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Majorana Qubits

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Abstract- We present an overview of Majorana qubits based on one-dimensional semiconducting nanowires partially covered with a conventional superconductor. Majorana zero modes emerge at the wire ends when this hybrid system transitions from a conventional superconducting phase to a topological phase, in general occurring on increasing a magnetic field. For sufficiently long wires different Majoranas are fully independent and Majorana-based qubit states become topologically protected, which make them insensitive to local sources of noise. We present qubit designs, materials and device development and ongoing experimental efforts.

I. INTRODUCTION

Majorana zero modes (MZM), or 'Majoranas', always come in pairs. To zeroth-order they can be viewed as "half-electrons", and thus a Majorana pair constitutes a "full electron", or a fermion. The ground state of a conventional superconductors consists of an even number of fermions, all paired up in Cooperpairs. A topological superconductor in addition to Cooperpairs hosts two Majoranas and thus can contain both an even and an odd number of fermions. These even and odd parities form a two-fold degenerate ground state (see introduction in Fig. 1), which can be used as the Majorana qubit states. Interestingly, measurements on one Majorana cannot provide any information on the parity of a pair of Majoranas. Also, local noise coupling to just one Majorana cannot extract information or influence the state of the qubit. This insensitivity due to absence of wave function overlap, or interactions in general, is provided by the large separation between the two "half-electrons". This is referred to as topological protection. The resulting enhanced qubit stability is the motivation for pursuing topological quantum computation [1].

II. THE SYSTEM

In conventional superconductors electrons with opposite spin pair up in Cooperpairs and collectively open a superconducting gap, Δ, in the energy spectrum. A magnetic field tends to polarize spins thereby breaking up Cooperpairs and lowering the value of Δ with gap-closure when the Zeeman energy $E_Z = g\mu_B B/2 = \Delta$. The same is true for induced superconductivity into a semiconductor which is electrically connected to a superconductor. The connection "proximitizes" the semiconductor with loosely-speaking having the Cooperpairs leaking into the semiconductor. The microscopic energy spectrum is known as the Andreev Bound State (ABS) spectrum. Figure 1 (lower left panel) illustrates that the gap in the ABS spectrum closes when increasing E_Z.

Interestingly, in the presence of strong spin-orbit interaction (SOI) spin polarization is negated by spatially rotating the spins. Since Cooperpairs in the parent superconductor are spatially extended, ABS states can still form but now with interesting spin structures. While the ABS are two-fold spin degenerate at $B = 0$, a finite B lifts the degeneracy causing level crossings of opposite spin states in the absence of SOI (lower left panel Fig. 1) and avoided level crossings in the presence of SOI (lower right panel Fig. 1). The Majorana mid-gap states have no spin, which is really peculiar since these states correspond to either even or odd fermion-parity and fermions always have non-zero spin. In addition to zero-spin, the defining property "particle-equals-antiparticle" implies that Majoranas also don't have electric charge. These are three easy to test Majorana properties, zero-energy, zero-spin and zero-charge.

Figure 2 shows the basic characterization measurement to detect the presence of Majoranas [2]. Tunneling into a Majorana state should yield a resonance at zero energy in the conductance. If particle-equals-antiparticle holds, the conductance value is predicted to be quantized at $2e^2/h$, irrespective of precise values for magnetic field or electron density. Figure 2 indeed shows a resonance at zero voltage, V, that remains at zero while changing B from 0.7 to 0.9 T (implying the absence of spin-degrees of freedom). Shown in Ref. x is that also an electric field does not move the resonance away from zero energy (implying the absence of charge). Energy, spin and charge being zero, together with the quantized value of the resonance, is the current evidence for the existence of Majoranas [3].

II. MAJORANA QUBITS

Qubits can be formed with two Majorana pairs where each pair either contains zero or one fermion, i.e. encodes for either even or odd parity. In a Majorana-transmon qubit as illustrated in Figure 3 the two inner Majoranas are tunnel coupled. Suppose that at some moment the left pair $\gamma_1\gamma_2$ has even parity and the right pair $\gamma_3\gamma_4$ has odd parity. The tunnel coupling between γ_2 and γ_3 creates a superposition between the parity combination even/odd and odd/even. Probing such superposition can be done with a circuit-QED setup commonly used for superconducting transmon qubits. Our device layout including the nanowire structure is shown in Figure 3.

An alternative to a tunnel coupling geometry, is a measurement based approach to topological qubits. Figure 4 illustrates how measuring the parity of a particular Majorana pair can create a superposition of parity states in a different pair. The measurements can be done via simple conductance measurements or by using quantum dots as parity sensors. The latter can yield a scalable architecture for topological qubits. We will present state of the art experiments on both Majorana-transmons as well as measurement-based qubits.

Work done in collaboration with colleagues and collaborators at QuTech in Delft and the Microsoft Quantum Labs in Santa Barbara, Copenhagen and Delft.

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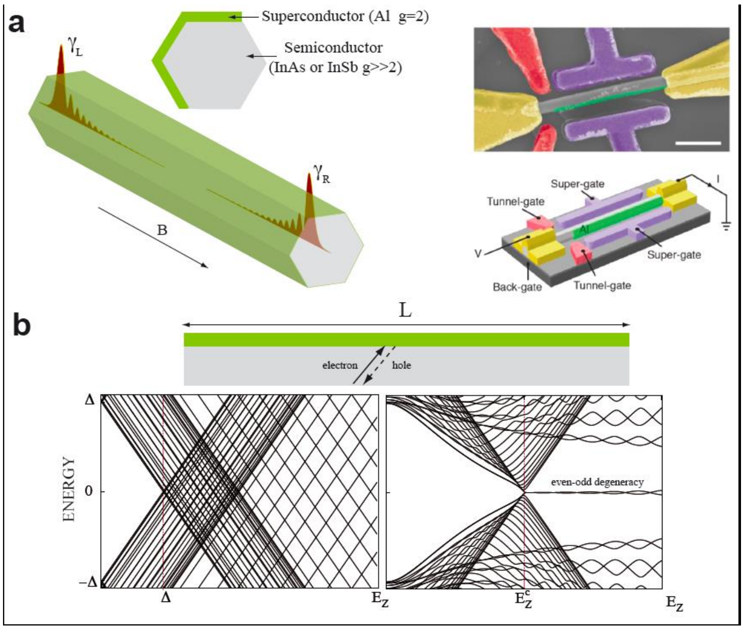

Figure 1. **Majorana Introduction (a)** Majorana nanowires consist out of a semiconducting wire with large spin-orbit interaction (e.g. InAs or InSb) partially covered by a conventional superconductor (e.g. Al). For appropriate electron densities and magnetic fields Majorana zero modes (MZM) appear at the two wire ends. The Majorana wave functions, γ_L and γ_R, decay and have vanishing overlap in the middle of long wires. Right side shows SEM photo and schematic of an elemental device, false colored to illustrate semiconducting nanowire (gray), Al coverage (green), source and drain contacts (yellow), gates to induce a tunnel barrier (red) and gates to tune the electron density (purple). White bar indicates 1 micron. **(b)** Electrons and holes form particle-in-a-box states with one of the walls being the semiconductor-superconductor interface These states are known as Andreev Bound States (ABS) with the symmetry property that electron-like states at energy +*E* have a hole-like partner at -*E*. When increasing the magnetic field, *B,* and thus the Zeeman energy for spin-splitting, $E_Z = g\mu_B B/2$, the superconducting gap, Δ, closes when $E_Z = \Delta$. Two energy spectra are shown. On the left (right) the case without (with) spin-orbit interaction. The spin-orbit interaction causes the gap to re-open, forming a topological superconducting phase with two Majorana mid-gap states very close to zero energy. Figure from Ref. 4.

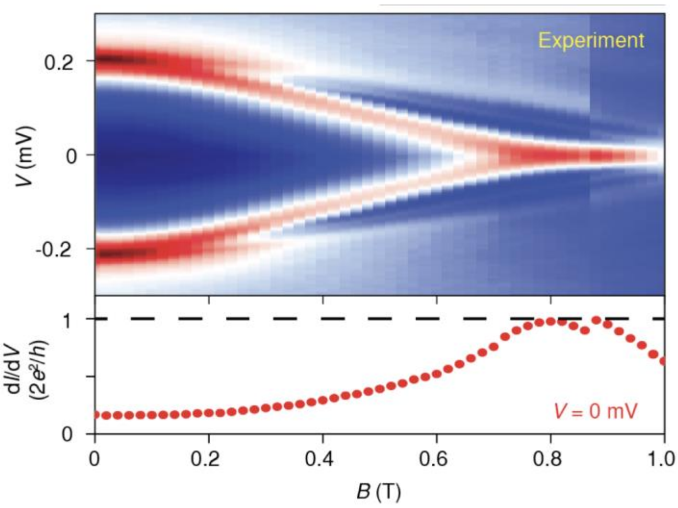

Figure 2. **Quantized Majorana Conductance**. Top panel: differential conductance, d*I*/d*V*, versus source-drain bias voltage, *V*, and magnetic field, *B*. The resonance with red color is electron-hole symmetric and decreases energy when increasing *B* until it reaches zero energy at 0.7 Tesla. Between 0.7 and 0.9 T the conductance resonance stays at zero energy and has a quantized value equal to $2e^2/h$. Bottom panel: line cut at $V = 0$. The quantization at $2e^2/h$ results from particle-equals-antiparticle, the defining symmetry for Majoranas.

Figure from Ref. 2.