2nd semester report

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PhD Program: Materials science and solid state physics
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PhD Thesis title:
Novel Cooper-pair splitting strategies using atomically thin materials

1. Introduction

My research is focused on achieving Cooper pair splitting (CPS) in graphene based devices. As I described in my previous report, I set out to study two different devices. The first device consists of a graphene based pn junction attached to multiple leads. The second device consists of a double Josephson junction geometry, consisting of a p-type graphene layer placed on top of a n-type graphene layer, with no direct coupling and superconductors are placed at either side of the graphene layers. In this semester I turned most of my attention on the second geometry and that is why I will be concentrating on it. I studied how different parameters of the device can be fine tuned in order to obtain a model that pertains to reality and is also numerically manageable. I performed analytical calculations to back up the numerical results and did an exhaustive investigation of the parameters of the device. The possibility of CPS is investigated by calculating the non-local, non-equilibrium differential conductance through the device.

2. Device and challenges

A schematic of the proposed four-terminal device is shown in Fig. 1. Two graphene monolayers of length L are placed on top of each other (red and blue) and two superconducting leads (dark gray) are attached to the edges of the graphene layers, at $y = 0$ and $y = L$. Two normal leads (light gray) N_t and N_b are weakly coupled to the middle ($y = L/2$) of the top and the bottom graphene layer, respectively. The device is also translation invariant in the x direction.

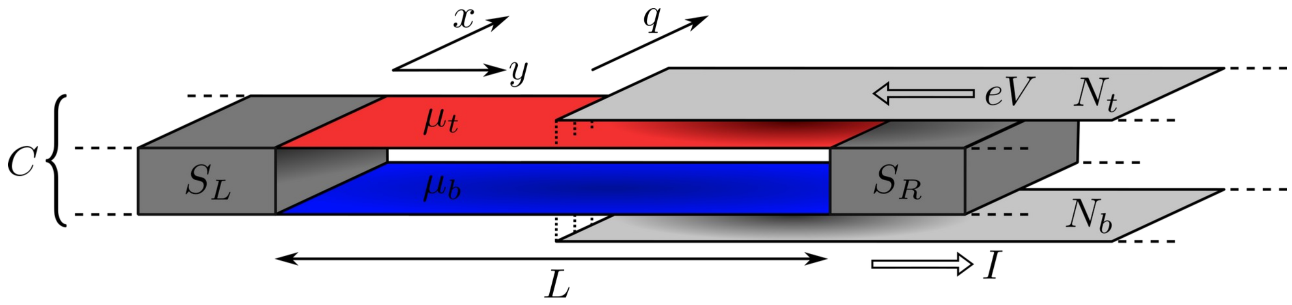

FIG. 1. A sketch of the proposed four-terminal device

A tight-binding approach was used to describe the device and the presence of the superconducting leads is accounted for by the Bogoliubov–de Gennes Hamiltonian. The superconducting leads were chosen as a compromise between accuracy and manageability. Initially we started calculations using a superconducting lead made up of three Bernal stacked graphene layers. When I tried comparing the results of the three layer lead with that of a thicker lead I found that the Andreev bound states (ABS) that formed in the graphene layers were substantially different. We were also presented with difficulties in choosing the appropriate hopping amplitude between the graphene layers and also doping of the superconducting leads. Eventually, a manageable lead consisting of 10 Bernal stacked graphene layers was chosen. I also studied how the coherence length of the superconductor is affected by different choices of parameters.

3. Results

After having created a good model of the proposed device, I tuned the parameters of the device and studied how the local density of states and the differential conductance dI/dV (see Fig. 1.) changes. The presence of negative differential conductance at energies below Δ would suggest that CPS is possible. This can be only achieved through a process crossed Andreev reflection (CAR), equivalent to CPS. My goal was to perform an exhaustive study of the important parameters of the device. Thus, the values of L, μ_t (μ_b) and φ had to chosen carefully: L=200 – 1500 nm, μ_t (μ_b)=4Δ – 80Δ and φ=0 – π, representing values that can achieved experimentally.

Firstly, setting $\mu_b = -\mu_t = \mu$, where $\mu>0$, leads to the appearance of CAR , whereas $\mu_b = \mu_t$ results in the suppression of CAR. Analytical calculation were performed with the aim of explaining this phenomenon, but unfortunately no straightforward explanation was found. The local density of states calculations I performed were helpful in understanding the underlying processes influencing the differential conductance. No convincing relation between the local density of states and the differential conductance calculations was observed.

Numerical calculations were performed using the tight-binding framework implemented in the MATLAB based EQuUs package. I also used Python to create codes for post-processing the results and facilitating the numerical calculations. I found that, in the long junction regime ($L\geq$1000 nm) strong negative differential conductance is present and robust for almost all values of μ and φ. For shorter devices I studied the role of μ and φ in the appearance of CAR. Both μ and φ can be used in enhancing the negative differential conductance, as show below, for a device with L=200 nm. In FIG. 2a. we can see that φ can be used to tune the differential conductance, and in FIG. 2b. we can see that increasing μ leads to the appearance of CAR for almost all energies eV. The same effect can be observed for longer devices too, but for L>1000 nm only φ can be used to tune the differential conductance.

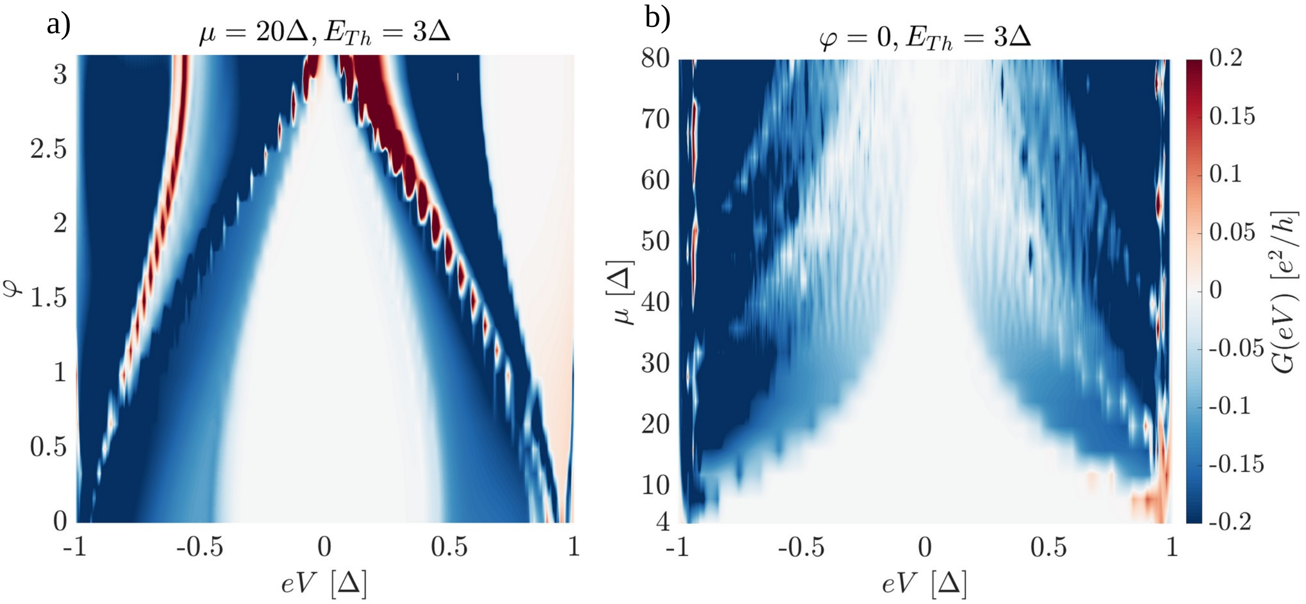

FIG. 2. The differential conductance $G(eV)=dI/dV$ as a function of a) φ, determined for a device with doping μ = 20Δ and L=200 nm, and as a function of b) doping μ, determined for a device with L = 200 nm, at φ = 0, for $|eV|$ < Δ.

The results suggest that CPS is possible using the proposed device, and is also robust for a wide range of the parameters. Numerous previous works were reviewed and we believe that our results are notable, since a device of this geometry wasn’t studied before in this manner. At the time of writing, we are working on a preprint and we are planning to publish our results by the end of August.

4. Studies

This semester I attended one course:

- Topologikus szigetelők II. (FIZ/1/043E)

5. Conferences and workshops

- I presented in a poster at the SuperTop workshop, 2022, Budapest University of Technology and Economics
- I will be attending the Frontiers in Condensed Matter Physics, 4th biennial QDev/NBIA PhD Summer School 2022 in July

6. Teaching activity

- I took part in the teaching of “Fizika numerikus módszerei II” (fiznum2f19la)