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限域插层调控范德华层状材料的超导性及涌现量子物态

摘要

我们以过渡金属硫族化合物为研究体系，聚焦层间限域客体插层对其磁电物性的精准调控，系统探索原子排布、能带结构及有机-无机客体空间构型的协同调控机制。围绕决定磁电性能的核心自由度—电荷、自旋、轨道与晶格，通过对客体种类、构型、分布及浓度的原子级调控，诱导出伊辛超导、量子相变等新奇物性。结合原子分辨的结构与电子态表征手段，建立起"结构-物性"定量关联，并揭示了器件界面电子态调制的微观机制。例如，通过有机/无机分子或离子限域插层，有效解耦范德华层间，使块体展现出单层结构特有的伊辛超导物性；首次在钽-硫基材料体系中观察到量子格里菲斯奇异性；衍生铁磁序和超导态共存；潜在拓扑超导体的发现等。

关键词

量子材料；超晶格；伊辛超导；拓扑超导

Abstract

This study employs transition metal chalcogenides as a research platform to precisely modulate their magnetoelectric properties via interlayer-confined guest intercalation. We systematically investigate the synergistic regulation mechanisms governing the atomic arrangement, band structure, and spatial configuration of organic–inorganic guests. By targeting the core degrees of freedom that control magnetoelectric performance—charge, spin, orbital, and lattice—we implement atomic-scale control over guest species, configuration, distribution, and concentration to induce emergent physical phenomena such as Ising superconductivity and quantum phase transitions. Combined with atomic-resolved structural and electronic characterization techniques, we establish quantitative structure–property relationships and elucidate the microscopic mechanisms underlying interfacial electronic state modulation in devices. For instance, confined intercalation of organic/inorganic molecules or ions effectively decouples van der Waals interlayer interactions, enabling bulk crystals to exhibit Ising superconducting behavior characteristic of monolayer structures. The quantum Griffiths singularity is observed for the first time in tantalum–sulfur-based materials. The coexistence of emergent ferromagnetic order and superconductivity is realized, and topological superconductor candidates are identified in these systems.

Keywords

Quantum materials; Superlattice; Ising superconductivity; Topological superconductivity

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