1st semester report

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PhD Thesis title:
Novel Cooper-pair splitting strategies using atomically thin materials

1. Introduction

Recently, the realization of Cooper pair splitting (CPS) in mesoscopic devices has attracted considerable interest in the field of solid state physics. In multi-terminal devices, CPS can be achieved through a process called crossed Andreev reflection (CAR). If we consider a device with a N_1SN_2 geometry, where N_1 and N_2 are non-superconducting metals (leads) and S a superconductor, CAR is the process whereby an electron incoming from N_1 with energy below the superconducting gap Δ is reflected on the metal-superconductor interface into a different lead (N_2) as a hole. A representation of this process is shown in Fig. 1. (The outgoing hole can be interpreted as an incoming electron). Experimental demonstrations of CPS have mostly relied on quantum dots, coupled to different materials, nanowires, carbon nanotubes and graphene quantum dots. Graphene is viewed as a unique tool in achieving CPS, due to its linear dispersion relation around regions of the Brillouine zone referred to as the Dirac points.

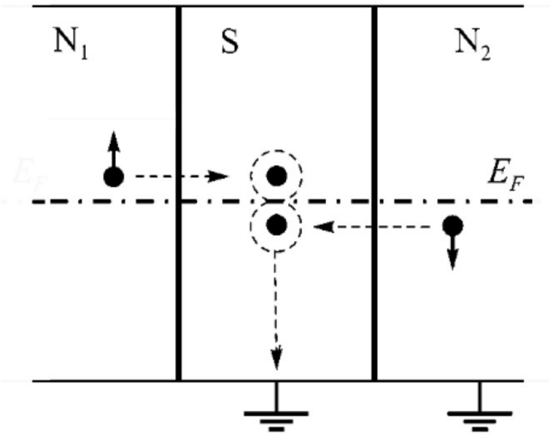

Figure 1. Crossed Andreev reflection.

The goal of my research, is to study how graphene based devices can be used in achieving CPS. In a recent work by P. Pandey et. al. a multi-terminal device consisting of a graphene square surrounded on all of its sides by superconducting electrodes was studied. It is argued, that in such a device the graphene square is doped by the superconductors, leading to the appearance of multiple pn-junctions. Studying the interplay of pn-junctions with Andreev reflection is therefore essential in understanding CPS in such a device.

In a study by J. Cayssol it was shown, that in a device with a NSN geometry, where N are graphene samples, the doping of the graphene affects the probability of CAR. If the doping is chosen to be μ on one side, and $-\mu$ on the other, all processes except CAR are blocked for subgap energies. It is important to study how this effect can be achieved in different geometries, and also how limiting the condition of $|\mu| < \Delta$ is to achieving CPS in such devices.

2. Research

During this semester, I studied two different graphene based setups that might be useful in achieving CPS, each inspired by the studies mentioned in the introduction. I constructed a multi-terminal graphene device, and I studied the effect of a pn junction on the transmission probability through different channels. The second setup is a device consisting of two graphene ribbons placed on top of each other, connected with two superconducting leads placed on the side of the ribbons. In this system the object of interest was the differential conductance.

2.1 Four terminal pn-junction

In order to study how Andreev reflection is influenced by the presence of a pn-junction, we use a device that is composed of a rectangular graphene region (scattering region) to which a superconducting graphene lead S and three non-superconducting graphene leads are attached as shown in Fig. 2. The device is constructed using a Python package called kwant.

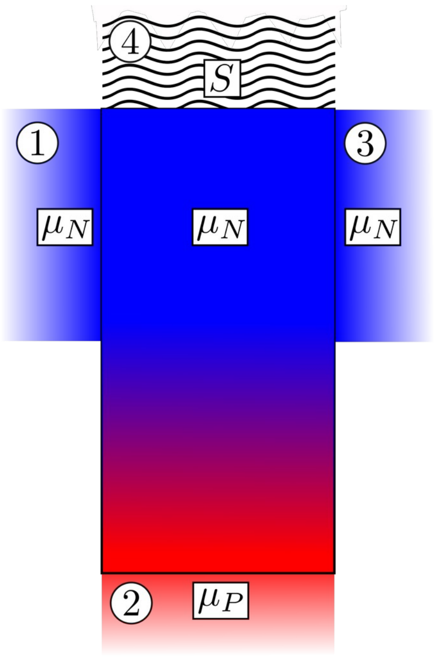

Fig. 2. The 4 terminal pn-junction

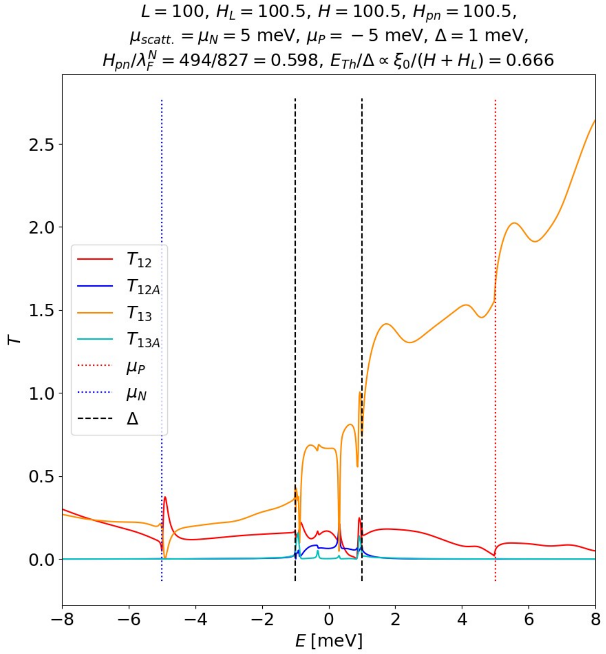

Fig. 3. Transmission through the pn-junction

Two leads L_1 and L_3 are negatively doped with $\mu_N = \mu$, while the doping in L_2 is set to $\mu_P = -\mu$. A pn-junction is created in the scattering region, by gradually changing the doping from μ_N to μ_P as represented in Fig. 2. We study the equilibrium transmission in this system, some of the results being shown in Fig. 3. As expected, the transmission from lead L_1 and L_3 (T_{13}) is not greatly influenced by the pn-junction, and the transmission through the pn-junction T_{12} is suppressed if the doping in the scattering region changes from μ_N to μ_P on a larger distance (smooth junction). However, we found that T_{13A} becomes comparable to T_{13} for subgap energies, thus opening the possibility of CPS in such a system.

It is also remarkable ,that for energies $|E|<\Delta$, peaks appear in the transmission amplitudes suggesting the presence of Andreev bound states (ABS) in the scattering region. Thus, the results can interpreted by regarding the pn-junction as a hard barrier for the states incoming from lead L_1. These peaks also appear in the electron-hole transmission amplitudes T_{12A} and T_{13A}. The parameters of the system were tuned to find the best conditions for obtaining high values of electron-hole transmission.

2.2 Bilayer graphene SNS device

The second setup I studied consists of two graphene monolayer ribbons stacked on top of each other, with no hopping amplitude connecting them. At the each edge of the ribbons a superconductor *S* is placed, vertically connecting the two ribbons, resulting in a Josephson junction-like geometry. In Fig. 4. only a section of the device is presented, since the system is translation invariant in the *y* direction. This symmetry allows us to introduce a *q* conserved quantity.

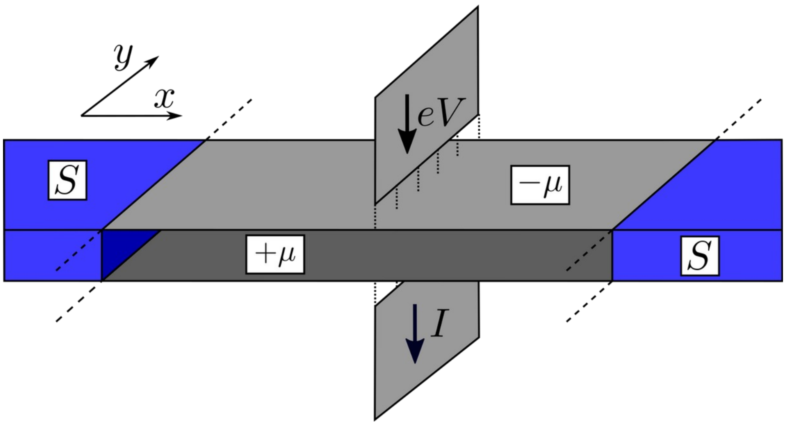

Fig. 4. The bilayer graphene SNS device.

The upper layer of the device is positively doped with -μ, and the lower layer negatively doped with +μ. By studying the density of states (DOS) of each layer, we find that ABS appear in this device too. Furthermore, it turns out that the amplitude of the electron-like and hole-like components of the ABS is different in the two layers. In other words, the DOS is polarized, as shown in Fig. 5.

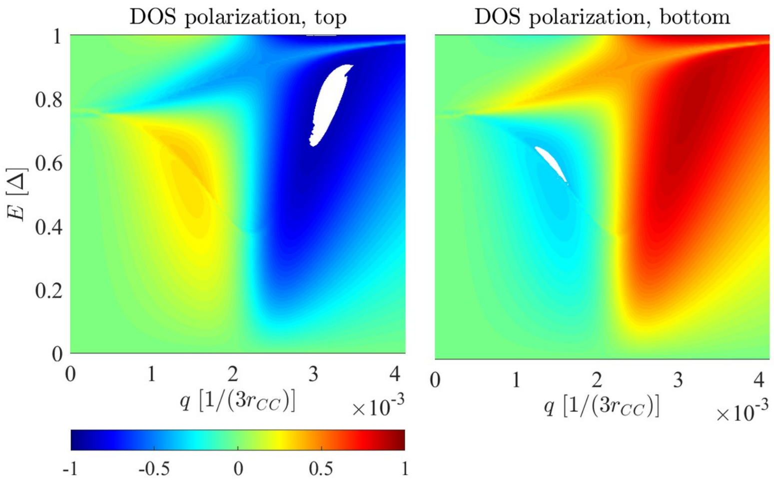

Fig. 5. The polarization the DOS in the upper and lower layer.
Red (blue) stand for electron (hole) polarization.

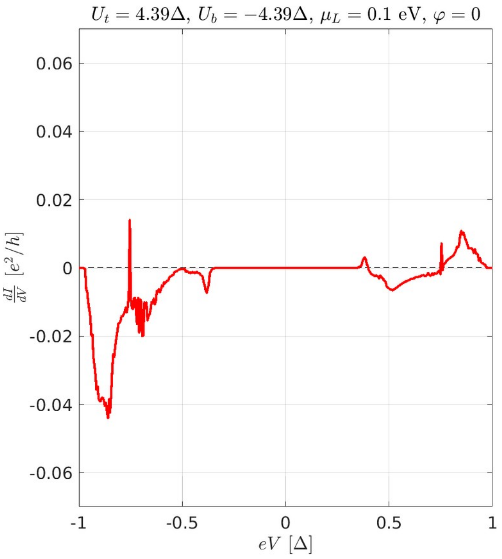

Fig. 6. Differential conductance
through the device.

I studied the non-equilibrium differential conductance of the ABS by weakly coupling two out of plane non-superconducting leads to the top and bottom layer, respectively (see Fig. 4.). Electrons of energy *eV* are injected into the device from the upper lead, and the current arising at the lower lead *I* is calculated. An example of the resulting differential conductance *dI/dV* is shown in Fig. 6. One can clearly see, that a large portion of the curve gives negative differential conductance, which suggests the presence of CAR (the injected electron comes out as a hole). Multiple parameters of the system, such as μ, the distance between the superconductors, the phase difference of the superconductors are very important in obtaining substantial negative differential conductance.

3. Studies

I attended 3 courses:

- Soktestprobléma II. (FIZ/3/050E)
- Teljesen integrálható sokrészecske rendszerek (FIZ/2/077E)
- Transzport komplex nanoszerkezetekben (BMETE11MF24), at Budapesti Műszaki Egyetem

4. Teaching activity

I took part in the teaching of “Programozási alapismeretek és Haladó numerikus módszerek” (halnumf19la).