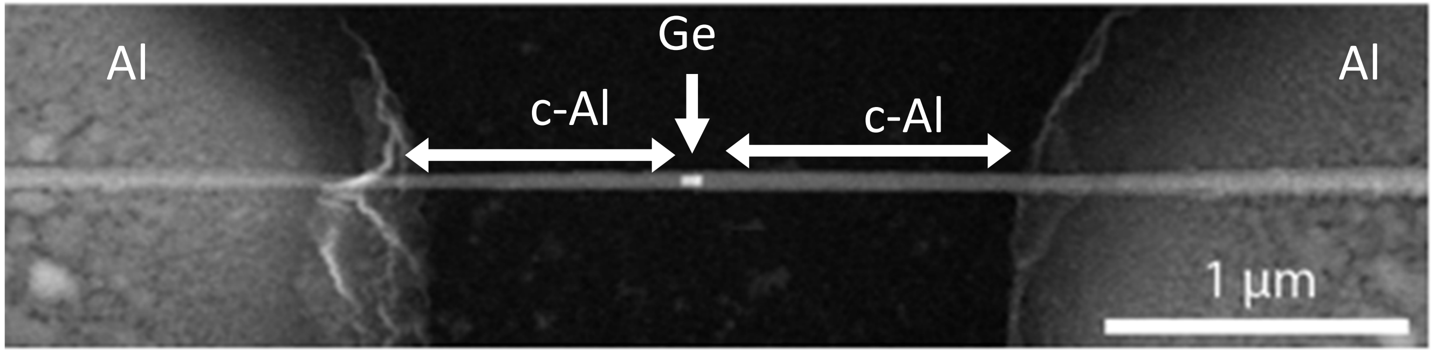
Quantum transport in monolithic crystalline Al-Ge-Al heterostructure nanowires



HAADF STEM of Al-Ge-Al device
with L_{Ge} = 100 nm.

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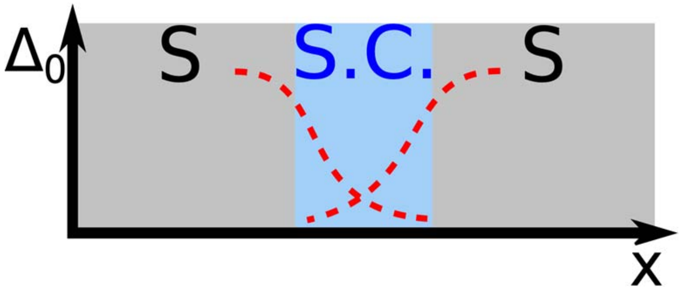
(3) CEA grenoble

Quantum Engineering
Univ. Grenoble Alpes

Motivations

Superconducting hybrid junctions based on semiconductor nanowires

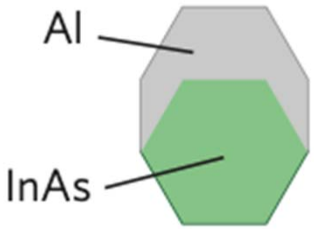


Combine the properties of both materials:

Tunable Josephson junction with an electrostatic gate.

Promising quantum device:

- Gate tuneable Josephson junction (Gatemon)
- Topologically protection (Majorana, Multi-terminal junctions)



The superconducting material is obtained by proximity effect.

Key point: semiconductor-superconductor interface.

Al-InAs: Chang, W. et al. Nature Nanotechnology 10,232–236 (2015).

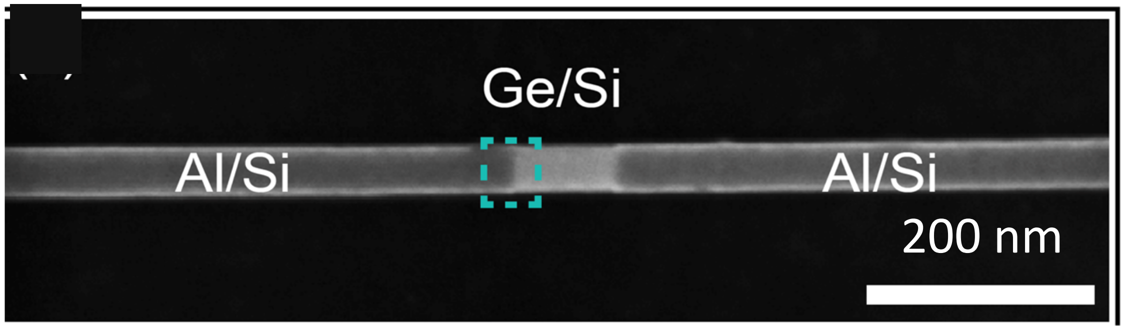
Al-InSb: Gazibegovic, S. et al. Nature 548, 434–438 (2017).

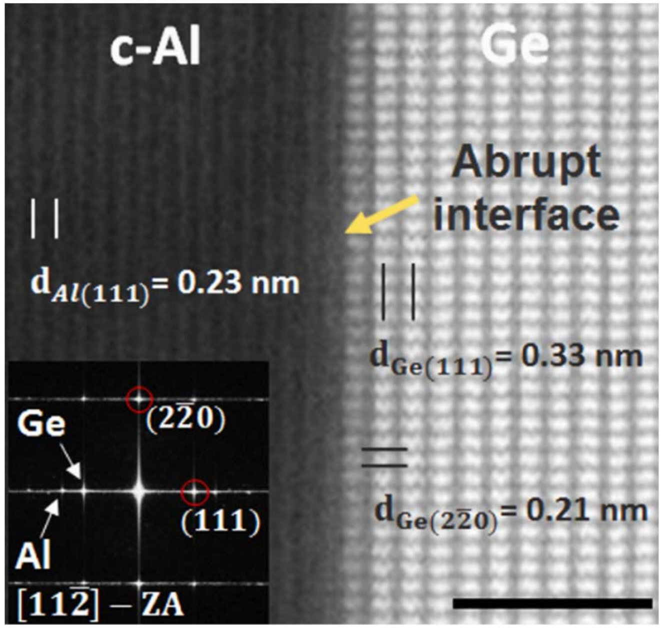
Motivations

Superconducting hybrid junctions based on Ge nanowires

<u>Ge based hybrid junctions:</u>

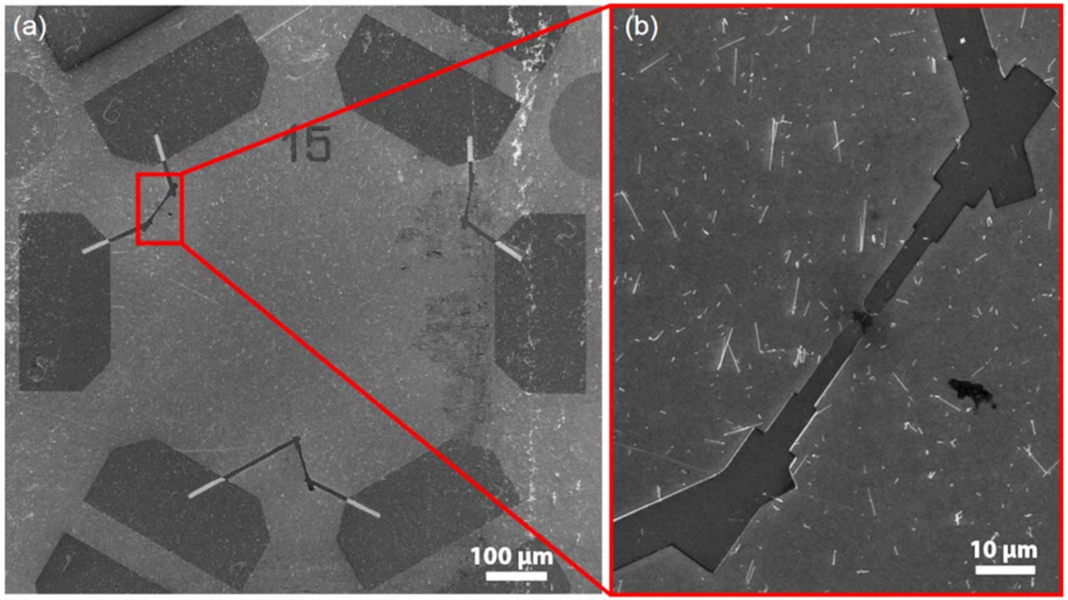
- Large hole mobility
- Large spin-orbit coupling
- No nuclear spin
- CMOS compatible material
- High quality interface (Al/Ge exchange process)

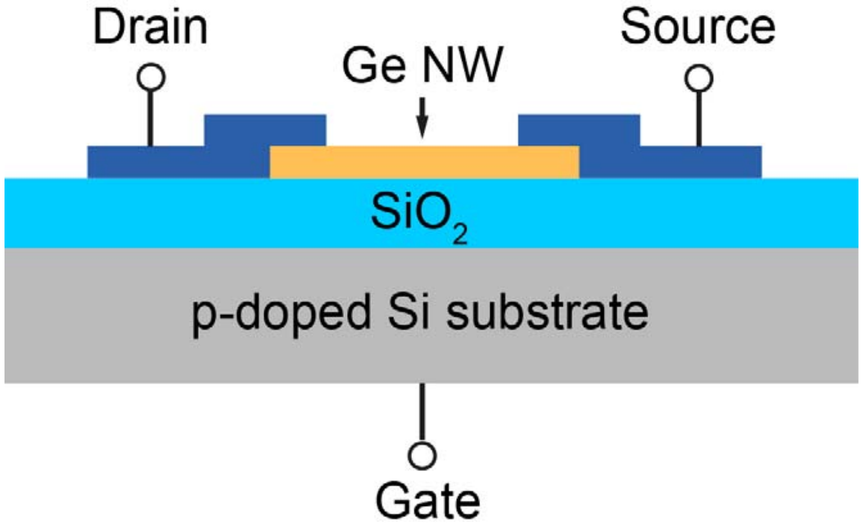


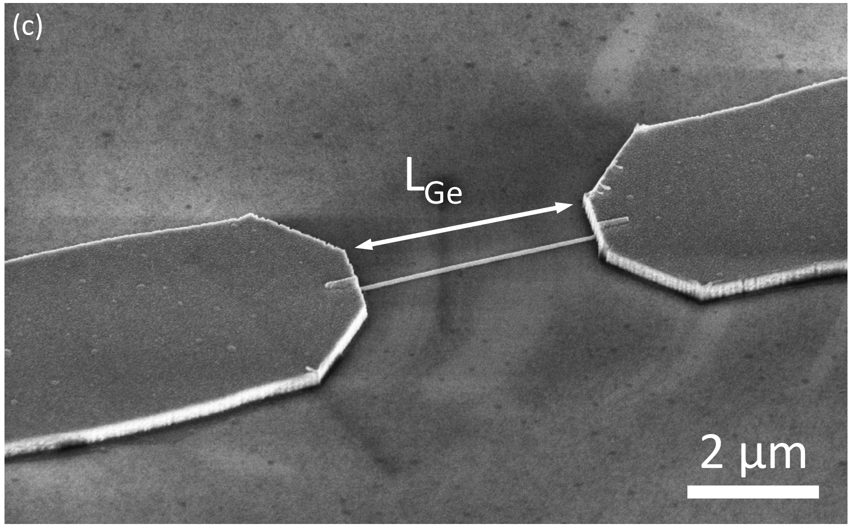


Heterostructure fabrication

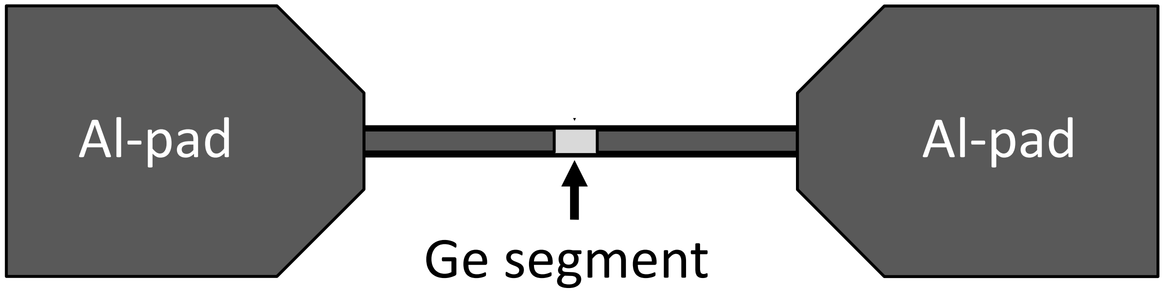
- Oxidized p-doped Si wafer
- Macroscopic Au bond pads
- CVD Nanowire transfer
- Source/drain Al contacts (EBL)

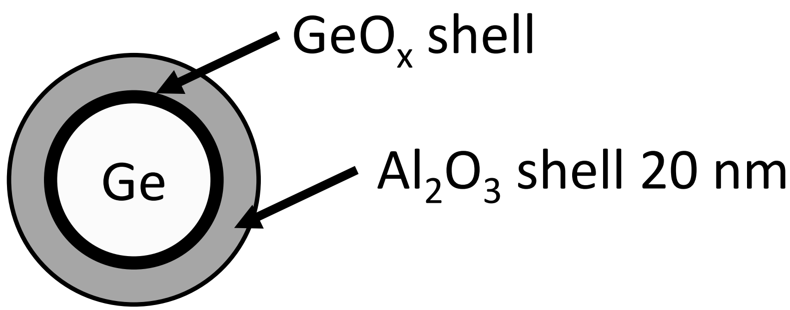


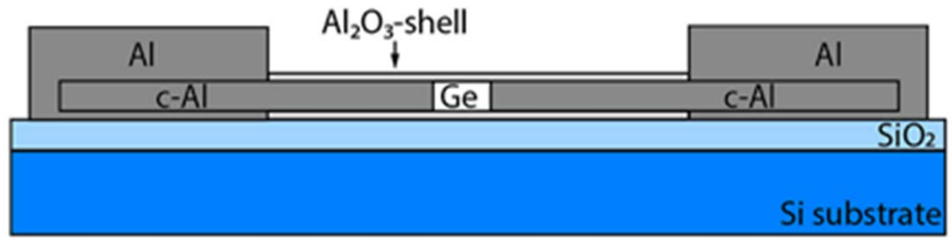




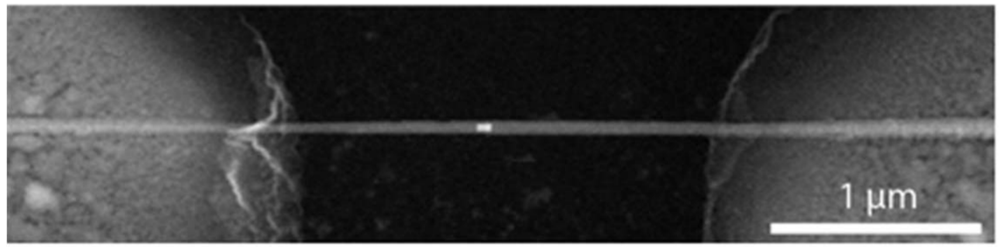
Selective Substitution



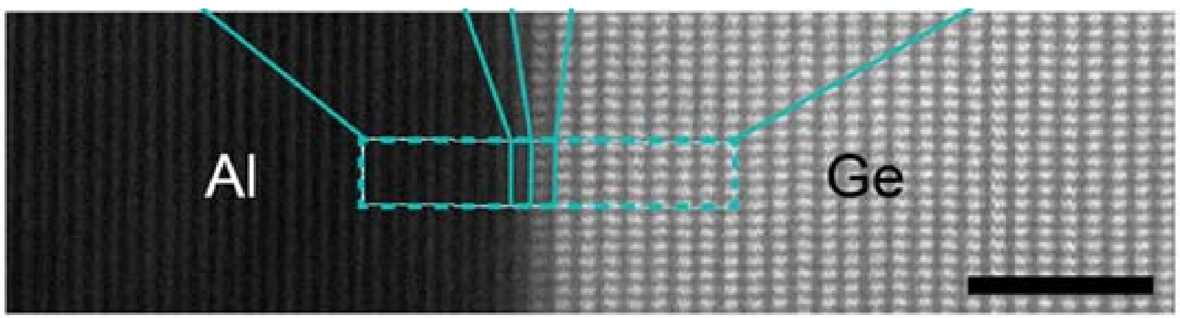




Monolithic Al-Ge-Al structure:



- Self-aligned quasi-1D c-Al leads
- Controllable Ge segment length
- Abrupt M-S interfaces

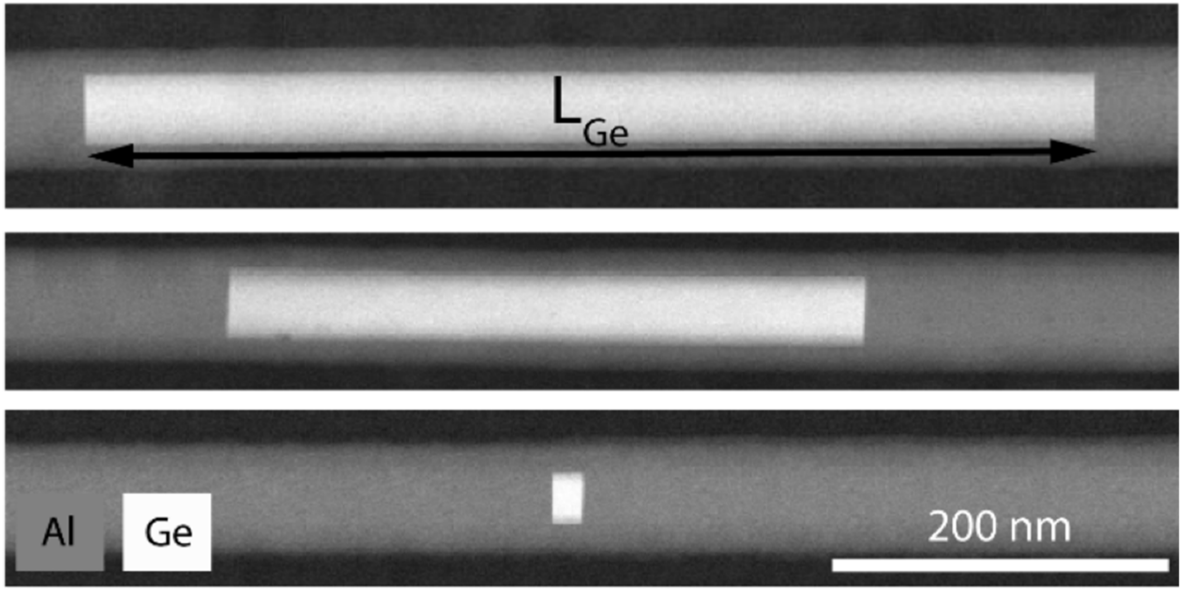


K. El Hajraoui, *et al.*, *Nano Letters*, 2019, 19, 2897–2904

Control of the Ge segment

Reproducible and well controlled process :

- The duration of the thermal annealing allows to obtain ultrashort Ge segment.



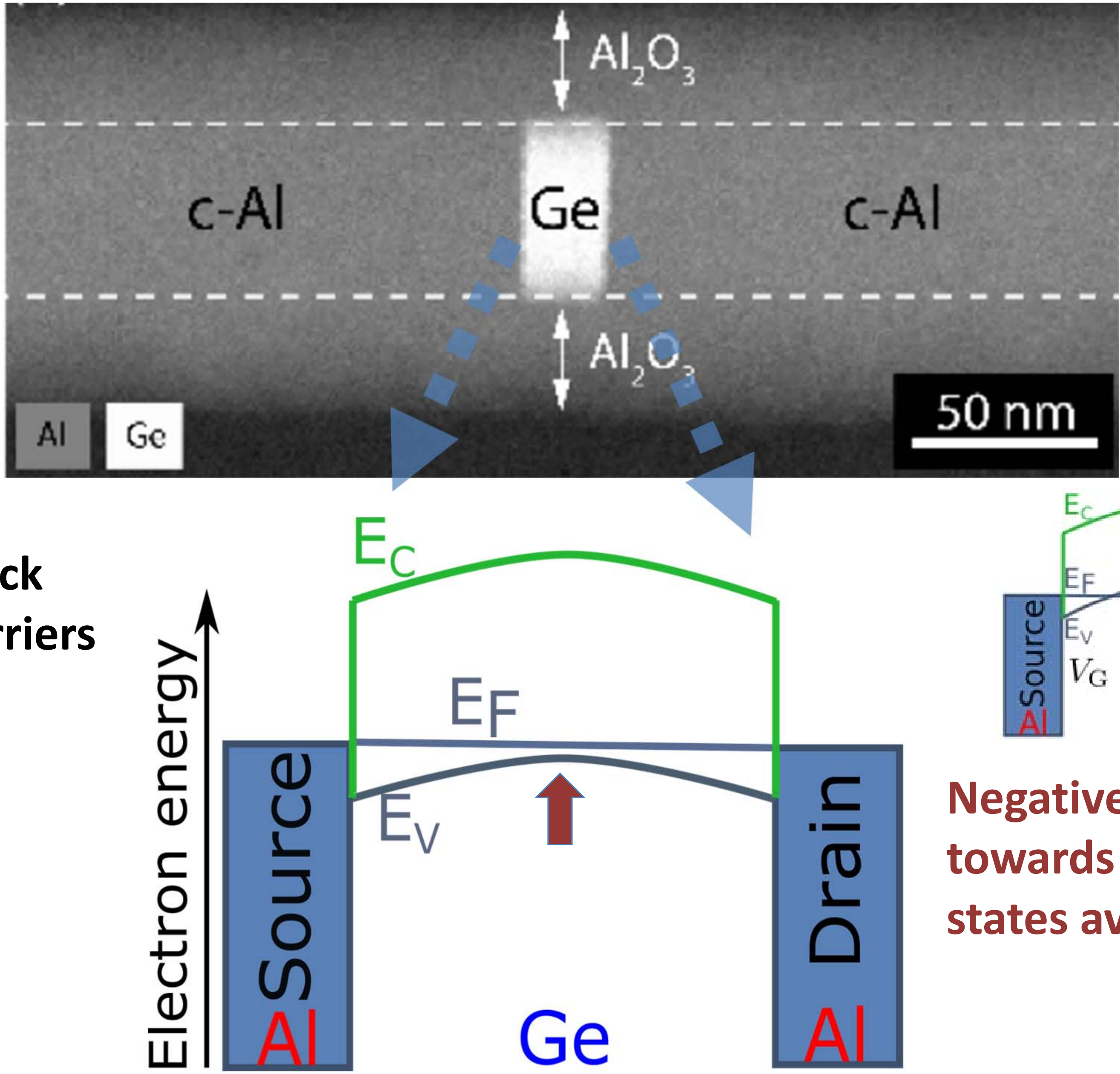
L_{Ge} = 600 nm

L_{Ge} = 400 nm

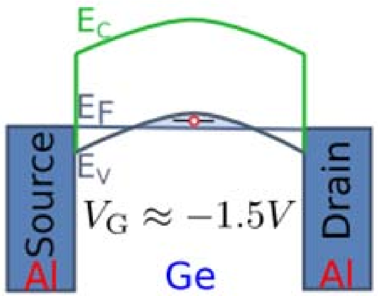
L_{Ge} = 15 nm

HAADF STEM Zoom of Al-Ge-Al devices

Al/Ge Schottky Barrier

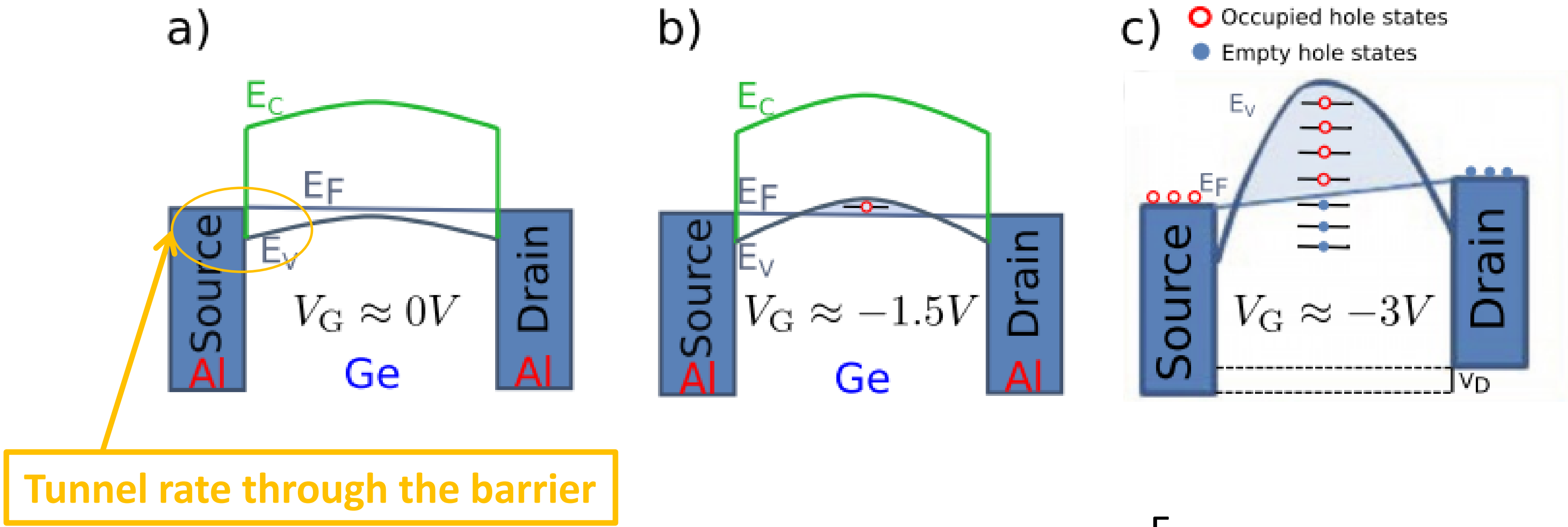


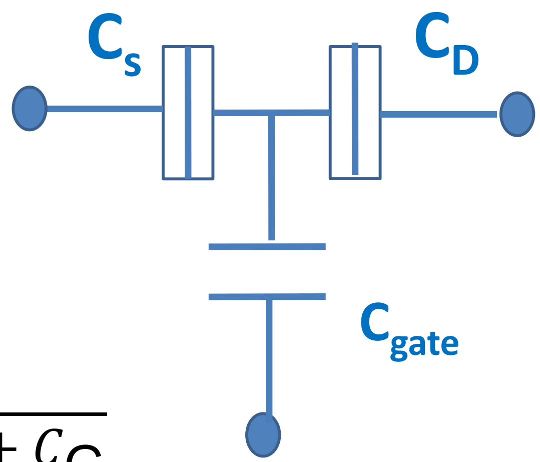
2 Back-to back Schottky Barriers

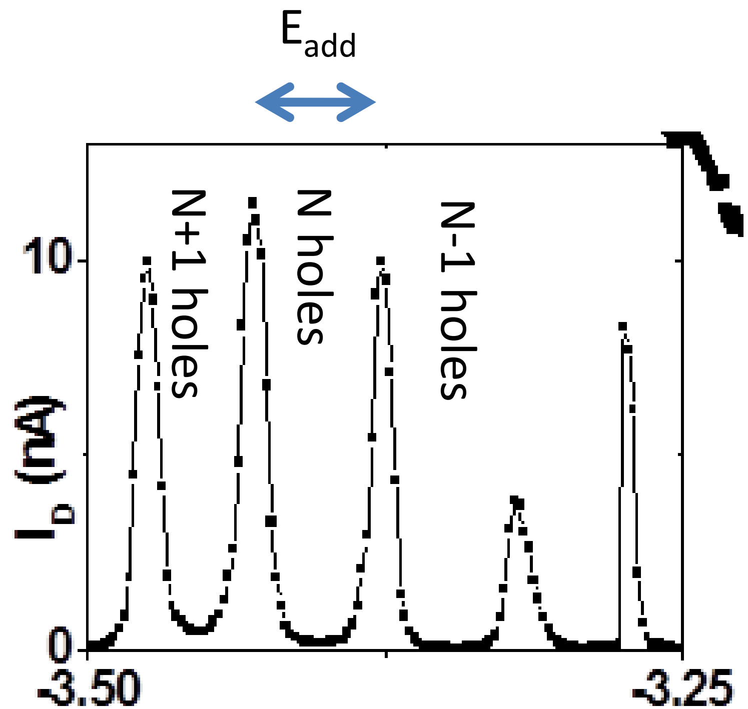


Negative V_G bends VB towards E_F making VB states available.

Tuning the barriers versus the gate voltage





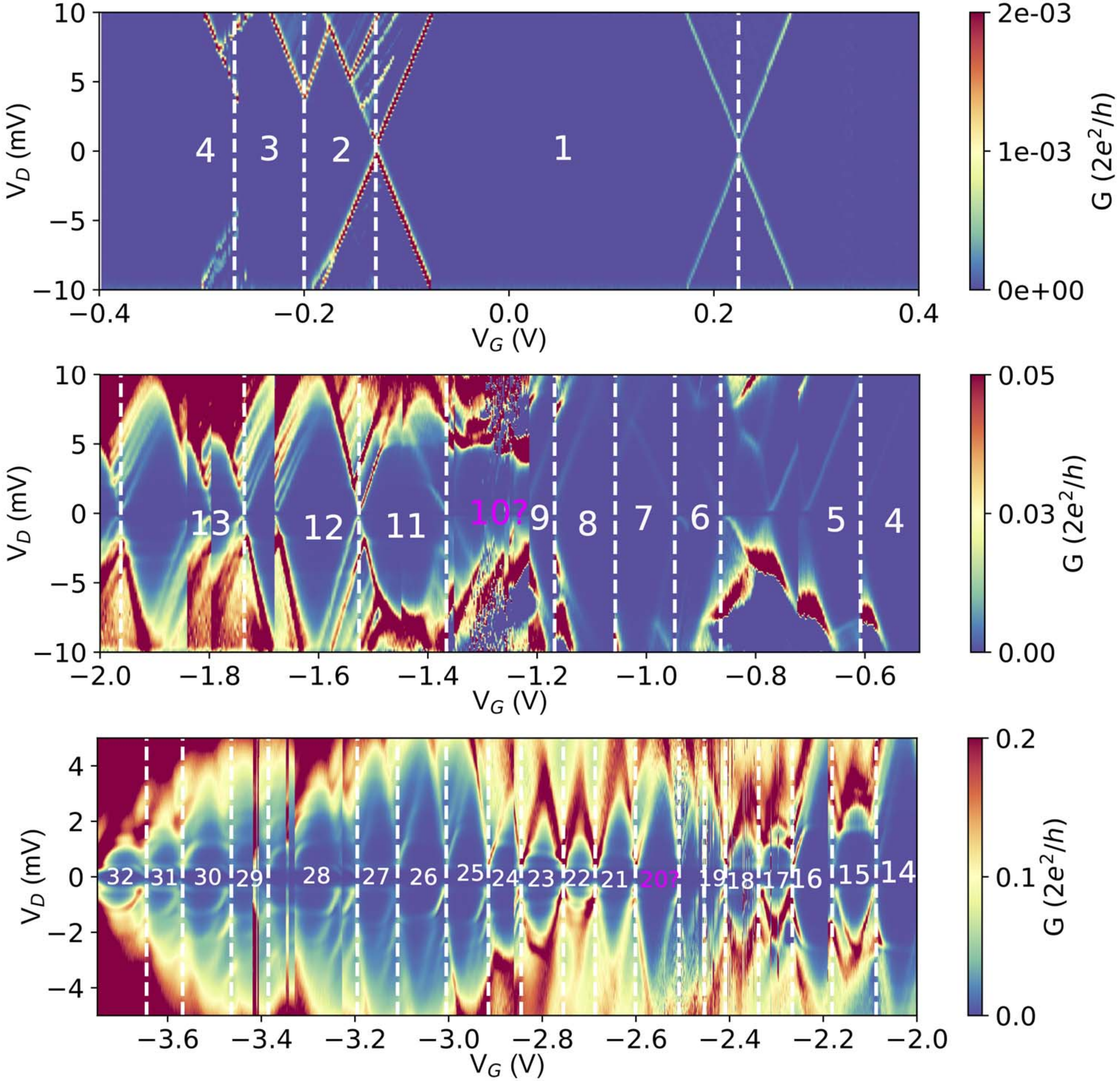


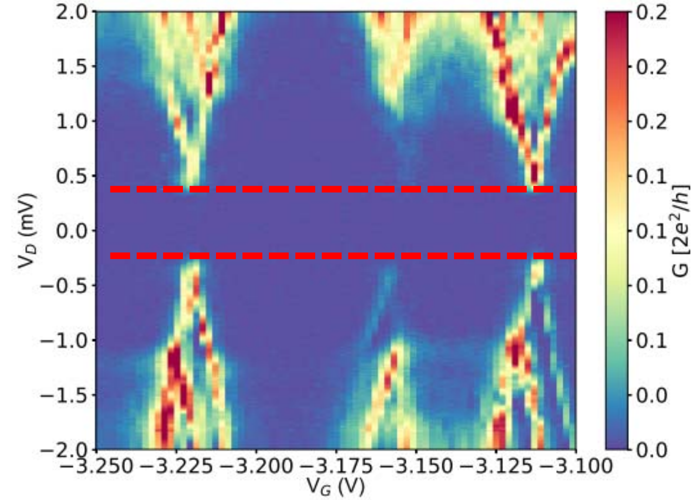
$E_{add} = E_C + \delta$

$$E_C = \frac{e^2}{C_S + C_D + C_G}$$

δ : energy level spacing of the dot

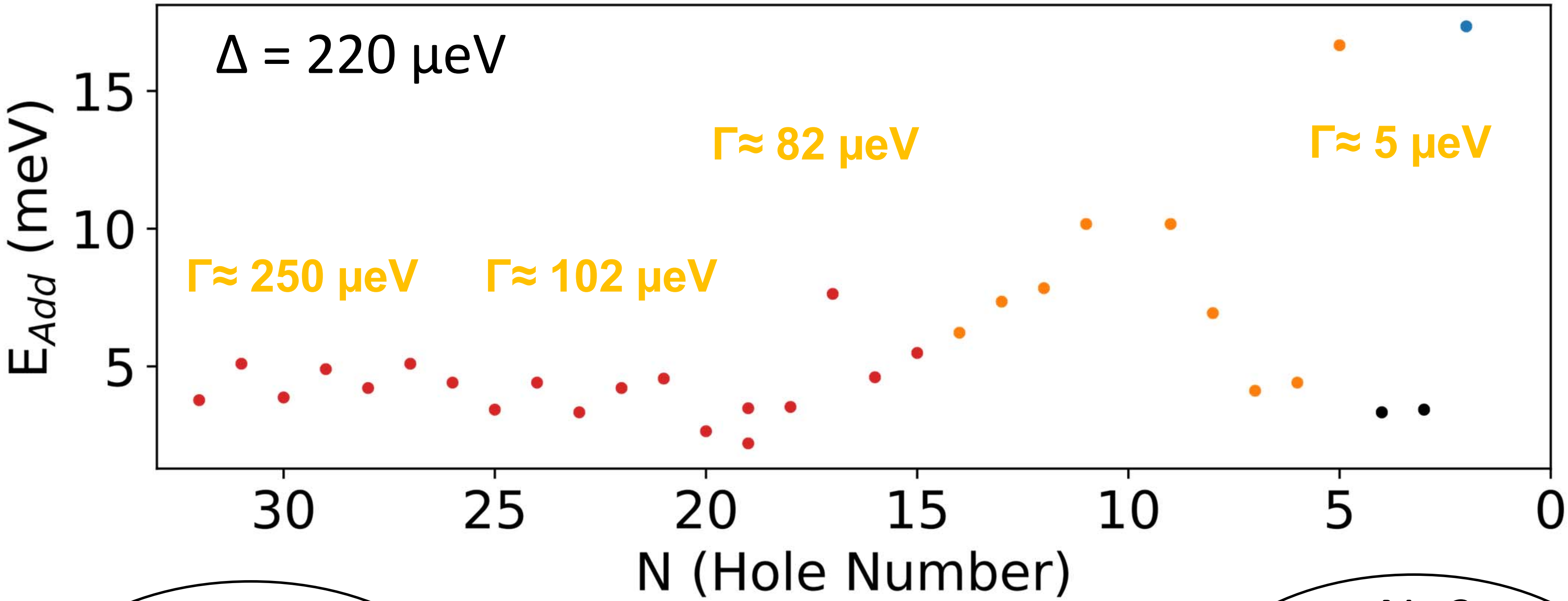
Coulomb pattern for a short sample L_{Ge}=42 nm





Gap of the junction :
+/- 2 Δ

Addition energy and tunnel rate



N=31

Γ≈ 250 μeV

E_c= 3 meV

Γ : increases with N

E_C : decreases with N

Δ : Al gap (220 μeV)

N=2

Γ≈ 5 μeV

E_c= 32 meV

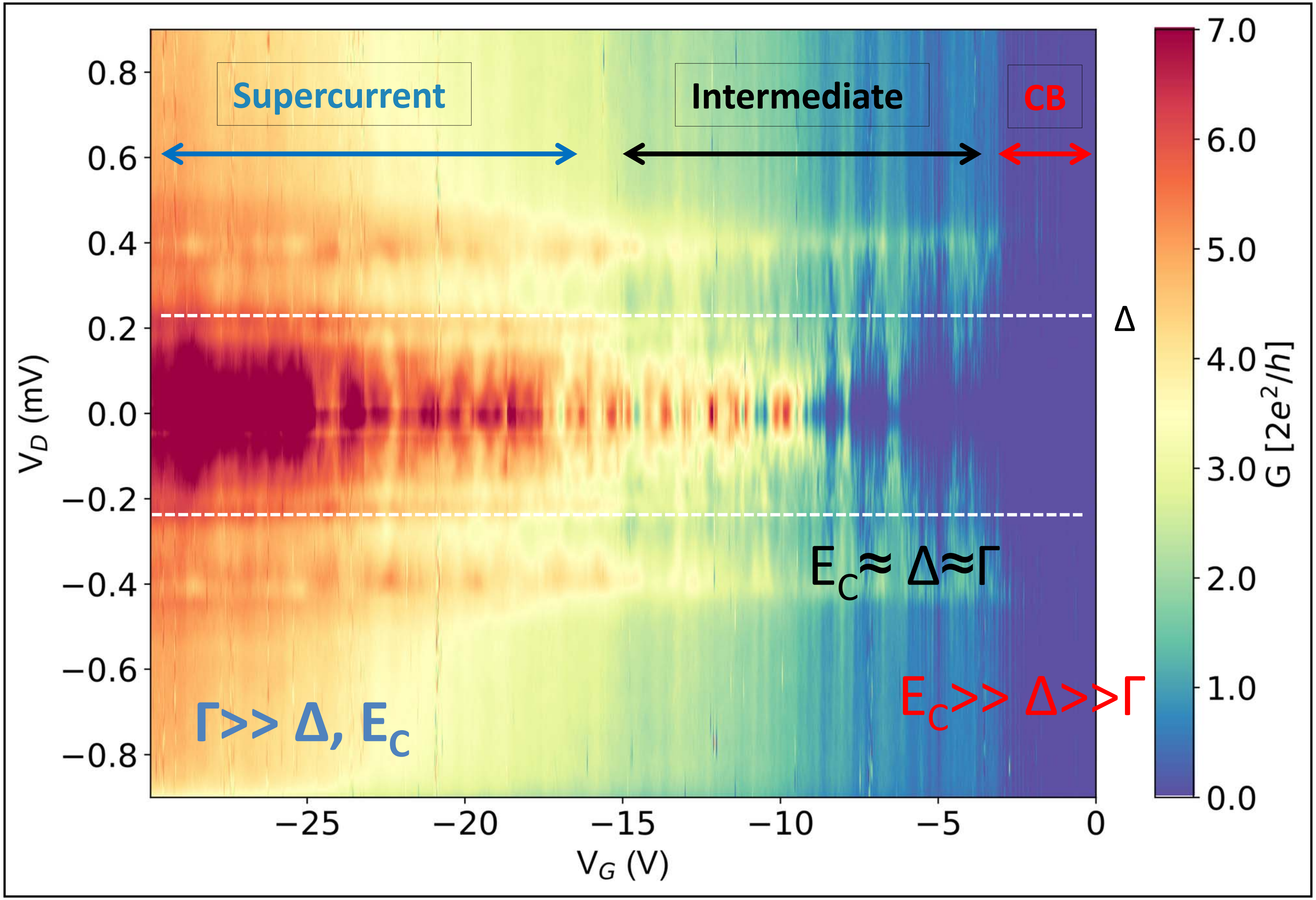
E_C≈ Δ≈Γ

Intermediate coupling

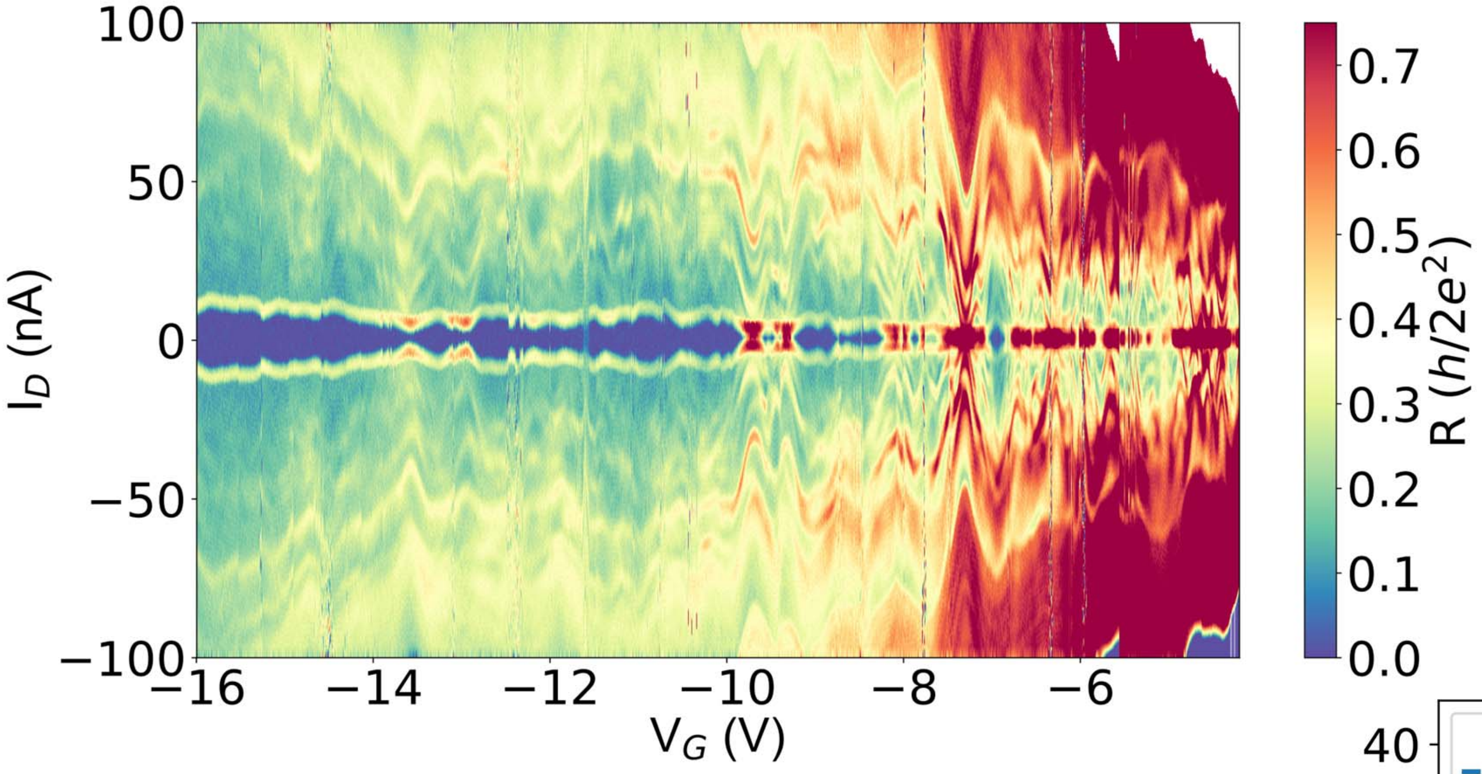
E_C>> Δ>>Γ

Weak coupling

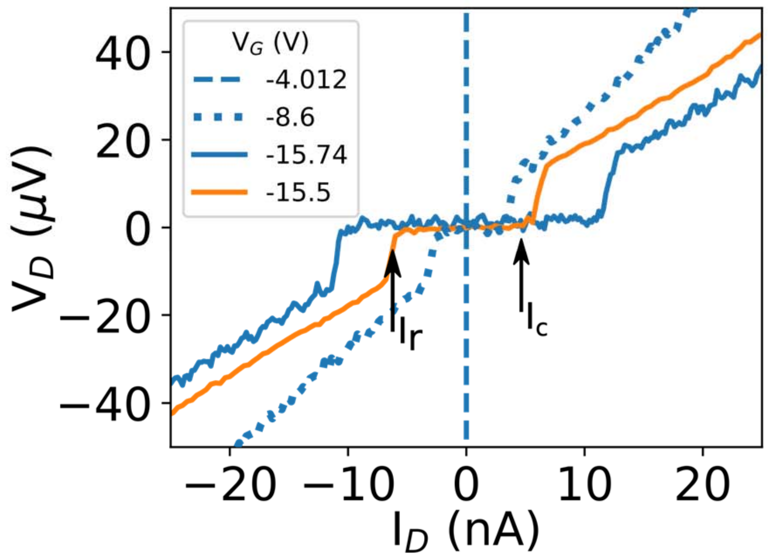
Transport overview for a short sample L_{Ge}=42 nm



Superconducting regime L_{Ge} ~ 40 nm



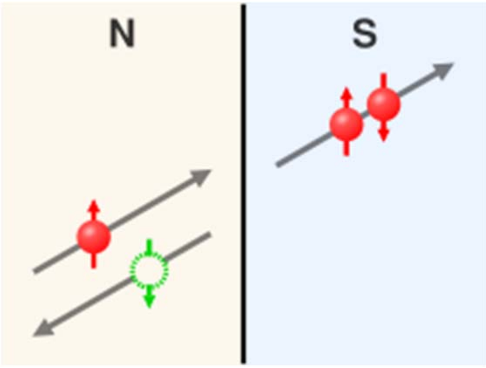
Tuneable supercurrent up to 10 nA



- Zero resistance around I_D=0A: supercurrent.
- Snake like fashion of the resistance.

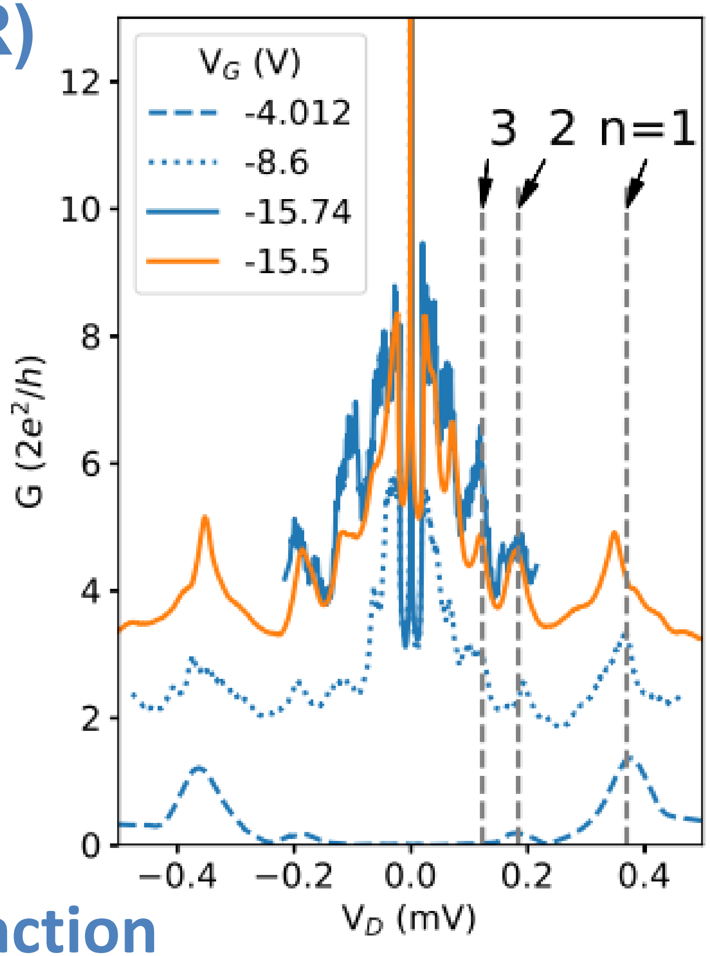
Multiple Andreev Reflection (MAR)

Normal / superconductor interface

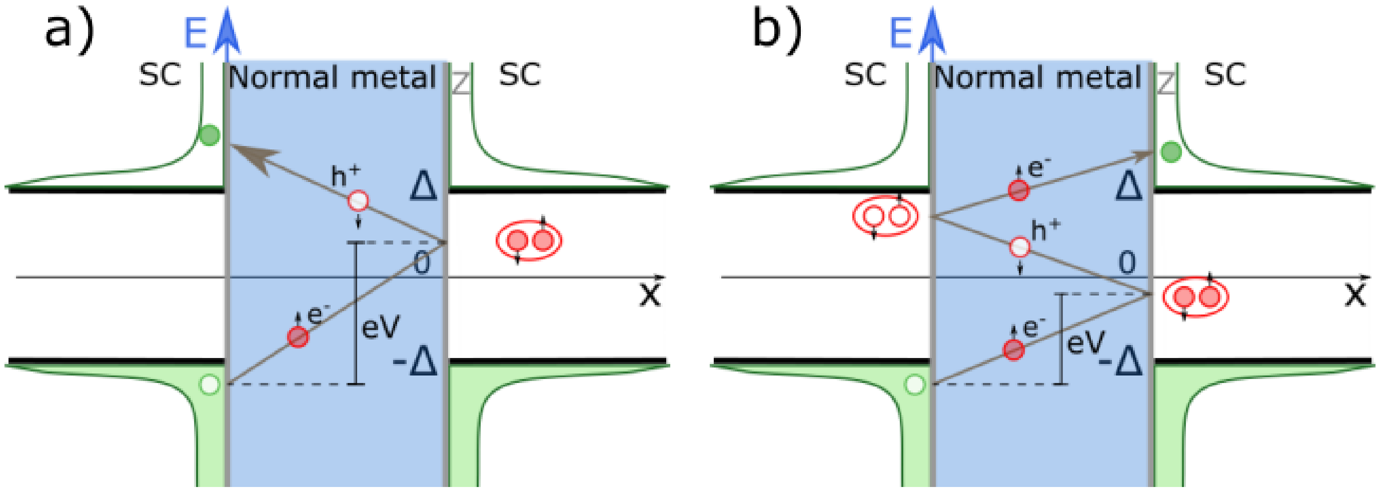


Andreev reflection

- The probability depends on the transparency of the interface



Superconductor / Normal / Superconductor junction

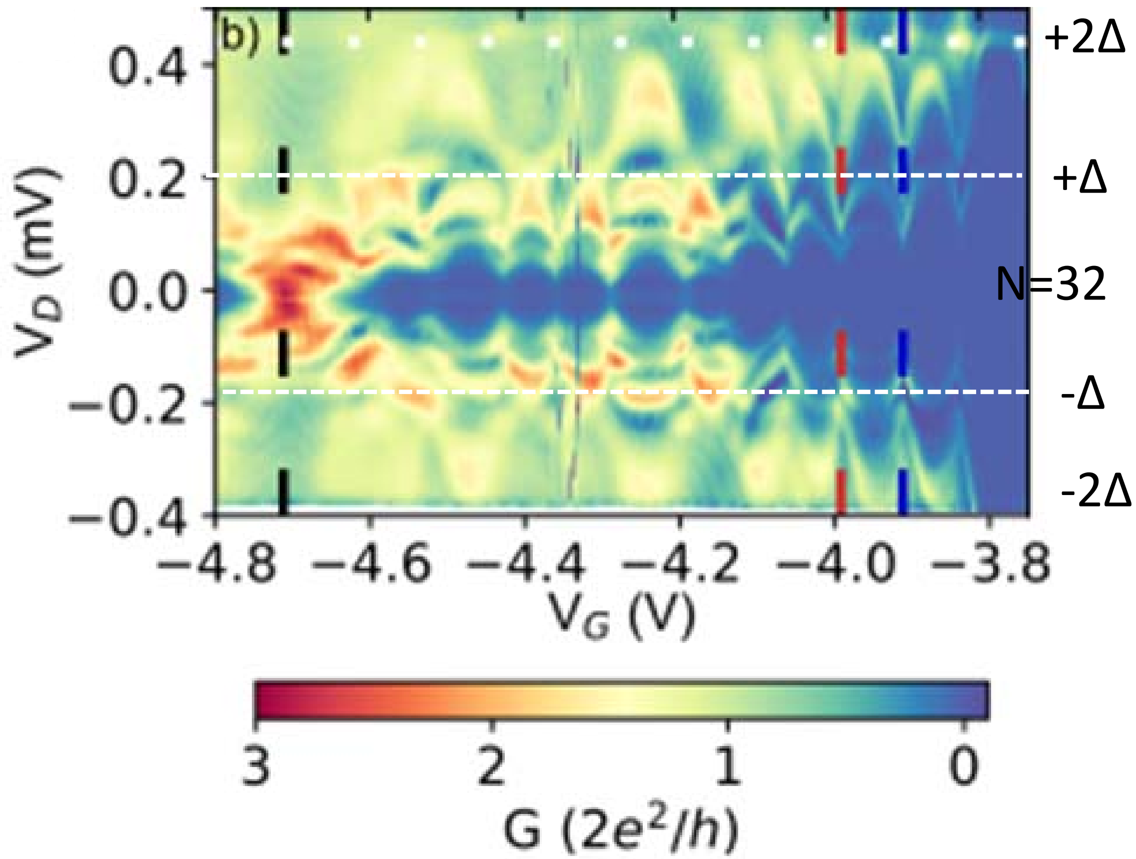


Resonances for

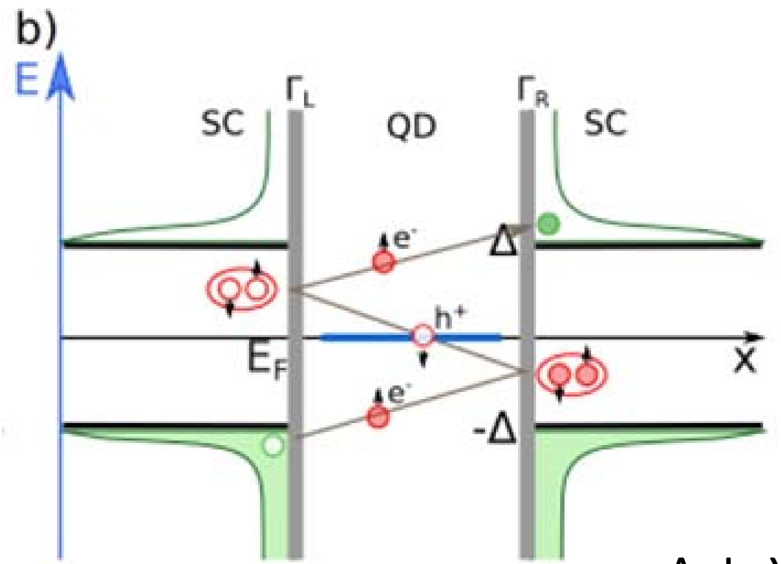
V_n =

Multiple Andreev reflections

Sub-gap features if the intermediate regime



Periodic resonances
with facing bell-shaped:
Signature of the single-hole filling



Interplay between MAR and resonant tunneling

A. L. Yeyati, et al. Phys. Rev. B 55, R6137–R6140 (1997).

Conclusions

- **Gate tunable Schottky barriers at the Al/Ge interface.**
  - Coulomb Blockade regime.
  - Intermediate regime: sub-gap features.
- **Supercurrent regime: gate tuneable supercurrent**.
  - Excellent transparencies

- *"Highly transparent contacts to the 1D hole gas in ultra-scaled Ge/Si core/shell nanowires"*
M. Sistani*, J. Delaforce*, R. Kramer, N. Roch, M.A. Luong, M.I. den Hertog, E. Robin, J. Smoliner, J. Yao, C.M. Lieber, C. Naud, A. Lugstein, O. Buisson,
ACS Nano, American Chemical Society, 2019, 13 (12), pp. 14145-14151;
doi: 10.1021/acsnano.9b06809t

- *"Coulomb blockade in monolithic and monocrystalline Al-Ge-Al nanowire heterostructures"*
Masiar Sistani, Jovian Delaforce, Karthik Bharadwaj, Minh Anh Luong, Jorge Nacenta, Nicolas Roch, Martien den Hertog, Roman Kramer, Olivier Buisson, Alois Lugstein, and Cecile Naud,
Appl. Phys. Lett. **116,** 013105 (2020); doi: 10.1063/1.5126088

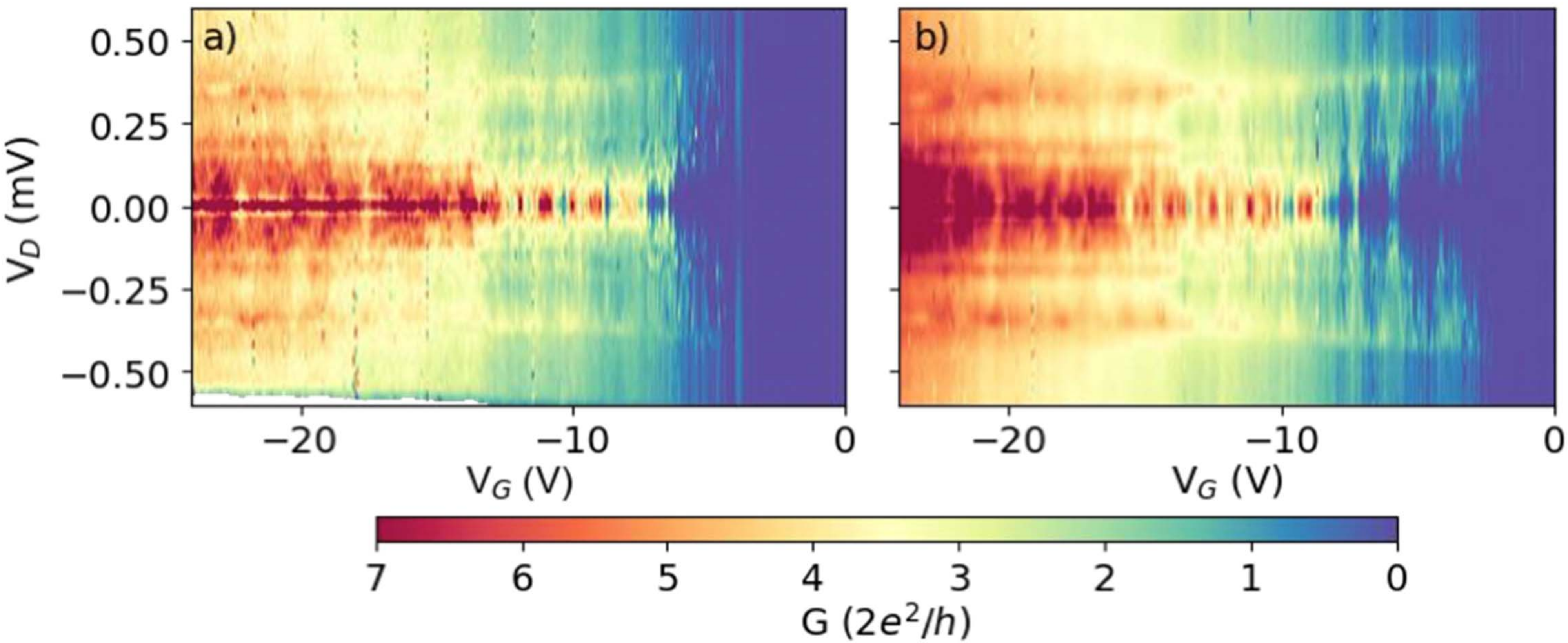
Perspectives

- Transmon/gatemon qubits.
- Dilution fridge + magnetic field.
- Local gates.

- *" Al-Ge-Al Nanowire Heterotructures: From Single-Hole Quantum Dot to Josephson Effect "*
Jovian Delaforce, Masiar Sistani, Roman Kramer, Minh A. Luong, Nicolas Roch, Walter M. Weber, Martien den Hertog, Eric Robin, Cecile Naud, Alois Lugstein and Olivier Buisson,
Adv. Mater. **2021**, 2101989

Thank you for your attention.

We are looking for a PhD student.

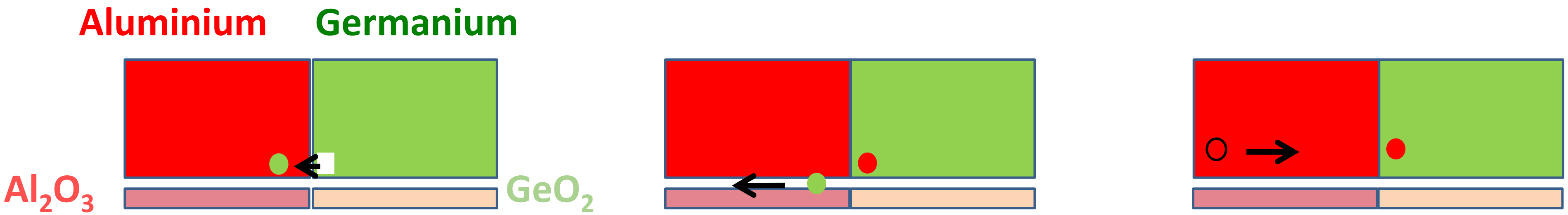

a)
b)
0.50
0.25
0.00
−0.25
−0.50
V_D (mV)
−20
−10
0
V_G (V)
7
6
5
4
3
2
1
0
G (2e²/h)

Diffusion of Al and Ge

Diffusion of	Aluminium	Germanium	Aluminium	Germanium
In	Aluminium	Aluminium	Germanium	Germanium
D [cm²/s]	$1,46.10^{-12}$	$3,27.10^{-11}$	$1,25.10^{-25}$	$9,91.10^{-25}$

Fast (Al in Al, Ge in Al) — Slow (Al in Ge, Ge in Ge)

Diffusion coefficient for Al and Ge at the annealing temperature of 350° C. [1, 2]



Ge enters Al, leaves vacancy behind

Ge diffusing in Al, vacancy filled by Al

Al self diffusion

- Ge diffuses on grain boundaries and surfaces
- No Ge in core Al crystal
- Al and Ge diffuse in opposite directions

[1] Beke D. vol. 33A of Landolt-Bornstein – Group III Condensed Matter. Springer Berlin Heidelberg, 1998.
[2] Gale W. Totemeier T. Smithells Metals Reference Book. Elsevier Science, 2003.