Plasma Doping of Silicon Fin Structures

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Outline

- Introduction to plasma doping and 3D doping challenges
- Experimental details
  - PULSION hardware features
  - Si fin test structures
- Results
  - SIMS profiles for BF_3 and AsH_3 plasma implants into bare wafers
  - Amorphous layer produced by BF_3 plasma implant
  - XSEM images of fins chemically stained to highlight B dopant
  - Top-down SIMS profiles through unannealed and annealed fins doped by BF_3 and AsH_3 plasmas
  - XTEM image of annealed BF_3 plasma doped fin
- Summary

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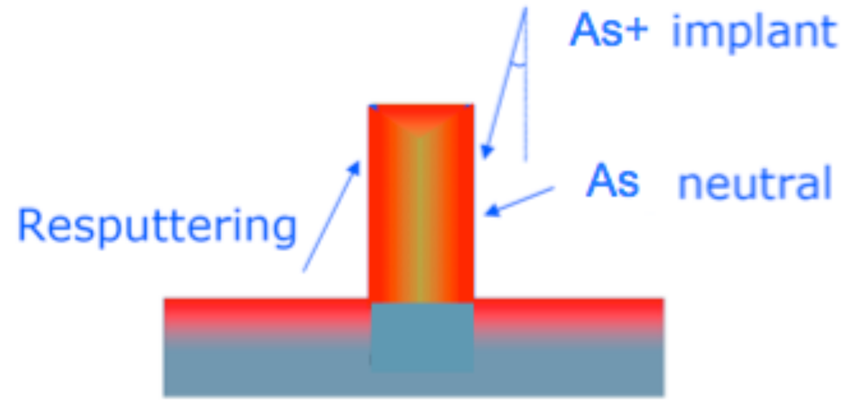
Introduction

- Plasma doping in R&D for over 2 decades
  - Ultra-shallow junctions
  - Conformal doping of trenches and fins
- Two very high dose, DRAM applications in production today
  - Polysilicon gate counter-doping
  - Contact doping
- Multiple gate and FinFET devices now in development to enable continued scaling
  - Candidate replacements for conventional planar CMOS devices
    - Excellent short channel effect immunity
  - Conventional, directional beam-line implant processes not well-suited
  - Plasma doping is an attractive implant alternative
    - Uniform junctions in 3-dimensional structures
    - Damage-free after anneal

3D Doping Challenges

- 3D implant is a combination of:
  - Direct implant
  - Sputtering effect
  - Deposition



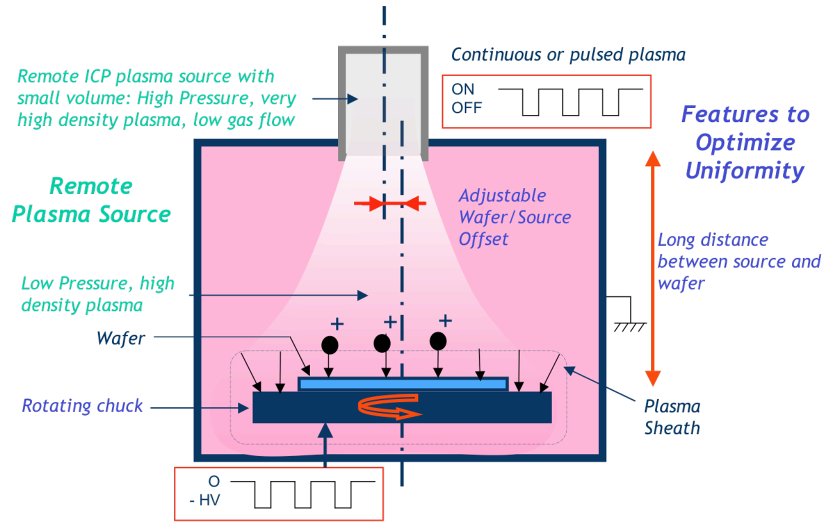
- 3D doping performance targets:
  - Good conformality
  - No fin erosion

- Fine process parameter tuning is needed to achieve optimal 3D performance.

- Key Factors of Success:
  - Large number of process parameters
  - Wide process window for each parameter
  - Independent tuning of process parameters

PULSION® Hardware Features for 3D Plasma Doping

- **Wide process range due to remote plasma source**
  - Independent tuning of plasma density and chamber pressure
  - Adjustable pressure differential between source and chamber: up to 2 orders of magnitude
  - Multiple independent knobs to find optimal process conditions and chemistries
  - Ability to balance implant versus deposition to get best conformal doping
- **Use of low implant energies**
  - No fin corner rounding and height erosion
  - Thin amorphous layers
  - Minimal damage after implant and anneal



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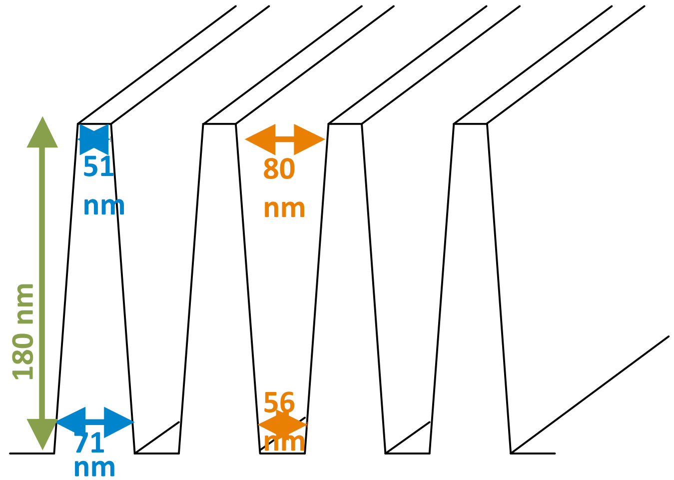
Silicon Fin Test Structures



- Fins wider than 16nm node device, but useful to evaluate lateral implant depth and diffusion of dopants
- Fabricated on bulk-Si wafers
- Plasma doping using BF_3 or AsH_3 gas
- Anneal splits to simulate source/drain junction anneals
- Sample analysis
  - Top-down SIMS after additional amorphous Si deposition and CMP
  - XSEM after delineation etch
  - XTEM to compare vertical and horizontal fin damage

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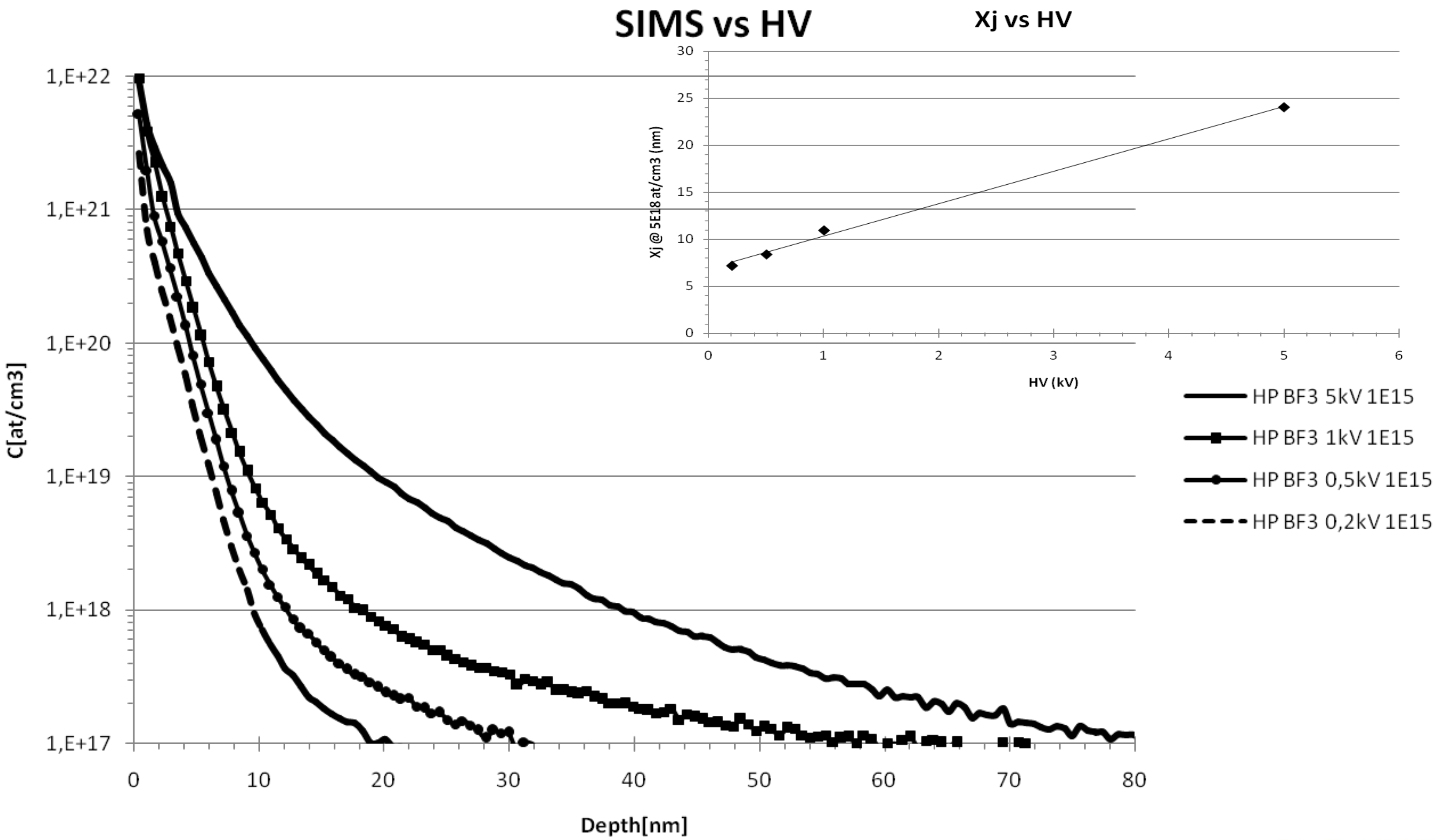
BF_3 SIMS Profiles for Four Wafer Voltages

- Implant depth proportional to wafer voltage
- Low energies desired to form ultra-shallow junctions and to minimize sputtering, fin erosion, and implant damage



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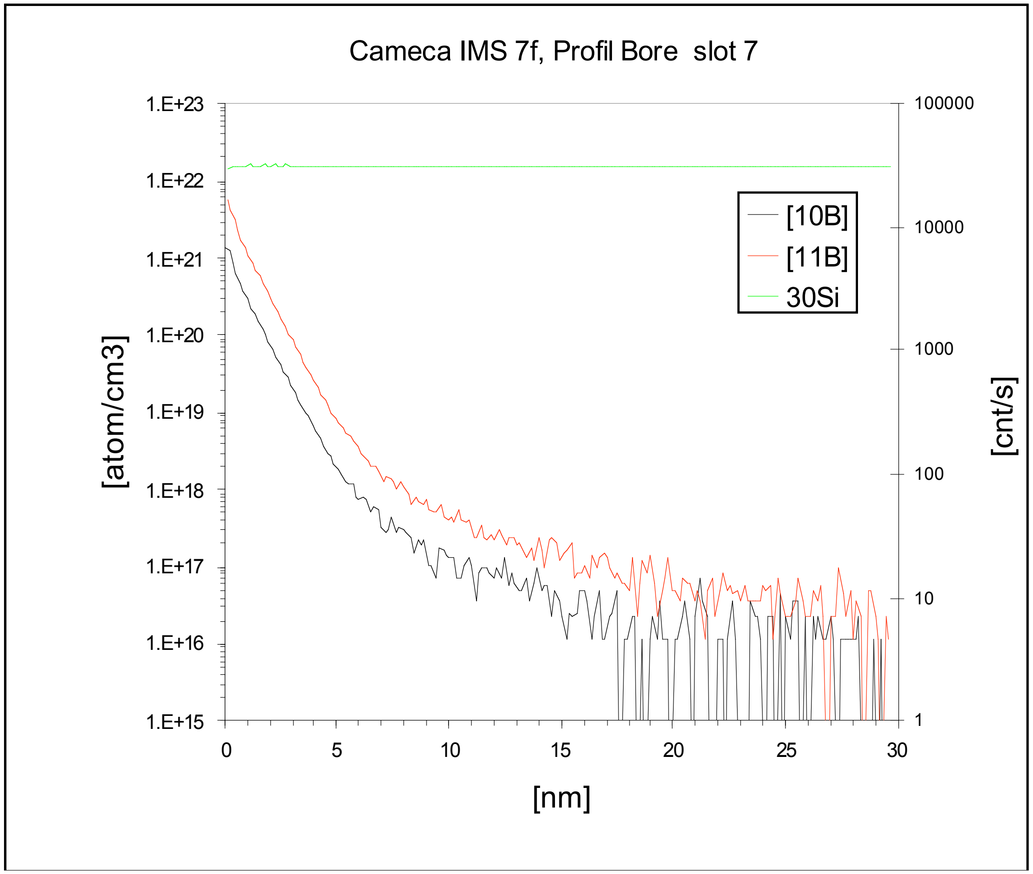
SIMS Profile for BF_3, 0.5 kV, 1E15 cm^{-2}

- **11B depth at 1E18 cm^{-3} = 7.69 nm**
- **Total SIMS dose (11B + 10B) = 4.35E14 cm^{-2}**
- **Both B isotopes detected, since this gas was not isotopically enriched**



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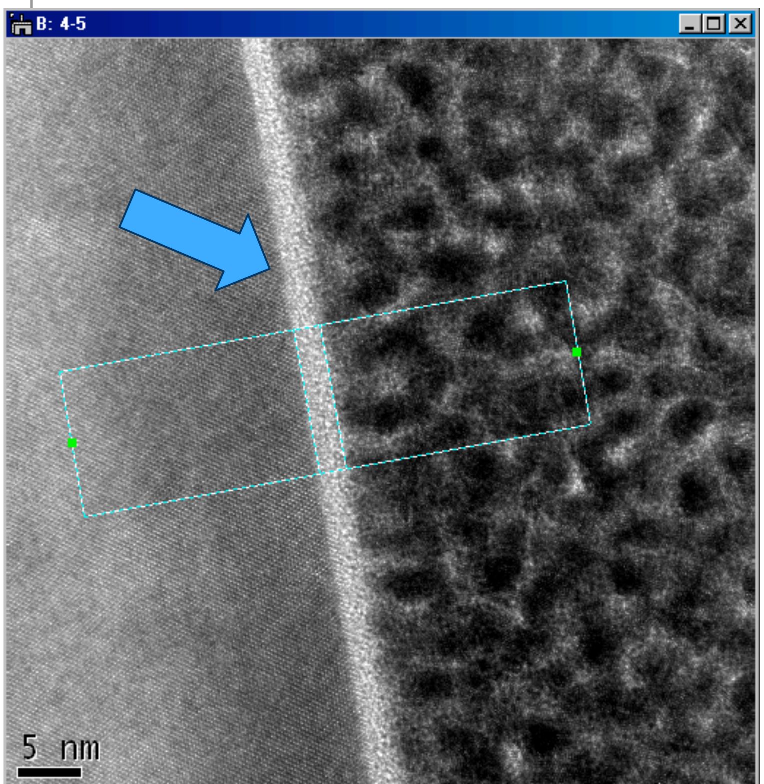
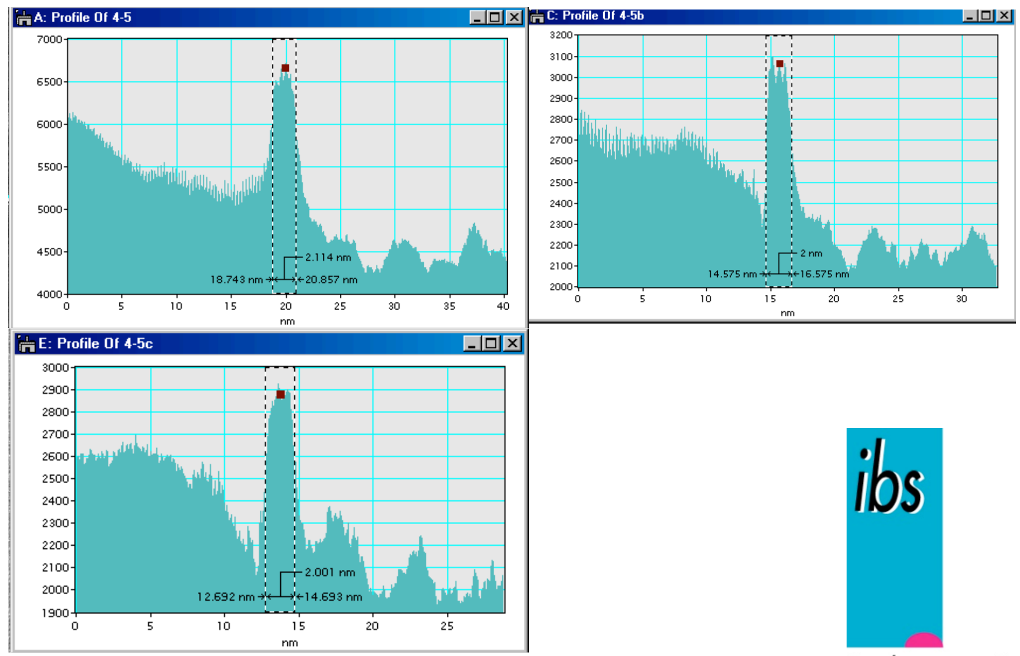
Amorphous Layer Thickness for USJ Implant

- HRTEM image of BF_3, 0.5 kV, 1E15 cm^{-2} implant
- Thickness of amorphous Si layer ~2 nm
  - Thin enough to leave crystalline Si region in interior of 16nm node fin and enable complete regrowth of fin Si





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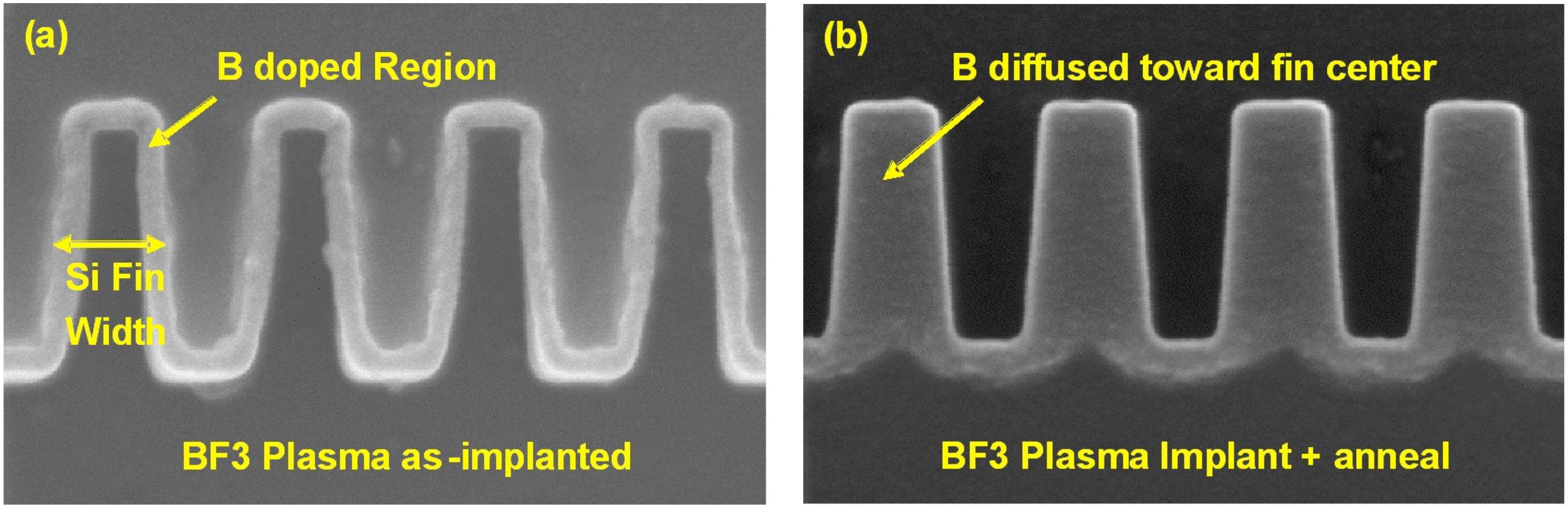
XSEM Images of Fin Structures after BF_3 Plasma Doping



- **Conformal doping of as-implanted sample**
  - **White regions on top of fins, along sidewalls, and between fins are B-doped, not B deposition on surfaces of fins (see next slide)**
  - **Equal thicknesses of all regions**
- **Entire fin is light-colored after PMOS source/drain anneal**
  - **Anneal caused B to diffuse toward center of fin**

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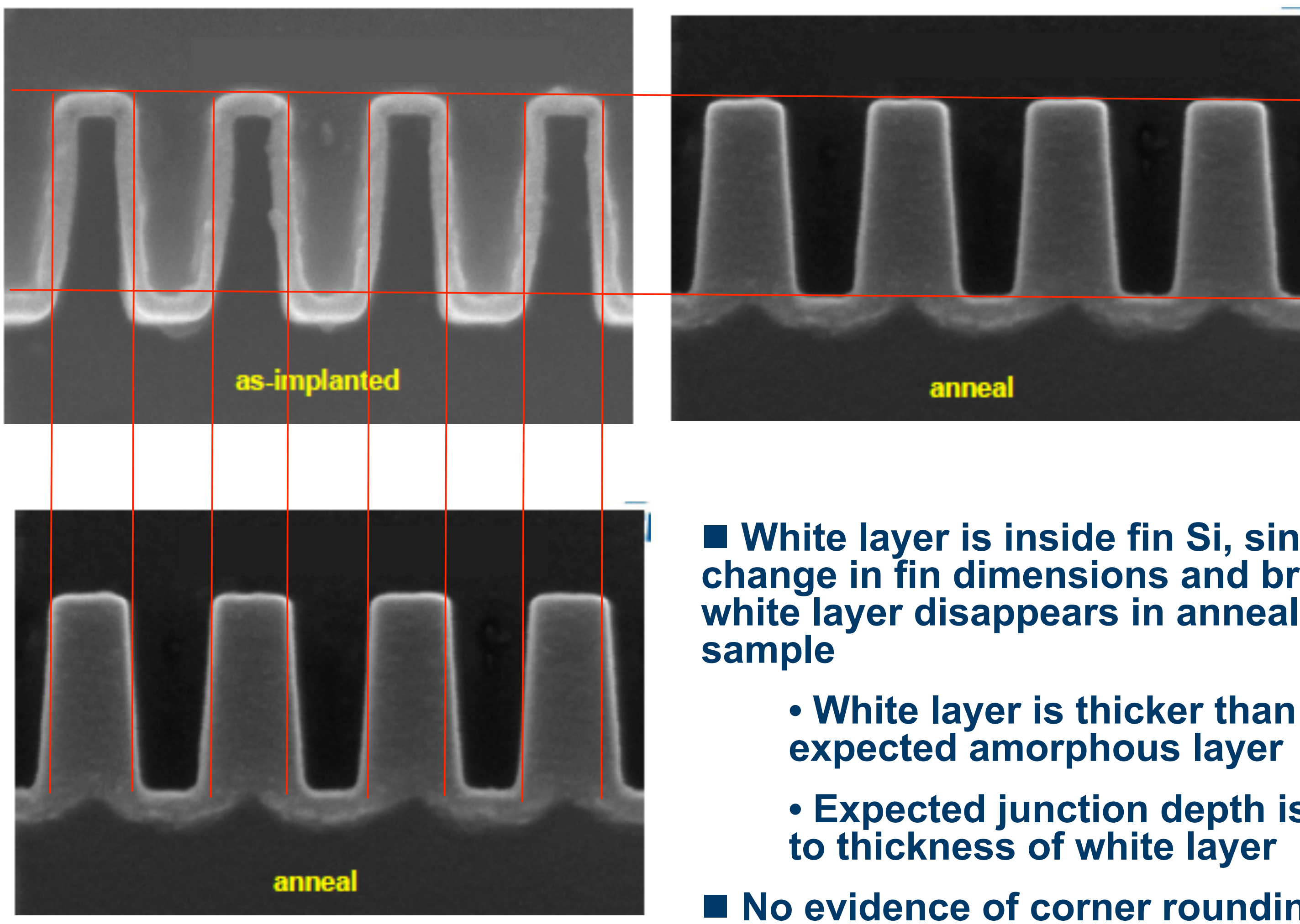
Unchanged Dimensions of Plasma Doped Fins



- White layer is inside fin Si, since no change in fin dimensions and bright, white layer disappears in annealed sample
  - White layer is thicker than expected amorphous layer
  - Expected junction depth is close to thickness of white layer
- No evidence of corner rounding or fin erosion

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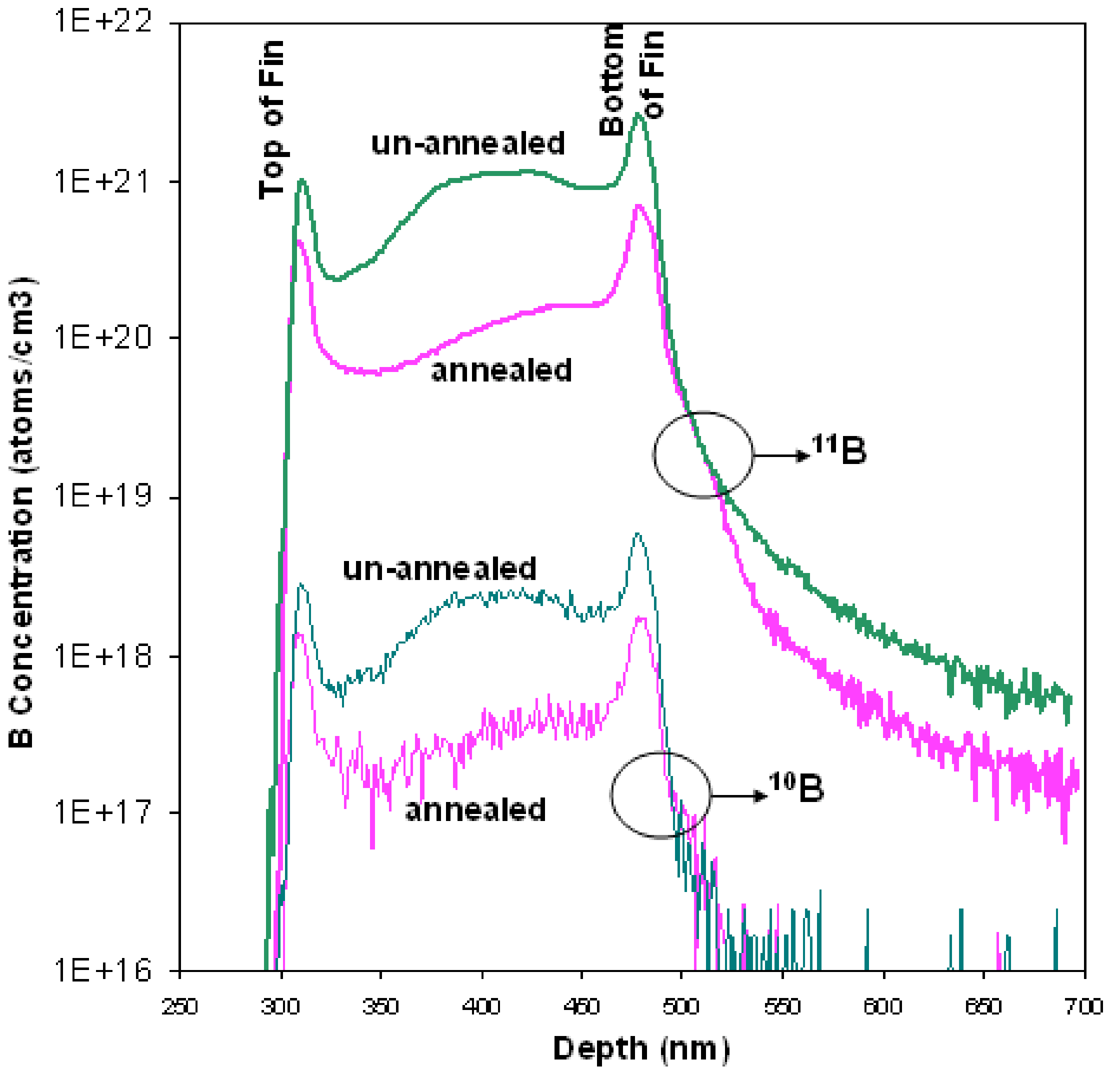
SIMS Depth Profiles through BF_3 Plasma Doped Fins



- **Anneal improved top-to-bottom uniformity of fin doping**
  - **Sputtering from fin bottoms may be dominant mechanism**
- **Significant B outdiffusion caused by anneal**
  - **Annealed B concentration ~ B solid solubility limit and maximum electrical activation level for typical spike anneal**
- **^{10}B isotope much lower than ^{11}B due to use of isotopically enriched BF_3 gas**

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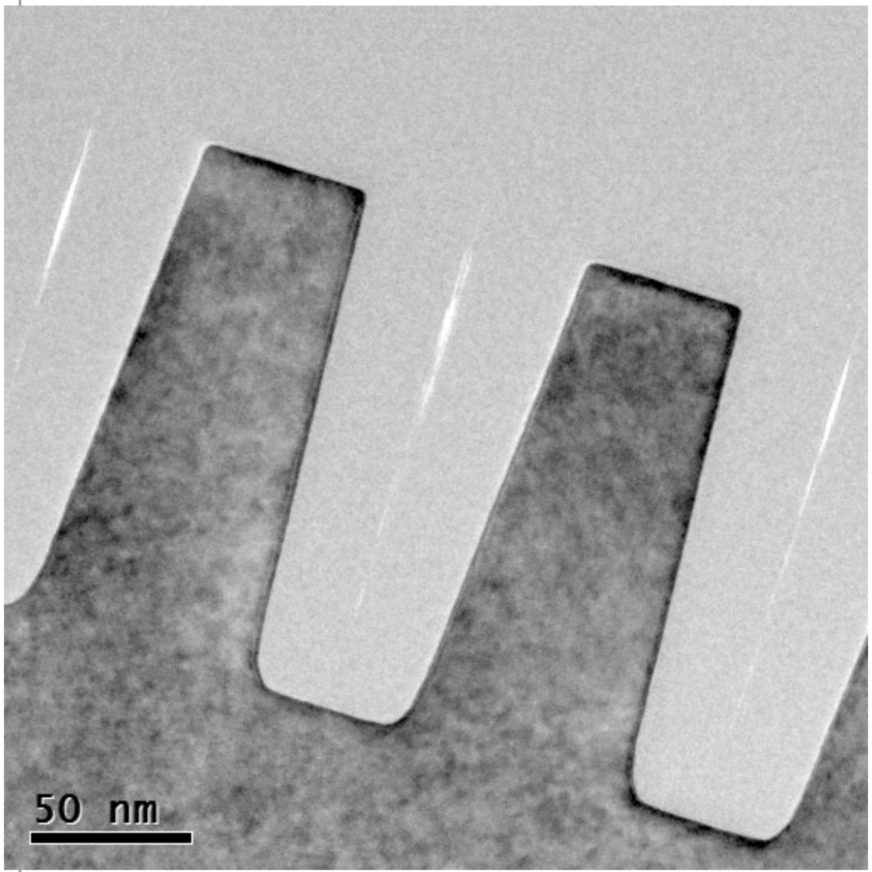
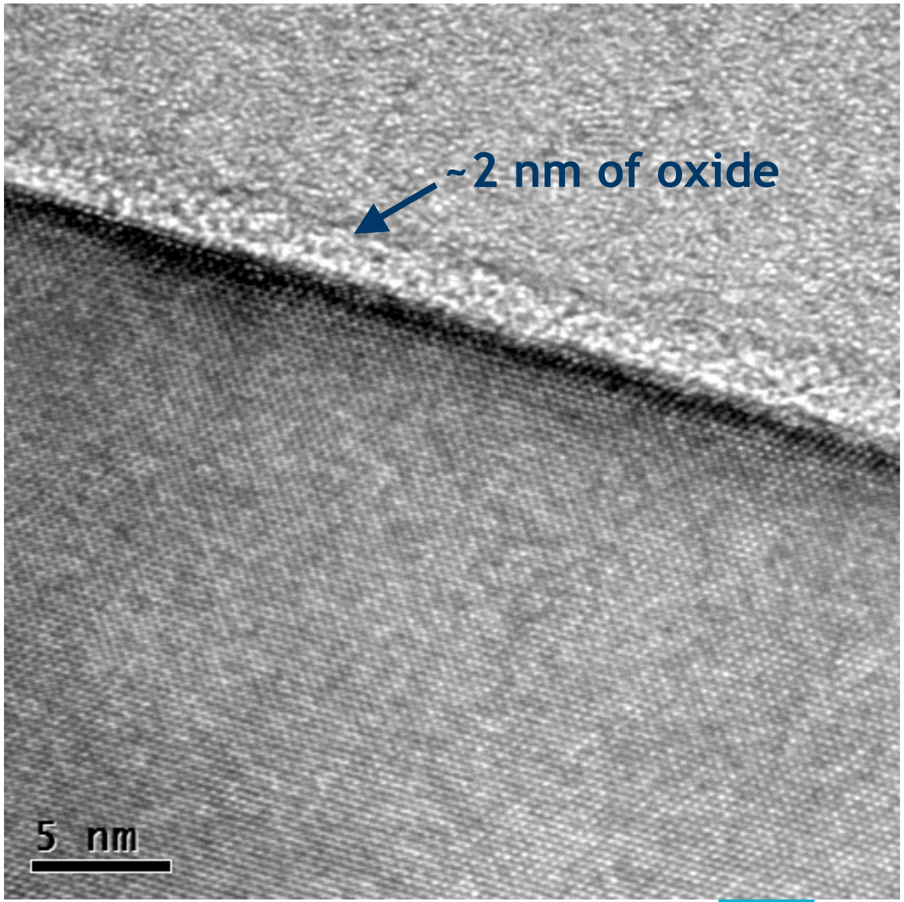
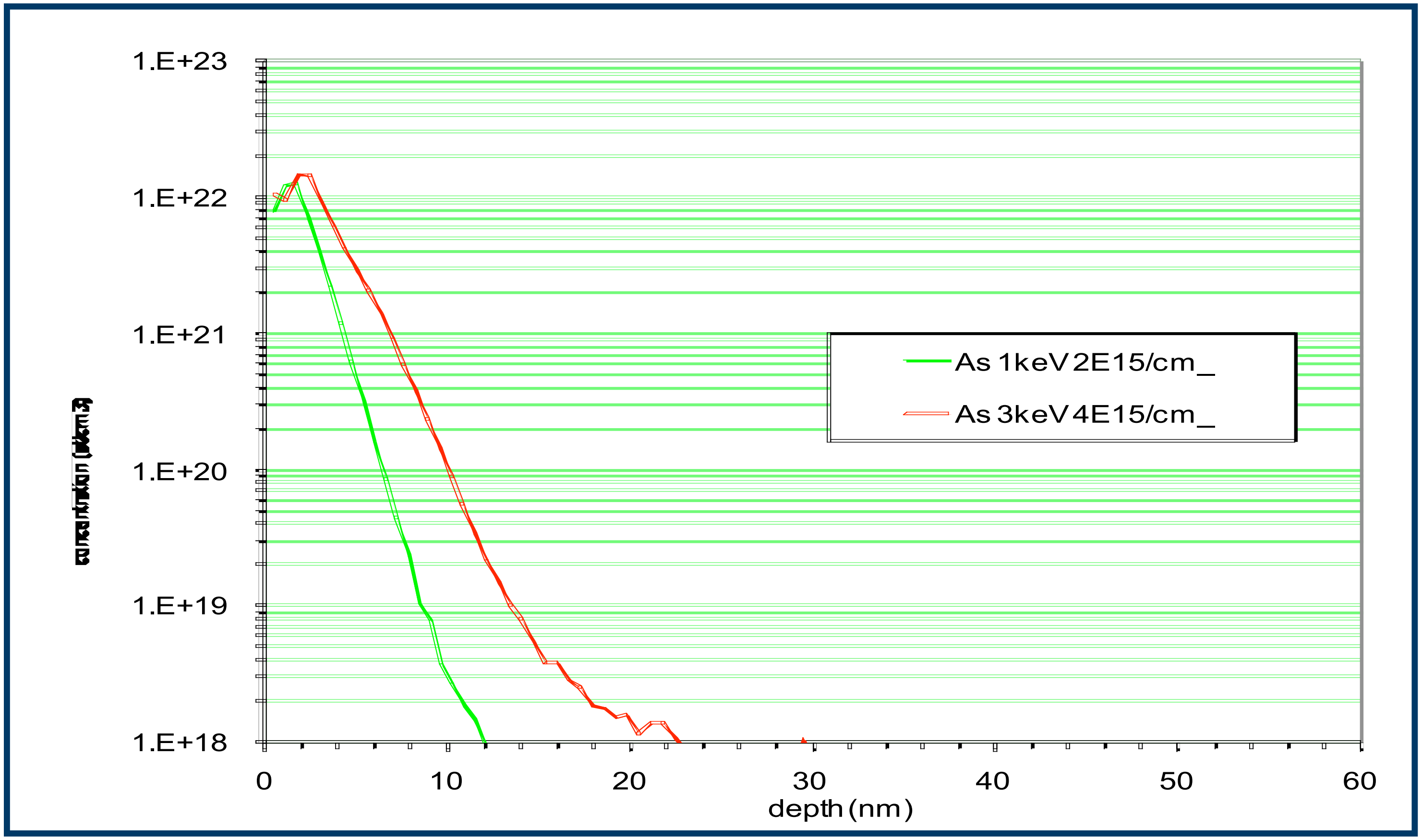
XTEM Images of Annealed BF_3 Plasma Doped Fins





- No visible damage along tops or sidewalls of fins
- Regrown Si shows good crystalline quality throughout fin
- Thin (~2nm) native oxide present around fin

SIMS Depth Profiles for AsH_3 Implants



- For 1 kV implant, As depth at 1E18 cm^{-3} is 12 nm
- As studied as n-type dopant due to its high electrical activation and low diffusivity

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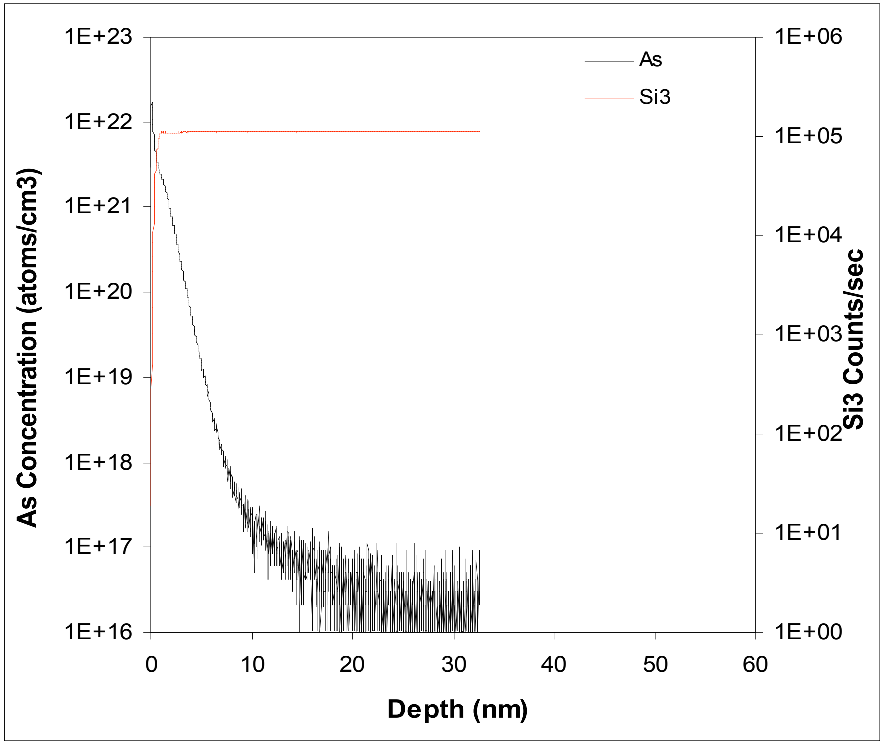
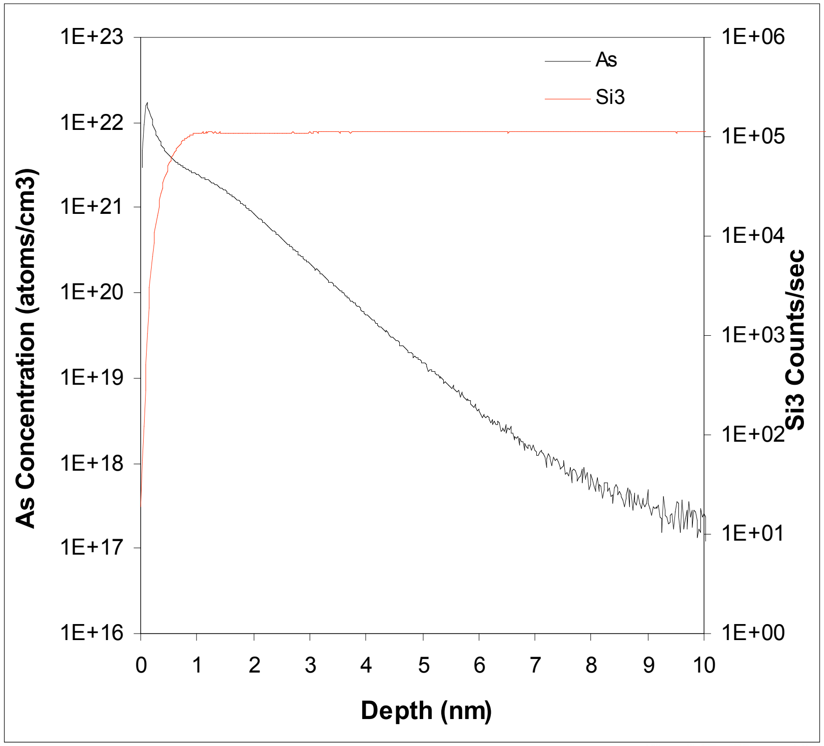
SIMS Profile of Arsenic USJ with Flash Anneal

- AsH_3, 0.3 kV, 2E14 cm^{-2}
- 1200C flash anneal
- As depth at 1E18 cm^{-3} is 7 nm





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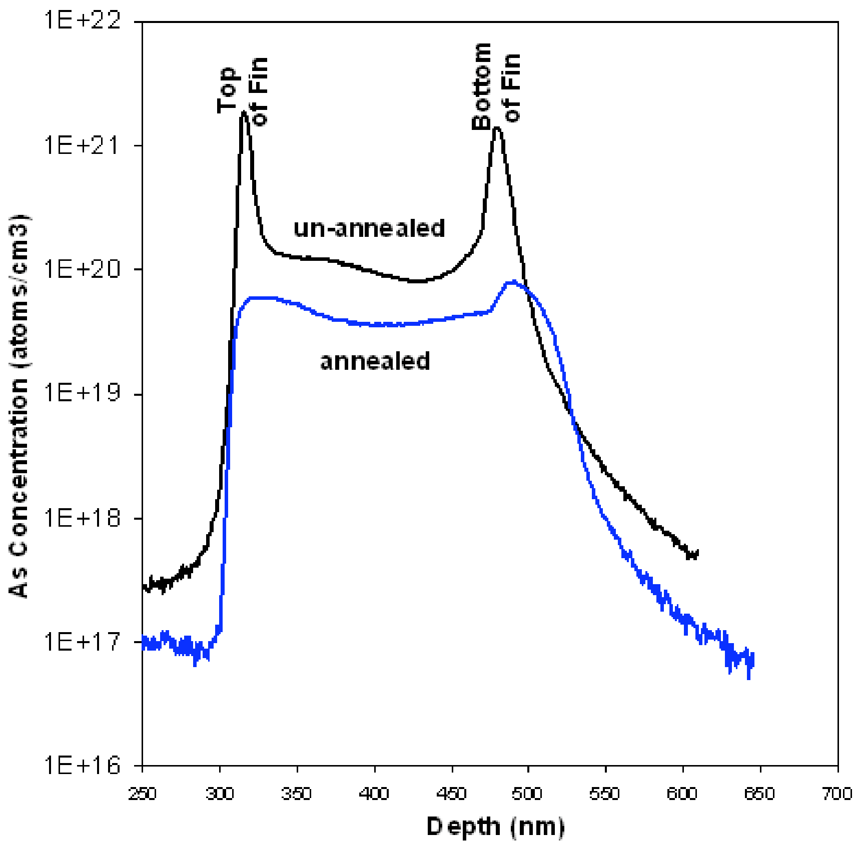
SIMS Depth Profiles through AsH_3 Plasma Doped Fins



- Top-to-bottom doping uniformity along sidewalls is quite good for both samples
- As sidewall concentration decreased by half order of magnitude due to NFET source/drain anneal
  - Much less than that for BF_3 implanted fins
  - Concentration at fin tops and bottoms decreased by ~ order of magnitude
  - Due to combination of diffusion into fin and substrate and outdiffusion
- As tail extending to right of fin bottom is due to As diffusion into substrate

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Summary

- Plasma doping has good conformality around fin structures for source/drain doping applications
- Subsequent annealing diffuses dopant toward center of fin
- Top-down SIMS through fins indicated that subsequent anneal caused significant Boron out-diffusion for BF_3 plasma implant, whereas As out-diffusion for AsH_3 plasma implant was smaller
- TEM analysis of annealed samples found no significant damage along top or sidewall of BF_3 plasma implanted fin