

Function follows form: When shape dictates functionality of quantum materials

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Abstract

Symmetry is a core guiding theme in condensed matter research, informing the search for novel materials with unusual response functions. It enforces certain response functions to vanish if they are incompatible with the symmetry of the crystal lattice. For example, centro-symmetry and electronic directionality, such as diode-like behavior, is fundamentally incompatible. While this is rigorously true for bulk response functions, mesoscopic shapes may change the effective symmetry group of the problem, and unlock functionality forbidden by symmetry in the bulk. With recent advances in 3D mesoscopic control of single crystal structures via focused ion beam machining, shape control emerges as a powerful design principle towards electronic functionality in quantum materials.

This principle is applied to 3D microstructures of crystalline bismuth[1], in which strongly quantizing magnetic fields push electric transport currents to the surface – replacing completely the electronic symmetry of its hexagonal unit cell by the designed shape. Shape control uncovers a 3D version of the quantum Hall effect, in which geometric edge currents encircle the device in the quantum limit. In the iron-based superconductor FeSe[2], an inversion symmetric material, strong superconducting diode effects can be designed, tuned and even inverted by shape control over the formation of nematic domains on the mesoscale. Lastly, in CoTa_3S_6 , shape and magnetic field direction are found to conspire to reduce the symmetry[3], allowing an otherwise symmetry forbidden coupling between a nematic and a chiral magnetic order. These cases serve as an example for the emergent paradigm of 3D shape control over electronically active quantum materials.

[1] J. Seo et al., Nat. Phys. 22, 232 (2026); [2] R.D.H. Hinlopen et al., arXiv:2604.26631; [3] Y. Hu et al., arXiv:2603.12072

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