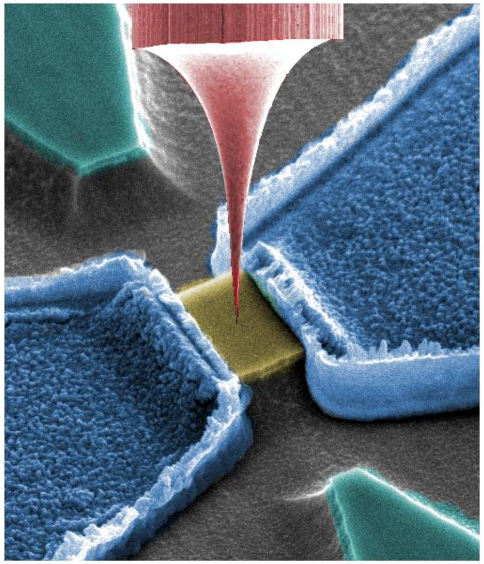
Electron transport and Scanning Gate Microscopy studies on ballistic hybrid SNS junctions



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Supervisors

Dott. Francesco Giazotto

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Motivation

- Research on hybrid superconductor-normal region-superconductor (SNS) devices with a 2DEG-based N region is an innovative field. More spatial information about electron transport distribution are needed.

- Tunable with gates → Josephson Field Effect Transistors (JoFETs). Technologically useful, for example as tunable elements for silicon electronics, SQUIDs, or superconducting qubits.

- Scanning Gate Microscopy (SGM) has never been performed on these superconductive devices.

Objectives

- A full characterization of these devices in the superconductive regime with electron transport measurements.
- Verify the compatibility of these devices with the Scanning Gate Microscope.
- Take the advantage of our setup to obtain further information from the quantum Hall regime.

Outline

- The devices, the experimental setup, the SGM technique.
- Superconductivity.
- The quantum Hall regime and SGM measurements.
- Conclusions and future perspectives.

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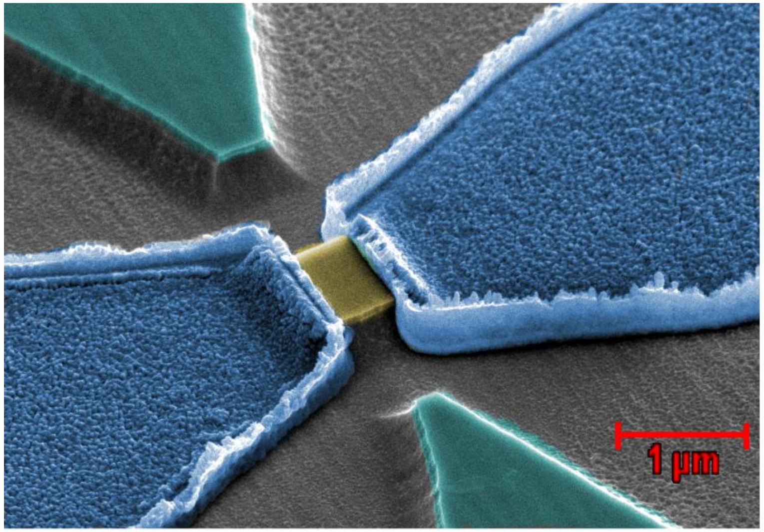
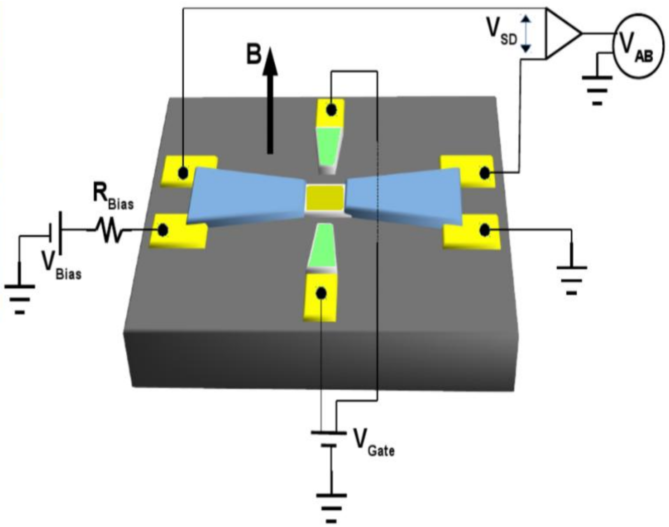
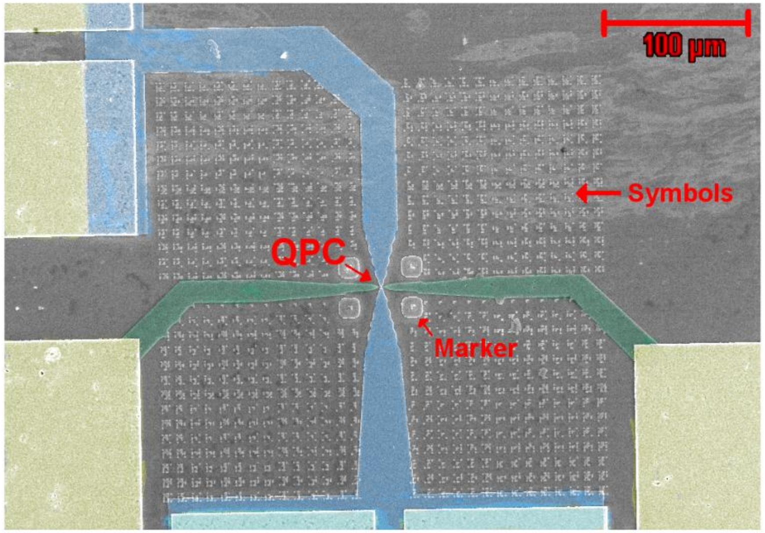
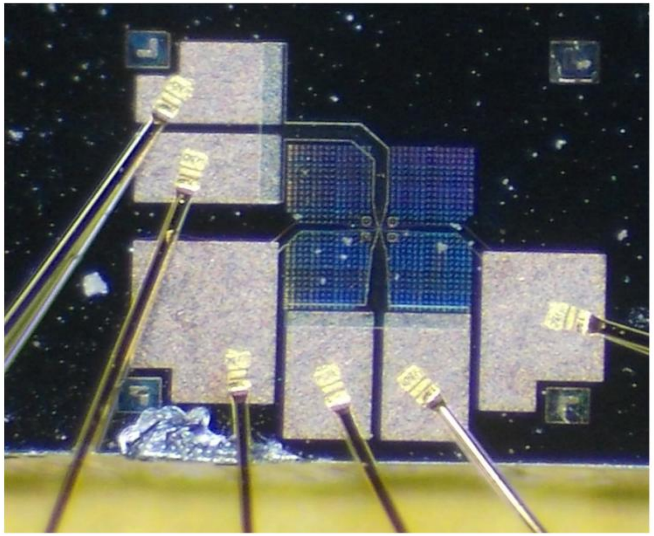
Devices









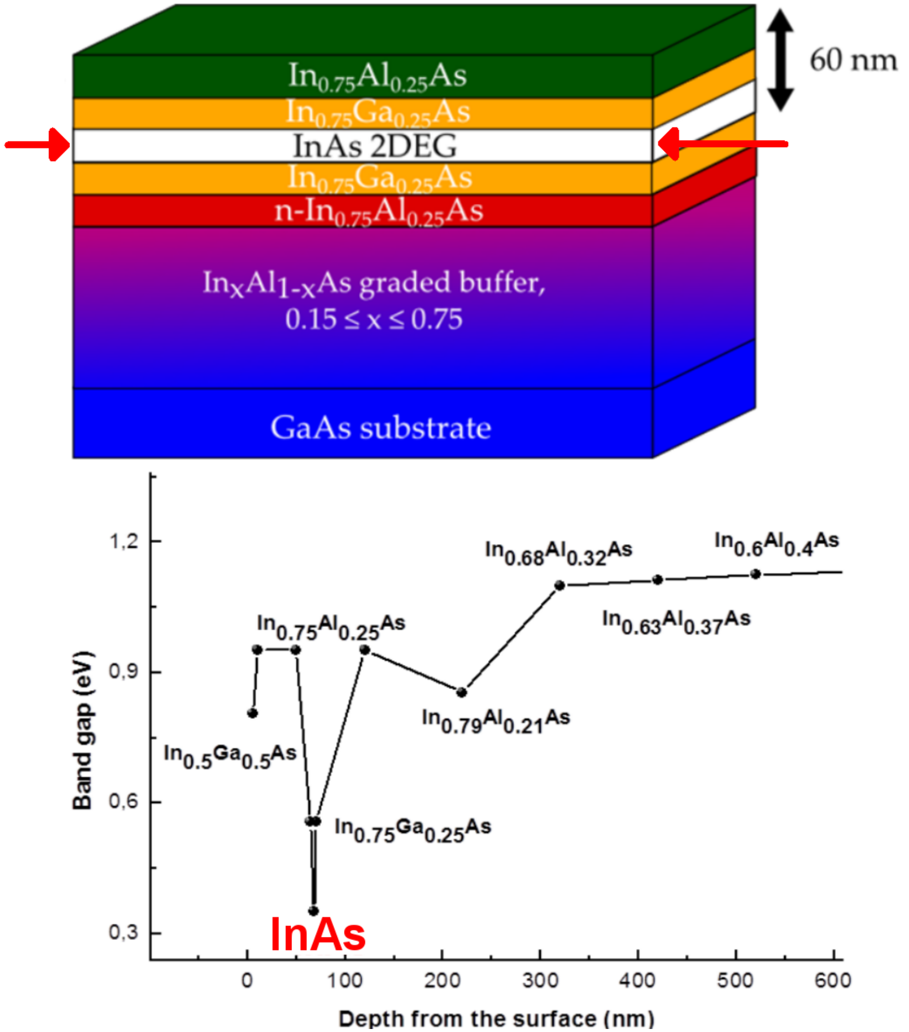
Why 2DEGs?

- Large L_{mfp} and L_{ϕ} → ballistic junctions and supercurrent over microns.
- Electron density can be controlled with gates.
- Split-gate geometry → 1D constrictions in the 2DEG can be created, i.e. Quantum Point Contacts (QPCs).
- Large Fermi wavelength → conductance quantization.

Why InAs-based 2DEGs?

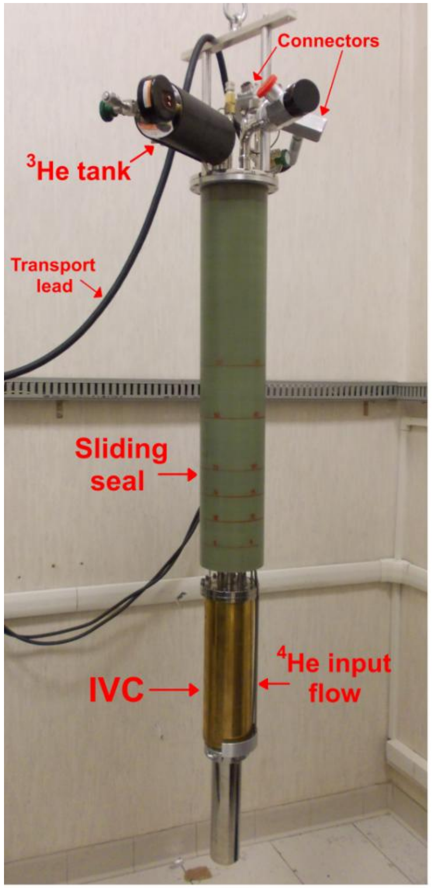
- No Schottky barrier →

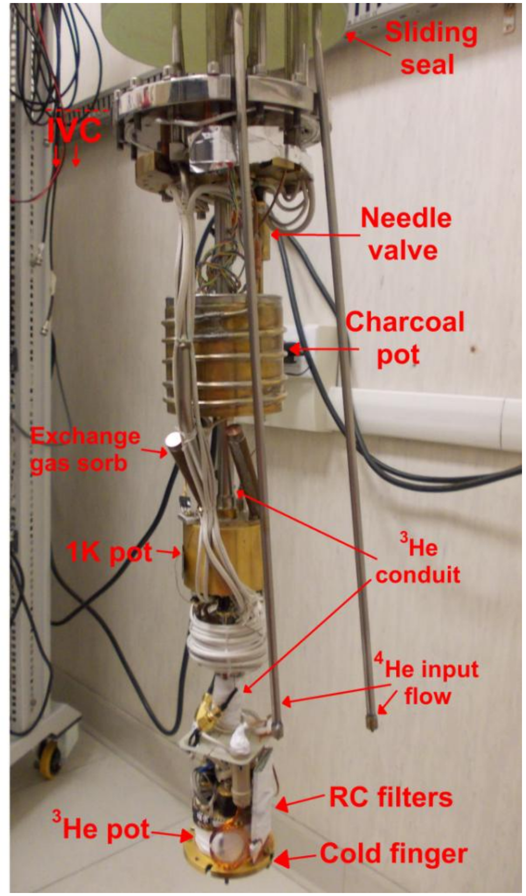
→ High transparency SN interfaces.



A. Fornieri, Master's thesis, 2012

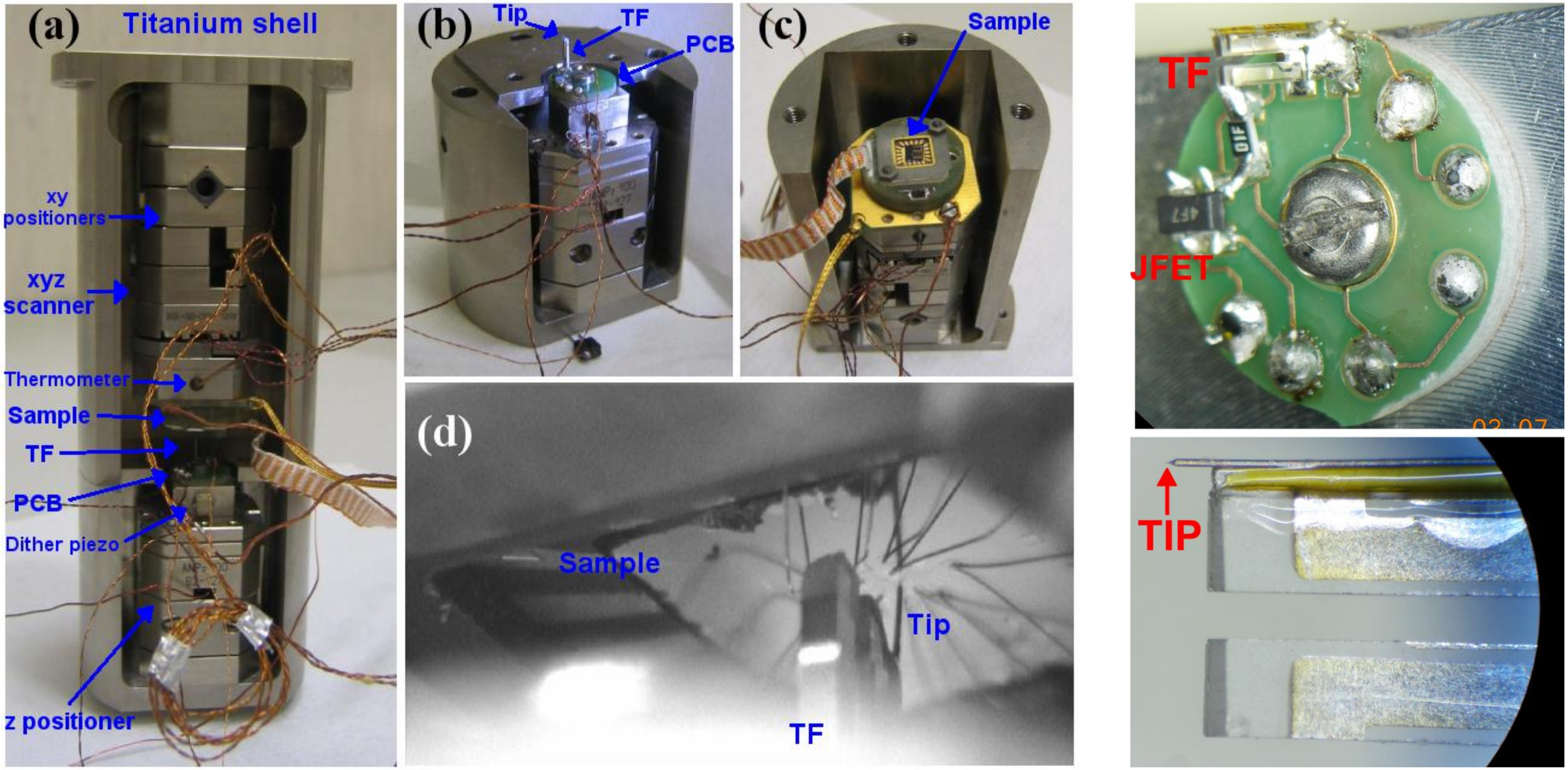
The cryostat





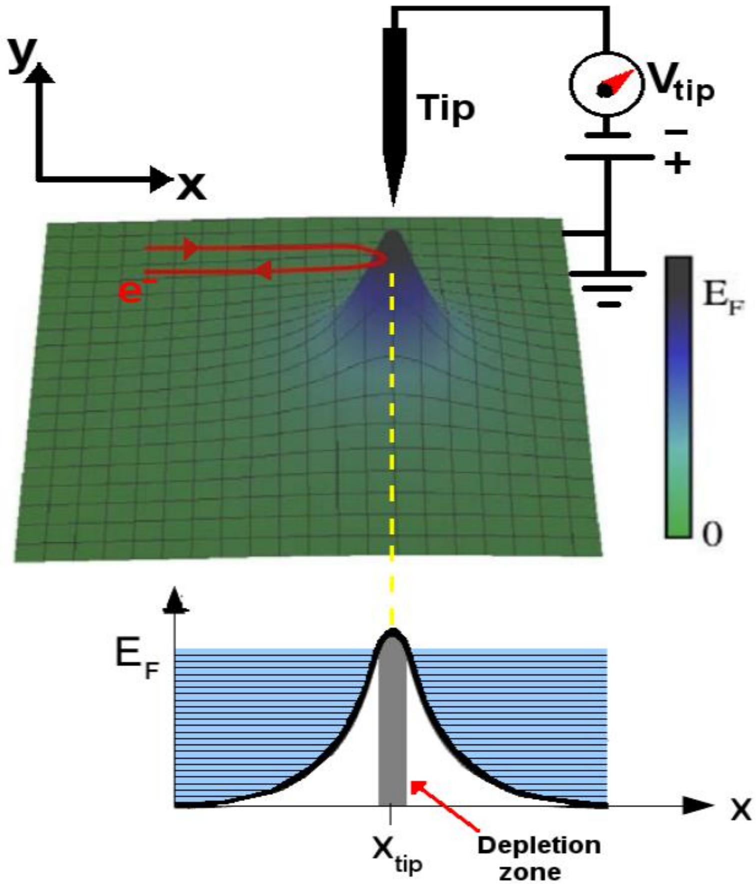
- ^{3}He cryostat: it uses ^{3}He to cool the sample.
- Minimum temperature 310mK at the cold finger. Sample minimum temperature 350mK.
- The setup includes a magnet that can generate fields up to 9 Tesla.

The microscope



- Atomic Force Microscope (AFM) with a 20nm sharp tungsten tip for the interaction.
- Scanner and positioners are piezoelectric motors that control the tip-sample relative position with subnanometric precision.
- The dither piezo and the quartz tuning fork (TF) are part of a feedback system that keeps the tip-sample distance fixed.

Scanning Gate Microscopy



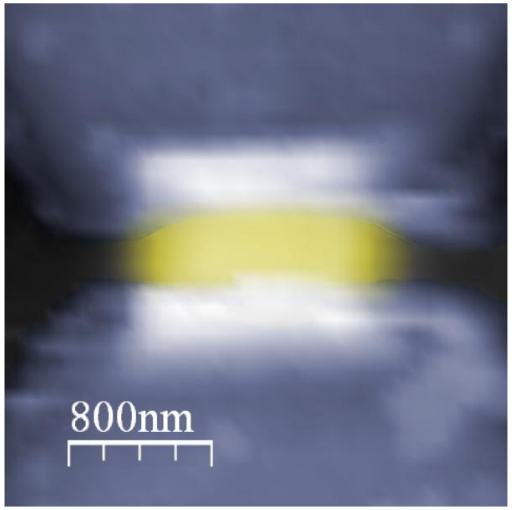
B. J. LeRoy, PhD Thesis (2003).

A negative voltage-biased tip locally increases the electrostatic potential in the 2DEG:

- The tip reduces the electron density in the 2DEG.
- The tip acts as a backscatterer for electrons.

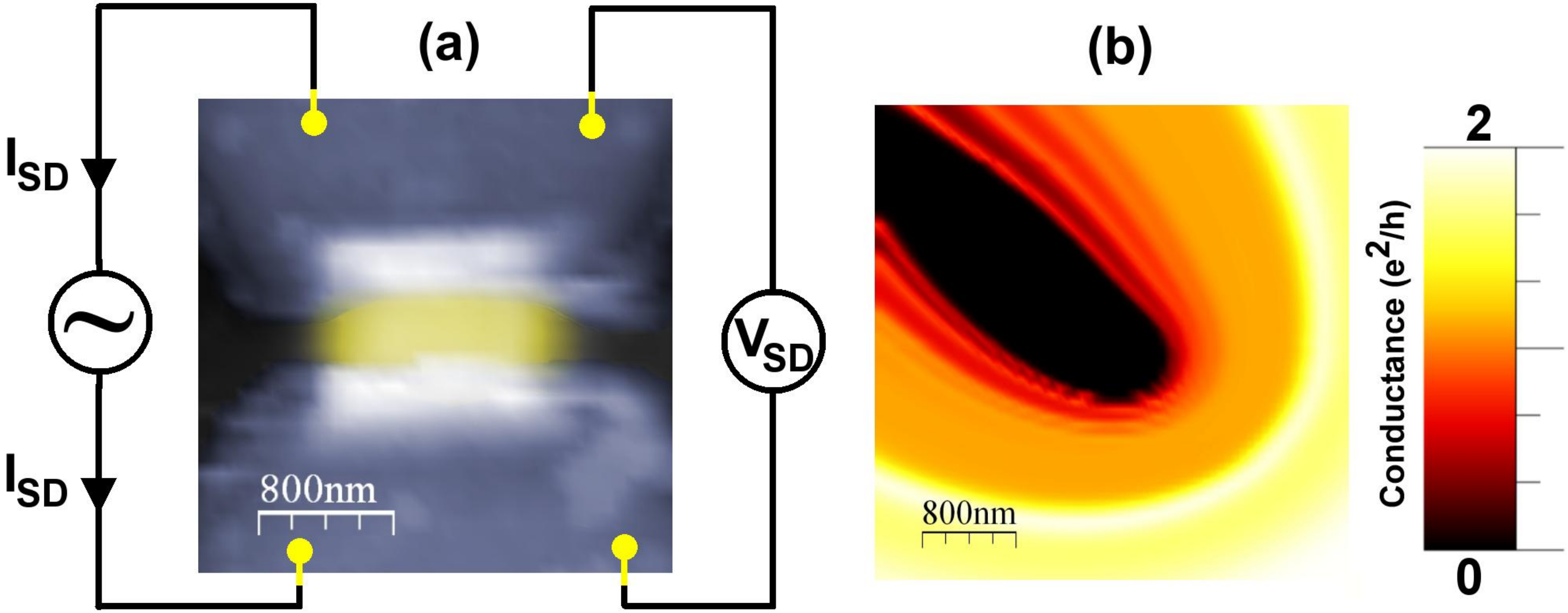
Scanning Gate Microscopy

(a)



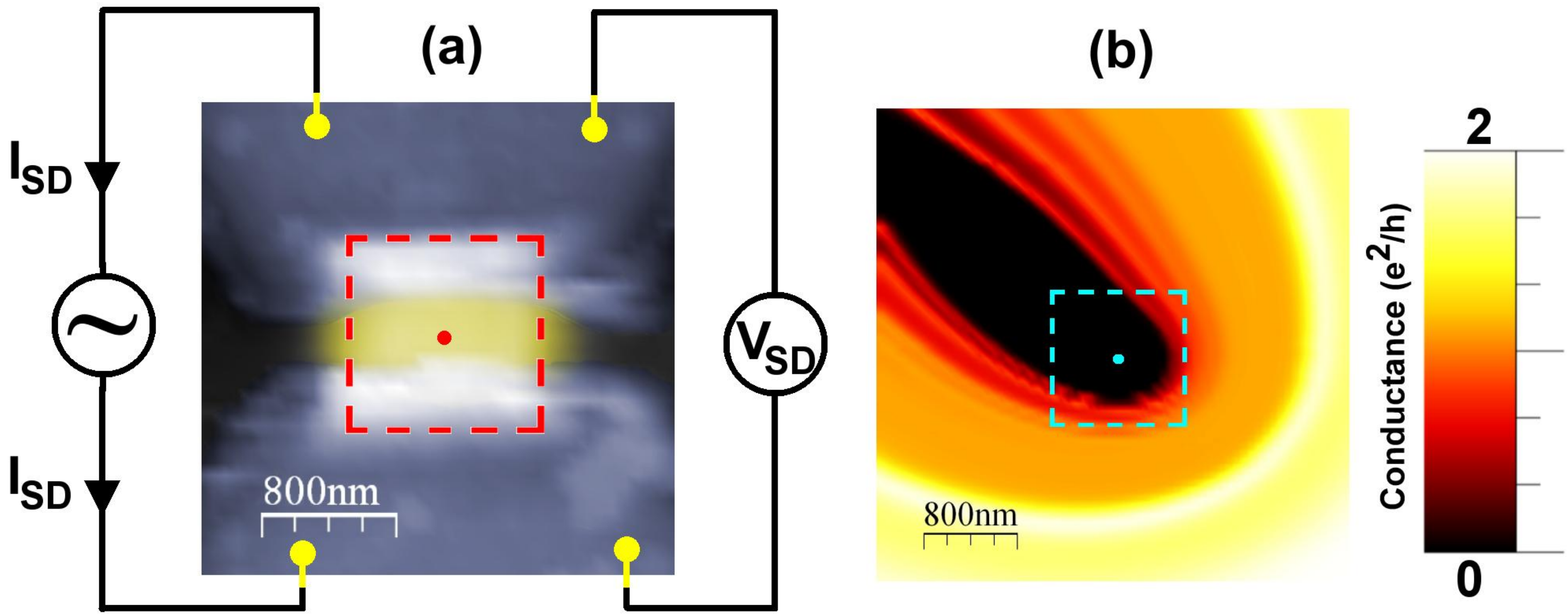
- (a) Preliminary AFM scan to locate the junction (colored).

Scanning Gate Microscopy



- (a) Preliminary AFM scan to locate the junction (colored).
- Current injected → (b) Conductance is measured while scanning the sample → Conductance map as a function of the tip position → Spatial information about the electron transport.

Scanning Gate Microscopy



- (a) Preliminary AFM scan to locate the junction (colored).
- Current injected → (b) Conductance is measured while scanning the sample → Conductance map as a function of the tip position → Spatial information about the electron transport.
- 2DEG in the square. Tip negatively biased → Conductance reduced as it approaches the center.
- No circular symmetry → Asymmetric tip.
- Series of SGM scans while changing only one parameter. We can track the evolution of structures as a function of the parameter.

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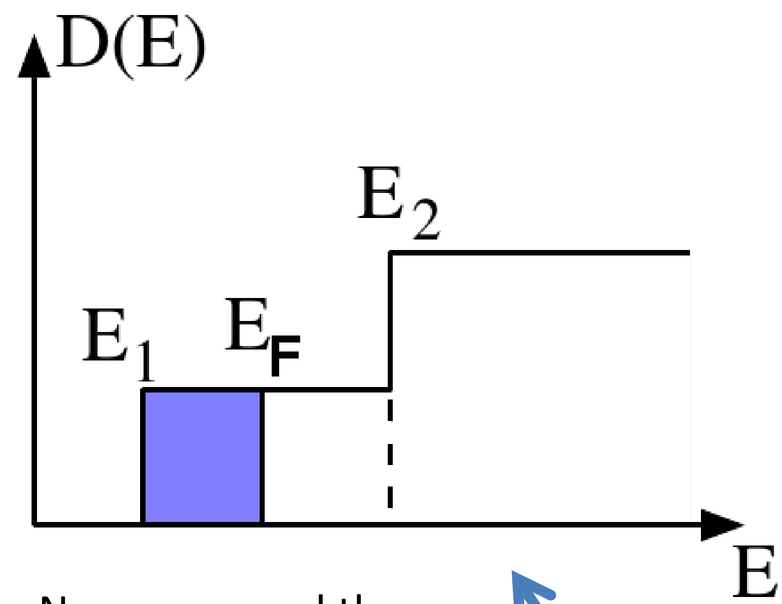
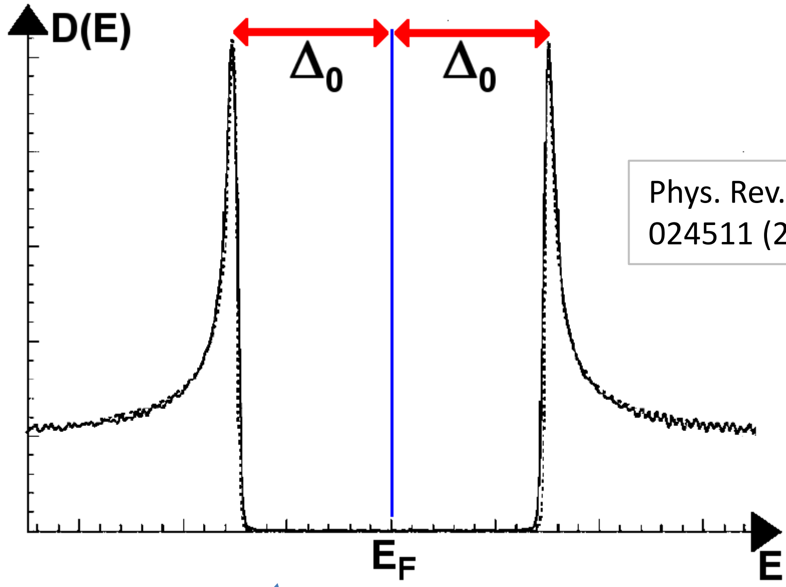
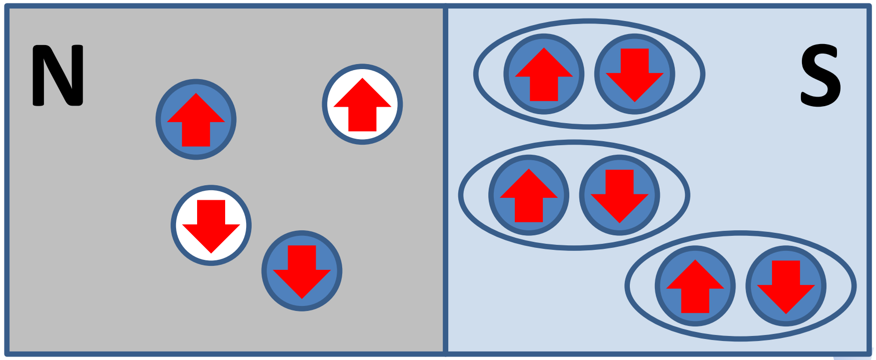
Single-particle density of states



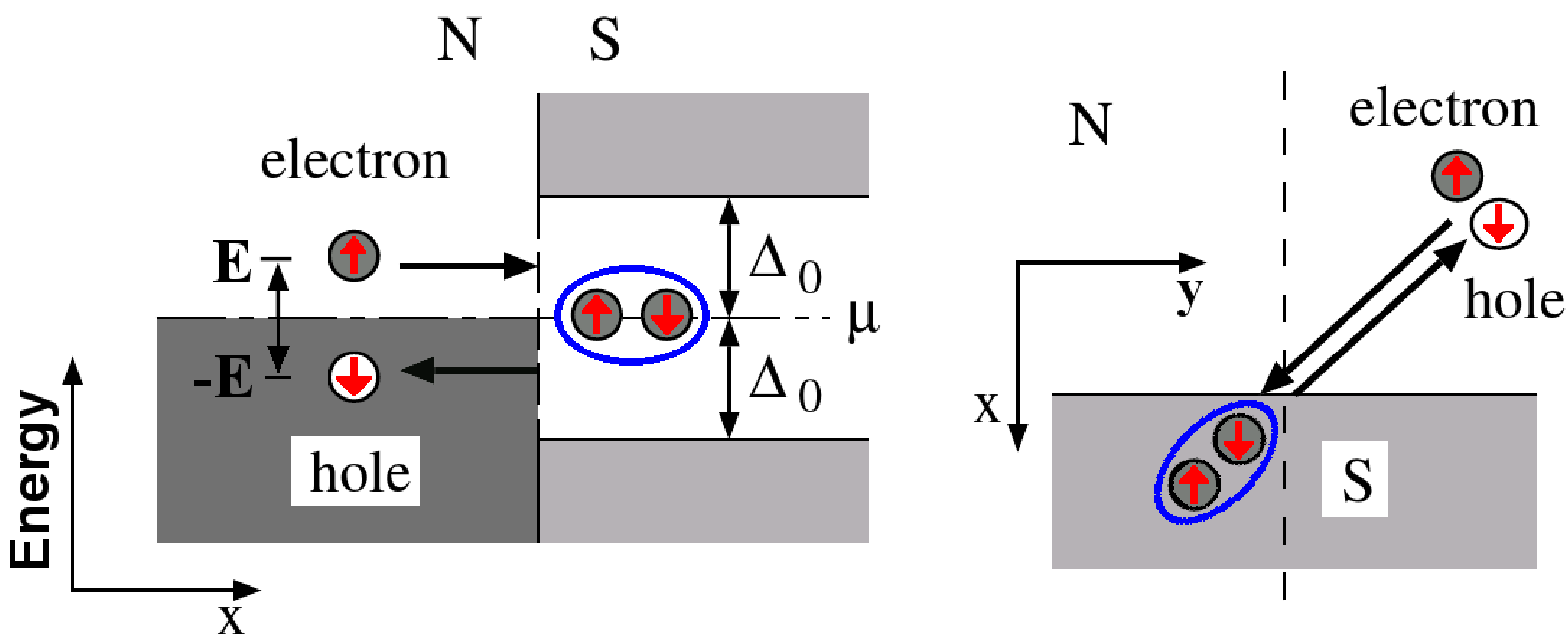


- No gap around the Fermi level in the 2DEG.
- E_1, E_2 levels in the quantum well.

- Gap in the superconductor around the Fermi level.

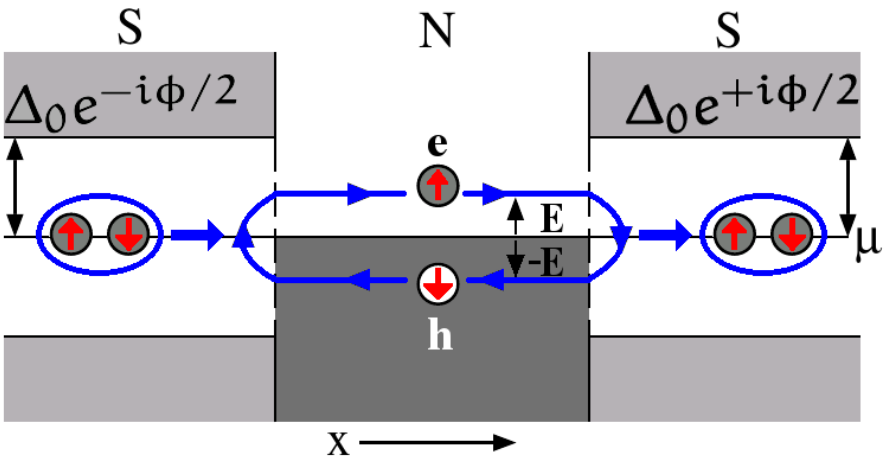


Andreev Reflection



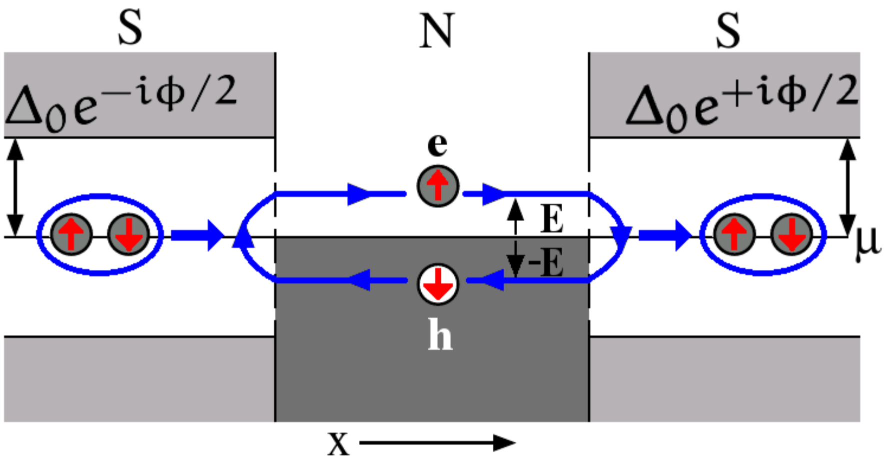
- $|E|<\Delta_0$: electrons (holes) cannot enter the superconductor (due to the gap) or be reflected (no barrier at the interface).
- An electron can, however, be reflected as an hole with opposite energy and group velocity. In this way a charge 2e is transferred to the SC (as a Cooper pair).
- This mechanism is named Andreev reflection and is phase coherent.

Andreev bound states



- Phase coherence is crucial.
- Condition for the formation of bound states: total phase acquired during one cycle is a multiple of 2π.
- They carry a supercurrent, i.e. no voltage drop across the N region.
- During one cycle a Cooper pair is transferred from the left S to the right.

Andreev bound states



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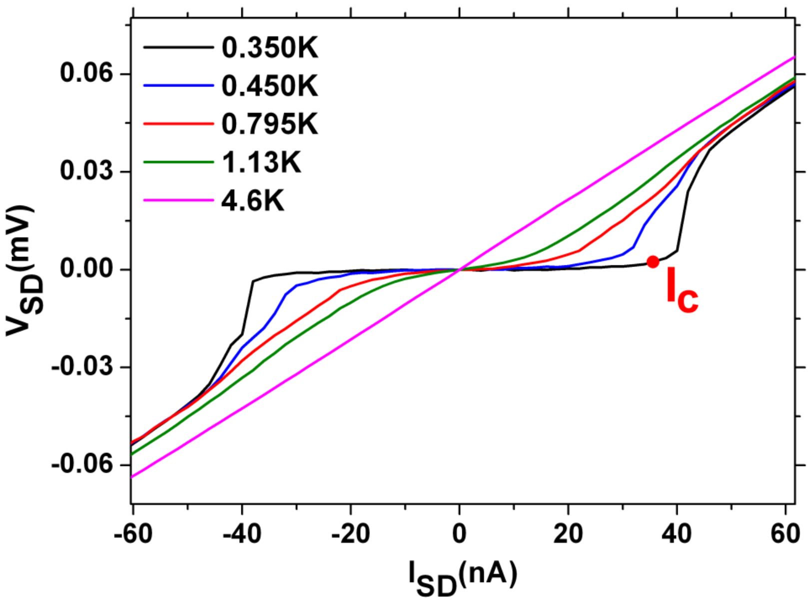
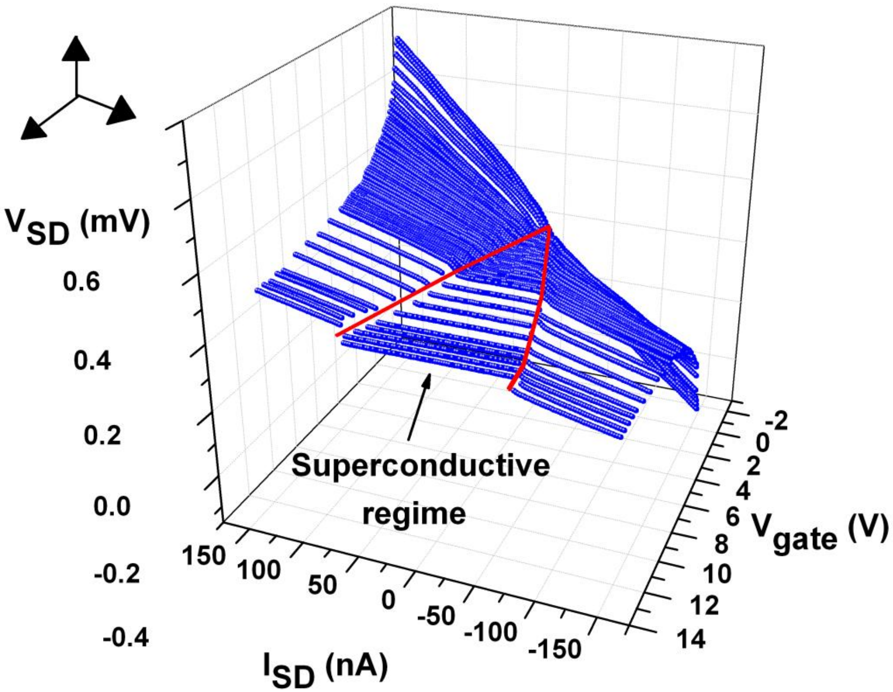
- Andreev levels in the short junction limit:

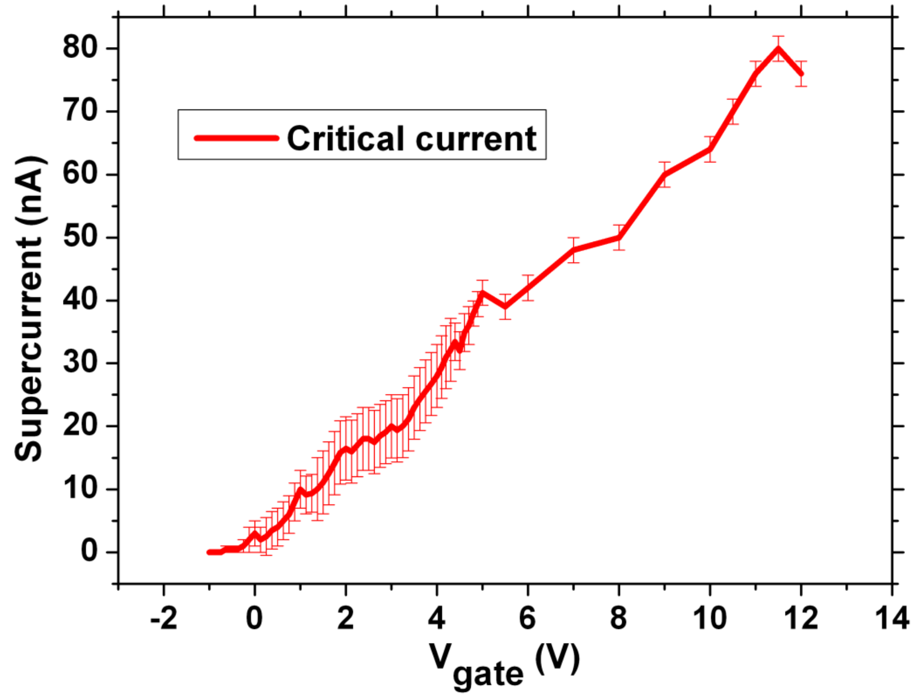
$$E^{\pm}(\phi) = \pm\Delta_0 \cos(\phi/2)$$

- V_{SD}=0 → Non-dissipative or Josephson regime.
- The current at which the junction switches to the dissipative state is the critical current (I_c).
- The critical current is suppressed by increasing temperature.



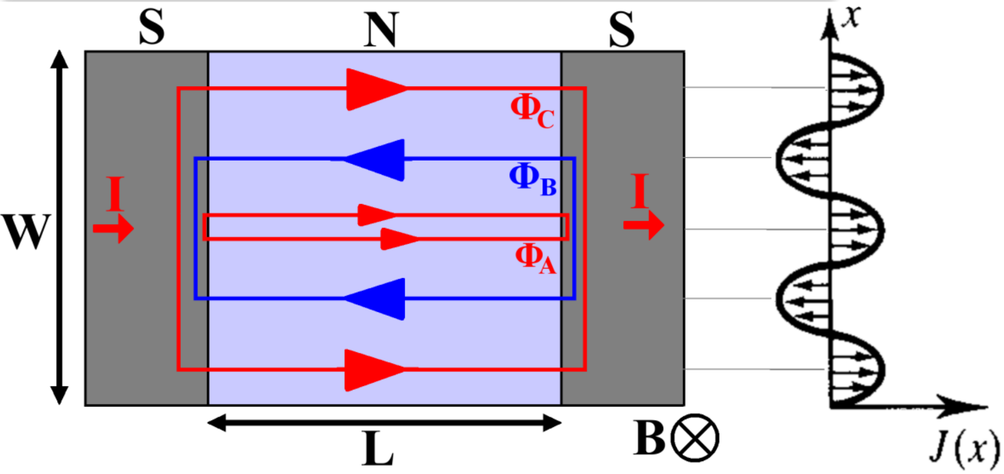
Supercurrent vs gate voltage





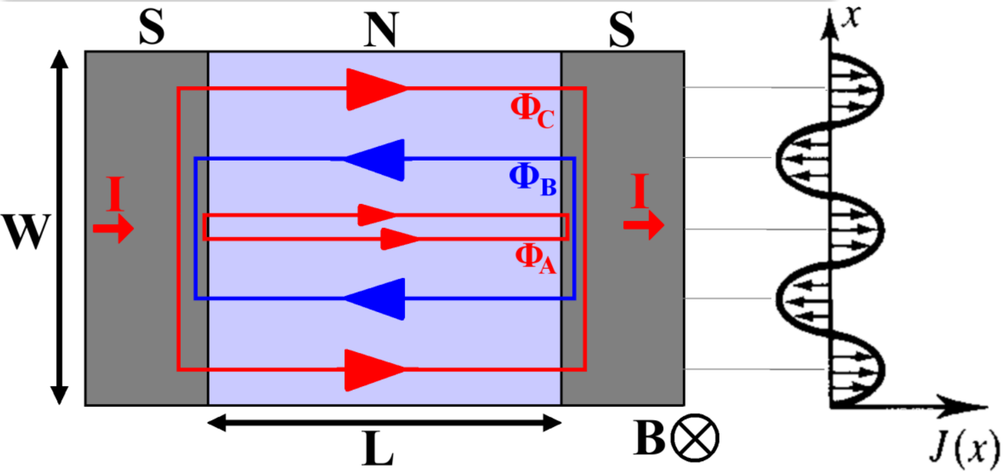
- The magnitude of the supercurrent can be controlled with side gates (V_{gate}).
- The supercurrent decreases with decreasing V_{gate} .
- The Josephson effect is suppressed below V_{gate} =-1V.
- Supercurrent tunable with gates → these devices are Josephson field effect transistors (JoFETs).

Fraunhofer pattern



- Due to magnetic flux, which is different for every loop, supercurrent gains a position-dependent phase.
- Supercurrent J(x) can even go in opposite directions in the N region.
- The critical current is the integral of all possible paths (interference pattern).

Fraunhofer pattern



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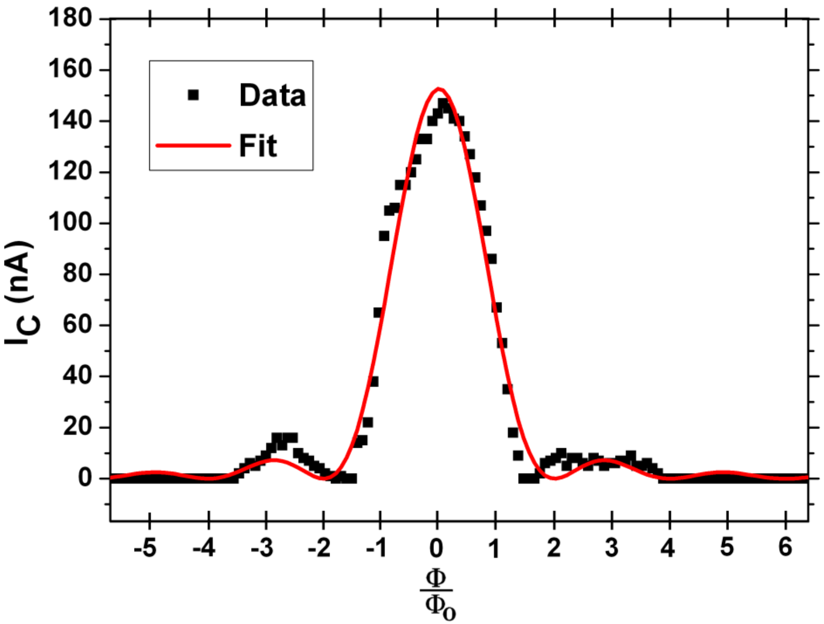
- The critical current is the integral of all possible paths (interference pattern).

- In the limit W≈L (Heida's model), we obtain:

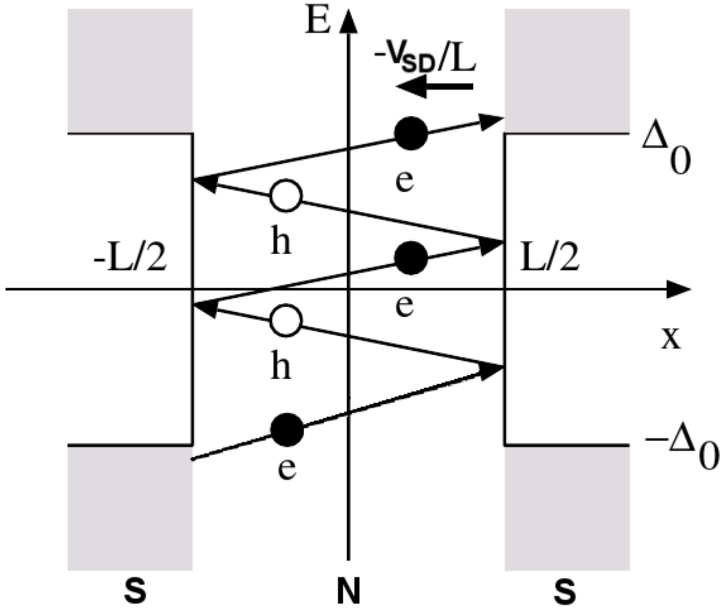
$$I(\Phi) = I_0 \left(\frac{\sin\left(\frac{\pi\Phi}{2\Phi_0}\right)}{\frac{\pi\Phi}{2\Phi_0}} \right)^2$$

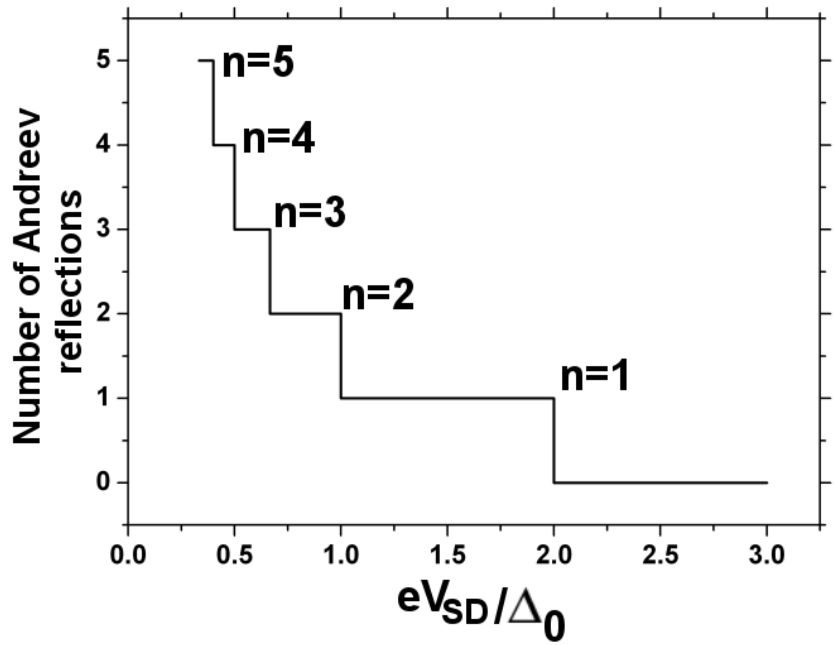


- Φ_0 magnetic flux quantum.
- Minima of critical current :

$$\Phi = 2n\Phi_0 \quad n = \pm 1, \pm 2, \pm 3\ldots$$

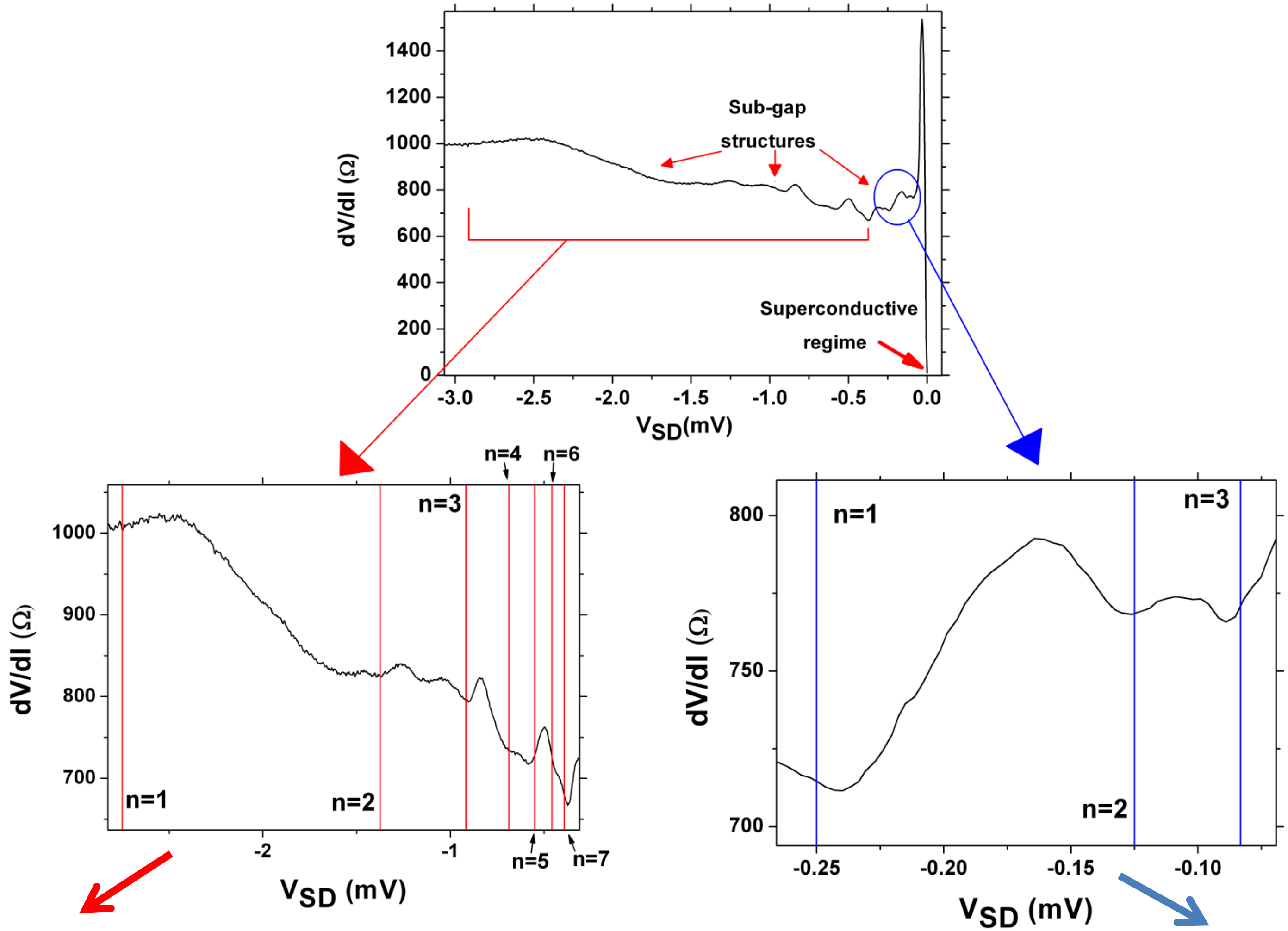
Multiple Andreev Reflections (MARs)





- An electron injected from SC1 cannot enter SC2 since the density of states is zero for $|E|<\Delta_0$, therefore it is trapped in N and Andreev reflected multiple times. At the same time it is accelerated by the electric field due to V_{SD}.
- The number of Andreev reflections needed before the particle can enter the SC as an excitation, i.e. $|E|>\Delta_0$, depends on V_{SD}. The smaller V_{SD}, the higher the number of Andreev reflections.
- Dip in differential resistance expected at $V_{SD} = \frac{2\Delta_0}{en}$ $\quad n = \pm 1, \pm 2, \pm 3\ldots$

Multiple Andreev Reflections (MARs)



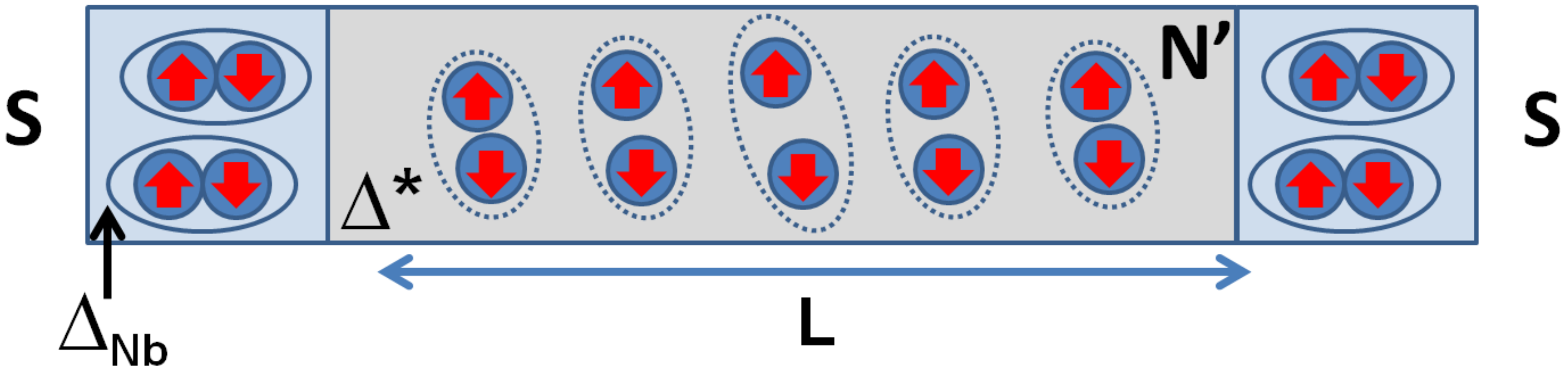
$$\Delta_{Nb} = (1.33 \pm 0.04) meV$$

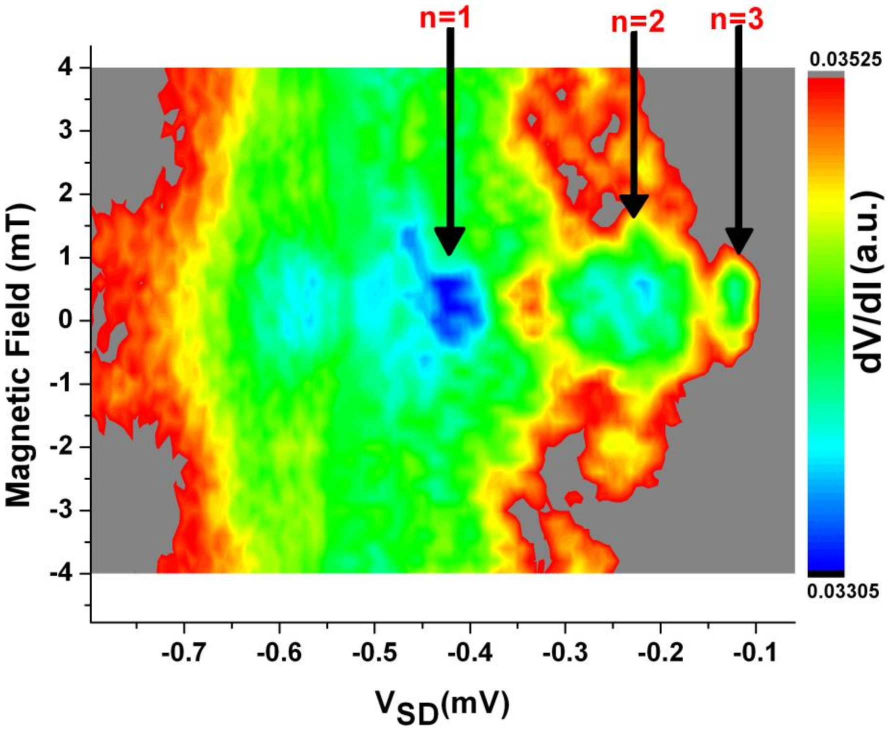
In agreement with the BCS theory.

$$\Delta^* = (0.125 \pm 0.005) meV$$

Minigap in the density of states of the 2DEG.

Multiple Andreev Reflections (MARs)





- Cooper pairs can leak into the 2DEG (N') and travel a length ξ_{2DEG} before they lose coherence, i.e. the pairs split. In our devices L ≈ ξ_{2DEG}.

- The 2DEG shows superconductive properties like the minigap (Δ*) and the Josephson effect. This is the proximity effect.

- The three minima in the differential resistance disappear above 2mT, therefore the minigap is suppressed above 2mT, i.e. the proximity effect is reduced at such fields.

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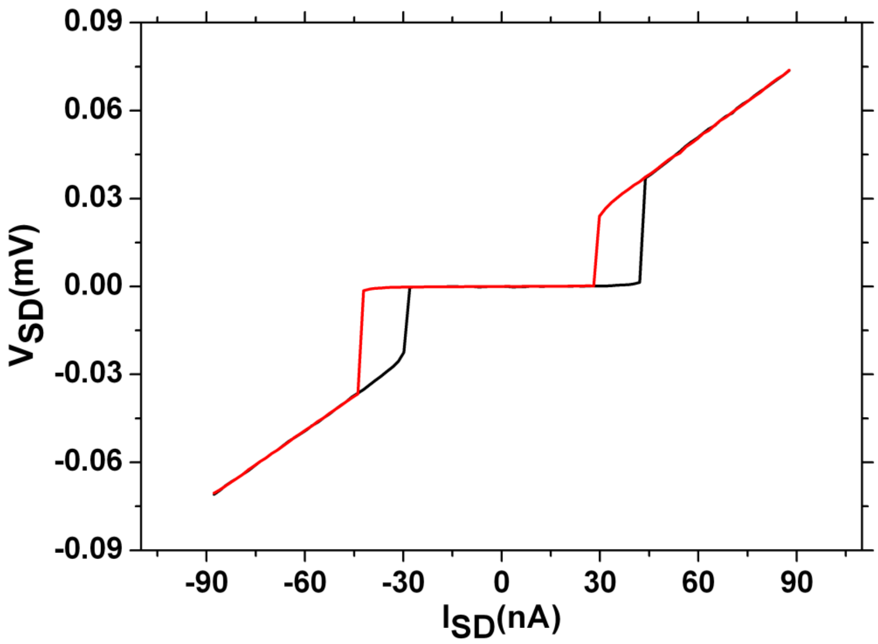
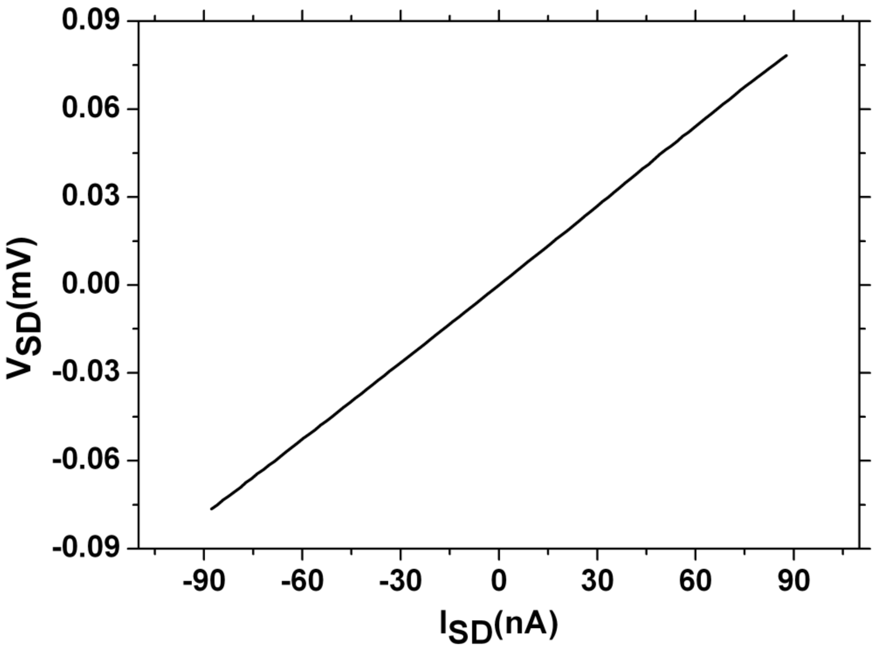
Filtering

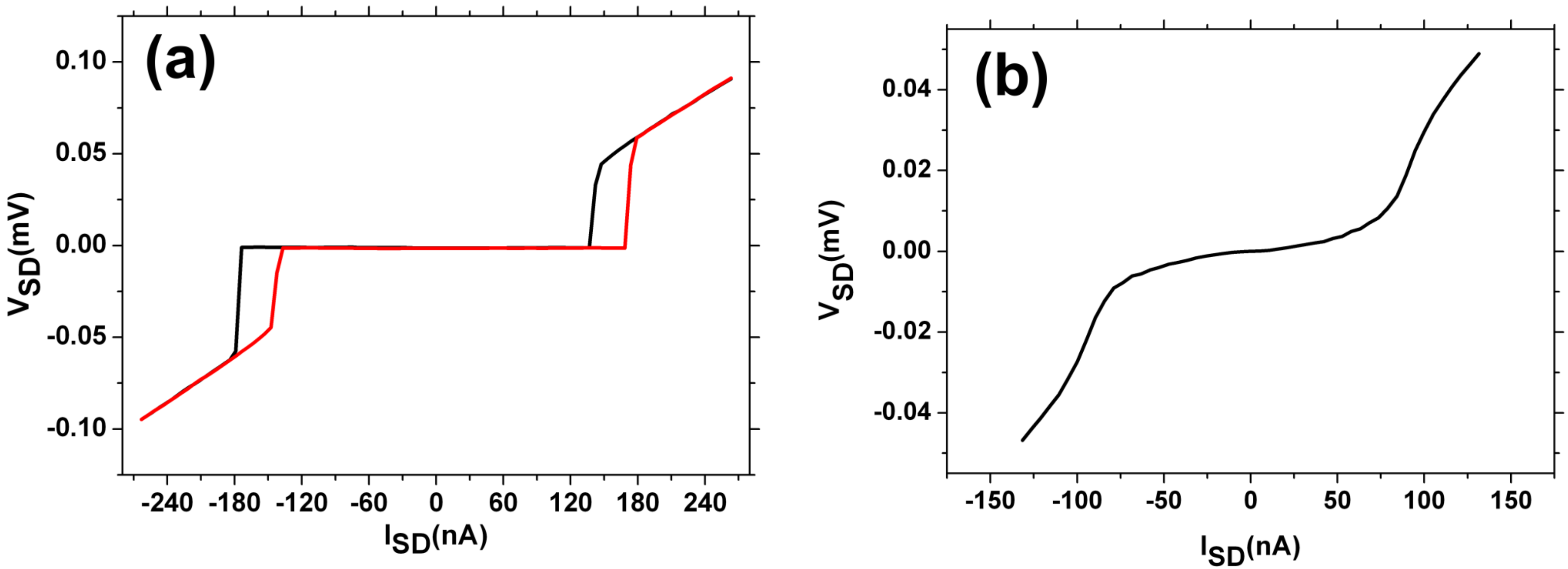


Only transport cables connected.



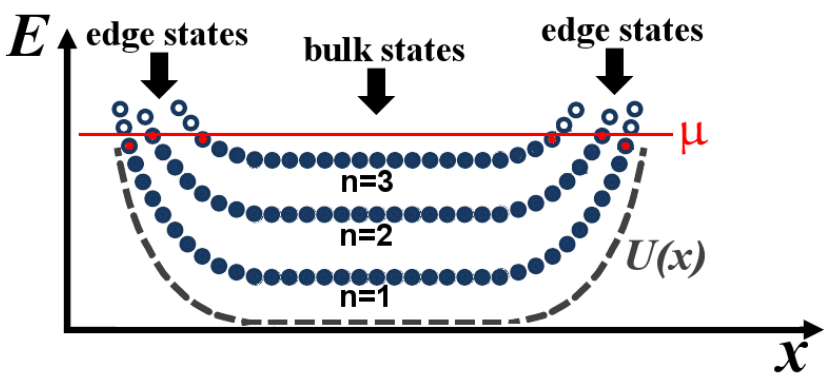
Also microscope cable connected.

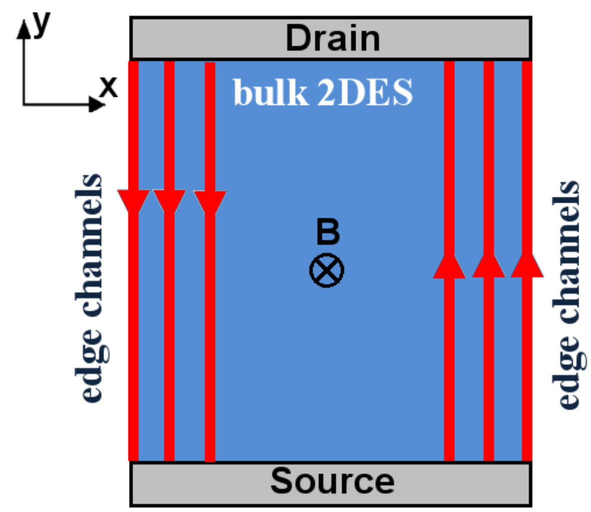
Filtering

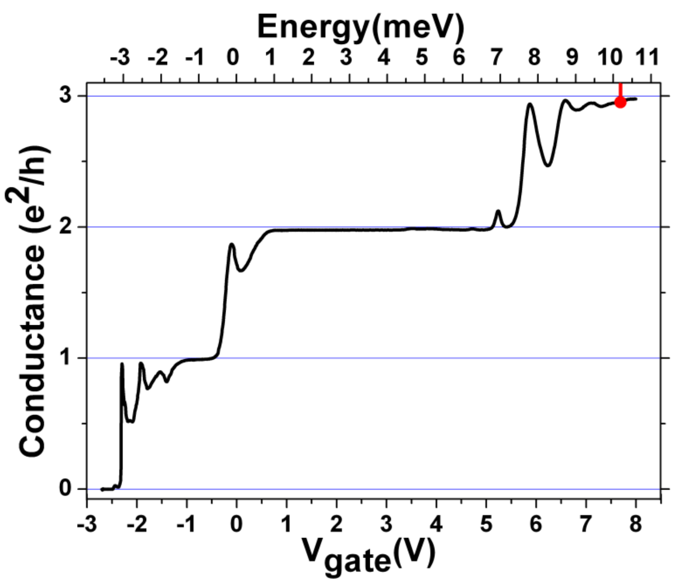


- The microscope is filtered with a stage of pi-filters at room temperature.
- (a) I-V curve with the microscope unplugged, (b) with all the 70 leads connected.
- Remarkable improvements compared to the unfiltered case, in fact still a precursor of supercurrent in (b). However, further upgrades at low temperature are needed.

Quantum Hall regime

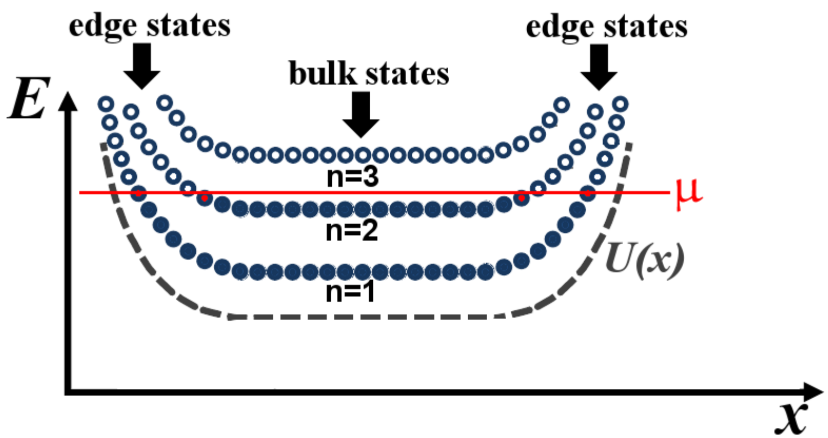


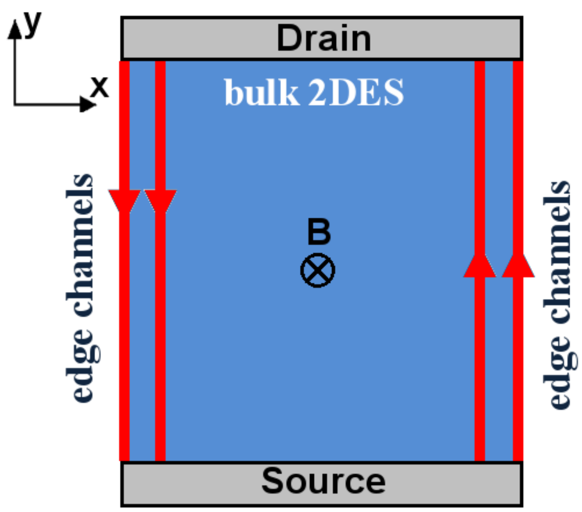


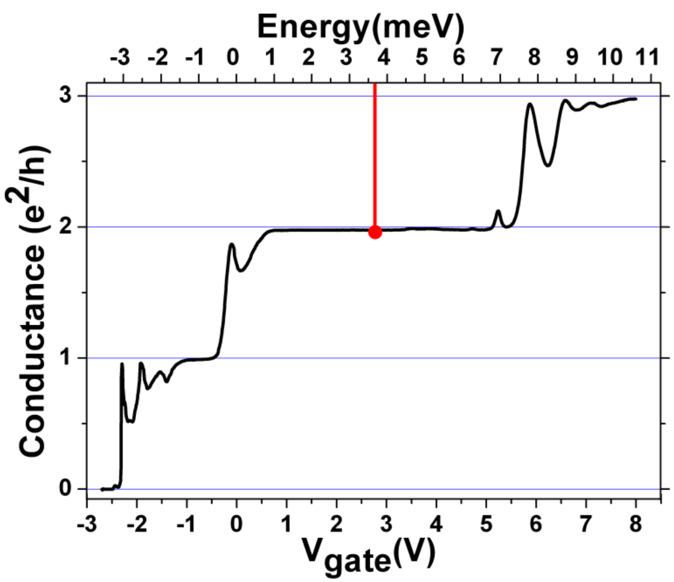


- With high magnetic fields (a few Tesla) the electron kinetic energy is quenched into Landau levels (LLs).
- When the chemical potential lies between LLs, the bulk is gapped, therefore insulating.
- The confining potential bends Landau levels upwards ; as a result, at the edges the chemical potential intersects the LLs (edge states).
- Conductance is restored at the edges and quantized: $G=\nu e^2/h$ (ν is the number of filled LLs).

Quantum Hall regime

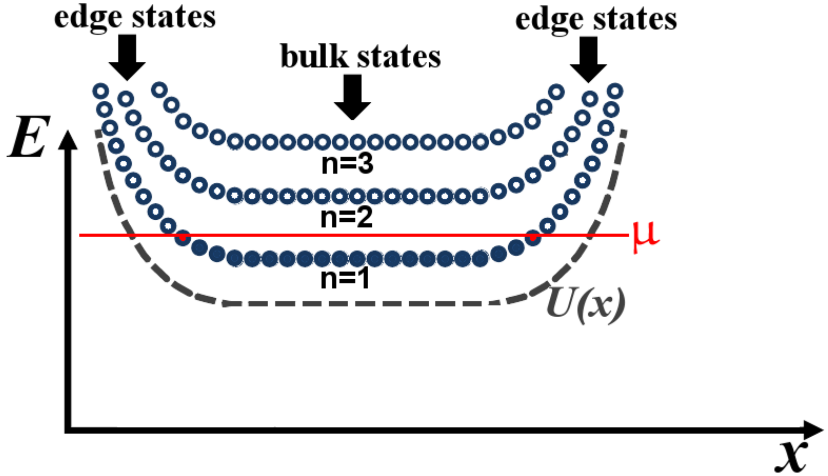


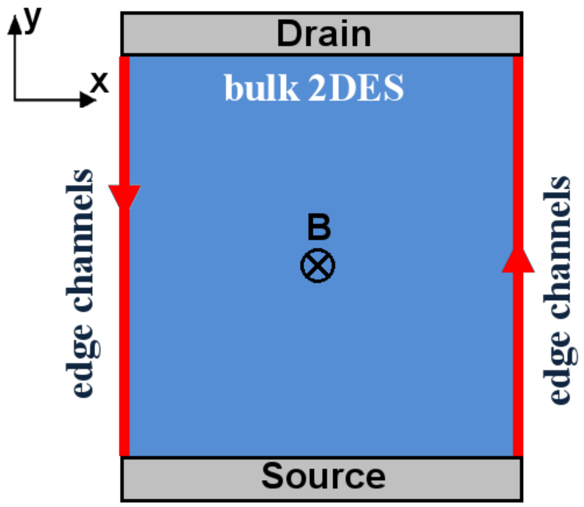


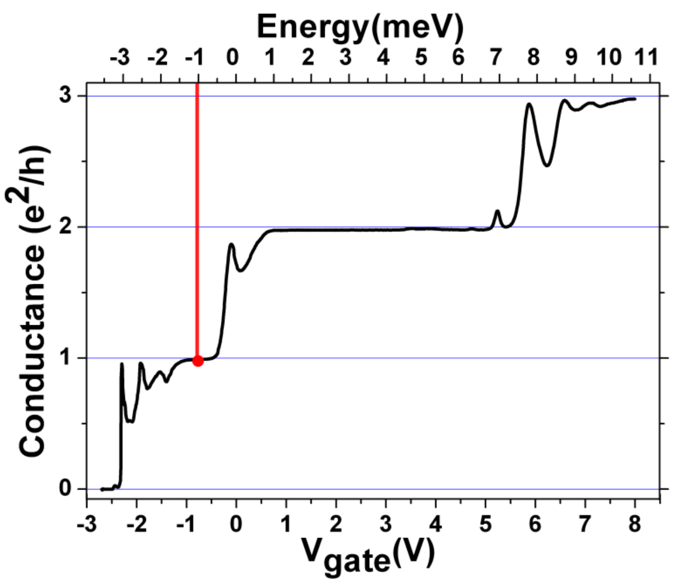


Two filled LLs → two edge states →
→ G=2e^2/h (plateau)

Quantum Hall regime







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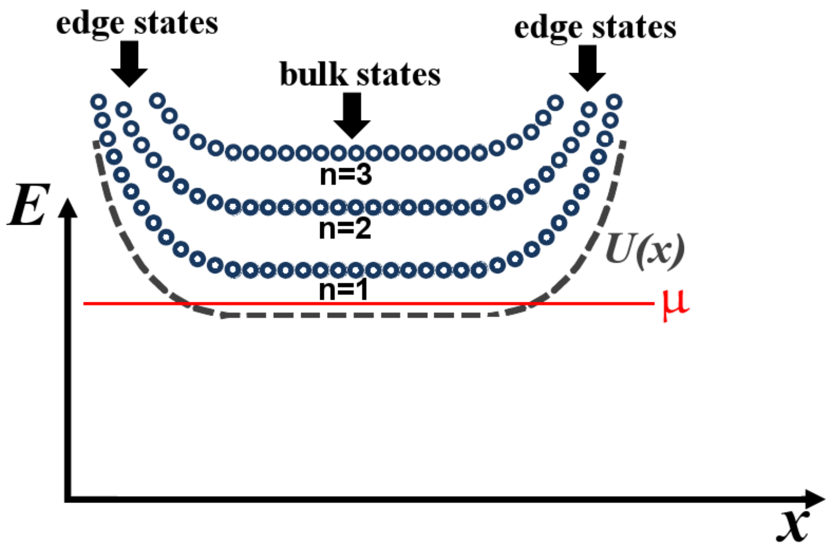
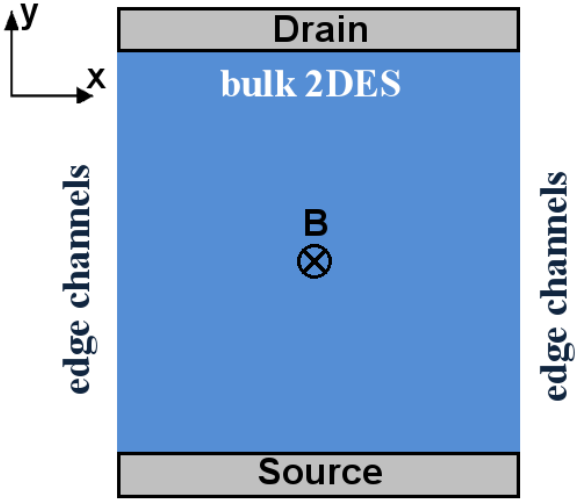
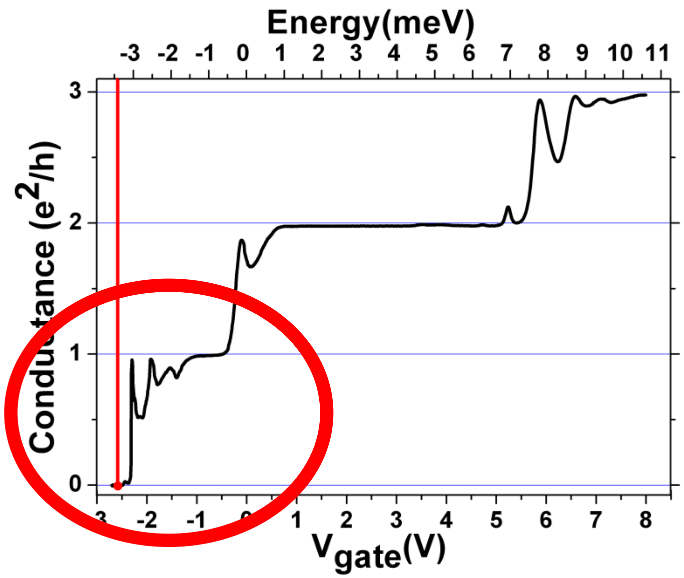
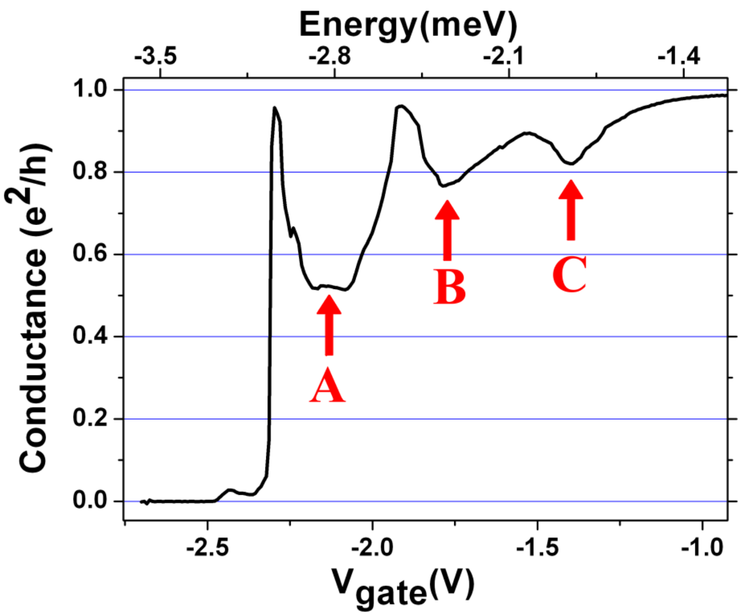






No filled LLs → No edge states → → G=0 (pinched off)

SGM and resonances



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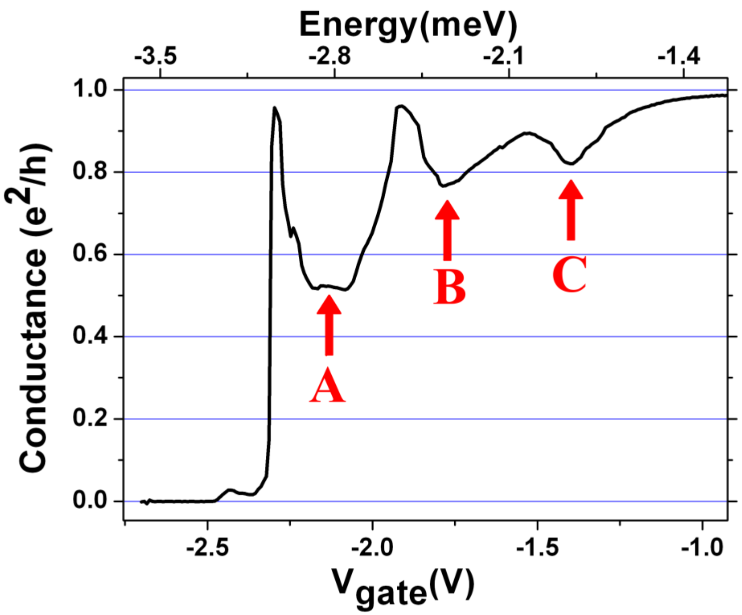
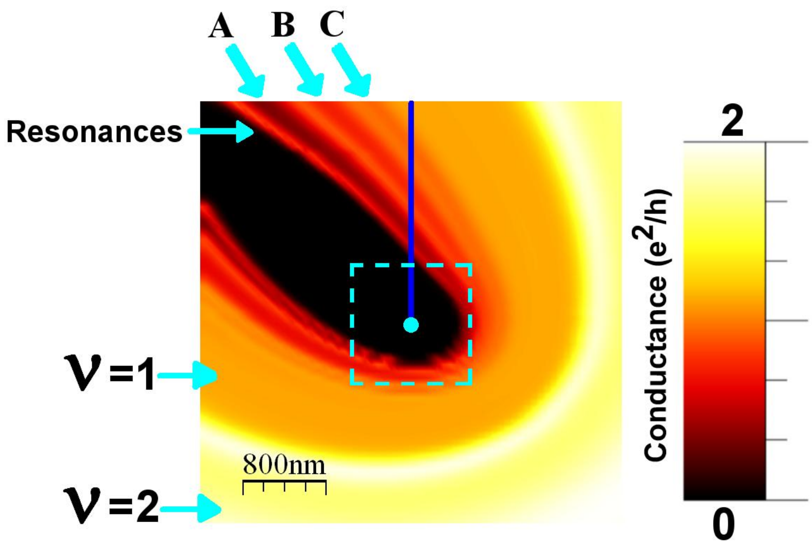
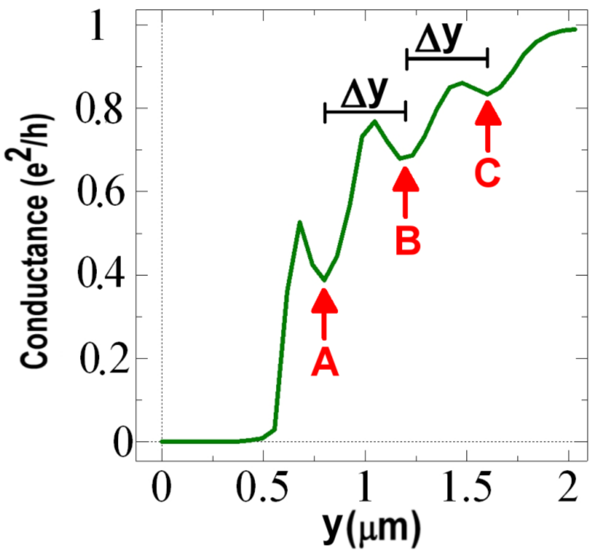
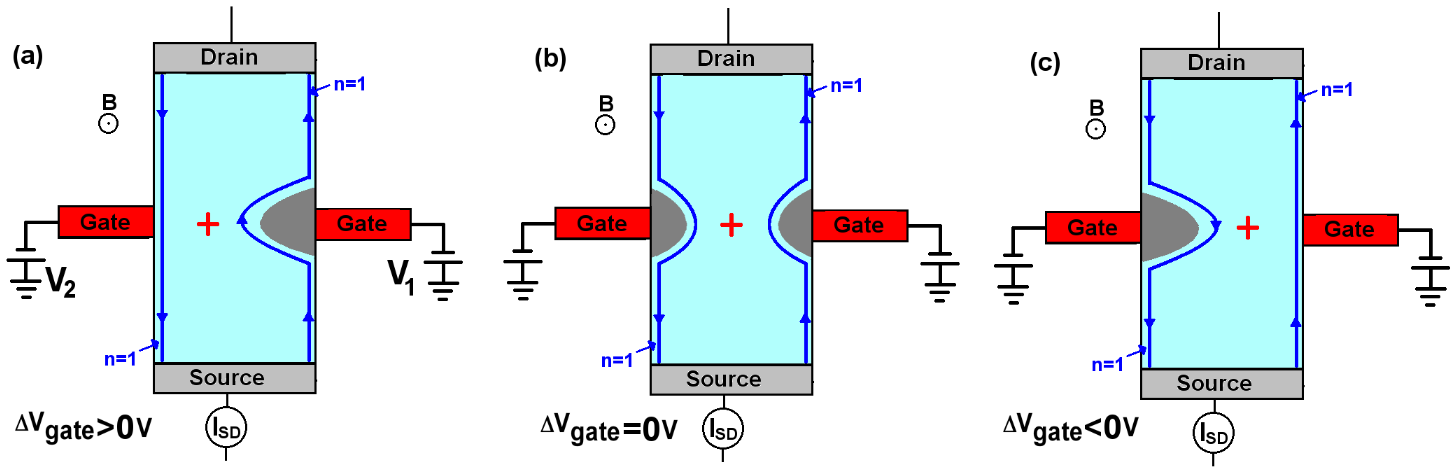




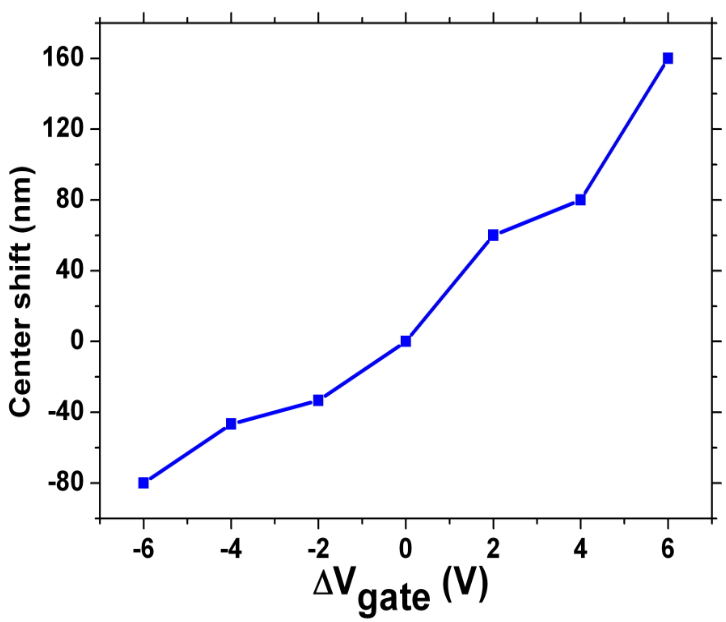


- SGM scan in the same conditions as the transport measurement (B=3 Tesla). Tip negatively biased.
- The profile starts from y=0μm and ends at the edge of the scan (y=2μm).
- Resonances (A, B, C) and quantum Hall plateaus (ν=1, 2) are clearly visible both in transport and in SGM.
- The resonances are equidistant and reproducible.
- They have never been observed with the SGM.

Channel shifting: the experiment

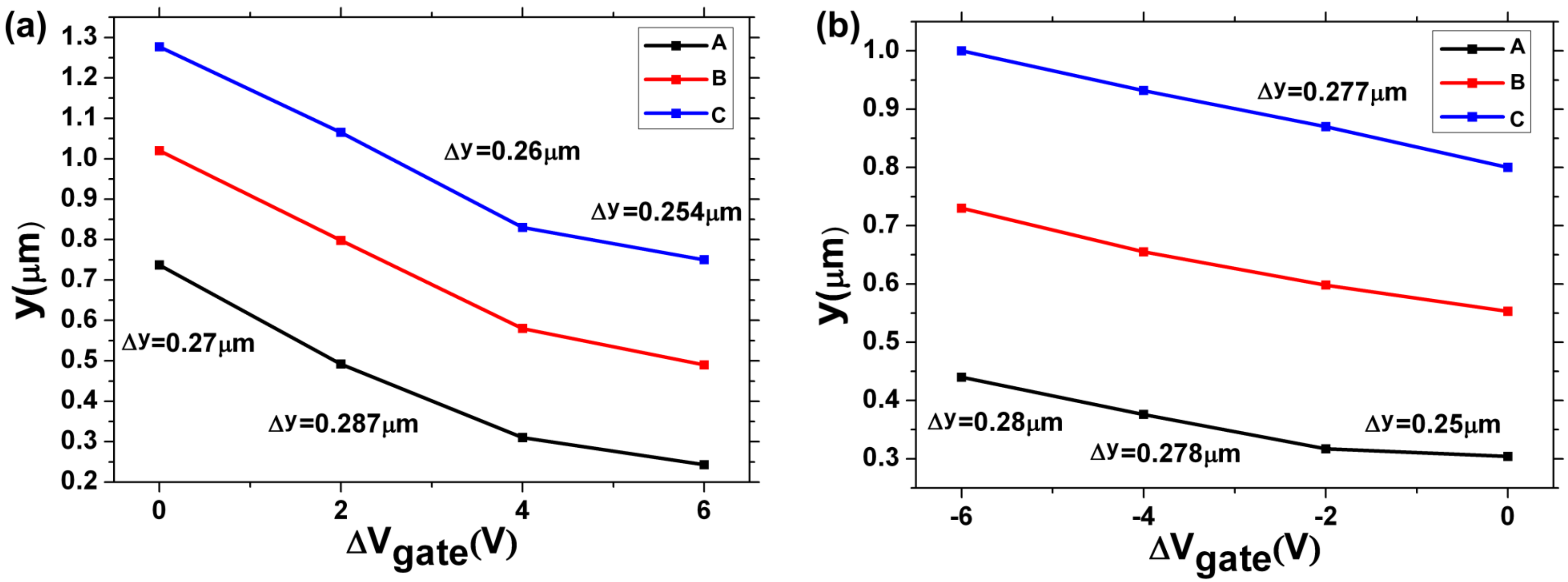


- We shift the position of the constriction in the 2DEG by using an asymmetric voltage bias on the two side gates ($\Delta V_{gate}=V_2-V_1$). At the same time the width of the channel is kept constant.
- This way we can figure out if there are any impurities or defects in the 2DEG that generate the resonances.



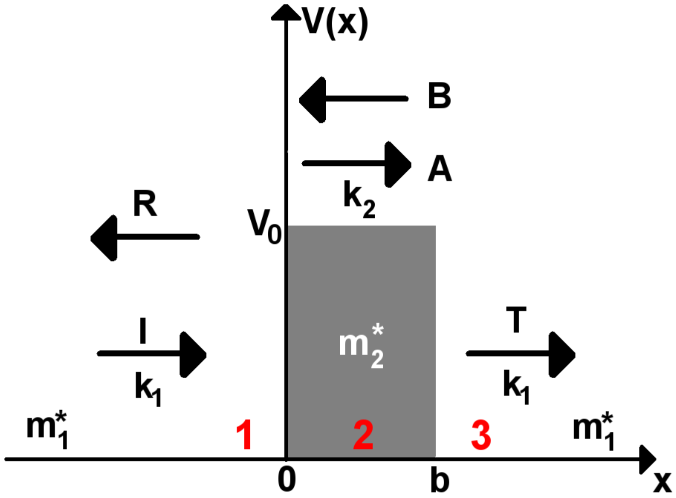
- From the plot we see that we have effectively shifted the channel.
- The shift is towards the gate with higher bias.

Channel shifting: results



- Two SGM series ($\Delta V_{gate} > 0$ and $\Delta V_{gate} < 0$). Each ΔV_{gate} value is an SGM scan. For every scan the position of the resonances (A, B, C) is plotted.
- The resonances are equidistant in every measurement and also their relative position is constant: Δy=(265 ± 15)nm.
- Overall, they are not influenced by the channel position, which means that the channel is clean and resonances are not due to impurities in the channel.

Resonances



- We model the system with a generic rectangular barrier. Solutions are plane waves. From the model we compute the transmission probability and then we fit the experimental data:

$$T(E)=\frac{1}{1+\frac{1}{4}\left(\frac{k_1}{k_2}-\frac{k_2}{k_1}\right)^2\sin^2(k_2 b)},$$

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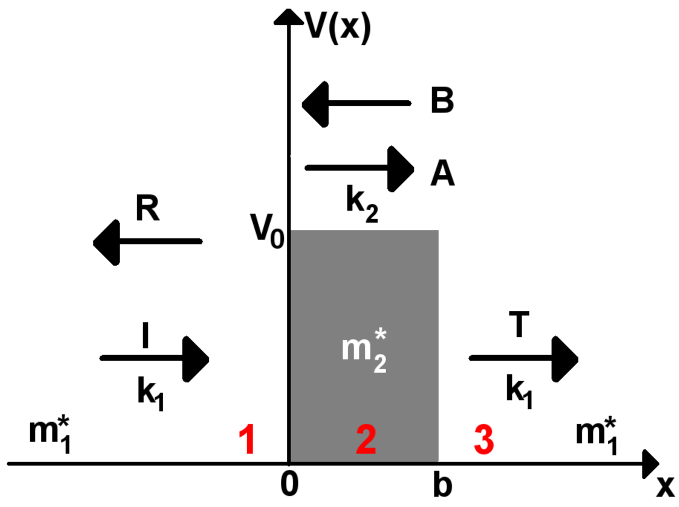

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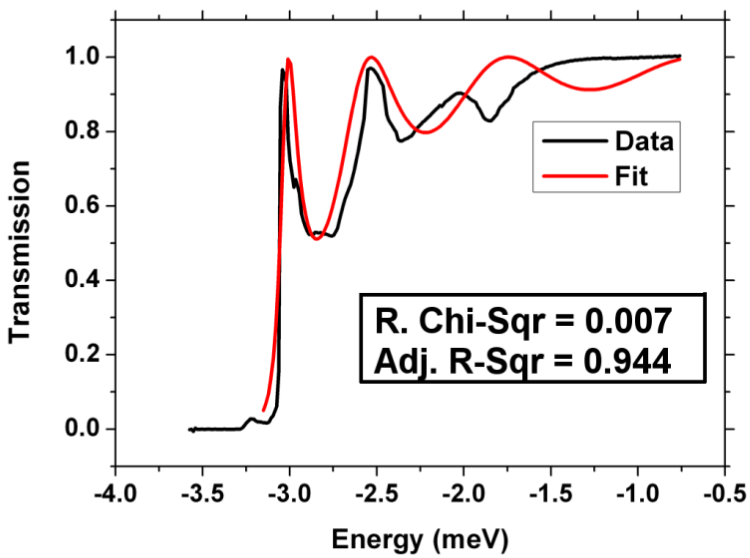


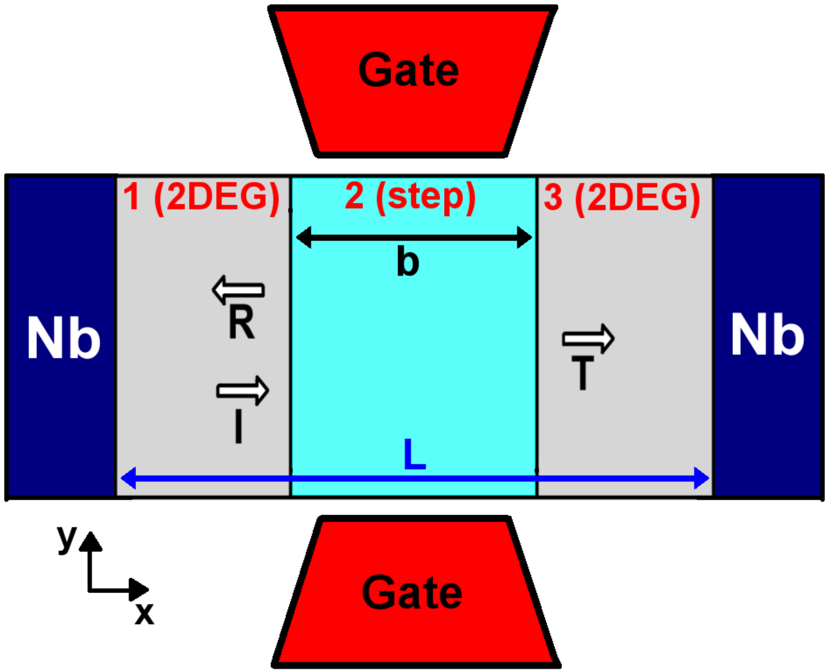
$$M = \frac{m_1^*}{m_2^*} = 1.02 \pm 0.03,$$

$$V_0 = (1.51 \pm 0.01)\, meV,$$

$$b = (350 \pm 50)\, nm < L = (900 \pm 20)\, nm$$

- Good agreement with experimental data.
- The fit parameters suggest that all the three regions are within the 2DEG.

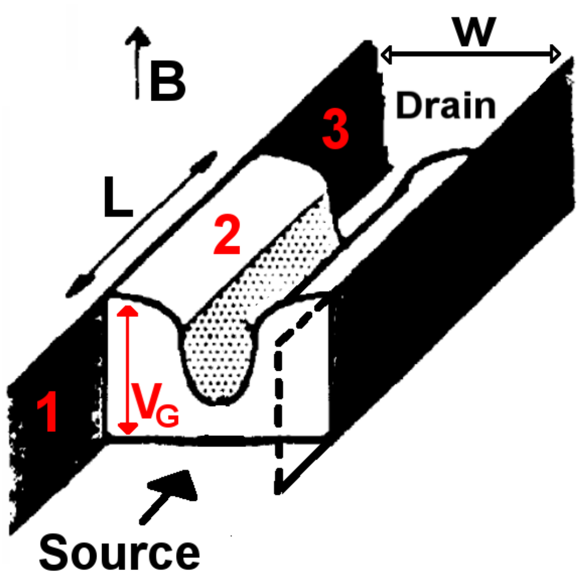
Resonances

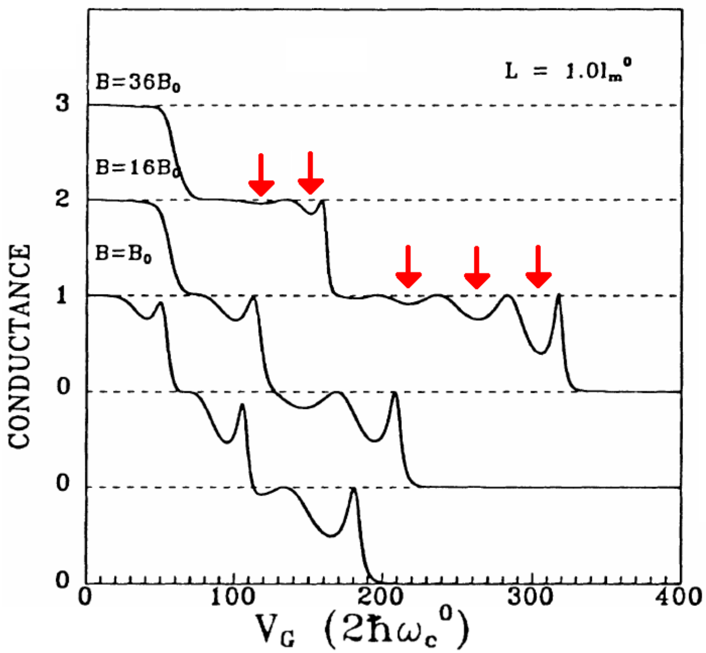


- The side gates create a step in the 2DEG electrostatic potential that extends from side to side.
- This step causes the interference of electrons observed with the resonances.
- This model is too simple for our system, which is 2D and transport is carried by edge states, however, the good agreement suggests that also edge states undergo these interference phenomena at the step.
- The niobium seems to play no role with these resonances.

Advanced model for resonances

- The model considers the 2D geometry, high magnetic fields, and a more complex shape of the electrostatic potential due to side gates.
- Also in this model resonances are observed on quantum Hall plateaus.
- The explanation arises from the interference of edge states reflected at the 1-2 and 2-3 interfaces and, therefore propagating in region 2 in a closed loop.





J. J. Palacios and C. Tejedor, Phys. Rev. B **45**, 13725 (1992).

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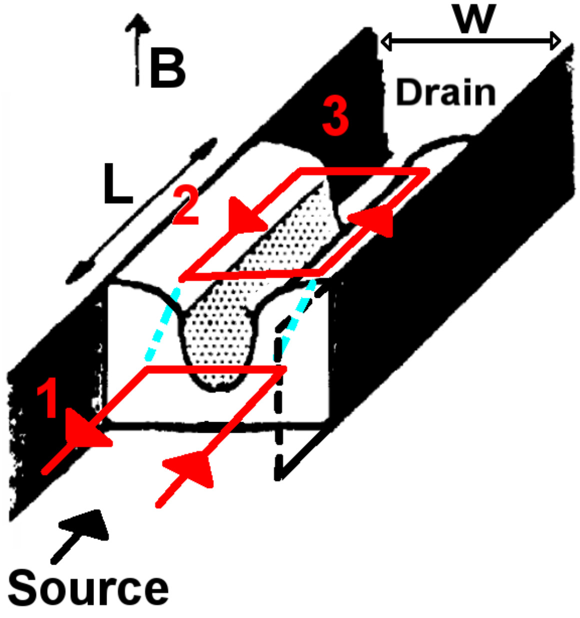

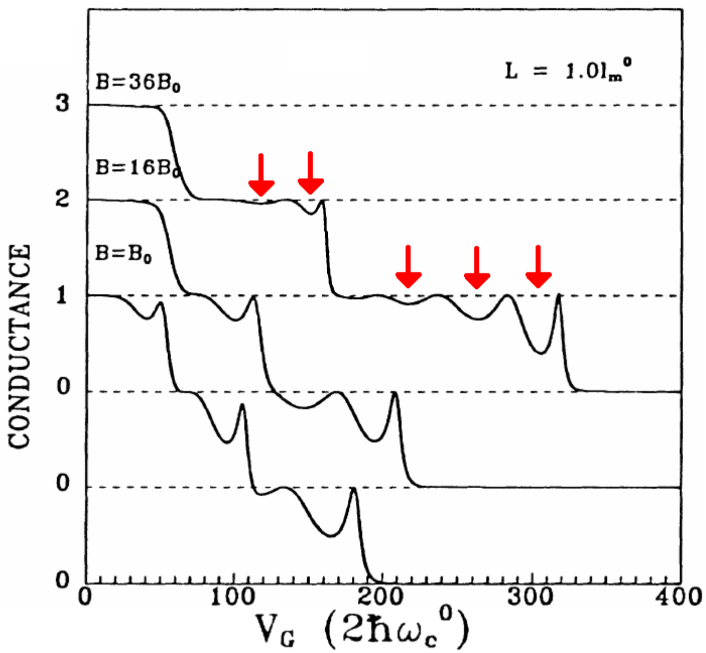

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Outline

- The devices, the experimental setup, the SGM technique.
- Superconductivity.
- The quantum Hall regime and SGM measurements.
- Conclusions and future perspectives.

Conclusions

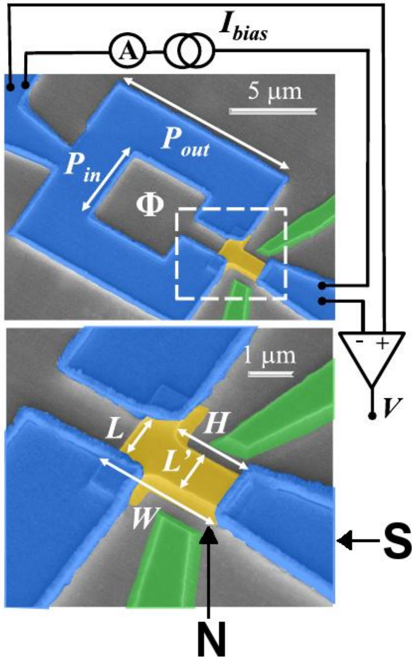
- We fully characterized 2DEG-based SNS junctions both in the Josephson regime and in the dissipative regime:
  - We observed a well-developed supercurrent.
  - We showed that the devices are Josephson Field Effect Transistors.
  - We observed high orders of multiple Andreev reflections, we measured and studied the niobium gap and the proximity gap.
  - Our devices showed a Fraunhofer pattern in the supercurrent as a function of the magnetic flux in good agreement with Heida’s model.

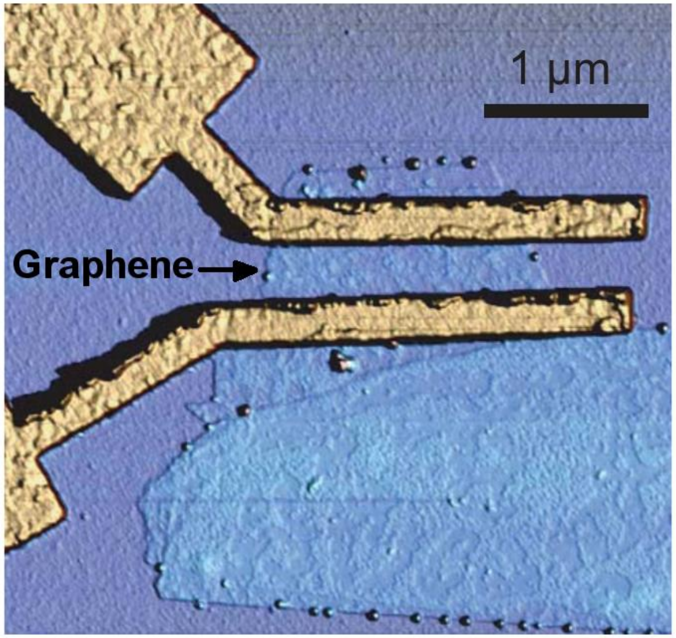
- We tested the compatibility between the devices and the microscope, then we upgraded our system with a stage of filters at room temperature.

- We studied the devices in the quantum Hall regime:
  - We observed resonances that were never seen before with the SGM.
  - We studied these resonances with the SGM.
  - We discussed some simple models to explain their nature.

Future perspectives

- Filter the microscope at low temperature, then novel measurements can be performed.
- Study the same devices in the Josephson regime with the SGM.
- Study the coexistence of superconductivity effects (like Andreev reflections) and the quantum Hall regime (edge states) using a high critical field superconductor (NbTi).
- SGM on Superconductive Quantum Interference Proximity Transistors (SQUIPTs).
- Study SNS junctions with graphene as N region with the SGM.





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Nature 56-59 (**446**) 2007.