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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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.

Motivations
Superconducting hybrid junctions based on Ge nanowires

Ge based hybrid junctions:
• 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

Control of the Ge segment

Reproducible and well controlled process:

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

![HAADF STEM Zoom of Al-Ge-Al devices](image)

- $L_{Ge} = 600 \text{ nm}$
- $L_{Ge} = 400 \text{ nm}$
- $L_{Ge} = 15 \text{ nm}$
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

\[ E_{\text{add}} = E_C + \delta \]

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

\( \delta \): energy level spacing of the dot
Coulomb pattern for a short sample $L_{Ge}=42$ nm

Gap of the junction: $\pm 2 \Delta$
Addition energy and tunnel rate

$$\Delta = 220 \ \mu\text{eV}$$

$$\Gamma \approx 250 \ \mu\text{eV} \quad \Gamma \approx 82 \ \mu\text{eV} \quad \Gamma \approx 5 \ \mu\text{eV}$$

$$E_c = 3 \ \text{meV} \quad E_c = 32 \ \text{meV}$$

$$\Delta : \text{Al gap (220 } \mu\text{eV)}$$

N=31
$$\Gamma \approx 250 \ \mu\text{eV}$$
$$E_c = 3 \ \text{meV}$$

N=2
$$\Gamma \approx 5 \ \mu\text{eV}$$
$$E_c = 32 \ \text{meV}$$

$$E_c \approx \Delta \approx \Gamma$$
Intermediate coupling

$$\Gamma : \text{increases with } N$$
$$E_c : \text{decreases with } N$$

$$E_c \gg \Delta \gg \Gamma$$
Weak coupling
Transport overview for a short sample $L_{Ge} = 42$ nm

Supercurrent

Intermediate

$\Gamma \gg \Delta, E_C$

$E_C \approx \Delta \approx \Gamma$

$E_C \gg \Delta \gg \Gamma$
Superconducting regime $L_{Ge} \sim 40$ nm

Tuneable supercurrent up to 10 nA

- Zero resistance around $I_D=0$A: 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 $V_n =$
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

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”
  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,
Perspectives

• Transmon/gateemon qubits.
• Dilution fridge + magnetic field.
• Local gates.

"Al-Ge-Al Nanowire Heterostructures: 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.
## Diffusion of Al and Ge

<table>
<thead>
<tr>
<th>Diffusion of</th>
<th>Aluminium</th>
<th>Germanium</th>
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<tr>
<td>In</td>
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<td>Aluminium</td>
<td>Germanium</td>
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<tr>
<td>$D$ [cm²/s]</td>
<td>$1.46 \times 10^{-12}$</td>
<td>$3.27 \times 10^{-11}$</td>
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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