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Low Energy States in Hybrid Semiconductor-Superconductor Majorana Devices

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Abstract: First hypothesized by Ettore Majorana in 1937 in the context of particle physics, Majorana fermions are special type of fermions which are their own antiparticles. While no elementary particle has been confirmed as Majorana fermions to date, Majorana zero-energy modes (MZMs), which comprise an equal superposition of electrons and holes, are predicated to emerge as quasiparticles in condensed matter systems. MZMs has generated significant interest recent years, mostly because they are anticipated to obey non-Abelian statistics and thus can be potentially exploited in topological quantum computation. Among various proposals for realizing MZMs, semiconductor nanowires with strong spin-orbit coupling and proximity induced superconductivity is a promising platform. Although several experiments have already reported signature of MZMS in such systems, none of them verified the long-standing prediction that MZMs should emerge in pairs with one on each end of a topological region. And a deterministic claim of MZMs is still an ongoing effort.

In this thesis, we first improved the required ingredients for generating MZMs. By optimizing the nanowire-superconductor interfaces as well as the NbTiN superconducting films, we achieved hard induced gaps and ballistic transport inside InSb nanowires.

With those improvements, in a two-terminal device with one normal lead to probe one end of the nanowire-superconductor hybrid region, we found zero bias conductance peaks (ZBCPs) in agreement with the Majorana theories. We also mapped out a phase diagram of the ZBCPs in magnetic field and chemical potential space. While this data favors the Majorana origin of the ZBCPs, non-Majorana ZBCPs emerge as ubiquitous features in similar devices. Due to the similarities between these two kinds of ZBCPs, we conclude it is impractical to unambiguously prove MZMs in a two-terminal geometry.

In a three-terminal geometry, we gain the ability to probe the two ends of the nanowire-superconductor hybrid region by adding one more normal lead. In simultaneously measurements on both ends, we identified delocalized states near zero field, which emerged with correlated gate dependence on the both ends. While correlation between the ZBCPs on both ends were not established, we demonstrated a robust method to distinguish trivial localized states from MZMs. Future experiments can use this method to identify MZMs. Once MZMs can be deterministically established, braiding experiments in nanowire networks could open the gate to topological quantum computation.

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