From many valleys to many topological phases — quantum anomalous Hall effect in IV–VI semiconductor quantum wells

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Phenomena belonging to the family of quantum Hall effects play a significant role in modern condensed-matter physics, serving as the source of many new theoretical concepts and driving the development of fields such as metrology, spintronics, energy-efficient electronics, and quantum computation. In those contexts, the quantum anomalous Hall effect (QAHE) occupies a prominent place: the quantization of the Hall conductivity, given by $\sigma_{\mathrm{H}} = \mathcal{C}e^2/h$ (with $\mathcal{C}$ an integer), results from the nontrivial topology of the band structures of 2D crystals with broken time-reversal symmetry, rather than from the formation of Landau levels as in the "conventional" quantum Hall effect. Of particular interest is the prospect of a quantum electrical resistance standard functioning at zero magnetic field, which, in tandem with the Josephson-effect quantum voltage standard, enables a quantum standard for the ampere. To date, thin films of ferromagnetic topological insulator $(\mathrm{TM,Bi,Sb})_2\mathrm{Te}_3$, where $\mathrm{TM} \in \{\mathrm{Cr, V}\}$, or sandwiched between ferromagnetic (Zn,Cr)Te barriers, along with multilayer graphene, are examples of the systems in which the QAHE has been observed but show the quantization accuracy relevant for metrology only at extremely low currents and temperatures below 50 mK [1], presumably, caused by a high defect concentration giving rise to parallel hopping conduction at non-zero source-drain electric fields and temperatures.

Guided by recent progress in the material development [2] and previous qualitative expectations for group IV–VI topological crystalline insulators, we demonstrate, based on band-structure and Chern-number calculations, that $\mathrm{Pb}_{1-x}\mathrm{Sn}_x\mathrm{Se}/(\mathrm{PbSe})_{1-y}(\mathrm{EuS})_y$ quantum wells constitute a promising and viable platform for realizing a variety of QAH phases [3]. Our basis-transformation procedure for the multiband $\boldsymbol{k}\cdot\boldsymbol{p}$ Hamiltonian enables the treatment of wells grown along arbitrary crystallographic directions while explicitly accounting for the anisotropy of the material's isoenergetic surfaces. Numerical studies of $\langle 111\rangle$-, $\langle 110\rangle$- and $\langle 001\rangle$-oriented quantum wells and spin-polarized Eu ions predict attainable Chern numbers with magnitudes ranging from 1 to 4, depending on the quantum well width, Sn content, and the orientation of the projected L valleys.

Crucially, magnetic lead-tin chalcogenides combine a larger dielectric constant and generally lower defect concentrations than bismuth-antimony chalcogenides. These material properties, together with the multivalley band structure (which enables $|\mathcal{C}|$ up to 4), may facilitate accurate Hall-conductivity quantization at higher temperatures and larger currents.

References:

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