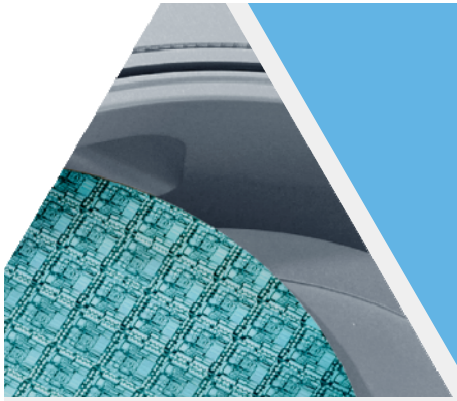
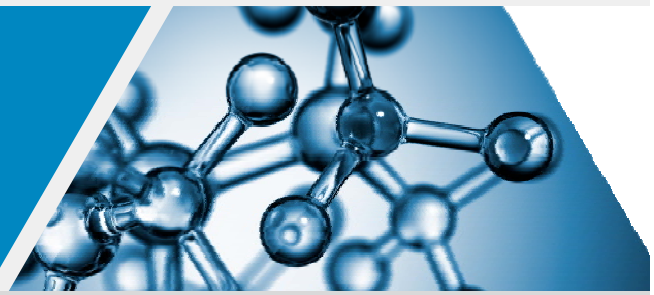



Ultra-Shallow Junction Formation on 3D Silicon and Germanium Device Structures by Ion Energy Decoupled Plasma Doping

YS Kim & Hyuckjun Kown

CTD, Lam Research



Overview

- **Introduction and challenges**
  - Challenges on device
  - USJ on 3D structure
- **Plasma-assisted doping (PaD) on Si**
  - Previous work for plasma-assisted doping on Si
- **Annealing vs Doping on Si**
  - PaD vs ALD vs GaP vs SOD
- **Plasma-assisted doping on Ge**
  - Various annealing for junction depth and P level
  - Plasma-assisted doping on Ge
- **Summary**

Overview

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- **Summary**

Man Made “Intelligent” but Power Inefficient System

AlphaGo handily beat world Go champions

74,000W

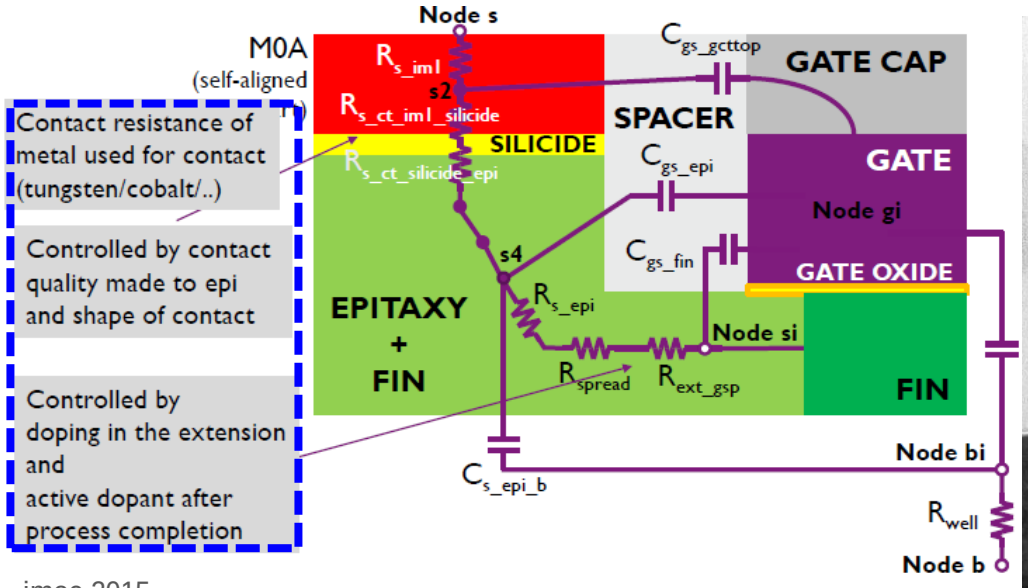
12W

AlphaGo: employs 1200 CPU’s and 280 GPU’s in 2016

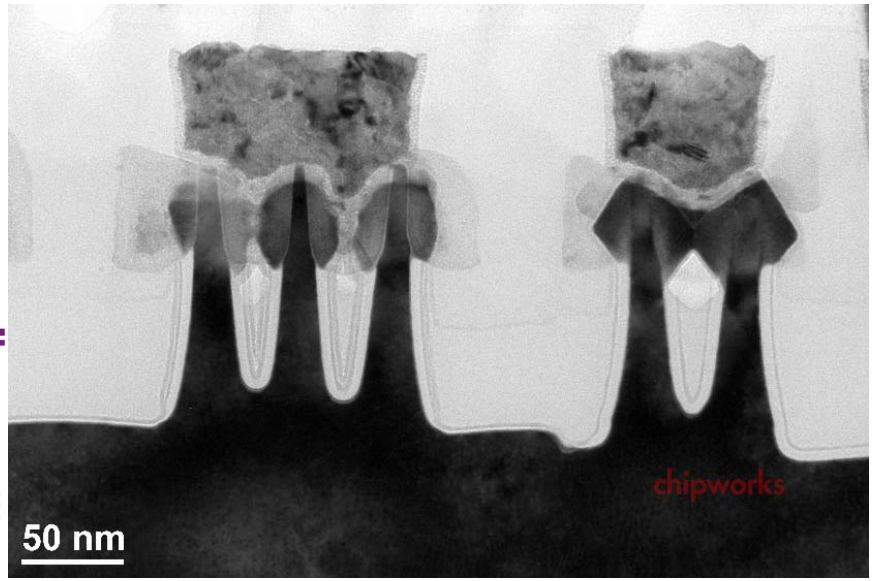
Human brain: 12W!

15% power reduced in 2017

Demands on Surface Engineering Due to Increasing of Both R and C Components on <10 nm Node Device



imec 2015



Source: Chipworks

$$R_{CO} = \frac{\rho_{CO}}{area} \propto \exp\left[\frac{4\pi\sqrt{\epsilon \cdot m^*}}{h} \cdot \frac{\Phi_{SBH}}{\sqrt{N_D}}\right]$$

To reduce R_c: Φ_B ↓ or N ↑ or A ↑

Φ_B : the Schottky barrier height
N : the electrically active dopant density at the interface
A : contact area

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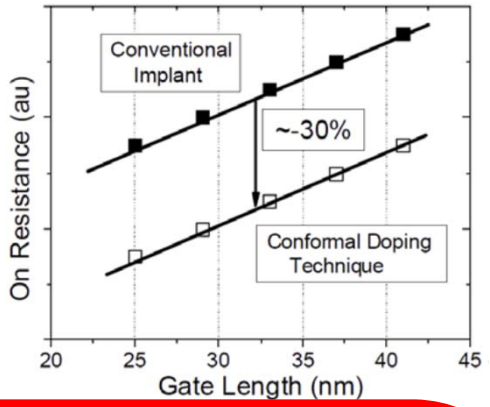
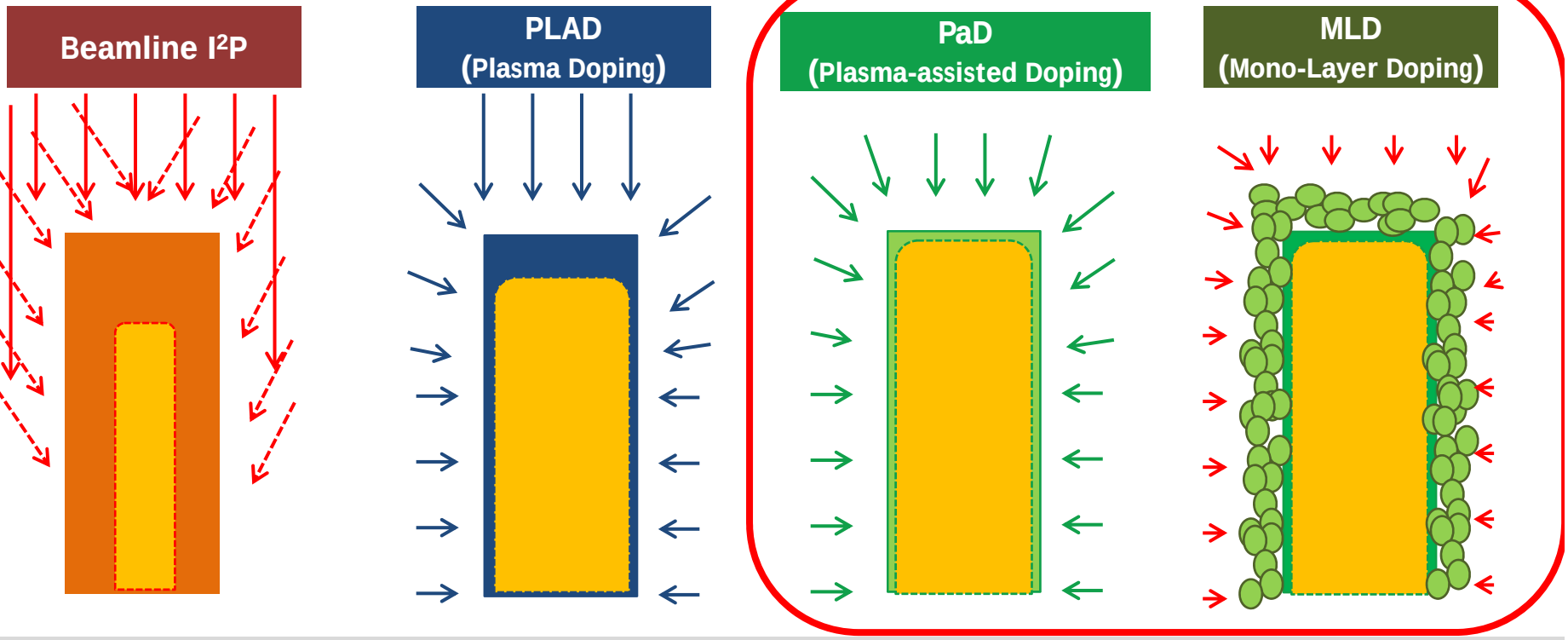
Comparison of Conformality for 3D USJ with Various Doping Schemes

- Doping on 3D structure will be a challenge due to its directionality during implantation
- To form shallow junction on 3D structure, reducing ion energy and increasing ion scattering will be necessary
- Monolayer doping by deposition of dopant will be an alternate option

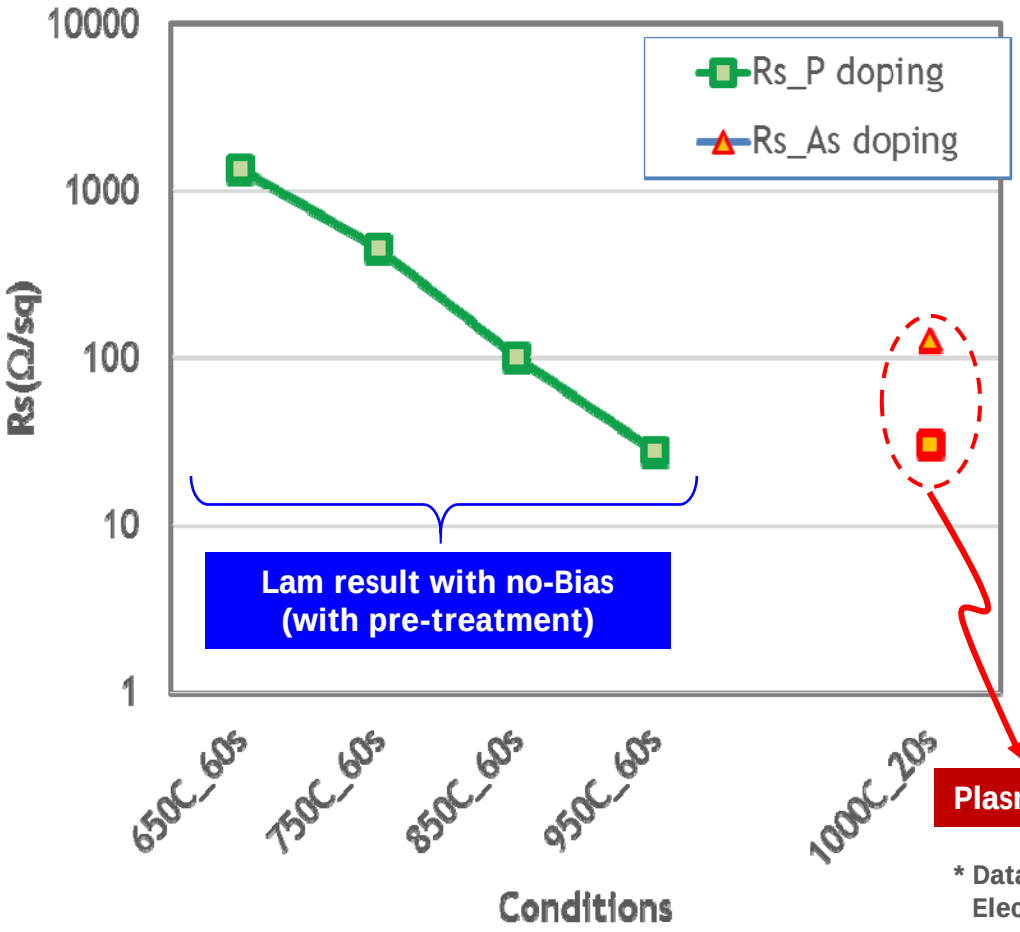
V. S. Basker et al, VLSI Tech. Symp., 2010

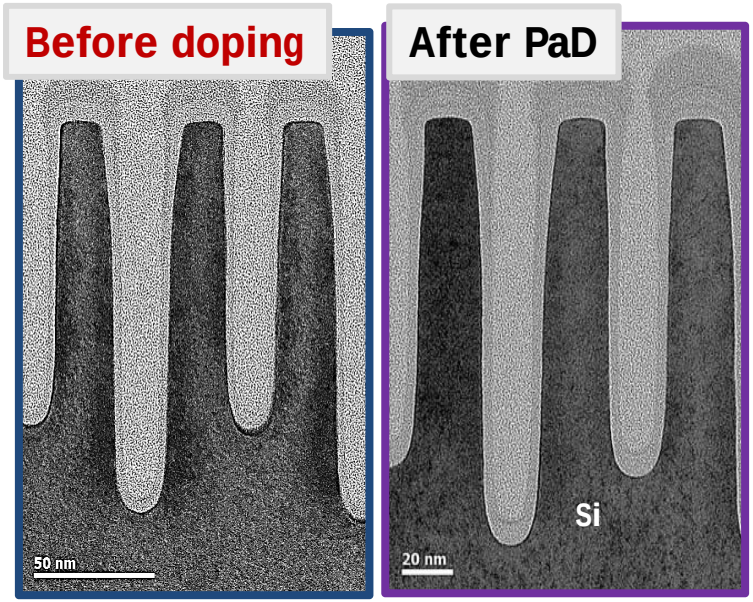




Comparison of PaD with Typical PLAD (with Bias)

Y.Kim et al, IWJT 2016





* Data Source from S Qin, IEEE Trans Electron Dev 62 (2015)

Rs from pre-treat but no bias power added is compatible with PLAD

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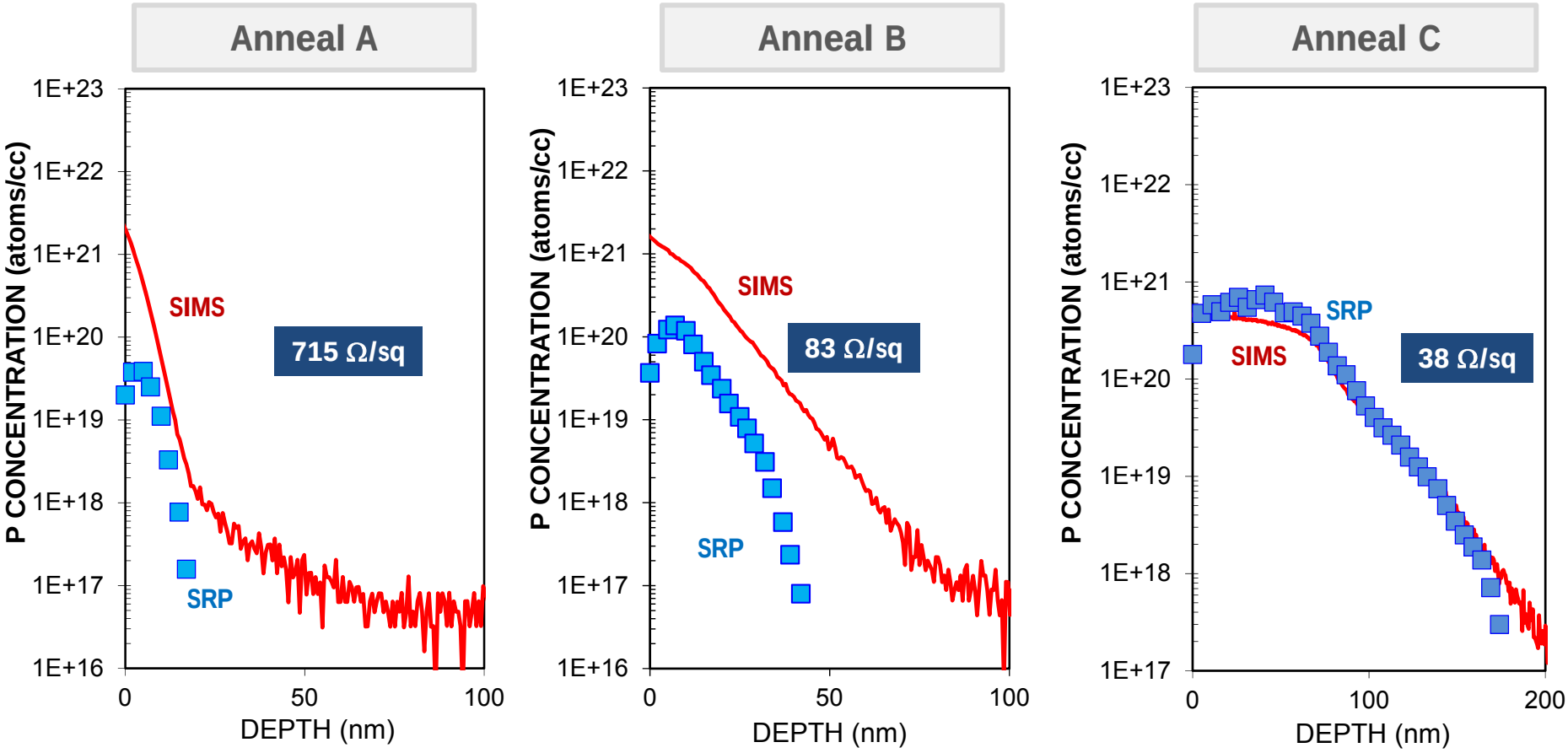
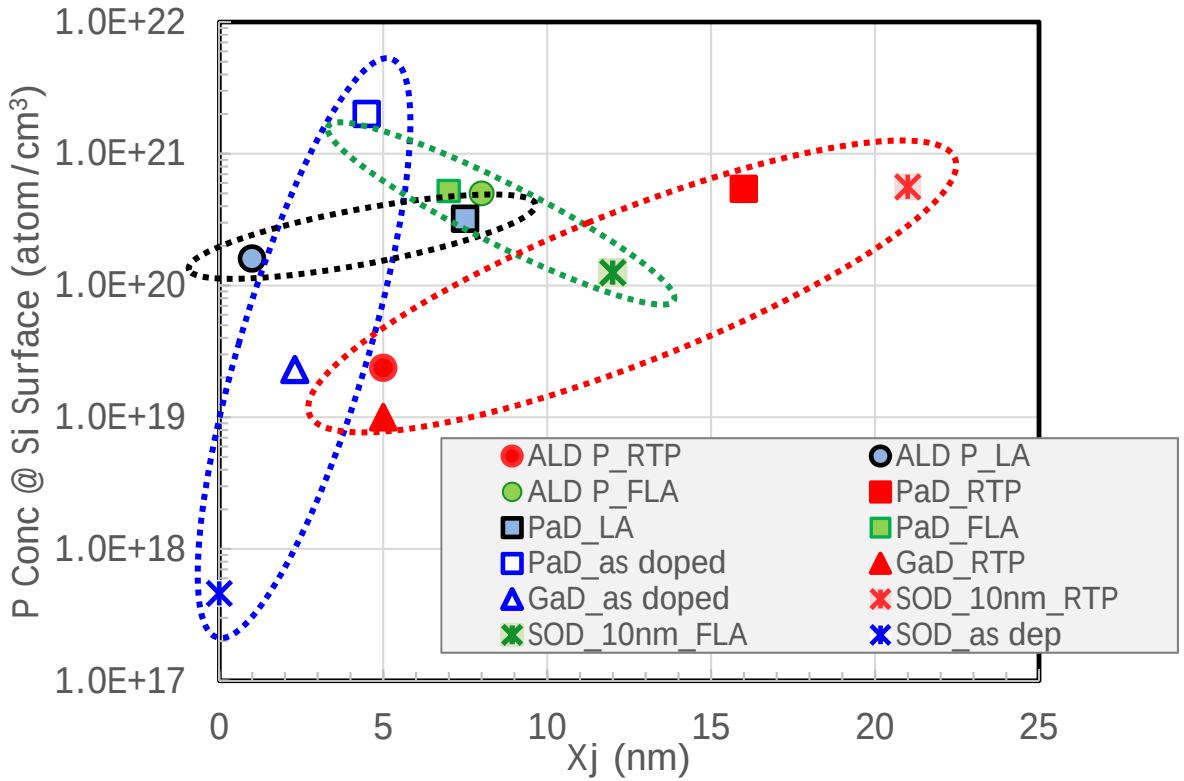
Various Annealing on PaD Processed Si Samples

- Junction depth can be optimized by annealing condition to form USJ
- Dopants activation confirmed with Rs measurement and SRP



X_j with Various Doping Technique vs. Annealing

- **Junction depth can be optimized by optimizing annealing condition to form USJ**
  - Dopants activation confirmed by SRP
- **Shallowest X_j can be produced by either ALD or MLD (GaD here)**
  - Dopant level with ALD is higher than MLD due to encapsulated surface to reduce out-diffusion
  - Highest dopant level can be produced by PaD with LA or FLA

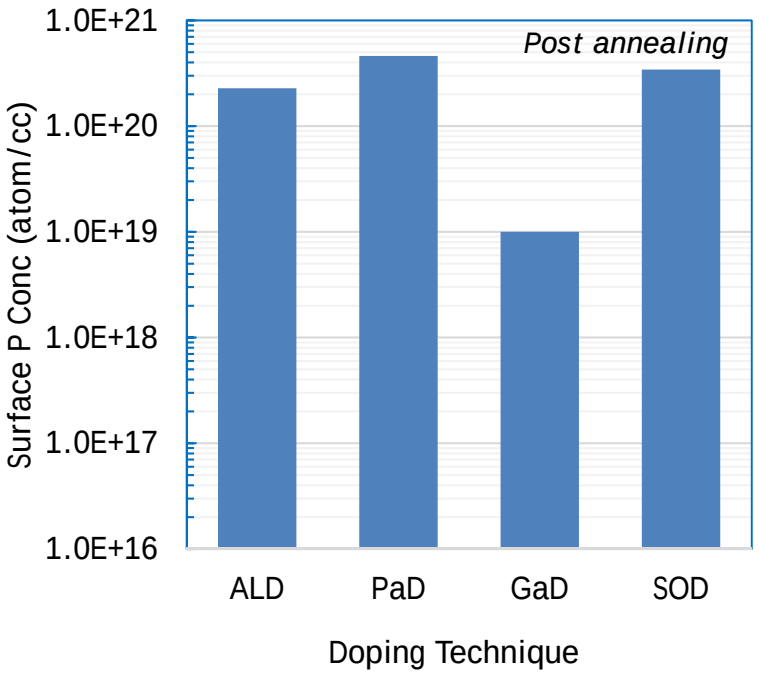


As doped/dep	< 5 nm
Laser annealed	< 7 nm
Flash annealed	<12 nm
RTP annealed	<21 nm

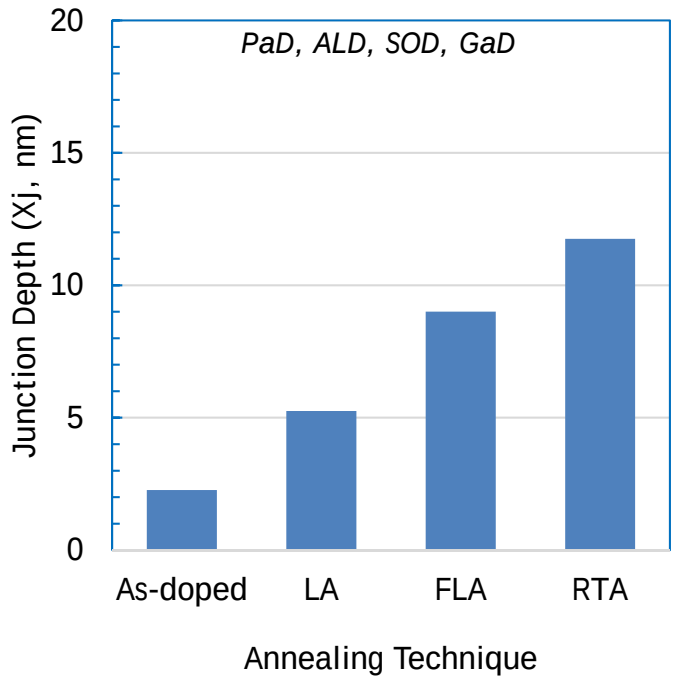
Dopant Level and Junction Depth (X_j)

Doping vs. Annealing Technique

Average Surface Dopant Level of P



Avg Junction Depth with Various Annealing



- **Dopant level at Si surface can be increased by plasma-assisted doping, while GaD/MLD shows the lower level due to its limited dopant source**
  - Highest dopant level can be produced by PaD with LA or FLA
  - Dopants activation confirmed by 4pt-pb & SRP
- **Shallowest X_j can be produced by laser annealing with the similar surface P level**

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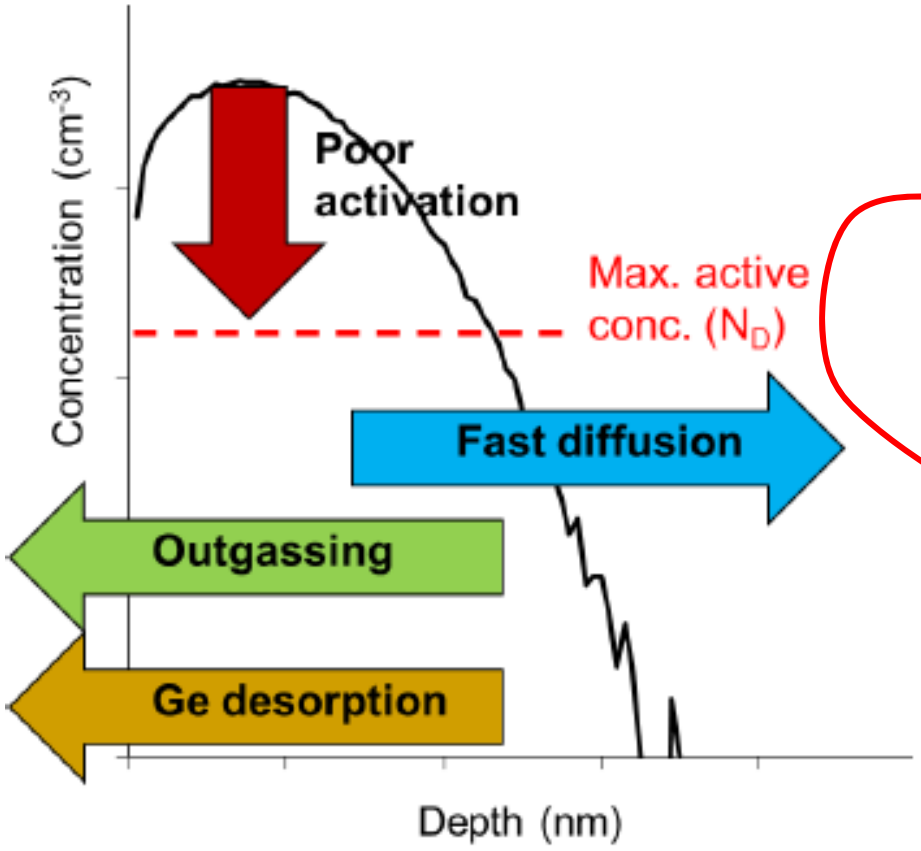
Issue of N Dopants on Ge



- **Fast diffusion of n-dopant is unfavorable to for USJ on Ge**
- **Efficient strategies to be developed**
  - To constrain the diffusion of n-type dopants
  - To increase the level of electrical activation, i.e., to hinder the formation of dopant defect cluster

Flash or Laser Anneal

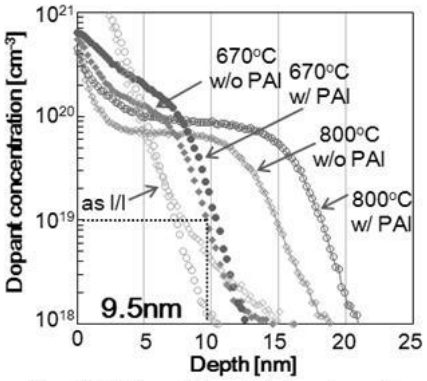
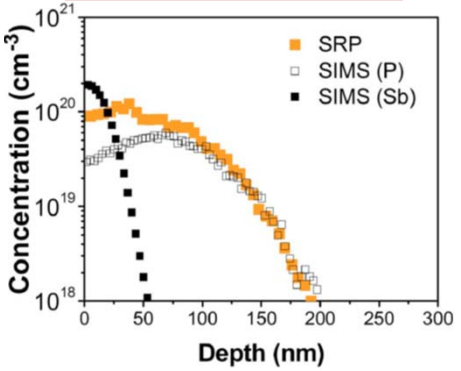


Fig. 2 SIMS profiles of P-doped samples. Shallow junctions below 10nm can be achieved.

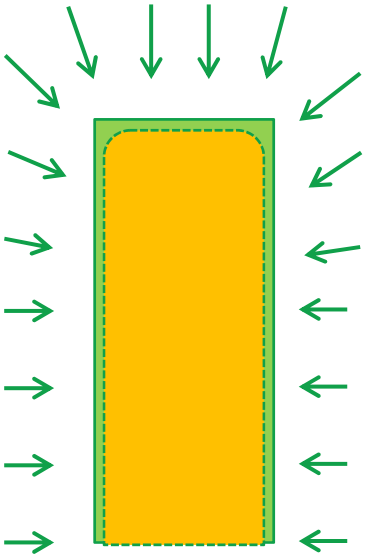
co-Doping



Plasma-Assisted Doping for P Doping on Ge

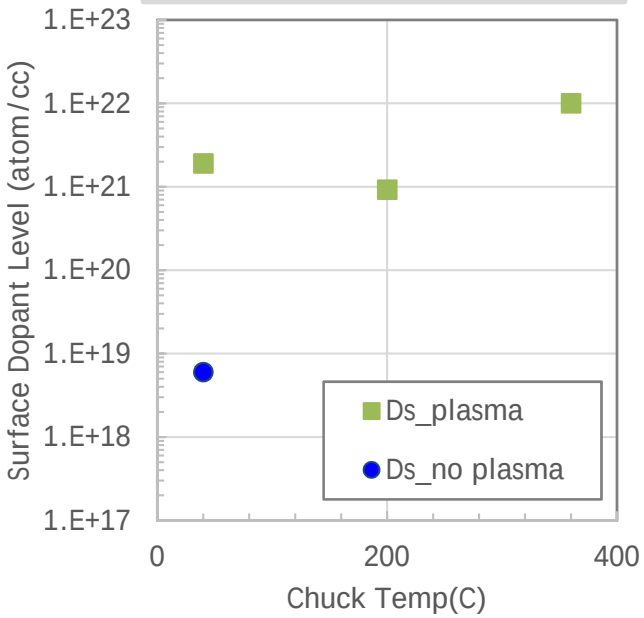
With vs. Without Plasma: As Doped

Plasma-assisted Doping

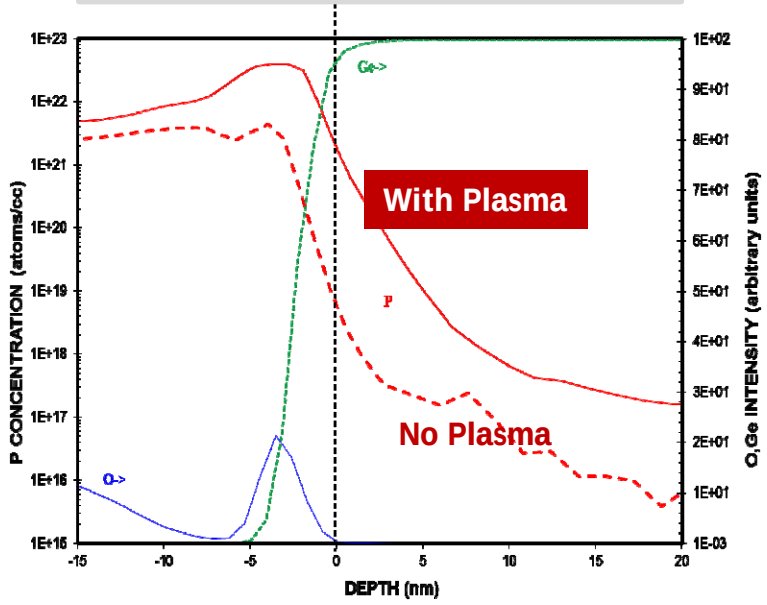


- **Plasma doping (no bias power, PH_3) produces ~5 nm junction depth, while no plasma (gas only) could not produce any**
- **No significant effect of wafer temperature is seen on plasma-assisted doping level at Ge surface**

Dopants Level vs. Plasma



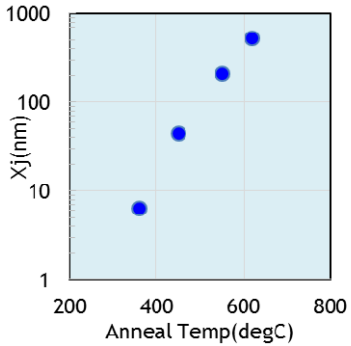
With vs. Without Plasma @ 45C



To Increase P Level on Ge

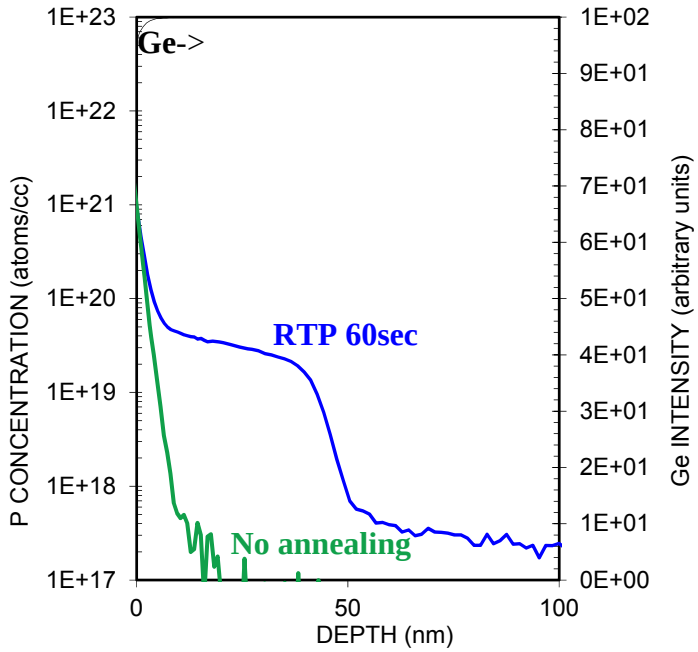
Annealing Variation and Other Enhancement

X_j vs. RTP Temp

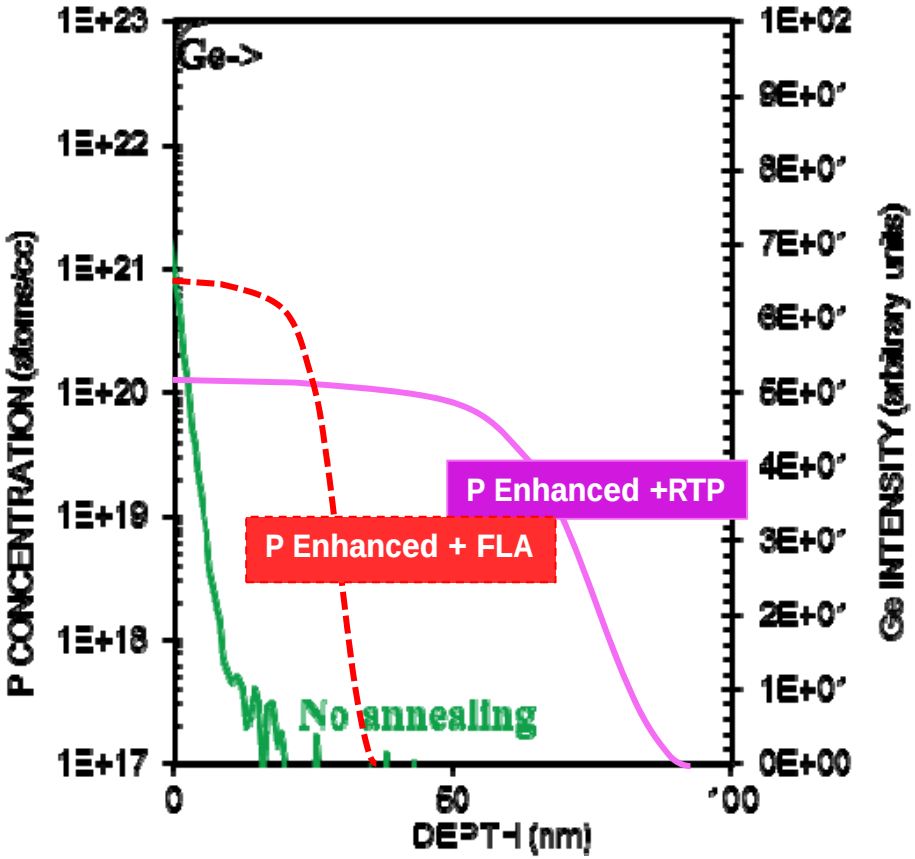


- **P level after annealing by RTP is < 3E19**
- **Flash or P Enhancement will be the option to increase the level**

Pre and Post RTP on PaD Ge

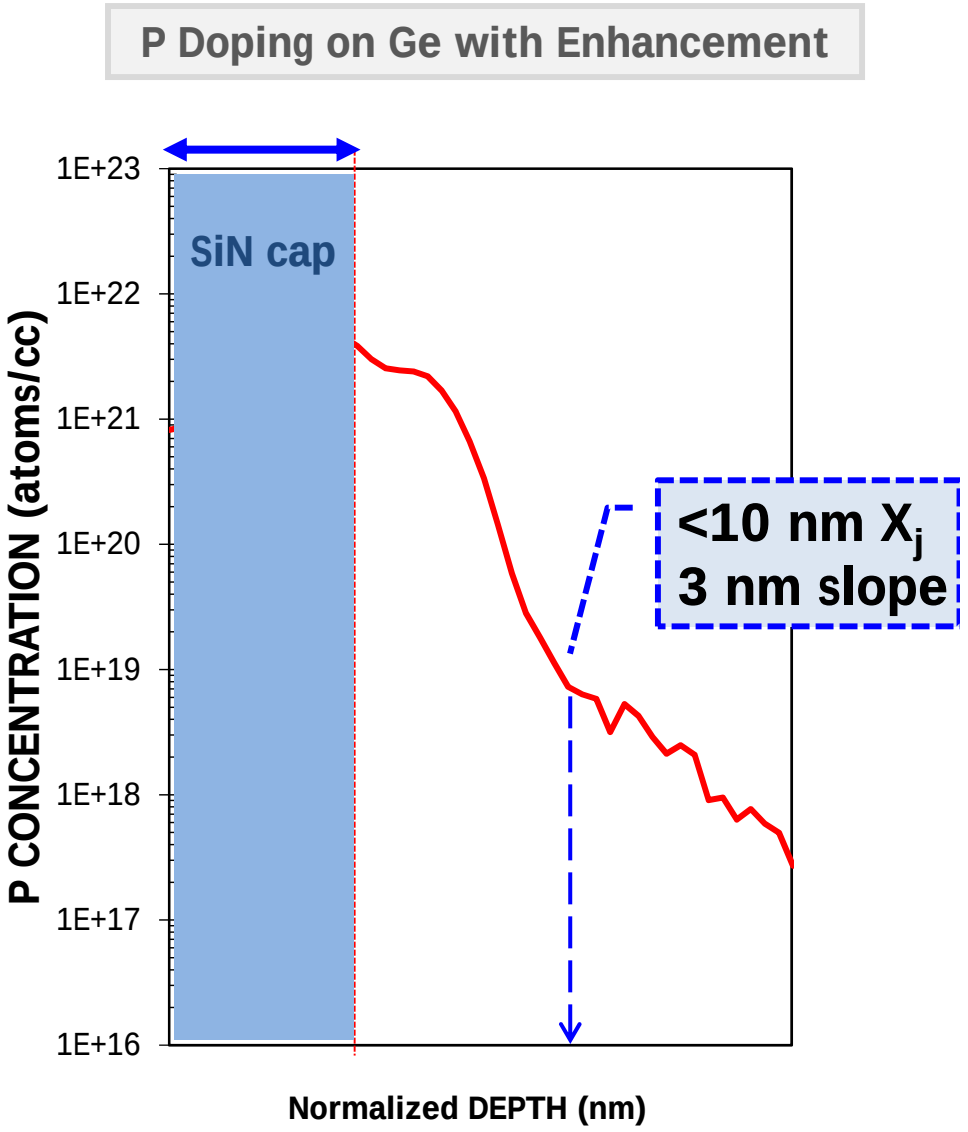


Expected P Concentration with *Enhancement + Flash Annealing*



Enhanced P Level of Plasma-Assisted Doping on Ge

After RTP 600C, 30 sec

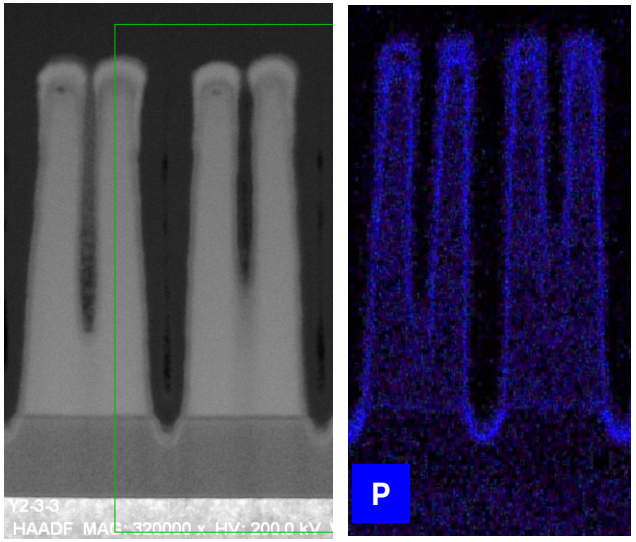


- P level after activation annealing by RTP is ~1E21
- P Enhancement with other annealing will be the option to increase the level
- Steeper profile is expected as FLA or LA will be applied

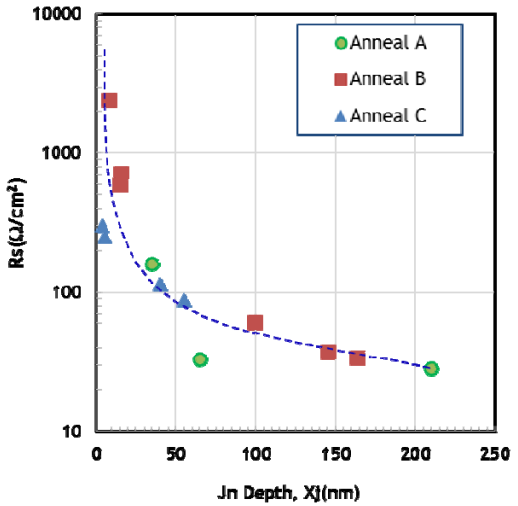
Executive Summary

- **Novel process approach has been developed to form USJ on 3D structure of Si and Ge using plasma**
- **Novel approaches increase P dopant level and lowers Rs further, therefore, conformal doping on 3D structure can be enabled without bias power**
  - No structure damage has been observed
  - Confirmed that doping with no bias power forms shallow X_j depth of <7 nm on 3D structure
- **Finally various annealing could reduce X_j to <5 nm**

Doping on 3D Structure



Annealing vs. X_j



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Fast **Solutions**

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