

Engineering electronic properties of 2D quantum materials in artificial and hybrid heterostructures

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Abstract

Two-dimensional quantum materials and forming heterostructures provide a facile route to manipulate their synergetic electronic states at the heterointerface, which have no counterpart in bulk systems. In this presentation, I will first introduce a brief overview of how 2D heterostructures can be realized by three strategies: (i) exfoliation and stacking of 2D materials, (ii) 2D quantum confinement in artificial oxide superlattices, and (iii) direct growth of 2D materials on suitable substrates. As an example of strategy (i), interfacial charge transfer and proximity effects can electrically modulate the quantum Hall effect in hybrid heterostructures [1]. In case of strategy (ii), 2D confinement enhances thermopower in artificial transition-metal oxide superlattices [2]. Recently, I have moved toward strategy (iii), directly growing 2D materials and probing their synergetic properties.

In the second part of the presentation, I will introduce monolayer FeSe as a model system of a 2D high-temperature superconductor. We grew high-quality monolayer FeSe films on Nb-doped SrTiO₃ substrates using molecular beam epitaxy and characterized their atomic-scale structure and superconducting properties via scanning tunneling microscopy and spectroscopy (STM/S). Atomic-resolution images confirmed the high crystallinity of the films, and high-resolution STS at 0.3 K, combined with correlation-based analysis of spatially resolved spectra, reveals hidden features within a superconducting gap. We further employed tunneling Andreev reflection measurements to investigate the superconducting order parameter. By acquiring spatially resolved STS spectra as a function of tip height z , we extracted the normalized tunneling decay constant κ/κ_0 which reveals nontrivial quasiparticle tunneling characteristics in the superconducting state. This highly sensitive probe of superconducting gap symmetry provides direct insight into the mechanism of unconventional superconductivity, offering quantitative constraints for theoretical models and enabling the identification of possible pairing scenarios in monolayer FeSe.

[1] D. Shin et al., *Adv. Funct. Mater.* **34**, 2311287 (2024).

[2] D. Shin *et al.*, arXiv:2512.05664 [cond-mat.mtrl-sci] (2025).