Field-controlled Dirac points and the fate of "end" states in broken gap semiconductor nanowires

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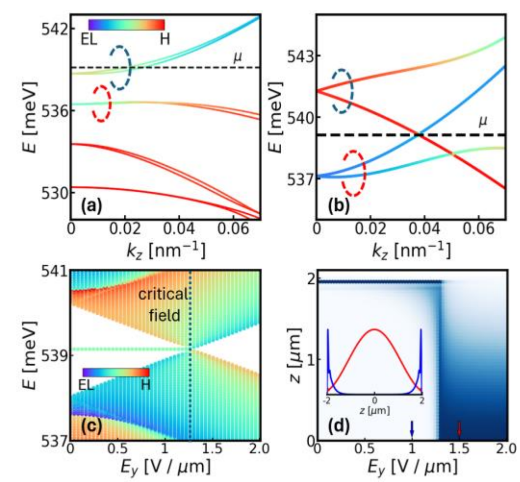
We numerically investigate the hybridization gap in InAs/GaSb core-shell nanowires. In the topological regime the material is known to be gapped by the valence-conduction kinetic interaction [1]. In this contribution we identify an unexpected gap collapse when the nanowire is immersed in a transverse electric field. Then, a semimetal phase develops at two Kramers-related Dirac points between spin-polarized subbands. Vanishing of the hybridization gap, steered by spin-orbit coupling resulting from the removal of inversion symmetry caused by the field, drives the system into the trival insulating phase.

In (a) we show the low-energy gapped bands in a prototype InAs/GaSb nanowire, calculated with an 8-bands $\boldsymbol{k}\cdot\boldsymbol{p}$ approach which also self-consistently includes the charge transfer between inverted valence and conduction subbands [2,3]. When a transverse field is applied [see (b)]: i) large Rashba spin-splitting occurs, and ii) at a specific field the gap collapses between subbands with opposite spin polarization. At the vanishing gap, which here is shown for a case where the chemical potential μ falls exactly at the massless Dirac point, the valence and conduction subbands decouple exactly.



(a) Subbands for a InAs/GaSb nanowire (inner radius 7 nm, shell width 4.88 nm) at zero field. (b) As in (a), with a field $E = 1.29\ V/\mu m$. The conduction (EL) or valence (H) character are calculated from the spinorial character. (c) Energy spectrum for a finite-length nanowire of 4 µm. (d) Localization of "end" states vs field. Inset: blue/red lines are taken below/above the critical field.

A Bernevig-Hughes-Zhang Hamiltonian, projected to a minimal basis to simulate a laterally confined quantum well and refitted to $\boldsymbol{k}\cdot\boldsymbol{p}$ calculations, is used to trace the formation of Dirac points to a compensation between the (almost constant) valence-conduction coupling and the Rashba spin-orbit coupling which is tuned by the electric field via inversion asymmetry.

In the topological phase, time-reversal symmetry and approximate particle-hole symmetry support zero-dimensional states – aka "end" states – at the two extremes of the structure [4], with energy in the middle of the inverted gap, as shown in (c), which reports calculated sates for a finite-length nanowire. Mid-gap "end" states are topological in nature, and they are (nearly) field insensitive and strongly localized, as shown in (d) at low field. At the critical field, however, when the Dirac point becomes massless, "end" states suddenly delocalize, and eventually merge to the valence and conduction bands bulk states, which are now in the normal order, showing that a quantum transition to a trivial state has occurred. Interestingly, the transition happens without altering the sign of the inverted gap at Γ. Symmetry analysis, connection to the quantum spin Hall phase and implications are provided.

References

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