High-temperature superconductivity in monolayer $Bi_2Sr_2CaCu_2O_{8+\delta}$

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[Ques] Does the essential physics of high-temperature superconductivity reside entirely within the two-dimensional limit? Specifically, can a single atomic layer of a copper-oxide material still sustain superconductivity identical to that of its bulk counterpart?

[关键问题]：高温超导的核心物理是否完全存在于单层极限中，即一个单原子层的铜氧化物是否仍能保持与块体相同的超导性？

[Sum] This study demonstrates that an isolated monolayer of the cuprate superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi-2212) retains all essential high-temperature superconducting properties of the bulk, defying expectations that superconductivity should be strongly suppressed in two dimensions. Through careful fabrication under cold, inert conditions, the authors obtain pristine monolayers whose doping can be continuously tuned *in situ*, revealing a full superconducting dome, a pseudogap regime, charge order, and the Mott insulating state—all nearly identical to their bulk counterparts. STM/STS and quasiparticle interference measurements show that the monolayer preserves the same atomic structure, superconducting gap magnitude, d-wave gap dispersion, pseudogap energy scale, nanoscale electronic inhomogeneity, and $4a_0$ charge-order wavevector. Even in the extremely underdoped regime, the evolution from Mott insulator to pseudogap mirrors bulk behavior. The optimal Tc of the monolayer matches that of bulk Bi-2212, proving that high-Tc cuprate superconductivity is intrinsically two-dimensional and establishing monolayer cuprates as an ideal platform for studying strongly correlated 2D quantum phenomena.

[亮点 1] 单原子层依然保持与块体几乎相同的高温超导特性

[亮点 2] 采用 低温惰性环境剥离 成功获得结构完整的单层 Bi-2212, 通过 原位吸附分子（如臭氧）调控掺杂，实现对单层从“极度欠掺杂 → 最优掺杂 → 过掺杂”的连续调节

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[思考 1] 如果单层 CuO_2 就能保留所有高温超导特性，那 bulk 中的多层结构究竟起到什么作用？

[思考 2] 为什么单层能够展现 “完整相图”：莫特 → 赝能隙 → 超导？是否意味着 cuprate 的强关联本质根本不依赖三维结构？

[拓展阅读 1] 拓扑缺陷是系统中局域的“特殊结构”，其性质无法通过连续变形消除，具有拓扑保护。涡旋在二维超导或 XY 模型中，自旋或相位沿闭合路径旋转 $+2\pi$ 的点。 反涡旋旋转方向相反，即沿闭合路径旋转 -2π。 其他系统中还有磁单极、缺陷线、边界态等。拓扑相变是由拓扑性质的改变引起的相变，而不是传统的对称性破缺。 系统的局域结构或对称性可能保持不变，但拓扑缺陷的行为发生变化。宏观物理性质（如关联函数衰减方式、相干性、导电性等）会突变。

[拓展阅读 2]BKT 转变是二维系统中特有的一种拓扑相变：在低温下，系统中的涡旋和反涡旋成对存在，使系统保持准长程有序，物理量随距离呈幂律衰减；当温度升高超过临界点时，这些涡旋对解开，涡旋自由出现，导致系统相干性迅速丧失，关联函数呈指数衰减。这种转变没有传统的对称破缺，而是由拓扑缺陷驱动，因此被称为拓扑相变。BKT 转变是由拓扑缺陷（vortex）驱动的相变，而不是传统的对称破缺。BKT 转变是一种二维系统中，由涡旋-反涡旋解绑定引起的拓扑相变，低温时系统呈幂律衰减的准长程有序，高温时涡旋自由导致相干性丧失。

[拓展阅读 3] 单层 CuO_2 的制备首先从双层铜氧化物 $Bi_2Sr_2CaCu_2O_{8+\delta}$（Bi-2212）块体晶体出发，在低温惰性气氛（如氮气或氩气 glovebox）下通过机械剥离方法，将块体的顶层分离，得到原子级厚度的 BiO-CuO_2-BiO 三明治结构，然后将剥离得到的单层原位转移至导电衬底上，如掺杂 Si 或金属薄膜，同时保持超高真空环境以防表面污染或氧缺陷；随后对单层进行轻微退火处理以去除残留有机物，并可通过氧化还原或电化学方法对载流子浓度进行原位调控，从而获得从 Mott 绝缘态到最优掺杂的完整电子相图。

[Introduction]

In systems with reduced dimensions, long-range order (superconductivity in particular) is strongly suppressed1,2, as in the case of conventional Bardeen–Cooper–Schrieffer-type superconductors3,4, and yet all high-temperature copper oxide superconductors have a

layered structure with varying degrees of anisotropy. This apparent dichotomy may be the key to high-temperature superconductivity (HTS)5–9, and it raises the question of whether HTS and various correlated phenomena associated with it are different in two dimensions. This question is important for two reasons. First, most HTS theories are based on purely two-dimensional (2D) models10–12, whereas experiments show that supercurrent phase coherence13, charge ordering14,15 and charge dynamics16 all have a 3D nature17. Second, much of what we know about HTS came from experimental tools such as scanning tunnelling microscopy/spectroscopy (STM/STS) and angle-resolved photoemission spectroscopy (ARPES) that probe the surface of the materials18–36; HTS as a bulk property was inferred from the surface measurements. The bulk–surface correspondence becomes ideal if the HTS is truly 2D. To resolve these issues experimentally, an isolated monolayer hightemperature superconductor is needed. Such an atomically thin crystal would represent an ideal correlated 2D system for exploring quantum phenomena in reduced dimensions. Monolayer HTS has previously been studied mostly in epitaxial oxide heterostructures37–39, where the active layers are buried between interfaces. Such systems are not accessible to spectroscopic tools such as STM/STS and ARPES. In recent years, an alternative, top-down approach has emerged: it has become possible to mechanically exfoliate monolayer atomic crystals (termed ‘2D materials’) from the layered bulk40,41. High-quality 2D materials ranging from insulators to metals and superconductors42 have been produced this way. Experimentally extracting monolayers from bulk high-temperature superconductors, however, turned out to be extremely challenging. Although many of the bulk high-temperature superconductors are considered stable under ambient conditions, they are highly prone to chemical degradation when thinned to monolayers. Indeed, monolayer Bi-2212 has been found to be insulating41,43 or superconducting with a much reduced transition temperature (Tc)44. The suppression is seemingly consistent with increased fluctuations expected in 2D superconductors. But given that the material is extremely sensitive to environment and to doping variations, all extrinsic factors must be eliminated before ascribing the reduction of Tc in monolayers to the effect of dimensionality. The outstanding challenge has been to fabricate high-quality monolayer crystals and probe their intrinsic electronic structure. Here we overcome these challenges by developing sample fabrication processes that preserve the intrinsic properties of monolayer Bi-2212. We first pinpoint two main causes of sample degradation—reaction with water vapour

and rapid loss of oxygen dopant. We find that the degradation slows down in a cold, inert environment, in which pristine monolayer Bi-2212 can be obtained. Unlike the bulk crystal, the monolayer Bi-2212 is extremely tunable: we can continuously vary its doping level insitu and map out major phases from the over-doped regime to the Mott insulating regime, in a single monolayer device. We find that the highest Tc of the monolayer is as high as that of optimally doped bulk. Moreover, STM/STS study reveals that the monolayer develops the same rich set of phases—HTS, pseudogap, charge order and Mott insulating phase, in particular—that were observed on the bulk surface. Detailed characterization of the phases reveals that they are indistinguishable from those in the bulk. A monolayer, therefore, contains all the essential physics of Bi-2212: that is, HTS in Bi-2212 is esse

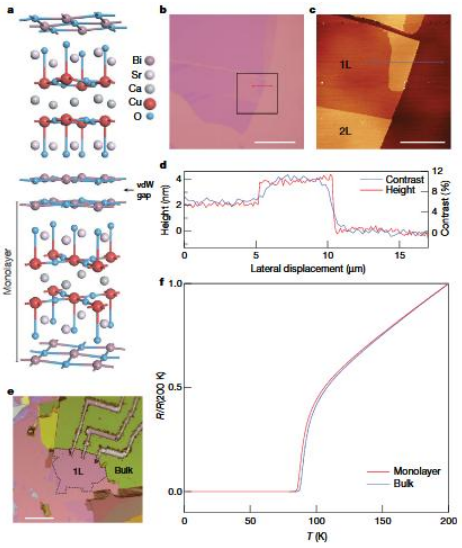

Fig. 1 | Fabrication and characterization of atomically thin Bi-2212 transport devices.ntially a 2D phenomenon.

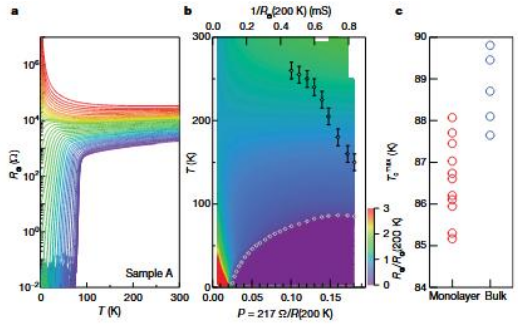

Fig. 2 | Tunable high-temperature superconductivity in monolayer Bi-2212.

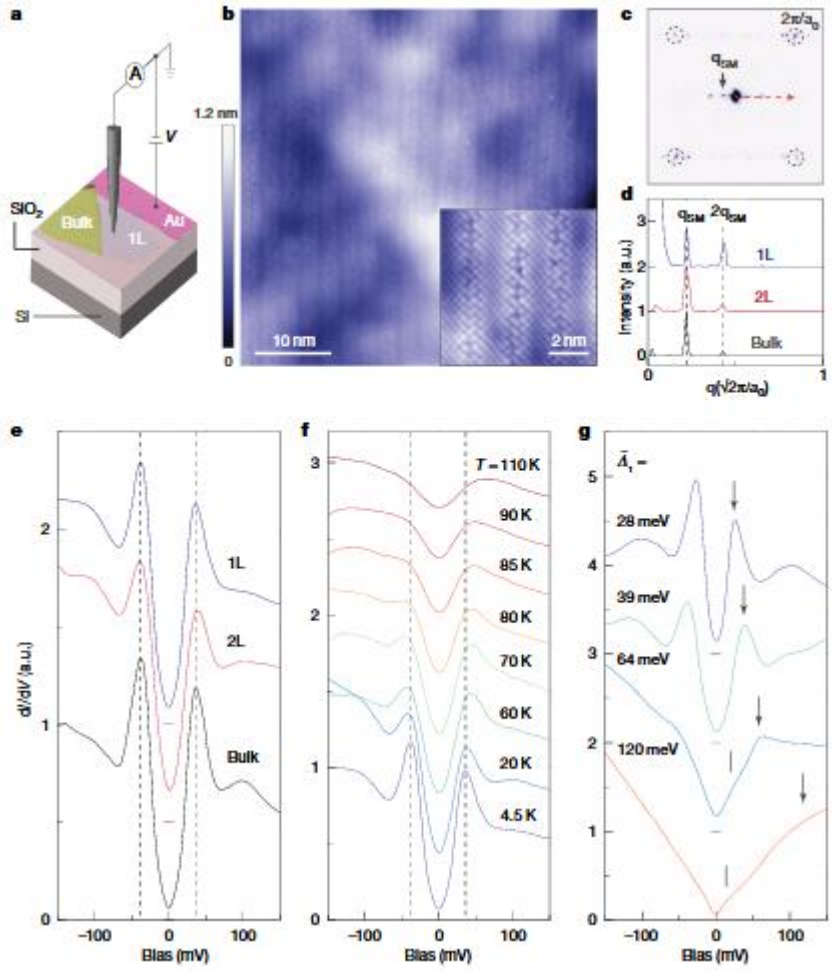

Fig. 3 | Tunnelling spectroscopy of monolayer Bi-2212.

Pure spin current polarizer enabled by antiferromagnetic insulator

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[Ques] This work demonstrates a highly efficient pure spin current polarizer at room temperature using a single-domain antiferromagnetic $LaFeO_3$ film, which controls both the transmittance and spin polarization of magnon currents, aligning the output polarization with the Néel vector.

[关键问题] 该研究利用单畴反铁磁 $LaFeO_3$ 在室温下构建了能同时调控磁子电流透射率与自旋极化方向的纯自旋电流偏振器，使输出极化与奈尔矢量严格对齐。

[Sum] This work establishes a functional pure spin current polarizer using single-domain LFO, enabling unprecedented control over spin current polarization and opening new avenues for energy-efficient spintronic devices.

[亮点 1] 该研究首次在室温条件下实现了功能完备的纯自旋电流偏振器，可同步控制自旋电流的透射率与极化方向，为反铁磁自旋电子学提供了关键器件基础。

[亮点 2] 发现透射自旋电流的极化方向与 LFO 的奈尔矢量自然对齐，并由此在 Pt 中产生了传统对称性禁阻的面外阻尼型转矩，揭示了反铁磁控制自旋极化的新机制。

[思考] 基于单畴反铁磁绝缘体的自旋偏振调控能否与多铁性材料（如 $BiFeO_3$）耦合，通过电场实现对自旋极化的动态、低功耗调制？此外，所生成的面外极化自旋流在垂直磁化翻转中的效率如何，是否具备在 MRAM 中实现无外场写入的潜力？

[拓展阅读 1] 反铁磁自旋偏振器的材料普适性与设计准则

[拓展阅读 1] 本文依靠斜切衬底外延得到单畴 LFO，但这一策略是否具有材料普适性仍是开放问题。不同反铁磁绝缘体（如 NiO、CoO、α-Fe_2O_3）在磁各向异性、畴结构、磁子寿命与界面耦合方面差异显著，单畴形成的条件也可能截然不同。未来研究需系统评估衬底晶格常数、失配率、热退火路径、外加应变等因素对单畴稳

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定性的影响，并建立“材料参数—偏振器性能”之间的量化模型，如偏振度、插入损耗、自旋传输长度等，为器件级材料筛选提供可操作的设计准则。

[拓展阅读 2] 面向自旋电流处理的偏振器集成与电路架构

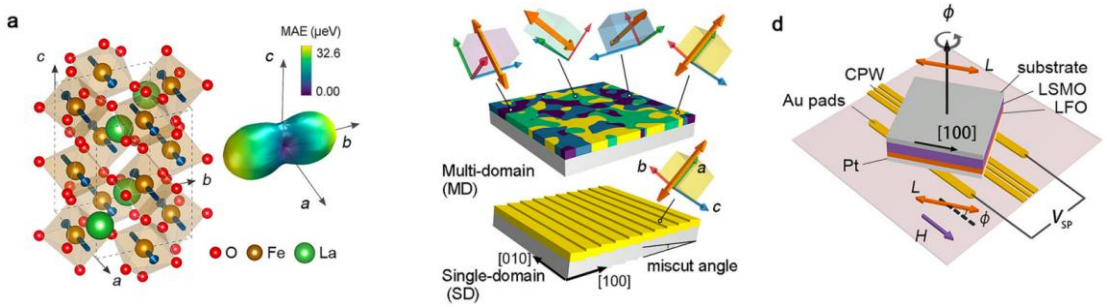
[拓展阅读 2] 自旋偏振器在功能上类似于光子学中的偏振器，可作为自旋信息处理系统的基础单元。未来可构建多级自旋逻辑，实现对自旋电流的选择、旋转与调制；还可与自旋波导、自旋隔离器、自旋调制器集成，发展类光子学的“自旋电路”。在计算架构方面，自旋极化可作为神经网络节点的内部自由度，实现概率计算、超低功耗互连与类脑处理。要实现这些愿景，则需材料科学、微波工程与 IC 设计的深度结合，包括低损耗自旋波导设计、可编程自旋极化控制、以及多层集成的版图策略等跨学科问题。

[introduction] Spin-polarized electrons, enabled by the manipulation of electron spin polarization using ferromagnetic or antiferromagnetic metals1,2,3,4, have been essential for the development of the commercialized magnetic random-access memory (MRAM)5,6. Recently, spintronics has evolved from exploiting spin-polarized current to pure spin current, which can more efficiently deliver spin angular momentum with a minimal or no charge carriers. This approach can minimize energy consumption due to Joule heating, a major limitation in conventional electron-based devices7,8,9. A critical aspect of advancing spintronics is mastering the control of both amplitude and spin polarization vector of the pure spin current10,11. This can be realized by developing a pure spin current polarizer as schematically shown in Fig. 1a, which selectively transmits pure spin current with a specific spin polarization, analogous to the role of optical polarizers in modulating light and spin filters in polarizing conduction electrons1,2,3,4. However, a fully functional polarizer for pure spin current that operates effectively at room temperature has not yet been demonstrated.

To develop a pure spin current polarizer, the ideal candidate materials should be insulating, exhibit polarization-dependent transmittance, remain stable against injected pure spin current, and integrate effectively between spin-current source and drain layers in spintronic devices. Identifying materials that meet all the criteria is challenging, but antiferromagnetic insulator films provide a promising platform based on collective excitations of spins known as magnons. In principle, the precession of Néel vector in collinear antiferromagnetic insulators, excited by injected spin current, can produce a

dynamic magnetization that transport magnon current with spin polarization aligned to the Néel vector12,13. Therefore, the single-domain antiferromagnetic insulator with a well-defined Néel vector can potentially serve as an efficient polarizer (Fig. 1b). Notably, the capability to control both transmissivity and spin polarization would largely deteriorate when domains with different Néel vectors are present (Fig. 1c). Recent studies have shown the magnon transport in antiferromagnetic oxides such as NiO, Cr_2O_3 and $Fe_2O_3$14,15,16,17,18,19,20,21,22,23. However, the control over the spin polarization vector of transmitted spin current and its effect on the spin-orbit torque have not yet been explicitly demonstrated, hindered by the challenges in achieving single-domain state at room temperature in these binary-oxide films. Complex oxides, as exemplified by the perovskites with chemical formula ABO_3, provide a promising solution to address the above challenge due to the rich structural variation and strong spin-lattice coupling24. The single-domain antiferromagnetic state can potentially be achieved at room temperature and zero magnetic field via fine-tuning the crystalline symmetry, making them suitable for demonstrating the highly efficient pure spin current polarizer.

Herein, we demonstrate a fully functional pure spin current polarizer by exploiting the strong correlation between the Néel order and the orthorhombic crystalline structure in $LaFeO_3$ (LFO) thin films, a model antiferromagnetic complex oxide. By tailoring the structural symmetry to lift the energy degeneracy of different domains, a single-domain antiferromagnetic LFO thin film with a well-defined Néel vector is realized. This design achieves a large magnon transmissivity difference at room temperature, depending strongly on the Néel vector of LFO, in the $La_{0.7}Sr_{0.3}MnO_3$ (LSMO)/LFO/Pt heterostructure. Through angular dependent spin Seebeck measurements, we explicitly demonstrate that the spin polarization of magnon current transmitted through LFO aligns with the Néel vector, unequivocally validating the polarizing effect. In contrast, the control over both transmissivity and spin polarization largely diminish in the multi-domain LFO, strongly supporting our design strategy. Furthermore, we show that this polarizer enables a large modulation of damping-like torques and emergence of out-of-plane torques, typical prohibited by symmetry using conventional spin source such as Pt. Our results represent a significant advancement in manipulation of pure spin current by leveraging the unique properties of crystalline antiferromagnetic oxides.



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