低维材料中的新结构与物性的探寻之路

陈 辉

2025年12月21日

中科院物理研究所

报告提纲

一、新型低维材料构筑与物性调控

二、STM的表面原子操纵技术

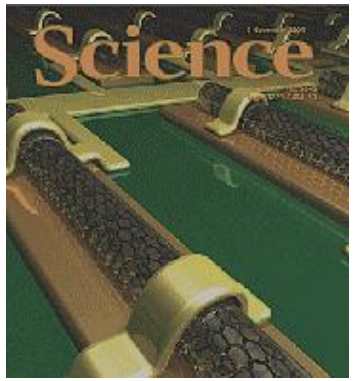
三、发展原子操纵实现新型低维结构与物性调控

四、总结与展望

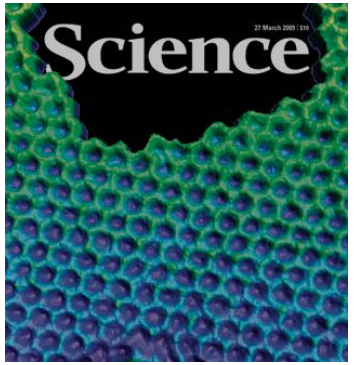
低维材料构筑及其物性：背景情况

零维量子点

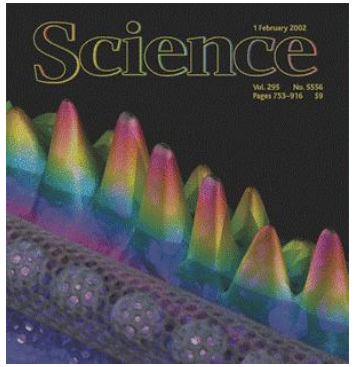
一维纳米线



二维层状材料

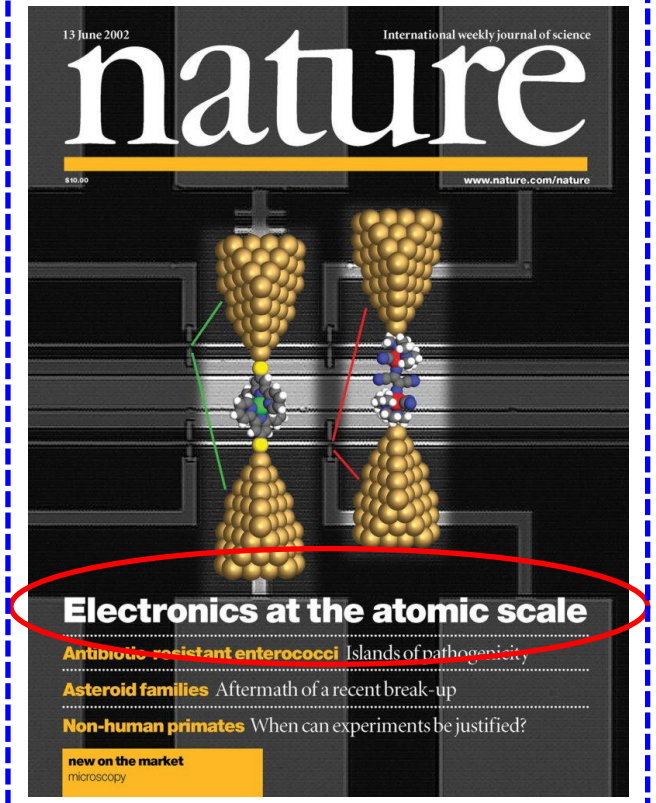


复合纳米结构



低维材料

原子尺度精准构筑器件



未来纳米器件

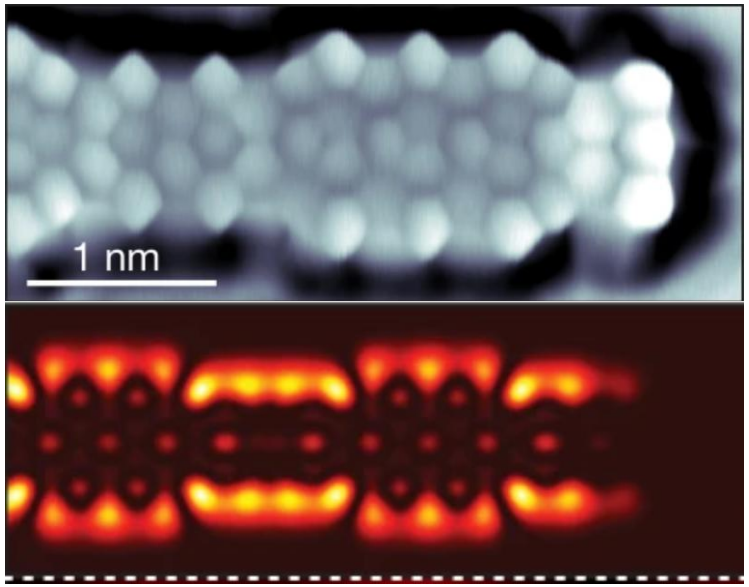
低维材料的构筑、物性测量与调控是

构造未来功能纳米器件的基石

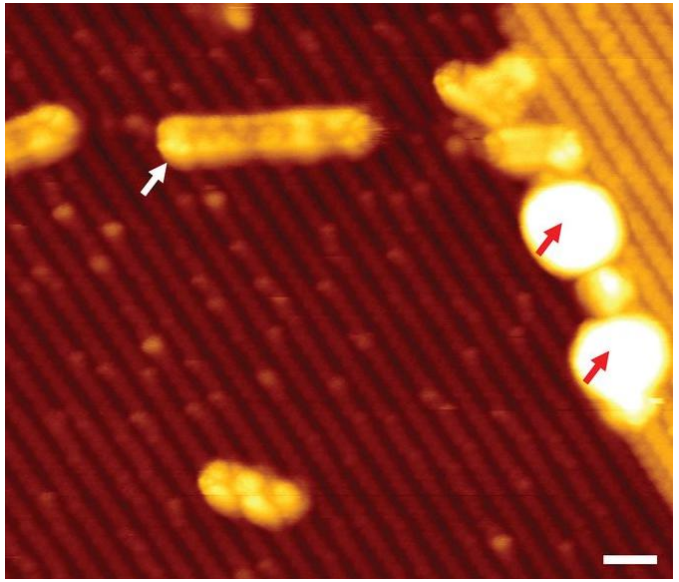
低维材料的构筑及其物性：现状与挑战

现状

“自上而下”与“自下而上”相结合
构筑低维纳米材料及其器件



Nature **560**, 204 (2018)



Science **369**, 571 (2020)

挑战

实现低维纳米材料的原子级精准构筑与操控

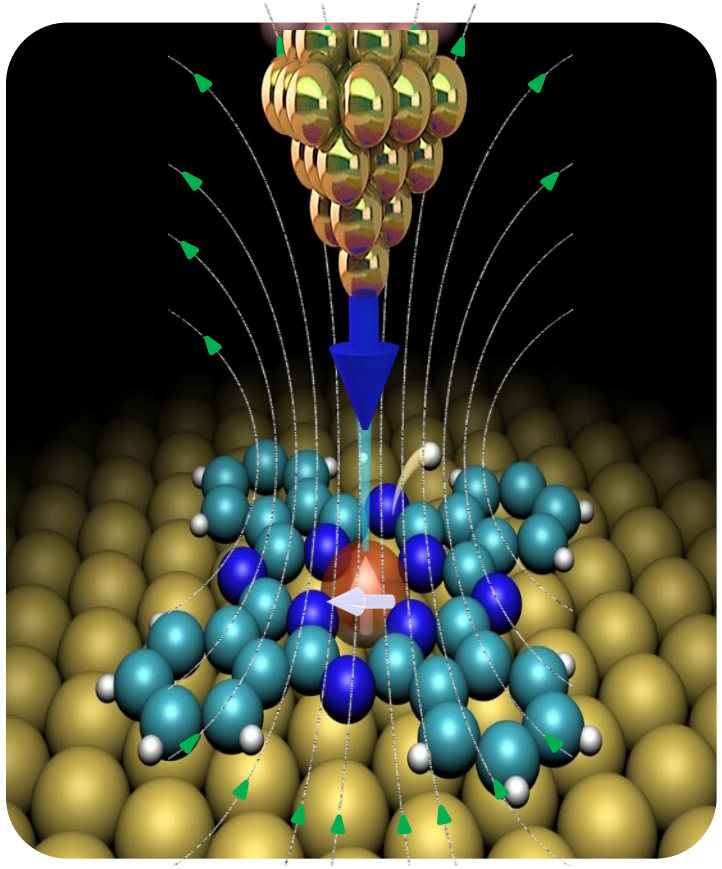
原子级精准构筑及物性调控的关键科学问题

如何实现：

1. 原子级精准构筑

2. 单电子、单自旋层次上物性的精准测量

3. 极低温、强磁场下物性的精准调控



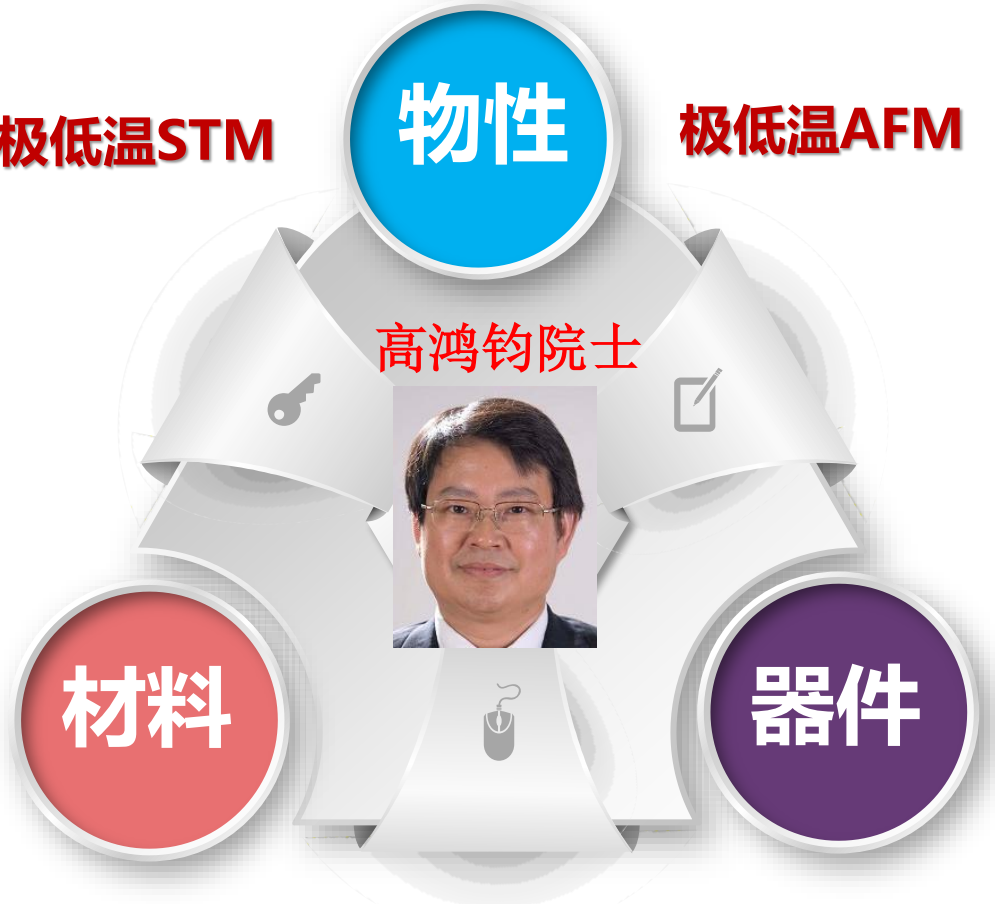
“原子制造和高精度物性研究”团队的人员构成

N04:STM的原子尺度构筑及物性表征

李 更
副研究员/博导

陈 辉
副研究员/博导

极低温STM



极低温AFM

朱诗雨
副研究员

黄 立
副主任工程师

杨海涛
研究员

郭 辉
副研究员

鲍丽宏
副研究员/博导

N12:MBE构筑低维信息材料及器件研究

□ 强有力的团队+全链条的研究

报告提纲

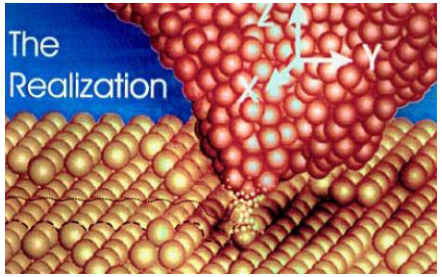
一、新型低维材料构筑与物性调控

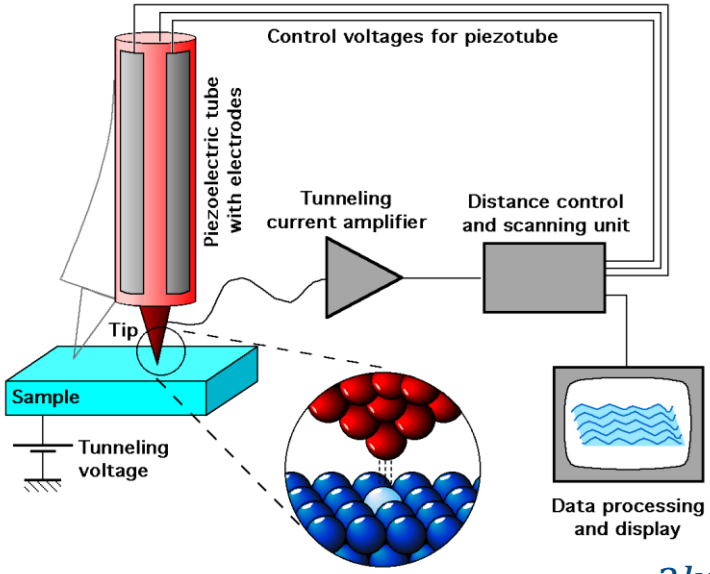
二、STM的表面原子操纵技术

三、发展原子操纵实现新型低维结构与物性调控

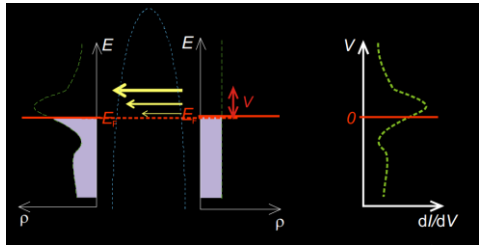
四、总结与展望

Scanning tunneling microscope/spectroscopy

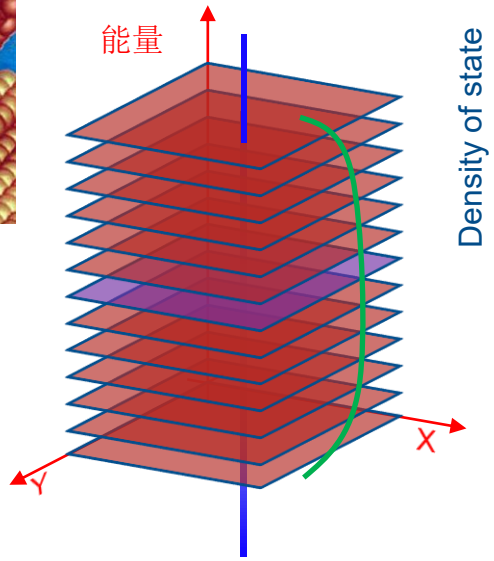




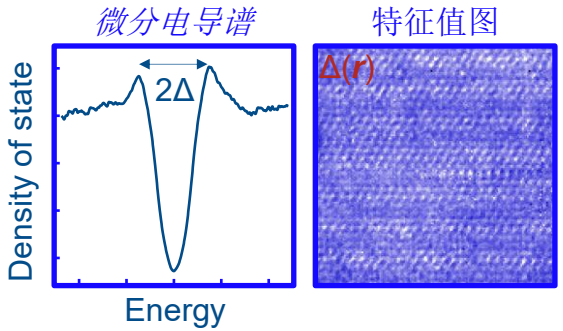
$$I = I_p e^{-2kz}$$

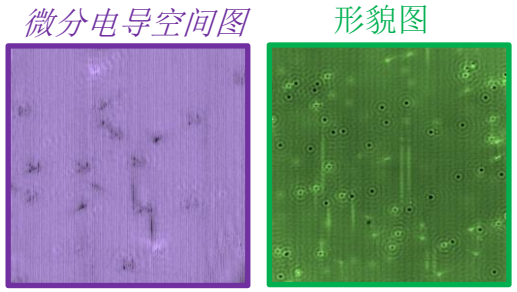


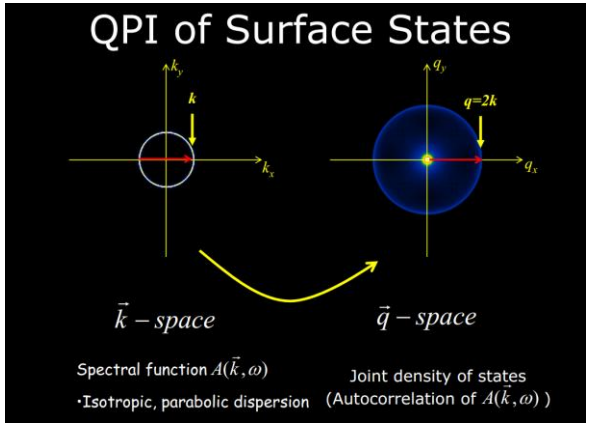
$$\frac{dI}{dV} \propto \rho_r(eV)$$

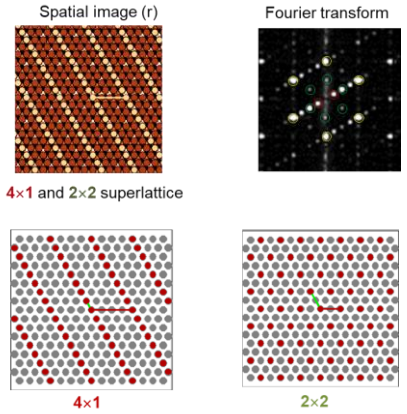


3维电子态密度



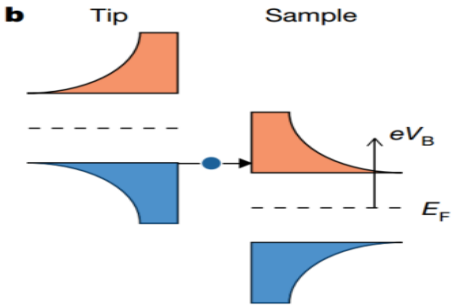


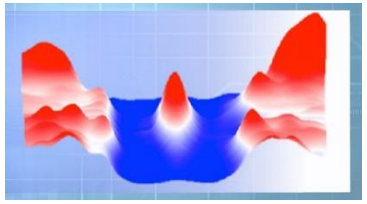


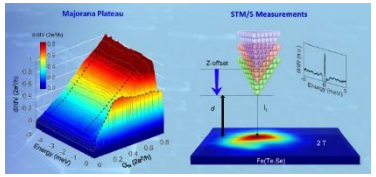


Functional STM-Various tunneling process

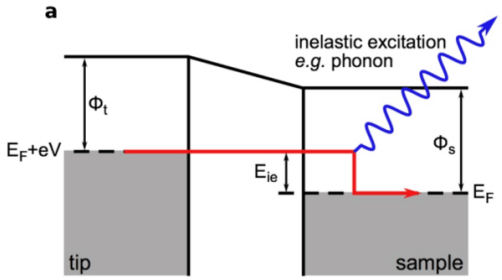
单电子弹性隧穿

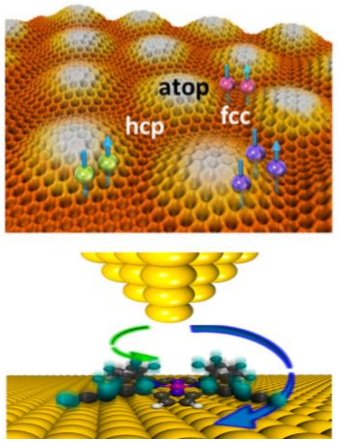






非弹性隧穿

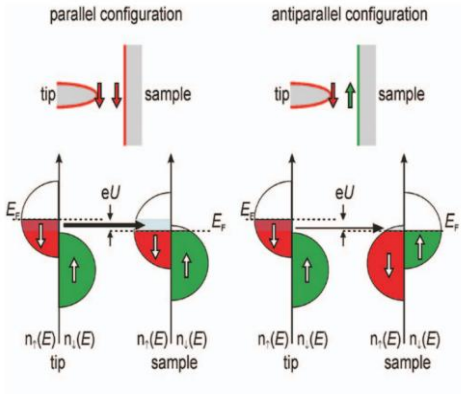




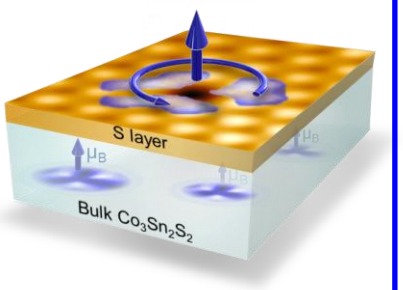
Nano Lett. 17,4929 (2017)

低能振动或自旋激发态

自旋电子隧穿



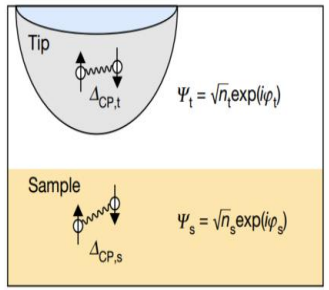
Spin-orbit polaron

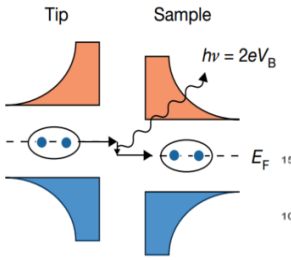


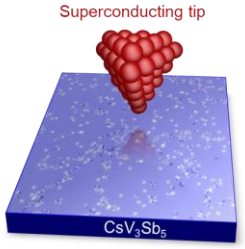
Rev. Mod. Phys. ***81***, *1495 (2009)*

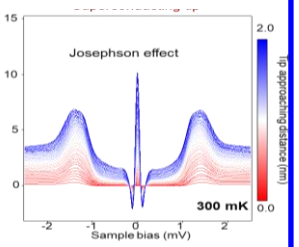
Spin-polarized STM

库珀对隧穿





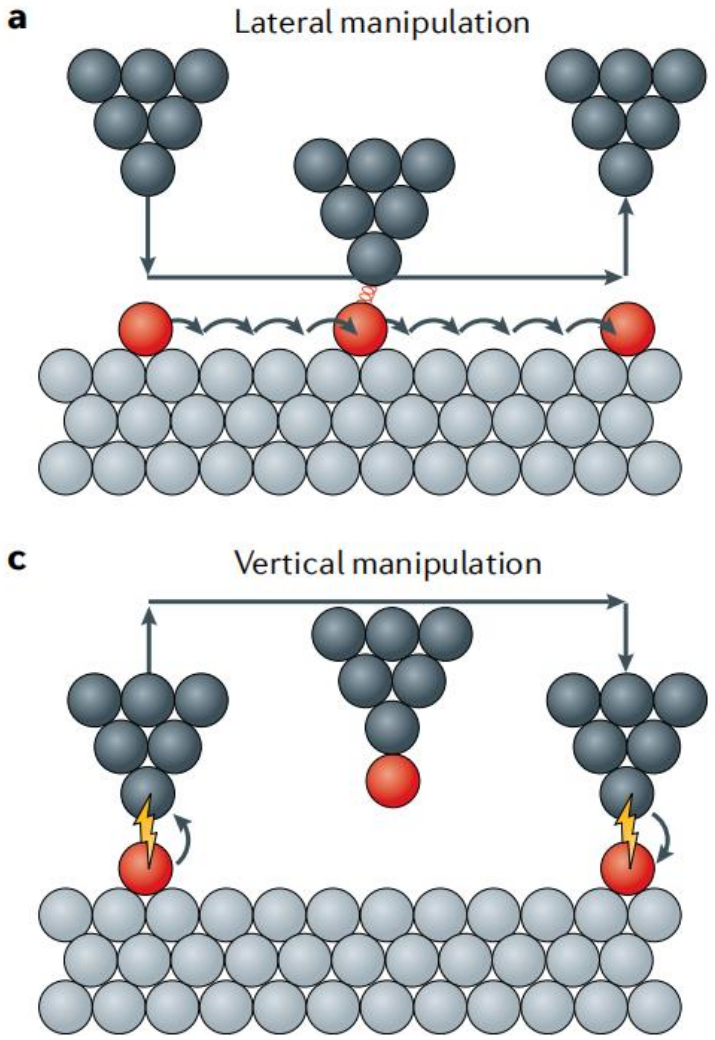


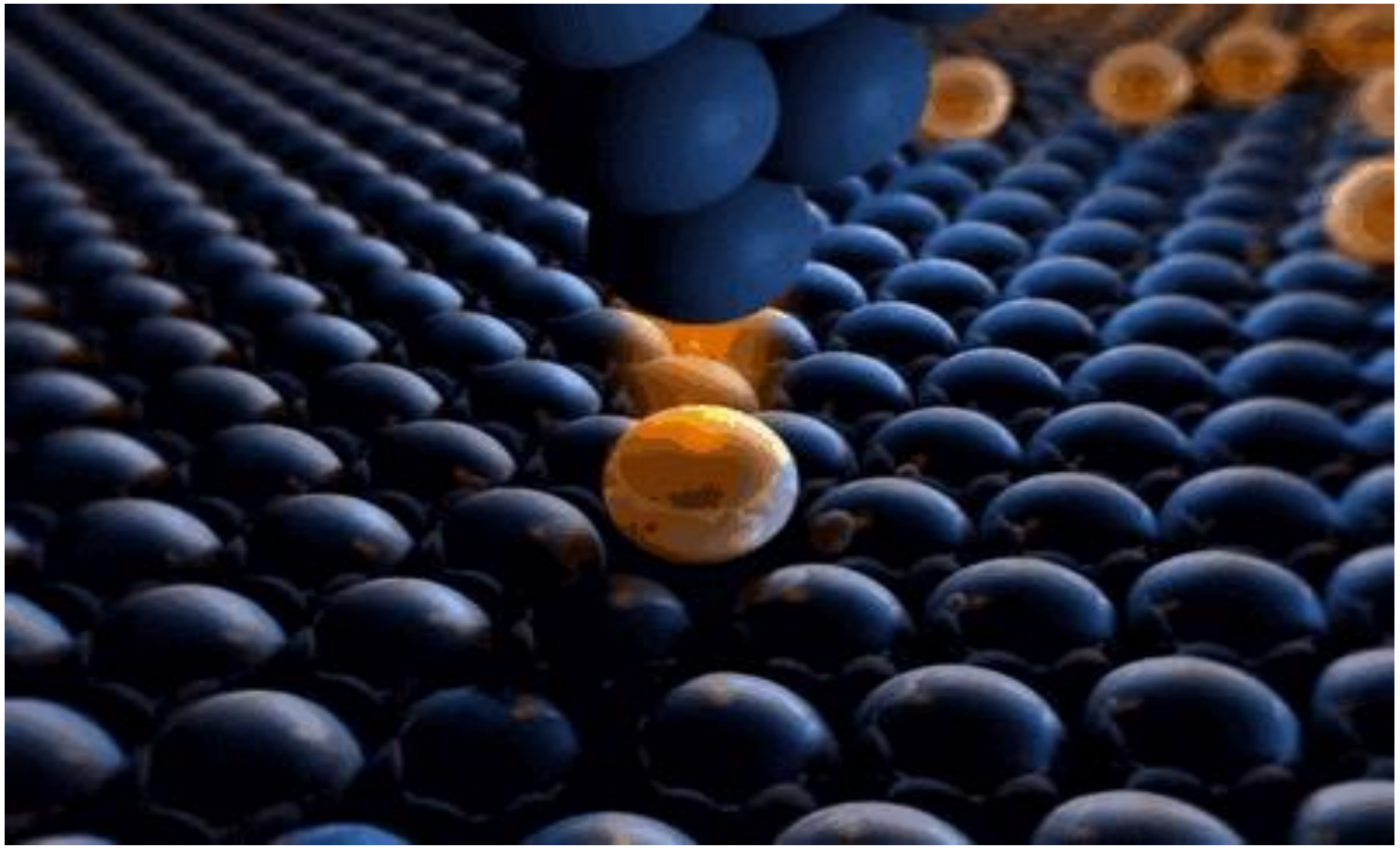


Scanning Josephson tunneling microscopy

Nature **571**, 541 (2019)

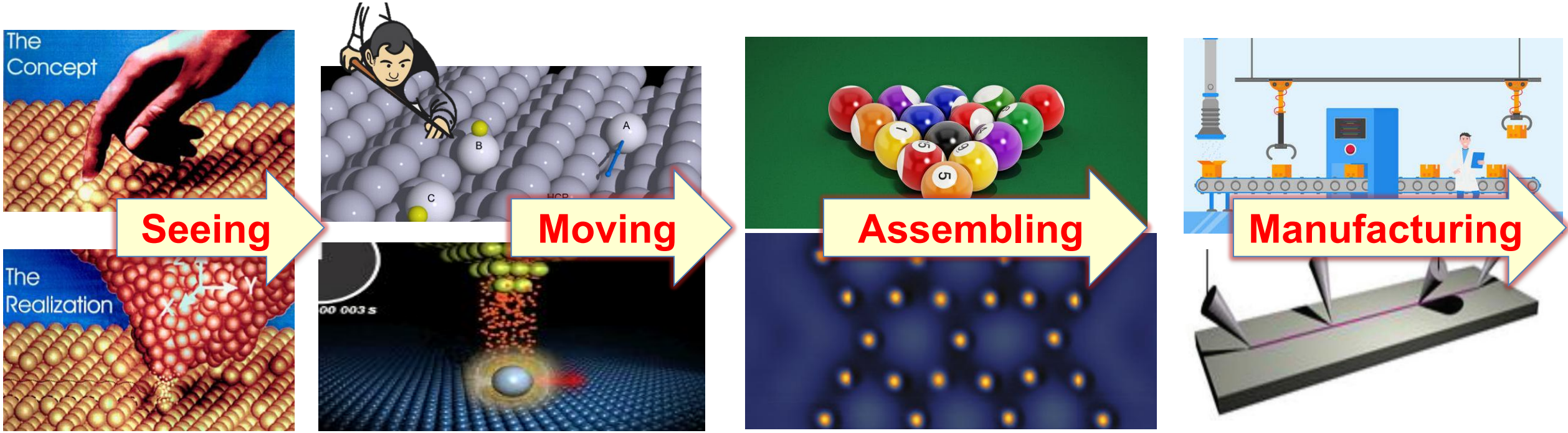
基于STM的表面原子操纵技术





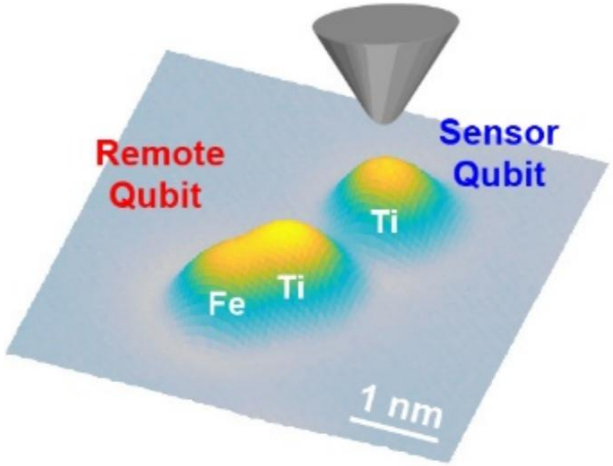
Nature Reviews Physics, 2019, 1(12): 703-715.

基于STM的表面原子操纵技术的发展趋势

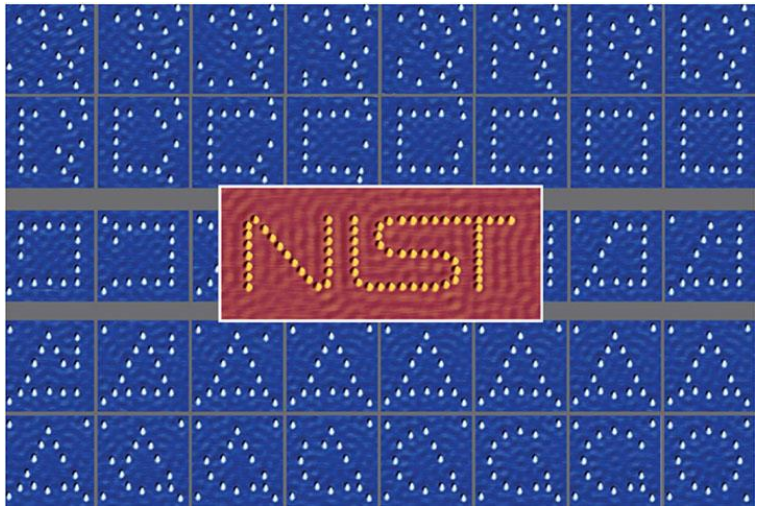


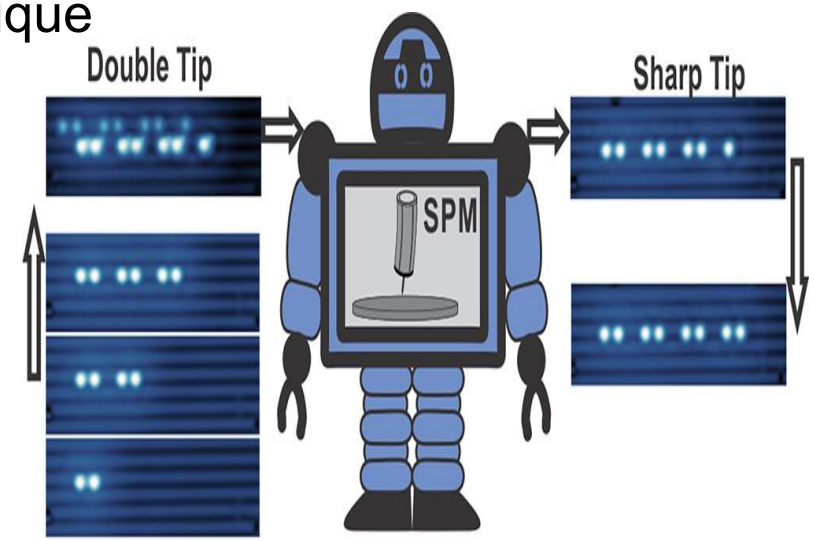
Pathway I: developing multiple manipulation mode

Pickup + drag mode

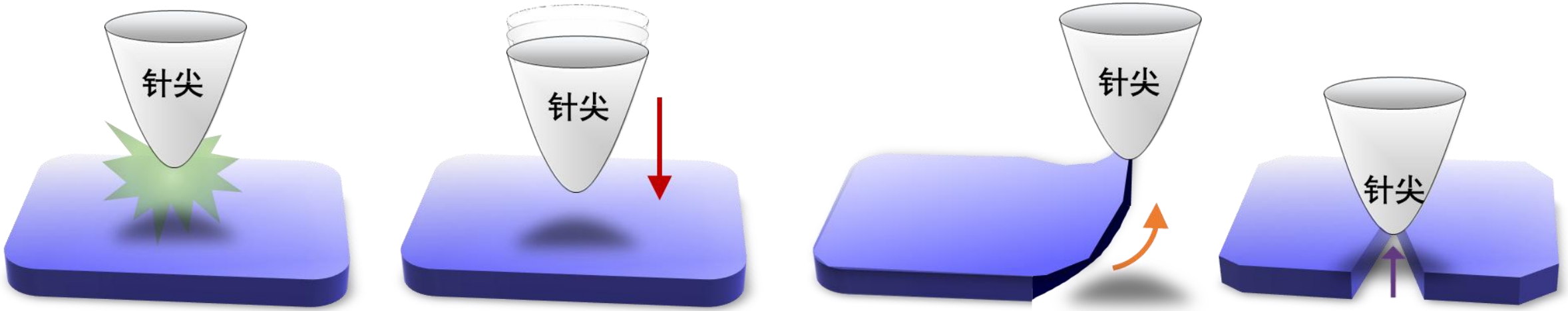


Automatic manipulation with AI technique





Pathway I: developing multiple manipulation mode



表面原子操纵与物性调控研究进展

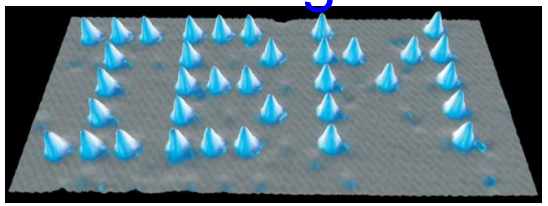
韩相和, 黄子豪, 范朋, 朱诗雨, 申承民, 陈辉, 高鸿钧

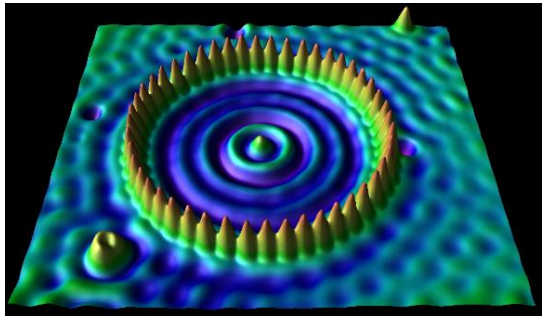
物理学报, doi: 10.7498/aps.71.20220405

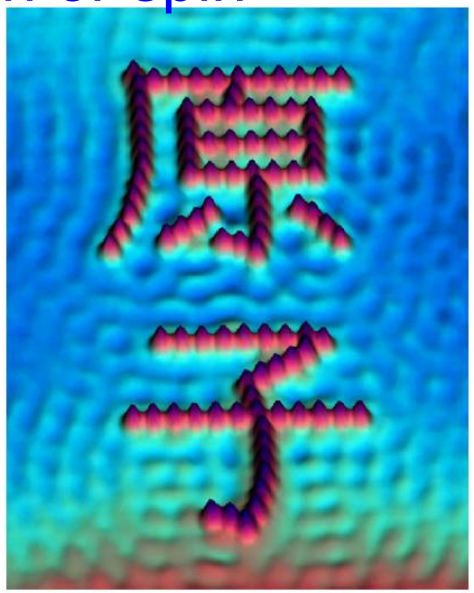
Pathway II: Extending the manipulating systems

Atoms/molecules based on Au, Ag, Cu noble metal surfaces (trivial surface states)

Single electron or spin

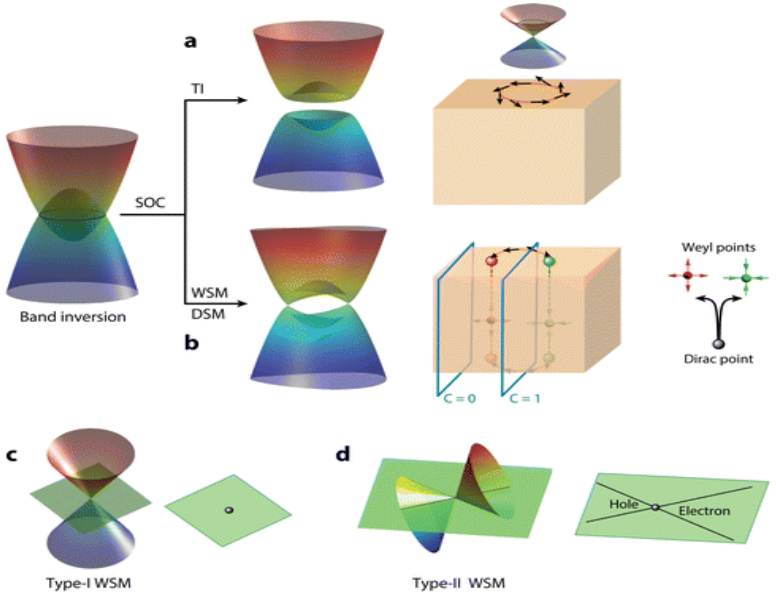






Topological quantum materials

Spin orbital coupling, charge/spin density waves, Cooper pairs….



Atomically-precise engineering of localized states in topological quantum materials?

报告提纲

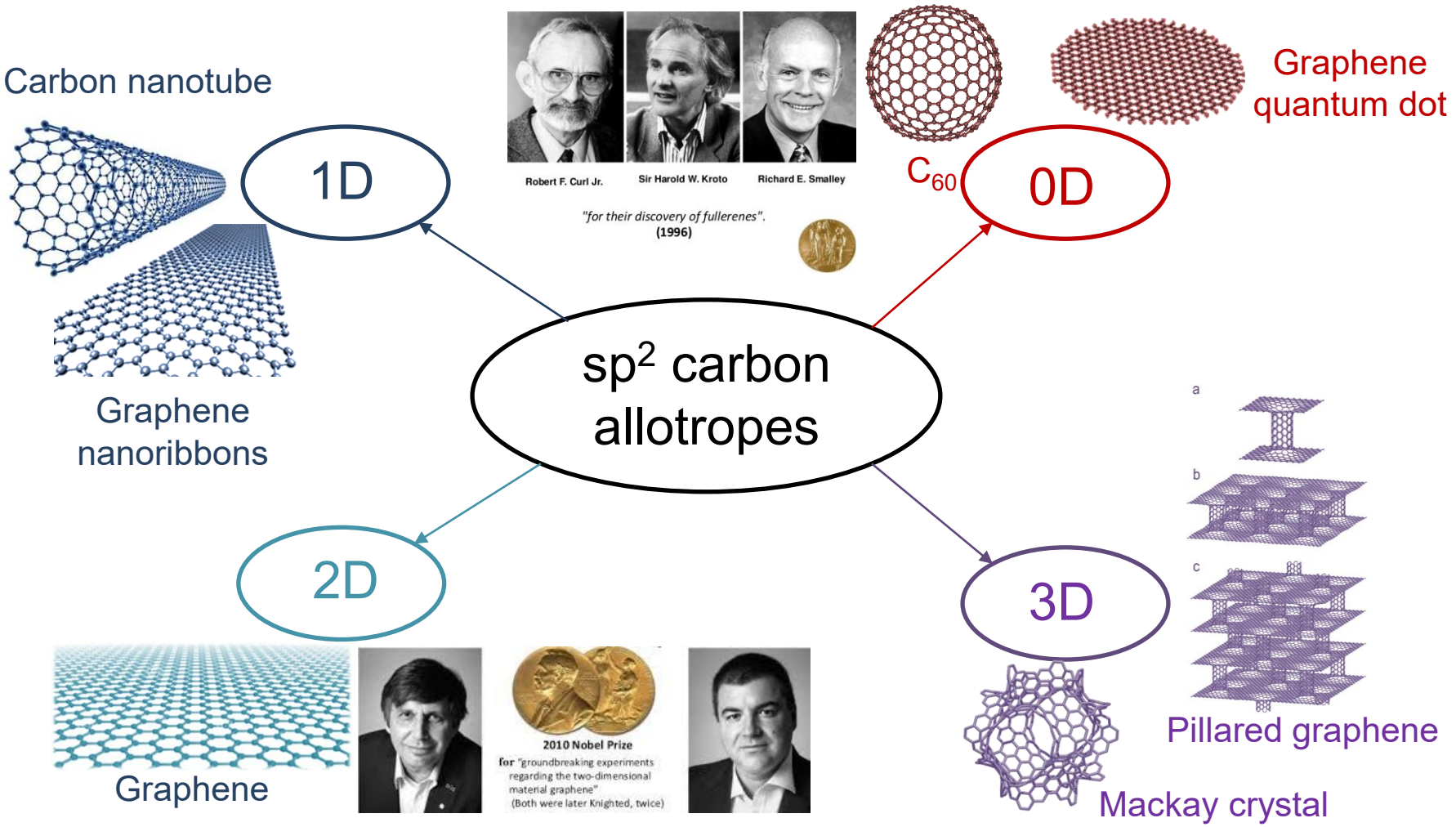
一、新型低维材料构筑与物性调控

二、STM的表面原子操纵技术

三、发展原子操纵实现新型低维结构与物性调控

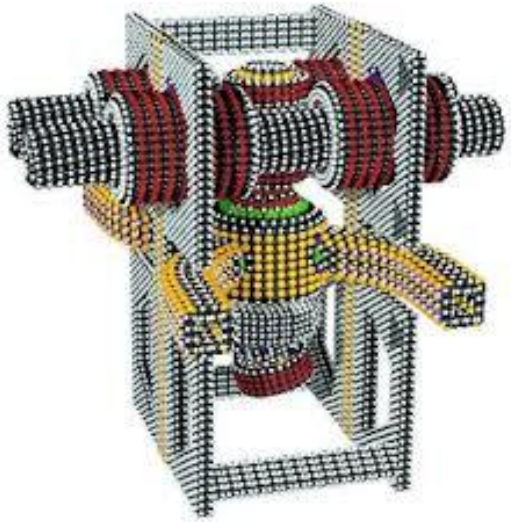
四、总结与展望

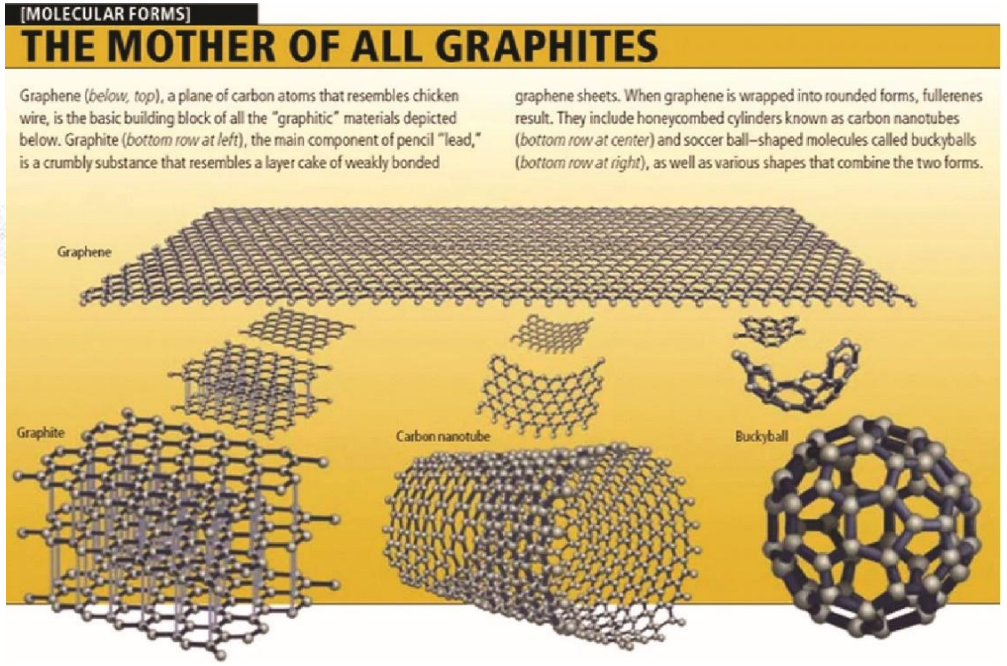
研究背景：sp^2 杂化碳纳米结构

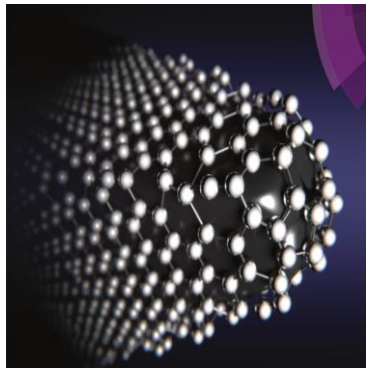


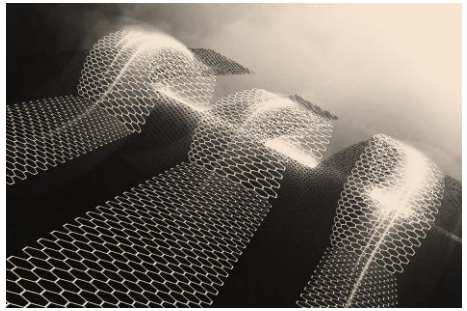
探索新型低维碳纳米材料及其新奇物性一直是当今科技领域的前沿科学问题之一。相关研究曾两次获得诺贝尔奖（富勒烯，1996 年诺贝尔化学奖；石墨烯，2010年诺贝尔物理奖）。

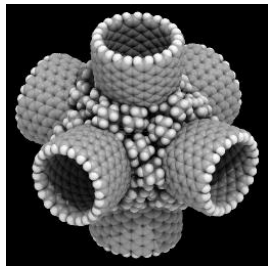
研究背景：石墨烯构建复杂纳米结构

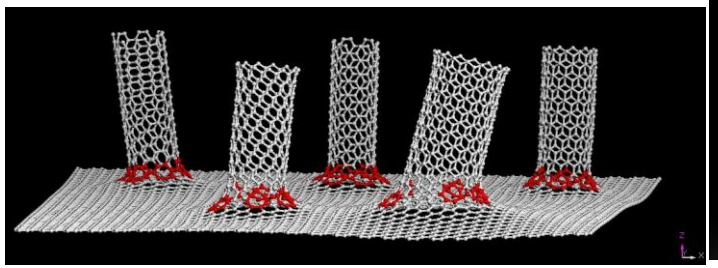


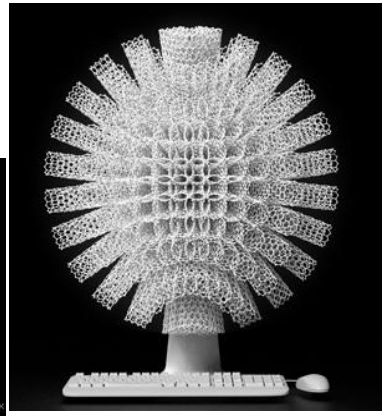






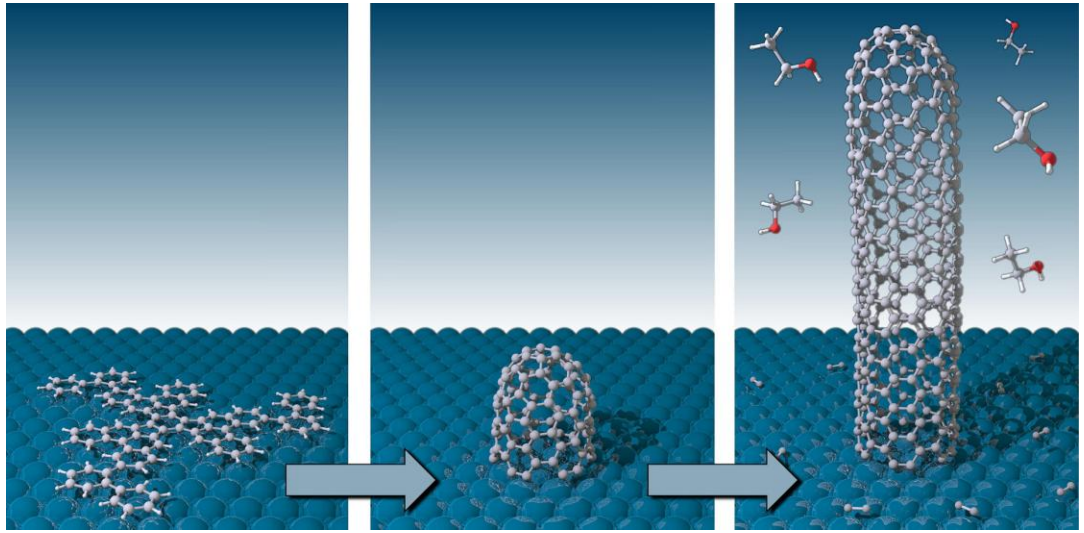




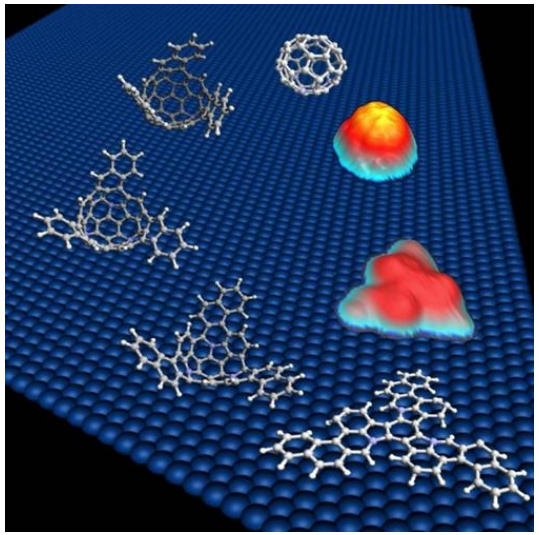


- 二维的石墨烯晶格结构被认为是其他众多的碳纳米结构的母体材料；
- 石墨烯在未来纳米学器件的应用，需要构筑具有三维形貌与精确复杂的新型功能化石墨烯纳米结构。

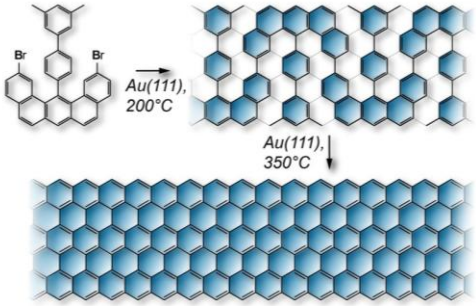
研究背景：进展与挑战

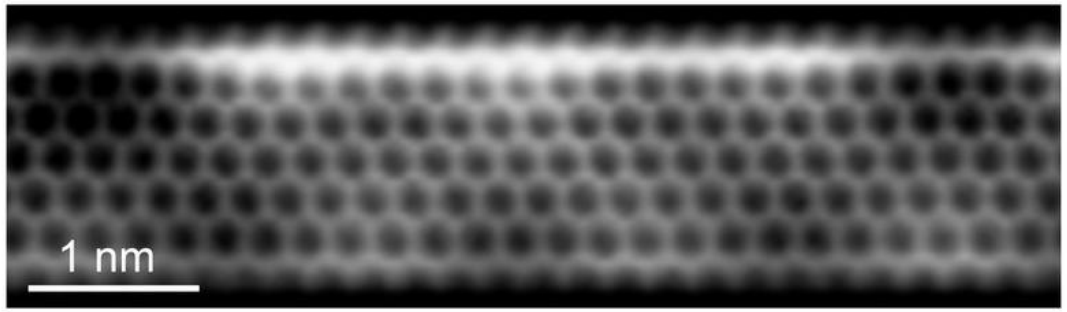


R. Fasel *et al.* Nature (2014)



G. Otero *et al.* Nature (2008)





R. Fasel *et al.* Nature (2016)

- 目前合成高质量的石墨烯纳米结构主要依赖自下而上的化学合成方法，但是获得原子结构均一的，构型精确可控且具有量子效应的新型低维纳米结构仍存在巨大的挑战。

新思路：“折纸术”

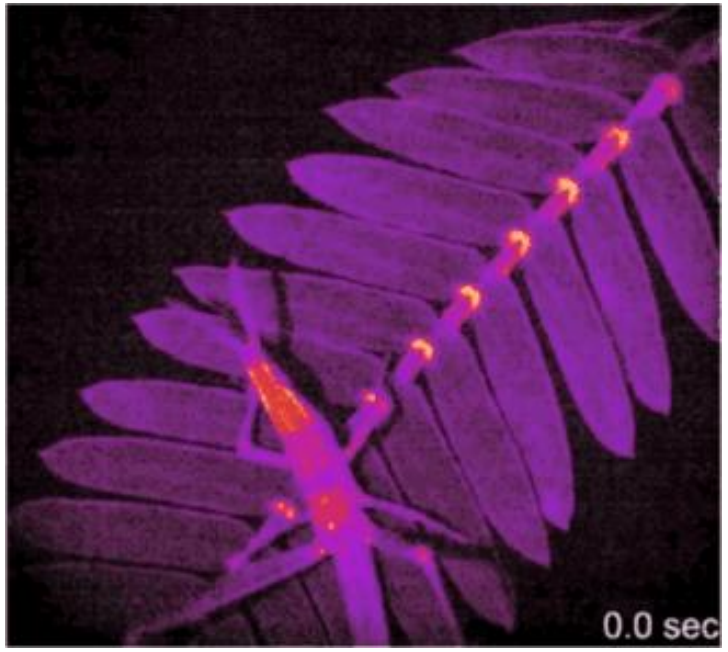
3D

折纸艺术源远流长

自然界中的“折纸术”

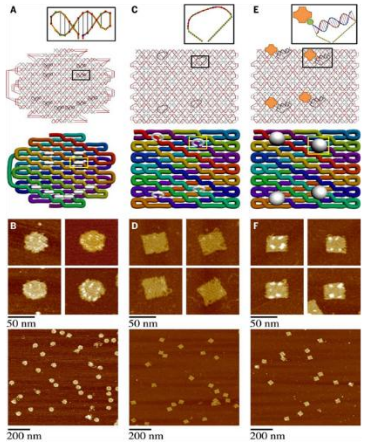
自然界中有多种具有类似折叠行为的植物

捕蝇草



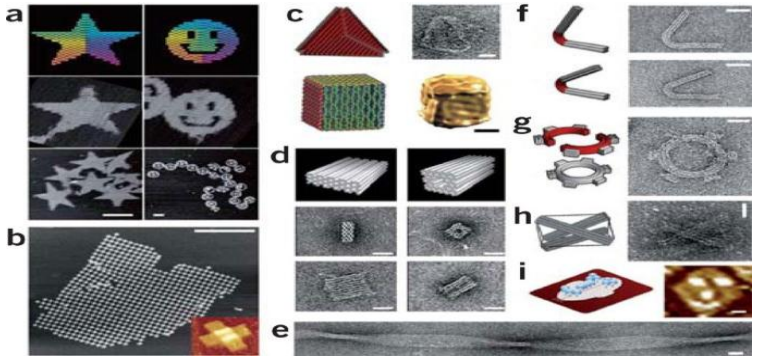
含羞草

生物学中的“折纸术”

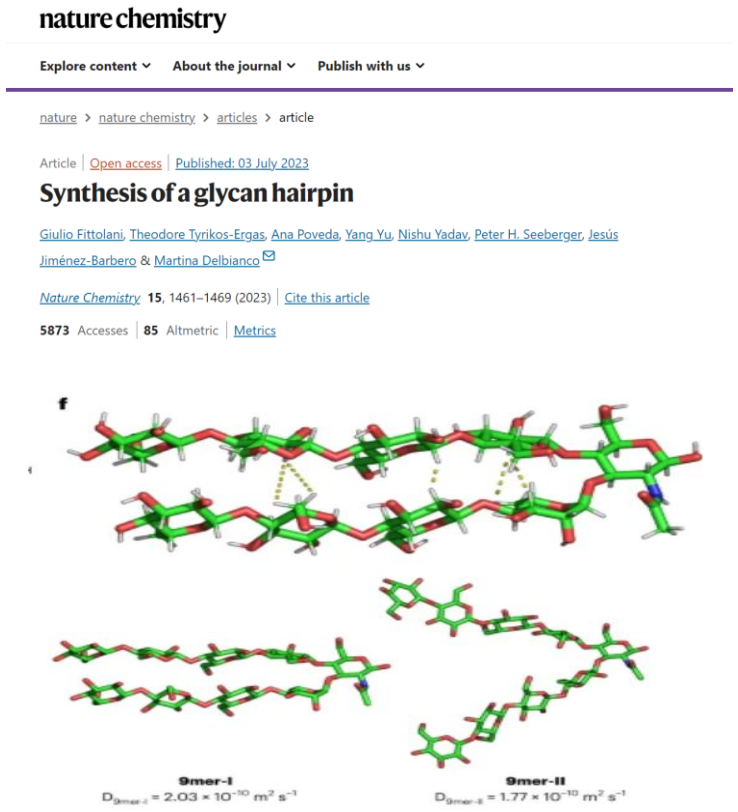


Science 358, 2648 (2017)

Nature 552, 67 (2017)



Nat Methods **8**, 221–229 (2011)



nature chemistry

Explore content | About the journal | Publish with us

nature > nature chemistry > articles > article

Article | Open access | Published: 03 July 2023

Synthesis of a glycan hairpin

Giulio Fittolani, Theodore Tyrikos-Ergas, Ana Poveda, Yang Yu, Nishu Yadav, Peter H. Seeberger, Jesús Jiménez-Barbero & Martina Delbianco

Nature Chemistry **15**, 1461–1469 (2023) | Cite this article

5873 Accesses | **85** Altmetric | Metrics

Nat. Chem. **15**, 1461–1469 (2023)

DNA，RNA与蛋白质等折叠

自折叠糖聚合物

理论预测：原子尺度的石墨烯折叠结构

PHYSICAL REVIEW B **85**, 035403 (2012)

Folded graphene nanoribbons with single and double closed edges

Nam B. Le and Lilia M. Woods
Department of Physics, University of South Florida, 4202 E. Fowler Avenue, Tampa, Florida 33620, U.
(Received 15 August 2011; revised manuscript received 12 October 2011; published 3 January 2012)

Graphene nanoribbon folds with single and double closed edges are studied using density functional t

PRL **105**, 106802 (2010) PHYSICAL REVIEW LETTERS week ending 3 SEPTEMBER 2010

Zero Landau Level in Folded Graphene Nanoribbons

E. Prada,[1] P. San-Jose,[2] and L. Brey[1]
[1]*Instituto de Ciencia de Materiales de Madrid (CSIC), Cantoblanco, 28049 Madrid, Spain*
[2]*Instituto de Estructura de la Materia (CSIC), Serrano 123, 28006 Madrid, Spain*
(Received 26 March 2010; published 1 September 2010)

e nanoribbons can be folded into a double layer system keeping the two layers decoupled. In m Hall regime folds behave as a new type of Hall bar edge. We show that the symmetry of the zero Landau level in metallic nanoribbons dictate that the zero energy edge states a fold are perfectly transmitted onto the opposite layer. This result is valid irrespective of fold magnetic field strength, and crystallographic orientation of the nanoribbon. Backscattering n on the $N = 0$ Hall plateau is ultimately due to the orthogonality of forward and backward nuch like in the Klein paradox.

03/PhysRevLett.105.106802 PACS numbers: 73.22.Pr, 75.47.−m, 75.60.Ch

PHYSICAL REVIEW B **86**, 195426 (2012)

Electron transport in folded graphene junctions

Yuee Xie, Yuanping Chen,* Xiao Lin Wei, and Jianxin Zhong
Institute for Quantum Engineering and Micro-Nano Energy Technology and Department of Physics, Xiangtan University, Xiangtan 411105, China
(Received 16 May 2011; revised manuscript received 19 June 2012; published 26 November 2012)

Using Green's function method, electron transport in graphene folding junctions (GFJs) are studied. All of these junctions are bilayer structures with AA or AB stacking. As for the AA-stacking GFJs, their transport properties are strongly dependent on the edge form and folding angle. The armchair GFJs (AGFJs) with a folding angle of 60° have high reflection to electrons, while those with a folding angle of 120° are nearly reflectionless and transparent. The zigzag GFJs (ZGFJs) show an opposite transport behavior: The junctions with a folding angle of 60° are nearly transparent while those of folding angle 120° have high reflection. As for the AB-stacking GFJs, their transport properties are insensitive to the edge form or folding angle, and all junctions exhibit less reflection to electrons. In addition, interesting edge states different from those in the unfolded nanoribbons are found in the GFJs. Our results indicate that GFJs can be served either as resistors for tuning attenuation of currents or as interconnects for changing directions of current in all graphene-based nanoelectronics.

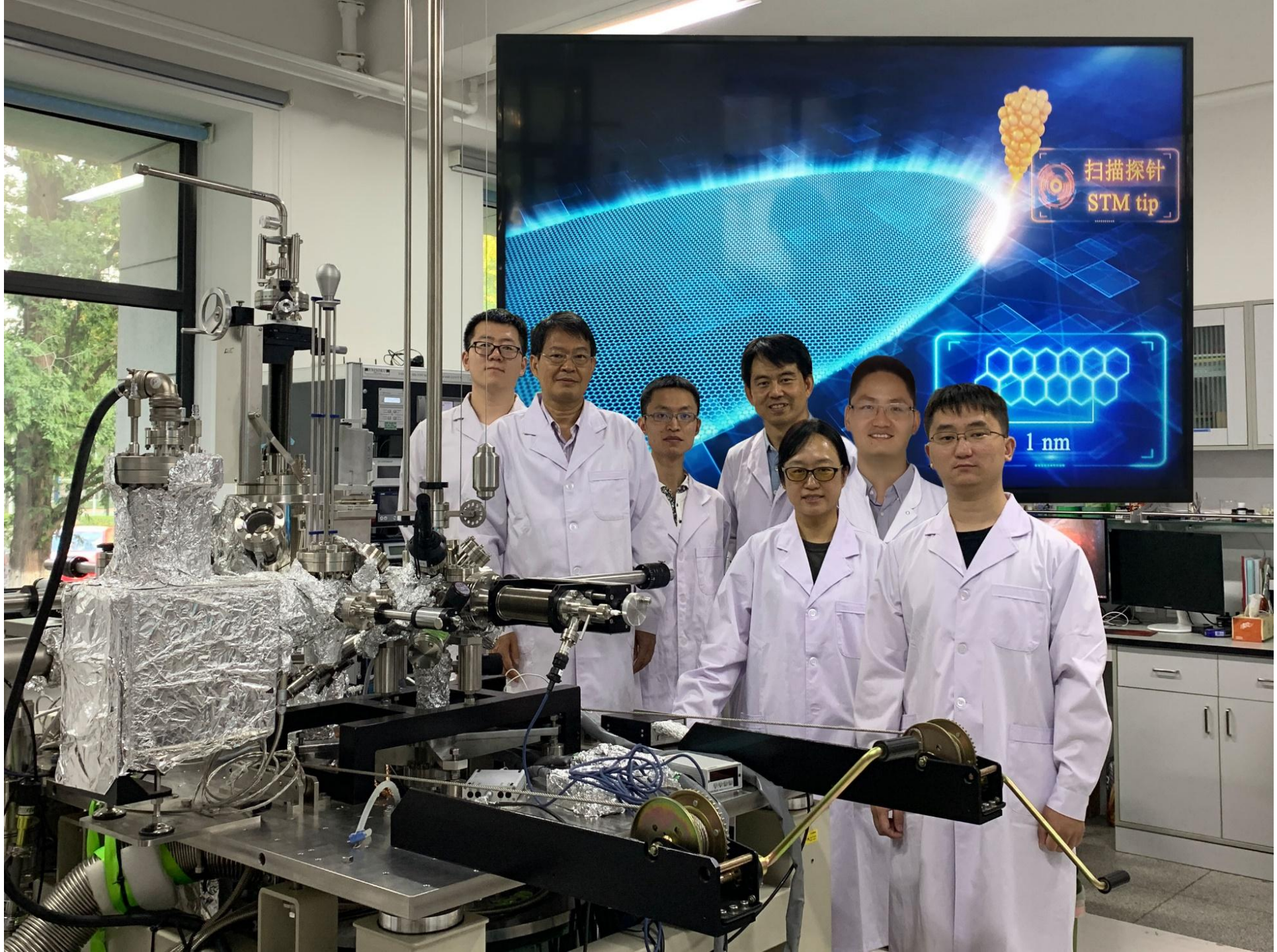
DOI: 10.1103/PhysRevB.86.195426 PACS number(s): 72.80.Vp, 73.22.Pr, 81.05.ue

Friedemann Queisser and Ralf Schützhold*
Universität Duisburg-Essen, Lotharstrasse 1, 47057 Duisburg, Germany
(Received 28 January 2013; published 22 July 2013)

ansport in graphene under the influence of a transversal magnetic field $\boldsymbol{B}(\boldsymbol{r}) =$ ics $B(x \to \pm\infty) = \pm B_0$, which could be realized via a folded graphene sheet in a or example. By solving the effective Dirac equation, we find robust modes with a ropagate along the fold—where particles and holes move in opposite directions. ole pairs with incident (optical or infrared) photons would then generate a nearly and thus a strong magnetophotoelectric or magnetothermoelectric effect—even

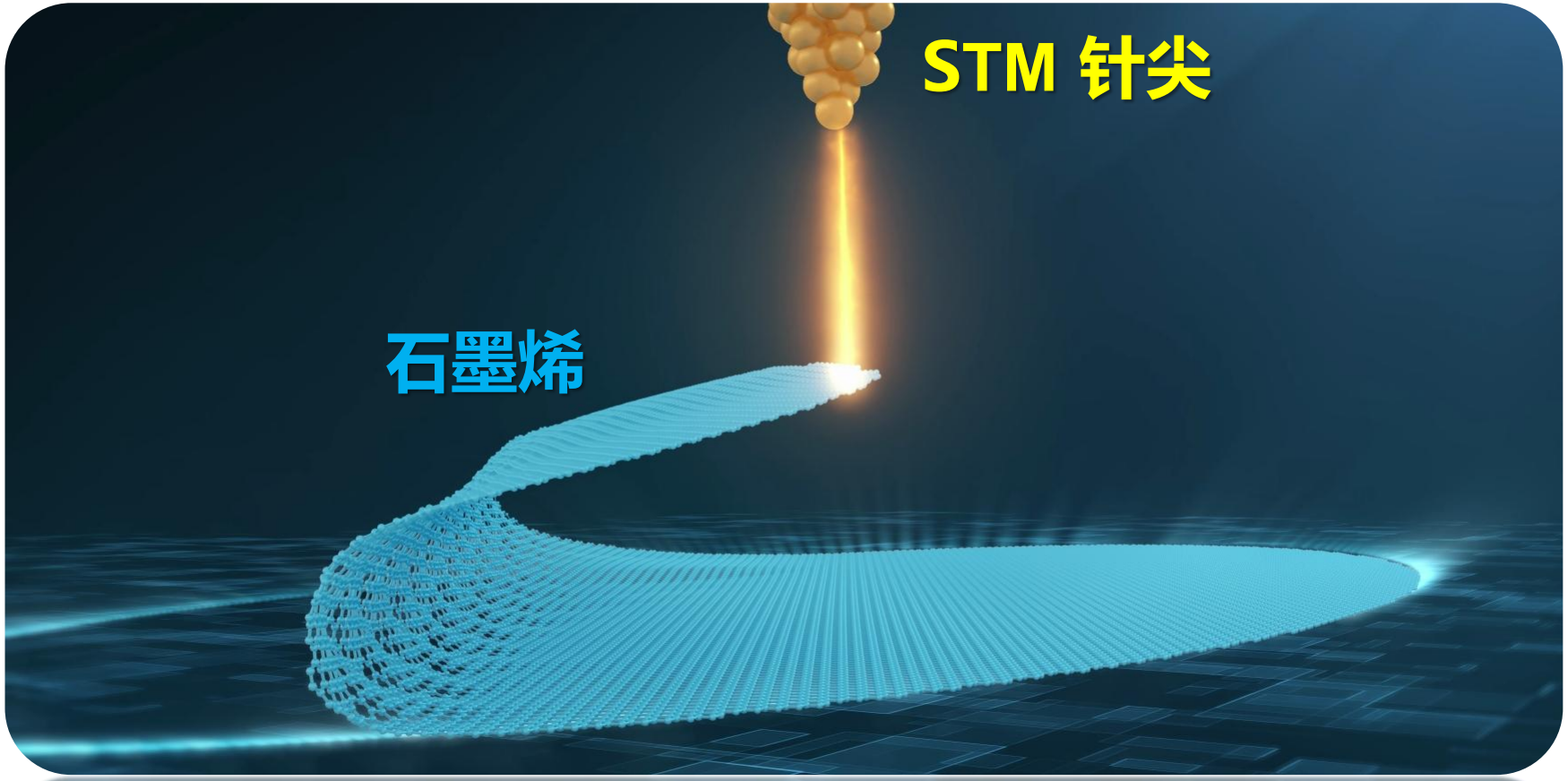
111.046601 PACS numbers: 72.80.Vp, 78.67.Wj, 85.80.Fi

- 理论预测发现，在原子尺度，通过对石墨烯的弯曲折叠，可以构筑出具有独特的电子学性质的新奇结构。然而，石墨烯弯曲结构的电子学性质容易受到局域的空位、增原子、边界等缺陷结构的影响。在单原子尺度精确地折叠石墨烯，特别是根据特殊需要沿特定方向对石墨烯进行折叠，具有极大的挑战性。

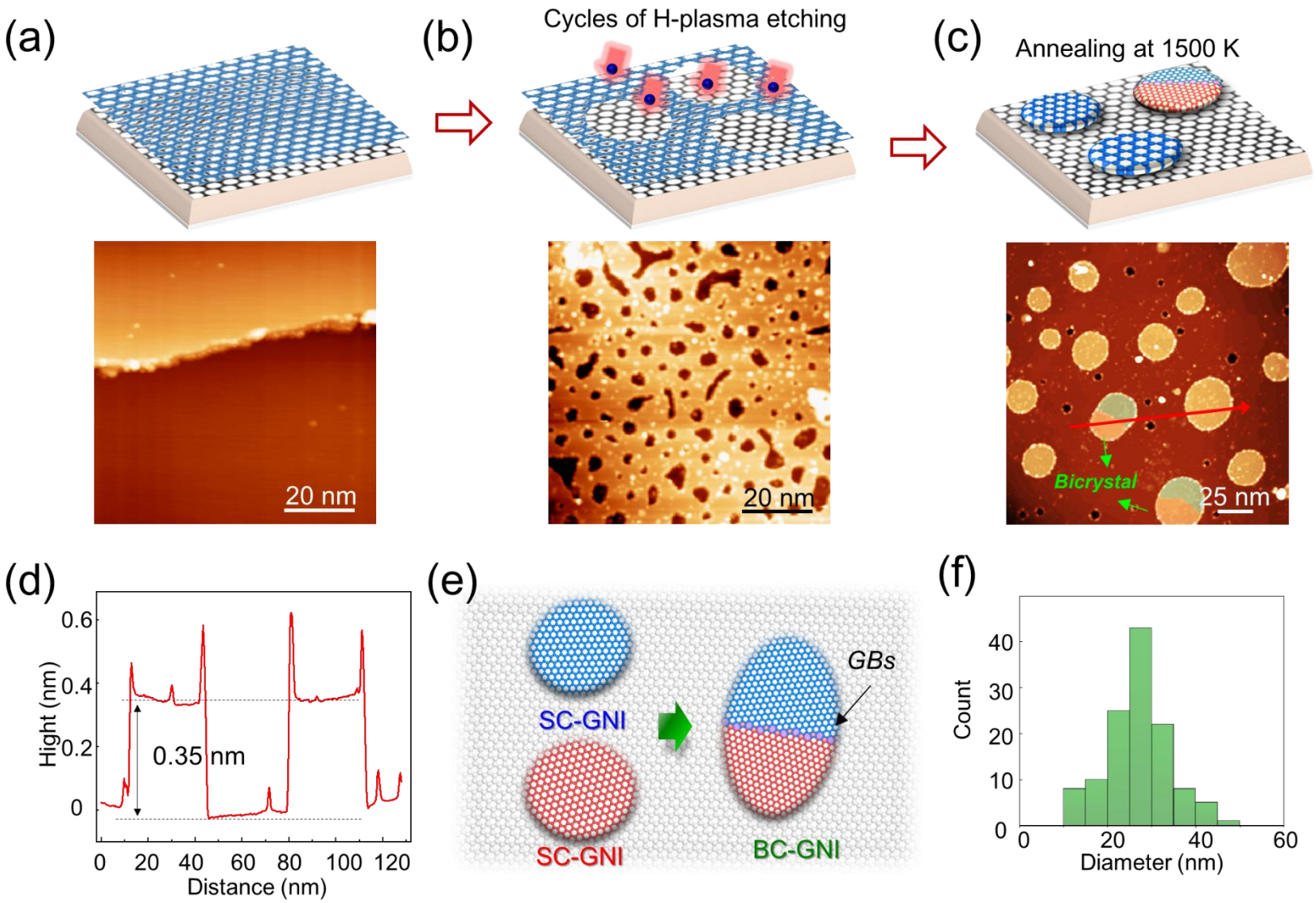

扫描探针
STM tip
1 nm

我们的研究方案

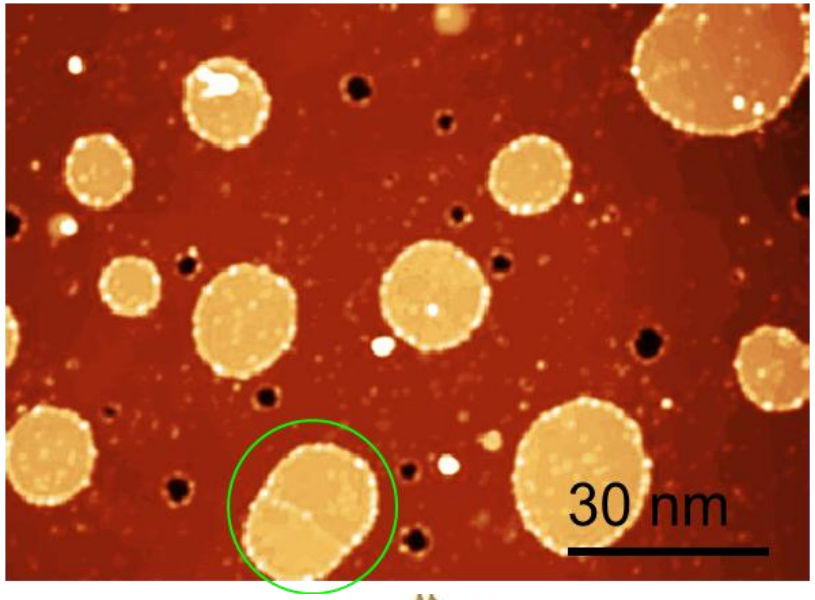
利用扫描隧道显微镜 (STM) “折纸术” 实现对转角石墨烯原子级精准构筑

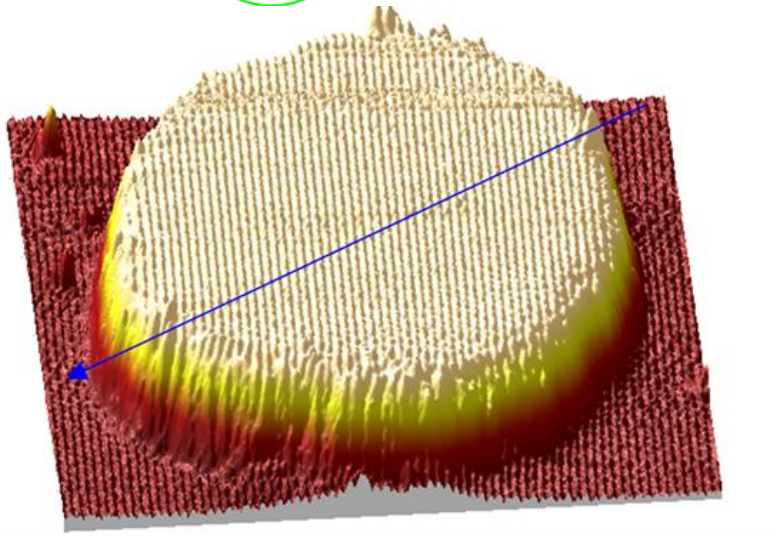


石墨烯岛的制备

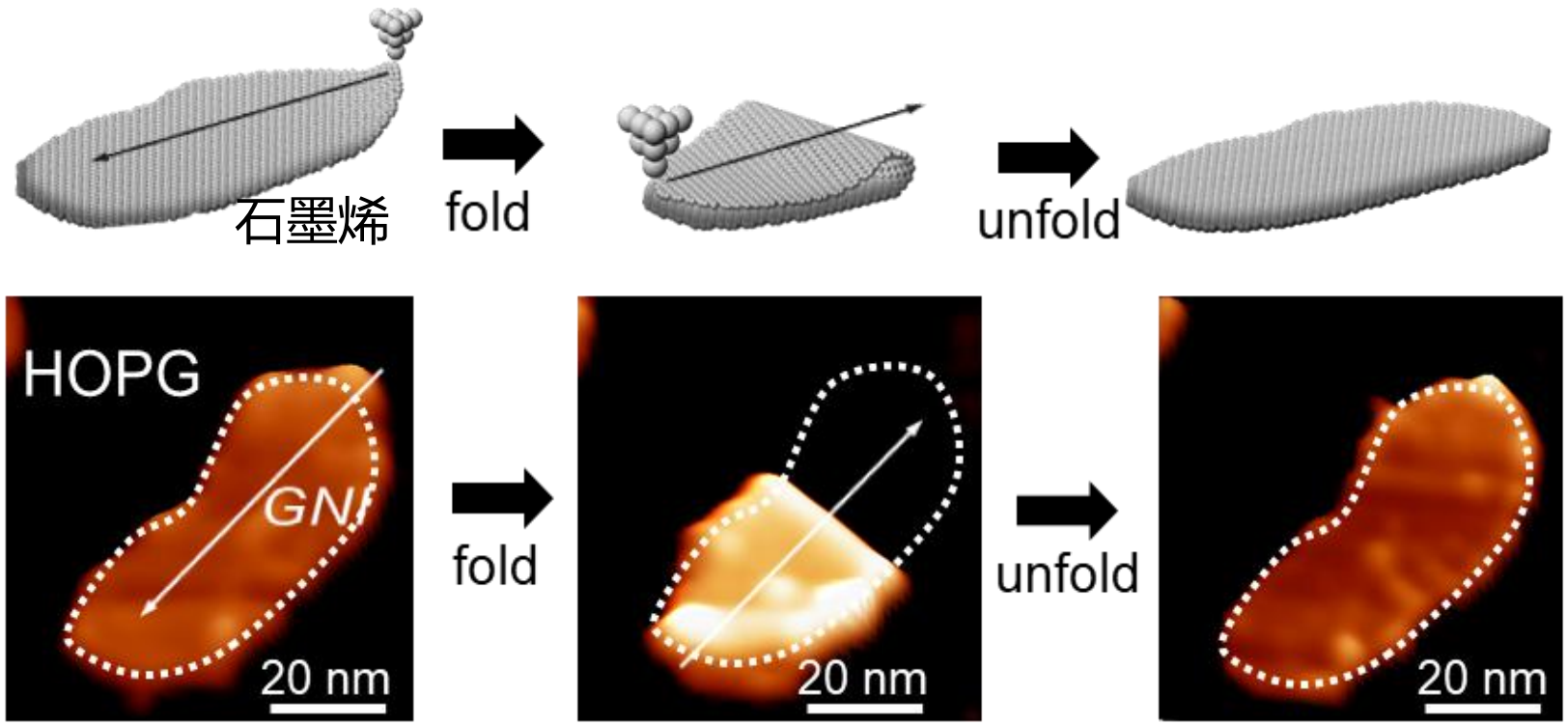

(a)
(b)
Cycles of H-plasma etching
(c)
Annealing at 1500 K
20 nm
20 nm
Bicrystal
25 nm
(d)
Hight (nm)
0.6
0.4
0.2
0
0.35 nm
0 20 40 60 80 100 120
Distance (nm)
(e)
SC-GNI
SC-GNI
GBs
BC-GNI
(f)
Count
40
30
20
10
0
0 20 40 60
Diameter (nm)

纳米世界的“王莲”



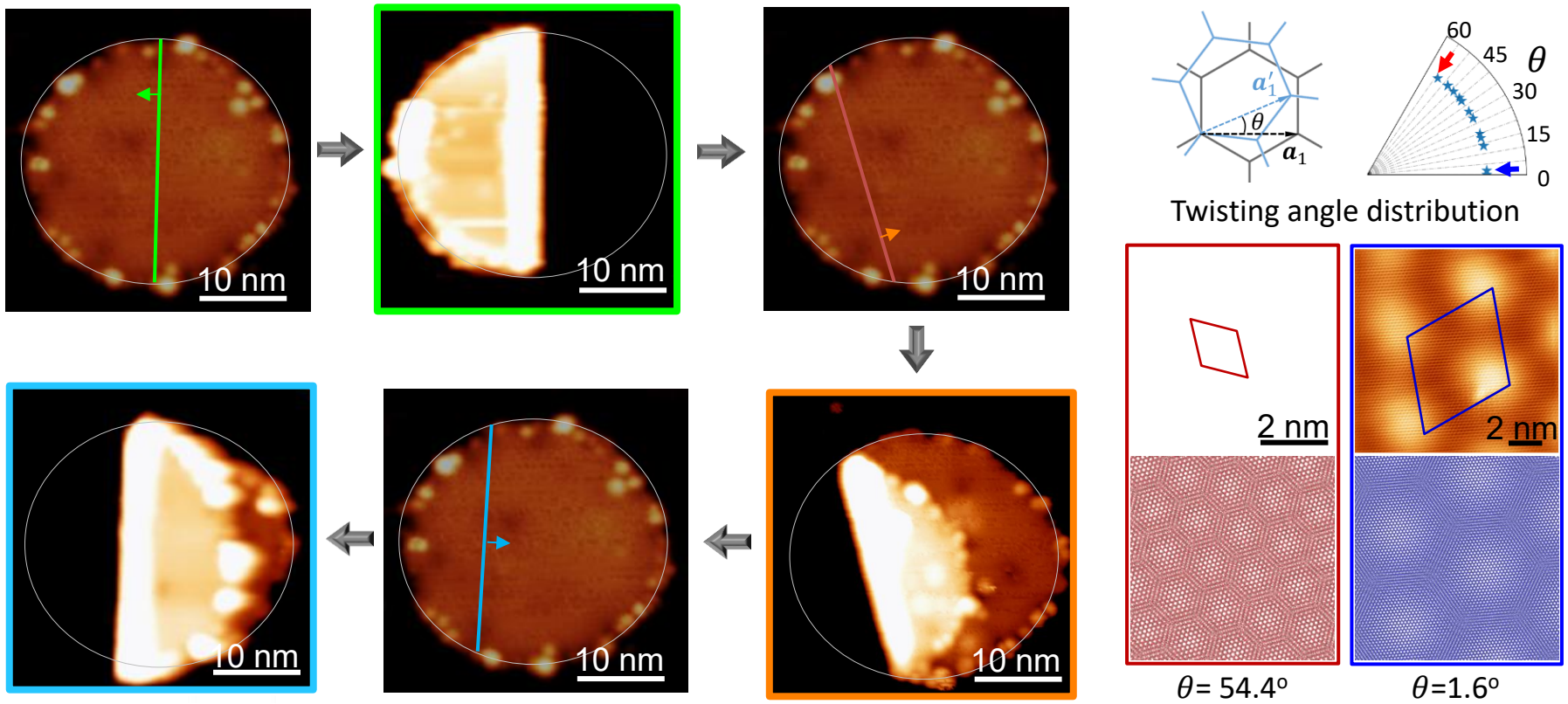


“折纸术”对石墨烯纳米岛的折叠



实现了对石墨烯纳米岛的**可重复折叠**

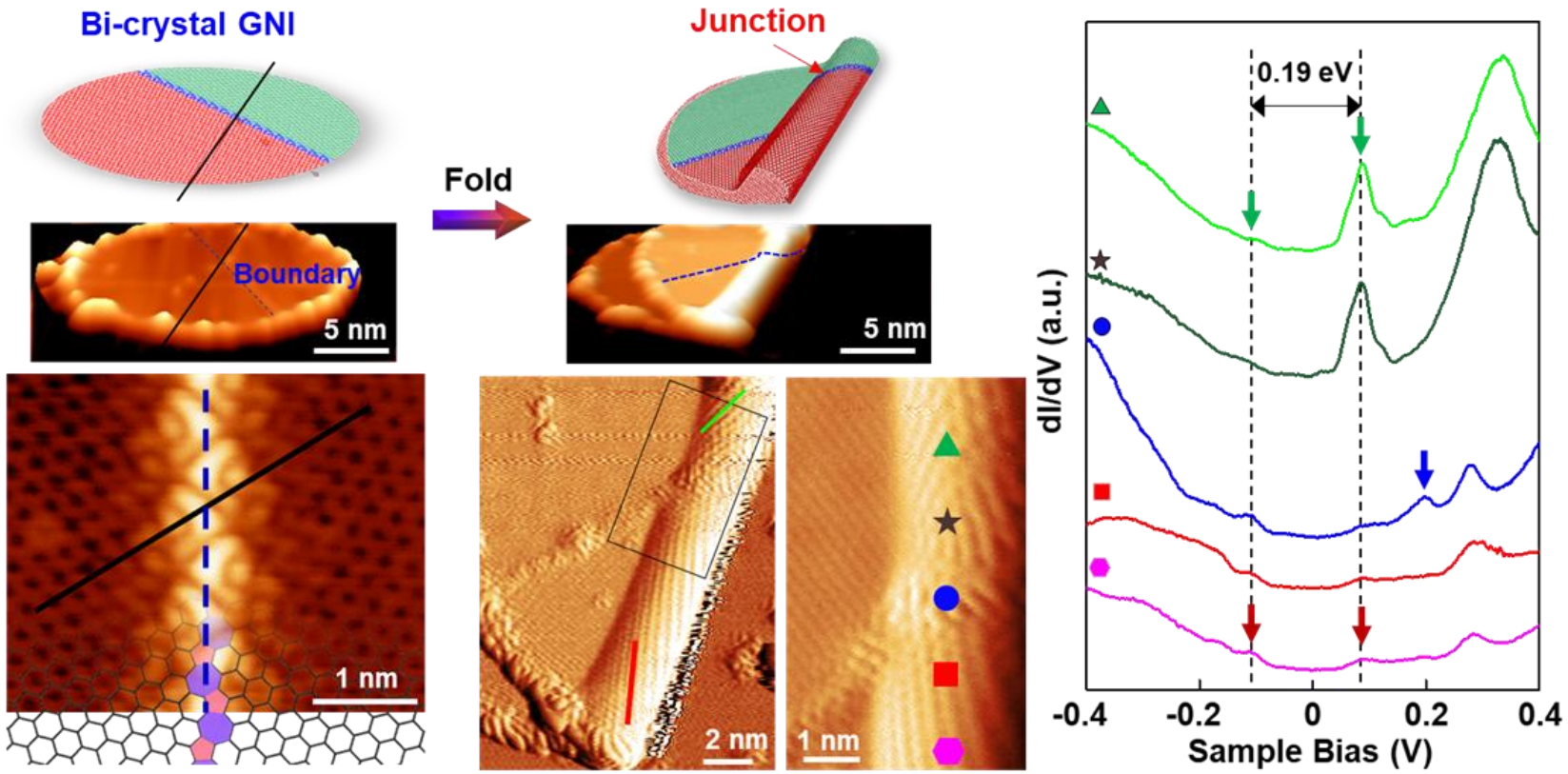
对石墨烯转角的精准控制



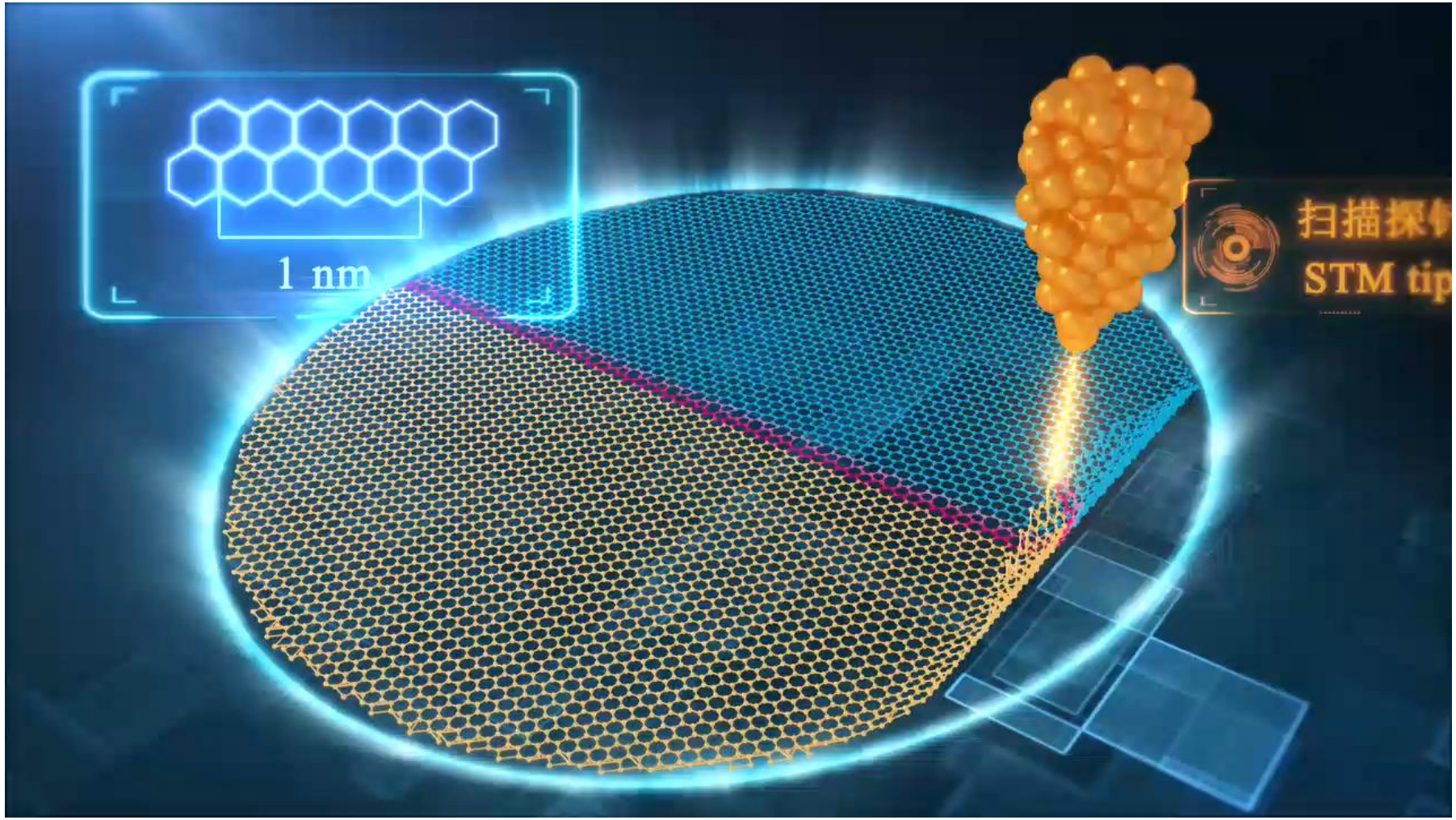
实现了对石墨烯折叠角度的任意控制，旋转角度精度可达

0.1 度（原子级精准）

对石墨烯异质结的可控构筑



实现了基于“折纸术”的类碳纳米管异质结的精准构筑



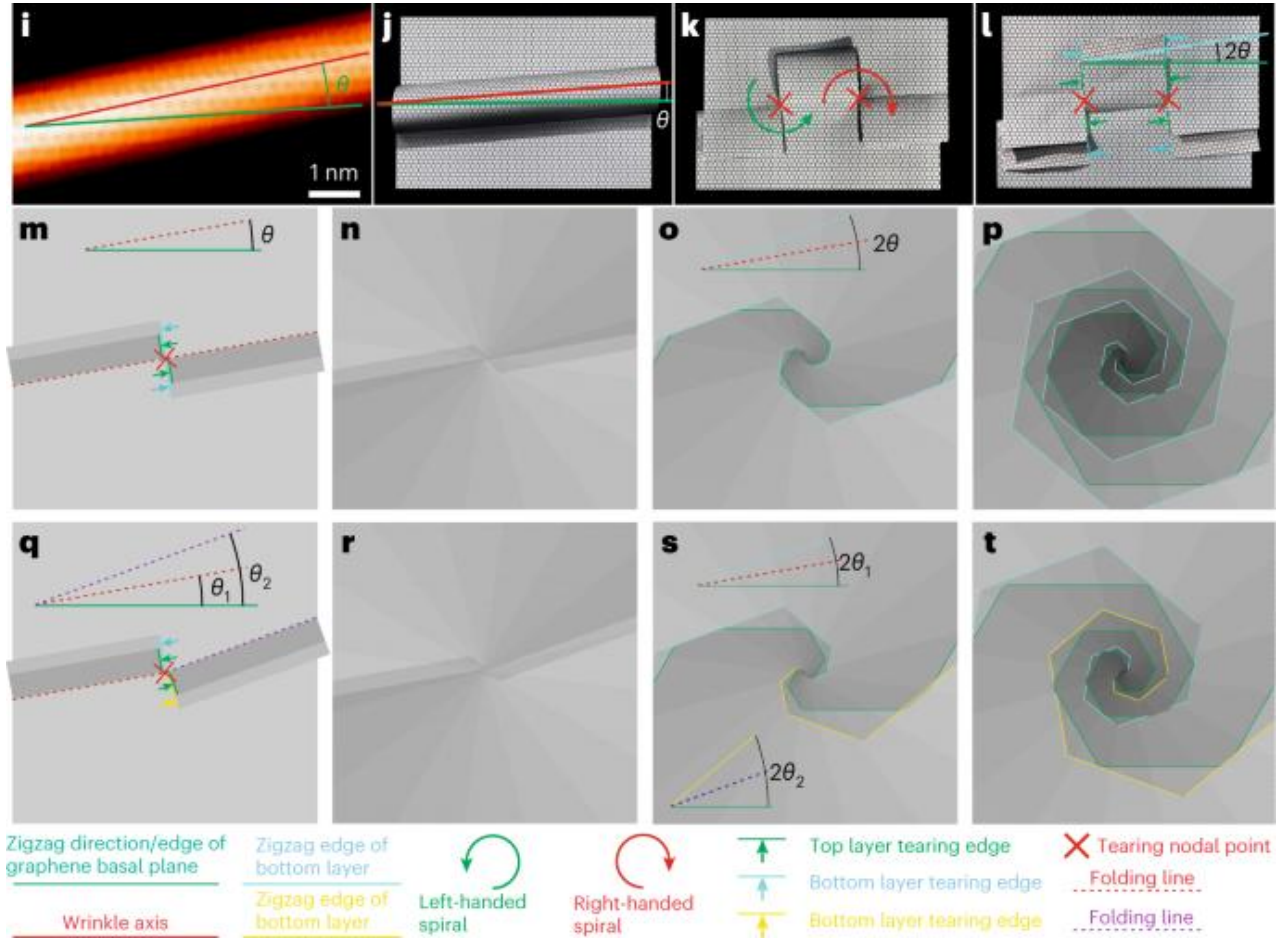
Hui Chen, Hong-Jun Gao *et al.*

Science **365**, 1036 (2019)

展望:基于“折纸术” 的丰富的纳米结构

植物中的**螺旋结构**

石墨烯折叠褶皱、撕裂与再生长，形成相互交织的**石墨烯螺旋**

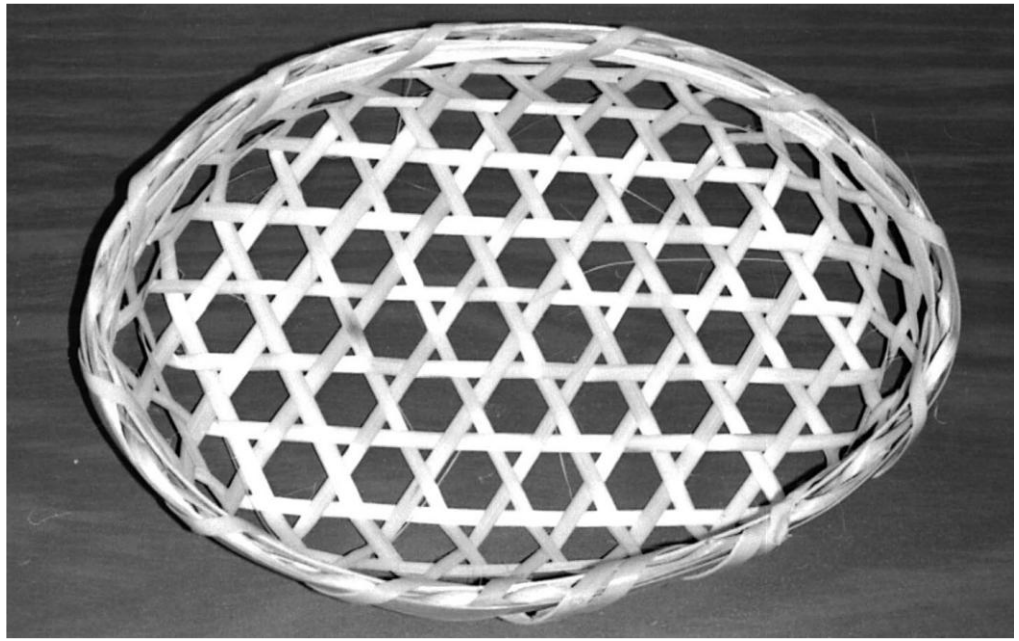


Zhu-Jun Wang, Hui Chen, Hong-Jun Gao *et al. Nat. Mater.* (2023)

From graphene lattice to Kagome Lattice

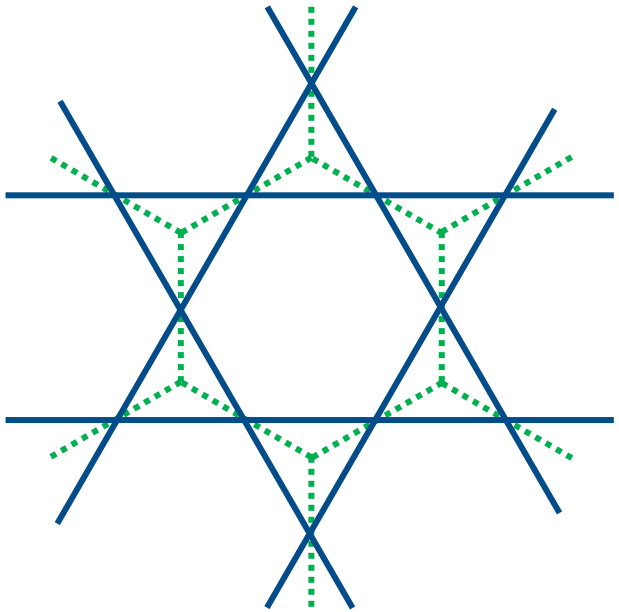
kagome pattern

Bamboo basket (*kago*) woven pattern (*me*)



M. Mekata Phys. Today (2003)

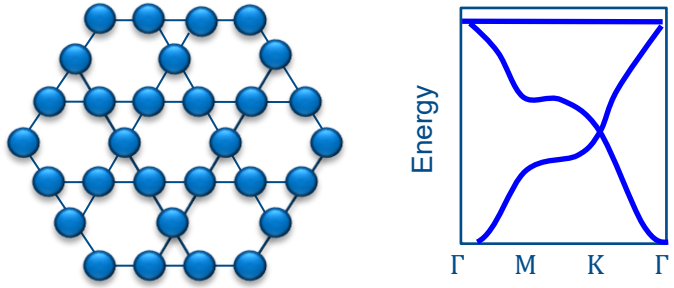
Honeycomb lattice $\xleftrightarrow{\text{Linegraph}}$ **kagome lattice**



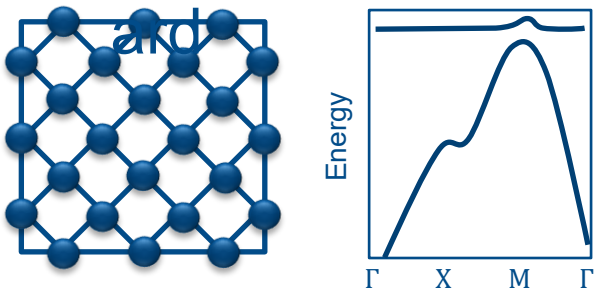
Kagome Lattice

2D flat band lattices

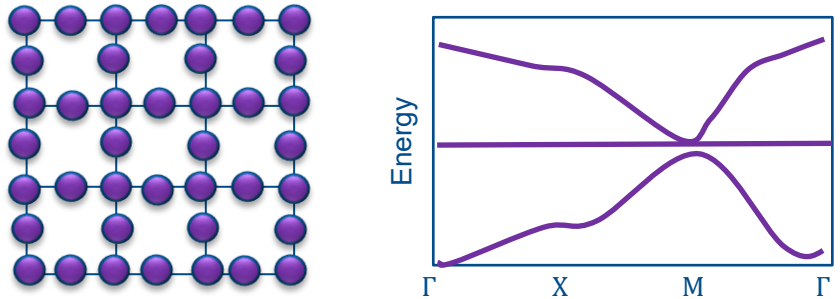
Kagome



Checkerboard



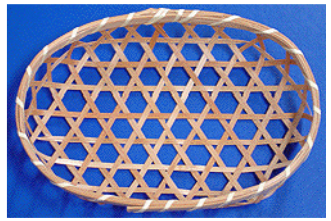
Lieb

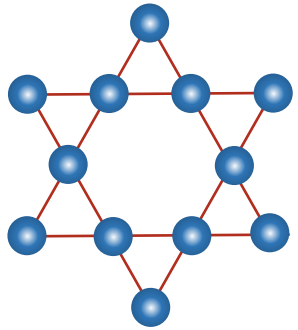


Bernevig *et al.* PRL (2020)

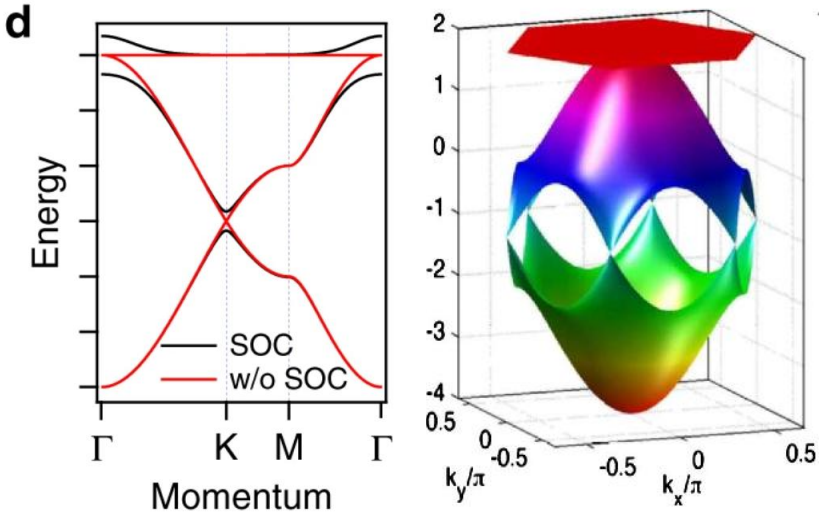
- Dirac points, VHSs and nearly flat bands that naturally promote topological and correlation effects
- Exciting opportunities for exploring frustrated, correlated, and topological quantum states of matter

Kagome





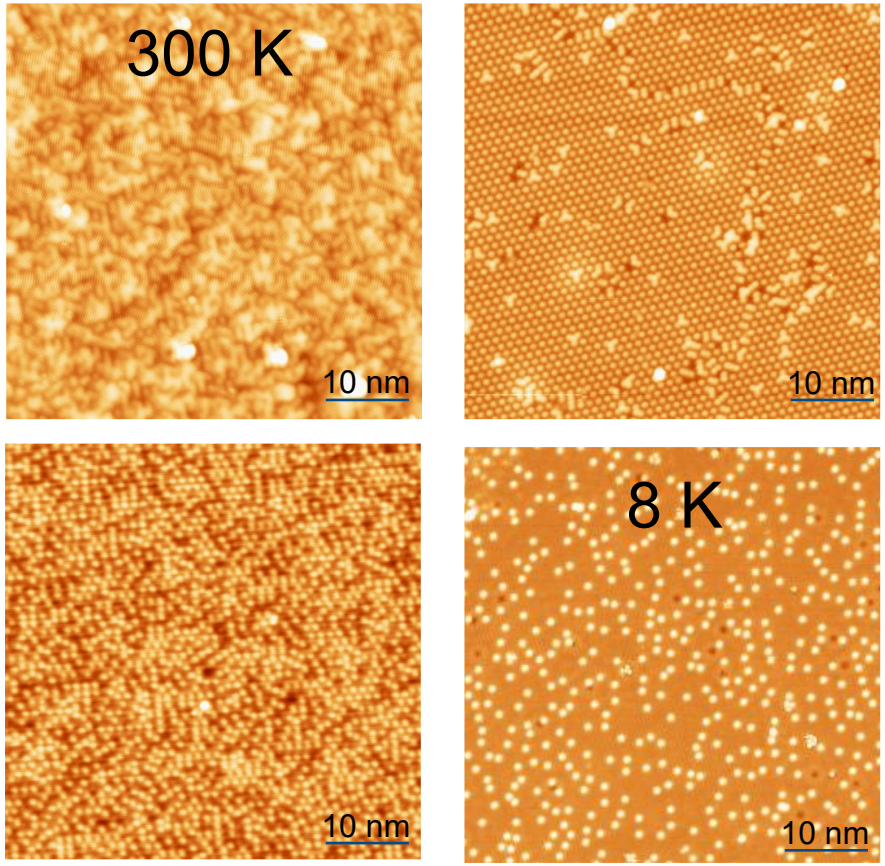
Crossing+Flat band

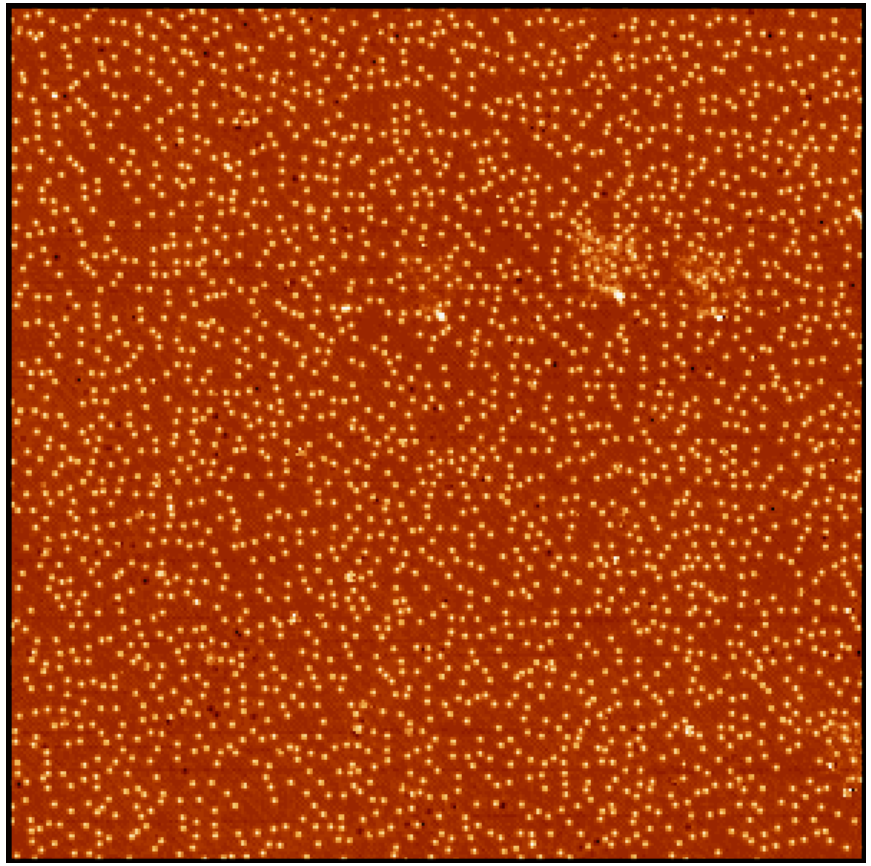


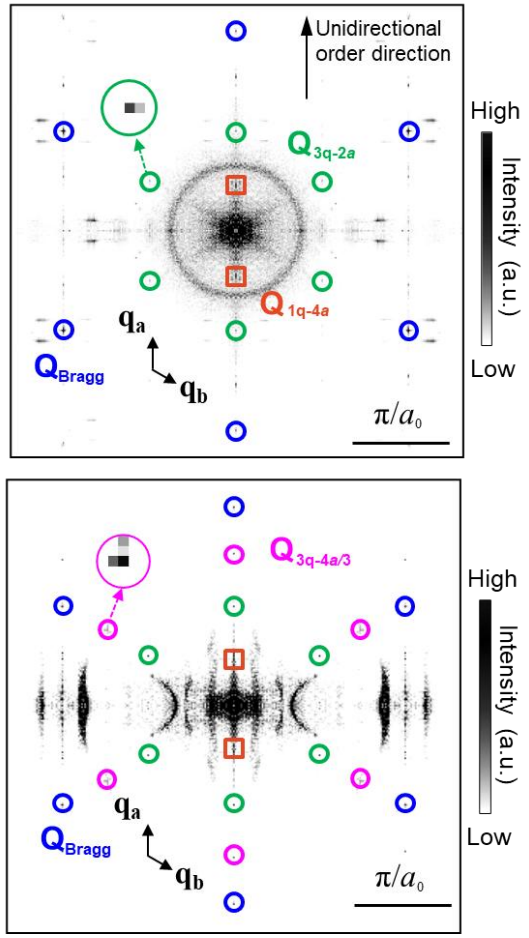
Liu et al. Nat. Commun. (2020)

笼目超导体表面的碱金属原子大规模操纵

传统金属与半导体表面少数次人工操纵 ➡ 拓扑超导体表面上百次自主操纵



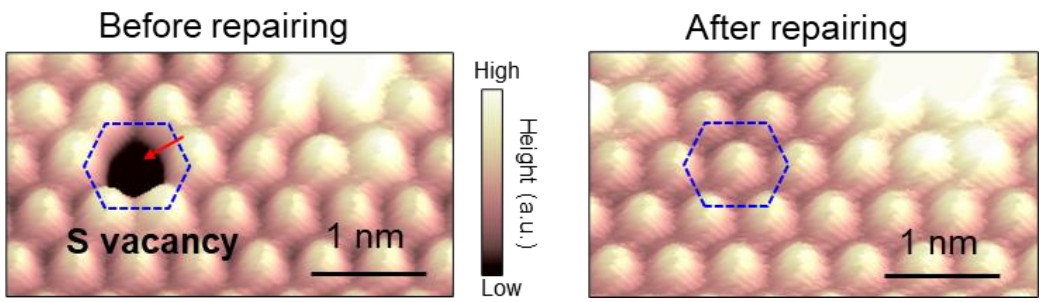


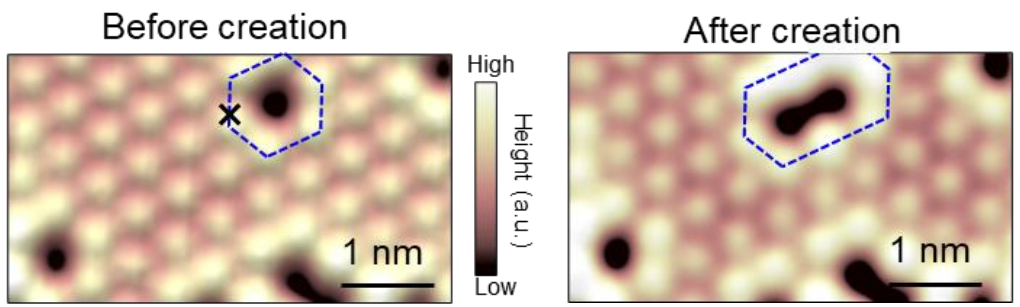


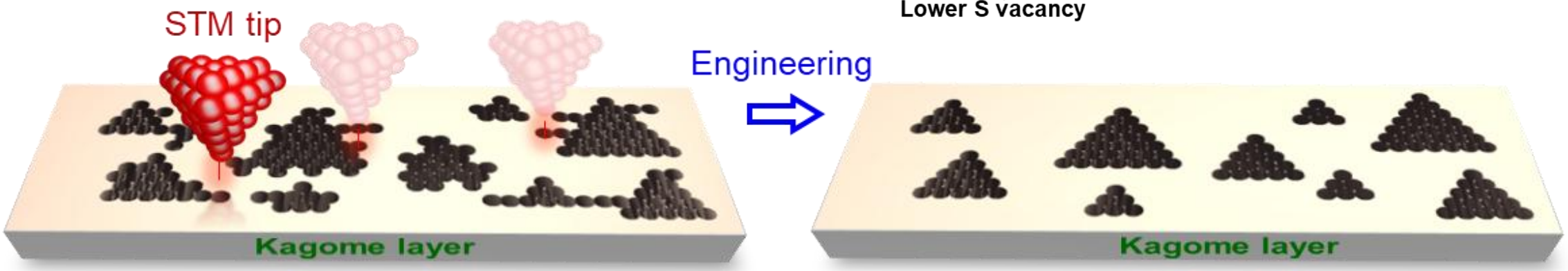
H. Chen and H.-J. Gao *et al. Nature* **599**, 222 (2021)

在磁性外尔半金属中实现“自旋轨道极化子”调控

传统贵金属表面的原子操纵（原子增）➡ 拓扑量子材料的空位缺陷人工操纵（原子减）



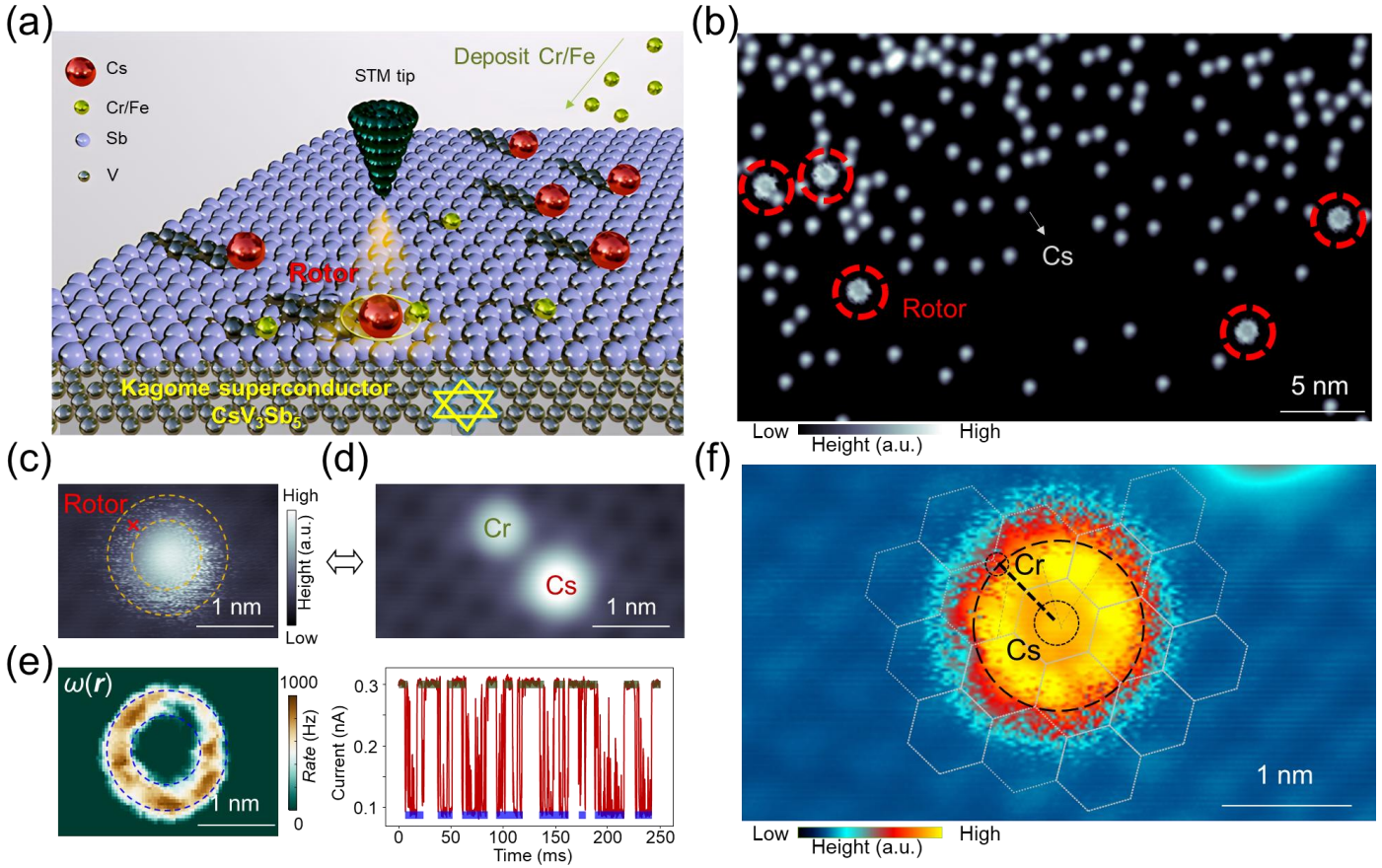


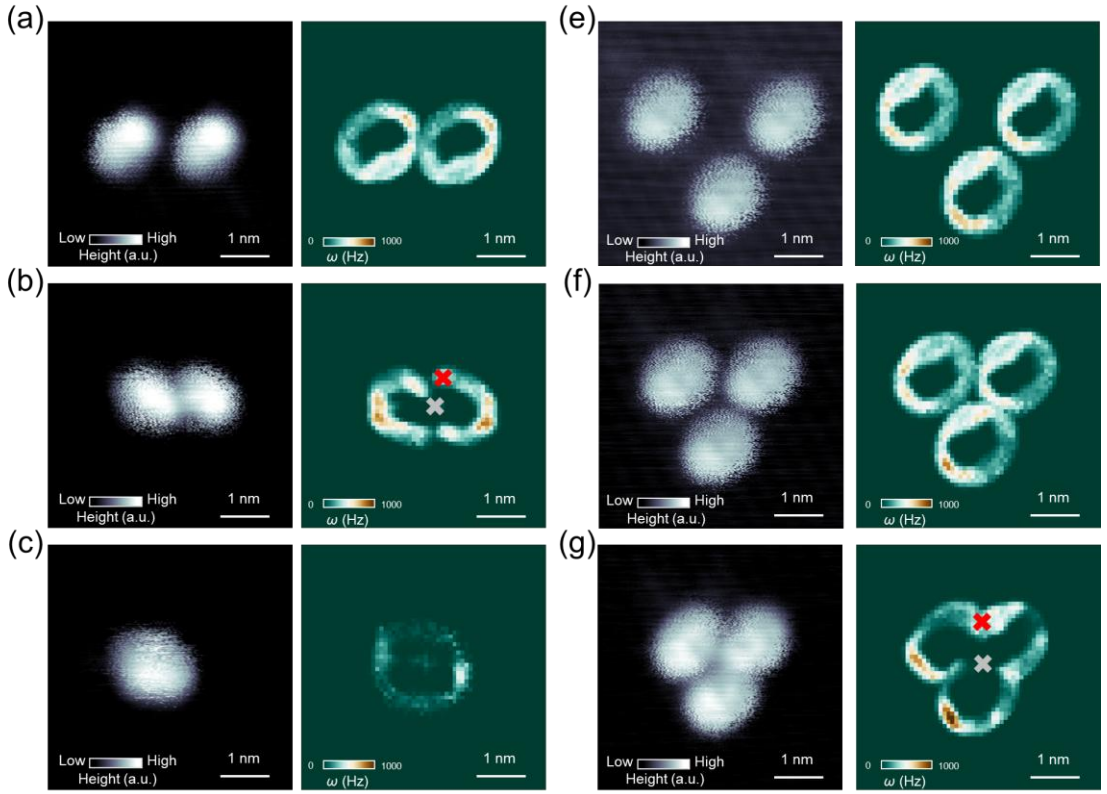


H. Chen and H.-J. Gao *et al. Nature Communications* 15, 2301 (2024)

笼目超导体表面双原子转子的可控操纵

单个原子操纵 ➡ 单个旋转原子体系的可控操纵

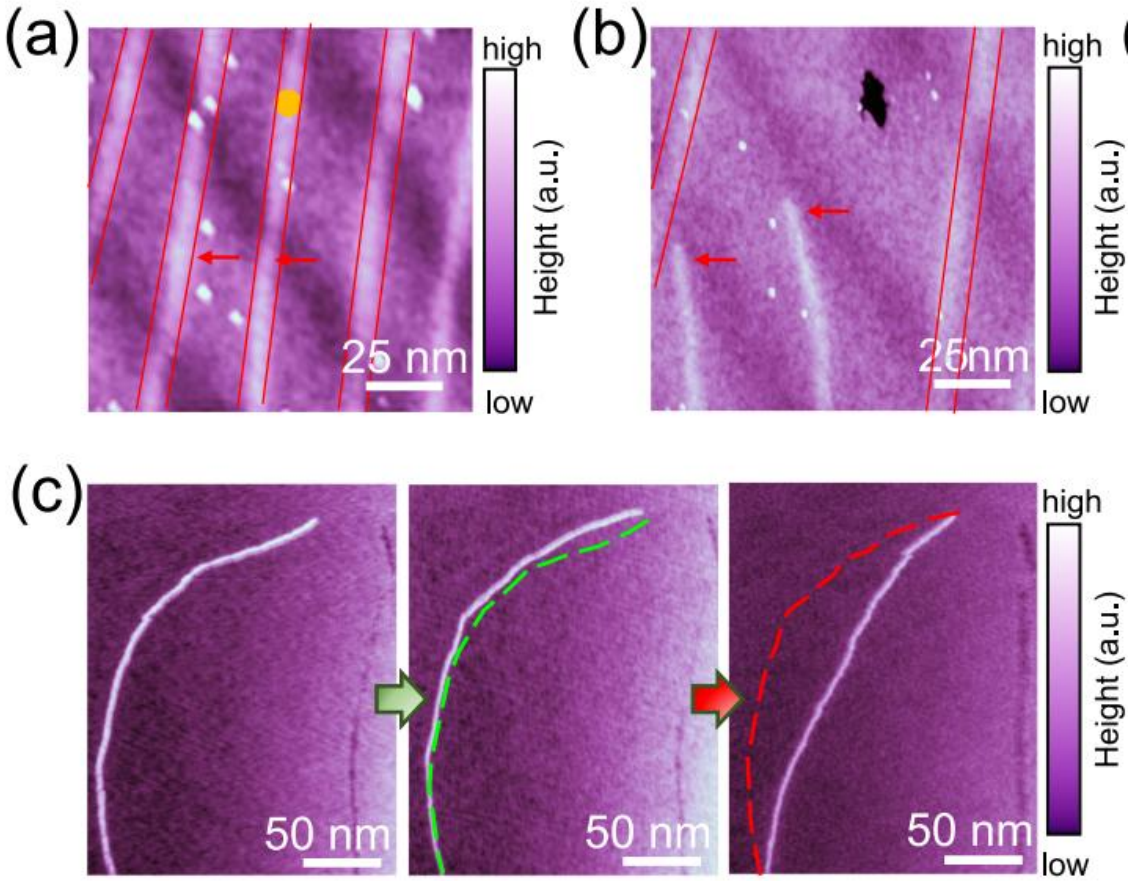


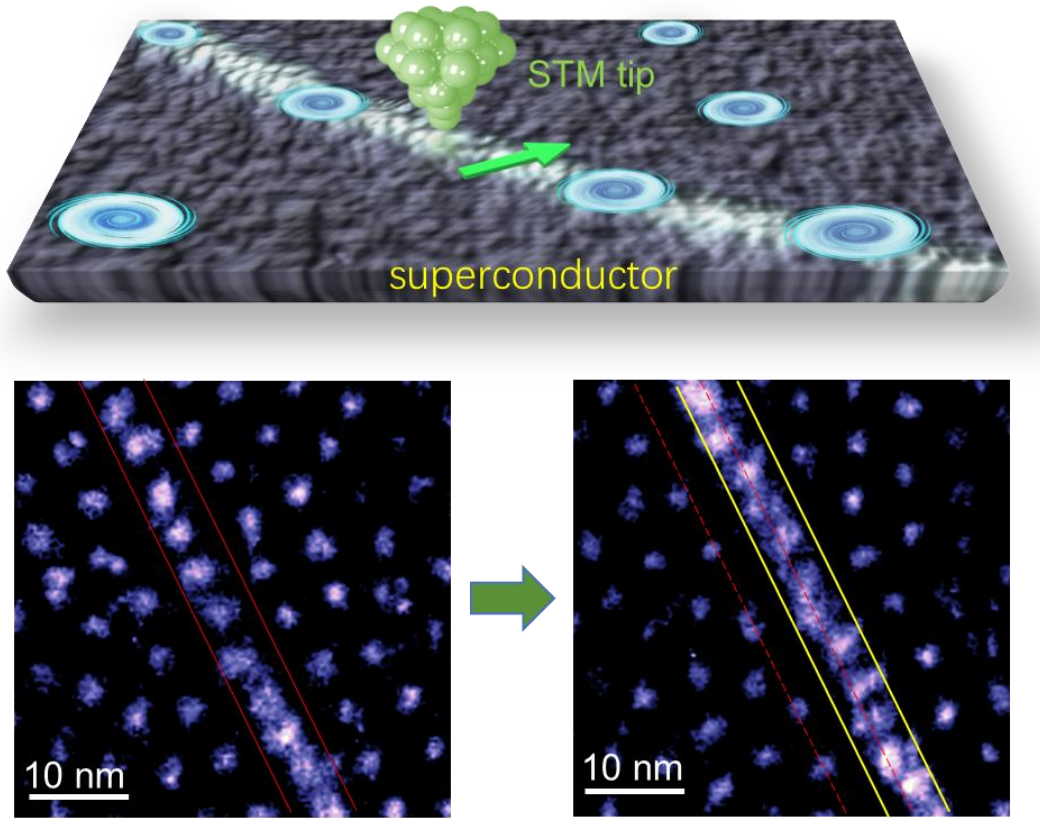


Z. Huang, H. Chen and H.-J. Gao *et al.*, Nano Lett. 24, 6023 (2024)

铁基超导体表面磁通涡旋的可控操纵

单个原子操纵 ➡ 超导体表面一维褶皱以及磁通涡旋线的可控操纵

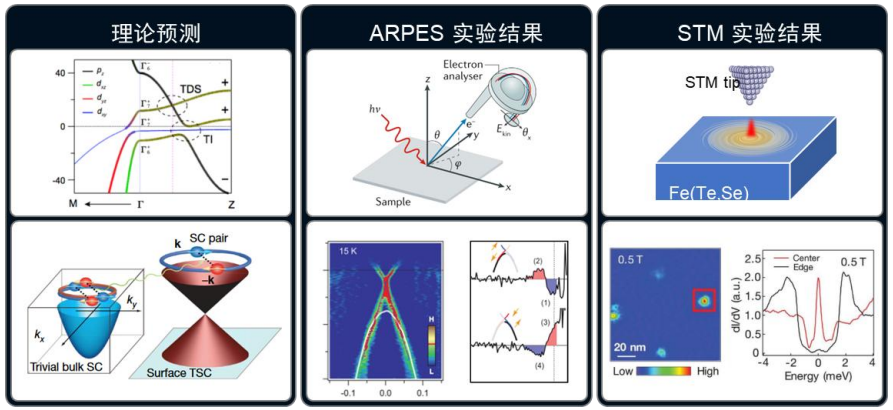




P. Fan, H. Chen, X. Zhou, H. Ding and H.-J. Gao *et al.*, *Nano Lett.* **23**, 4541 (2023)

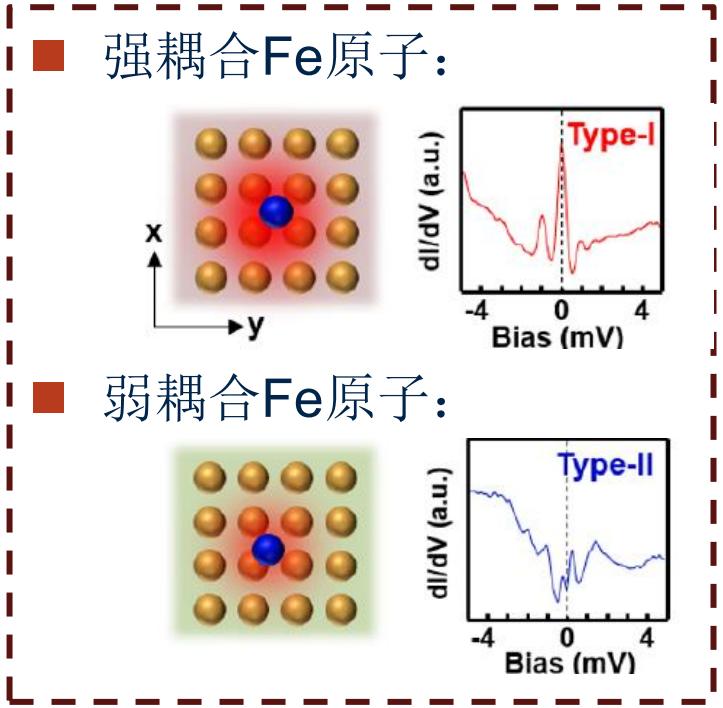
基于单个磁性原子的马约拉纳零能模的操纵

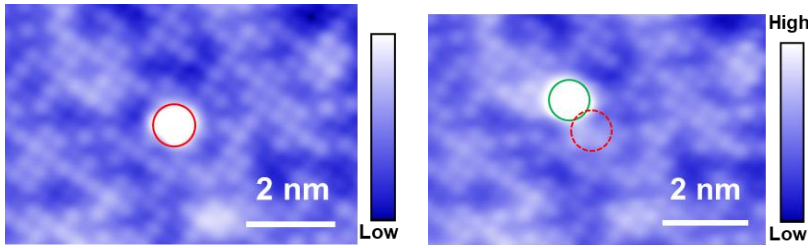
Fe(Te,Se) 单晶中的马约拉纳零能模

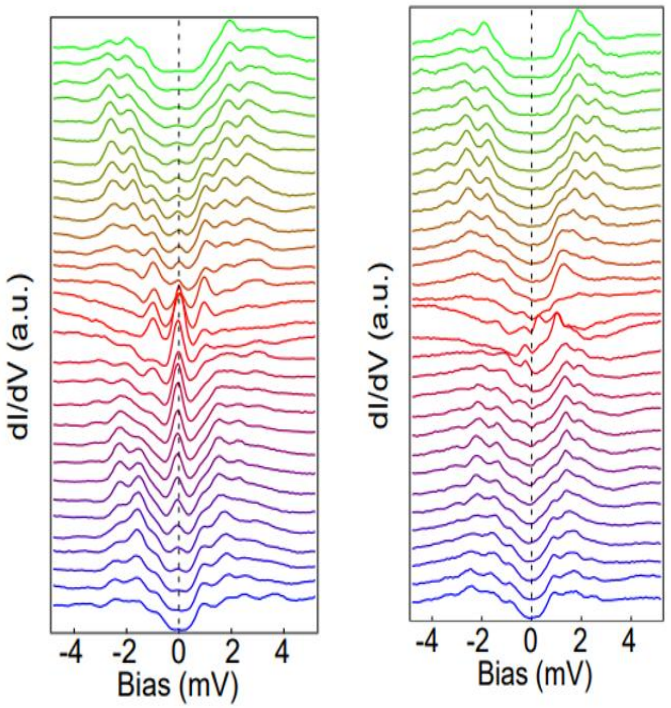


Science (2018), Nat. Phys. (2019), Science (2020)

在Fe(Te,Se)单晶表面上原子制造Fe单原子体系，是目前实现铁基超导体系中最有希望实现马约拉纳零能模编织操纵的研究方向之一。





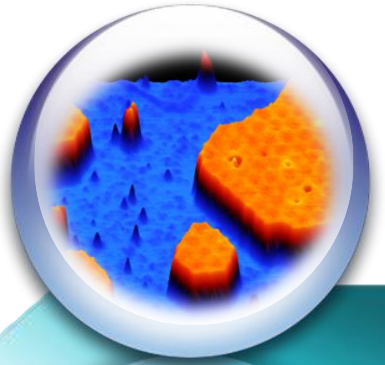


P. Fan, H. Chen and H.-J. Gao *et al.* *Nat. Commun.* **12**, 1348 (2021)

总 结

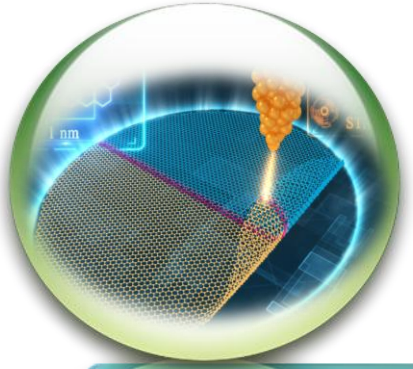
低维材料中的新结构与物性的探寻之路

- 新型石墨烯低维结构的探索



Adv. Mater. (2018) Ph.D.

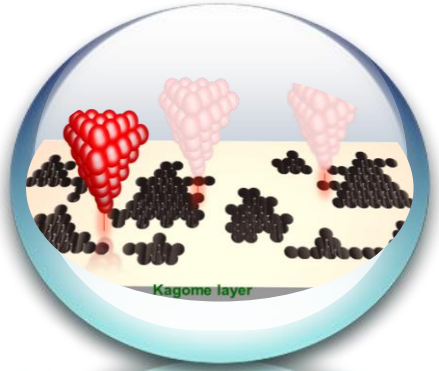
- 石墨烯纳米岛的“折纸术”



Science (2019)

Post Doc.

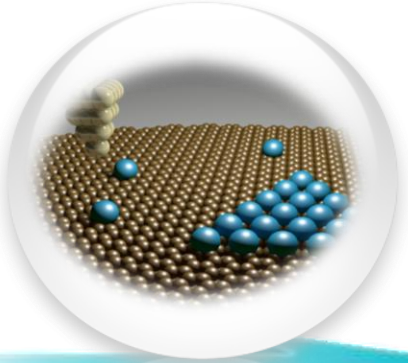
- 拓扑磁性材料低维结构与物性调控



Nat. Commun. (2020)

Nat. Commun. (2024)

- 拓扑超导材料低维结构与物性调控



Nature (2021)

Nat. Commun. (2023)

Nat. Commun. (2024)

Associate Researcher

欢迎青年才俊加入我们的研究团队！

科技强国 锐意进取

良好的科研和文化氛围

凝心聚力 团结奋进

高鸿钧院士

(hjgao@iphy.ac.cn)

欢迎各位青年才俊的加入！

课题组网页： http://n04.iphy.ac.cn/

欢迎参观、访问与交流，联系人：陈辉（17611520119）