Long-distance remote epitaxy

Jian Shi (Rensselaer Polytechnic Institute)

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[Ques] Remote epitaxy, in which an epitaxial relation is established between a film and a substrate through remote interactions, enables the development of high-quality single crystalline epilayers and their transfer to and integration with other technologically crucial substates1,2. It is commonly believed that in remote epitaxy, the distance within which the remote interaction can play a leading part in the epitaxial process is less than 1 nm, as the atomically resolved fluctuating electric potential decays very rapidly to a negligible value after a few atomic distances.

[关键问题] 远程外延中，作者如何突破传统认知，实现跨越数纳米的长距离晶格耦合？

[拓展背景]远程外延、剥离 freestanding

[Sum] Here we show that it is possible to achieve remote epitaxy when the epilayer–substrate distance is as large as 2–7 nm. We experimentally demonstrate long-distance remote epitaxy of CsPbBr3 film on an NaCl substrate, KCl film on a KCl substrate and ZnO microrods on GaN, and show that a dislocation in the GaN substrate exists immediately below every remotely epitaxial ZnO microrod.

[亮点 1] 实验首次实验证明远程外延可在 2–7 nm 范围内实现，突破传统“<1 nm”的限制。

[亮点 2] 发现位错可在衬底下方增强远程相互作用，揭示外延距离延伸的关键物理机制。

[思考] 远程外延的长距离实现提示电场或应变场可能在晶格匹配之外发挥重要作用。未来可探索通过外加电场或界面工程进一步延伸外延距离，甚至实现跨材料体系的异质外延。

[拓展阅读 1] 远程外延与直接外延，在晶体质量上有区别吗？远程外延的薄膜尺寸受否会受到晶界和位错的限制？

[拓展阅读 1] 远程外延与直接外延在晶体质量上的差异主要体现在界面相互作用的强度与可控性。直接外延要求原子级晶格匹配，界面应力与缺陷密度直接决定薄膜质量。而远程外延通过中间层（如二维材料或真空间隙）实现电势耦合，削弱化学键约束，使得薄膜更易于剥离、转移，并兼顾高结晶性。尽管远程外延的晶体质量通常略低于直接外延，但其可复用性与异质集成潜力极大，为柔性电子器件和多功能异质结构提供了新路径。

[拓展阅读 2]为什么引入位错可以延长外延层-衬底相互作用的长度尺度？

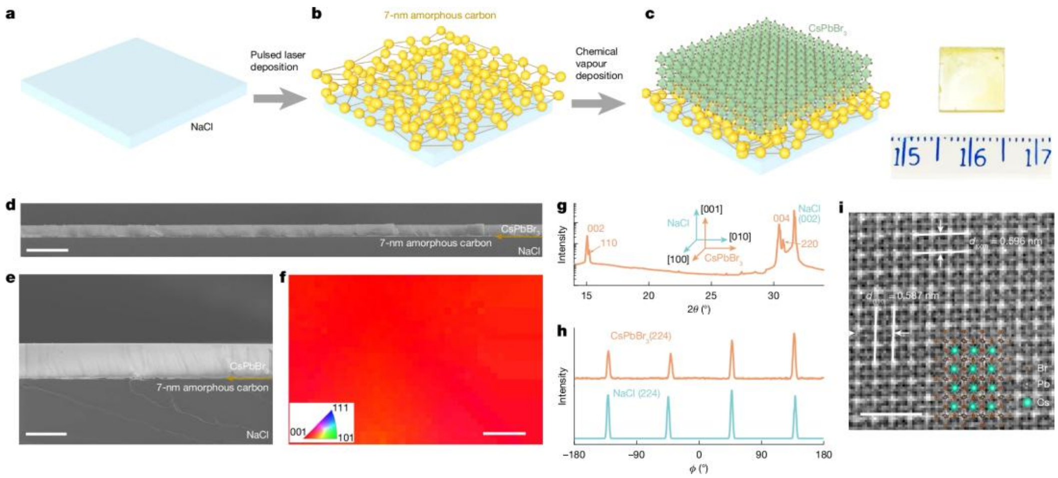
[拓展阅读 2] 位错能够延长外延层–衬底相互作用的长度尺度，原因在于其产生的局部电场与应变场可增强长程库仑相互作用。位错核心的电势扰动会穿透中间隔层，形成类似“电信号桥”的作用，使得原本快速衰减的远程势场在更远距离仍具影响力。此外，位错引入的弹性能量梯度也能诱导局部极化，进一步增强外延取向的有序性。这一机制为设计“可控缺陷辅助外延”提供了新思路。

[Introduction]

Flexoelectricity refers to the electromechanical coupling between electrical polarization and inhomogeneous deformations, such as strain gradients, in dielectric materials of any symmetry. The flexoelectric electric field generated by the strain gradient has the ability to modify and control various characteristics of materials, including defect distribution, barrier height, and photoelectric response, etc. This flexoelectric field can act independently or in combination with other built-in electric fields. However, due to the typically small intrinsic flexoelectric coefficients, substantial flexoelectric responses require large deformations. As a result, the most pronounced manifestations of flexoelectricity are often observed at the nanoscale, where achieving large gradients is more feasible. Consequently, researchers have increasingly utilized two-dimensional nanofilms or one-dimensional nanowires to investigate flexoelectricity and its associated applications. Nevertheless, the introduction of abundant and tunable strain gradients in nanofilms or nanowires remains a challenging endeavor.

For thin films, the mainstream approach to introduce strain gradient is through the strain relaxation during epitaxial growth. For example, in the traditional planar thin film structure, the vertical strain gradient can be achieved through substrate-induced lattice mismatch, composition gradient and defect doping. Tip induction is another widely used in thin films as a simple and efficient means to apply strain gradient to samples. By using an atomic force microscope (AFM) tip or tip arrays to squeeze the surface of the sample, a very large strain gradient (106–107m−1) can be formed near the elastic deformation contact zone below the tip. Despite their high sensitivity in producing large strain gradient, these methods mentioned above do have certain limitations. Firstly, the strain gradient is highly localized, mainly concentrated at the interface, defect sites, or within a very small area beneath the tip. Secondly, the film thickness is required to be on the order of tens of nanometers to avoid irreversible damage caused by the tip. Finally, the film is clamped by a rigid substrate, which limits the transfer, integration, and flexible applications of electronic devices in many cases. In order to broaden the application of strain gradient in perovskite films, researchers have shifted their attention to flexible self-supporting films and made many attempts by using the sacrifice-layer method, such as a self-supporting membrane drum, wrinkles, etc., which provided a basis for our experiments.

In order to obtain large-area and tunable strain gradient without causing damage, we propose here to prepared one-dimensional wrinkled single-crystalline thin films with controllable structures. Since strain gradient is inversely proportional to the curvature, it can be predicted that the peaks and troughs of the wrinkled free-standing film will produce a large strain gradient due to the small curvature , which we refer to as microbending (bending on a scale of a few micrometers or even smaller). Recently, an electromechanical coupling model was developed to theoretically deal with the flexoelectricity in wrinkled thin films by Liang et al. . Large-area and tunable strain gradients can be introduced by inhomogeneous deformation in wrinkled thin films subjected to in-plane compression. The microbending process, as described in this study, involved the transfer of a free-standing oxide thin film onto a prestrained flexible substrate. The results demonstrate that precise control over the structure of wrinkles and the size of strain gradient can be achieved by adjusting either the film thickness or the prestrain applied to the substrate. Furthermore, it has been shown that strain gradient enables tuning of the conductivity in wrinkled films.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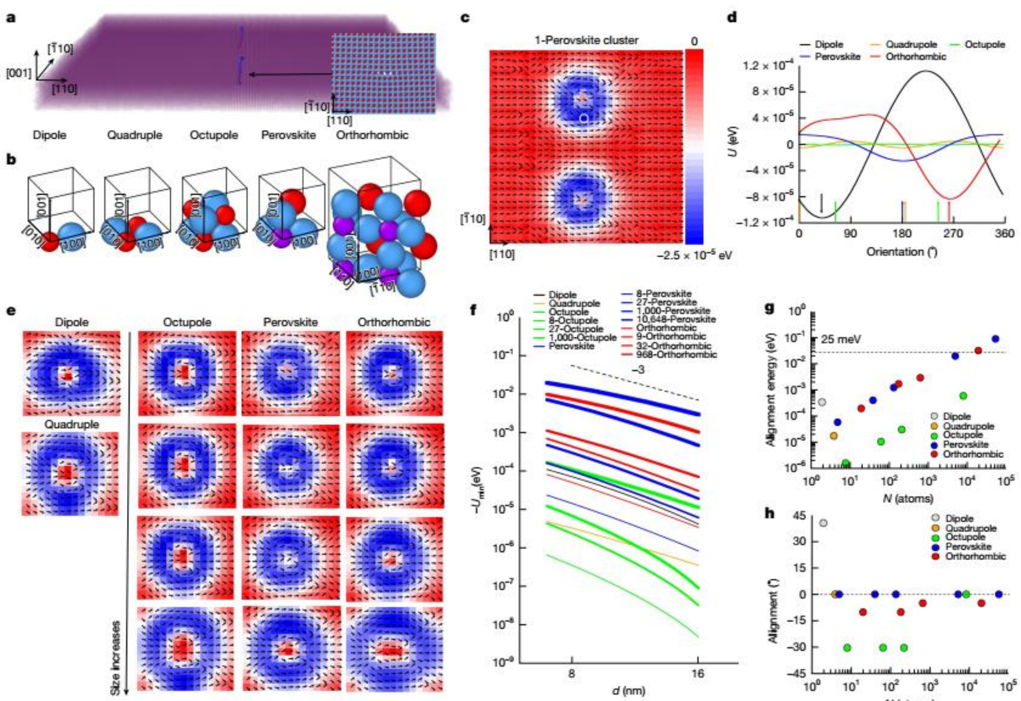
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Alignment energy (eV)
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N (atoms)

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Spin-Orbital Altermagnetism

Lun-Hui Hu (Zhejiang Univ)

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[Ques] Altermagnetism is a newly discovered magnetic phase, characterized by nonrelativistic spin splitting that has been experimentally observed.

[关键问题] 如何在无自旋轨道耦合条件下实现自旋与轨道的耦合分裂现象？

[拓展背景] 自旋轨道交磁

[Sum] Here, we introduce a framework dubbed “spin-orbital altermagnetism” to achieve spin-orbital textures in altermagnetic materials. We identify two distinct classes of spin-orbital altermagnetism: intrinsic and extrinsic. The intrinsic type emerges from symmetry-compensated magnetic orders with spontaneously broken parity-time symmetry, while the extrinsic type stems from translational symmetry breaking between sublattices, as exemplified by the Jahn-Teller-driven structural phase transition. In addition to directly measuring the spin-orbital texture, we propose spin conductivity and spin-resolved orbital polarization as effective methods for detecting these altermagnets. Additionally, a symmetry-breaking mechanism induces weak spin magnetization, further revealing the peculiar feature of spin-orbital altermagnetism. We also utilize the staggered susceptibility to illustrate a potential realization of this phase in a two-orbital interacting system.

[亮点 1] 提出“自旋轨道交磁”新框架，揭示无需自旋轨道耦合即可形成自旋–轨道纠缠纹理的可能性。

[亮点 2] 区分内禀与外禀两类交磁机制，并提出可通过自旋电导率与轨道极化观测该相的新实验手段。

[思考] 自旋轨道交磁为探索非相对论自旋物理开辟新方向。未来可尝试在二维材料或过渡金属化合物中，通过应变或电场调控晶格对称性，诱导不同类型的交磁态，从而实现可控的自旋–轨道逻辑功能。

[拓展阅读 1] 自旋轨道交磁与普通交磁有本质区别吗？

[拓展阅读 1] 自旋轨道交磁与普通交磁的区别在于前者涉及自旋与轨道自由度的协同调制。普通交磁仅通过晶格对称性导致自旋反向排列，不涉及轨道参与；而自旋轨道交磁通过磁序与晶格畸变的协同破缺，使自旋方向与轨道分布发生锁定，形成复杂的自旋–轨道纹理。这种锁定可在无自旋轨道耦合情况下产生有效的“非相对论自旋分裂”，从而在能带结构中呈现出奇异的对称性破缺特征，为新型自旋电子材料提供理论支撑。

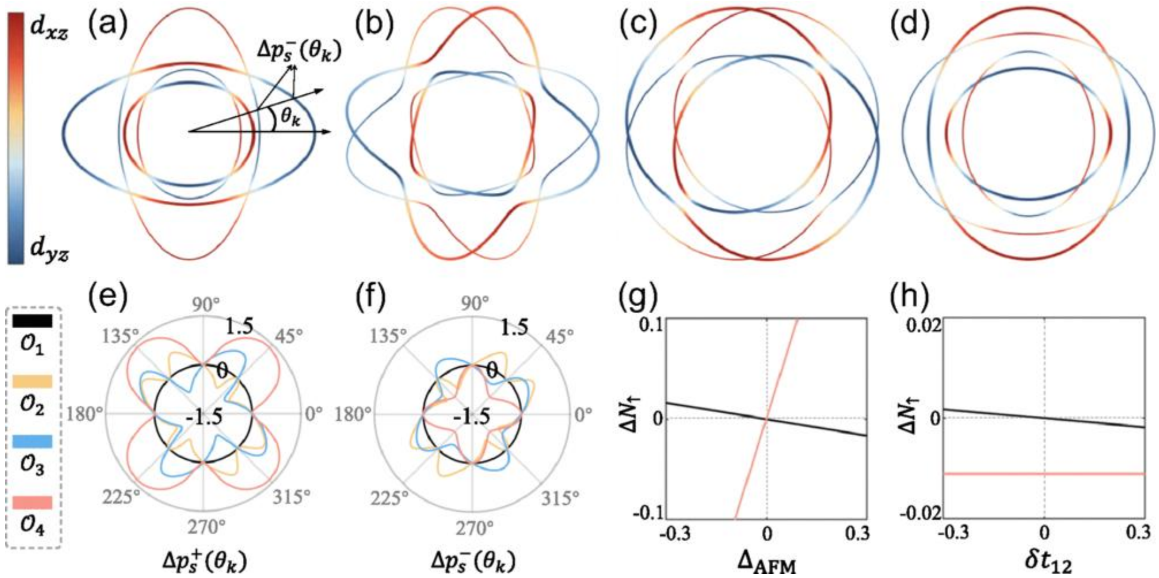
[拓展阅读 2] 自旋电导率和自旋分辨轨道极化在实验上如何表征？

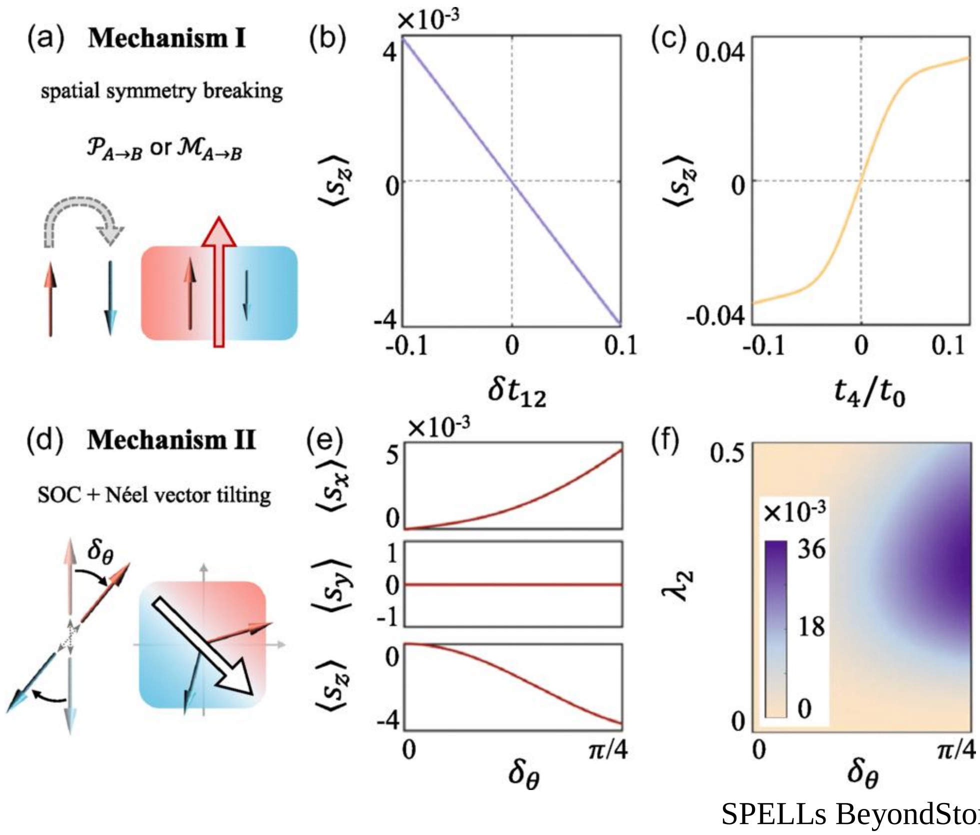
[拓展阅读 2] 自旋电导率与自旋分辨轨道极化是实验检测自旋轨道交磁的重要手段。前者可通过自旋霍尔测量或非局域自旋输运实验获取，反映自旋流响应外场的能力；后者则可借助角分辨光电子能谱（ARPES）结合光子极化分辨技术，实现能带层面的自旋–轨道纹理成像。近年来，利用自旋分辨 ARPES 与 X 射线磁圆二色性（XMCD）技术，人们已在多种材料中观测到自旋轨道分裂的直接证据。这些实验手段将成为验证自旋轨道交磁理论的重要工具。[Introduction]

Spin and orbit are two fundamental degrees of freedom of electrons, and their intertwining is crucial for understanding various electronic states and phenomena in quantum materials. Spin-orbit coupling (SOC), a relativistic effect in solids, couples these degrees of freedom, lifting the Kramers spin degeneracy and resulting in spin-split energy bands with distinctive spin textures in reciprocal space. Recent experiments using spin-resolved and photon-polarized angle-resolved photoemission spectroscopy have revealed entangled spin-orbital textures—a locking phenomenon between spin and atomic orbital degrees of freedom—in strongly spin-orbit coupled systems such as topological insulators. This breakthrough opens novel avenues for manipulating spin polarization by targeting the orbital domain.

Nonrelativistic mechanisms for spin-splitting effects have also garnered significant attention in recent years. These SOC-free phenomena have become prominent after the discovery of altermagnetism (AM), which is a new magnetic phase characterized by momentum-dependent spin splitting despite zero net magnetization. Subsequent experimental studies have confirmed AM-induced spin-splitting bands in diverse materials. A few earlier theoretical works for nonrelativistic spin splitting were established through spin-channel Pomeranchuk instabilities and d-wave spin-density wave states. Furthermore, noncoplanar antiferromagnetic materials also exhibit significant nonrelativistic spin-split bands. These novel magnetic systems can exhibit intriguing properties and potential functionalities.

Although distinct mechanisms for altermagnets have been proposed recently, other spin-related nonrelativistic phenomena, particularly the physics of spin-orbital textures without SOC, remain largely unexplored. This can be achieved through intertwined symmetry-compensated magnetic orders that couple these two degrees of freedom. Here, we establish a new theoretical framework to attain nonrelativistic spin-orbital textures through altermagnetic orders, dubbed “spin-orbit altermagnetism.” Among various altermagnetic orders permitted by spin-space symmetry, we identify two distinct classes of spin-orbital altermagnetism: one arising intrinsically and the other necessitating crystalline symmetry breaking due to structural phase transitions. We demonstrate that the spin conductivity and spin-resolved orbital polarization are effective tools for detecting and distinguishing between these phases. We also examine the weak ferromagnetic magnetization caused by symmetry breaking, relevant to the hysteresis loop observed in the anomalous Hall effect. Furthermore, the staggered susceptibility is employed to illustrate a potential realization of such a phase in two-orbital interacting systems.





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