All-Silicon Superconducting Josephson Transistor

A. van Waveren, A. Chepelianskii, Y. Sun, G. Hallais, J. Bourçois, S. Berthelot, T. Baptiste, D. Bouville, J. Labar, B. Pecsz, D. Débarre, F. Chiodi

Goal: Controlling supercurrent in an all-silicon SNS Josephson junction
- Reliable fabrication of all-silicon Josephson junctions
- Electrostatic top gate → Superconducting Josephson Field Effect Transistor (JoFET)
- Studying & Understanding physical mechanism

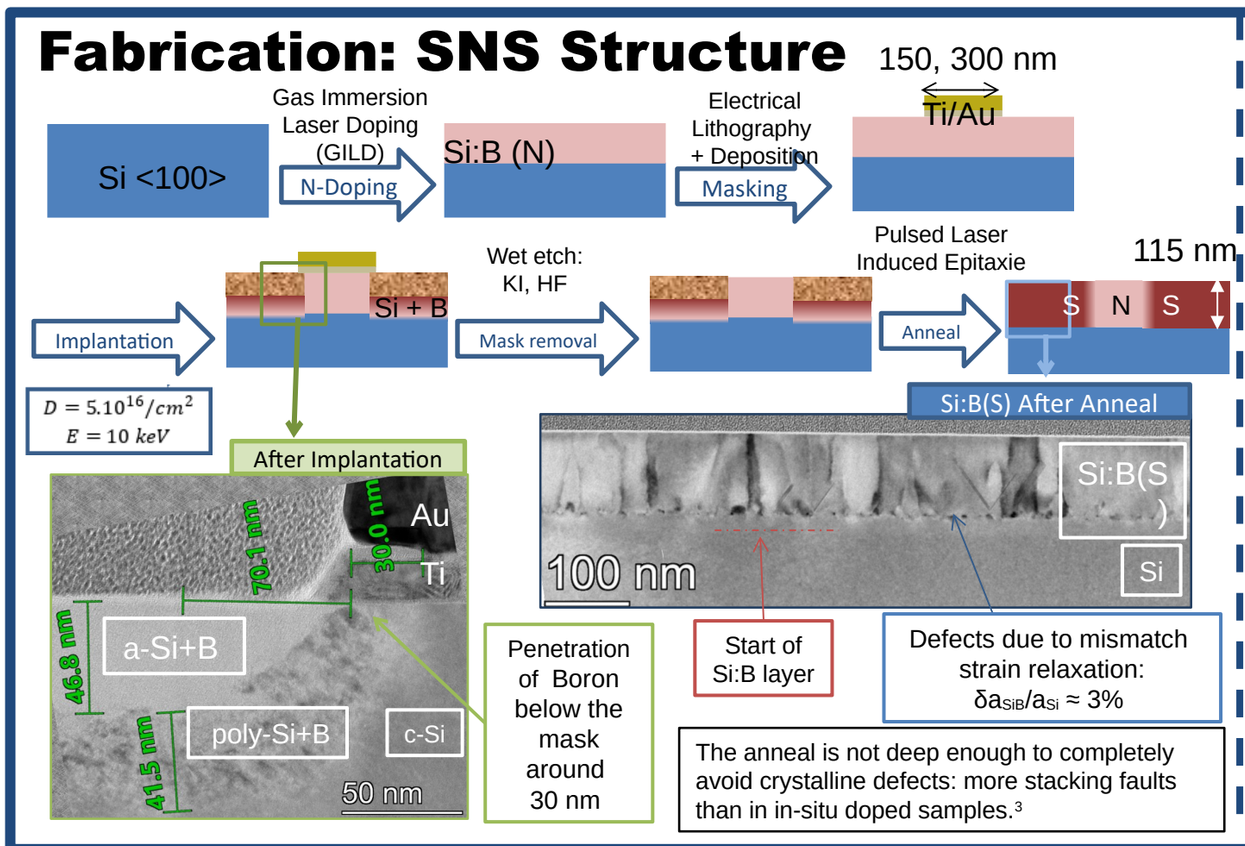
Long-term: Large-scale implementation on wafers

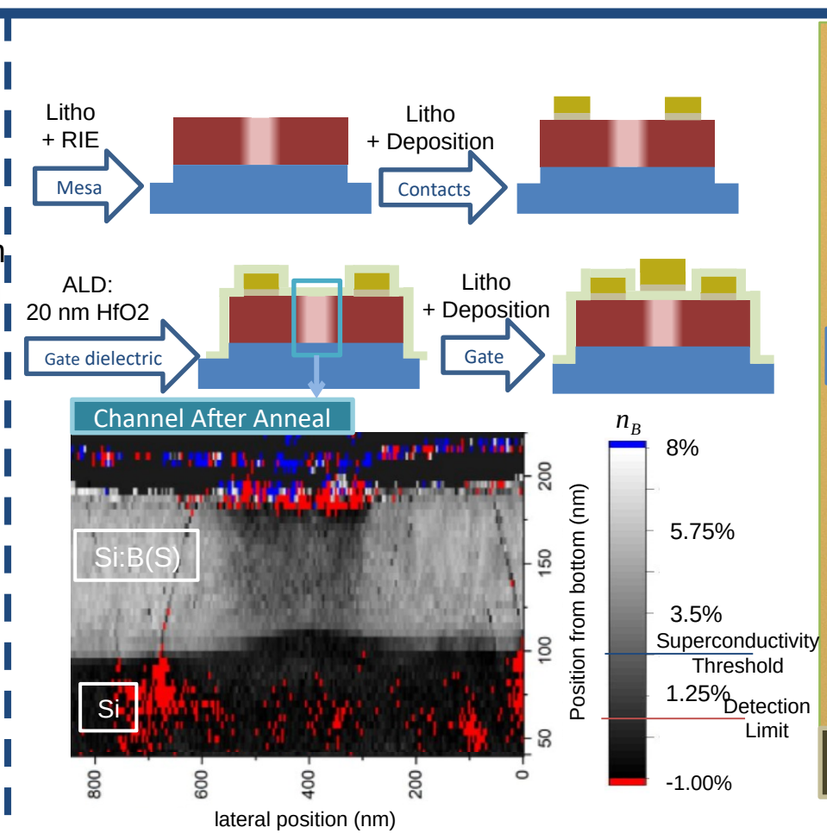
Superconducting Silicon[1,2]:
- ✓ High intrinsic electron-phonon coupling
- Low charge carrier concentration,
- ✓ Extremely high active doping (n_B>1 at.%) **with nanosecond laser doping** (λ=308 nm; t=25 ns)
- ✓ Modulation of DOS -> tunable

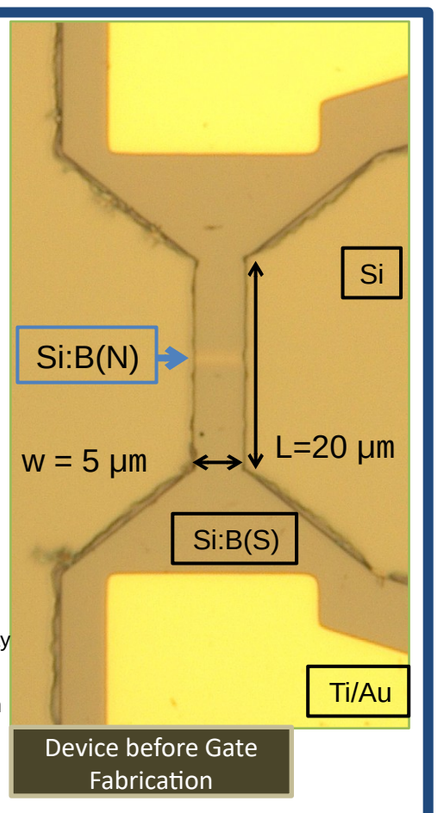
$$T_{C,BCS} \sim e^{-1/\lambda}$$

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

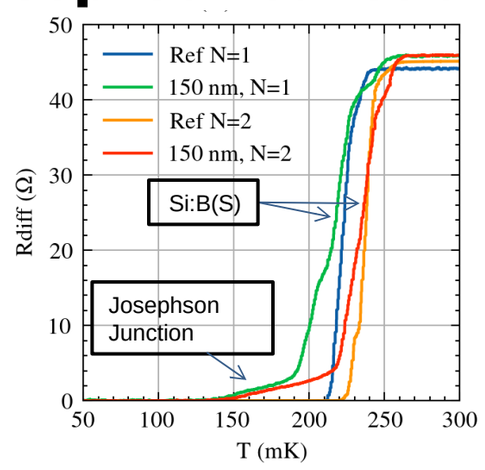
Fabrication: SNS Structure







Josephson Junctions!



Josephson Junction transition:
No large differences between N=1, N=2
- Diffusion of dopants into the channel during anneal dominates charge carrier concentration
- Slightly broader Source/Drain transition due to diffusion of Boron into channel

Energy scales:

$\Delta = 0{,}39\ K$

$E_{th} = \frac{\hbar D}{L^2} \approx 1\ K$

$eI_cR_N = 0{,}42\ K$

- Intermediate length scale

Ic (T)

For $k_BT < 2.5\,E_{Th}$,:

$$\frac{eRI_c}{E_{Th}} = b\left(1 - a\,e^{-bE_{Th}/(3.2\,k_BT)}\right)$$

Valid where k_BT<2.5 E_{Th}

Diffusive Junction:

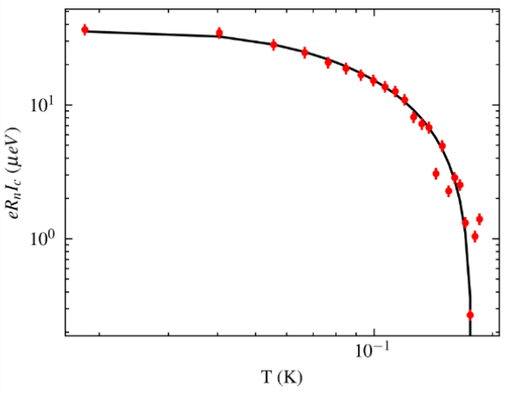
Long wire limit (Δ/E_{Th}>5.10⁴):

$b = eRI_c(T=0)/E_{Th} = 10.82$

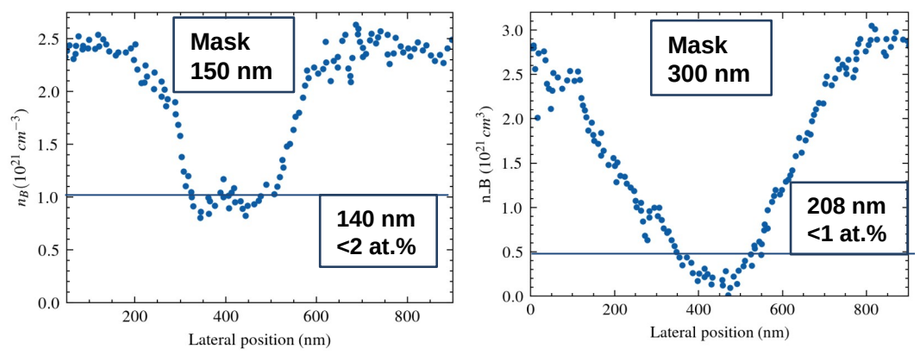
Short wire ($\Delta/E_{Th} \ll 1$):

$b = eRI_c(T=0)/\Delta = 2.07$

Fit: $a = 2.1;\ b\,E_{Th} = 35\,\mu eV$



Channel Doping after Anneal



Boron diffusion into channel during laser anneal
→ Wider, highly doped channels
→ Only **'150 nm'** is a Josephson Junction;
300 nm is **not**

Gate effect

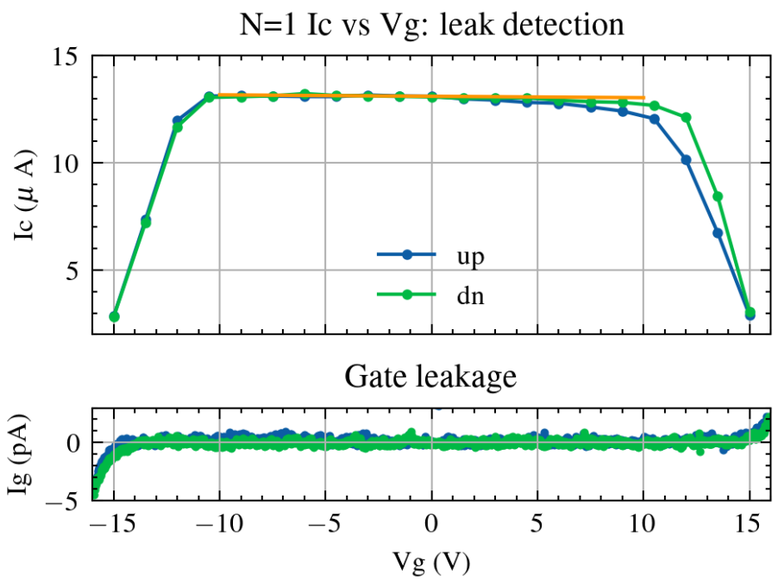
Theory:

$$\delta n = \frac{\epsilon_0 \epsilon_r}{e\,d_{HfO2}} U$$

$$\delta n = 3{,}2.10^{12}/V$$

$$\frac{\delta n}{n} \approx 0.2\%/V$$

$$\rightarrow \frac{\delta R}{R} = 0.2\%/V$$

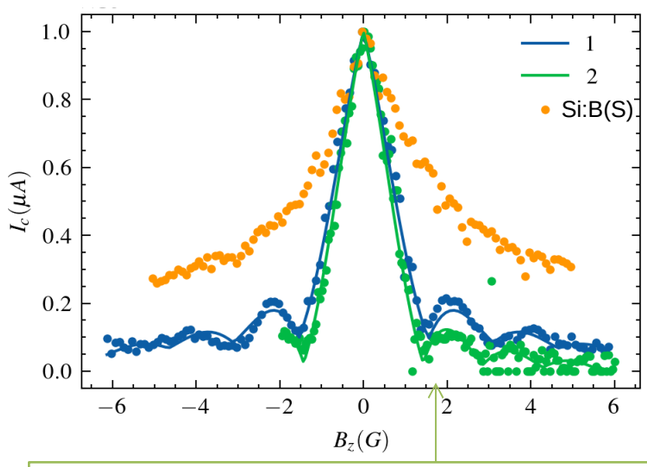


There seems to be a small gate effect:
- I_c (~2% over ±10V)
- R_N (~4% over ±10V)

Difficulties:
- Highly doped channel (~1.5 at. %)
- Reproducibility
- Reducing Channel Doping by optimizing Anneal

Above ±10V few hot electrons leaking from the gate and breaking the superconducting state.
- This effect is similar to gated metallic superconductors, but much more sensitive (due to lower DOS)
- The junction acts as a current detector that is more sensitive than our picoammeter (shown below).

Fraunhofer Interference



Theory:

As $\lambda_p \gg d,\ L_S \gg w_{jj}$:

$$B_0 = 1.842\frac{\Phi_0}{w_{jj}^2}$$

$w_{JJ} = 5\ \mu m$

$B_0 = 1{,}52\ G$

Fit:

$B_{0,1} = 1{,}50\ G$

$B_{0,2} = 1{,}43\ G$

London Length:

$$\lambda_L(0) = \sqrt{\frac{m^*}{\mu_0 n_S e^2}}$$

$$\lambda_L = \lambda_L(0)\sqrt{\frac{\xi_0}{l_e}}$$

$$\xi_0 = \frac{\hbar D}{4}$$

$$l_e = \frac{v_F m_e}{n_B \rho e^2}$$

$n_B \approx 3{,}3.10^{21}/cm^3$

$\rho \approx 1.10^{-3}\,\Omega cm$

$m^* = 0{,}34 m_e$

$v_F = 1{,}6.10^6 m/s$

$\lambda \approx 1{,}5\ \mu m > d$

$\lambda_p = \frac{\lambda^2}{d} \approx 15\ \mu m \gg d$

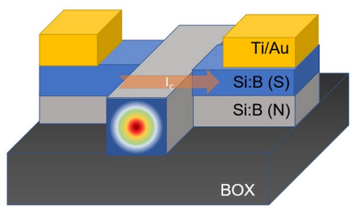
- Unshielded
- Geometry dominates

- N=2 has a more homogeneous current distribution, leading to an almost complete negative interference

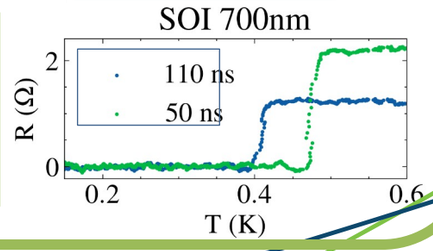
Perspective: Optical Modulation

- Using photons instead of an electrostatic gate to modulate the supercurrent

Advantages:
- Faster modulation
- Integration with complex photonic circuits (PICS)



Preliminary Studies: Doping SOI
- Low thermal conductivity of SiO2-layer reduces the maximum active concentration obtainable
- 220 nm/ 2000 nm: No superconductivity found
- 700 nm/3000nm:upto 0.5K for 80 nm doped layer



1: Desvignes, L. (2023, April 27). PhD Thesis, https://theses.hal.science/tel-04137471v1
2: Nath, S. (et al.Physica Status Solidi (A), 221(24). https://doi.org/10.1002/pssa.202400313
3: Hallais, G.et al.(2023) Semiconductor Science and Technology, 38(3), 034003, https://doi.org/10.1088/1361-6641/acb0f0
4. Debos et al. (2001) Phys. Rev. B 63, 064502, https://doi.org/10.1103/PhysRevB.63.064502