Metrologies to Study Ion Implanted Semiconductor Materials

Temel Buyuklimanli

Eurofins | EAG Laboratories

Formerly Evans Analytical Group,

Formerly Charles Evans Assoc. And Evans East

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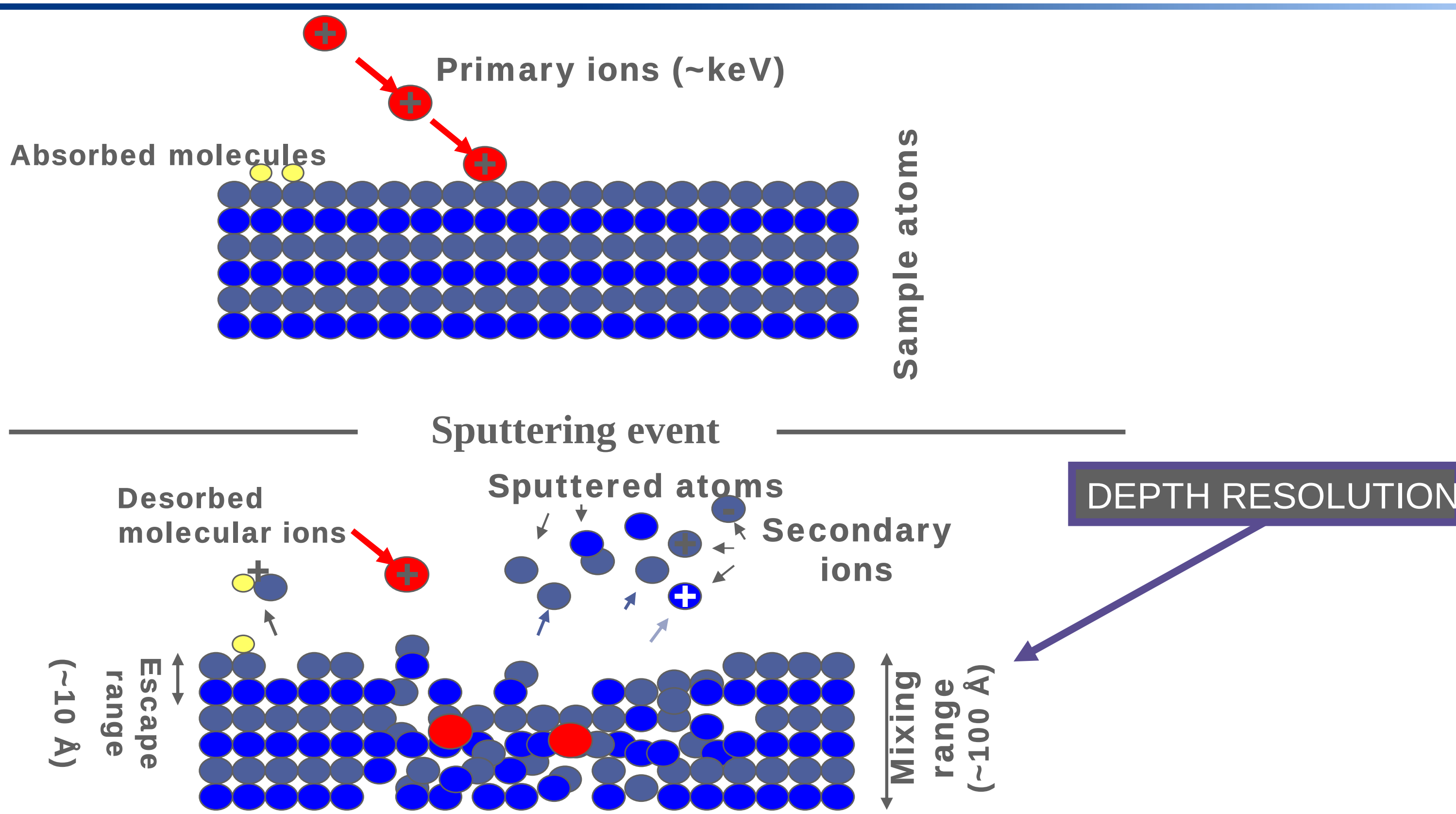
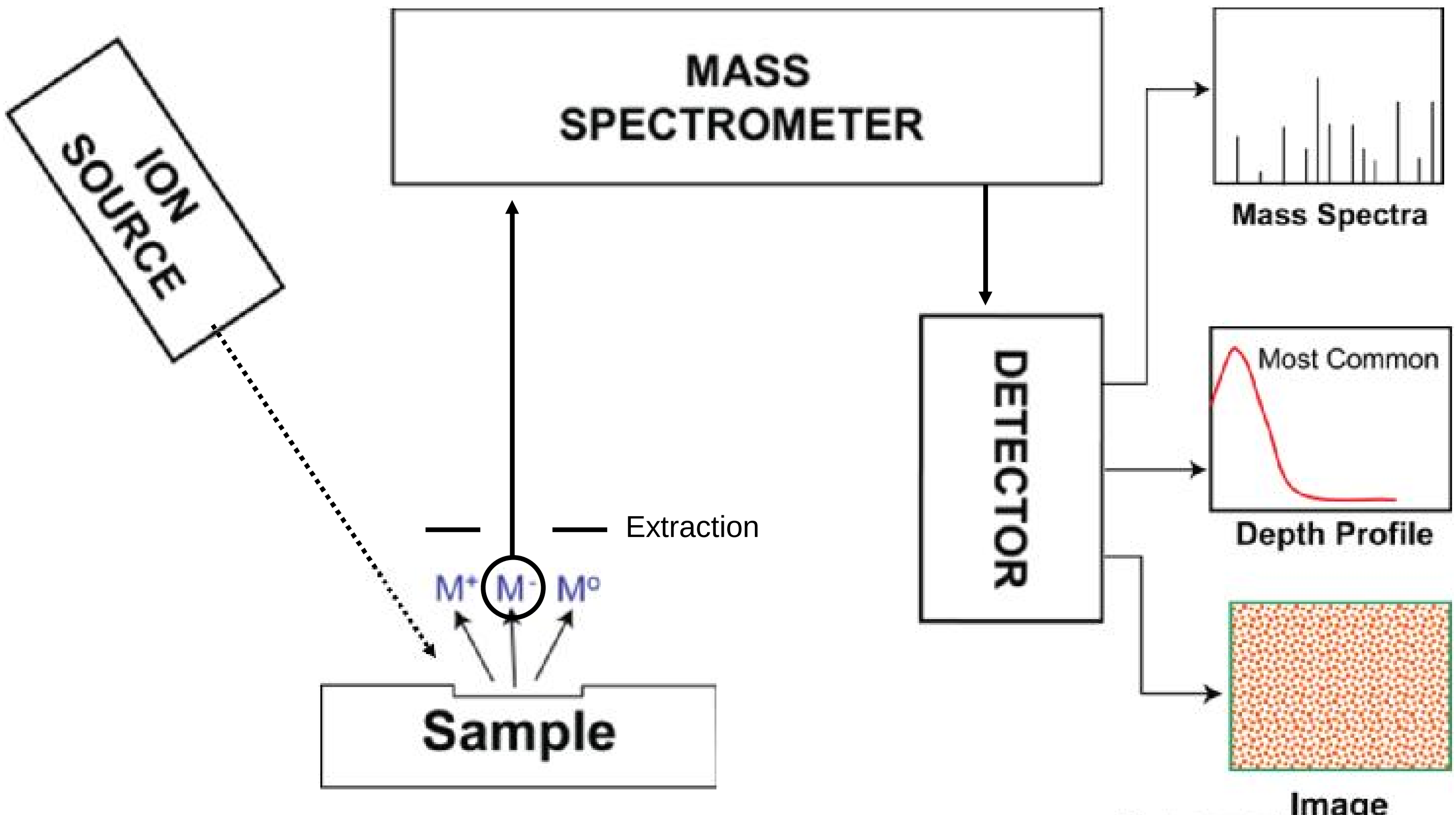
Ion Implant & SIMS
A Marriage of Necessity

- Why does Ion Implant need SIMS?
  - To determine implant profile shape and dose
    - Used to help understand ion-solid interactions
    - Used to develop annealing schemes
  - To match implant tools
  - To determine energy impurities
  - To determine surface and implanted elemental impurities

Basic Sputter Process in Dynamic SIMS

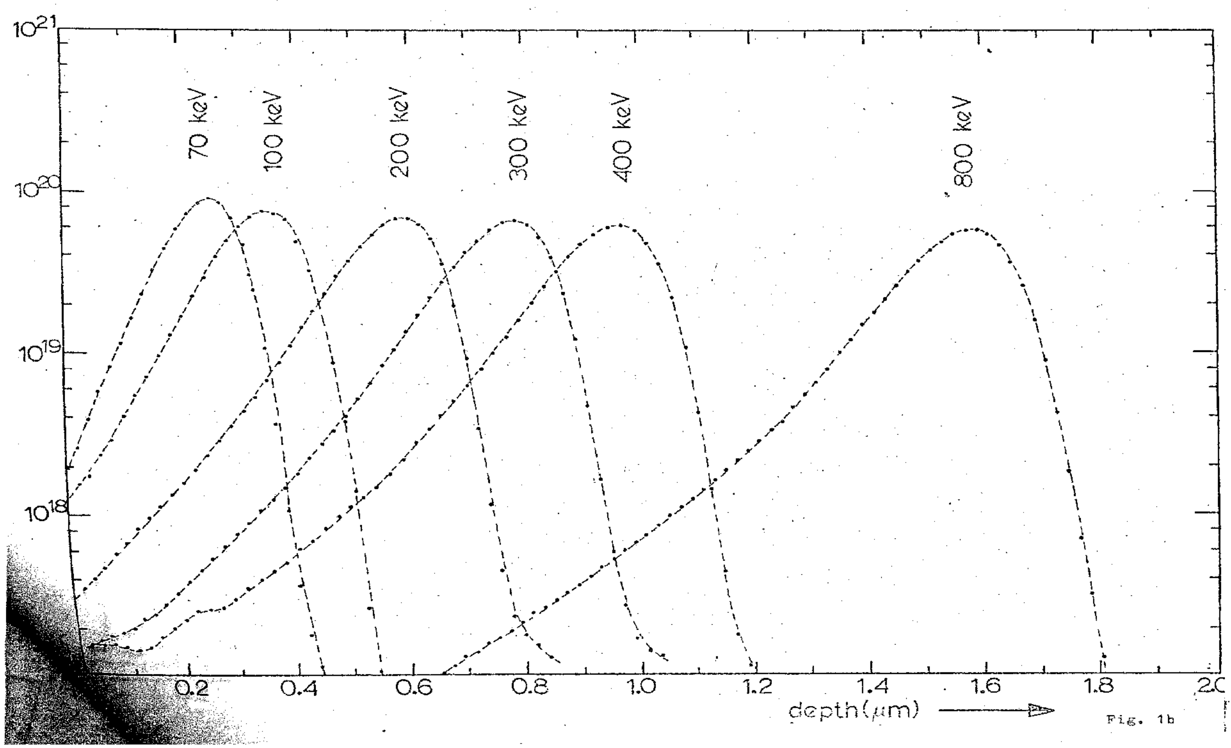


Basic SIMS Detection



Early Boron Implant Profiles Circa 1970s

Asymmetric profile shape was initially not believed by the implant community!

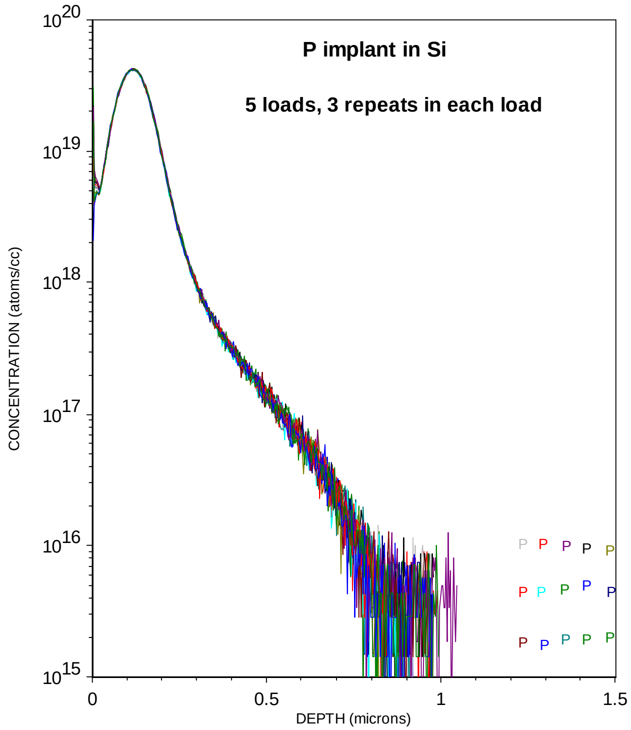


Courtesy of Charles W. Magee

Why Ion Implant Needs SIMS

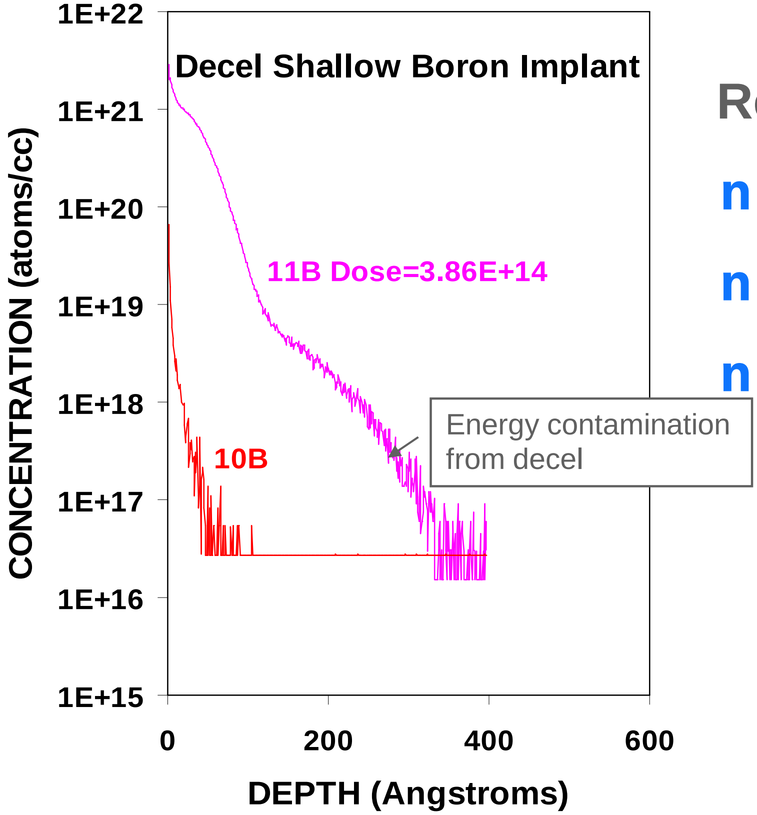
- Determination of absolute implant dose
  - While all implant tools are spec'ed for implant uniformity, they are NOT spec'ed for accuracy of absolute dose.
  - SIMS can provide this information for B, P and As in Si through use of
    - NIST (National Institute for Standards and Technology) Standard Reference materials for these elements
    - and HPIC (High Precision Implant Characterization) protocol

Tool Matching Analysis
with High Precision SIMS Depth Profiling



- This HPIC experiment shows SIMS profiles from 5 pieces cut from the center of an implanted wafer, analyzed in 5 different loads, with 3 repeats for each load.
- These results demonstrate a precision of 0.17% RSD for the total dose.
- Dose differences of <2% can be measured.

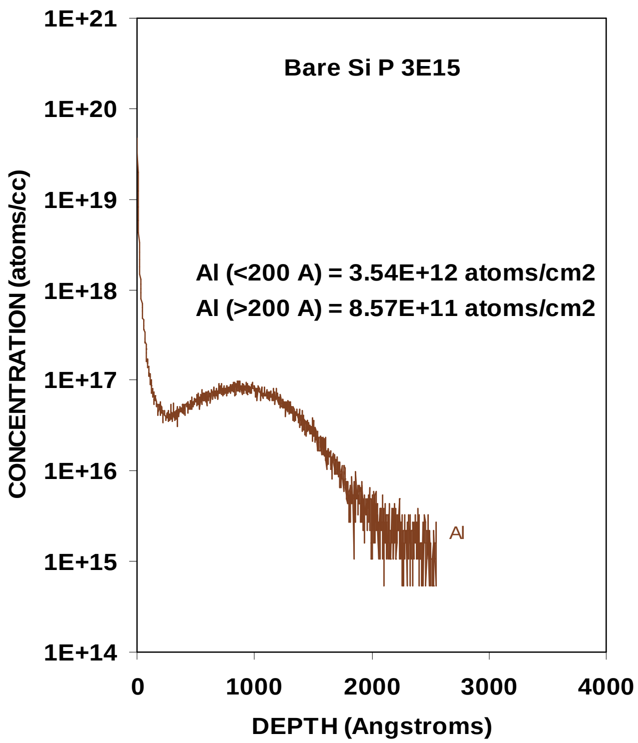
Energy Contamination Analysis with SIMS Depth Profiling



Requirements:

- High depth resolution
- High dynamic range
- Low memory effect

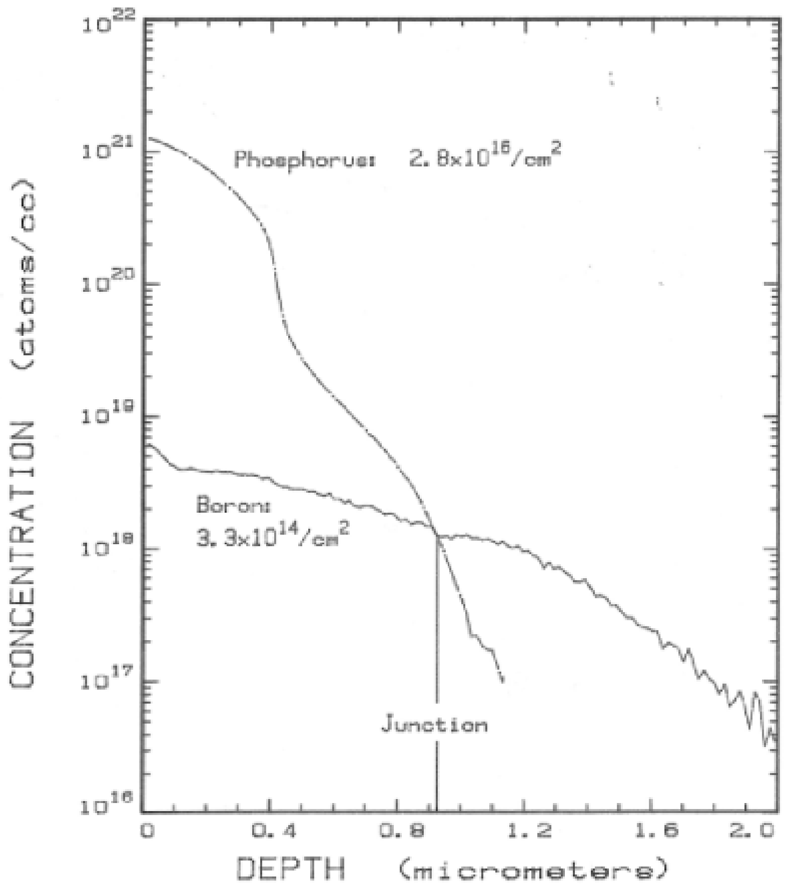
Energetic Metal Contamination Analysis with SIMS Depth Profiling



SIMS depth profile showing aluminum energetic contamination from a phosphorous implant.

1970's Junction Depth Determination

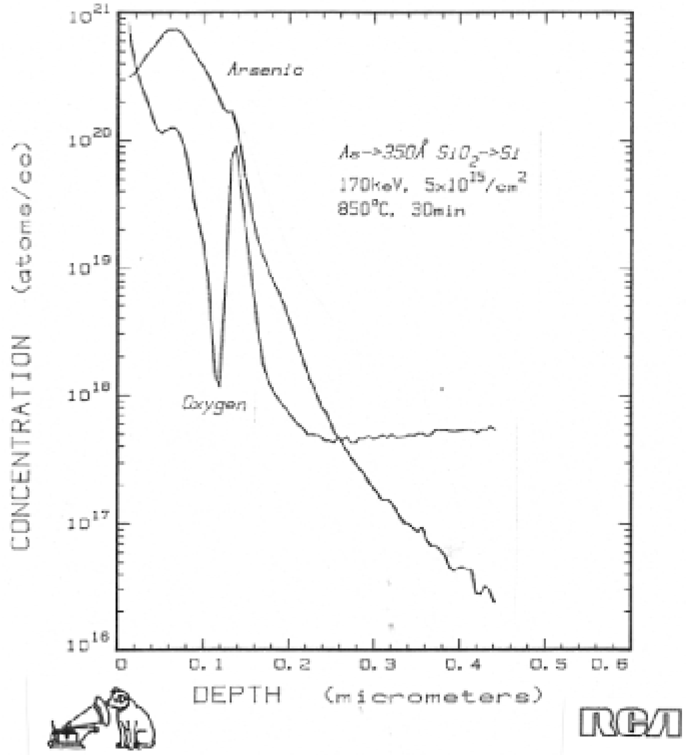
- Furnace-annealed B and P implants to form PN junction
- B profile shows the "emitter suck effect" as evidenced by the dip exactly at the junction
- Electrical measurements such as SRP would show only the net carrier concentration, not the individual p and n-type dopants



Courtesy of Charles W. Magee

Optimizing Annealing Schemes

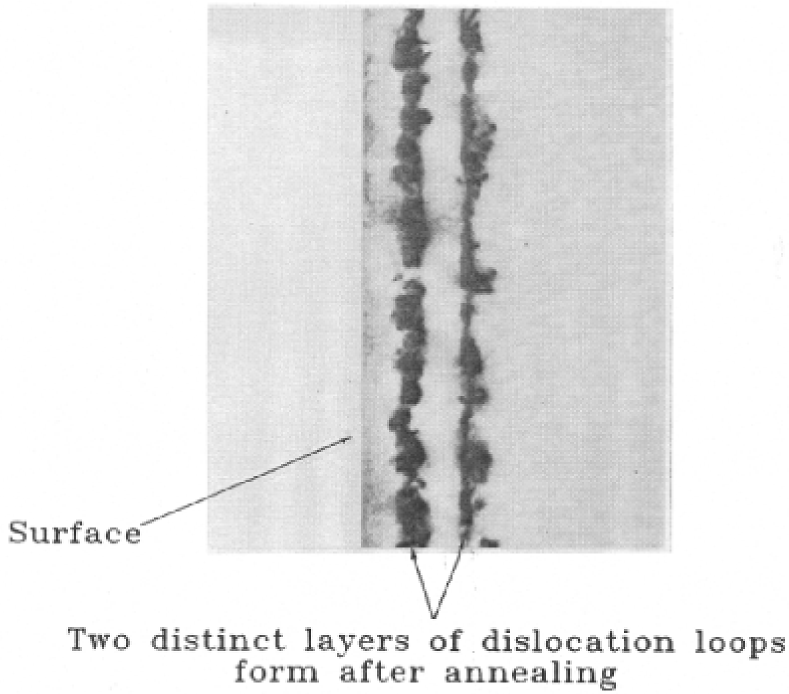
- SIMS profile of a late 1970's furnace anneal of an As implant made through a screen oxide
- We see redistribution of the As near the top of the peak
- We also see peaks in the oxygen profile.
- Are these features related to defects?
- Let's do TEM



Courtesy of Charles W. Magee

Optimizing Annealing Schemes

- Here is the TEM image of the same sample
- How are these defect bands are related to the arsenic profile?
- Did any of the oxygen from the screen oxide become incorporated into the defects after the anneal?



Courtesy of Charles W. Magee

Optimizing Annealing Schemes

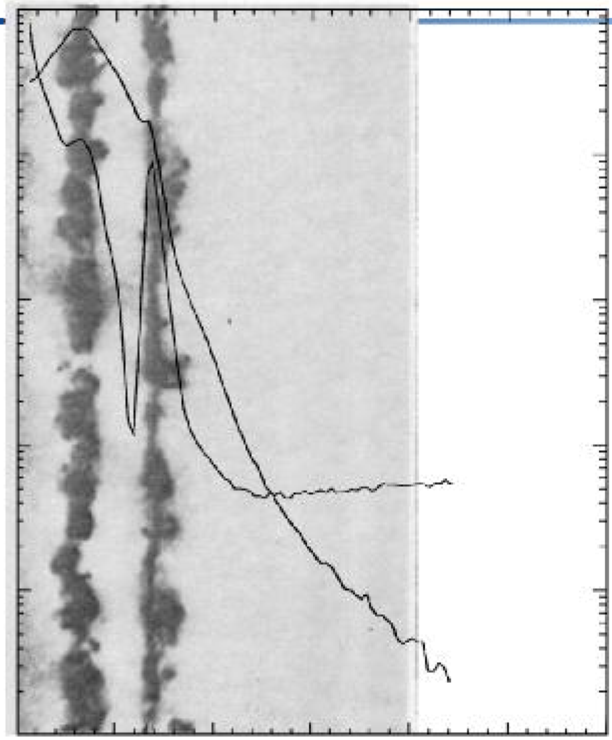
- So…let's put these two sides together!.

Optimizing Annealing Schemes

SIMS and TEM *together* show that:

•the inflection in the As profile was due to decoration of a layer of dislocations

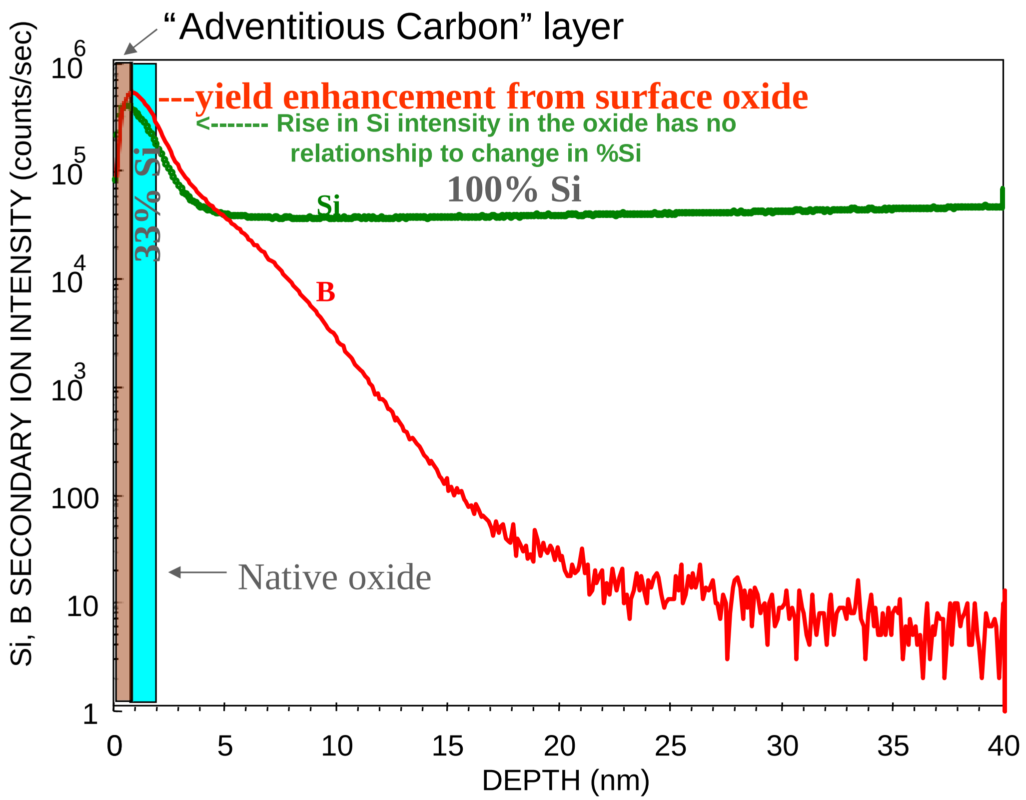
•The two peaks in the oxygen profile were both due to decoration of layers of dislocations



Courtesy of Charles W. Magee

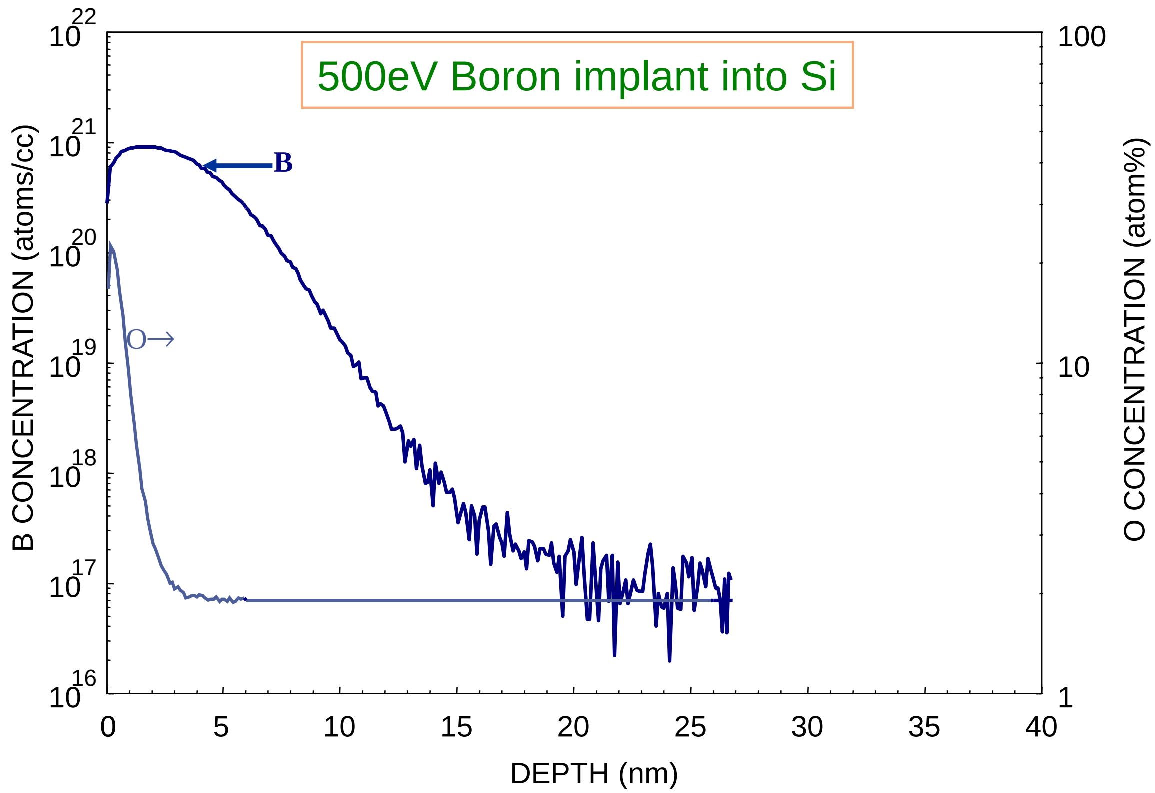
SIMS Characterization Development of Shallow B Distributions in SiO_2/Si

Boron Implanted into Si with Native Oxide



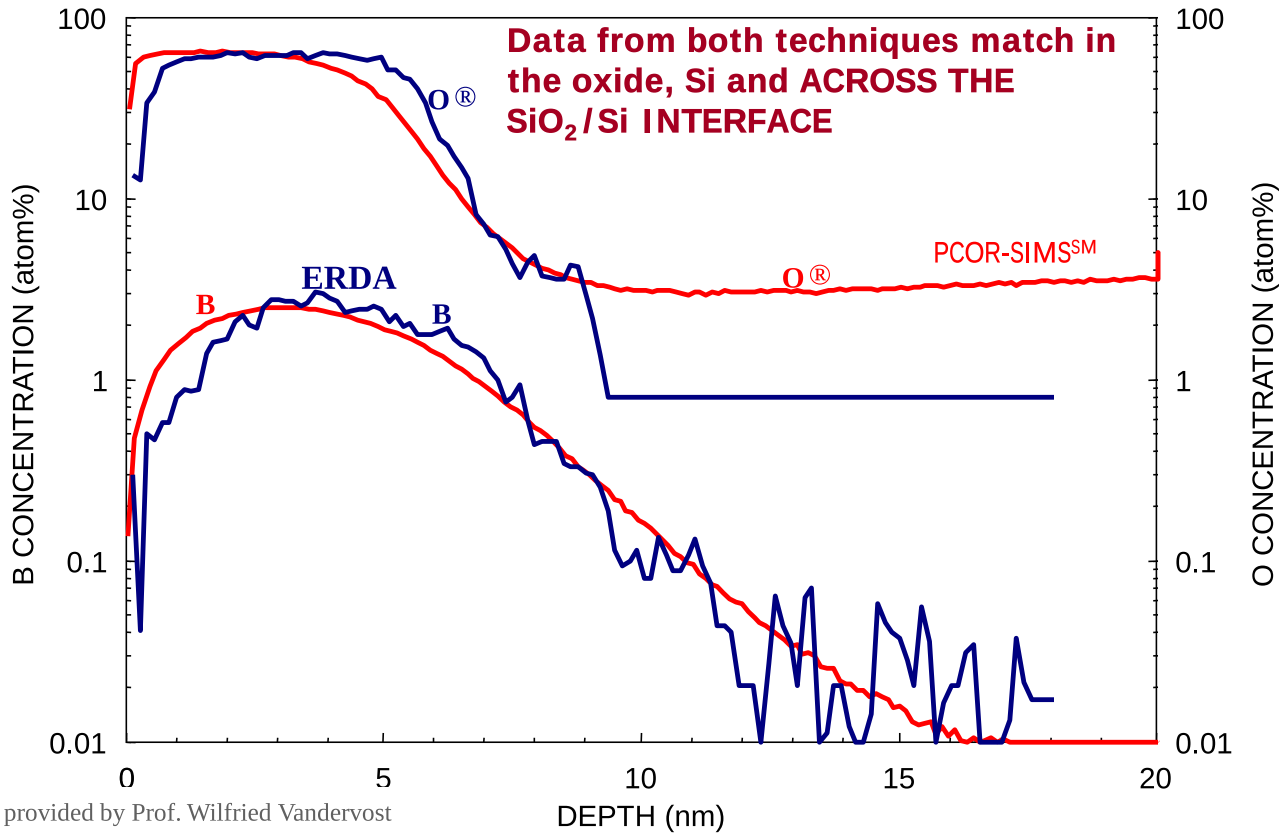
Boron Implanted into Si with Native Oxide Quantified Data

PCOR-SIMS[SM]



PCOR-SIMS[SM] and Elastic Recoil Detection Analysis (ERDA) data comparison

500eV Boron implant into SiO_2/Si



ERDA data provided by Prof. Wilfried Vandervost

500eV B ion Implantation Comparison

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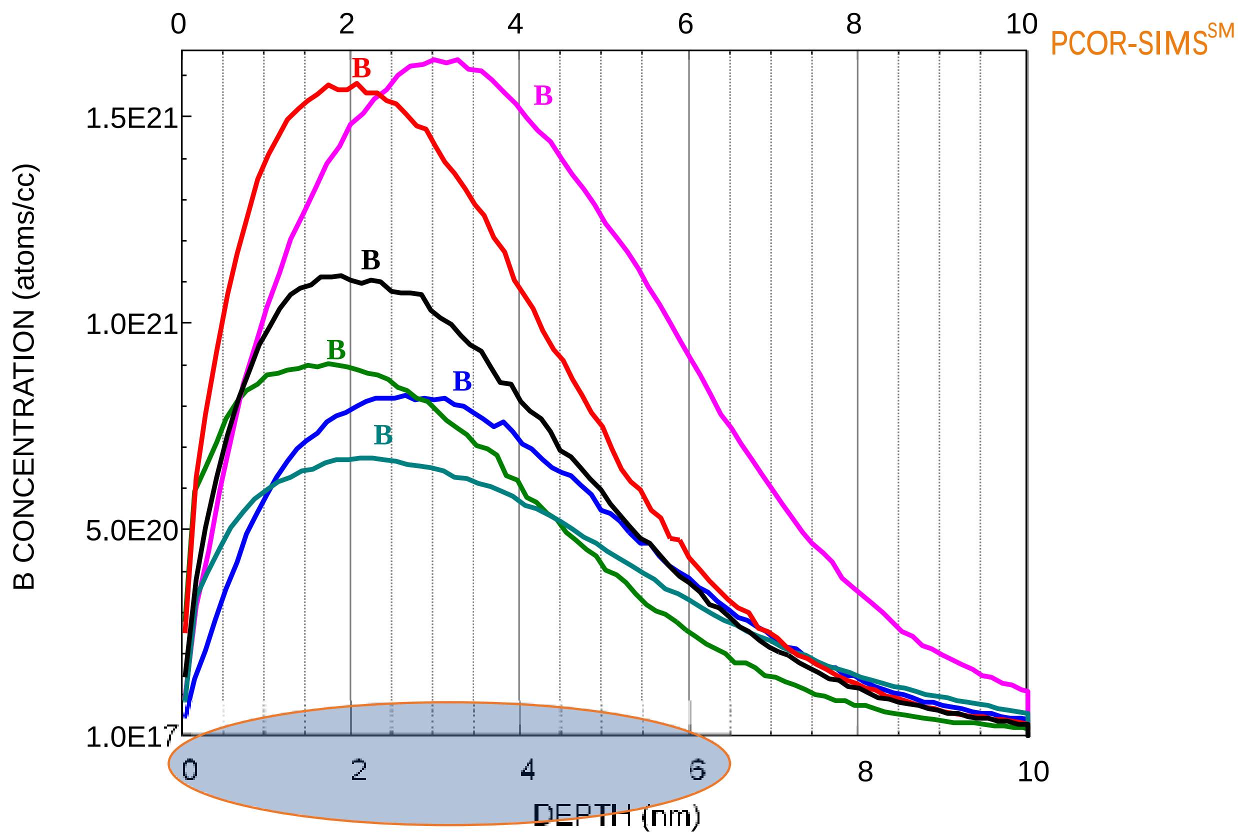
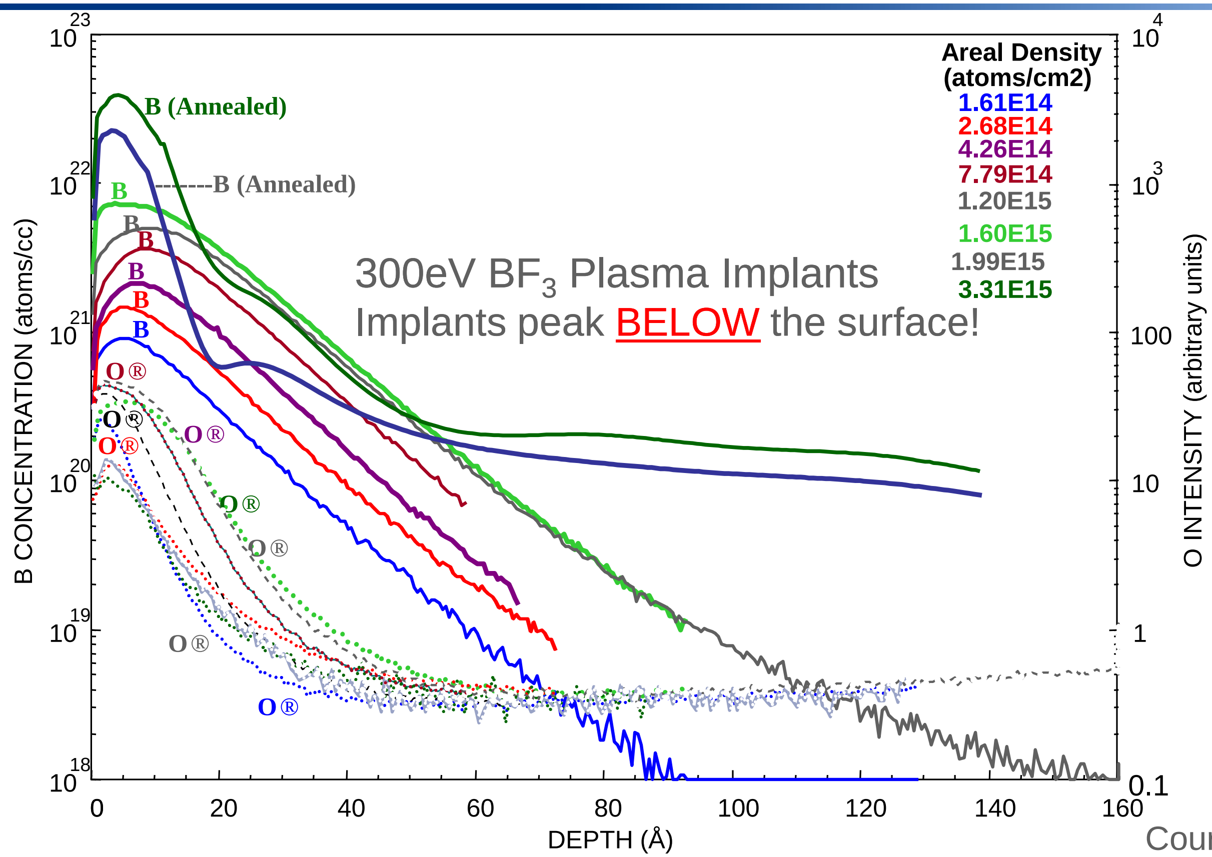


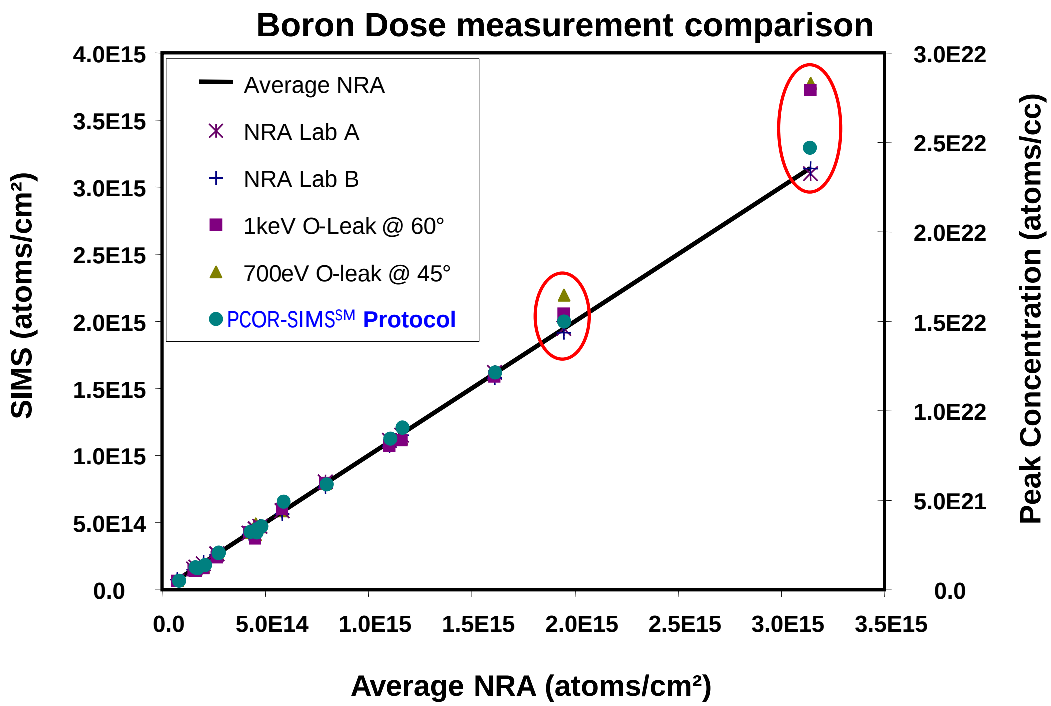
Quantification challenges in plasma doped Si with atom % level B

NRA test of High Dose Implants

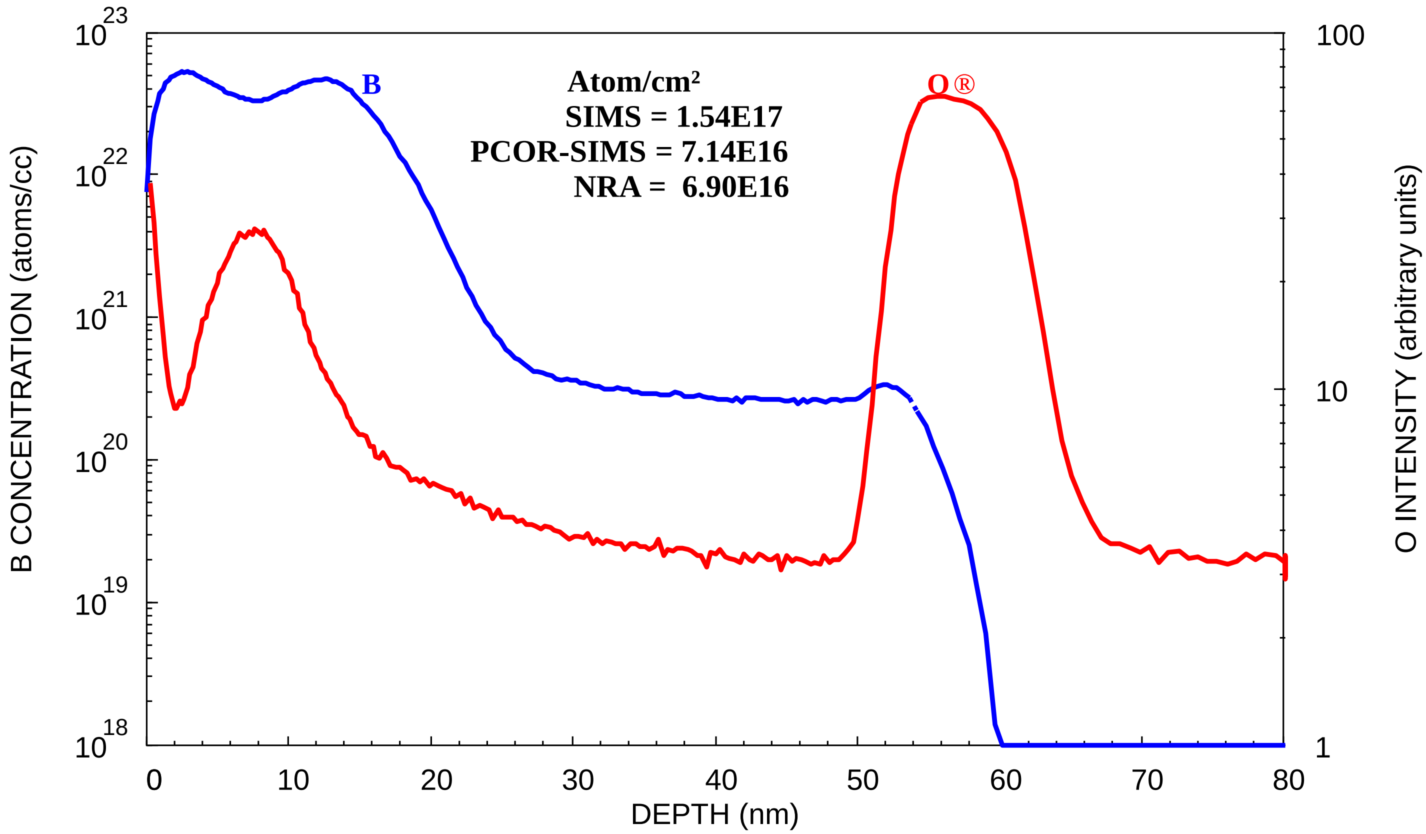


Courtesy of Dan Downey

Dose measurement comparison
2 Independent NRA labs, 3 SIMS protocols



PLASMA DOPED Poly-Si
Dose measurement comparison



PLASMA DOPED Poly-Si

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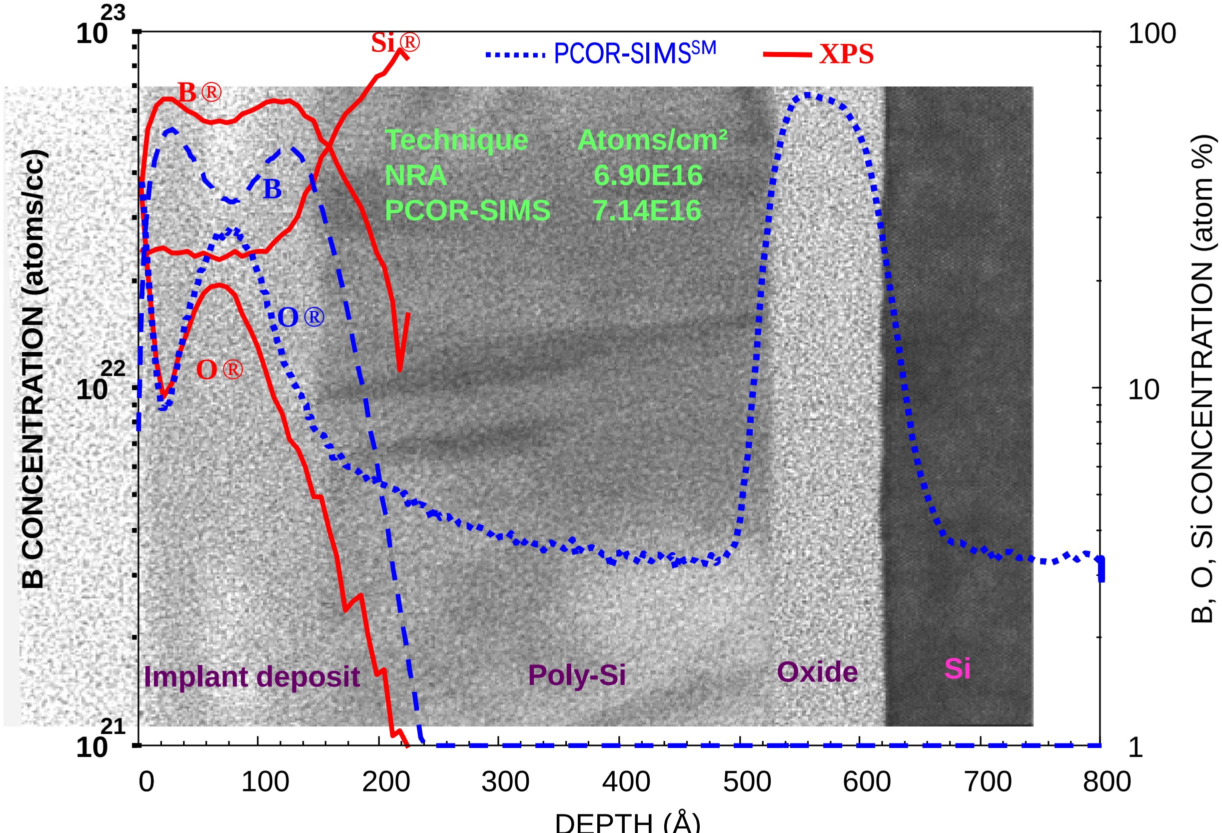
Dose measured by PCOR-SIMS agree with NRA.

The XPS confirms the dip in the PCOR-SIMS B data in the 6nm region.

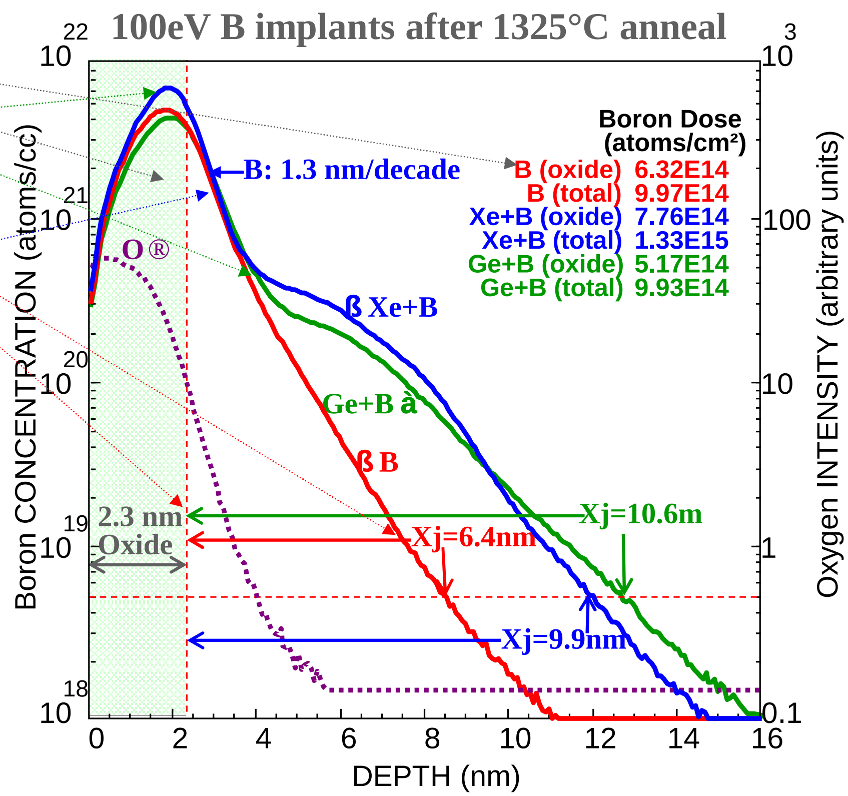
In addition, the high concentration B region, poly-Si and SiO_2 layer thicknesses agrees between the PCOR-SIMS and TEM data.



PCOR-SIMS^{SM}
MOST ADVANCED SIMS ANALYSIS PROTOCOL

Information provided by PCOR-SIMS^{SM}

- **Dose loss in oxide**
- **Inactive excess B concentration**
- **Xj measured from the oxide/Si interface**
- **Profile abruptness**

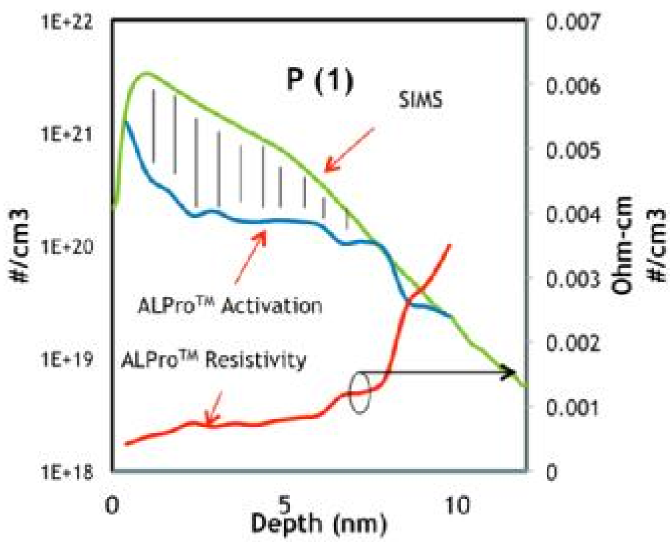


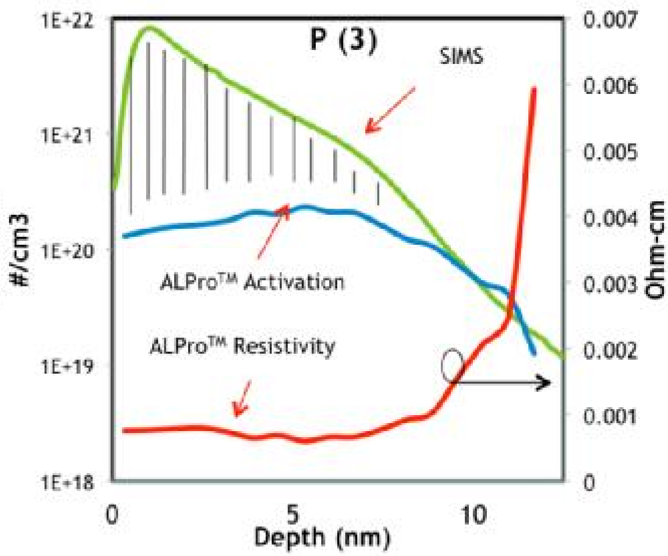
Active Dopant profiling using Differential Hall Effect Metrology

Example: <10nm shallow P in Si for S/D

Goal: *Measure details of dopant activation in the top 10nm of P-doped epi-Si films processed under different conditions.*

Dose P(3) = 3x Dose P(1) + millisecond anneal (MSA) conditions

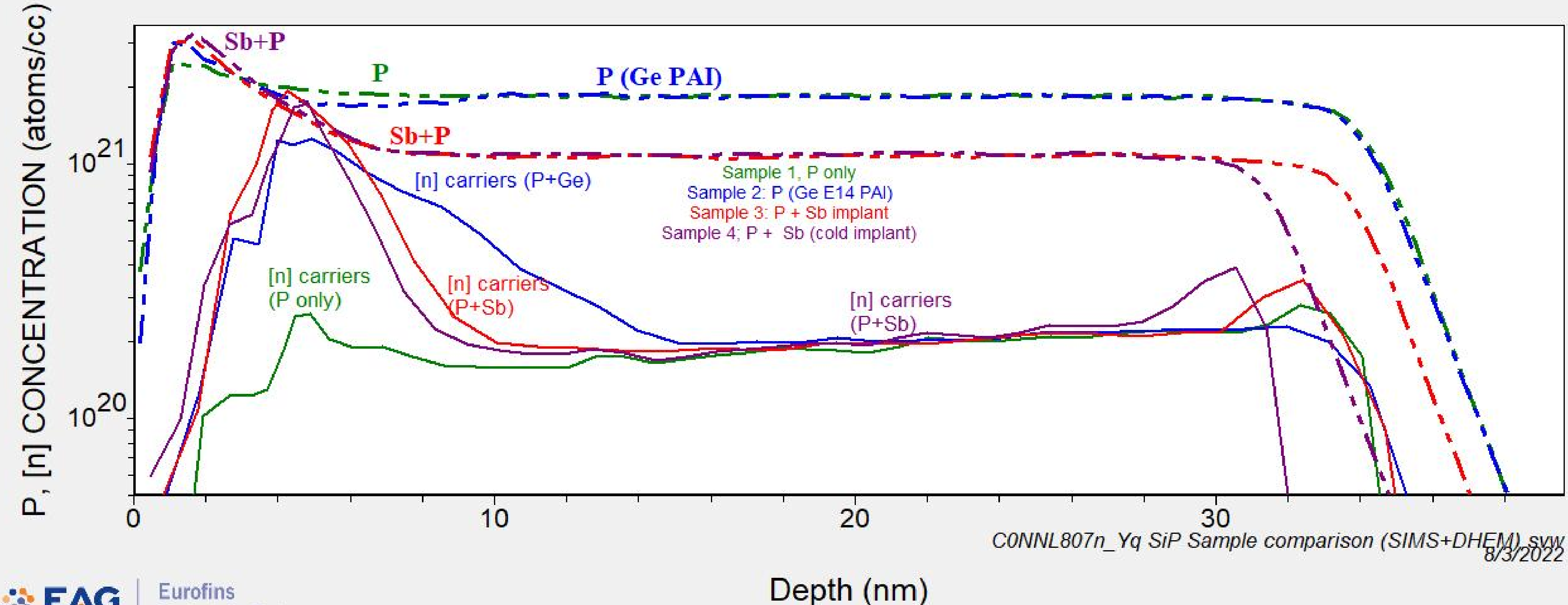




Result: *Different surface dopant activation was detected for samples processed under two different conditions. Higher dose dopant yielded lower carrier concentration.*

Dopant activation with Sb and Ge added to Si:P

Courtesy of Varian/AMAT



Challenges with Mg doping for p-type contact for GaN

SIMS depth profiles of Mg implanted GaN Before and after anneal

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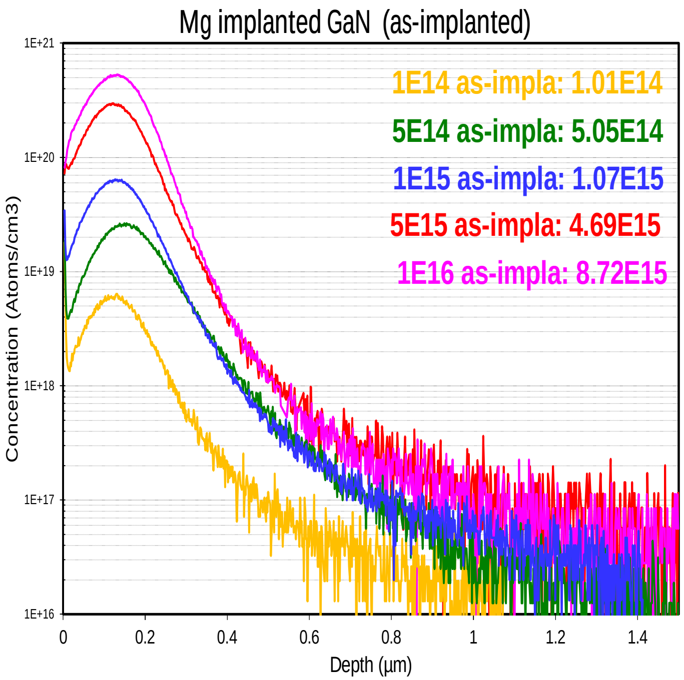
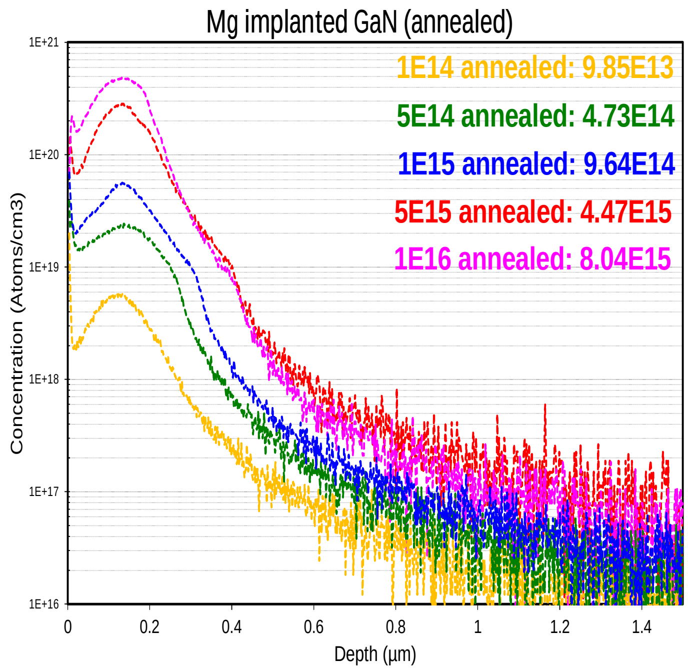
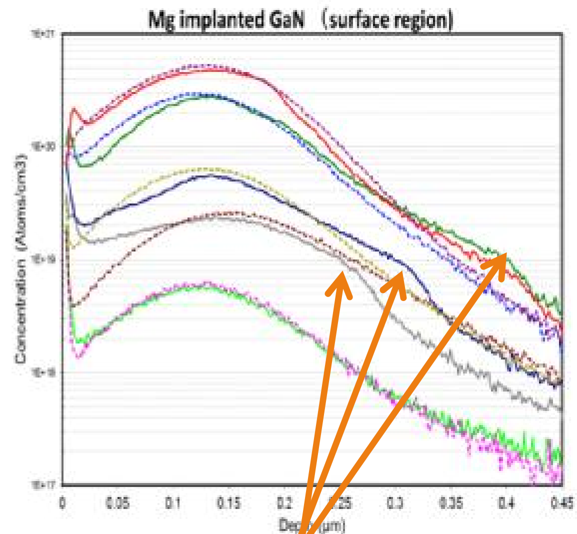






Curious humps in the anneal sample profiles

Acknowledgments

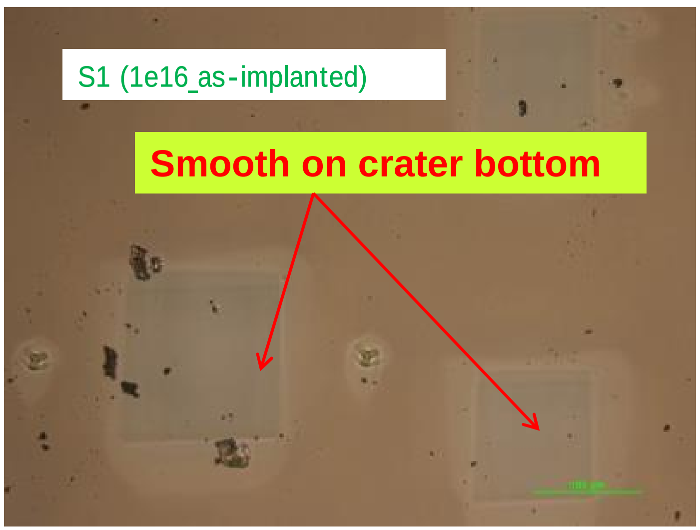
Prof. Tohru Nakamura, Prof. Tomoyoshi Mishima, Prof. Tomoaki Nishimura, Dr. Kiyoji Ikeda of Research Center of Ion Beam Technology, Hosei University and Kazue Shingu, Wei Zhao, Mike Salmon, Daniel Tseng of EAG

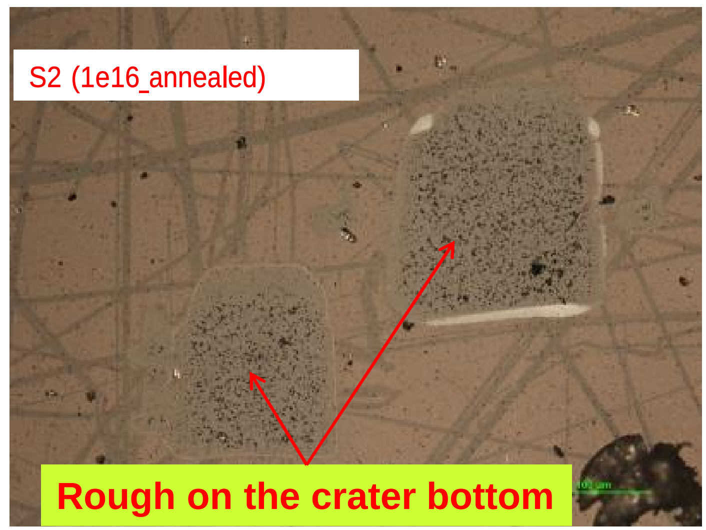
Optical Evaluation of the SIMS Craters

We found roughness at SIMS crater bottom in the annealed sample and saw a difference of roughening between as-implanted and annealed samples.

Interesting!

Optical microscope photo on Crater bottom in 1E16 as-implanted and 1E16 annealed after SIMS measurement

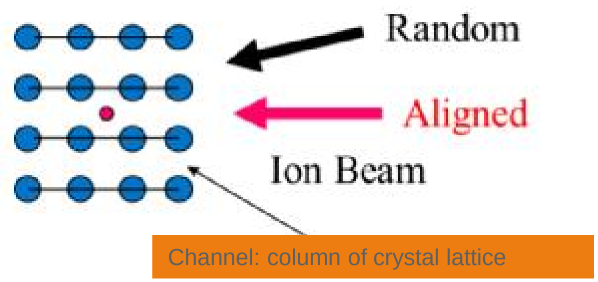




RBS Channeling Analysis for Crystallinity

Basic Concept of Channeling

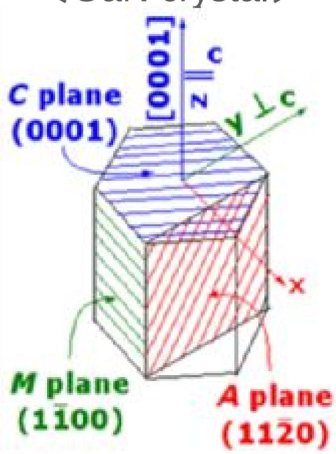
When an ion beam is aligned along a major crystal axis or plane, ion-atoms interaction probability is significantly reduced and this results in the large reduction of scattering events and ions penetrate deeper into the crystal.



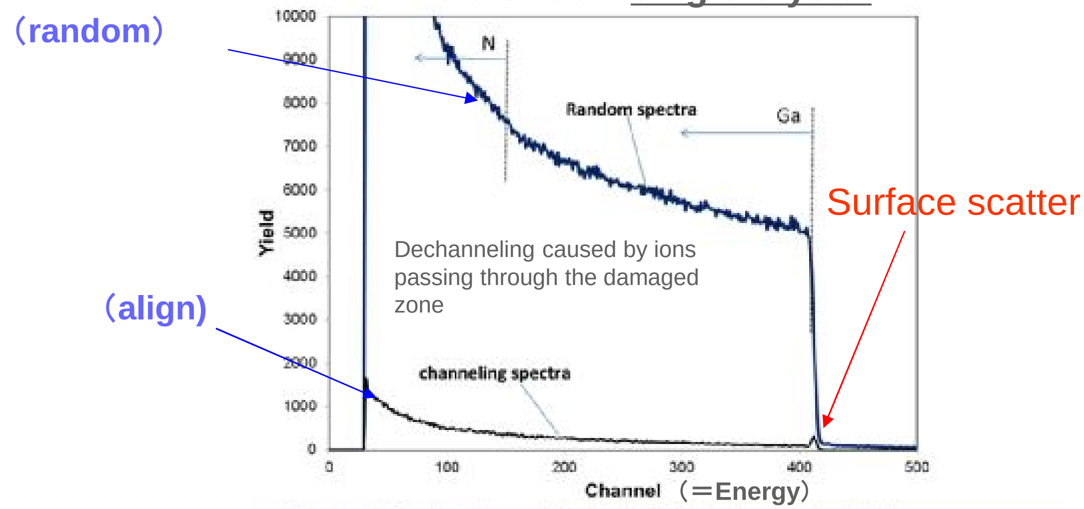
Evaluation of crystallinity

used to study the crystal damage, defect concentration after implantation（displacement of lattice atom）

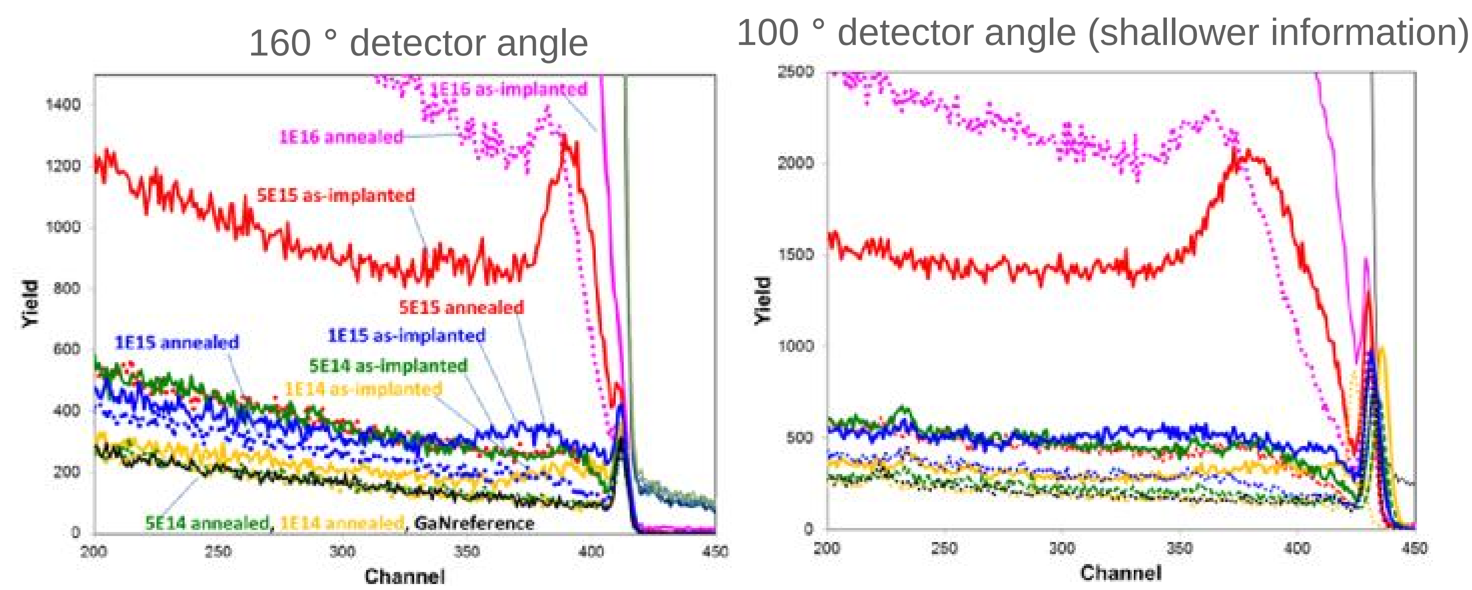
<GaN crystal>



Data of GaN **single crystal**



Comparison of Channeling Spectra at Different Detector Angles

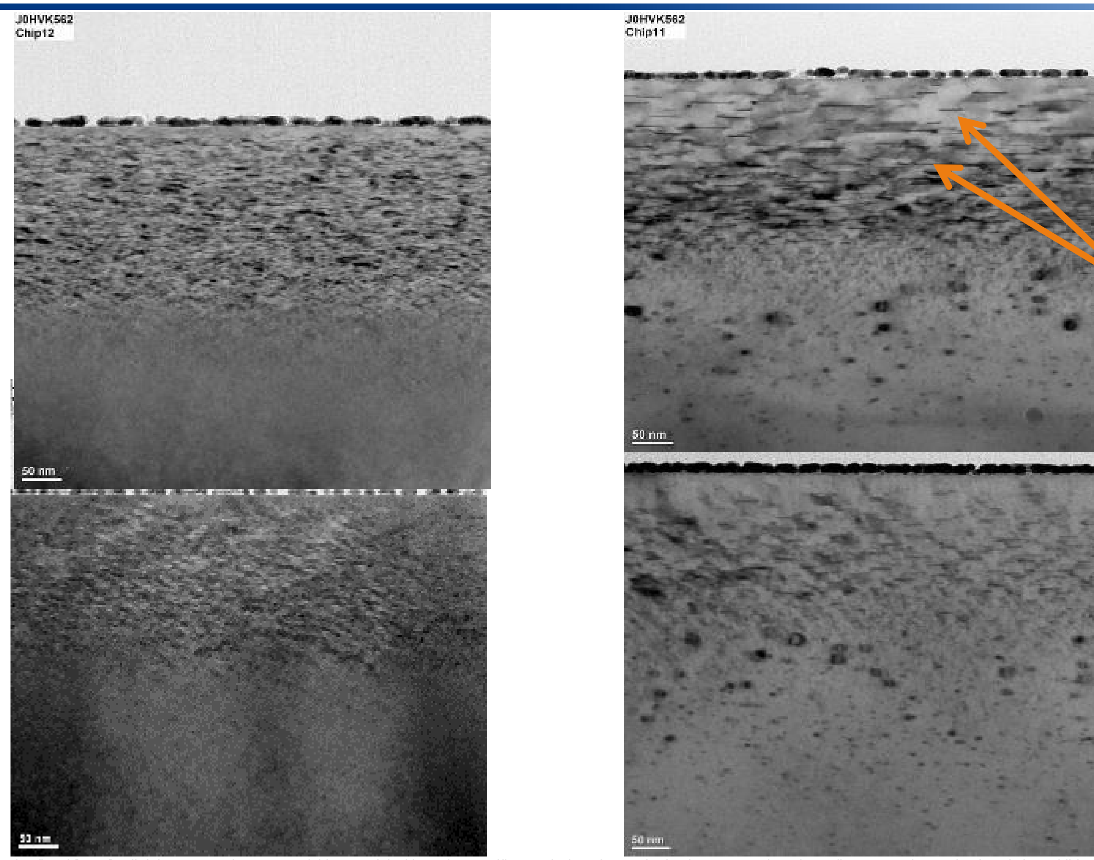


- **Reduction of intensity is detected in annealed samples of all dose samples. It concludes recovery of damage by annealing.**
- **1E14 & 5E14 annealed samples detect no significant displacement. (same as reference data)**

TEM analyses of high dose implanted samples (S1 – S4)

S1 (1E16_as-implanted)

S3 (5E15_as-implanted)

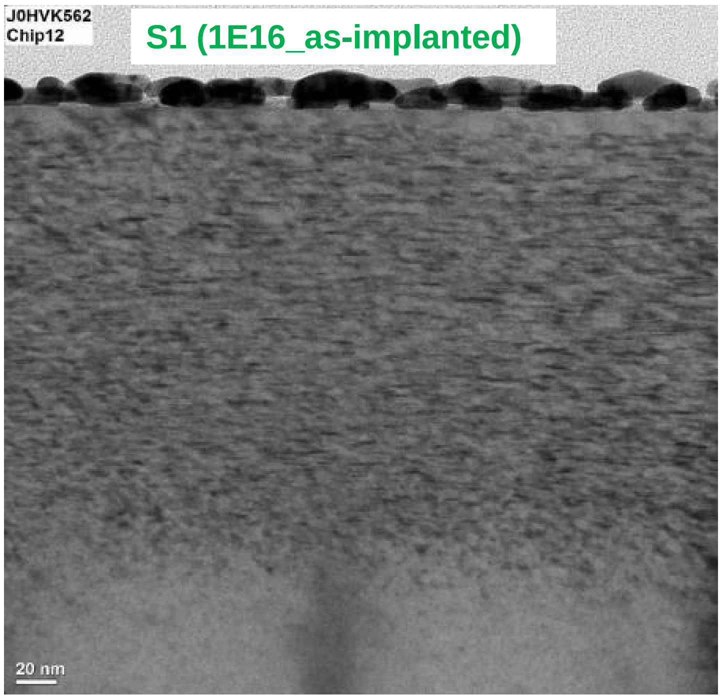


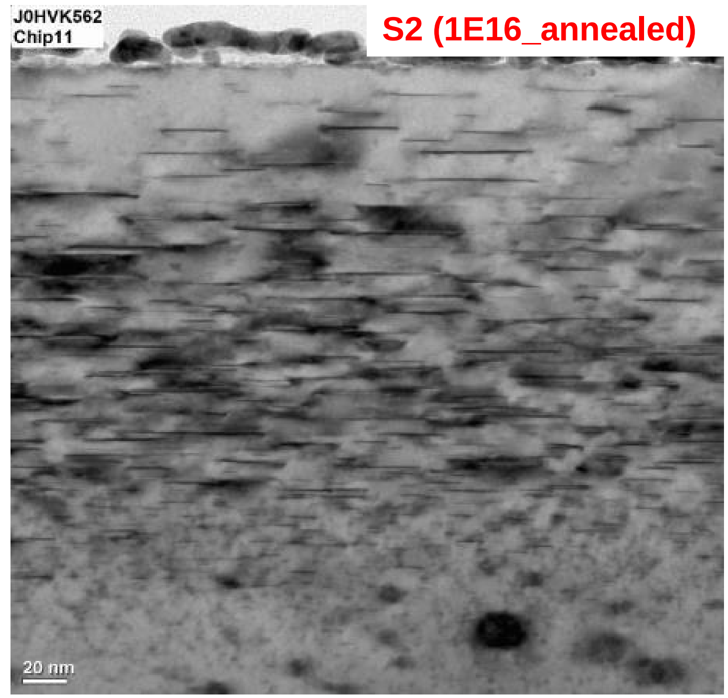
S2 (1E16_annealed)

Line like defects!

S4 (5E15_annealed)

TEM Analyses of 1E16 Dose Implanted Sample
A Closer Look

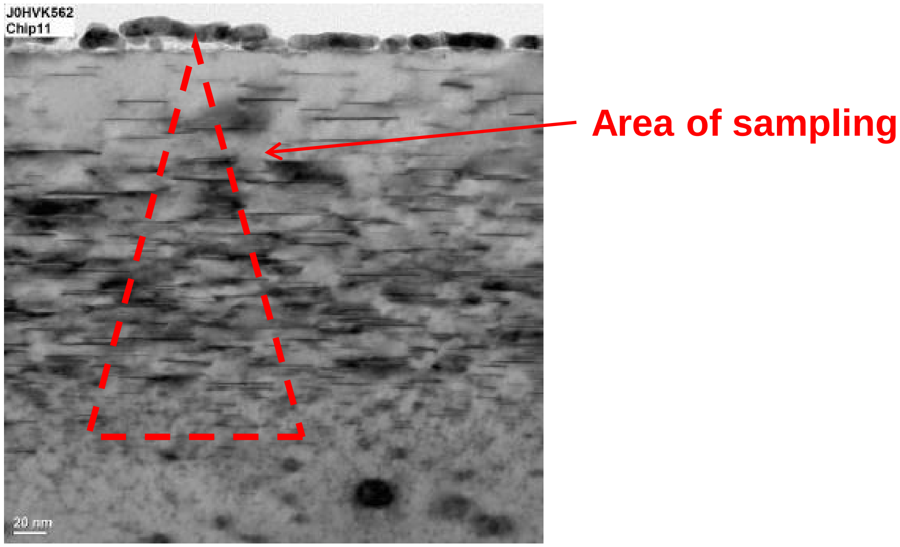




In as-implanted samples, many of small defects have been detected. In annealed samples, there is some crystal recovery, but line like defects are observed. At deeper region, dot defects still exist in annealed samples.

3D - Atom Probe Tomography analysis of Mg in GaN

Sample：S2（Mg 1E16 implanted + annealed）



3D - Atom Probe Tomography analysis of Mg in GaN

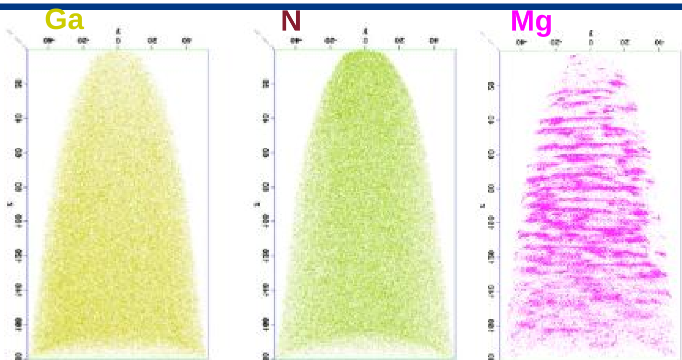
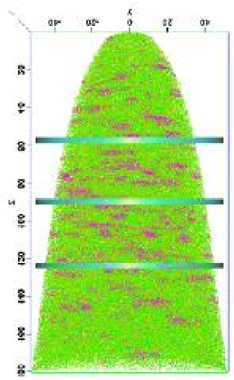


Fig 1（total mapping of each element）



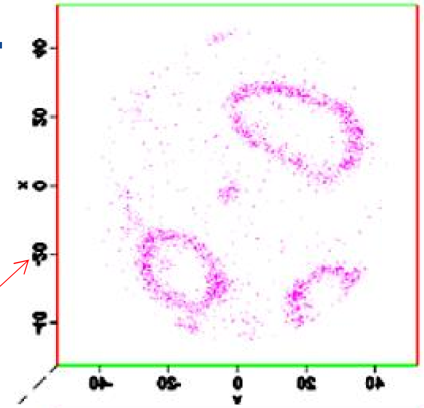


Fig2-1

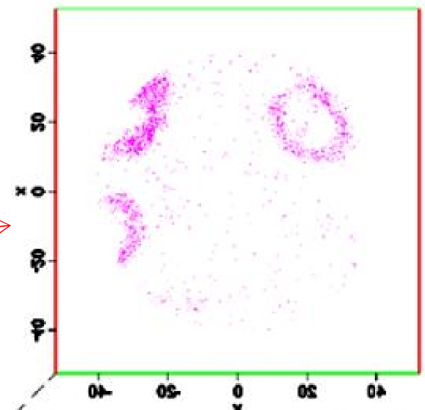
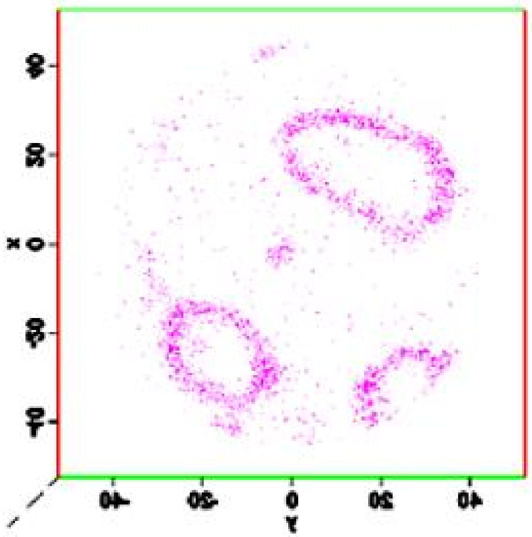


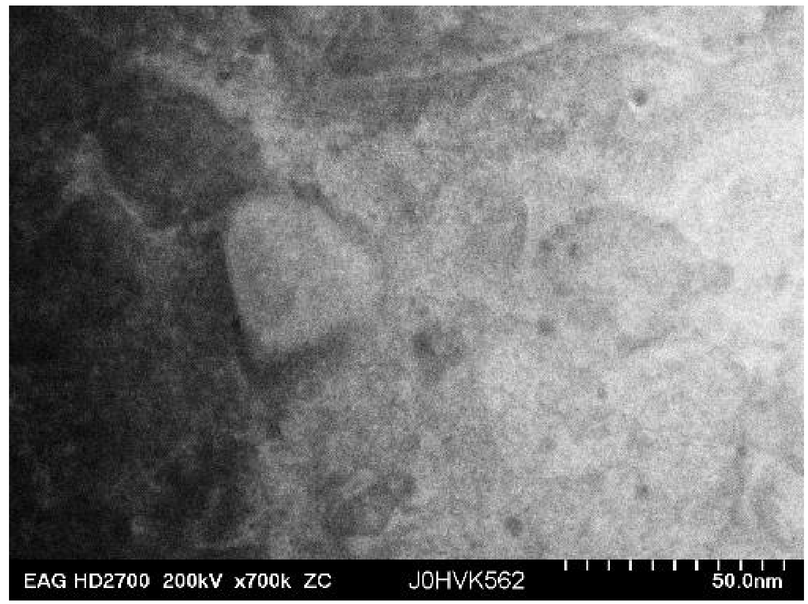
Fig2-2

Fig2-1, 2-2：lateral distribution in a slice 3nm thick

Ring-like accumulation of Mg is observed.

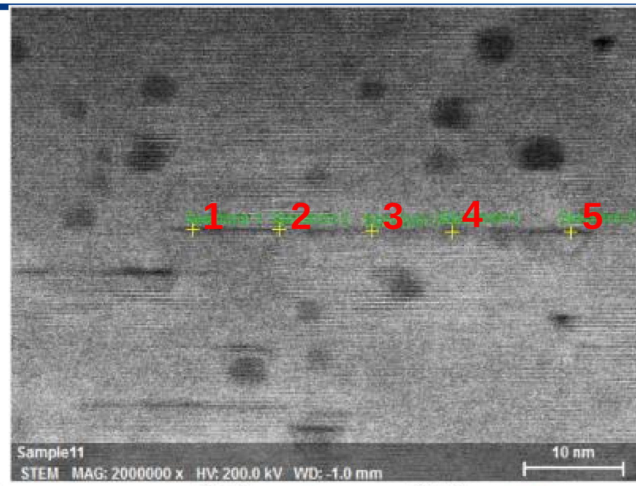
Comparison
PlanView STEM and 3D-APT





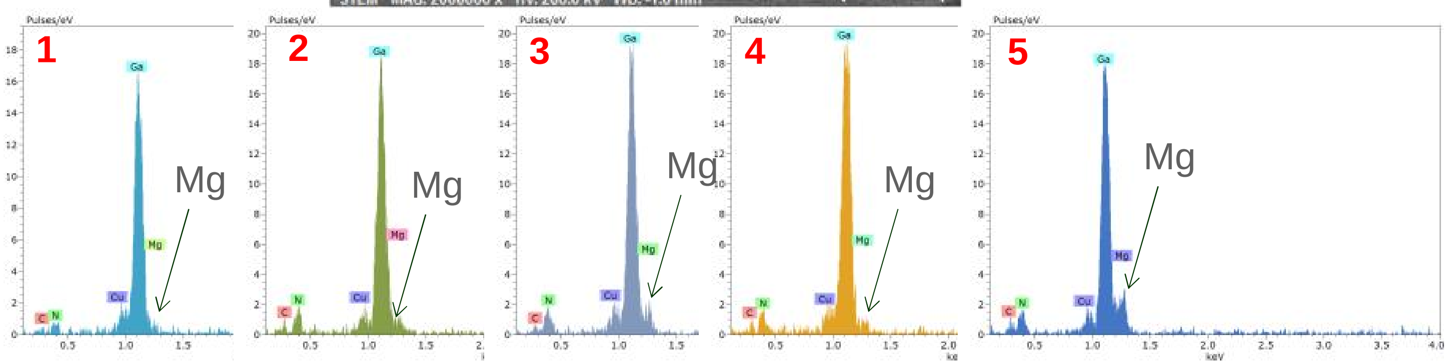
The size of ring defect by PV-TEM agree well to the size of Mg distribution by 3DAP. We conclude that Mg accumulates in a ring-like-plan-defect.

STEM-EDS analysis – Line defects

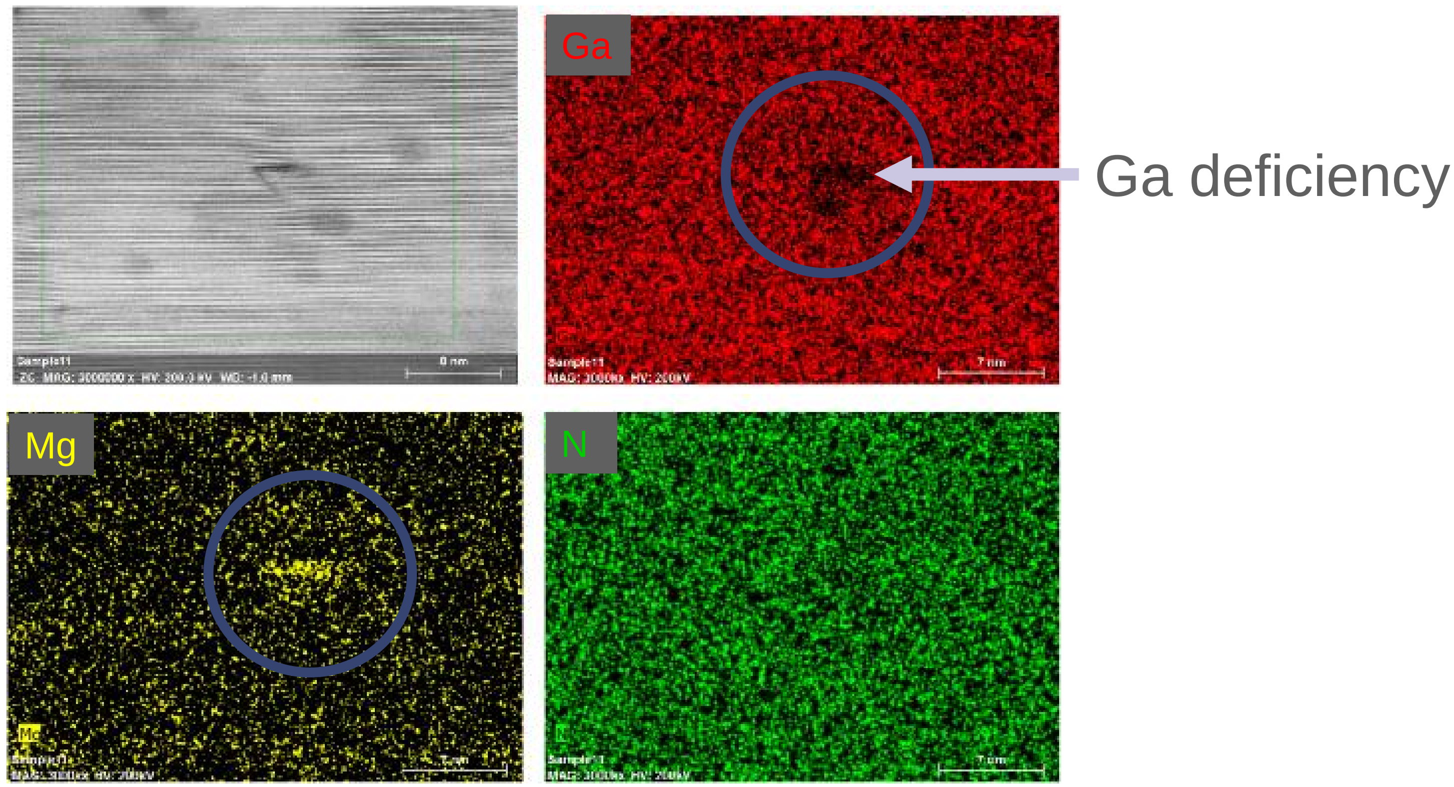


TEM-EDS analysis is done at a line defect.

Mg is detected clearly along with the line defect.



STEM-EDS mapping



Summary

1. RBS detected change in crystallinity before and after annealing.
2. TEM detected Mg implantation damage in GaN after annealing, even at low dose of 1E14atoms/cm^2 sample.
3. It is confirmed that while annealing leads to crystalline recovery, it also made some defects grow.
4. In 1E16 annealed sample, Mg accumulation along a ring like pattern defect is confirmed by 3D-APT and TEM-EDS.
5. Assuming Mg exists with Nitrogen, i.e. MgN due to lack of Ga, in the area Mg exist in TEM mapping. This would make a preferential sputtering during SIMS profiling, because of different hardness between GaN and MgN, which will to roughening. This probably is the cause of SIMS crater bottom roughness.
6. In this study, we confirmed Mg accumulation in the higher dose sample. We can assume Mg accumulation would occur in lower dose implanted sample also, in consideration of the fact that defects were observed after annealing.

Summary

- SIMS characterization is readily used for Ion Implant characterization. However, it often requires special methods to characterize shallow and high concentration ion implants.
- These SIMS method developments require combination of analytical techniques, such as RBS, ERDA, NRA, TEM, APT, etc.
- For a complete understanding of ion implant characterization combining these techniques is essential