The Importance of Ion Implantation for Superconducting Silicon Devices

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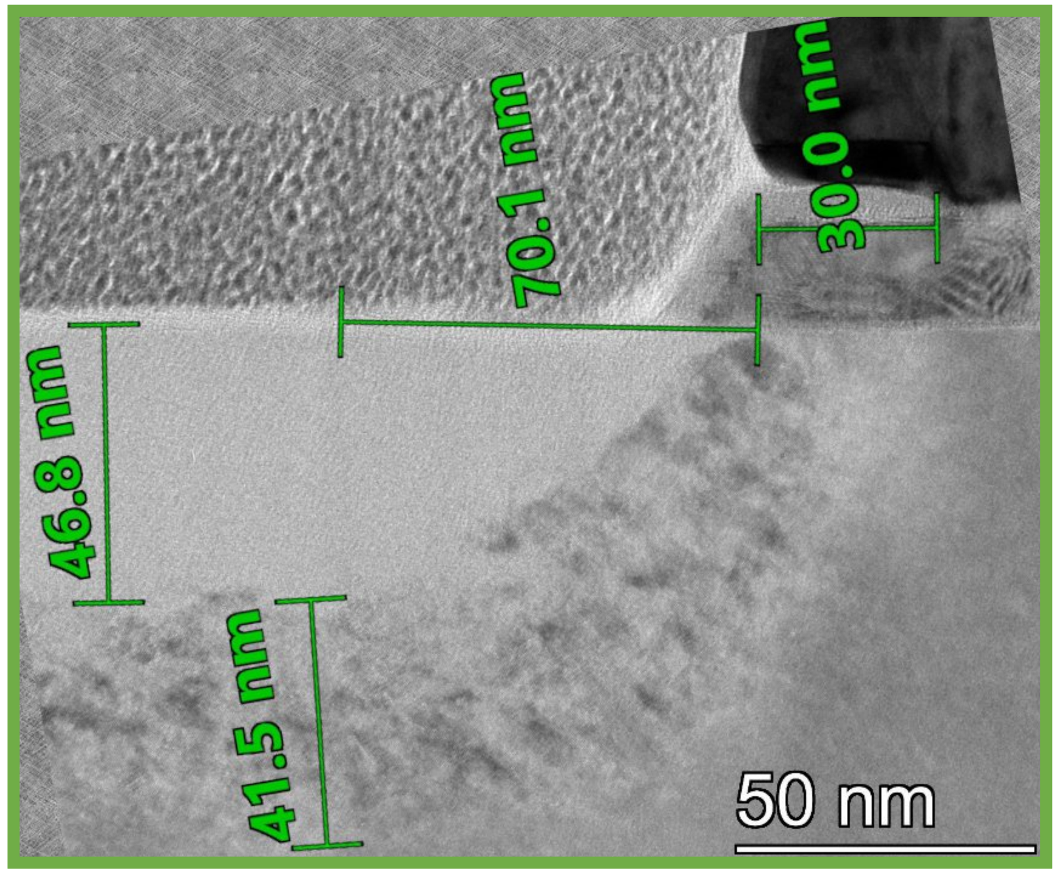
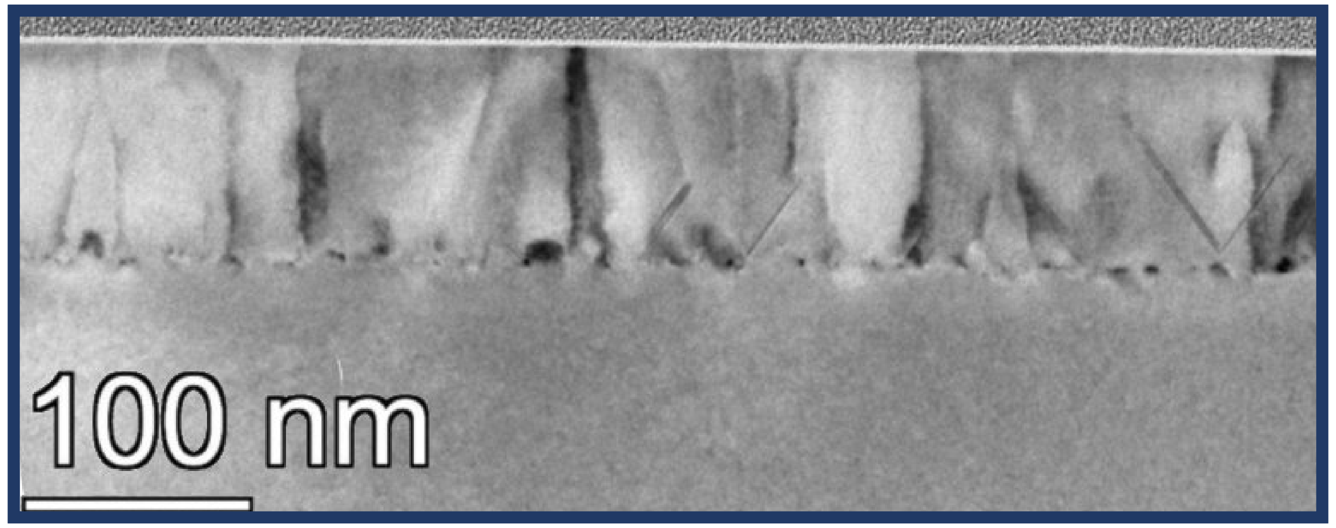
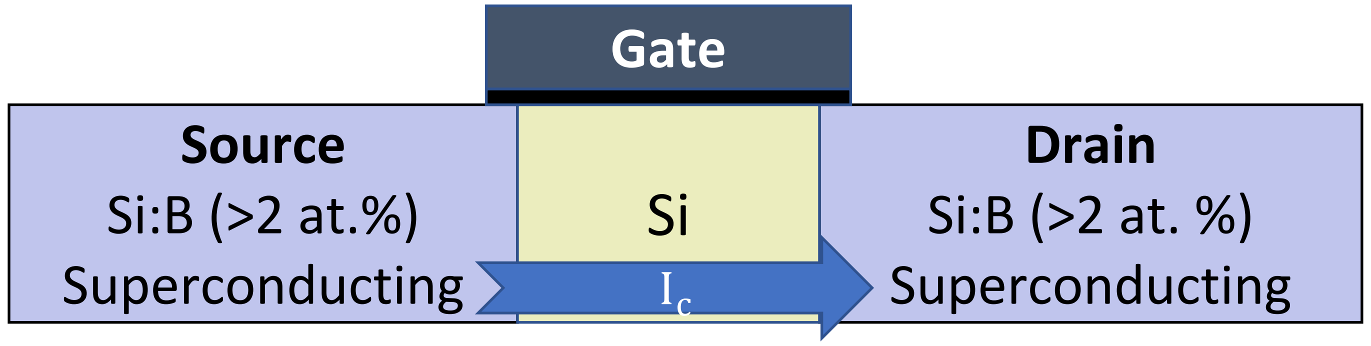
MOSAIC Users' Meeting 2026





Superconducting Silicon ?!

Goal: Josephson Transistor (JoFET)



Supercurrent through weaklink: $R = 0$

BCS Theory:

$$T_c \sim e^{-1/\lambda}$$

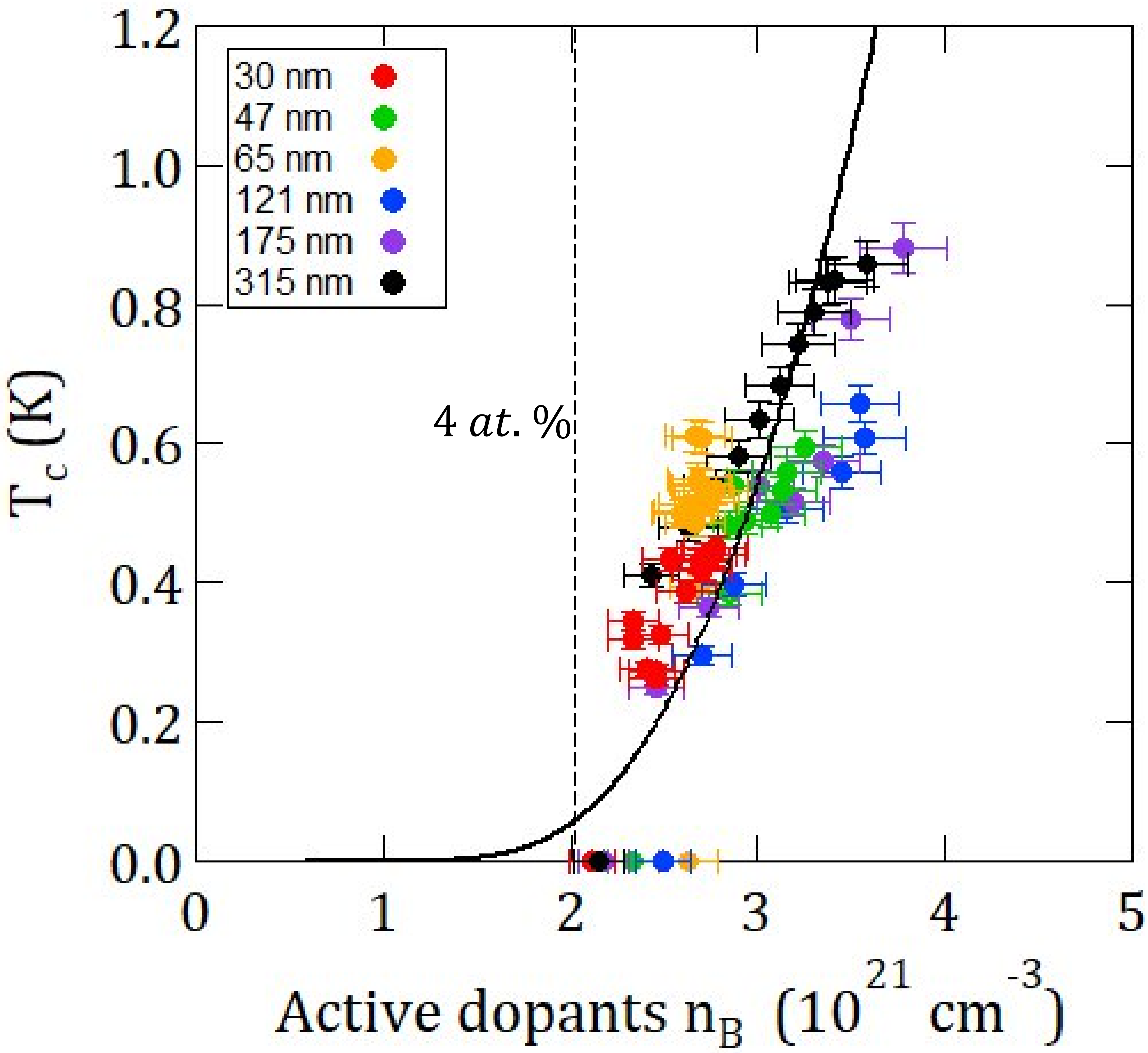
$$\lambda = N(E_F) V_{e-ph}$$

Silicon:

- Covalent bonds (sp3) $\Longrightarrow$ large V_{e-ph}
- Semiconductor $\Longrightarrow$ small $N(E_F)$

Increasing $N(E_F)$:

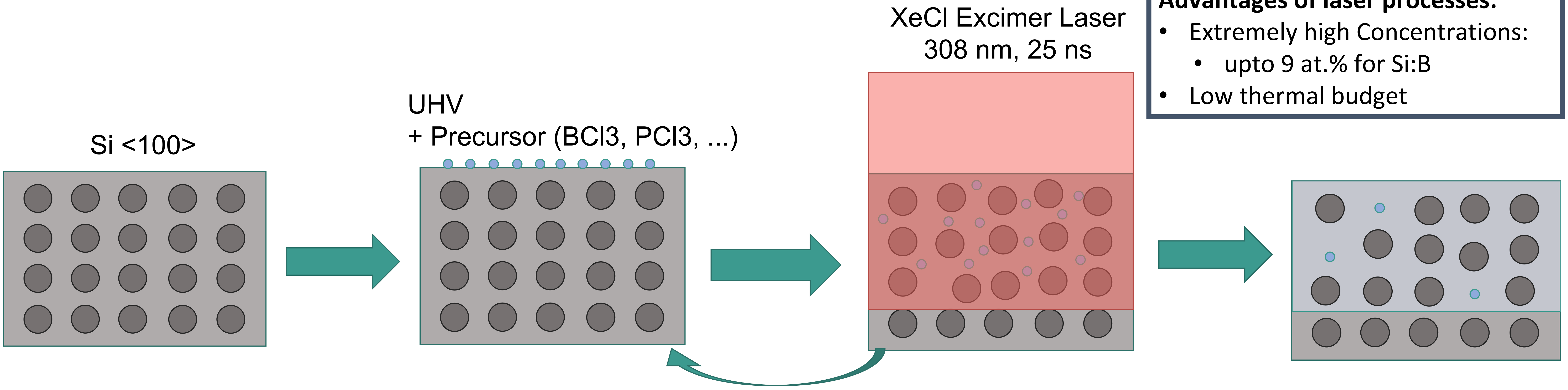
- Superconductivity: $n_B > 4\ at.\%$
- $n_{B,sol} = 1 at.\%$ → Out-of-equilibrium process



Thèse L. Desvignes,. Université Paris-Saclay, 2023
these.hal.sciences/tel-04137471

Nanosecond Laser Doping & Annealing

Advantages of laser processes:
- Extremely high Concentrations:
  - upto 9 at.% for Si:B
- Low thermal budget



Extremely quick epitaxial regrowth (4 m/s)
-> High segregration coefficient ($k > 0.99$)
-> Ultradoping

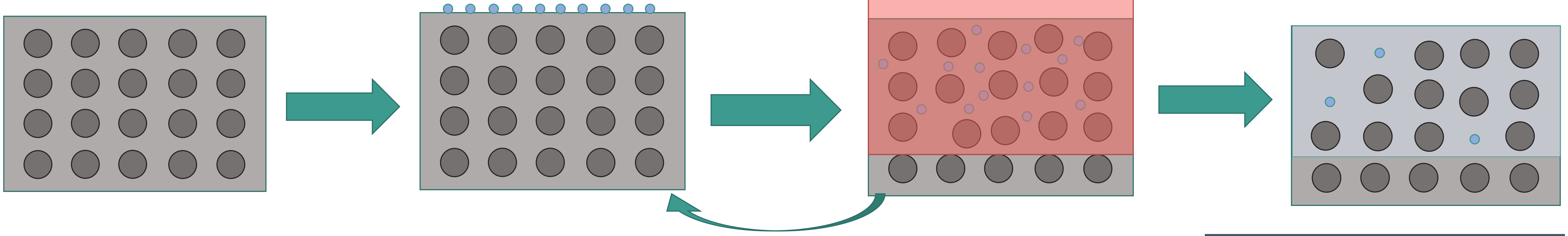
Nanosecond Laser Doping & Annealing

Advantages of laser processes:
- Extremely high Concentrations:
  - upto 9 at.% for Si:B
- Low thermal budget

Si <100>

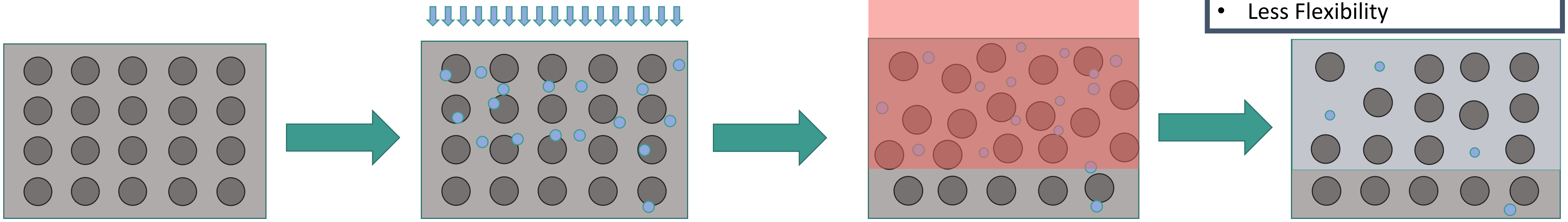
UHV
+ Precursor (BCl_3, PCl_3, ...)

XeCl Excimer Laser
308 nm, 25 ns



Implantation

Implantation:
- Close to industrial processes
- Less Flexibility



Difficulty of masking the laser directly

XeCl Excimer Laser
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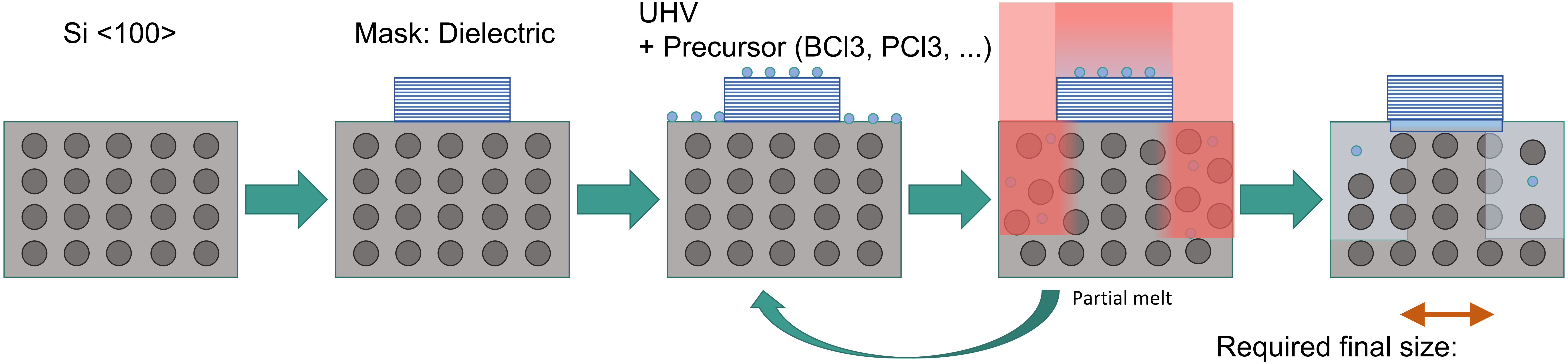
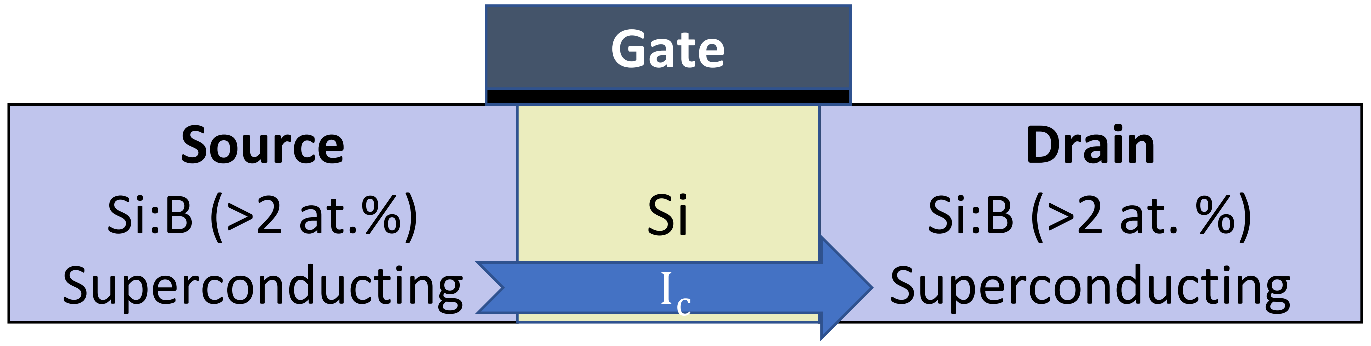


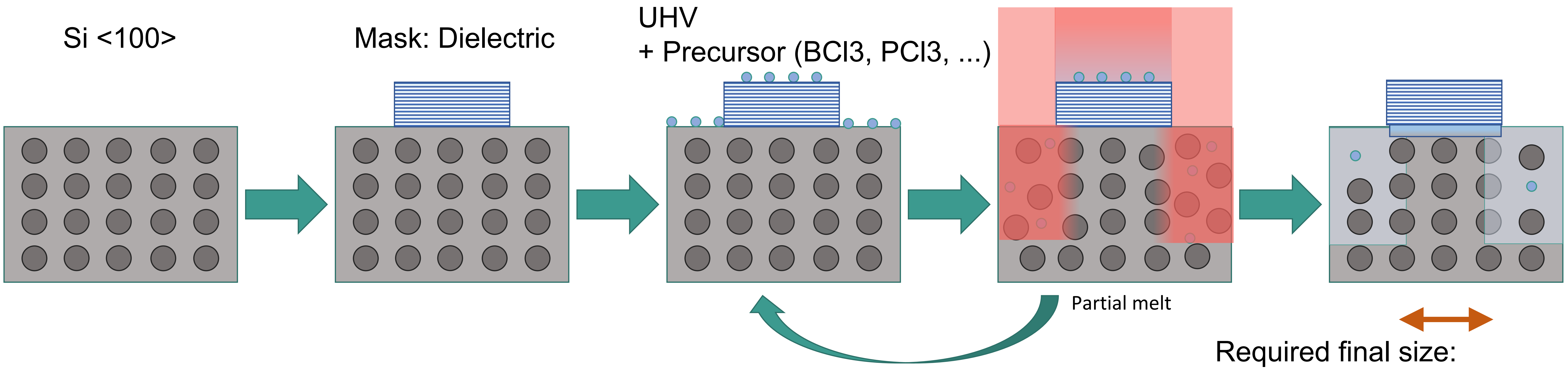
Required final size:
- Josephson Junction ~100 nm

Goal: Josephson Transistor (JoFET)



Supercurrent through weaklink: $R = 0$

Difficulty of masking the laser directly



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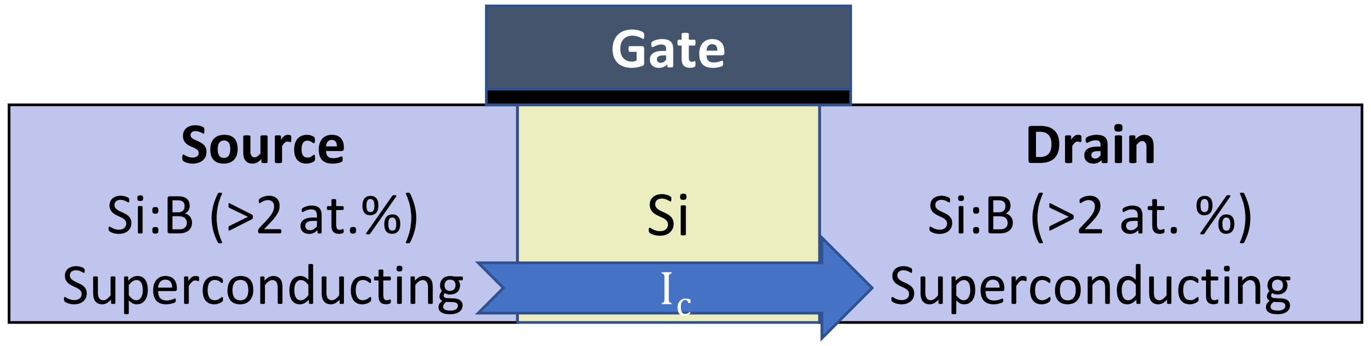
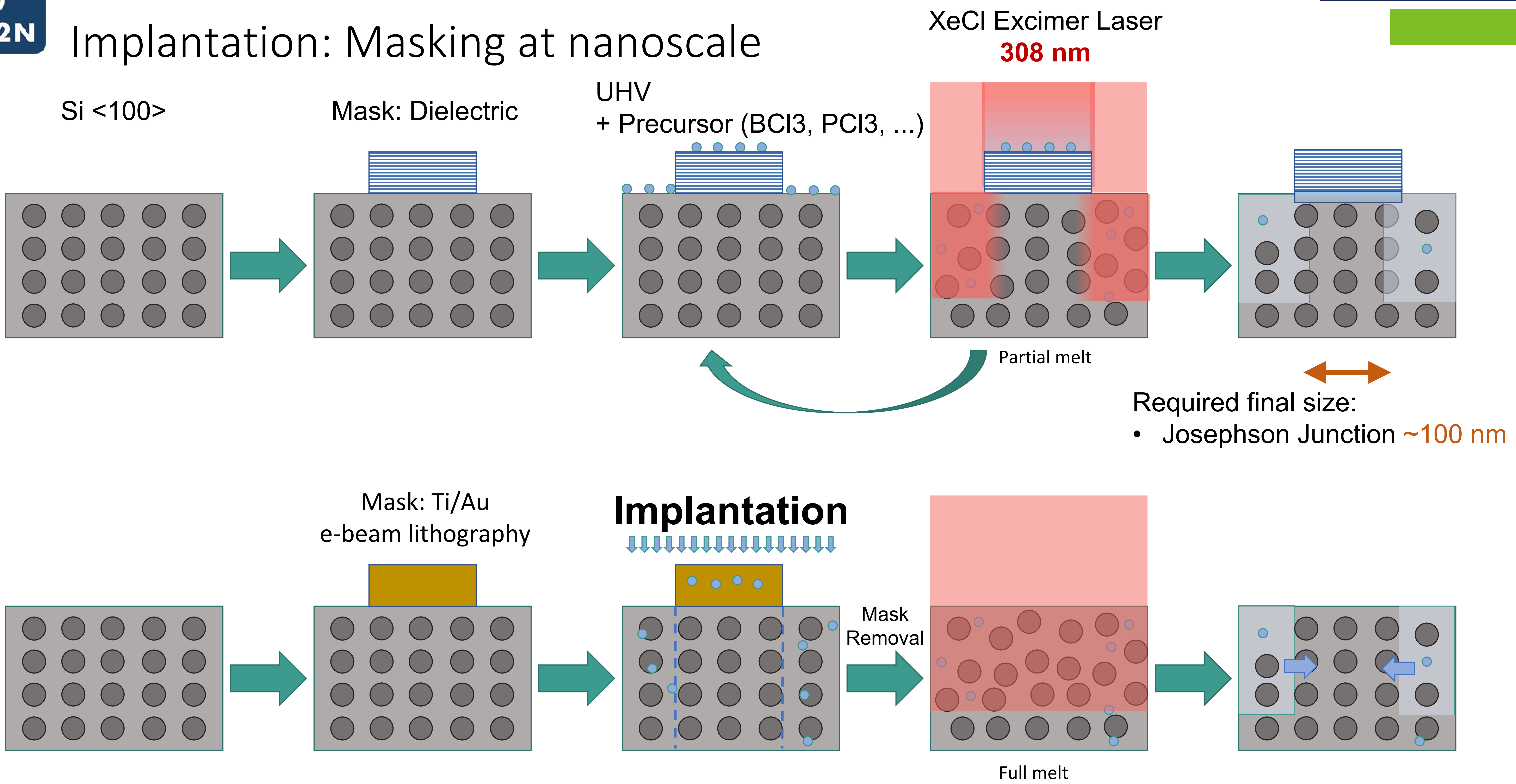


Supercurrent through weaklink: $R = 0$

Problems
- Diffraction
- Difficult to remove the mask
  - Bad interface for gate stack

Implantation: Masking at nanoscale



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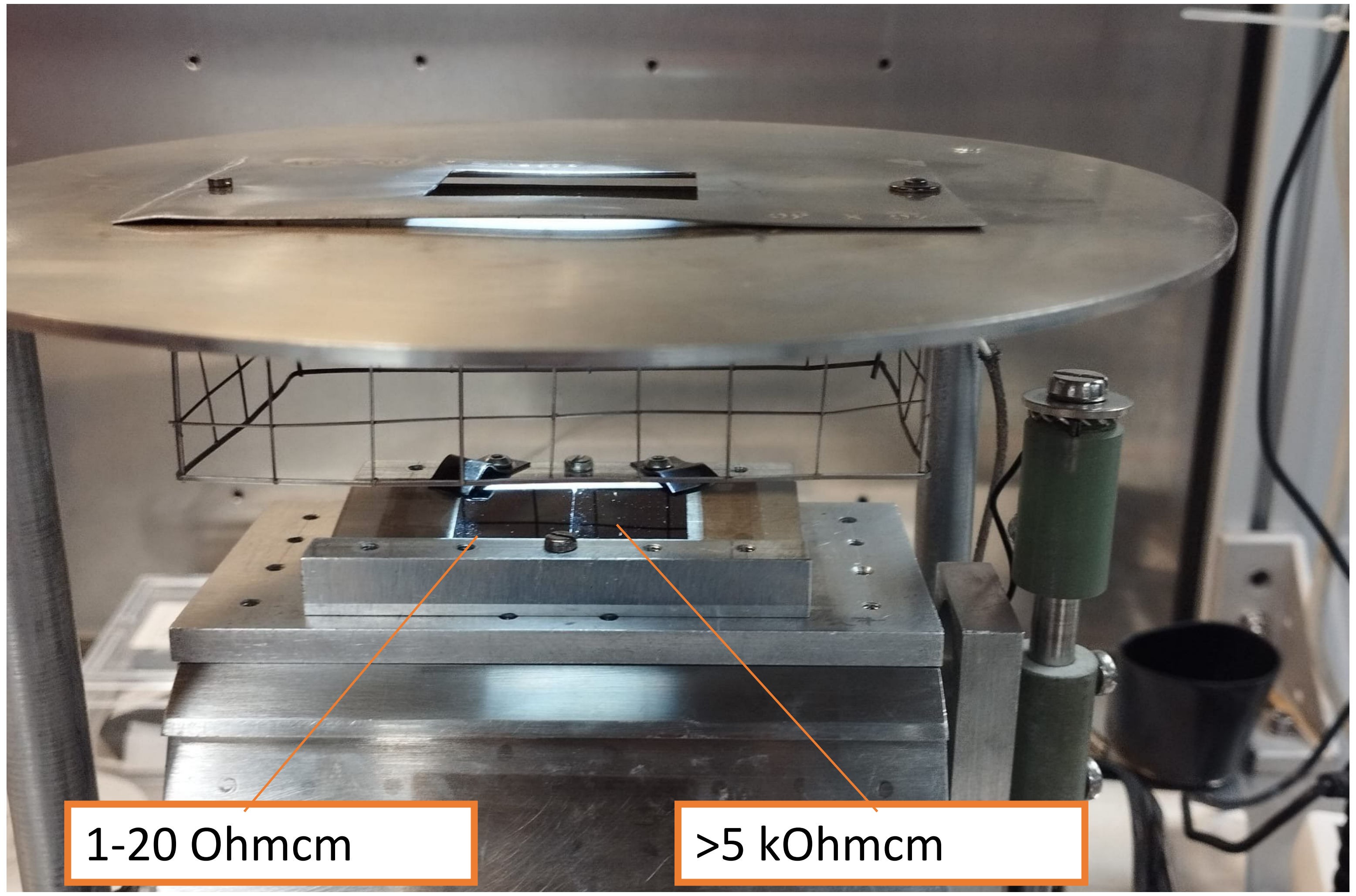
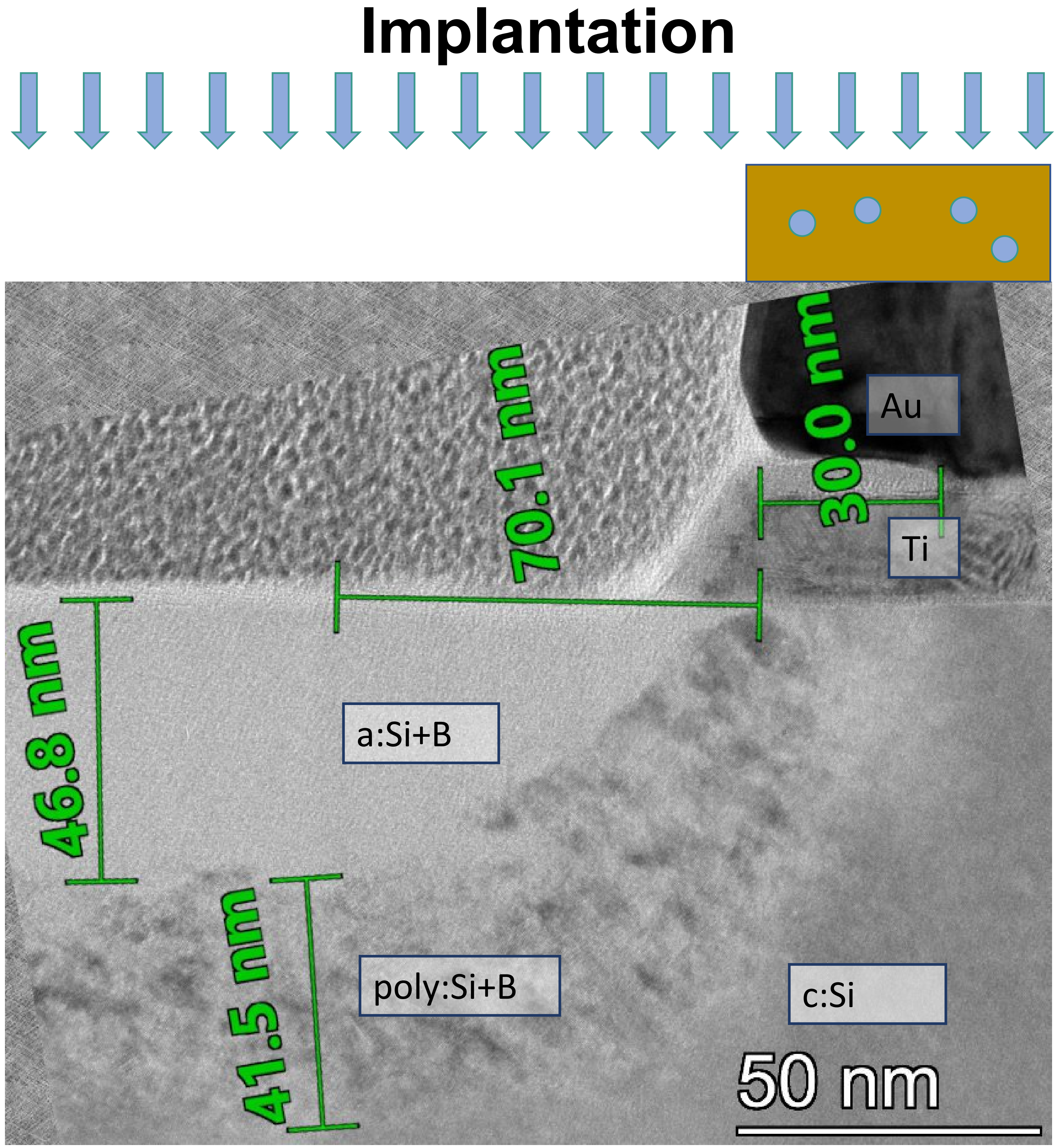
Implantation: Dopant Distribution

Implantation: $\mathbf{6.10^{16}/cm^2}$ (Tilt: 7°)
- 10 keV -> 80 nm with peak concentration
  - 45 nm amorphous
  - 40 nm with many defects
- Deep defects > 250 nm
- 30 nm defects below mask (Ti/Au 20/80 nm)





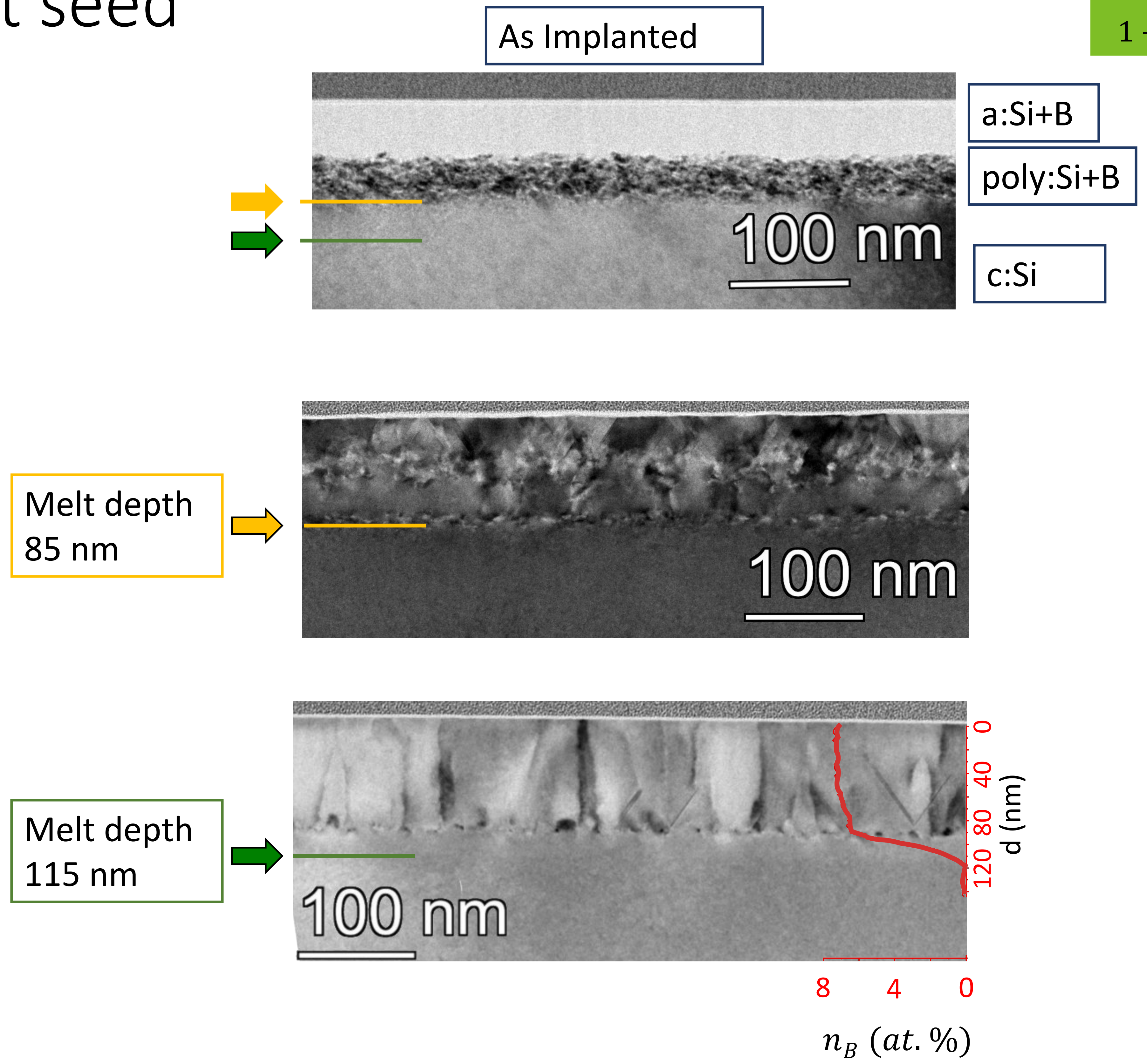
Melting depth: Finding the right seed

$1-20\ \Omega cm$

Implantation: $6.10^{16}/cm^2$ (Tilt: 7°)
- 10 keV -> 80 nm with peak concentration
  - 40 nm amorphous
  - 45 nm with many defects
- Deep defects > 250 nm

TEM: 15 shots to homogenize
- 85 nm -> Still two clearly separated layers
- 115 nm -> 1 reasonably homogeneous layer, but many defects (Stacking Faults, twinning)

➢ **At least 100 nm anneal required to get 1 layer**

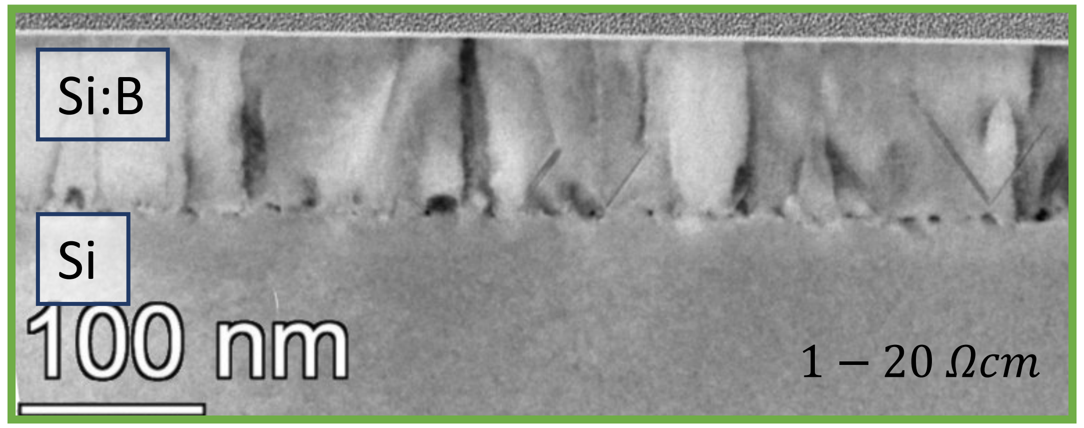


7 at. % homogeneous active doping!
Superconductivity?

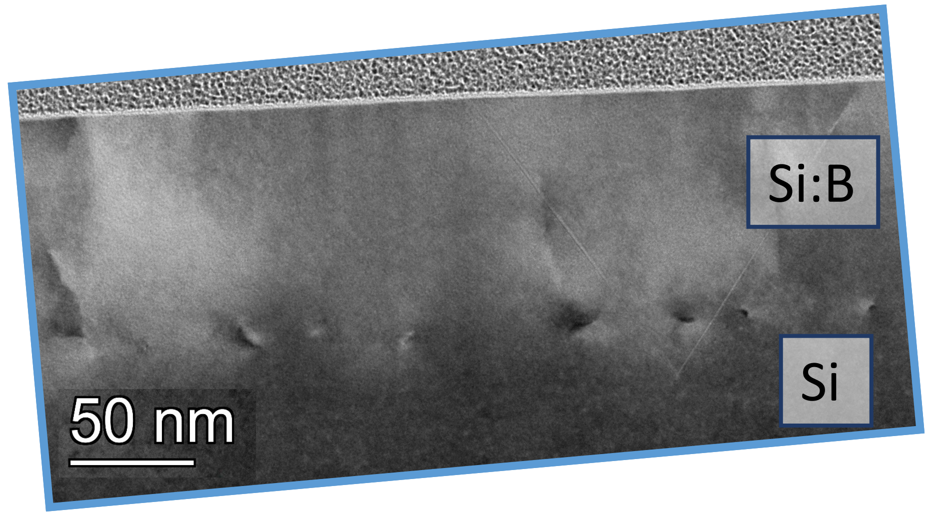
First test: High activation, Tc very close to GILD

Implantation: $\mathbf{6.10^{16}}/cm^2$ (Tilt: 7°)
- 10 keV -> 80 nm with peak concentration
  - 40 nm amorphous
  - 45 nm with many defects
- Deep defects > 250 nm

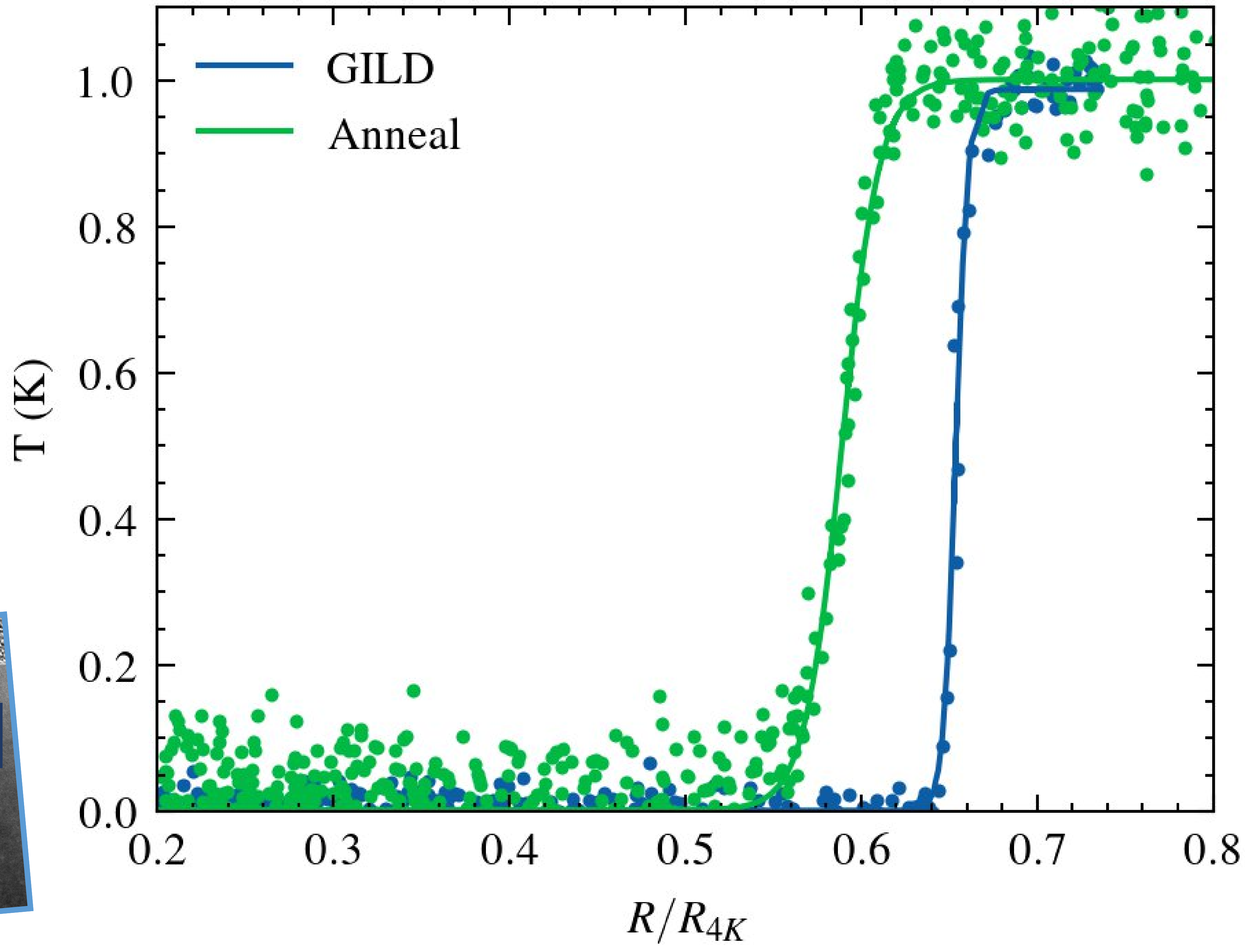
- Activation of $4{,}4\ 10^{16}/\mathrm{cm}^2$ (>70% activation)
  - $n_B = 3.8\ 10^{21}\ /cm^3$
- Double the amount of defects & more stacking faults than GILD
- $T_c = 0{,}6\ K$ (GILD: 0,7 K)



Anneal:
~18 nm between defects



GILD:
~30 nm between defects



Géraldine Hallais *et al* 2023 *Semicond. Sci. Technol.* **38** 034003; **DOI:** 10.1088/1361-6641/acb0f0

J. L. Lábár *et al* 2023 *Nanomaterials*, vol. 13, no. 6, p. 1007, Mar. 2023; **DOI**: 10.3390/nano13061007

Substrate resistivity: Reduction in activation & Tc

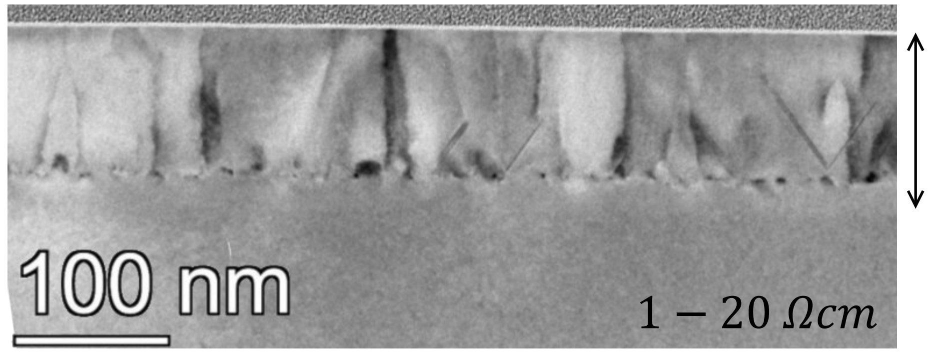
Implantation: $6.10^{16}/cm^2$ (Tilt: 7°)
- 10 keV -> 80 nm with peak concentration
  - 40 nm amorphous
  - 45 nm with many defects
- Deep defects > 250 nm

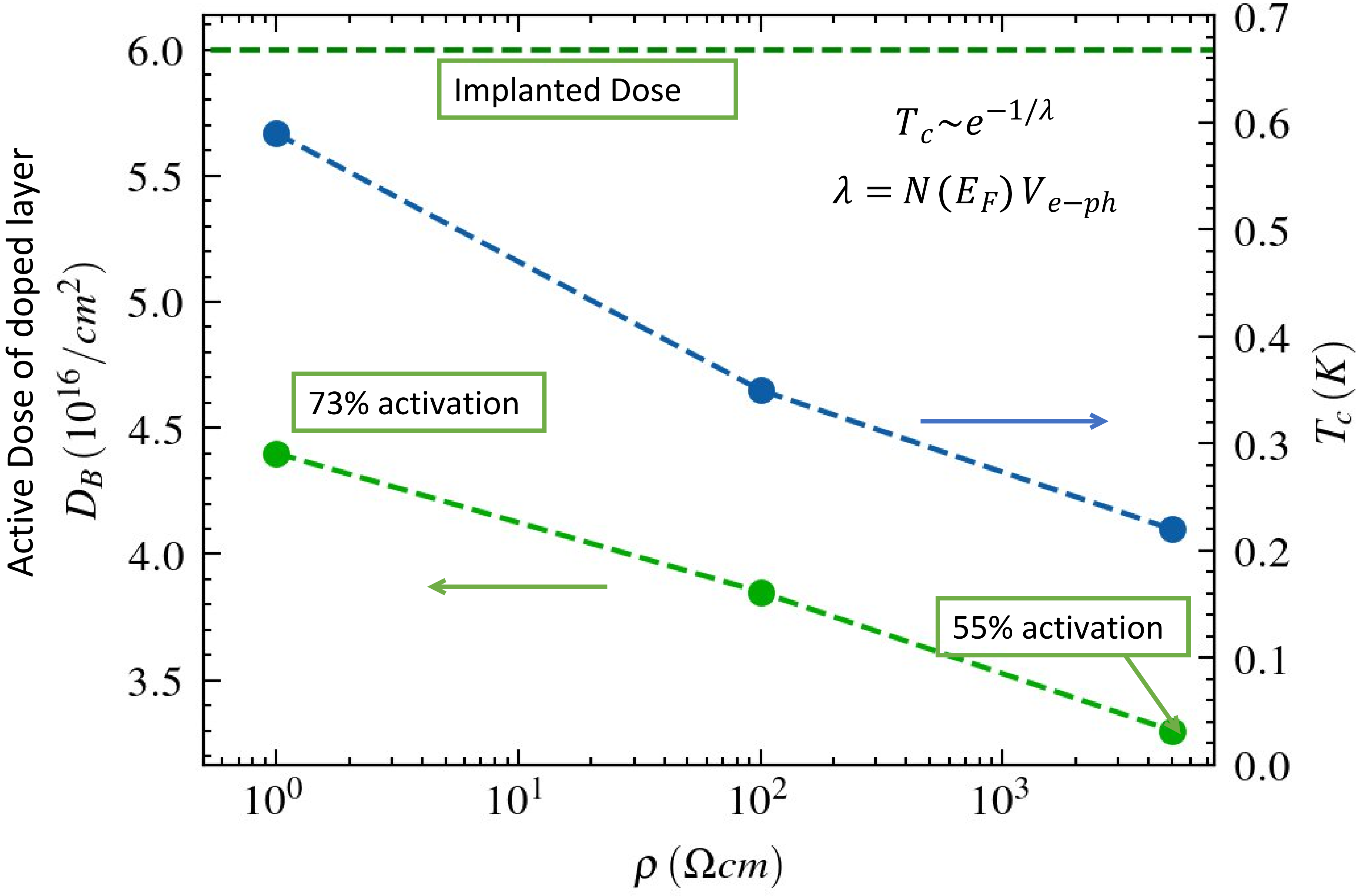
- No known effect of resistivity on nanosecond-laser **anneal**
- No significant discrepancies expected during **implantation**
  - ✓ Current measured on the sample

Where did the Boron atoms go?
- Possibility: Bound to defects during implantation
  - Higher resistivity -> Compensated substrate? (n+p-dopants)

  -> More defects in higher resistivity
- Other Possibility: Slight angle in substrate

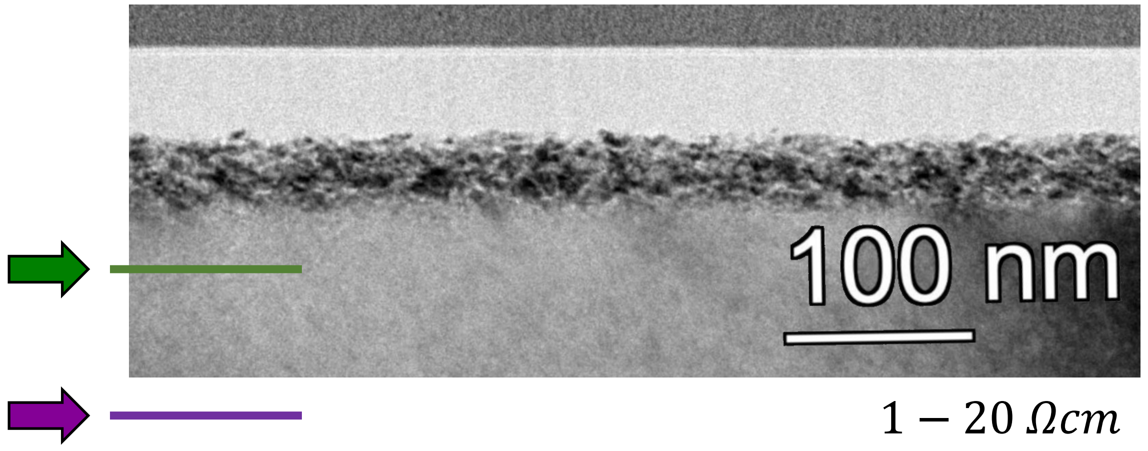
  -> Different Dopant Profile due to channeling
- Anneal at higher Energy:
  - ➢ Higher activation (upto 80%)

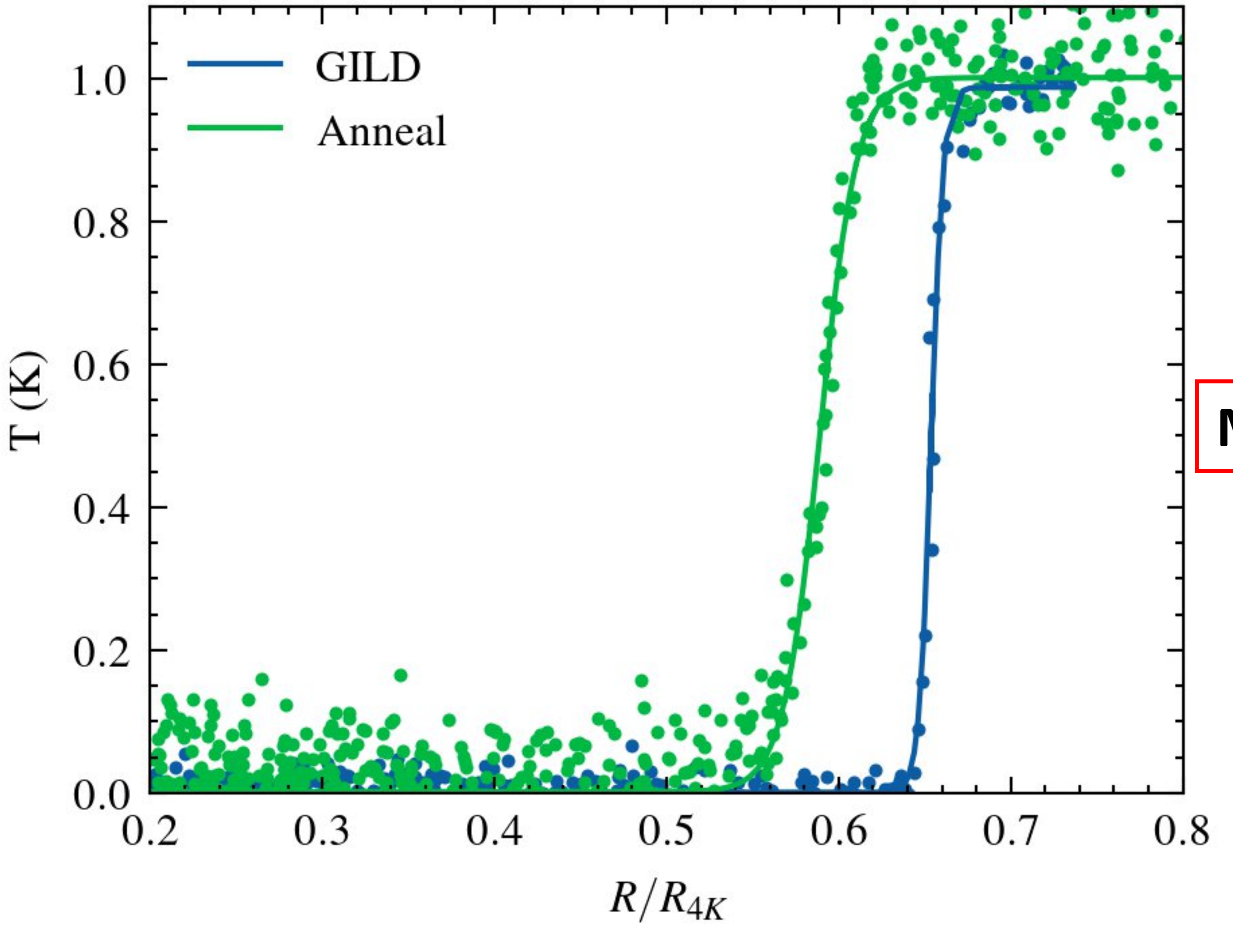




Initial **Wafer** Resistivity

Anneal with 1 deep anneal: Clean epitaxial growth

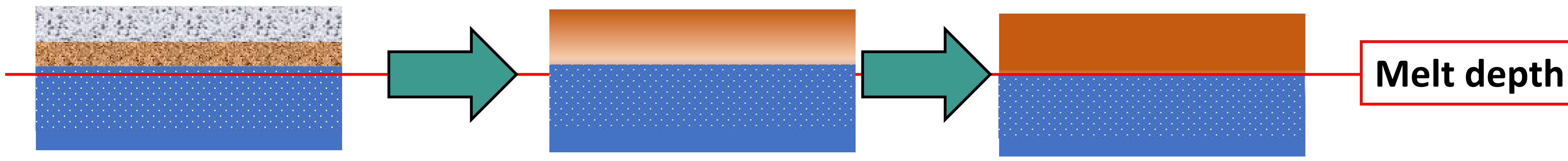




Shallow Melt => High Concentration, crystalline defects

1 shot @ 115 nm

14 shot @ 115 nm



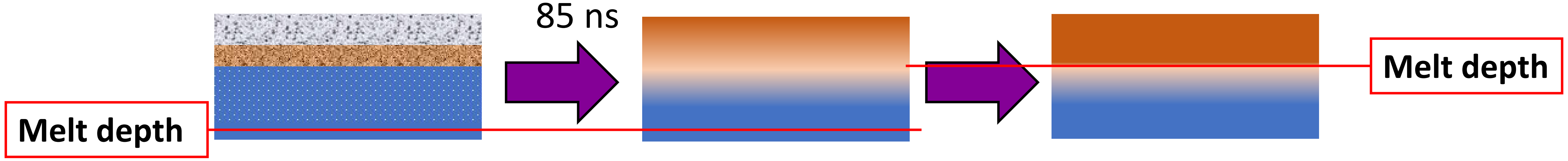
Deep Melt => Low Concentration, optimal crystalline quality

1: Low-defect Seed

1 shot @ 250 nm
85 ns

Homogenization

14 shot @ 115 nm

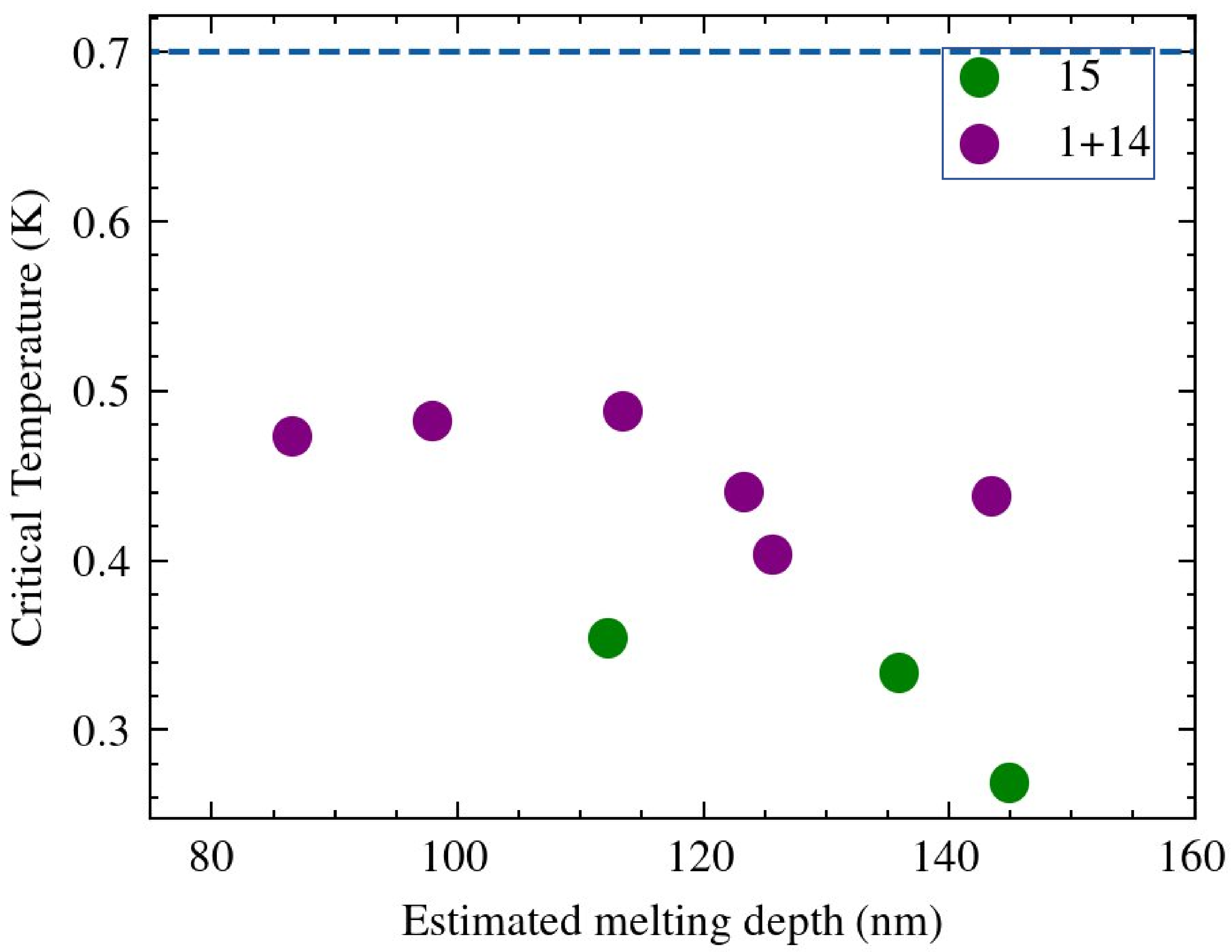


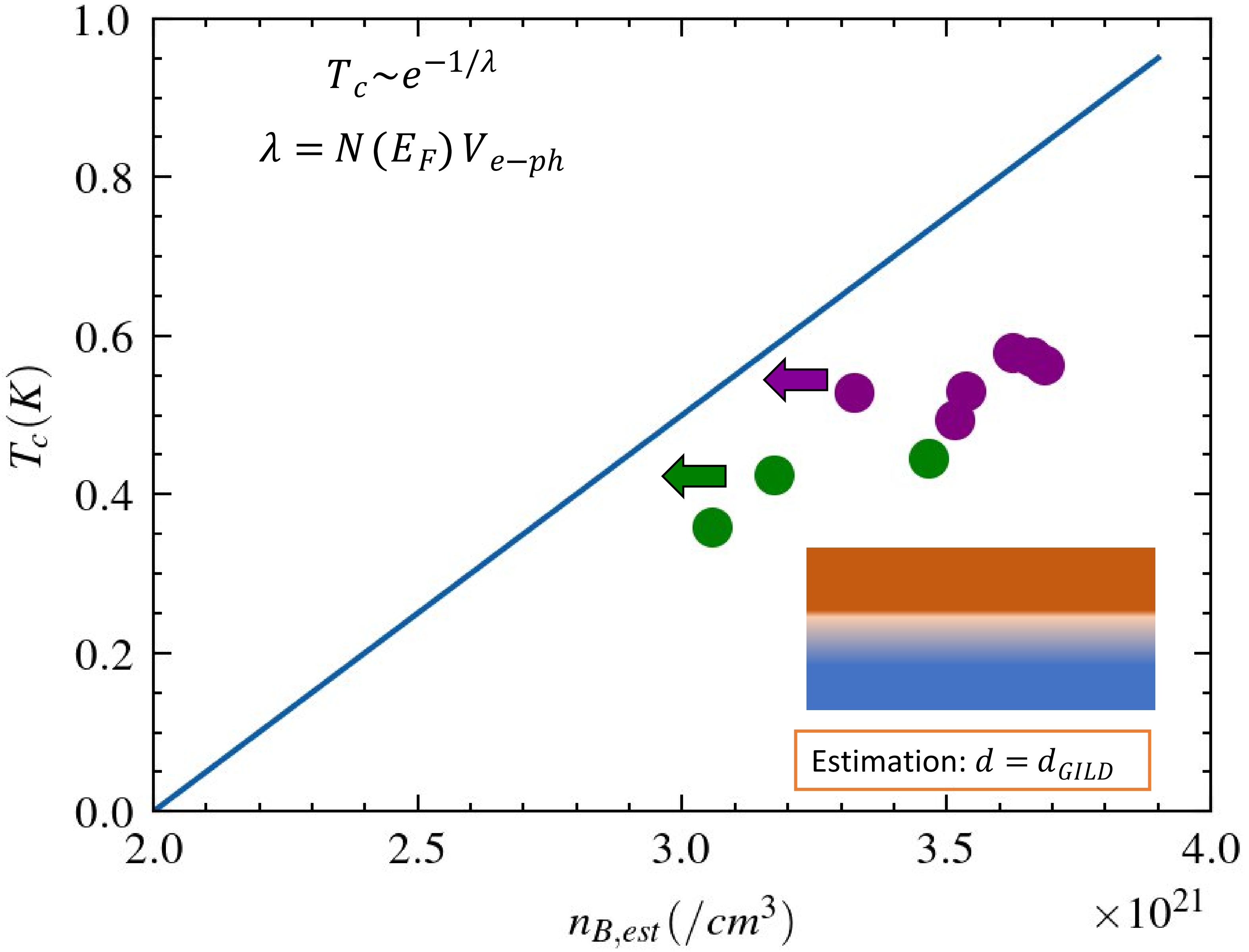
Melting deeper to get a clean epitaxial seed:

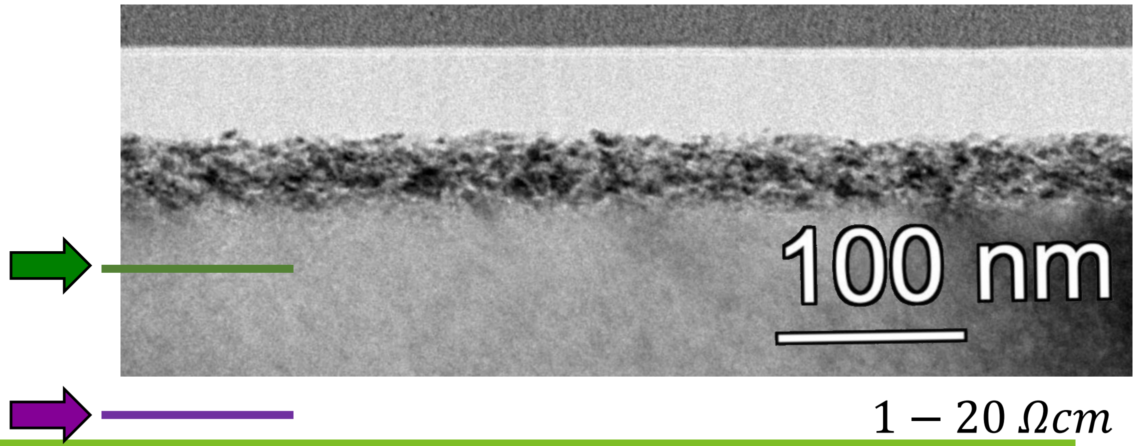
- Growing from low-defect seed:
  - **Less strain relaxation & more activation**
- Less for Boron out-diffusion:
  - Higher concentration

Anneal with 1 deep anneal: Increase in Tc

100 Ωcm







1 − 20 Ωcm

1 Shot Deep anneal:

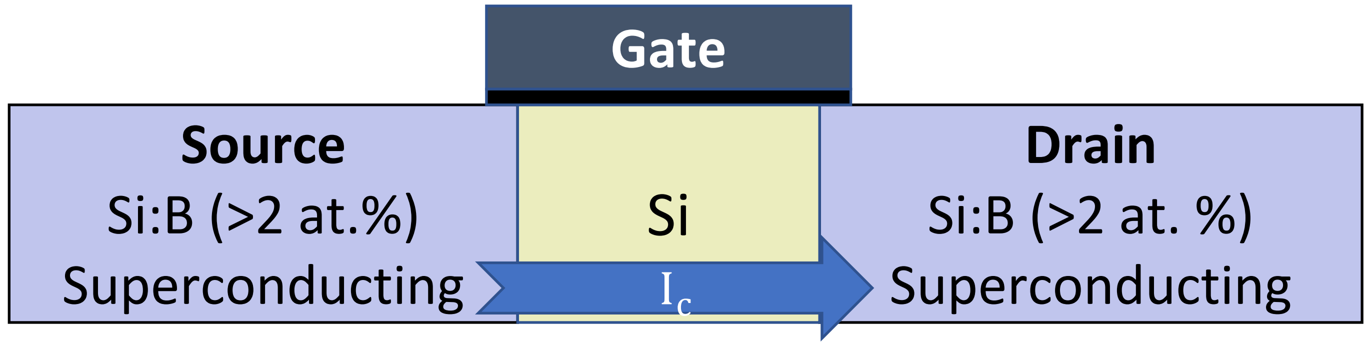
- Less defective epitaxial seed
  - **Less strain relaxation & more activation**
- Less time for Boron out-diffusion:
  - Higher concentration

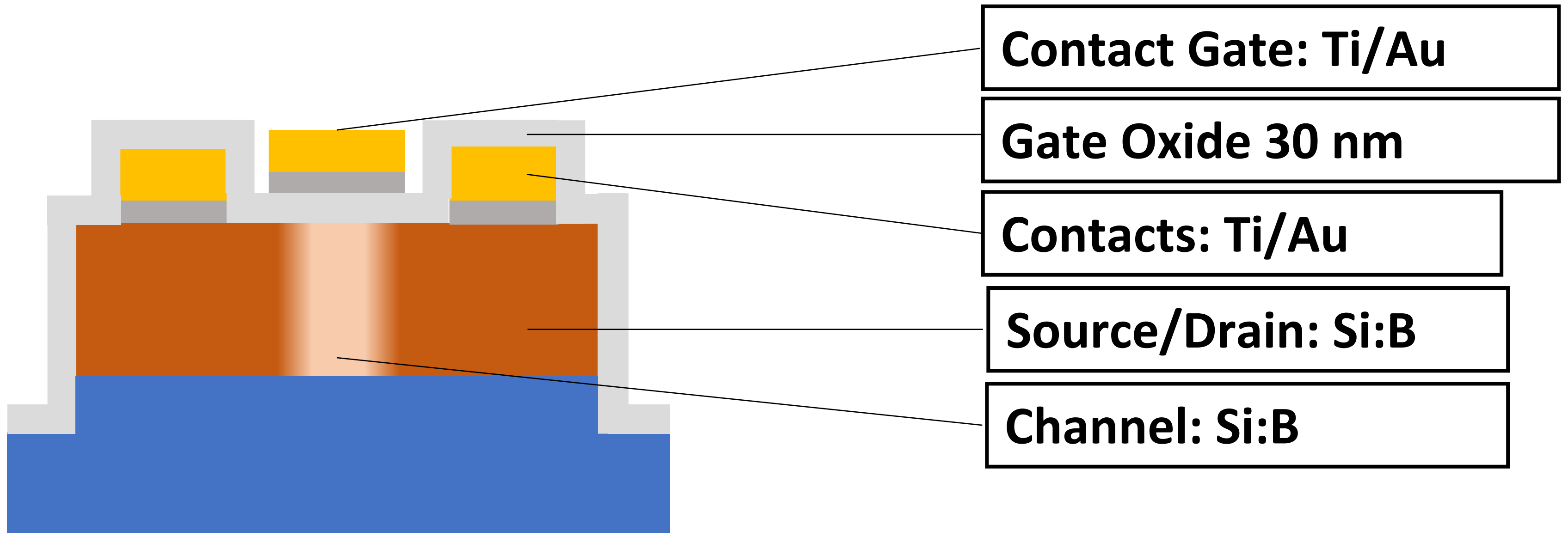
➢ **Significant & repeatable increase in Tc**

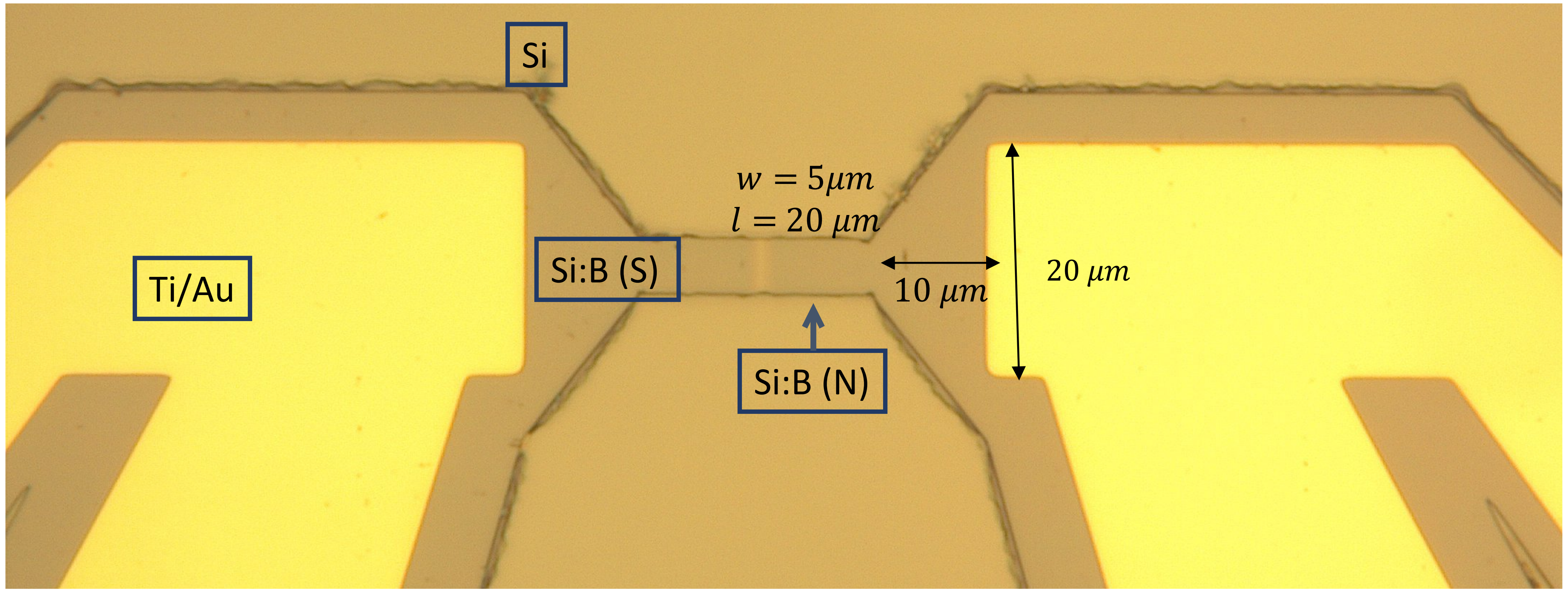
Junctions: Fabrication

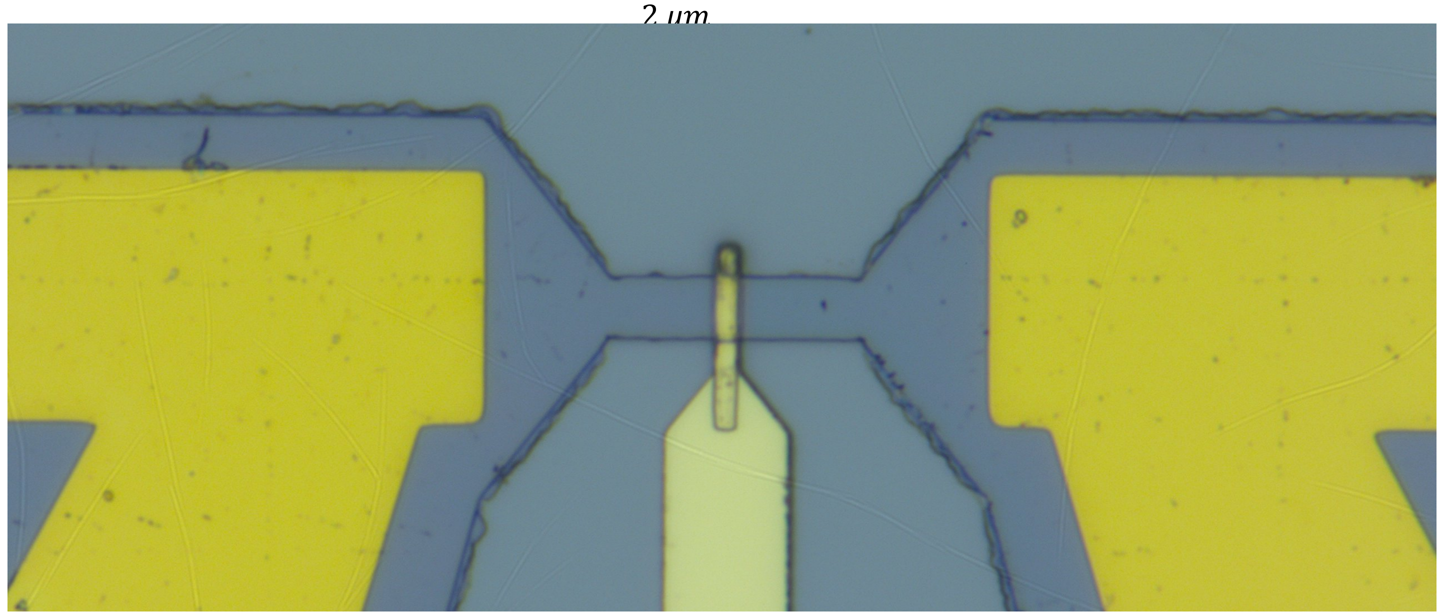
$> 5\ k\Omega cm$

Goal: Josephson Transistor (JoFET)



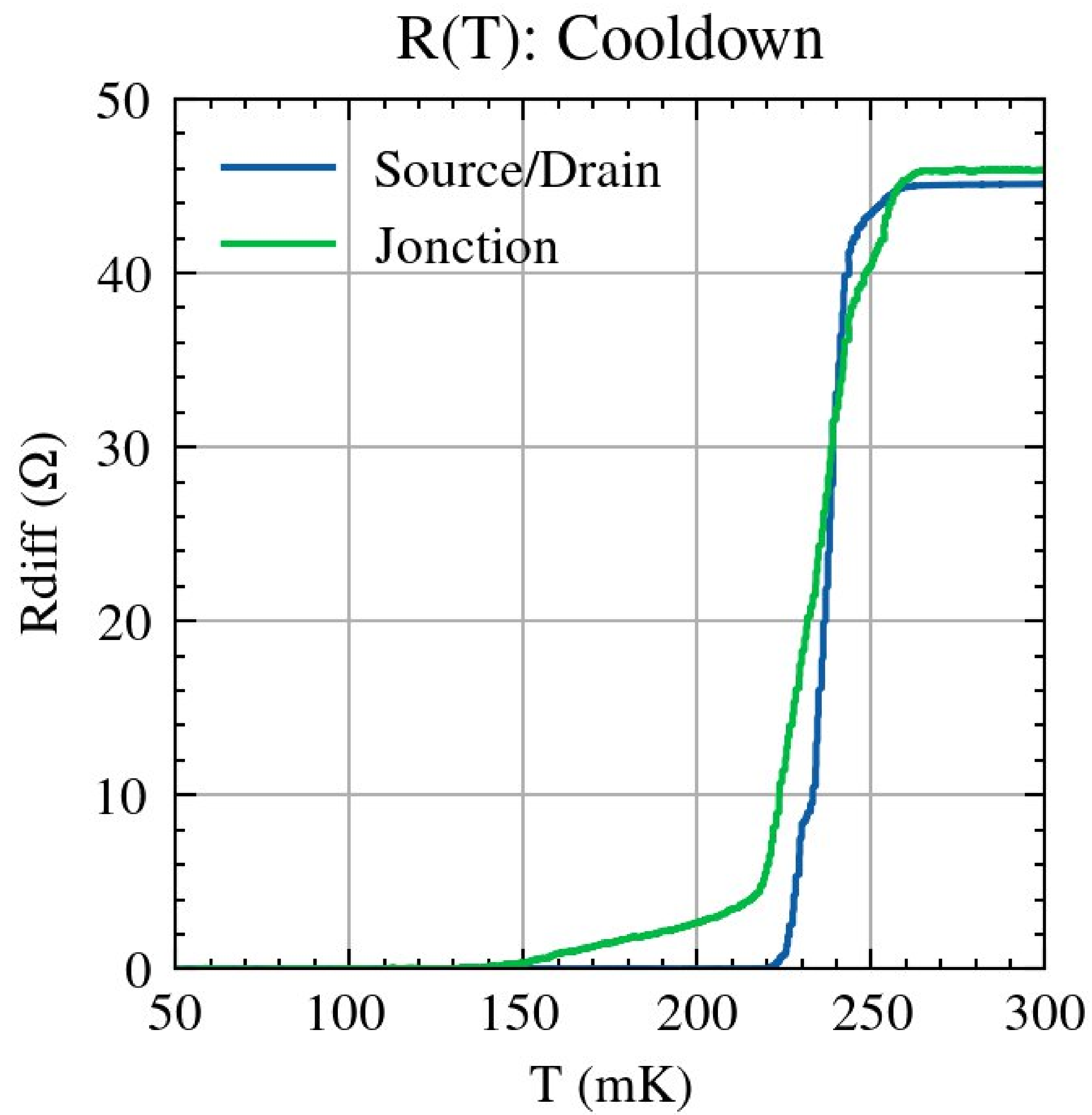






Josephson Junctions!

$> 5\ k\Omega cm$

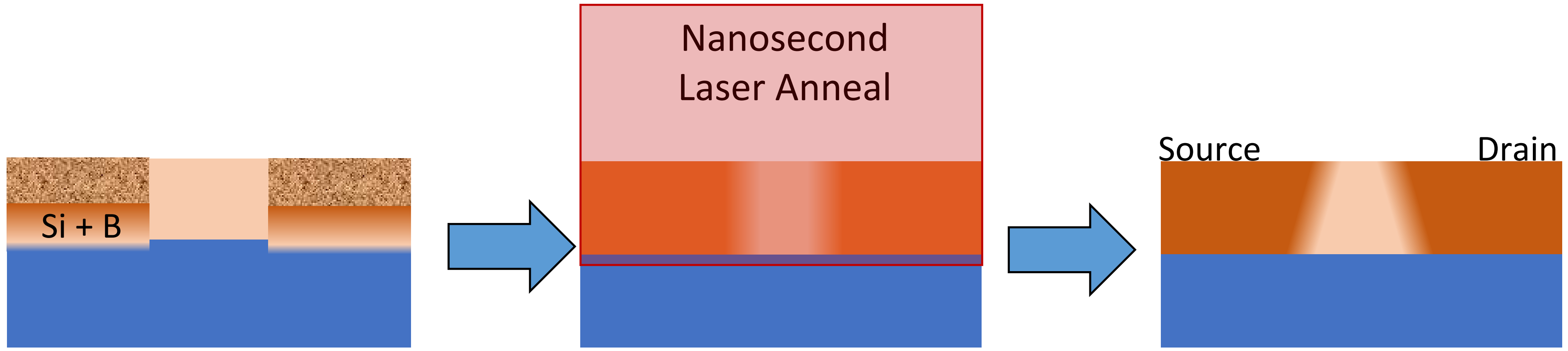


First batch:

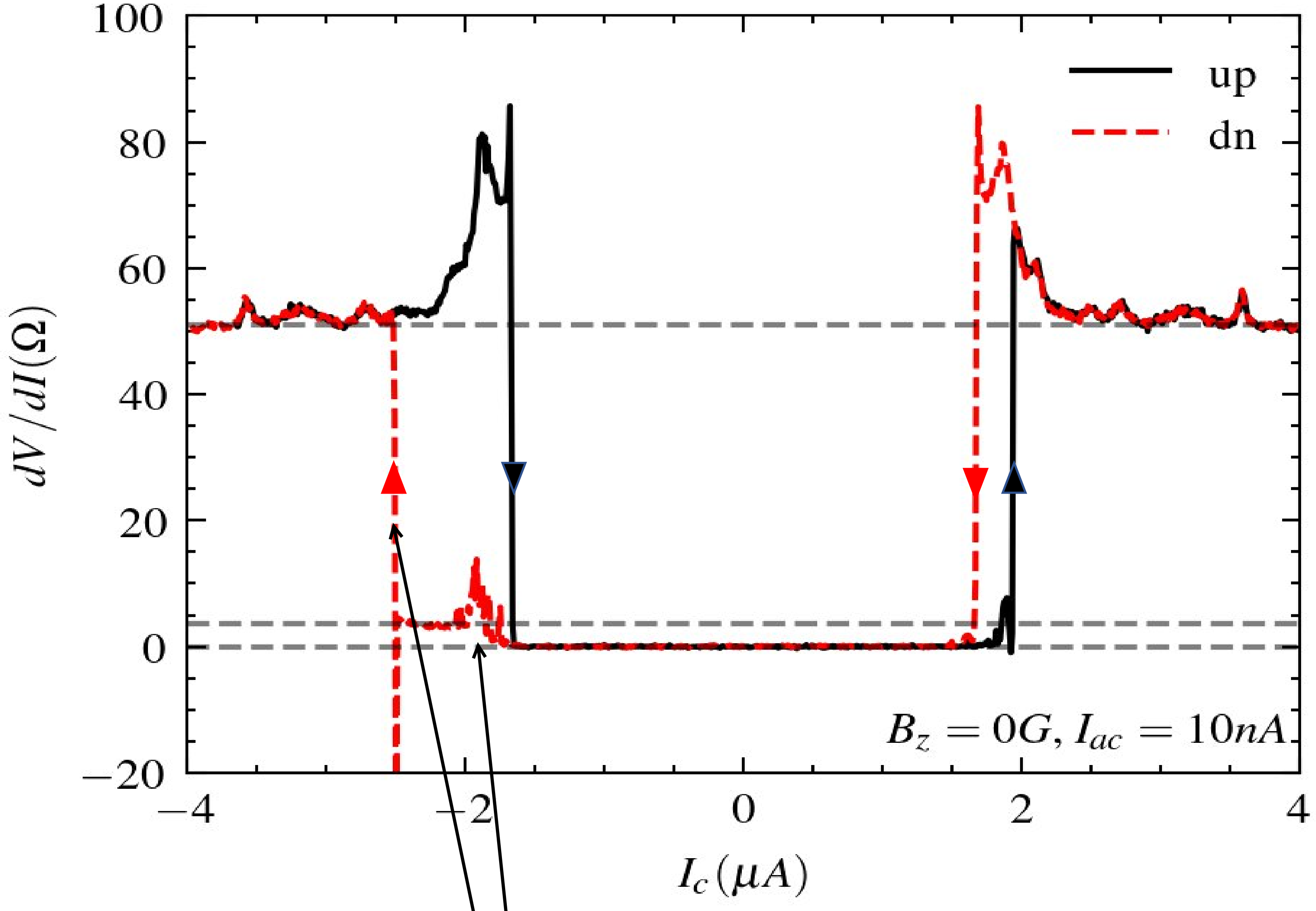
- Mask: 150 nm
- Anneal: 115 nm depth, 15 shots

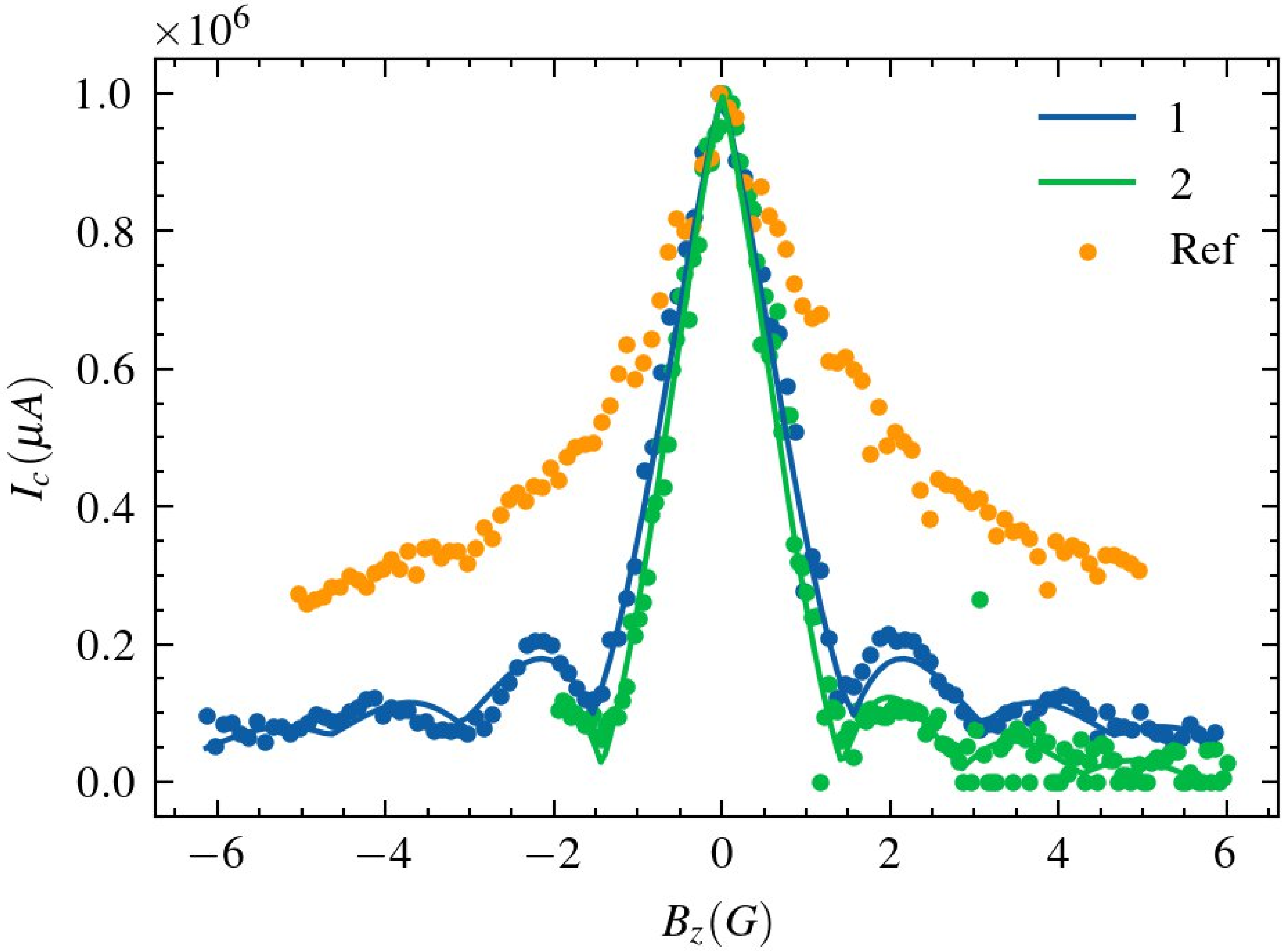
R(T): Cooling down

- First step: Contacts
- Junction: R=0 below 130 mK
- "Ramp": In-homogeneity due to Boron diffusion during anneal



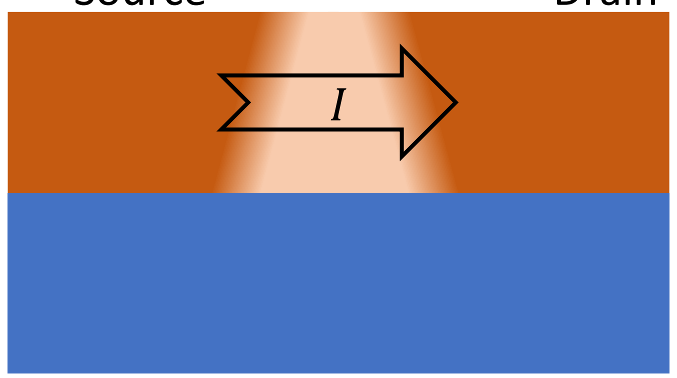
For those in doubt: Ic & Interference Fraunhofer Interference Pattern





dVdI:

- Junctions
- Contacts



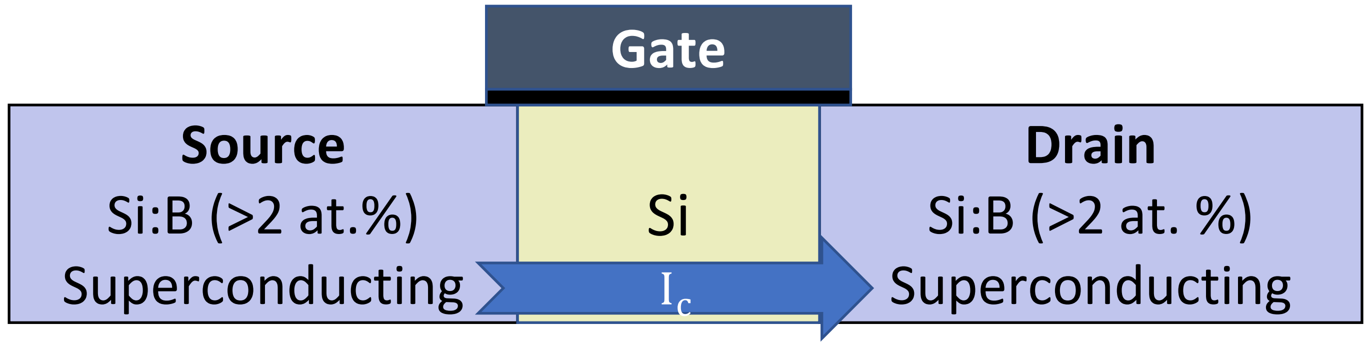
Interference with magnetic field: Fraunhofer

- $\lambda = 1{,}4\ \mu m$
- Destructive interference close to 0

To be improved: Gate effect

$> 5\ k\Omega cm$

Goal: Josephson Transistor (JoFET)



Supercurrent through weaklink: $R = 0$

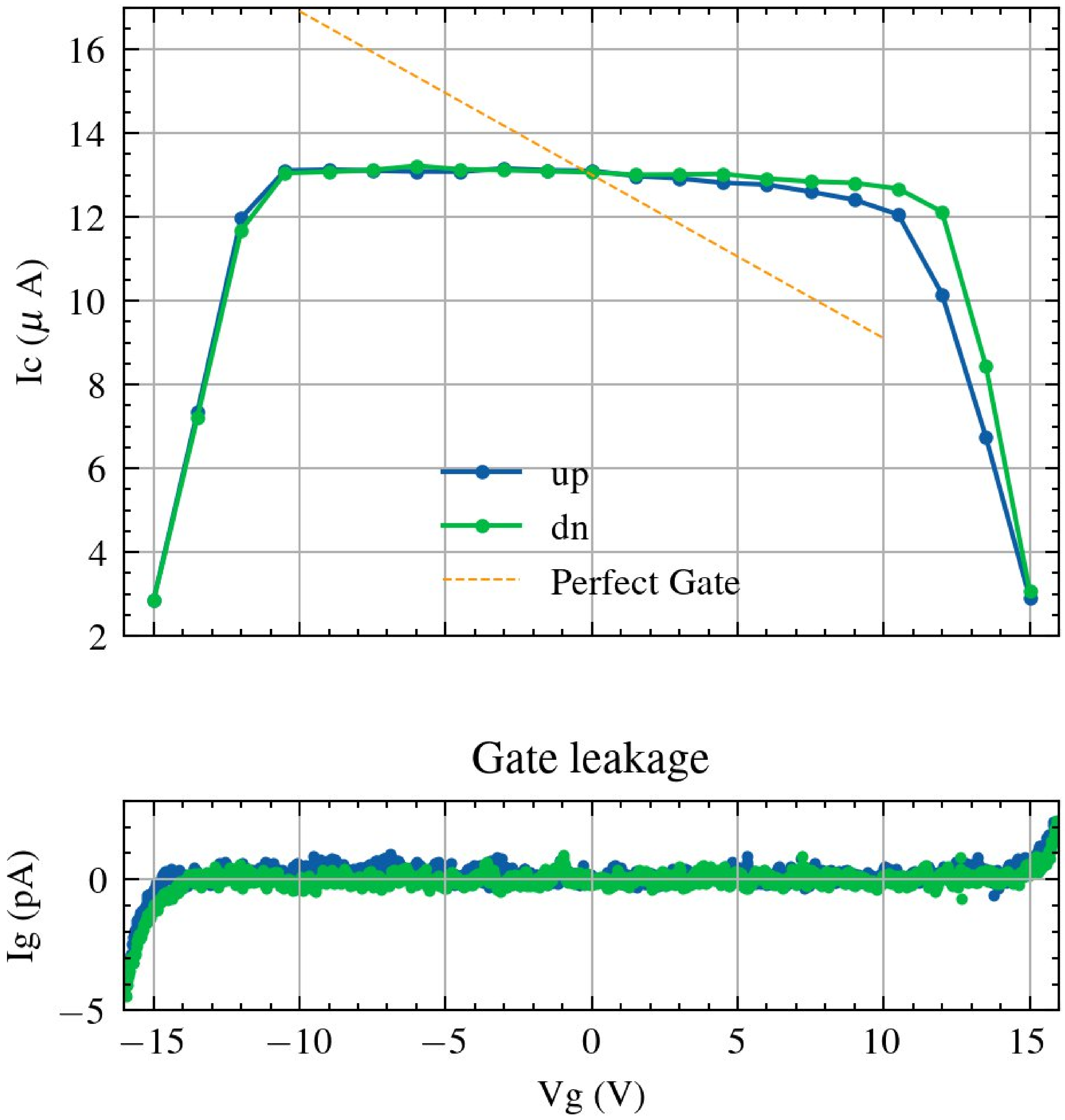
First batch:

- Mask: 150 nm
- Anneal: 115 nm depth, 15 shots
- Gate Oxide: 30 nm HfO2

- Tiny effect density of states
- Ic decreases significantly due to hot electrons creating hot spots

Improvements:

- Lower channel doping & Thinner channel
- Fabrication: Cleaner Interface with oxide layer



Implantation: Precise masking for superconducting Si:B devices

$> 5\ k\Omega cm$

Advantage of using Implantation:

- Precise masking -> Reliability
- Planar Josephson Junctions (Previously only vertical)
- CMOS Compatible

Well controlled process:

Implantation

- Dose, Angle & Energy -> Initial Dopant profile

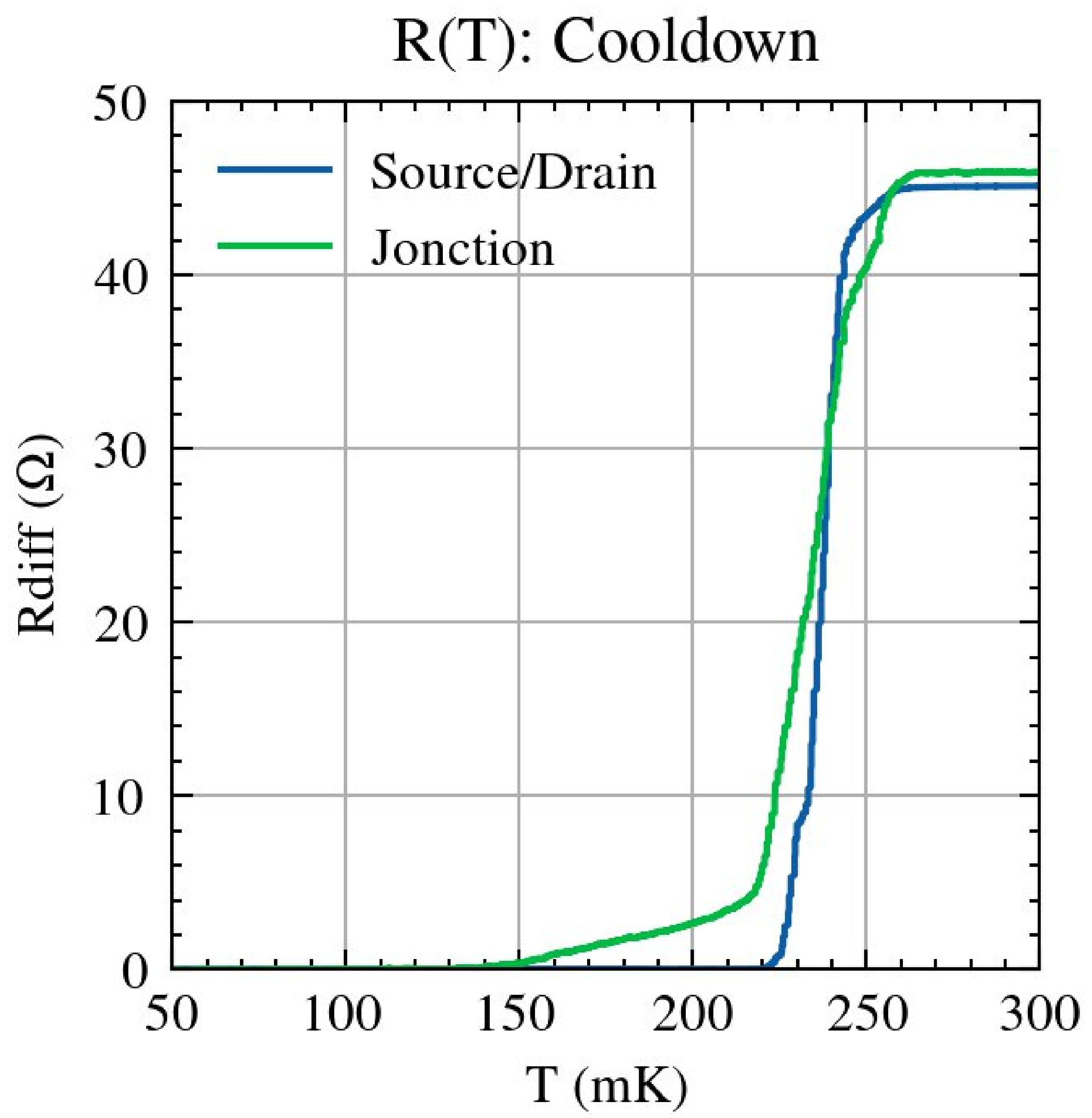
Nanosecond laser doping

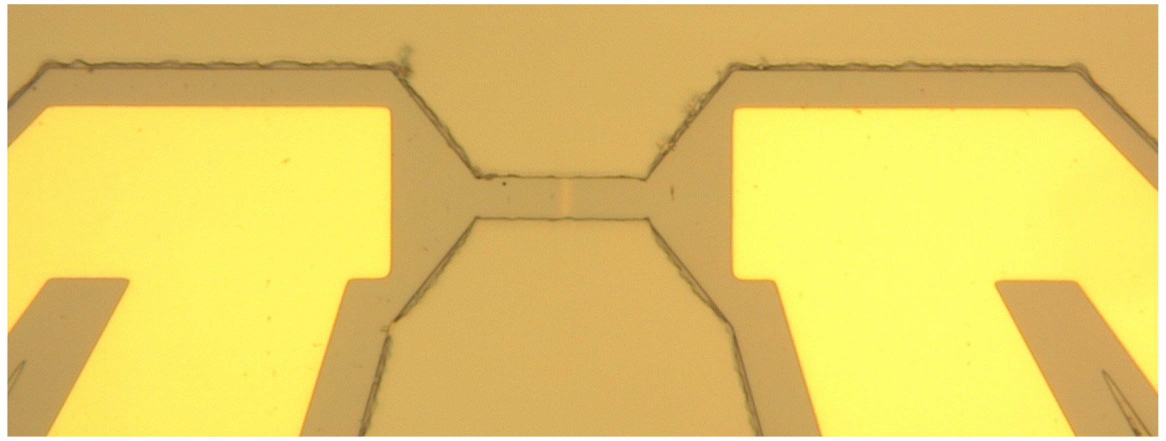
- Control of melting depth:

➢ Extremely high activation (**upto 80%**) & active concentration (7,6 at.%)
  - Cleaner seed to grow from
  - Breaking unwanted bonds
- Low thermal budget

Future plans:

- Gate modulation
- Using the diffusion into the channel to optimize the junction
- Connecting junctions to more complex circuits (resonators, waveguides)



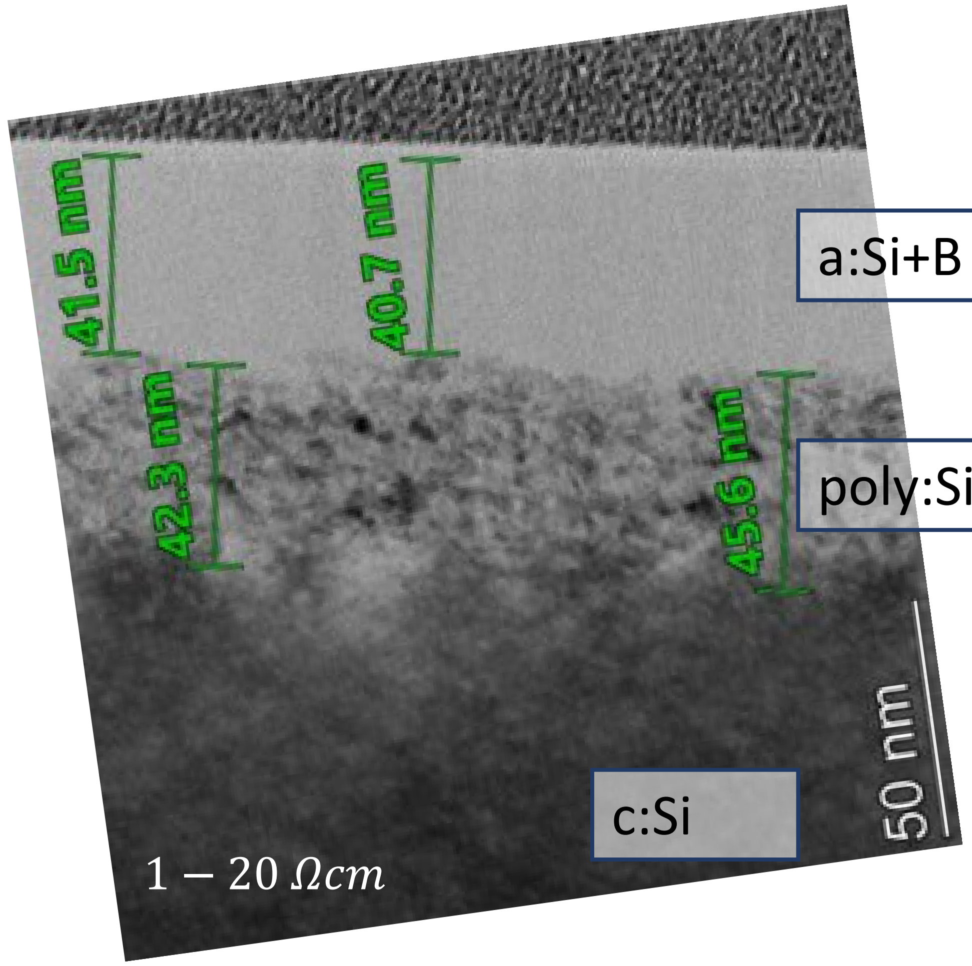


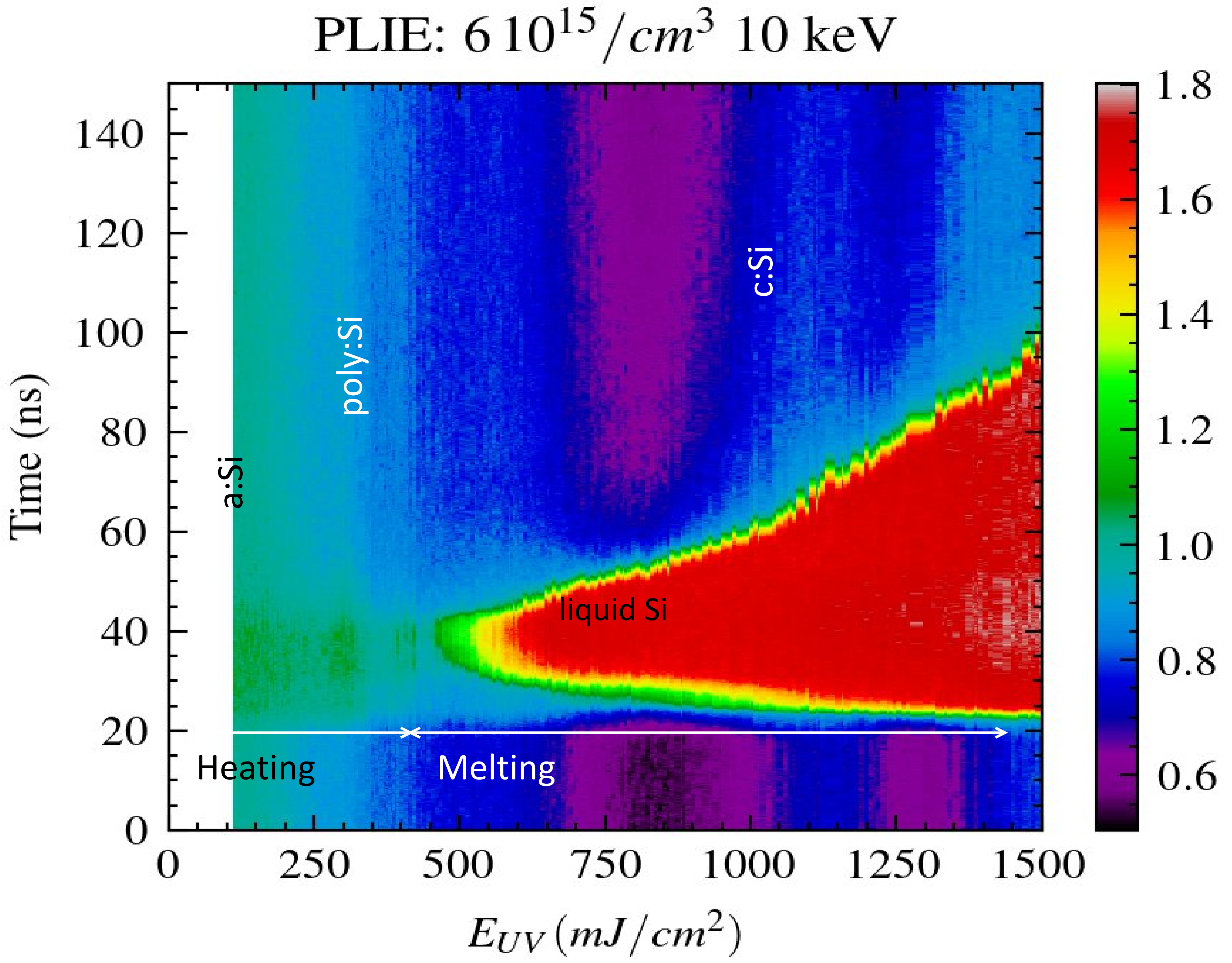
Anneal: Time Resolved Reflectivity

100 Ωcm

Implantation: $6.10^{16}/cm^2$ (Tilt: 7°)
- 10 keV -> 80 nm with peak concentration
  - 40 nm amorphous
  - 45 nm with many defects
- Deep defects > 250 nm

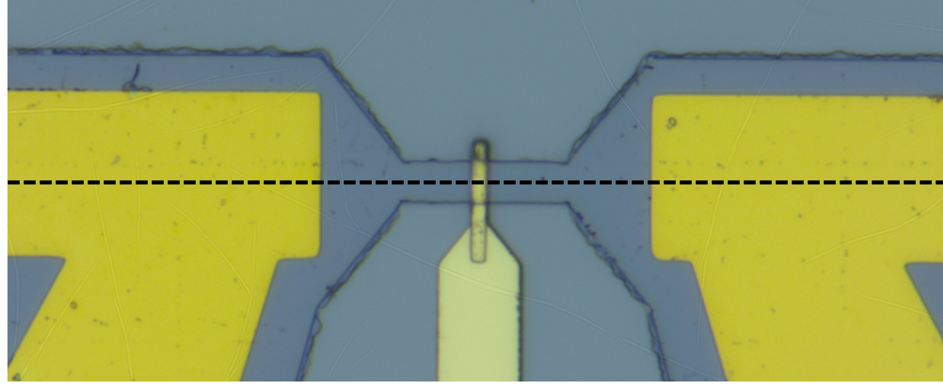
PLIE:
300 mJ/cm^2: Explosive recrystallization -> Poly-crystalline
From: 500 mJ/cm^2: Melting -> Crystalline top layer
After 1000 mJ/cm^2: Stable Reflection -> Mono-crystalline

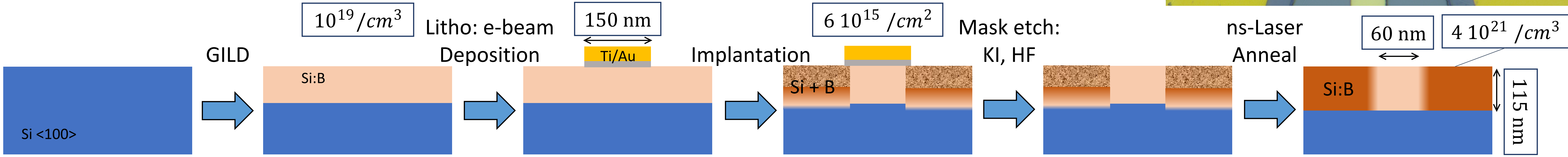




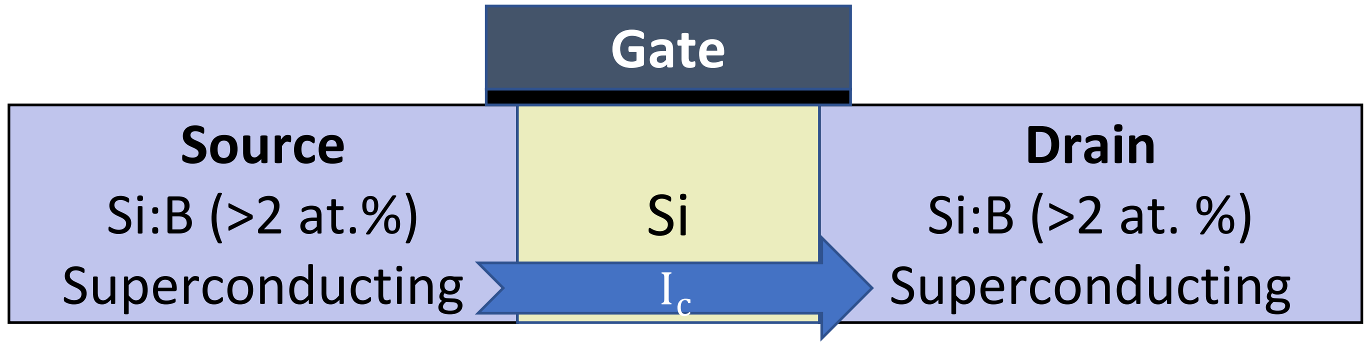
Junctions: Fabrication

$> 5\ k\Omega cm$





Goal: Josephson Transistor (JoFET)



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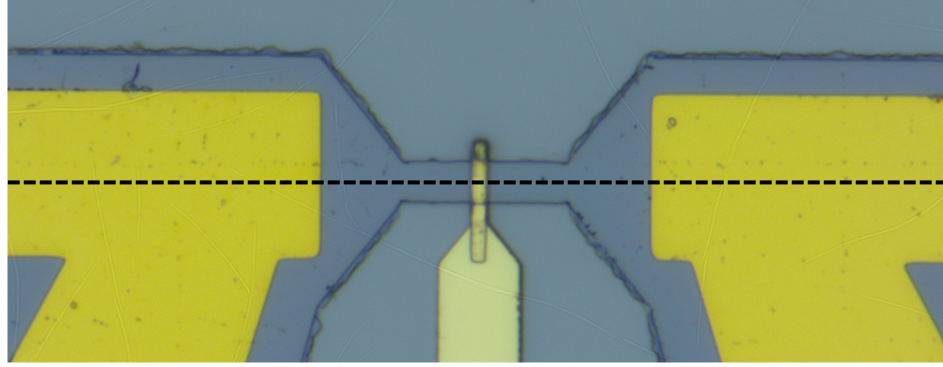

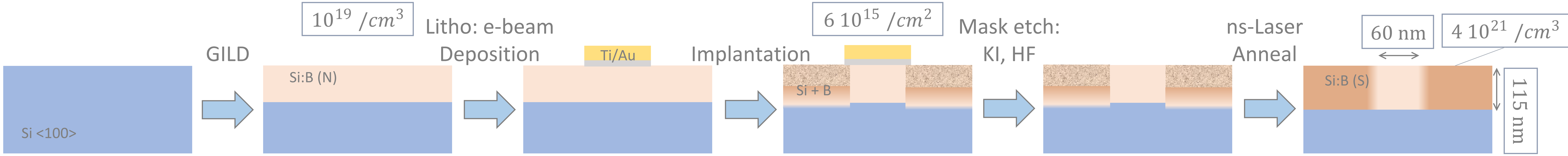

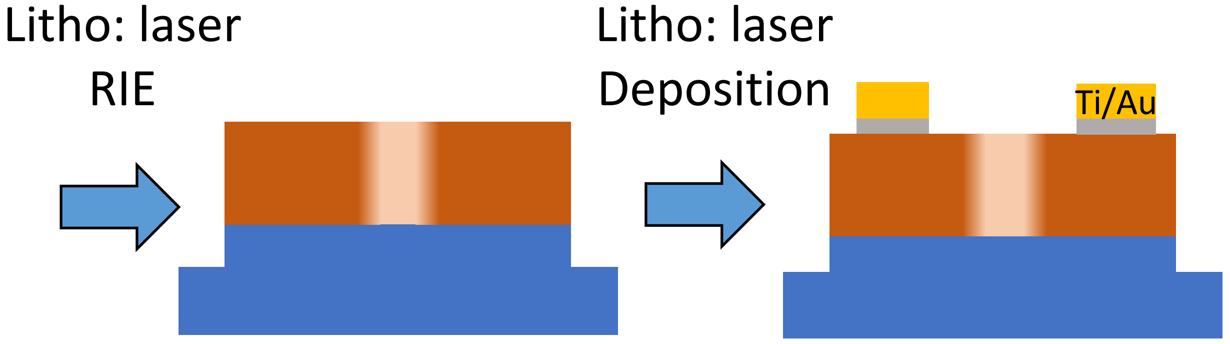

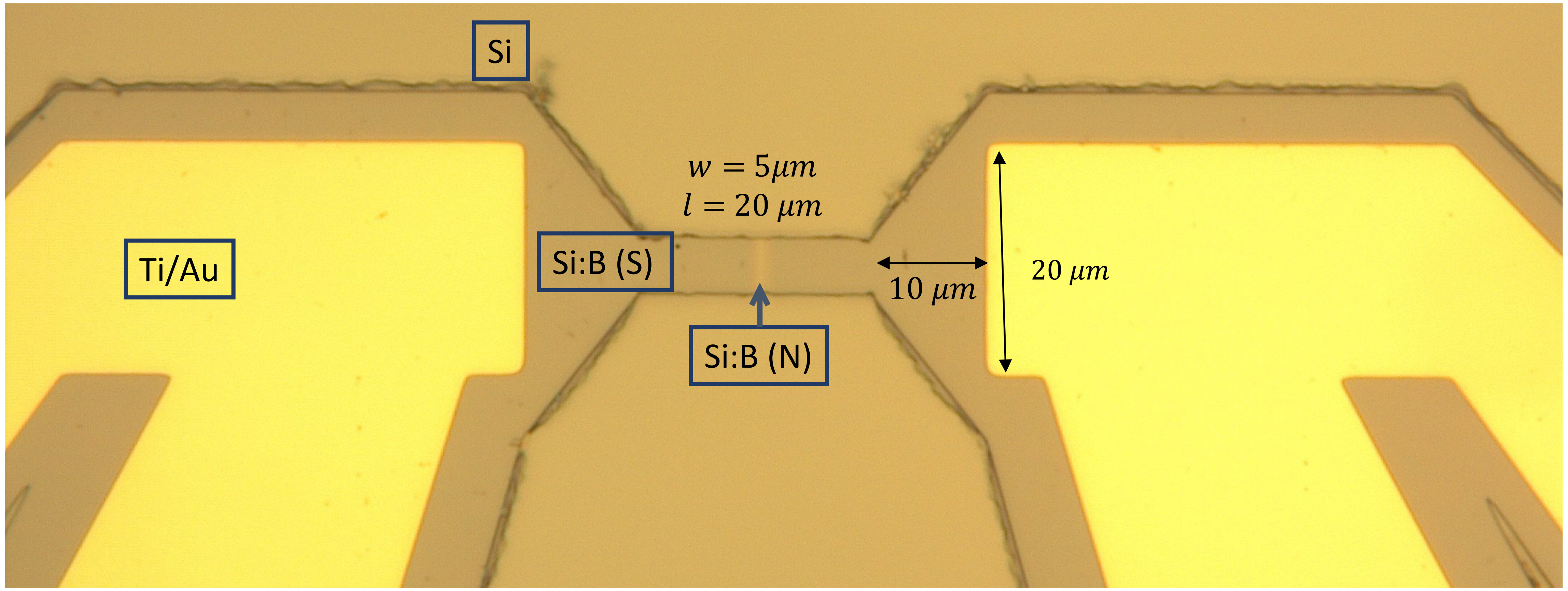

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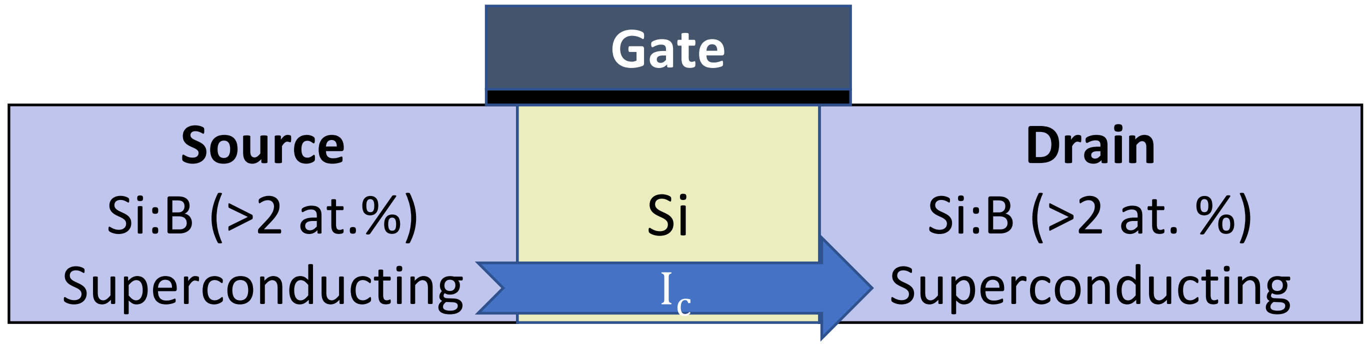

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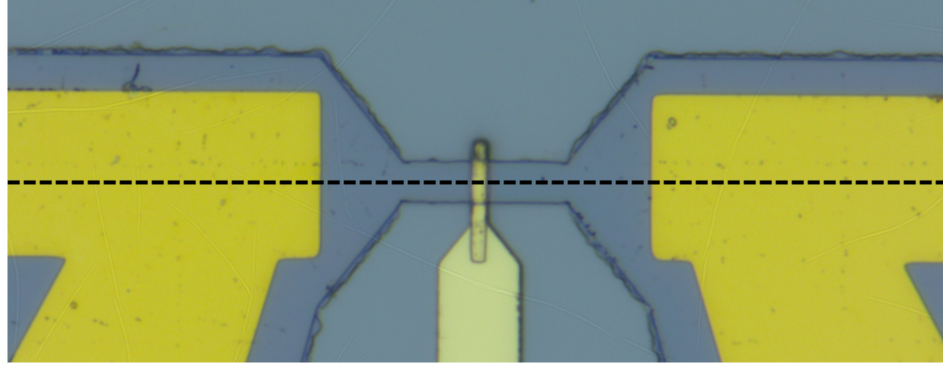

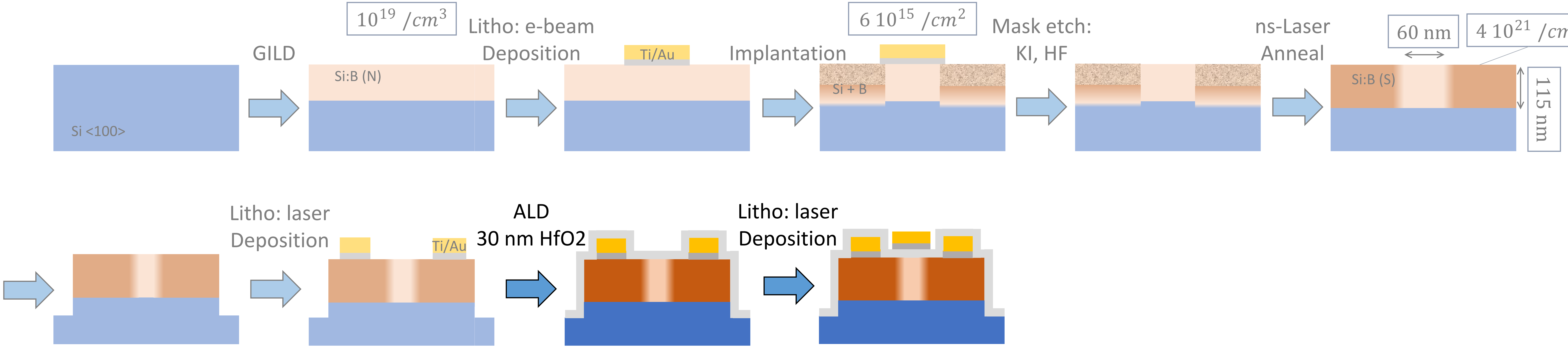

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