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PhD Thesis booklet

Cooper pair splitting in indium arsenide nanowires

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Introduction

Quantum entanglement is a cornerstone of quantum mechanics, manifesting in intriguing phenomena. Besides the fundamental interest, it is enticing with various applications: entanglement is the essence of quantum algorithms, which can be used to speed up the solution of certain problems tremendously, for example factoring integer numbers and computing discrete logarithms [Nielsen and Chuang, 2010]. A quantum bit (qubit), on which quantum algorithms operate, can be represented by any two-level quantum mechanical system. For example, the electron spin can be used to realize a spin qubit. The development of nanofabrication techniques in the past few decades enabled the experimental realization of spin qubits in semiconductor nanostructures [Petta et al., 2005]. The possibility to entangle qubits separated in space is a key feature to operate quantum computers. Superconductors are a natural source of entanglement, because the electrons form spin-singlet Cooper pairs in the ground state. To use them in the preparation of entangled spin qubits, the Cooper pairs must be extracted and separated.

The devices accomplishing this are called Cooper pair splitters (also known as Andreev entanglers). Historically, the signatures of Cooper pair splitting (CPS) have been first observed in metallic circuits with normal-superconducting-normal (N-S-N) [Russo et al., 2005; Kleine, 2010] and ferromagnetic-superconducting-ferromagnetic (F-S-F) structures [Beckmann et al., 2004]. Such a circuit can be depicted as a Y-junction, with S as the middle electrode. Ideally, the electrons of a split pair leave the junction to different N electrodes. However, in these devices the CPS current arising from this process was a small portion of the total current, because dominantly both electrons of a broken pair were transmitted to the same N electrode. Recher et al. proposed that the splitting can be enforced by embedding quantum dots (QDs) in the junction, and by that the efficiency of producing a stream of entangled electrons can be increased significantly [Recher et al., 2001]. In their proposed N-QD-S-QD-N structure the Coulomb repulsion on the QDs suppresses the transmission of both electrons of a Cooper pair to the same normal lead. There are various systems in which Cooper pair splitter devices based on double QDs can be realized. CPS has been demonstrated in indium arsenide (InAs) nanowire (NW) [Hofstetter et al., 2009; Das et al., 2012], carbon nanotube (CNT) [Herrmann et al., 2010; Schindele et al., 2012] and graphene [Tan et al., 2015; Borzenets et al., 2015] circuits.

Objectives

In the first experimental demonstration of the CPS process in an InAs NW circuit the splitting efficiency was only a few percent [Hofstetter et al., 2009]. In that device the microscopic parameters, first of all the coupling strengths between the QDs and the leads were not under experimental control. The poor performance was explained with an overly large coupling broadening of the Coulomb resonances, compared to the superconducting gap, which resulted in a large quasiparticle and local pair tunneling current. The objective of my PhD work was the realization of tunable Cooper pair splitters, in which the coupling strengths can be adjusted in-situ, and thereby the Cooper pair splitting process can be explored in a wide parameter range.

Experimental techniques

In my PhD research I realized InAs NW-based Cooper pair splitter devices using electron beam lithography in combination with thin film deposition techniques (vacuum evaporation, sputtering) and etching techniques (reactive ion etching, focused ion beam milling). InAs NWs are an attractive platform, since it is relatively easy to form electrical contacts to them with both normal-conducting and superconducting materials, and form QDs. I investigated devices with aluminum (Al), niobium (Nb) and lead (Pb) superconductor electrodes. To form QDs with tunable tunnel barriers, I used an array of local gates below the NW, separated by a thin (≈25 nm) silicon nitride layer. The CPS experiments were carried out in a dilution refrigerator at a temperature of $T \approx 30$ mK. I had a substantial contribution to the development of the cryogenic filtering, the electronic setup and the measurement automation of the employed low temperature system. The electric conductance of the nanocircuits was measured with a low-frequency (< 1 kHz) lock-in technique, using an ac excitation voltage on the order of 10 μV.

Thesis points

1. I studied and compared wet etching methods as quantum dot formation approaches in indium arsenide nanowires (NWs): piranha, galvanic and alkaline etching. I developed a wet etching method based on the material selectivity of a dilute piranha etching solution (sulfuric acid, hydrogen peroxide and water). The NW is thinned on a lithographically defined segment, and the same lithographic mask can be used for the formation of ohmic contacts on the thinned segments in a self-aligned fashion. I also developed an alternative etching method, which allows the thinning of the NW next to the ohmic contacts. I observed that in this latter approach

the etching process is strongly enhanced. I explained this observation with the formation of a local galvanic element, with the metallic contact electrode and the semiconducting NW playing the roles of the anode and cathode. I fabricated quantum dot (QD) devices in NWs patterned with galvanic etching, and carried out electronic transport measurements at low temperature (300 mK). These measurements show that the NWs patterned with the novel etching methods can serve as building blocks of nanoelectronic devices. [1]

2. I participated in the development of fabrication techniques of tunable Cooper pair splitter devices. An array of local gates is fabricated on a silicon wafer, and covered with a thin dielectric layer ($\sim$ 25 nm). An InAs NW is placed over the gate structure with a micromanipulator, and contacted with a superconductor and two normal electrodes. I showed that the electric potential along the NW is tunable by applying voltages on the gates. I demonstrated that QDs can be formed by introducing potential barriers in the close vicinity of the superconducting contact, furthermore, the coupling strengths between the QD and the leads can be tuned. I investigated the Cooper pair splitting process in such novel gate-tunable devices, and showed that the non-local signal strongly depends on the tunnel couplings. [2, 3]

3. In the Cooper pair splitting process, through the injection of two single electrons to opposite QDs, an equal current enhancement is expected in both arms, i.e. positive non-local signals of the same amplitude. In the investigation of tunable Cooper pair splitters, I found unequal non-local amplitudes, furthermore, even a strong negative non-local signal. To interpret this finding, I studied the non-local signal in an incoherent rate equation model, as a function of the QD-lead and interdot coupling strengths. I found that unequal non-local signals can originate from the asymmetry of the coupling strengths of two arms, however, negative non-local signal can only be generated with a finite interdot coupling. The presence of a finite interdot coupling is consistent with the device structure, where a NW segment connects the two QDs. [2]

4. In the investigation of the non-local signal in the Cooper pair splitter nanocircuit as a function of magnetic field and gate voltages, I observed strongly asymmetric non-local signals with Fano-like lineshapes. This in contrast with the theoretical calculations, which predict symmetric non-local lineshapes, resembling the Lorentzian Coulomb resonances of the tuned dot. I interpreted the experimental findings in a more elaborate model of the CPS circuit, which was developed in collaboration with theoreticians. In this coherent three-site model the emergence of the asymmetric non-local signal and its amplitude variation can be explained. These

originate from interference effects between alternative electron transport pathways. [3]

5. I investigated the Cooper pair splitting process out of equilibrium. I found that the non-local signal at finite bias diminishes at a lower temperature than the critical temperature of the superconductor. I studied a Cooper pair splitter with QDs exhibiting subgap resonances arising from Andreev bound states. I mapped the non-local signal originating from Andreev resonances with CPS tomography measurements. I found a strong non-local signal when the Andreev transport pathway opens up in both QDs at the resonant bias voltage. I showed that the non-local signal strongly depends on the bias voltage and the ground state of the QDs. The sign of the non-local signal can be even reversed by tuning the QDs through a quantum phase transition or by reversing the bias voltage. [4]

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List of publications

Publications related to my PhD work

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