Design of a trijunction of Majorana nanowires

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by

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Contents

1
Background

1.1. Introduction

1. Majorana bound states (MBS) can be used to create a non-local qubit robust against local noise.
2. While coupling a single MBS pair can be done using a quantum dot, selective coupling of multiple pairs remains a challenge.
3. In this work we propose a semiconducting cavity connected to three Majorana stripes that allows for an all-electric controlled interaction between all pairs of MBS.
4. Several cavity geometries are analysed, and a triangular cavity with varying angle is found to have the largest coupling for all pairs.
5. The electrostatics effects of the gate-defined triangular cavity are analysed and the operational point is described.

1.2. Majorana bound states

1. MBS are the non-local degenerate ground state of a topological superconductor as initially proposed by Kitaev.
2. Quantum information can be encoded in the ground state since even and odd parity states are degenerate.
3. Since a pair of spatially separated MBS encodes a single fermionic mode, its quantum state is protected against local errors by particle-hole symmetry.

1.3. Experimental platforms

1. MBS can be realised in hybrid one-dimensional systems defined on two-dimensional electron gases (2DEGs) or semiconducting nanowires in proximity to a superconductor and in the presence of a magnetic field.
2. A quasi-one dimensional semiconducting system contains multiple transverse subbands whose energy and other properties, such as spin-orbit or effective mass, are affected by the geometry and the coupling to the superconductor.

3. Control over the chemical potential and tunnel coupling to nearby leads is mediated via electrostatic gates, but it is mostly screened inside the nanowire by the presence of the superconductor.

4. Disorder in the nanowire bulk can be detrimental for MBS since it affects its localisation and properties, such as induced gap, while disorder inside the superconductor enhances the induced gap in the nanowire.

1.3.1. Two dimensional electron gases

1. 2DEGs are a good platform for MBS based quantum computation because complex geometries can be defined in the same layer, whereas nanowires require mechanical matching.

2. Initial experiments focused on characterising the properties of semiconducting layers, such as large g-factor and large spin-orbit, with a superconducting layer.

3. Later experiments focused on tunnel spectroscopy of stripe-like geometries where a zero bias peak (ZBP) was found, but its origin was trivial Andreev states rather than MBS.

4. 2DEGs are suitable to create gate defined shapes with interesting geometry dependent properties in the ballistic regime, yet in MBS experiments only stripes and planes have been developed so far.

1.4. Quantum operations with Majorana bound states

1. The dimension of the computational Hilbert space depends on the number of MBS, and thus multiple parallel Majorana nanowires are required for MBS based quantum computing.

2. The state of the degenerate manifold of MBS can be non-trivially changed by adiabatically moving the particles around each other, i.e. non-Abelian exchange statistics.

3. Initial proposals were based on moving MBS around each other in gate defined nanowire networks, but this method requires high degree of control and is highly susceptible to thermal errors.

4. An equivalent approach that does not require to move the MBS is given by joint parity measurements, but it requires simultaneous measurement of different pairs of MBS.

5. There are several proposal for a MBS based qubit using quantum dots and floating superconducting nanowires whose working principle is electron co-tuneling.

6. To the best of our knowledge, there is a single study where MBS are connected via a semiconducting cavity in a fork-like geometry, yet geometry role has proven to be fundamental in how leads states couple.

2

Coupling of two Majorana bound states

In this chapter we discuss the coupling of two MBS using a quantum dot and the role of the superconducting phase difference in a topological Josephson junction.

2.1. Topological Josephson junctions

1. A Josephson junction is a S-N-S junction where the excitation spectra is controlled by the flux, Φ, with 2π periodicity.

2. A Josephson junction made with topological superconductors is 4π periodic as a consequence of the presence of a zero-energy fermionic mode made of two MBS.

3. While the frequency is fixed, the phase shift is determined by the complex part of the hopping term between the two structures, which in our case is given by the

4. Control of the normal section as a quantum dot allows for the MBS to couple with a maximum at $\varphi = \pi$.

5. If the two superconductor are in a parallel geometry, chiral symmetry is required to couple the MBS.

3

Coupling of three Majorana bound states

In this chapter we make a systematic study of the role of geometry in the pair coupling of three MBS via a semiconducting cavity.

4

Gate defined triangular cavities

In this chapter we discuss the implementation of a triangular cavity via electrostatic gates as well as the operational point where the coupling of all MBS pairs is maximum.