV As (circles) with an electron probe beam energy of 25 kV. Implants at 25 C filled symbols, at 450 C open symbols. Defect-related recombination emission is in the range of 1350 to 1600 nm. Transverse optical emission (TO) peaks are emissions from phonon-assisted (non-defect) recombination from conduction to valance band.

Anneal: 950 C/ 3 min/ N_2 (O_2)

5. PL Defect Imaging (λ >1300 nm)

Photon generated carriers
523 nm

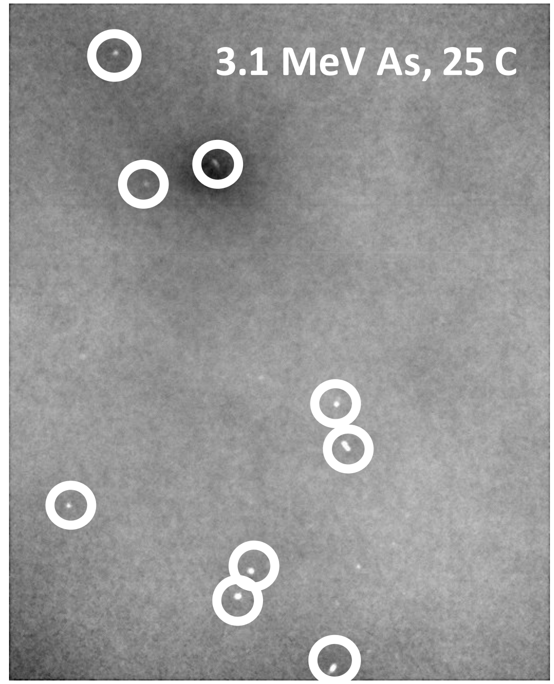
Image collected from >1300 nm.

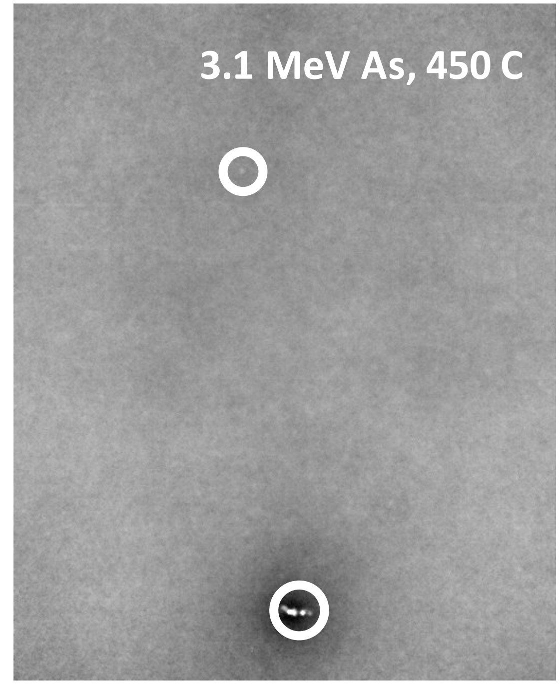
Room Temperature: (25 C).

Upshot:

1. **Dense damage for B (no spots).**

2. **Fewer defects for P & As (especially for 450 C).**

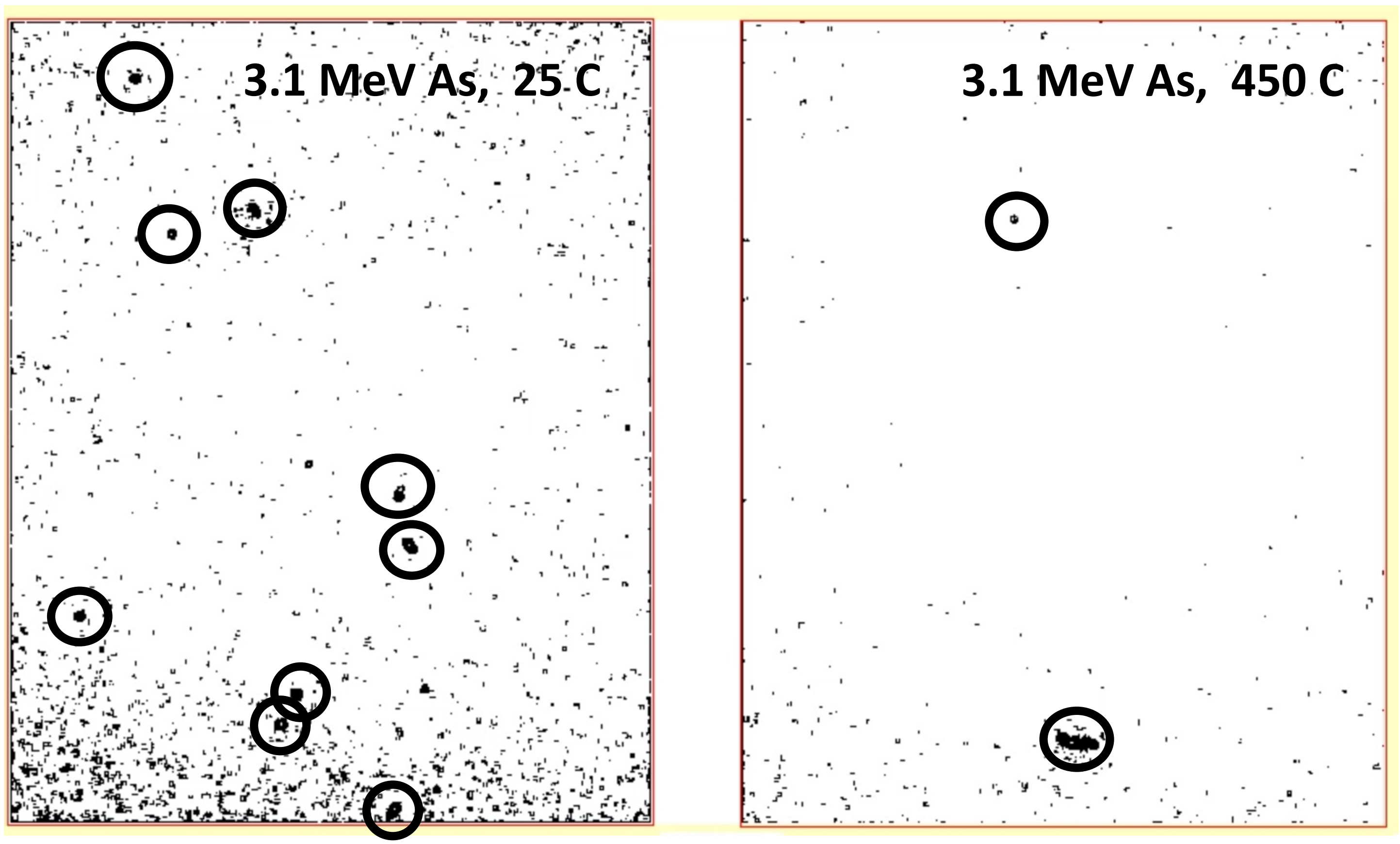




PL-imaged defects at a depth of ≈5 um over a 175x140 um field of view for annealed 3.1 MeV As implants at 25 C (left) and 450 C (right). Defect sites are circled in white.

Anneal: 950 C/ 3 min/ N_2 (O_2)

More PL Imaging.



Images scanned by PicMan (W-S. Yoo).

PL Defects for *non-channeled* 1.39 MeV Phosphorous (6e13 P/cm^2)

For *non-channeled*, higher dose (60x) 1.39 MeV Phos implants (annealed at 950 C for ≈3 min),

increasing the implant temperature from 25 to 500 C *increases* the residual defect density.

So, initial defect density in the as-implanted profile changes the defect annealing behaviors.

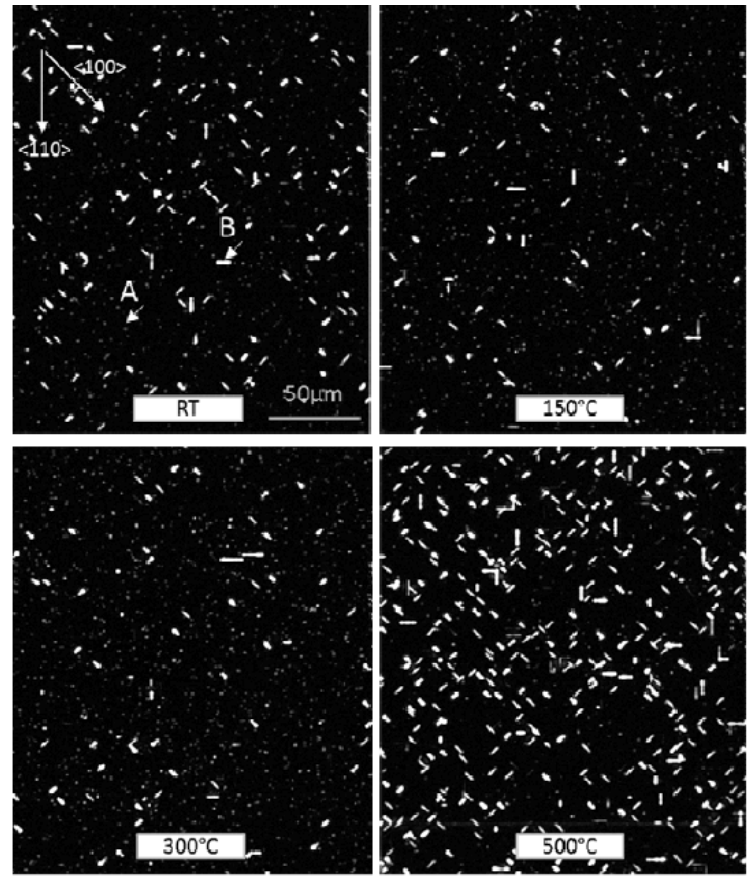


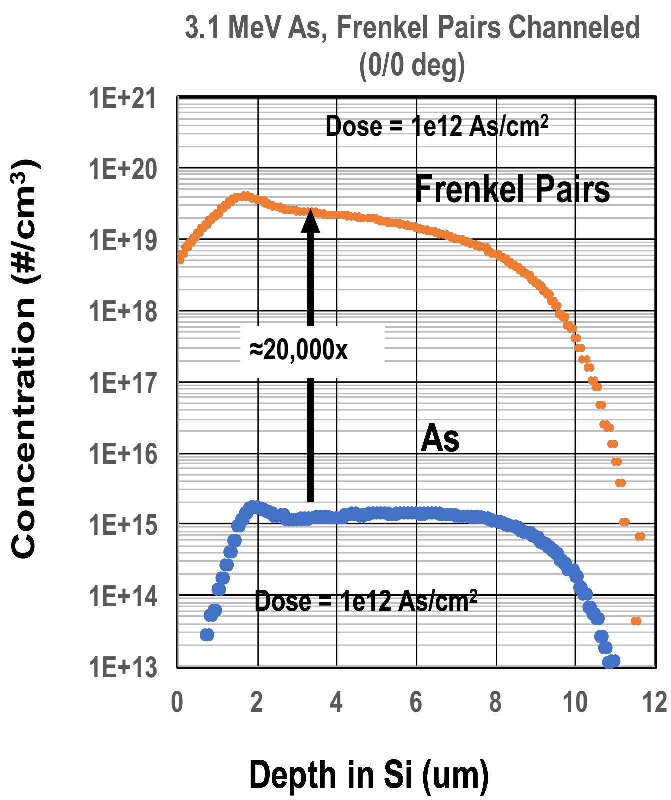
Fig. 4. PL results on Phosphorus 6E13 at/cm² after anneal at 950°C N2/O2 (5%) 3min. Radiative dot and elongated defects are exhibited. Arrow A defined a dot defect, arrow B defined an elongated defect.

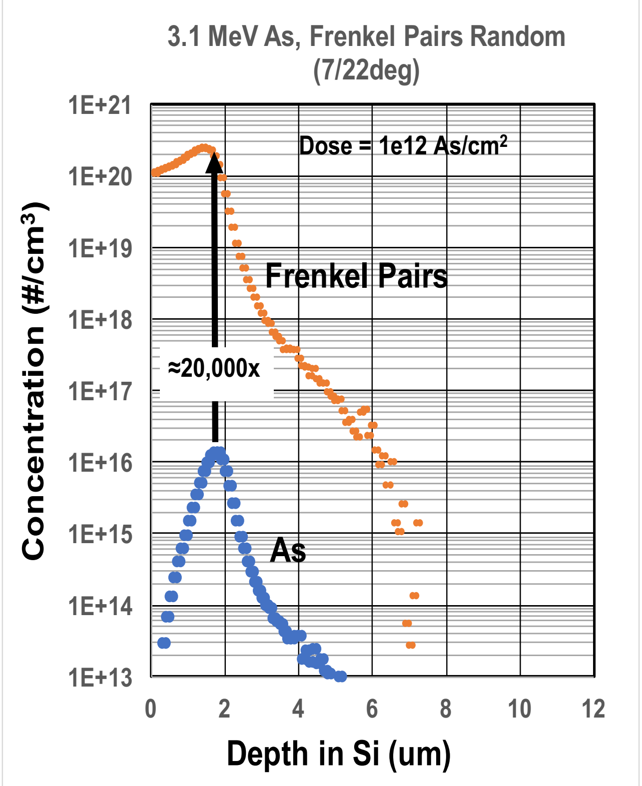
Ref: Sylvain Jablot (STMicro) et al., IIT18.

3.1 MeV As Primary Defect Profiles: IMSIL (25 C)

Channeled FP defects:

1. **are spread out over a much deeper range.**
2. **lower peak defect concentration.**
3. **FPs per ion are similar (≈20k/ion) for both channeled and random incidence.**





Summary:

1. **Actual channeled MeV dopant profiles (SIMS) are not as highly channeled as the IMSIL simulations (with ideal, 0° divergence beams, perfect alignment).**
   **** Further improvements in deep channeled profiles are possible*.**

2. **Channeled implants at 450° C showed increased de-channeling and *evidence of lower residual defect density* (in some cases).**

3. **Effects of beam divergence are significant, especially for heavy, high charge state ions (As^{3+}).**

4. ***MC modeling is a useful tool for process evaluation.***

5. ***Luminescence methods provide valuable defect measures.***

Acknowledgements:

SMIT (implants): M. Sano, H. Sasaki, S. Ninomiya, T. Bergman

Nanostructures (annealing): P. Mauger

WaferMasters (PL spectra): W-S. Yoo

Panasonic & Toray (CL spectra): Y. Sato, R. Sugie, S. Shibata

SemiLab (PL imaging): V. Samu, G. Rududvari, G. Nadudvary

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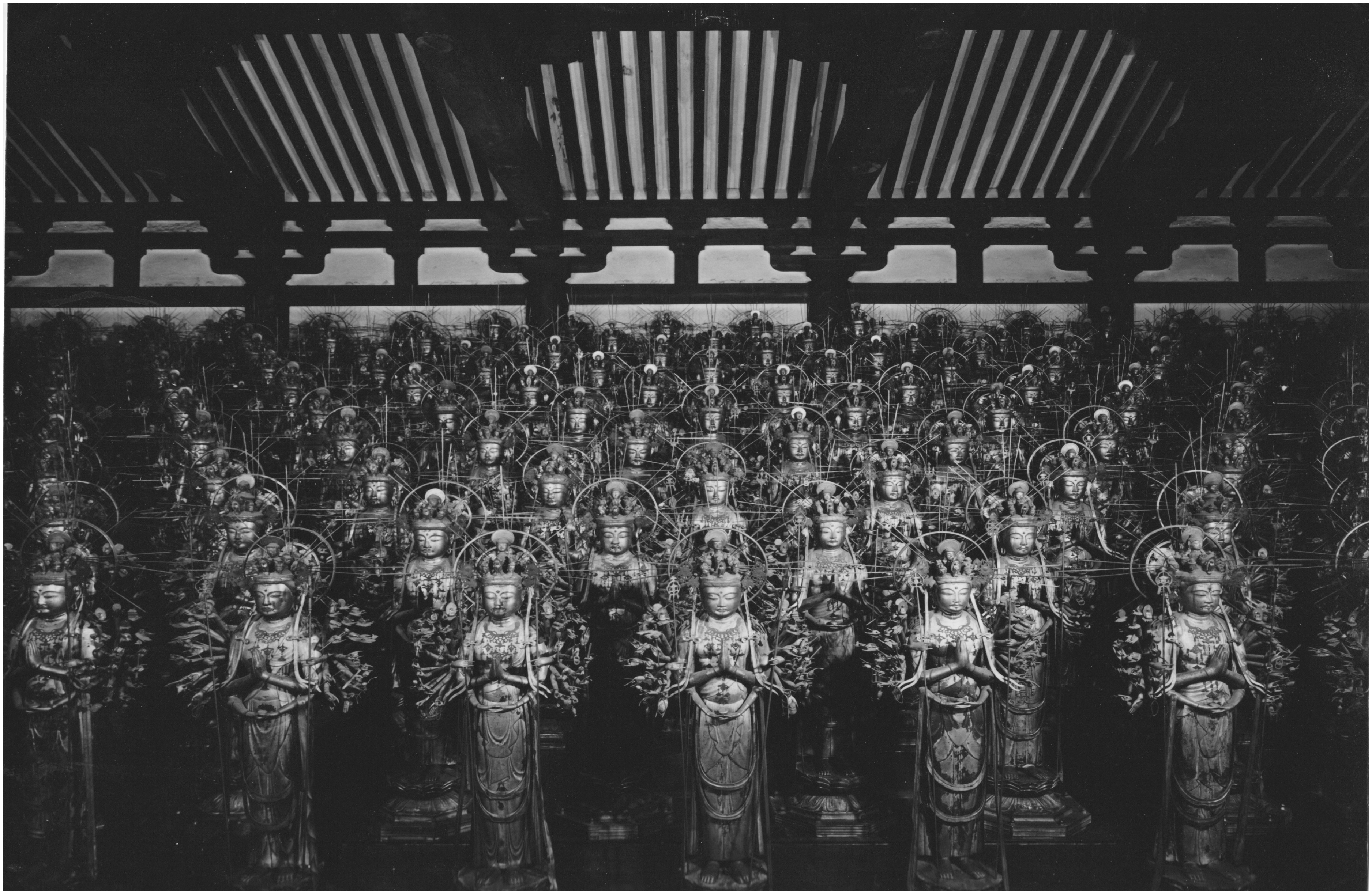
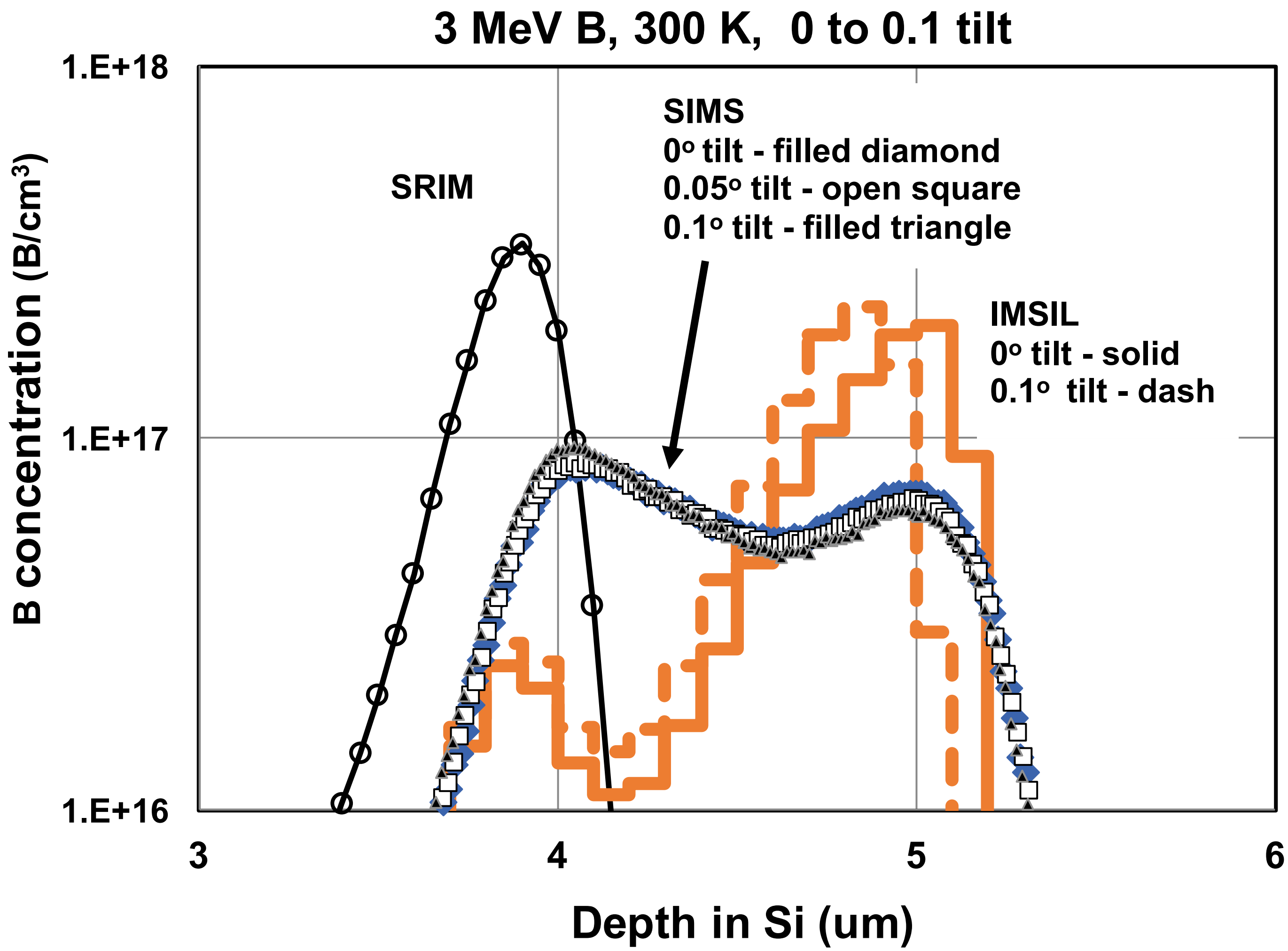
6. **Summary**

IIT 2020: San Diego, CA

- **Conference:** Sunday - Thursday, **Sept. 20-24, 2020**
- **School:** Thursday - Saturday, **Sept. 17-19, 2020**
- Location: U.S. Grant Hotel, 326 Broadway, San Diego, CA
- Co-Chairs: Mitch Taylor, Susan Felch, Aaron Vanderpool, Wilfried Lerch, Larry Larson
- **General topics: implant/doping and annealing technologies, processes, device applications, equipment, metrology, and modeling**
- **Abstracts due: May 2020**
- Administrative support: Materials Research Society (MRS)
- Everyone must opt in via MRS website to receive conference information (EU GDPR. Privacy rules)
  - Create MRS account at www.mrs.org/alerts
  - Conference will be listed at www.mrs.org/meetings-calendar
  - IIT2020 website will be active in July 2019
- For additional information, contact Susan Felch at sfelch@sbcglobal.net



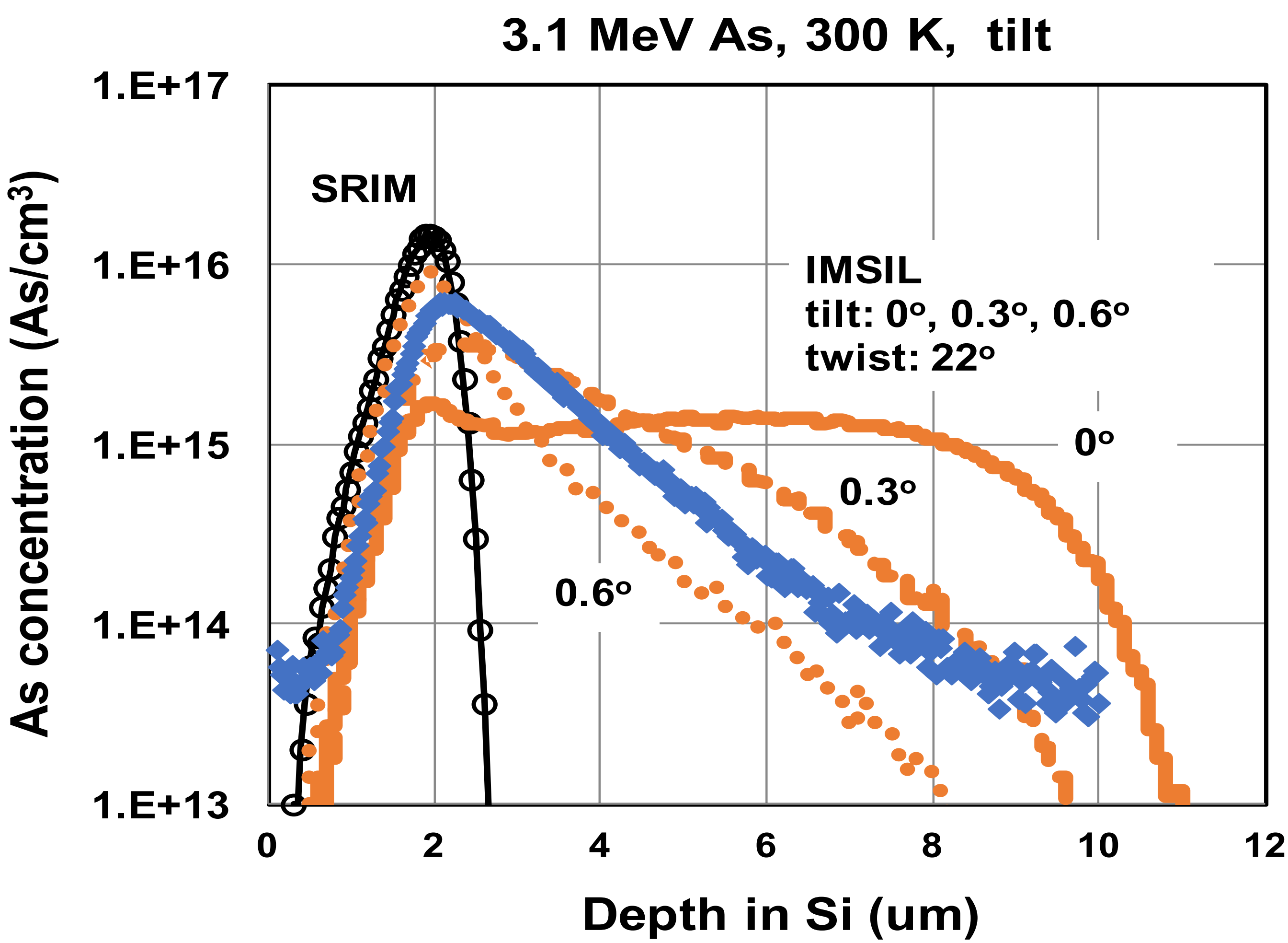
4. Tilt effects: Boron



3 MeV B, tilt= 0, 0.05, 0.1°, SIMS (symbols), IMSIL (0, 0.1°, histograms) and SRIM (amorphous Si, circles). Dose = 1e13 B/cm².

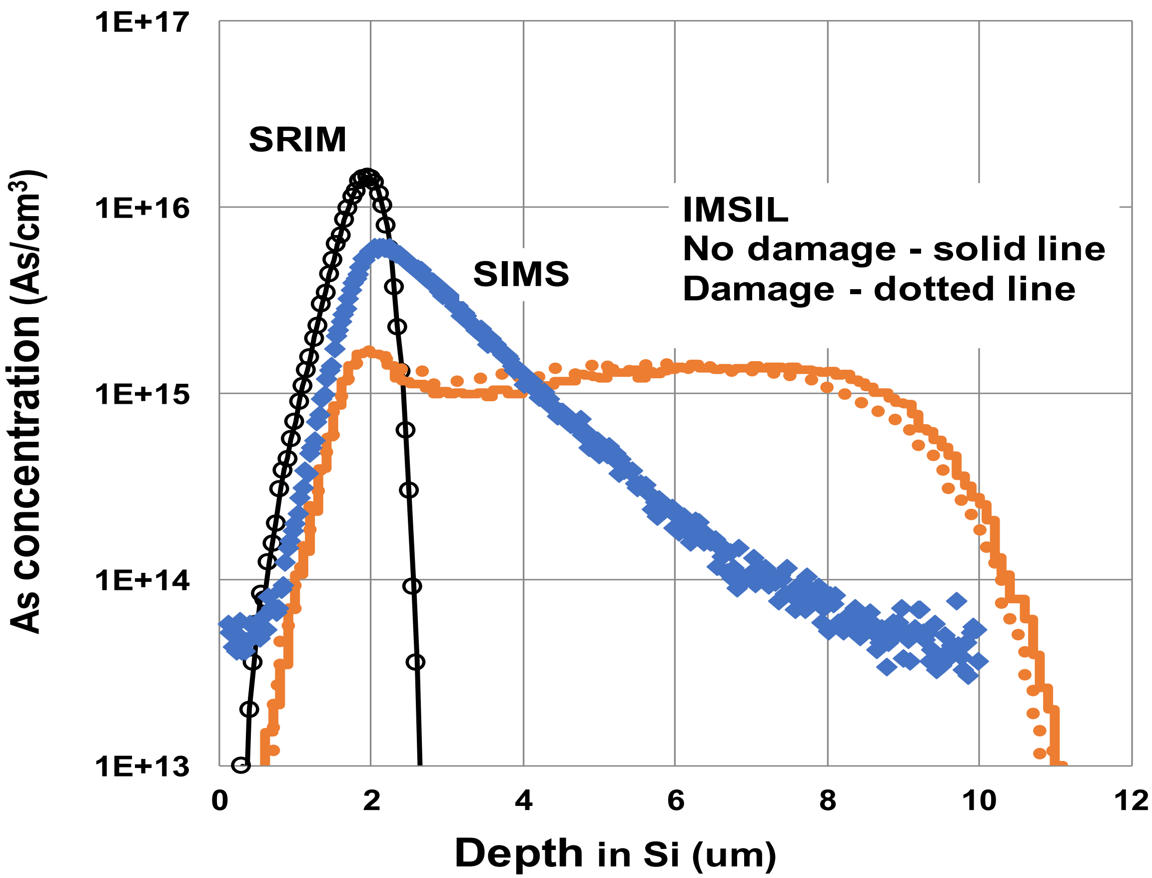
IWJT2019

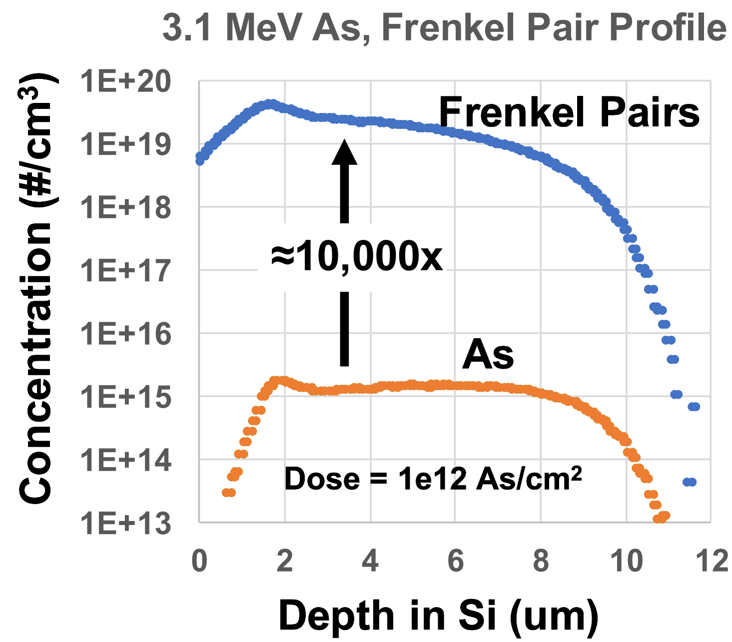
4. Tilt effects: Arsenic



3.1 MeV Arsenic channeled profiles, (SIMS (at 0° tilt, symbols), IMSIL (0, 0.3 and 0.6° off axis, 22° degree twist, histograms), SRIM (open circles, amorphous Si). Dose = 1e12 As/cm².

5. Damage effects: Arsenic





3.1 MeV Arsenic channeled profiles, SIMS (symbols), IMSIL with and without damage accumulation, (histograms), SRIM (open circles, amorphous Si). Dose= 1e12 As/cm^2