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Andreev Spin Qubit (ASQ) in GeSi Nanowires

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Abstract: We propose to build and study a new type of spin qubit, the Andreev spin qubit (ASQ). It is realized as a fermionic degree of freedom by a single electron trapped in a gate-tunable highly transmissive Josephson junction (JJ). This odd state, which in a normal JJ is "dark", carries a supercurrent if strong spin-orbit interaction (SOI) is present. The project's aim is to realize and study the ASQ in GeSi core-shell nanowires (NWs), where a large gate-controlled SOI has been predicted. The ASQ will be interfaced with microwave circuits for readout and state manipulation.

Motivation: Quantum technology is one of the most rapidly developing field. It attracts the attention of our society and raises hopes for computing power way beyond everything we can imaging today. A quantum computer is "physical", meaning has to be implemented in a physical object. There are several solid-state implementations of quantum bits (qubits) that promise good properties. Examples are the spin[1] and superconducting transmon qubits.[2] While the former is very compact, based only on the microscopic spin of a quasiparticle (QP), the later is larger, rooting on the macroscopic many-body wavefunction of the superconductor (SC). Both have advantages and disadvantages. A transmon qubit is composed of a single metallic Josephson junction JJ, which acts as a weakly non-linear inductor and together with a capacitor forms a non-linear LC circuit whose lowest two eigenstates define the qubit states.

The Andreev Spin Qubit: SCs provide (ideally) a very clean electronic environment, since a SC is free of single-particle excitation within the gap. Junctions made from SCs are therefore expected to provide long quantum coherence times. However, a QP may trap inside a JJ. This even-to-odd parity change "destroys" the transmon qubit and for this reason this process is often called QP "poisoning". There is a large effort in the community to minimize this in order to improve qubit coherence times. Here, we propose to actually make use of this odd state to define a special spin qubit in a superconducting environment. This qubit is known as the Andreev spin qubit (ASQ). It was theoretically proposed in 2003, but did not received much attention yet.[3-5]

The ASQ is realized in a single (or few) mode JJ which needs to be highly transmissive. The supercurrent in such a junction is determined by the Andreev bound states (ABSs) that form as coherent standing waves within the gap of the SC and localized to the junction within a coherence length.[6] The phase dependence of the even parity $|e\rangle$ ABSs is outlined in Fig.1, where also the odd state $|o\rangle$ is indicated in green. It is this fermionic degree of freedom that we target in this proposal. it has been found that the junction may stay for much longer time in the odd state "poisoned" state than in the even one[7] and there is hope that this time can be increased. The odd state is a spin doublet and therefore forms a special kind of spin qubit. If there is spin-orbit interaction (SOI) and time-reversal symmetry is broken by a magnetic field, the odd state can also carry a current, which can be used to read, manipulate and couple qubits.[8, 9]

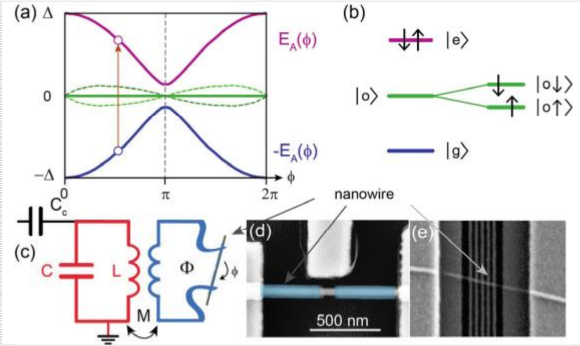

Fig. 1: (a) Energy of Andreev eigenstates as a function of phase difference φ localized in a single-mode short Josephson junction (JJ). The two branches colored blue (ground state) and purple (excited state) are even parity states that carry a supercurrent. Shown is also an odd parity state in green, which normally does not carry any current, as this state has no phase-dependence. It is a fermionic degree of freedom with a two-fold (spin) degeneracy, which can be used to define a qubit: the Andreev Spin Qubit (ASQ). The degeneracy is lifted and a supercurrent appears if there is spin-orbit interaction (SOI) and a magnetic field is applied (dashed green curves). (b) Effective state diagram in the excitation picture. (c) We aim to realize an ASQ (blue) in GeSi-nanowire (NW) JJs embedded in a RF SQUID inductively coupled to a microwave resonator. The qubit coupling can be turned on and off via a switchable SOI in GeSi core-shell NWs, which will be used in this project. The qubit can be read and manipulated through microwaves that are coupled via the coupling capacitor C_c into the circuit. (d) and (e) show NW devices recently realized by the team.

Work plan: We aim to realize an ASQ in GeSi core-shell NWs for the following reasons: 1) It has been shown that Al contacts can be alloyed with the Ge core yielding an alloy that is superconducting on its own.[10] This provides an elegant route to highly transmissive few mode JJs. 2) It has further been shown theoretically that large SOI is possible in holes of GeSi.[11] This coupling is switchable. If the SOI is off, the Andreev spin qubit is disconnected from the environment and therefore protected. By turning SOI on, manipulation and readout becomes possible. Working in a team of experts, the PhD student will analyze SOI in GeSi NWs, realize highly-transmissive JJ, and conduct qubit measurements and characterization of spin-full Andreev states using cavity QED techniques.

References

1. D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120-126 (1998).
2. J. Koch, *et al.*, Phys. Rev. A **76** (4), 19 (2007).
3. N. M. Chtchelkatchev and Y. V. Nazarov, Phys. Rev. Lett. **90** (22), 226806 (2003).
4. A. Zazunov, V. S. Shumeiko, E. N. Bratus, J. Lantz and G. Wendin, Phys. Rev. Lett. **90** (8), 087003 (2003).
5. C. Padurariu and Y. V. Nazarov, Phys. Rev. B **81**, 144519 (2010).
6. M. F. Goffman, R. Cron, A. L. Yeyati, P. Joyez, M. H. Devoret, D. Esteve and C. Urbina, Phys. Rev. Lett. **85** (1), 170-173 (2000).
7. M. Zgirski, L. Bretheau, Q. Le Masne, H. Pothier, D. Esteve and C. Urbina, Phys. Rev. Lett. **106** (25), 257003 (2011).
8. S. Park and A. L. Yeyati, Phys. Rev. B **96** (12), 125416 (2017).
9. D. J. van Woerkom, *et al.* Nat. Phys. **13** (9), 876-881 (2017).
10. J. Ridderbos, PhD Thesis, University of Twente, 2018.
11. C. Kloeffel, M. Trif, P. Stano and D. Loss, Phys. Rev. B **88** (24), 241405 (2013).