Super Activation Obtained by Melt UV Laser Annealing of Highly Surface-Segregated Dopants in High Ge Content SiGe

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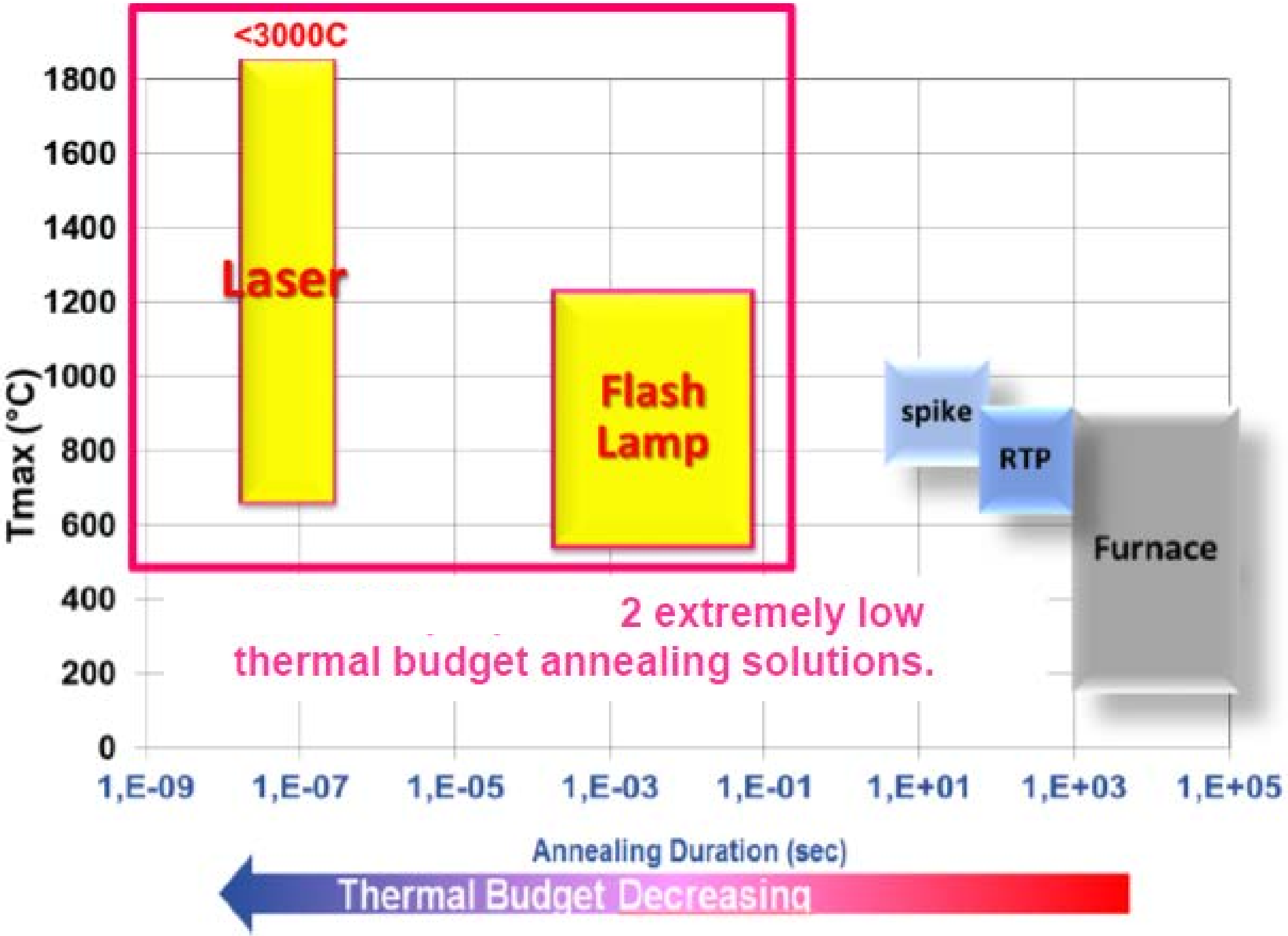
Outline

- Introduction
- Experiment Description
- Melting & Solidification
- Segregation
- Activation
- Conclusion

Advanced Nodes Have Reduced Thermal Budgets

- Allowable thermal budgets have been significantly reduced in recent years
- Higher temperatures favor dopant activation over dopant diffusion
- This has challenged the task of material modification without degrading the complex structure of advanced devices



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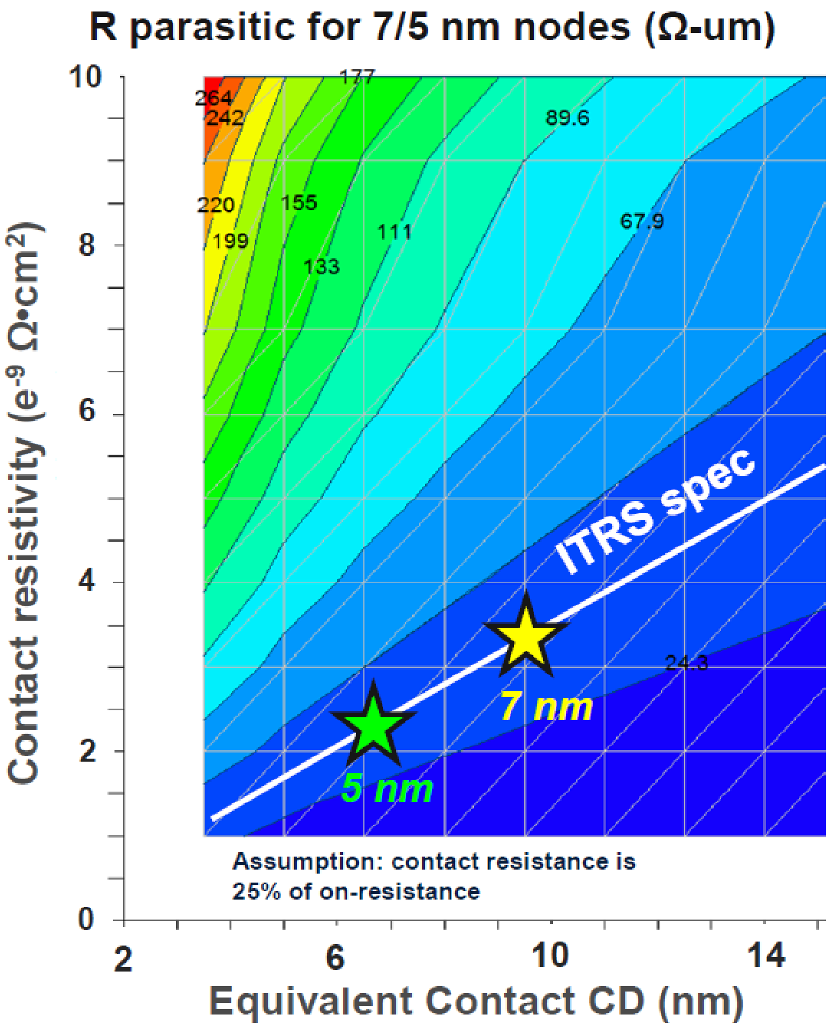
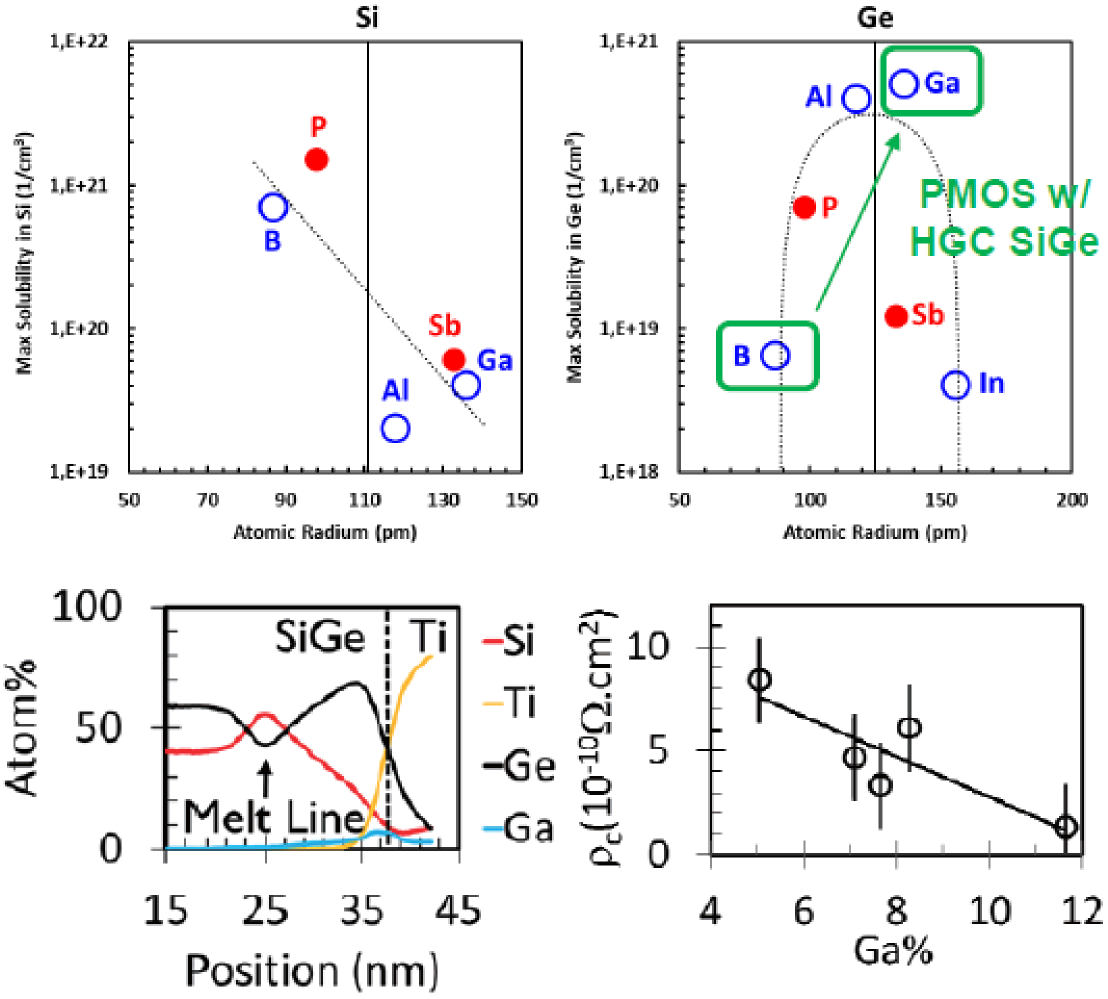
Record Low Contact Resistivity by Melt Laser Anneal (MLA)

- Extremely low contact resistivities are required for future nodes
- Need to ensure that p-type dopants are fully activated in SiGe



C.-N. Ni, et al., VLSI 2016, pp. 70-71.

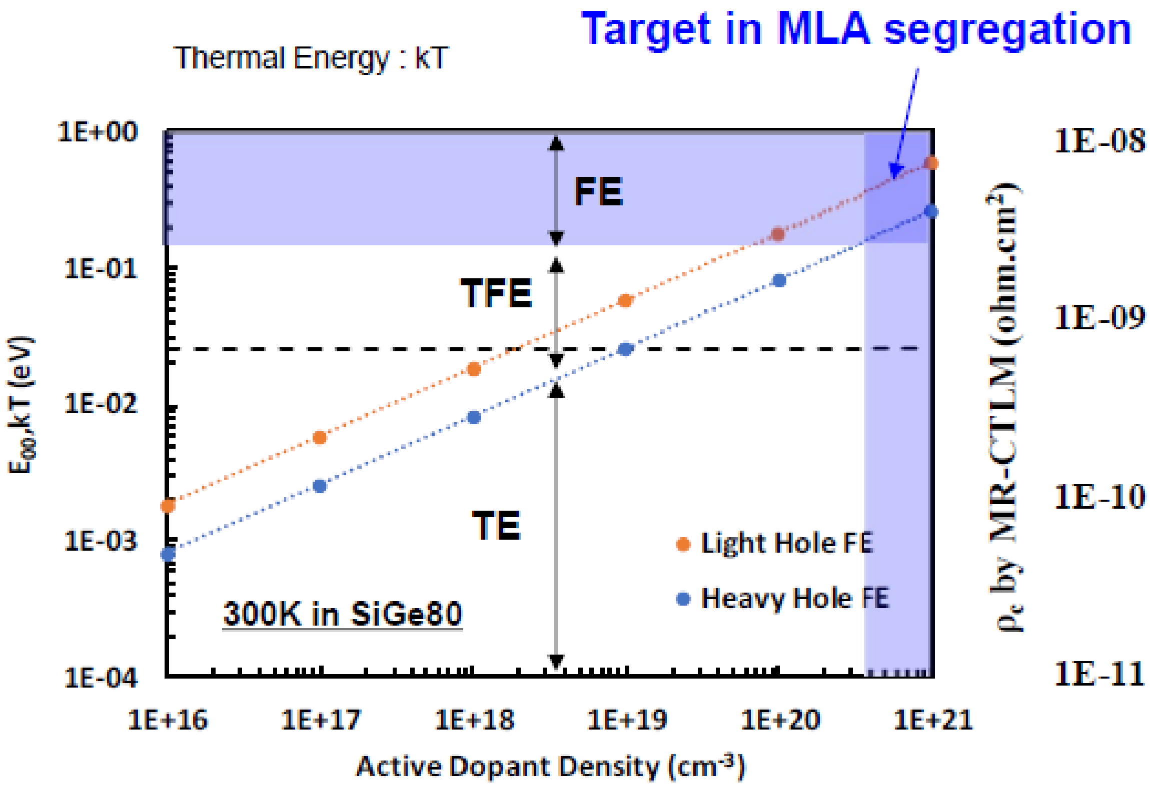


J.-L. Evareat et al., VLSI 2017.

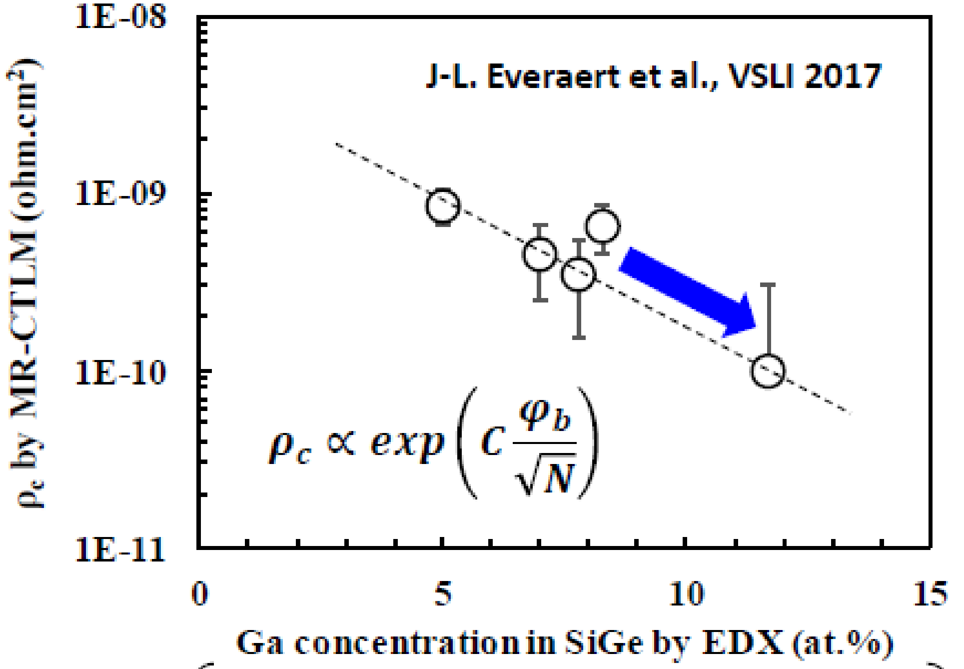
Challenges for Extremely Low ρ_C

- At the Schottky barrier, field emission dominates the carrier transport

- Increasing the amount of active Ga will decrease ρ_C



Calculated based on D. K. Schroder, "Semiconductor Material and Device Characterization," John Wiley & Sons, Inc., (2006), p. 130.



$$\rho_c \propto exp\left(C\frac{\varphi_b}{\sqrt{N}}\right)$$

Although EDX doesn't give active Ga%, one may expect N increase with Ga% increase.

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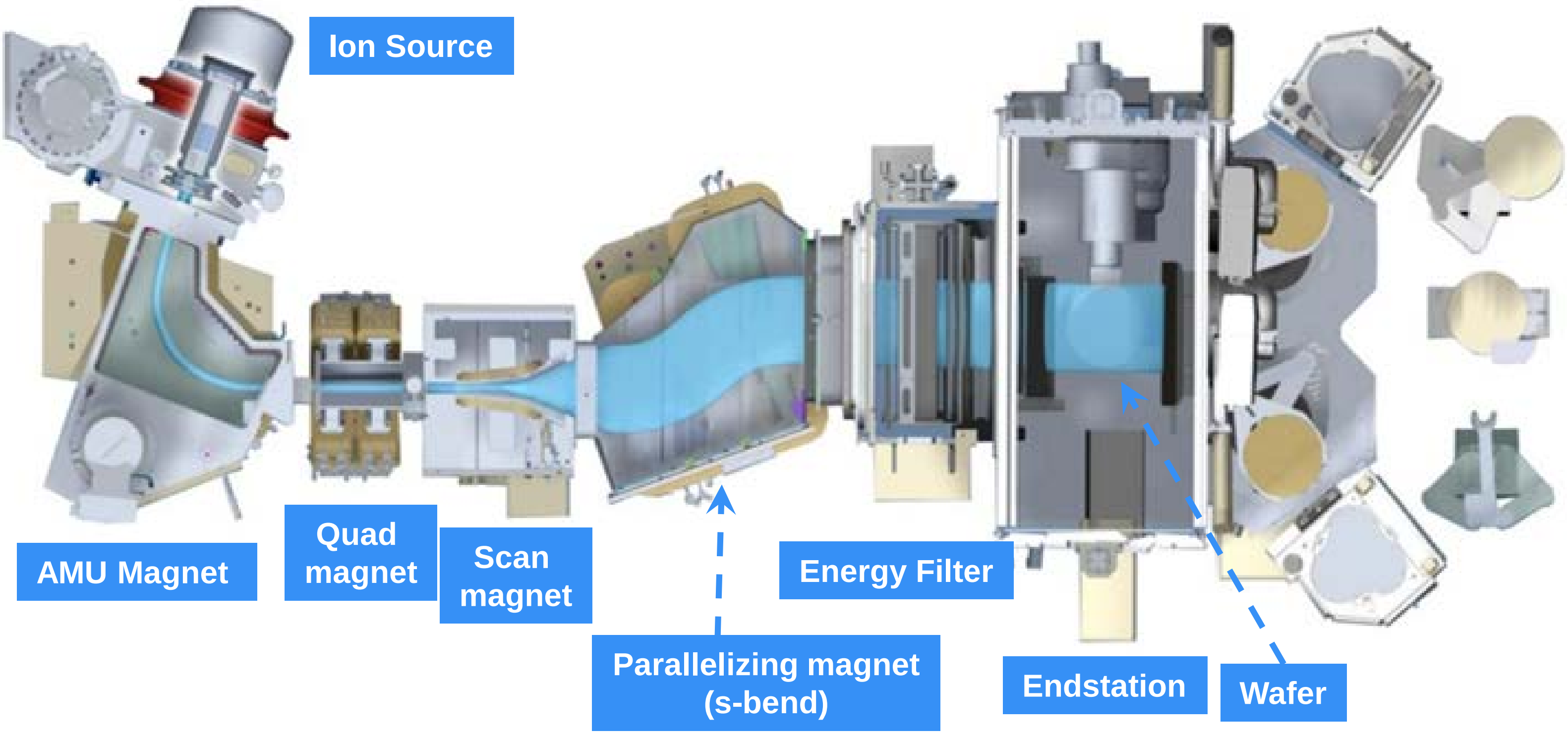
Axcelis Purion H High Current Implanter
Ga Implants

- Accelerates single charged ions from 500 eV to 100 keV
- Beam currents up to 35 mA
- Basic operation
  - Extract a spot beam and mass filter in AMU
  - Desired spot beam focused through resolving aperture (with defines mass resolution)
  - Quadrupoles focus beam into scanner
  - Scanned spot beam parallelized by s-bend correction magnet
  - Angular Energy Filter for energy purity



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SCREEN/LASSE LT3100 UV Excimer Laser Annealing System
Nanosecond Anneals

Experiment

- 300mm n-type Si(100) prime wafers
- 66nm thick SiGe 50% layer deposited by CVD
  - Growth pressure 20 Torr, purified H_2 carrier gas flow
  - 550°C deposition, using SiH_4 + GeH_4
- Film thicknesses controlled using X-ray reflectivity
- The deposited SiGe is partially relaxed
  - Macroscopic degree of relaxation is estimated to be 30-40%
- Gallium ion-implanted as a dopant (26 keV, ~1×10^{16} at/cm^2)
  - Projected range (R_p) ~20nm
- Samples were annealed at +20°C using a 308 nm UV excimer with different energy densities (ED)
  - Pulse duration 160 ns
- Dopant profile before and after MLA was measured by SIMS
- Dopant activation was studied by 4-pt. probe and electrochemical capacitance-voltage profiling (ECVP)

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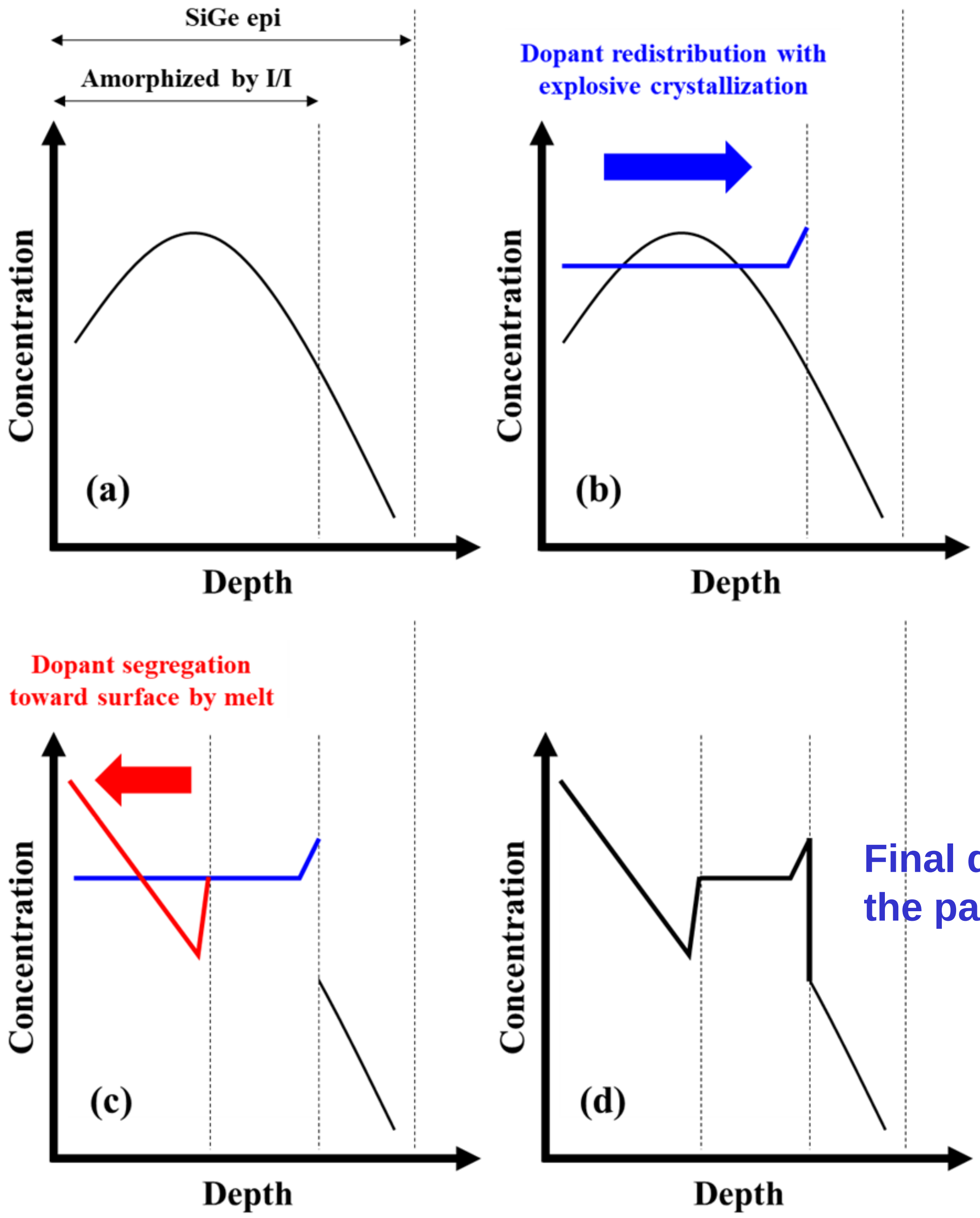
Dopant Redistribution During MLA

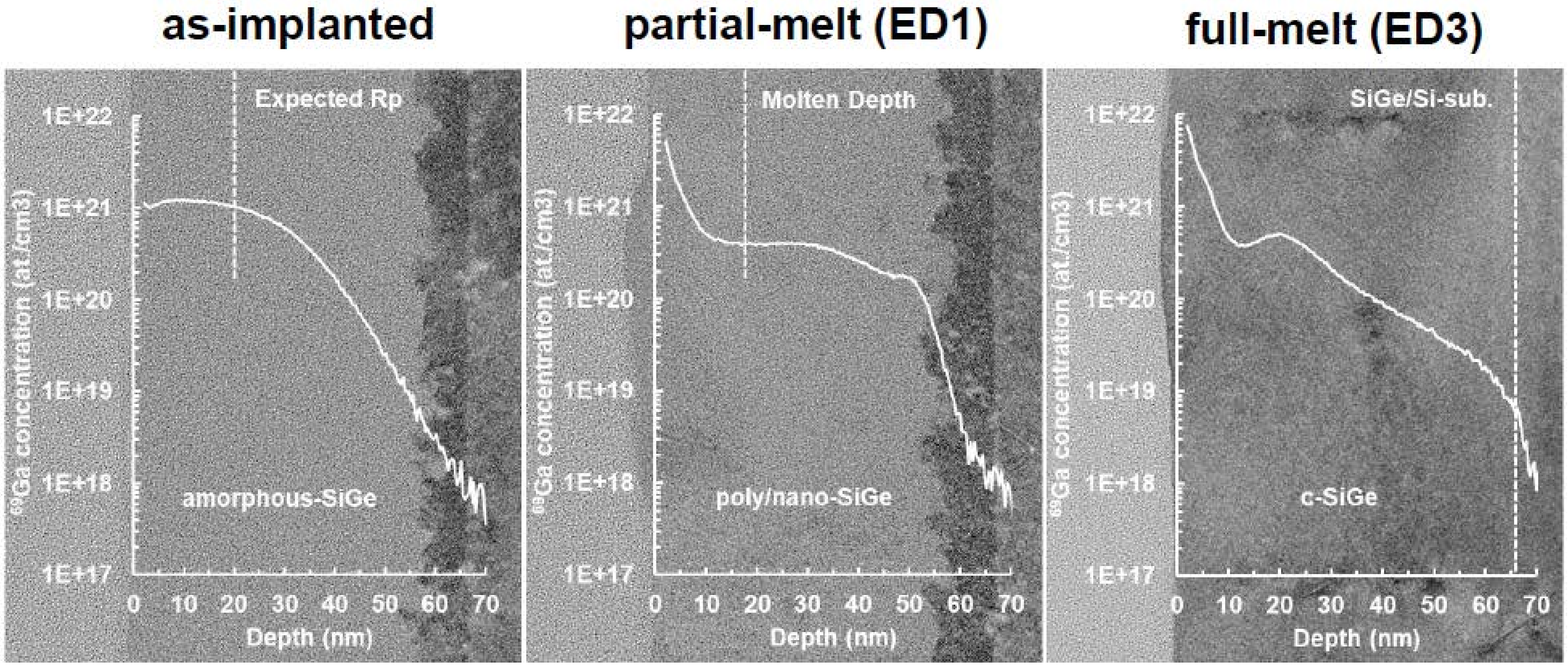


Final dopant profile after the partial MLA process.

Melting and Solidification in Melt Laser Annealing

- **Ga segregation is already observed in partial melt**
  - **Dopants are diffused up to the initial α-SiGe bottom (explosive crystallization)**

- **In the full melt case, the recrystallized SiGe is strained and contains defects**
  - **Dislocations near the relaxed initial epitaxy interface**



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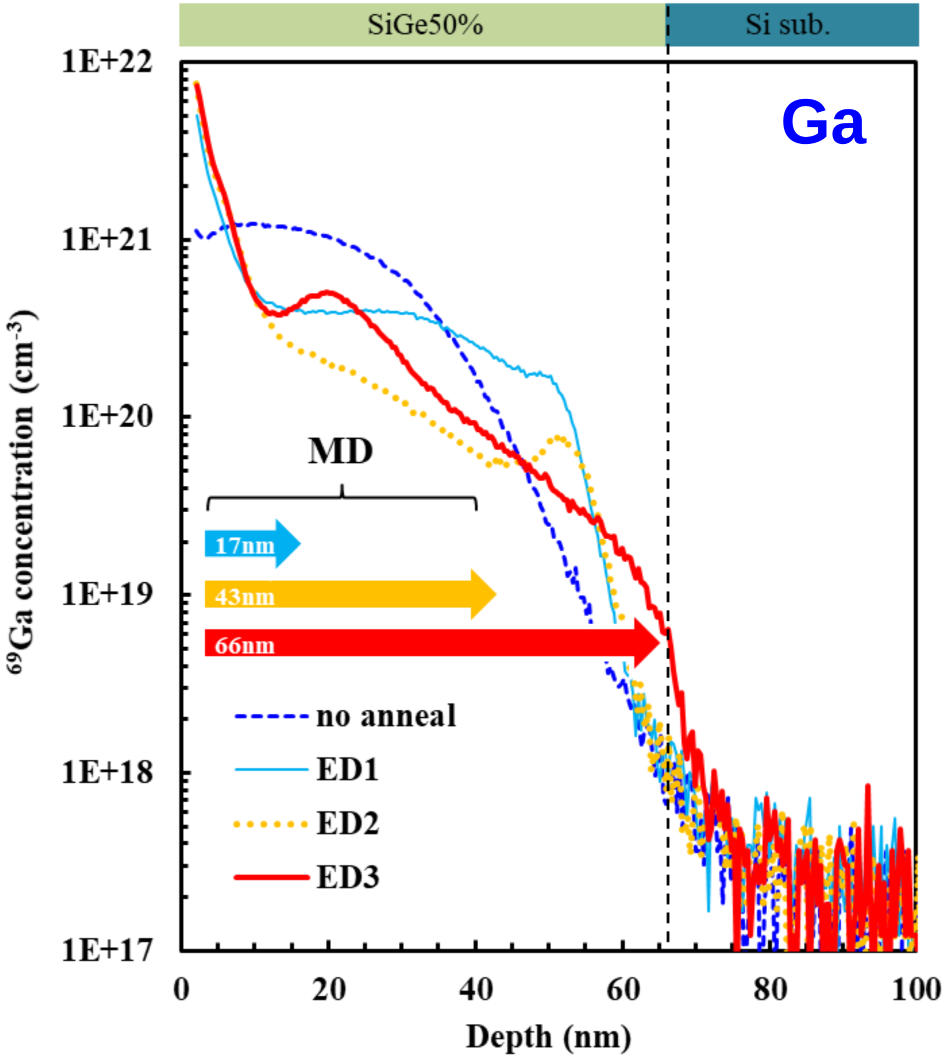
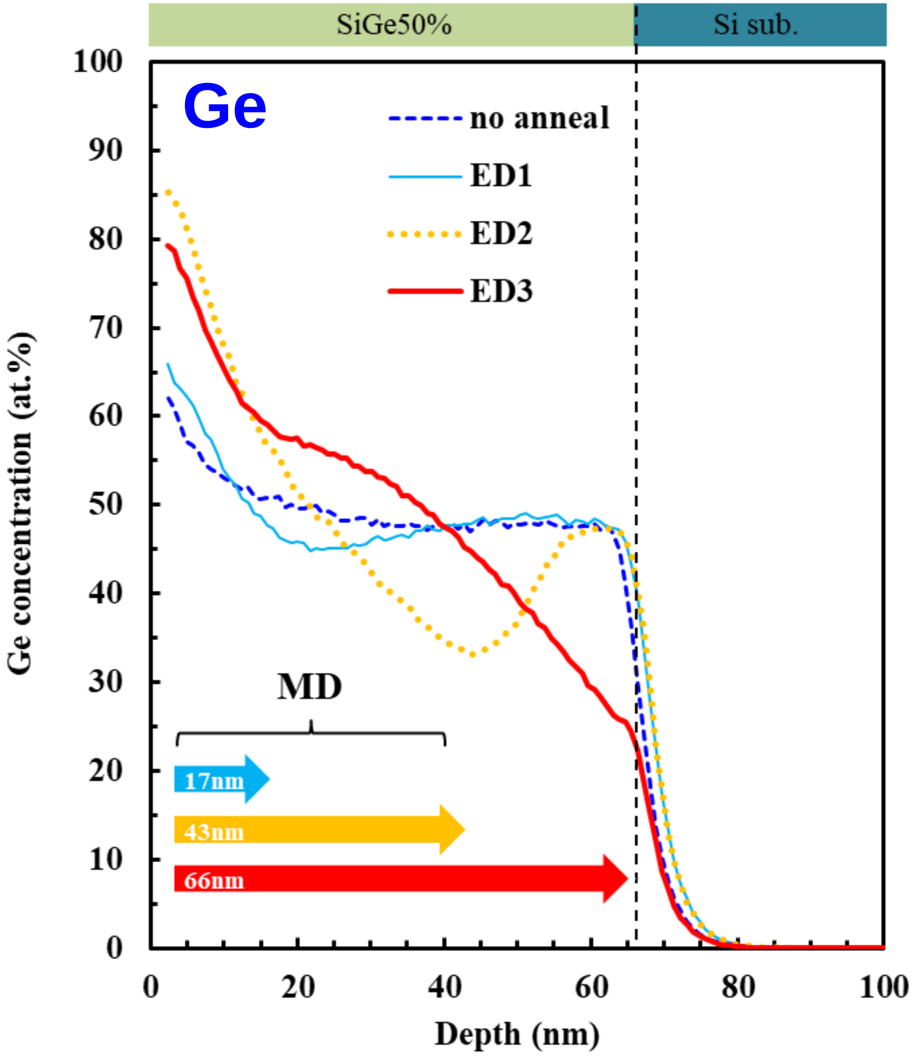
Significant Redistribution of Both Ga and Ge During MLA





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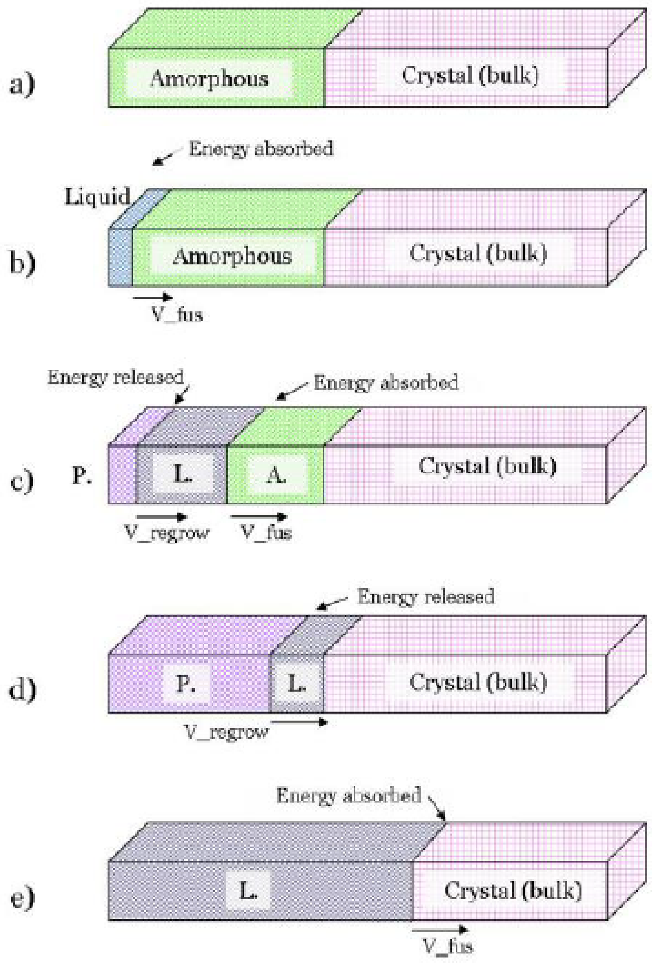
Explosive Crystallization Likely Occurring During MLA

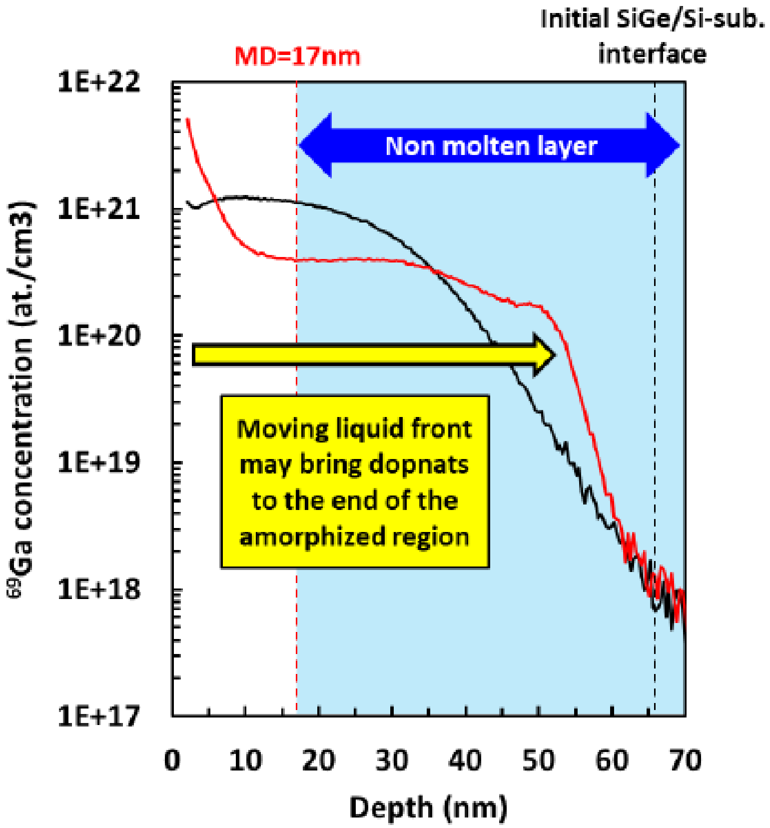


S. F. Lombardo et al., JAP 2018.

Self-sustained crystallization

1. Latent heat of solidification : l-Si ➔ p-Si
2. Heat for melting : a-Si ➔ l-Si

If 1 > 2, the process is self-propagating.



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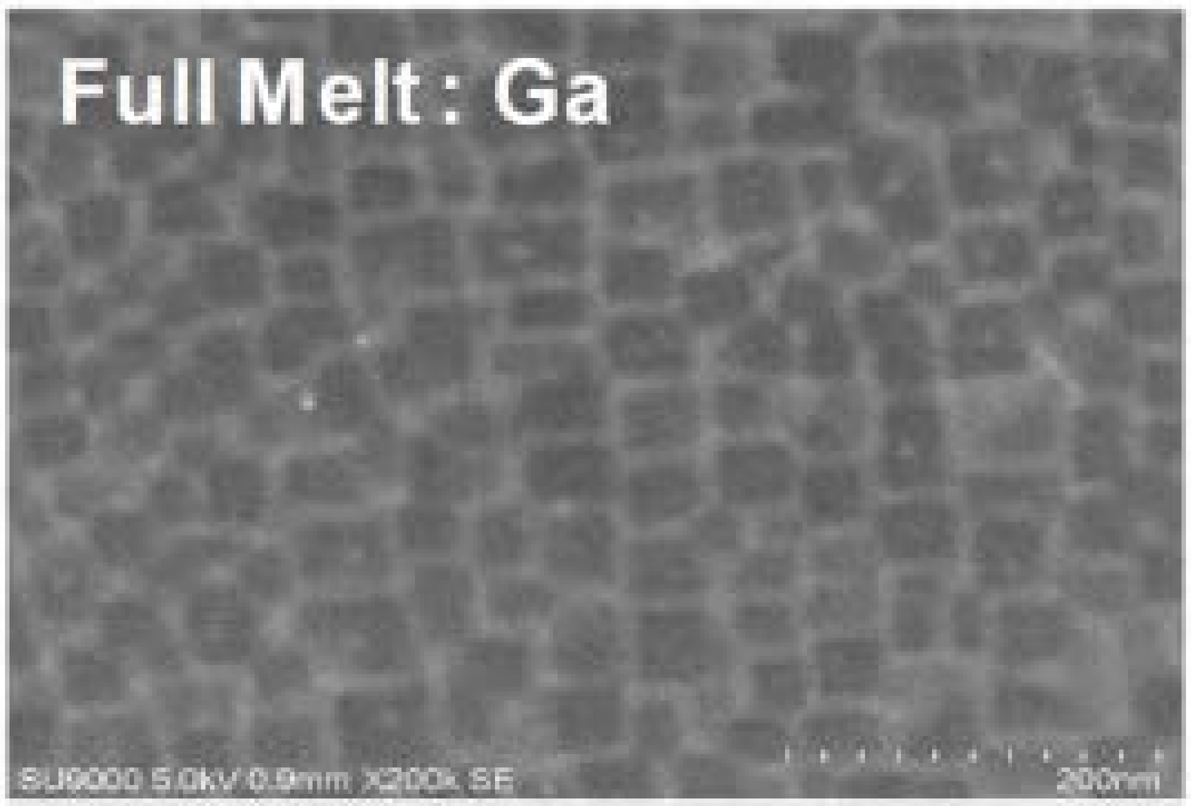
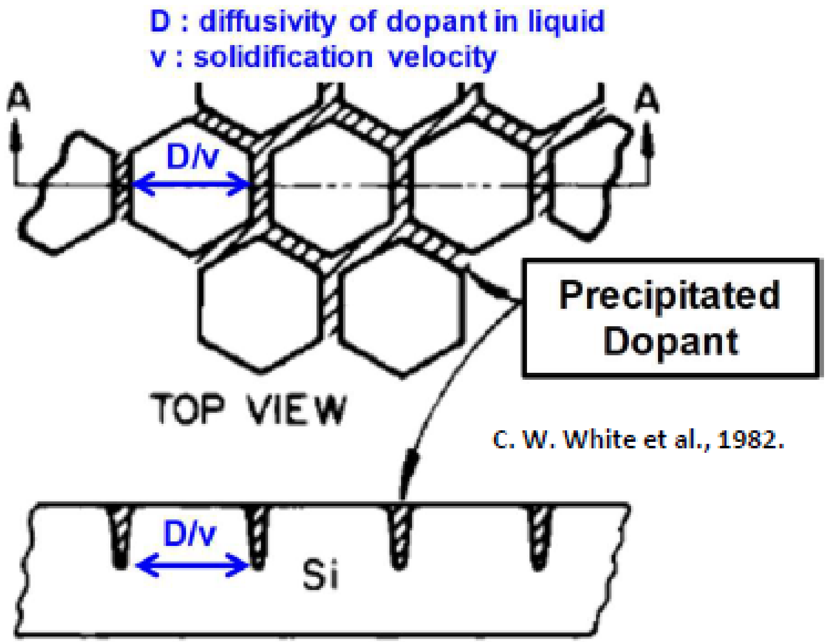
Dopant Precipitation Seen in Surface SEM

- Dopant precipitation forms honeycomb-like pattern on the surface
  - No pattern observed for undoped $SiGe_{50}$ with full melt
- Solidification velocity is dominated by the irradiated laser pulse and the thermal conductivity of the semiconductor





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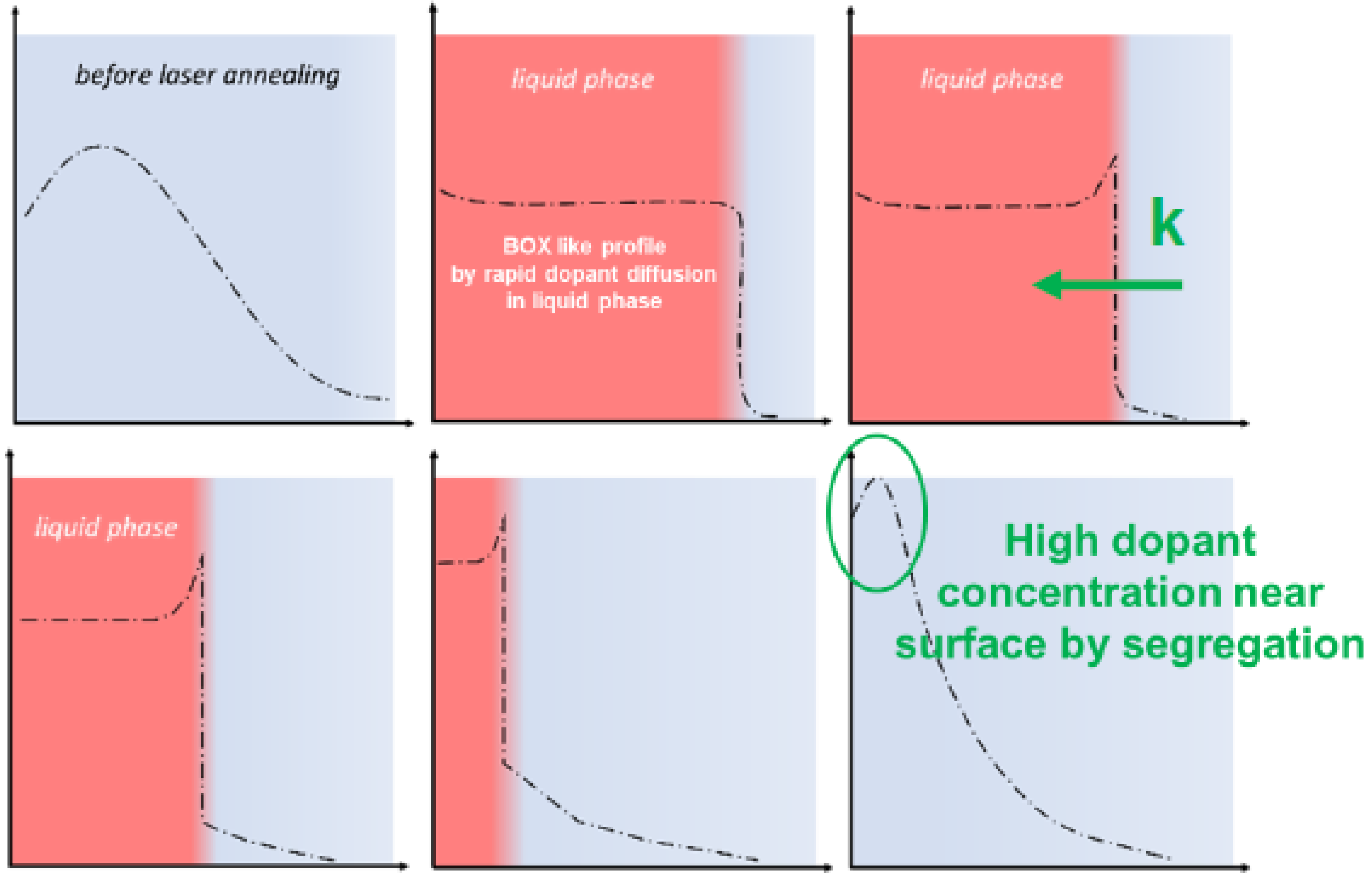
Segregation Coefficient (k)

- The segregation (or distribution) coefficient is the ratio of the solubility of the dopant in the solid phase to that in the liquid phase
  - The smaller the k value, the more segregation occurs



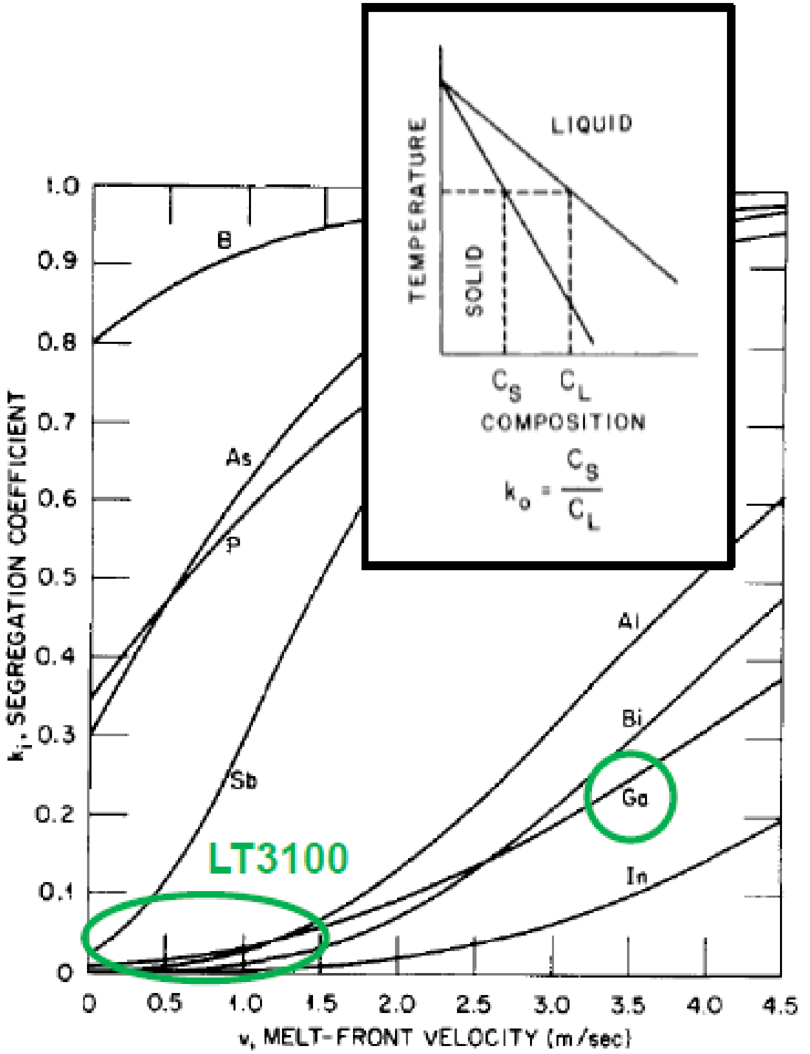


FIG. 1. Dependence of k_i in Si on melt-front velocity using Eq. (8b).

R. F. Wood, APL 1980

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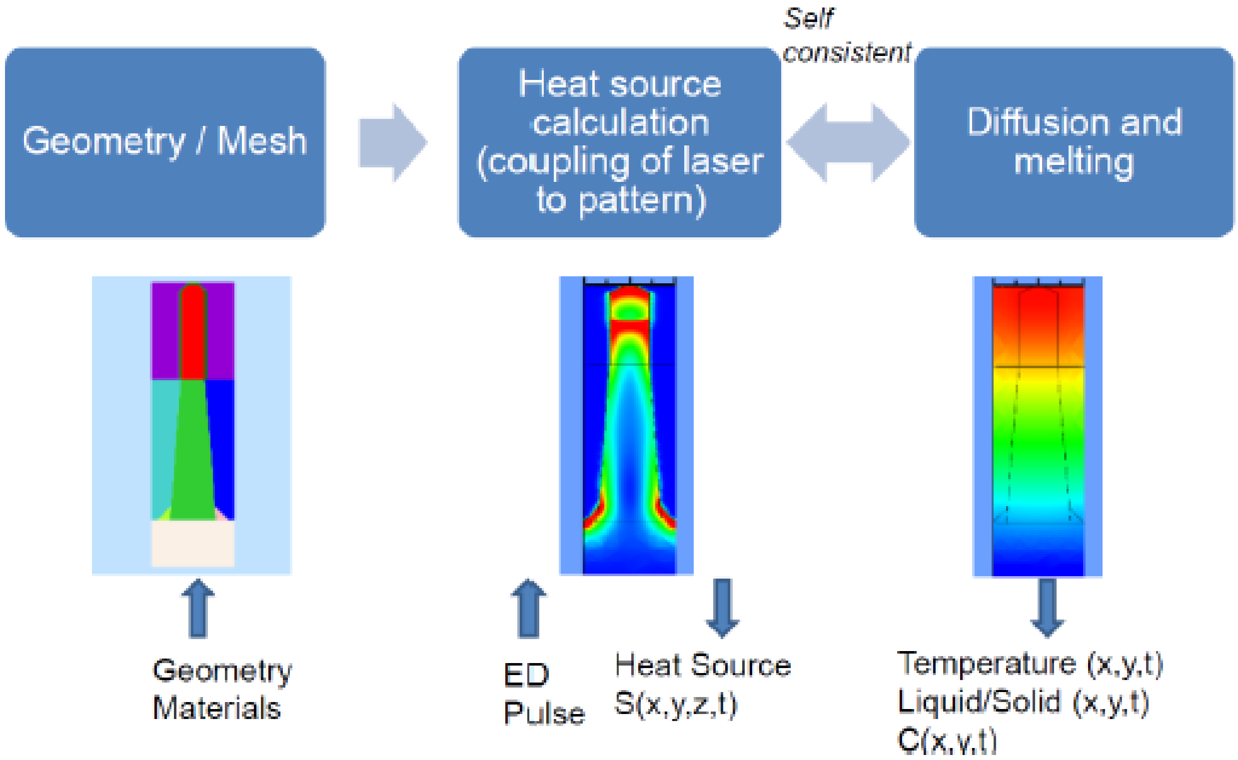
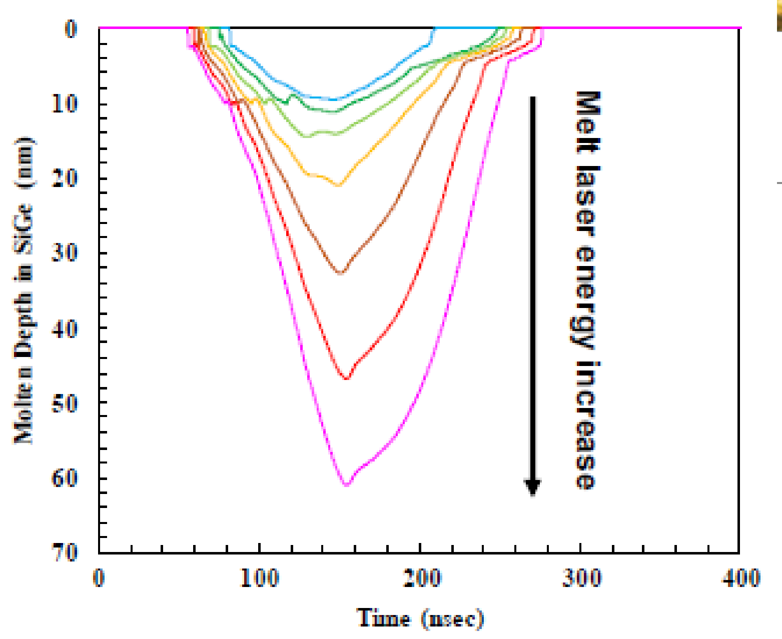
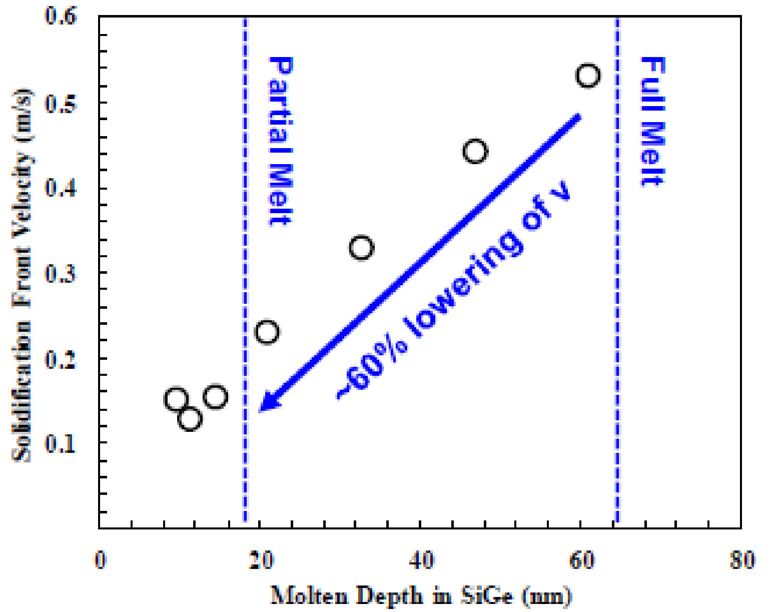
LASSE Innovation Application Booster (LIAB)

- In-house simulation software for 1D, 2D, 3D
- Self-consistent finite element approach







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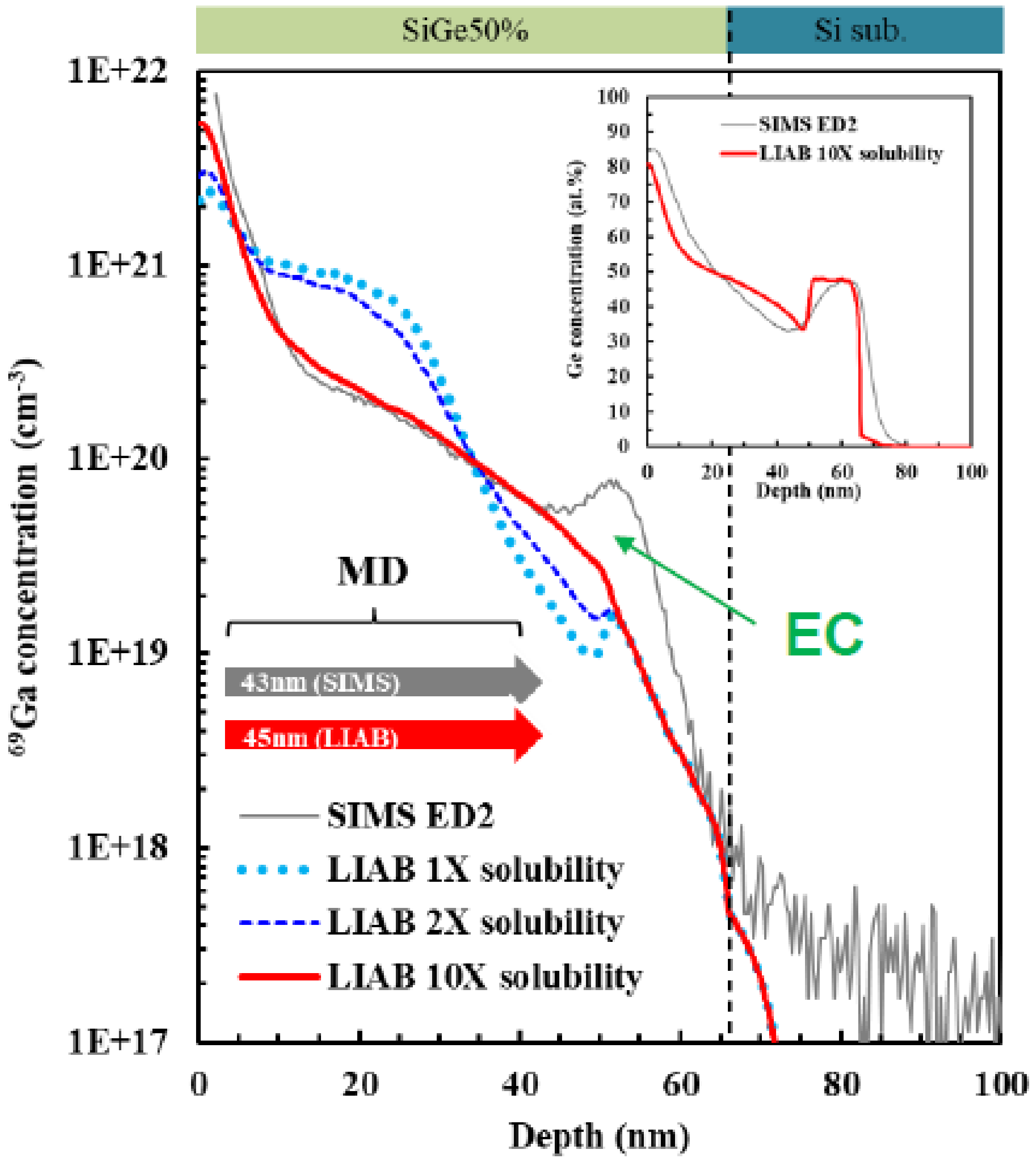
LIAB Results
What Changes in SiGe during MLA?

- **Solubility in the liquid needs to be 10X higher than in the solid to suppress dopant precipitation**



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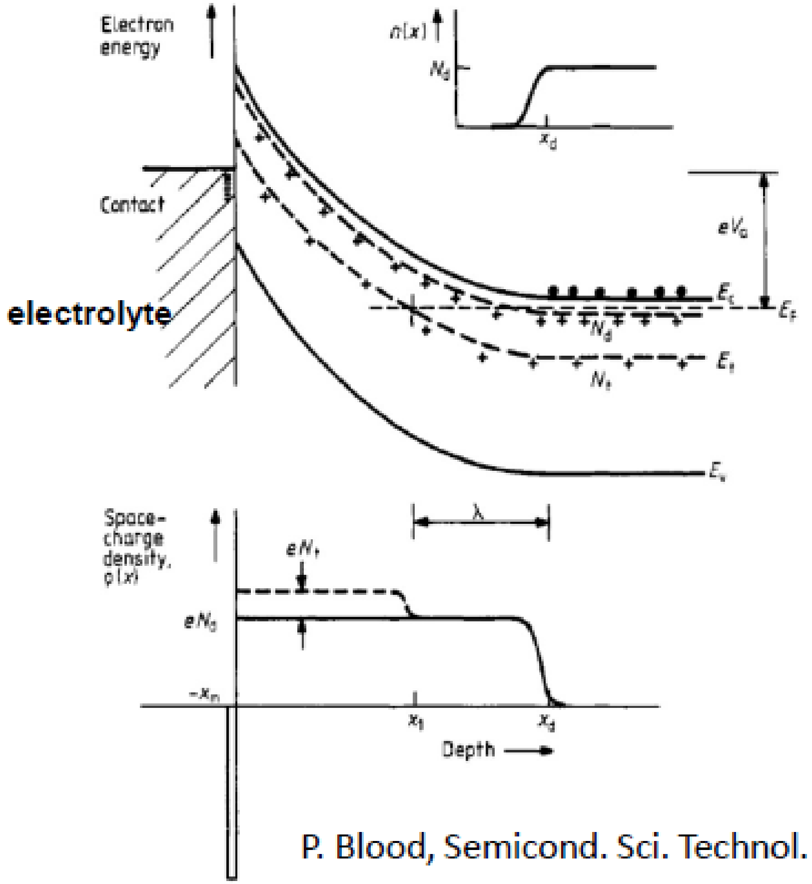
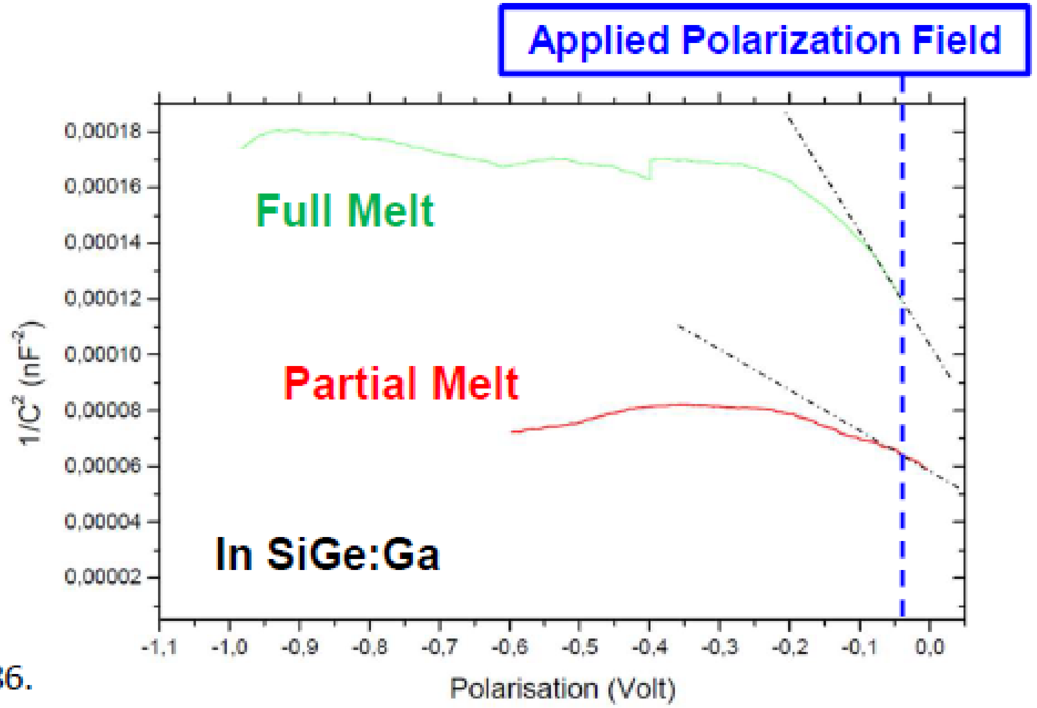
Electrochemical Capacitance-Voltage Profiling (ECVP)
Active Dopant Profiling in SiGe



P. Blood, Semicond. Sci. Technol. 1986.

$$\frac{1}{C^2} = \frac{2(V_{bi} - V_m)}{\varepsilon_r \varepsilon_0 q N^* A^2}$$

B. Sermage et al., JAP 2016.

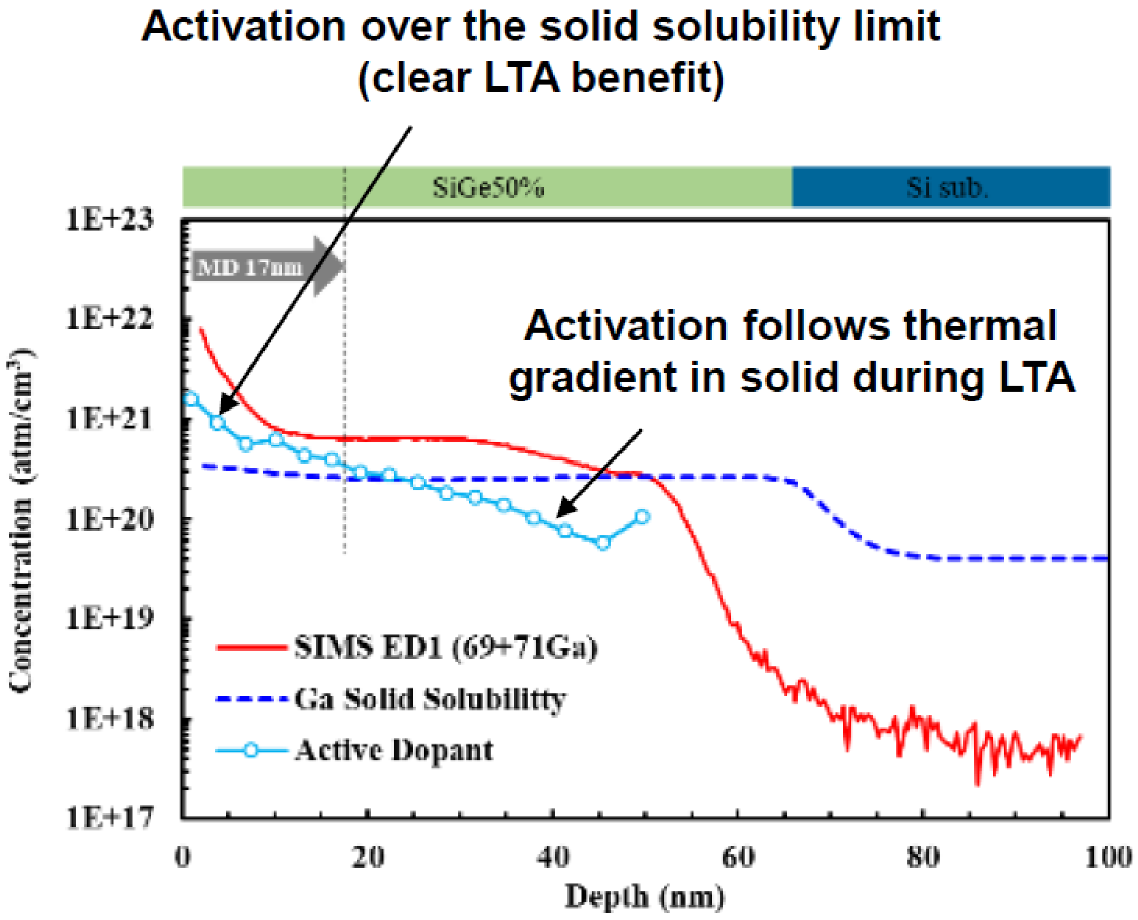


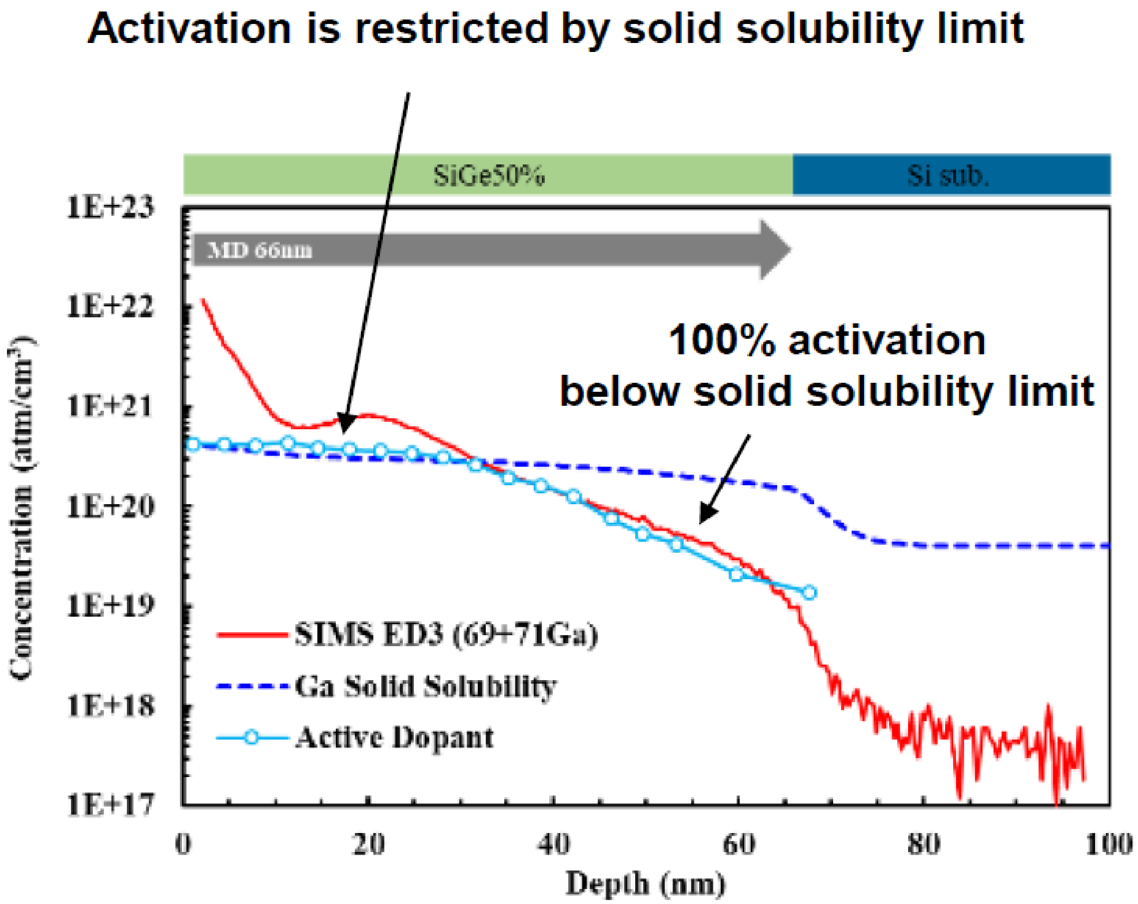
Active dopant concentration at the end of the space charge zone is measured.

The roll-off of $1/C^2$ – V curve comes from deep level defects.

ECVP Indicates LTA Can Activate Ga Over Its Solid Solubility Limit for Shallow Melt Depths

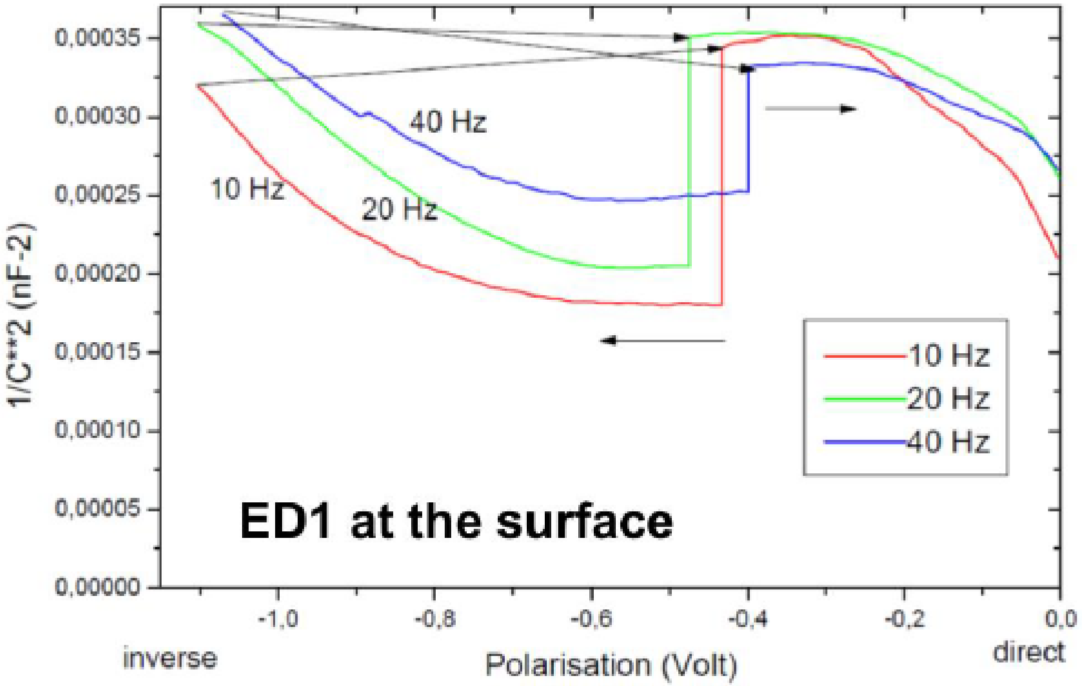
- This benefit seems to disappear for deeper melt depths

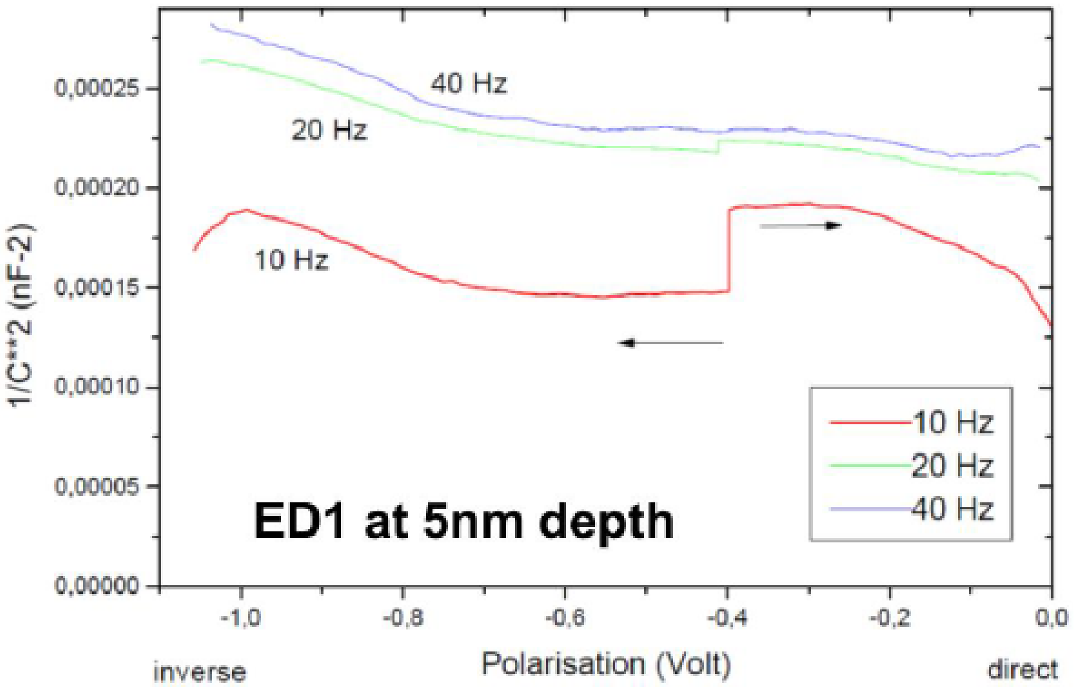




Why Are Some Dopants Inactive?

- **A large amount of segregated dopant (1E22 minus 2E21 = 8E21) is still inactive**



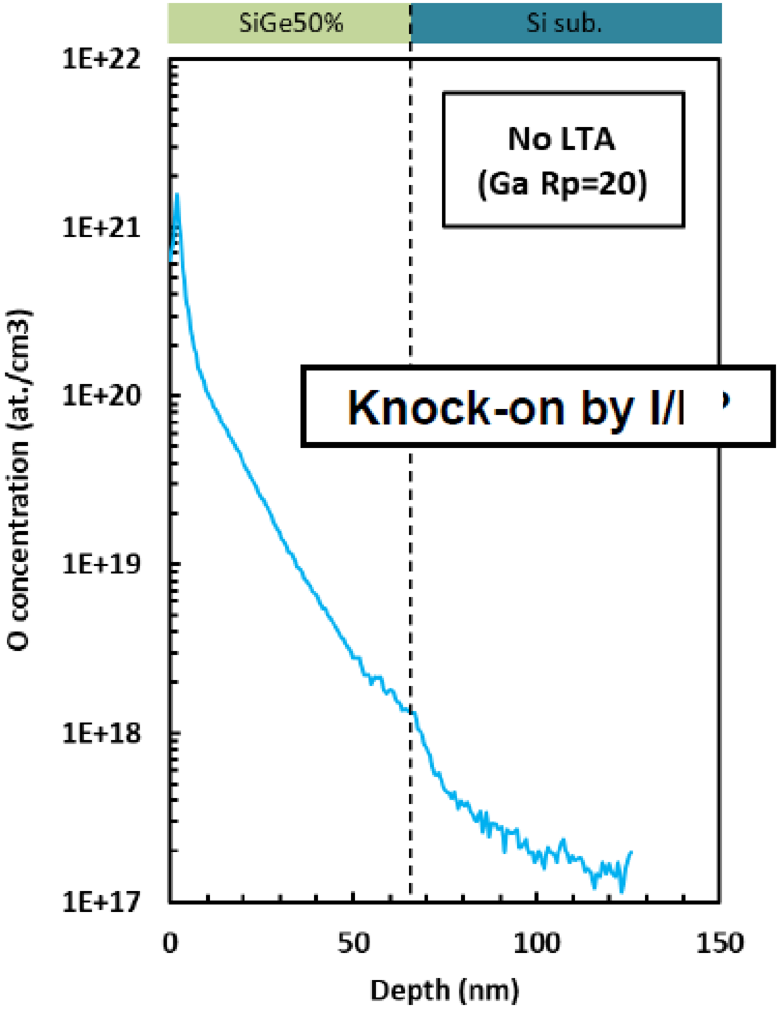


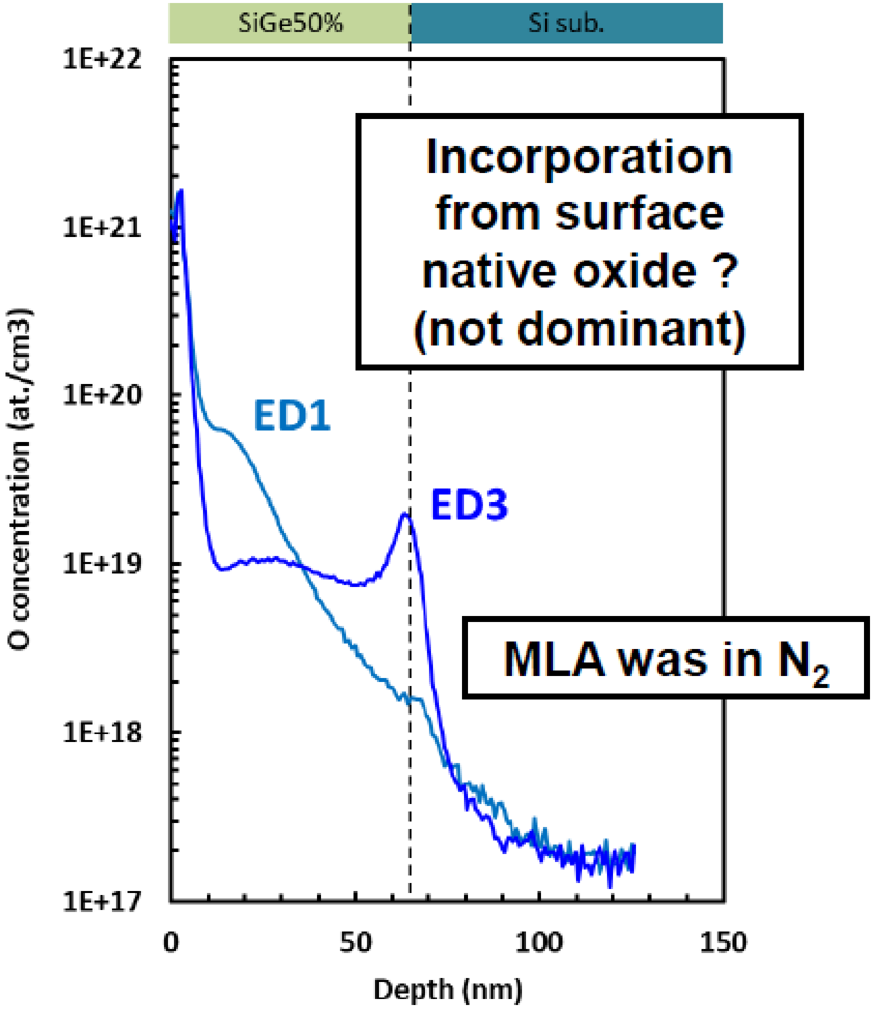
Deep donors with a lifetime of a few seconds exist at the surface.
In Si, they are associated to O-related defects.*

*Data in science and technology, Semiconductors, Group IV and III-V, Madelung, (Springer, Berlin, 1991), p. 25

Evidence of Oxygen Knock-On from Ion Implantation

- Possibility of further activation increases from optimizing the ion implantation steps





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Conclusions

- Ga shows promise for lowering ρ_C to SiGe
- Simulation suggests that Ga solubility in liquid SiGe might be 10X higher than in the solid
- Ga surface segregation and activation beyond equilibrium solubility limit were demonstrated for shallow melt depths
  - This is despite suspected oxygen incorporation
- Not all segregated Ga is active
  - Lowering the velocity of the solidification front may improve Ga activation
- Reduced oxygen incorporation may further improve the activation
  - But it is difficult to reduce oxygen knock-on effects