低维量子材料中的量子输运与物态调控

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7/3/2025

报告提纲

一、低温物理简介

二、量子输运介绍

三、石墨烯的量子输运性质

个人介绍

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研究员

国家和中科院高层次青年人才计划资助

研究方向：低维量子材料在极低温、强磁场量子输运和物态调控

- **南开大学物理学本科，美国加州大学河滨分校博士、博士后**
- **英国曼彻斯特大学博士后 (导师 Kostya Novoselov)**

代表性成果：

少层石墨烯量子输运：建立了少层石墨烯中电场、载流子浓度等对能带结构调控方法。

Y. Shi *et al*. ***Phys. Rev. Lett.*116**, 056601 (2016)

Y. Shi *et al*. ***Phys. Rev. Lett.***120, 096802 (2018)

S. Che, Y. Shi *et al*. ***Phys. Rev. Lett.*125**, 036803 (2020) (共同一作) （**编辑亮点论文**）

二维量子材料中量子物态调控：首次直接观测到WTe_2中拓扑边界态；构建了石墨烯基高度可调控的电子关联系统。

Y. Shi et al., ***Sci. Adv.*** 5, eaat8799 (2019)

Y.Shi *et al*. **Nature 584, 210–214 (2020)**

Y.Shi* **Nat.Phys.17,619–626(2021)（共同通讯）**

报告提纲

一、低温物理发展历史

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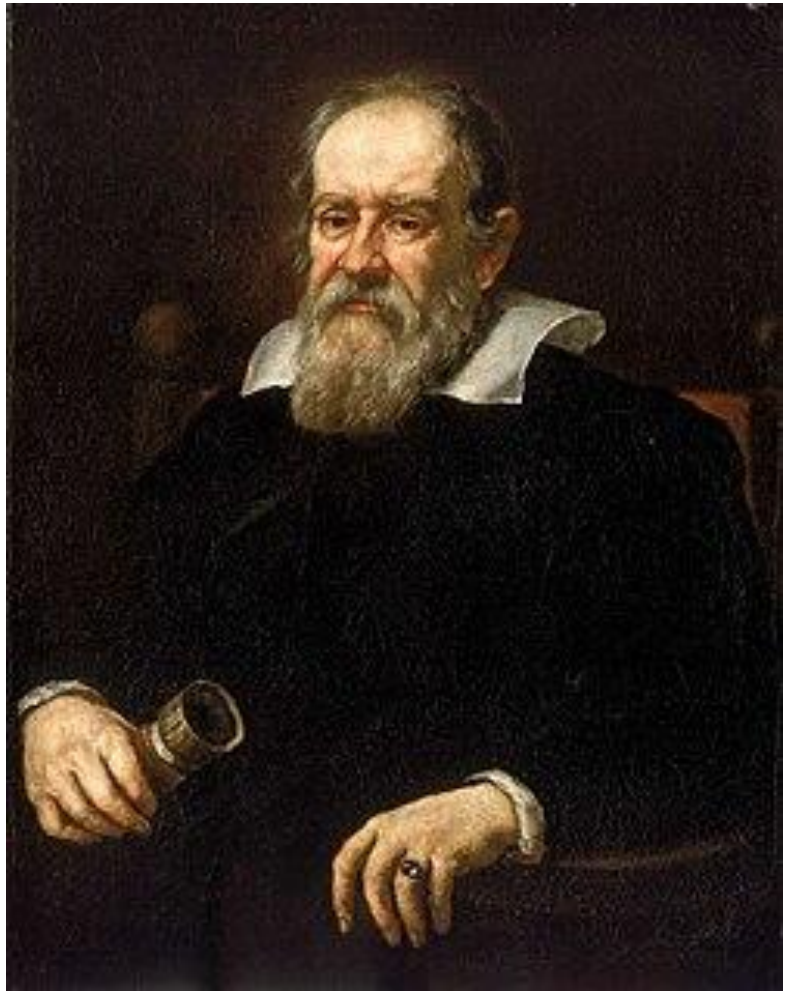
最早的热温度计



伽利略温度计： 液体热胀冷缩，不同重量的漂浮物指示温度（1592）

绝对零度

理想气体：

$$pV = nRT$$

阿蒙顿， 法国物理学家

实验结果表明，在压强不变的情况下，这些气体的温度每升高1°C，体积的增加量总是一个固定的值，大概是其在0°C时体积的273分之1。

绝对零度： -273.15 °C

追逐低温

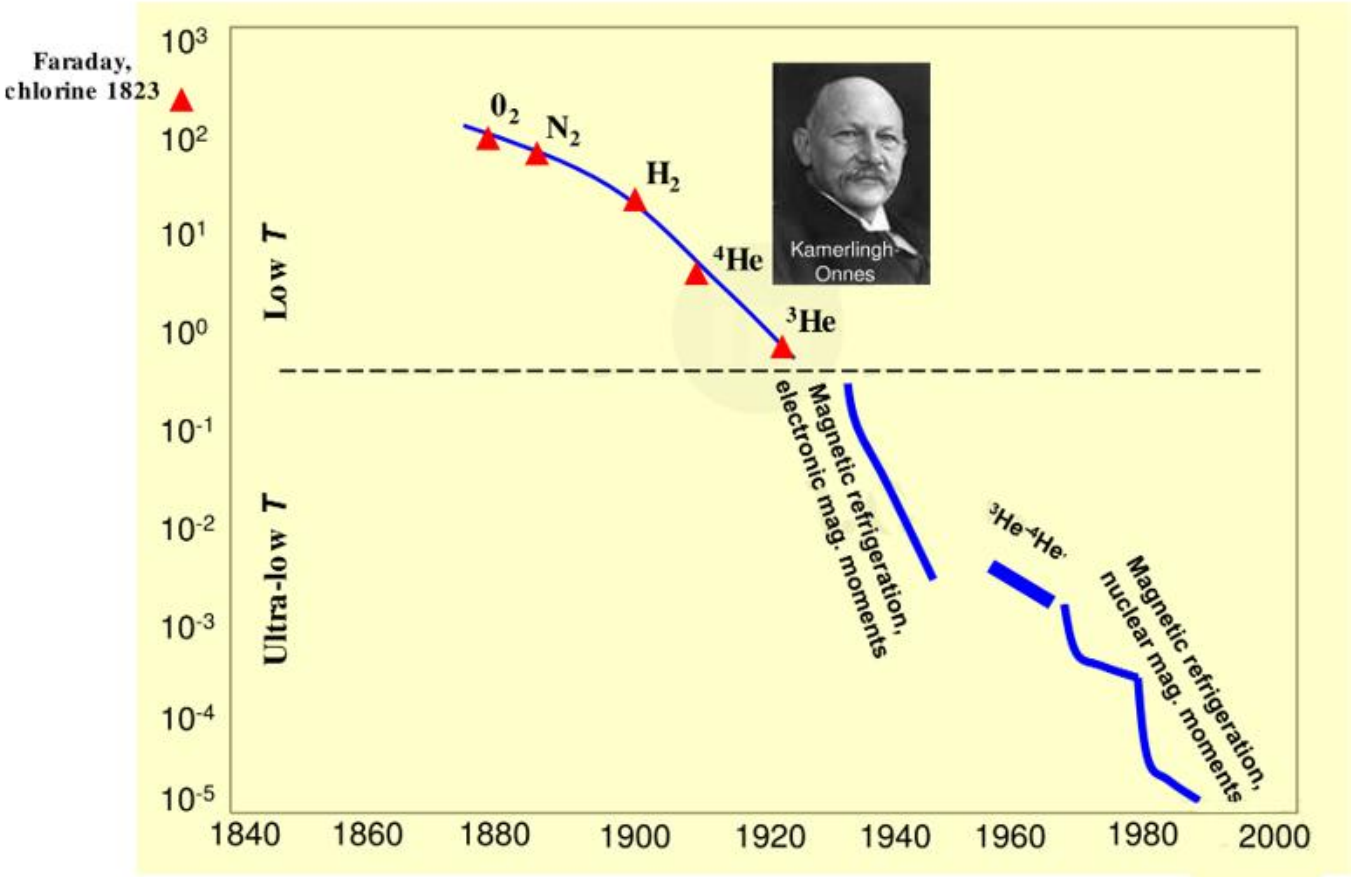


Table 1.1. Refrigeration techniques. The methods which dominate in the three temperature ranges are in italics

Temperature range		Refrigeration technique	Available since	Typical T_{min}	Record T_{min}
I	Kelvin	Universe			2.73 K
		Helium-4 evaporation	1908	1.3 K	0.7 K
		Helium-3 evaporation	1950	0.3 K	0.23 K
II	Milli-kelvin	**^{3}He–^{4}He dilution**	1965	10 mK	2 mK
		Pomeranchuk cooling	1965	3 mK	2 mK
		Electronic magnetic refrigeration	1934	3 mK	1 mK
III	Micro-kelvin	**Nuclear magnetic refrigeration**	1956	100 μK	1.5 μK[a]

[a]The given minimum temperature for the microkelvin temperature range is the *lattice* (*electronic*) *equilibrium* temperature. *Nuclear spin* temperatures as low as 0.3 nK have been reached (Table 10.2)

- 液氮： 77K
- 液氦^{4}He： 4.2K
- ^{3}He：0.3K
- ^{3}He-^{4}He: 10mK
- 绝热去磁制冷： μK

低温相关的物理诺尔贝尔奖

- 1913年荷兰Kamerlingh Onnes于1908年成功实现了氦气的液化，使地球上最后一种永久气体—氦气得到液化；并于1911年发现超导现象，导致了超导物理学的诞生。
- 1962年俄国Landau因1941年提出氦和碳流动性的量子理论，他个人因在超流动性方面的理论研究
- 1972年英国Bardeen, Cooper, Schrieffer因1957年提出超导体中存在着电子对，这些电子对可以不受任何散射地通过由失去部分电子的原子所组成的通道，不会引起原子振动，即为超导现象的理论（BCS超导电性理论）。
- 1973年英国Brain Josephson于1963年英国剑桥大学读研究生时从理论上预言超导隧道效应
- 1978年俄国Kapitsa于1937年发现氦的超流现象
- 1985年德国von Klitzing因1980年发现量子霍尔效应
- 1987年Bednorz和Muller1986年在发现陶瓷材料的超导电性方面所作的重大突破
- 1996年美国D.M. Lee, D. D.Osheroff, R.C.Richardson获奖。20世纪70年代初，在康奈尔大学的低温物理实验室发现氦的同位素—3He在绝对零度之上约0.002K时变为超流体，证明微观物理量子规律有时会直接影响宏观物体的行为
- 1997年朱棣文等人因激光冷却和陷解原子获Nobel奖
- 1998年崔琦等3人因发现分数量子霍尔效应获Nobel奖
- 2001年Cornell, Ketterle, Wieman因实现Na,Rb等金属原子气的Bose-Einstein凝聚获Nobel奖
- 2003年俄国Abrikosov获Nobel奖以表彰他们在超导体和超流体理论上作出的开创性贡献。
- 2010年Andrea Geima和Kostya Novoselov发现了石墨烯

一、低温物理发展历史

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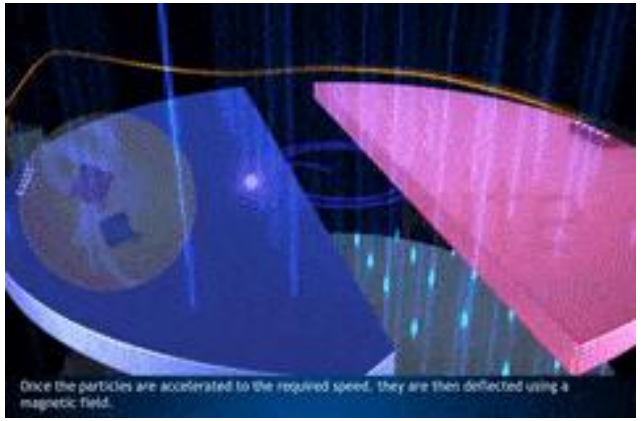
什么是量子输运?

输运问题: **粒子在外场作用下的运动规律**

回旋加速器

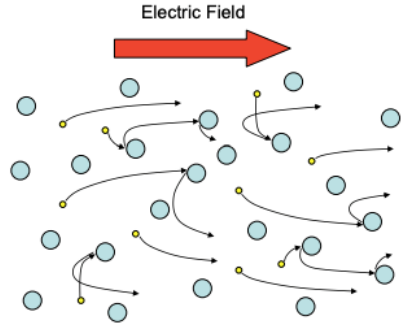


单粒子运动

$$m\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = q\vec{E} + q\vec{v}\times\vec{B}$$

固体物理
Drude's model

单粒子运动规律+统计平均



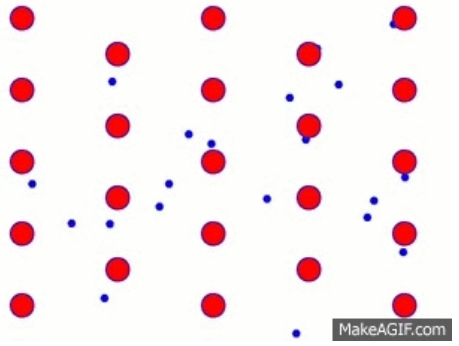
$$\vec{v}_d = -\frac{q\vec{E}}{m}\tau$$

$\vec{j} = -ne\vec{v}_d$

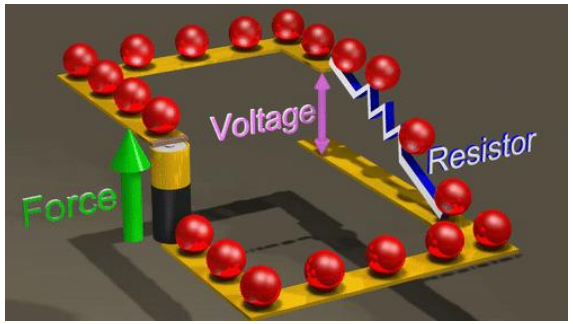
电导

$$\sigma = \frac{ne^2\tau}{m}$$

晶体中电子的集体运动



欧姆定律



什么是量子输运：霍尔效应 VS 量子霍尔效应

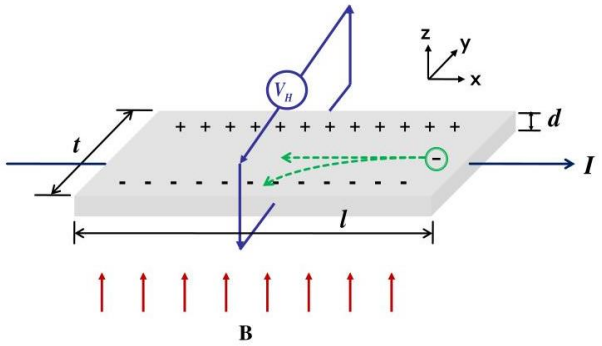
霍尔效应

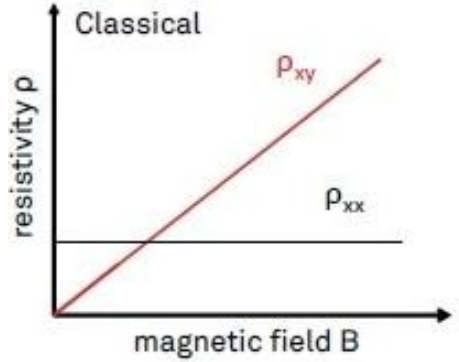
$$m\frac{\mathrm{d}\vec{v}}{\mathrm{d}t} = q\vec{E} + q\vec{v}\times\vec{B}$$

洛伦兹力=静电力

$$v_y = 0 \longrightarrow \rho_{xy} = -\frac{B}{ne}$$

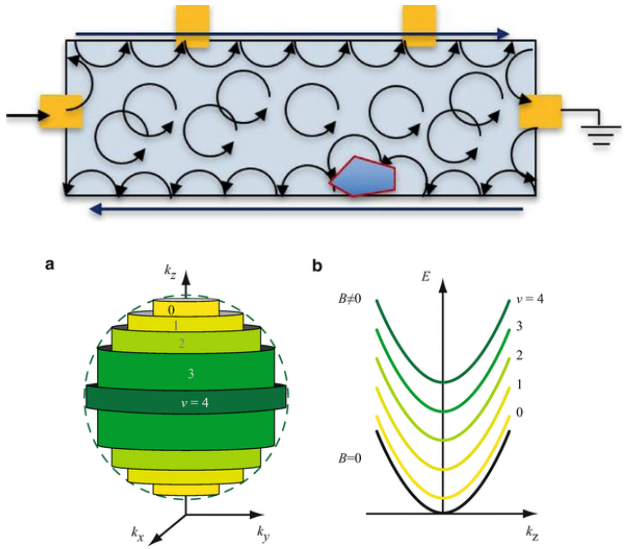
半导体工业的物理基础



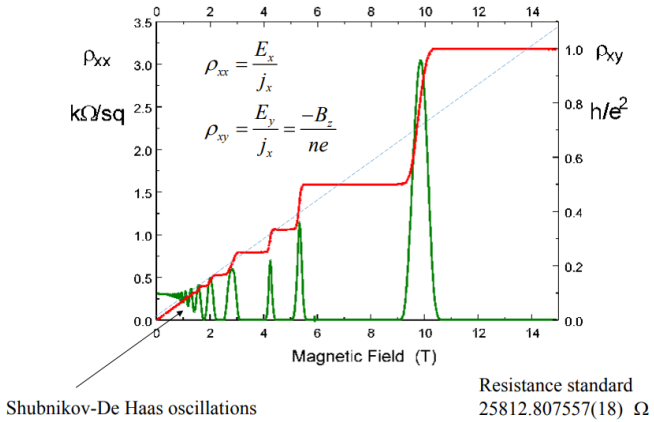


量子霍尔效应

朗道能级



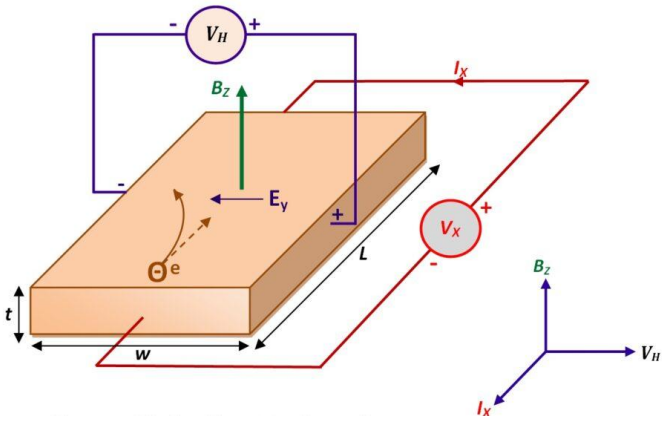
量子化电导

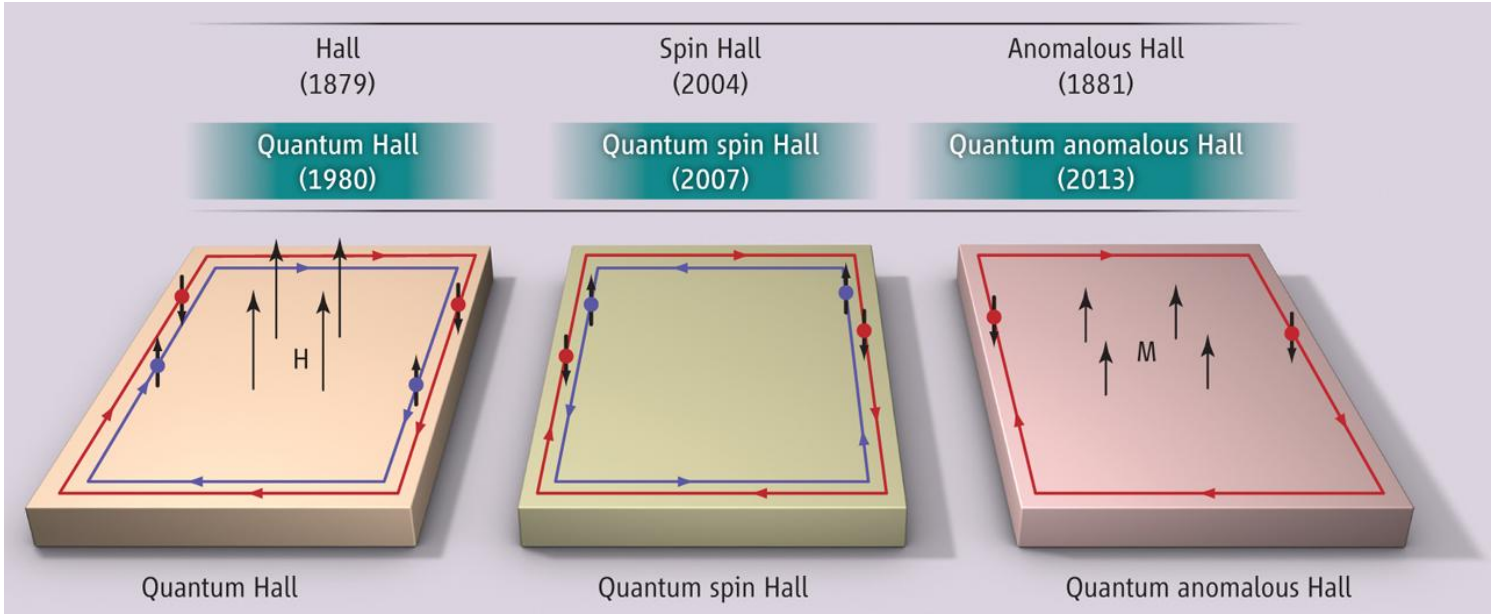


量子输运系统特性：
- 时间尺度 < 弛豫时间
- 空间尺度 < 平均自由程
- 能量尺度 < 量子能级

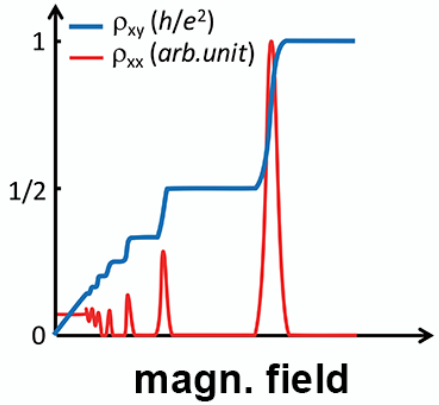
量子输运系统特性：
- 超快
- 弹道输运
- 低温、强磁场

The Family of Hall Effect

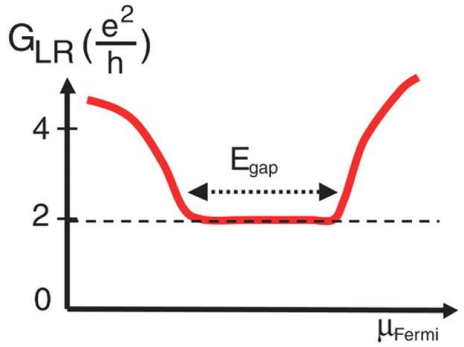




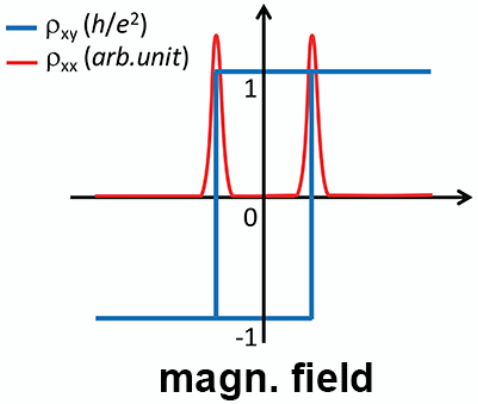
Quantum Hall



Quantum Spin Hall Effect

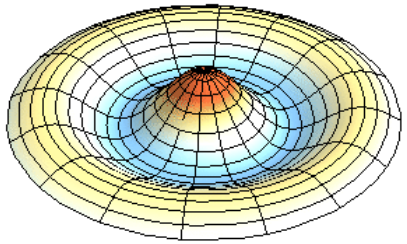


Quantum Anomalous Hall

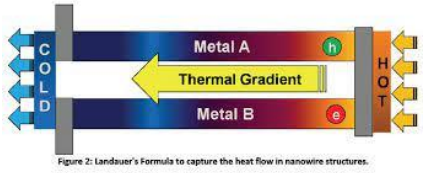


研究量子输运的实验手段

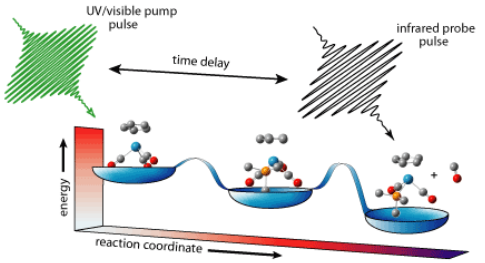
力



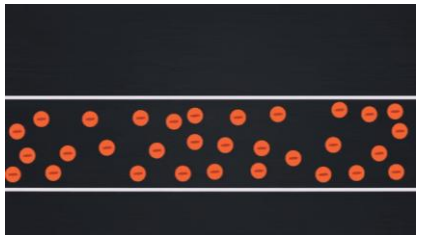
热



光

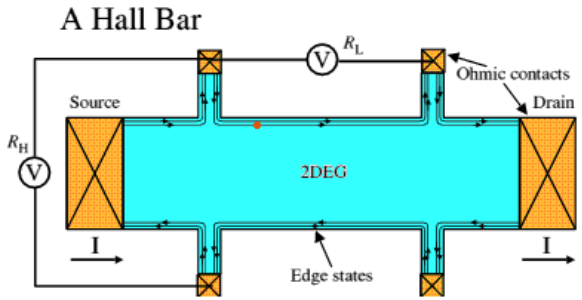


电

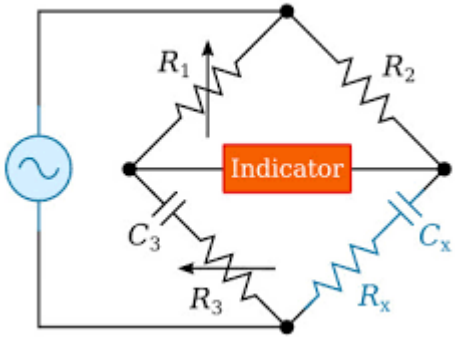


磁

电输运



电容测量



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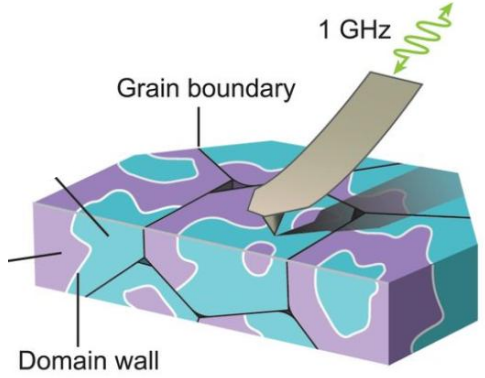

一、低温物理发展历史

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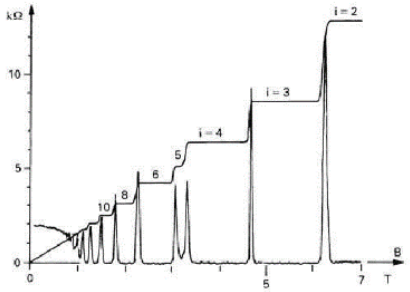
三、石墨烯的量子输运性质

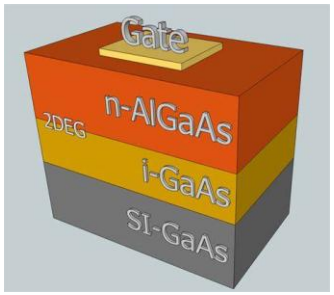
二维量子体系

2DEG: 量子霍尔效应(1980)



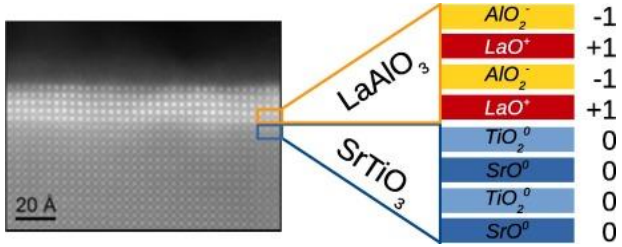
K. Von Klitzing, *et al*, Phys. Rev. Lett. 45, 494 (1980)

分数量子霍尔效应(1982)

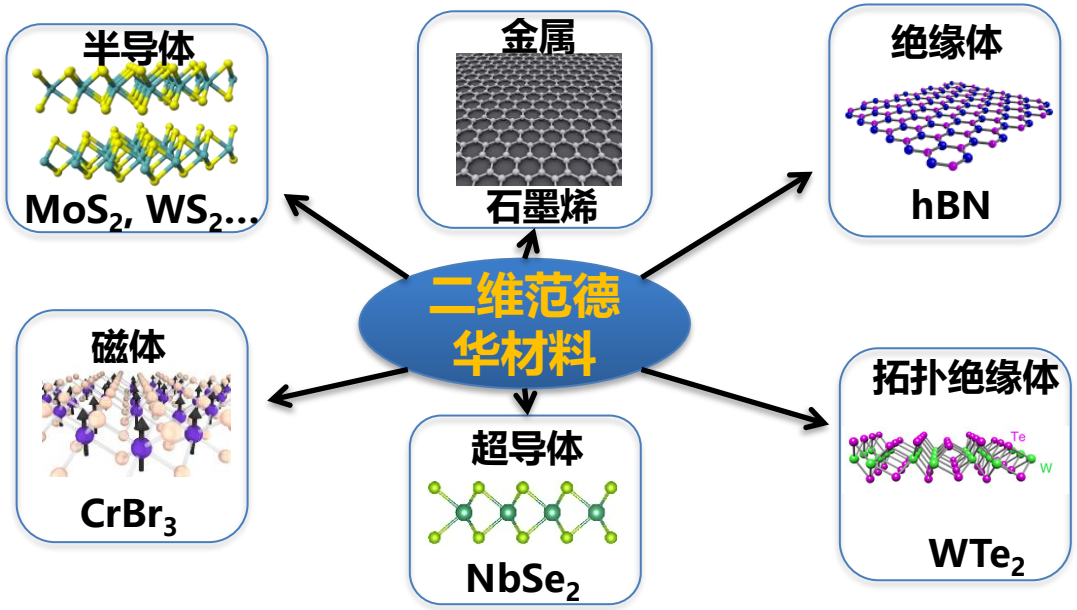


D..C. Tsui, *et al*, Phys. Rev. Lett. 48, 1559 (1982)

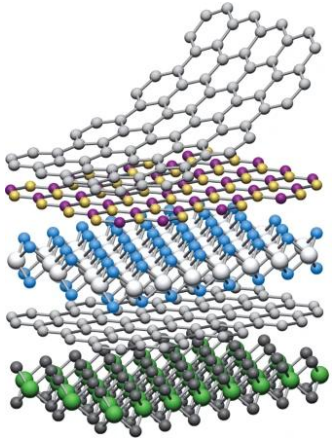
界面超导： LAO/STO



二维材料家族(2004)



范德华异质结： 裁剪物理性质有效手段

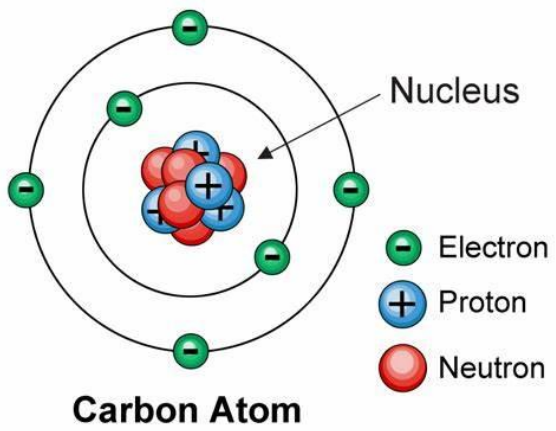


A.K.Geim, *et al*, Nature 2013

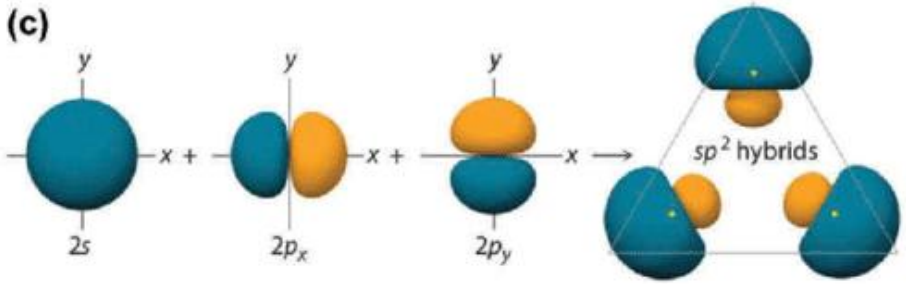
- 低维量子系统
- 新奇量子物态
- 量子调控
- 光电器件应用

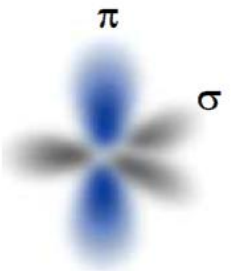
第六元素： C

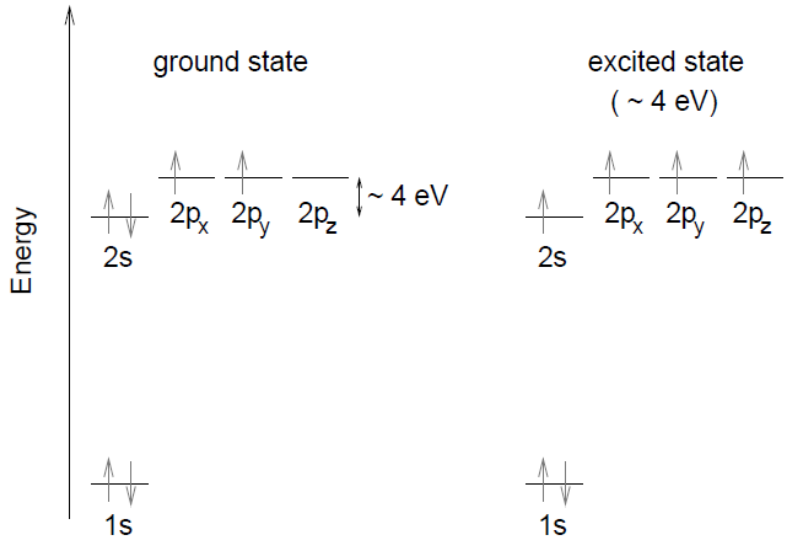
碳元素

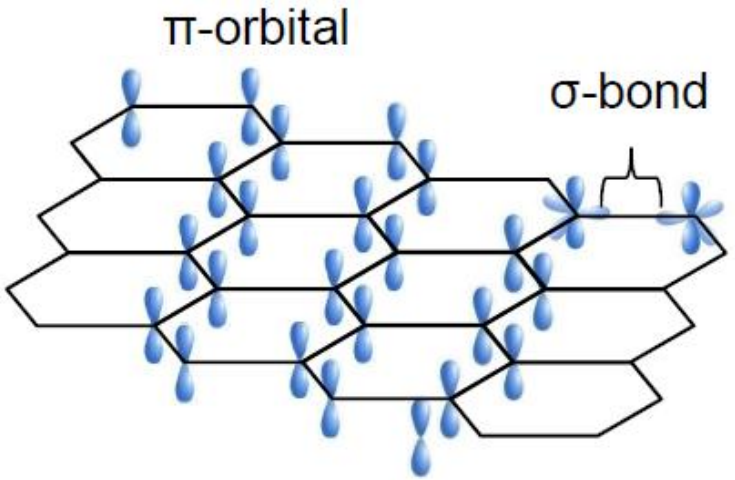


SP^2 轨道杂化

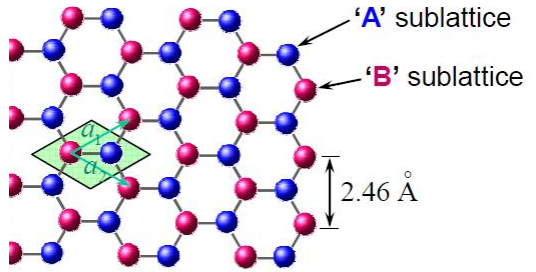






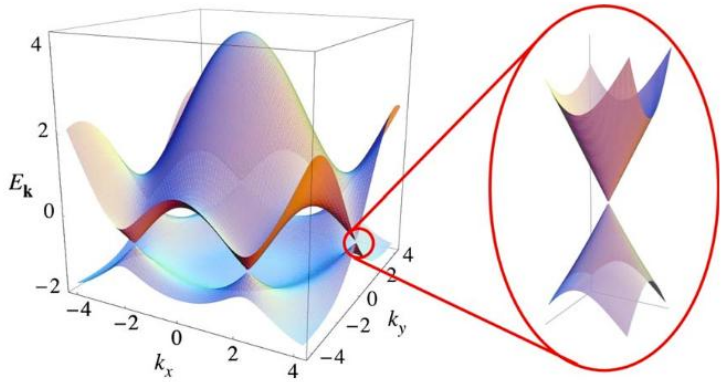


每个元胞包含A、B两个原子



单层石墨烯与石墨

单层石墨烯能带结构



$$E = \pm \hbar v_F |p|$$

$$V_F = \frac{\sqrt{3} a \gamma_0}{2\hbar} \approx 10^6 \text{m/s}$$

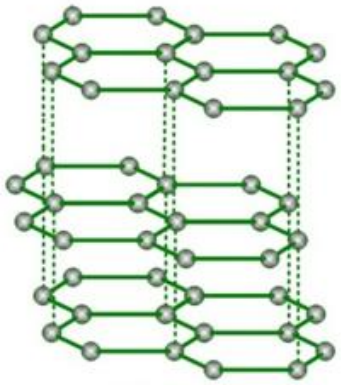
Andre Geim

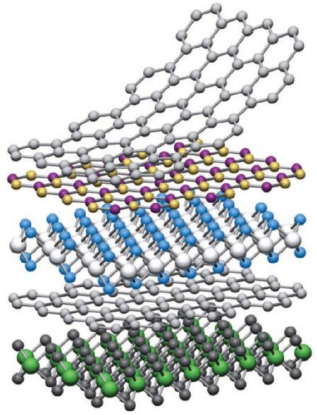
Konstantin Novoselov

Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1]* S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

多层石墨和范德华异质结

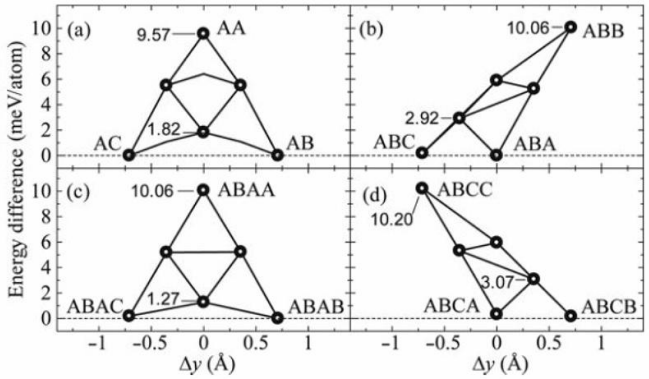

(3D) Graphite



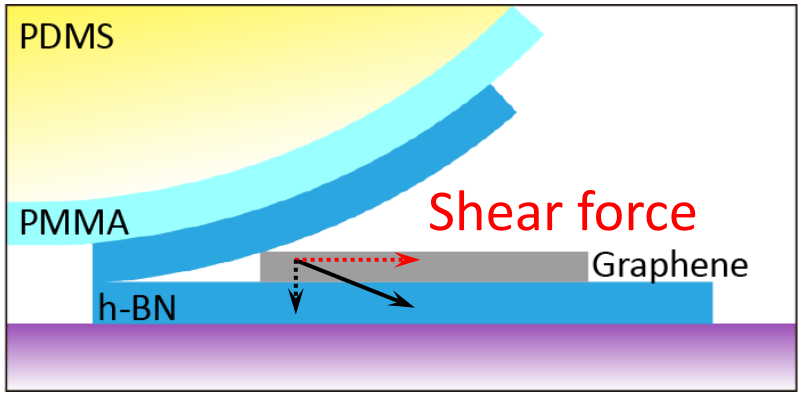
器件制备

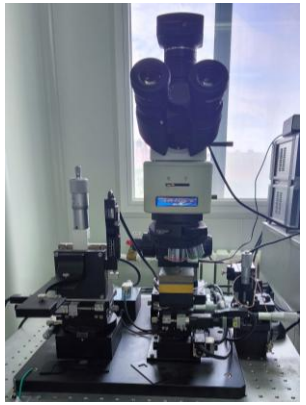
C.H. Lui, *et al* Nano Lett.(2010)
Y.Yang, *et al* Nano Lett.(2019)

M. Aoki *et al* Solid State Comm.(2015)

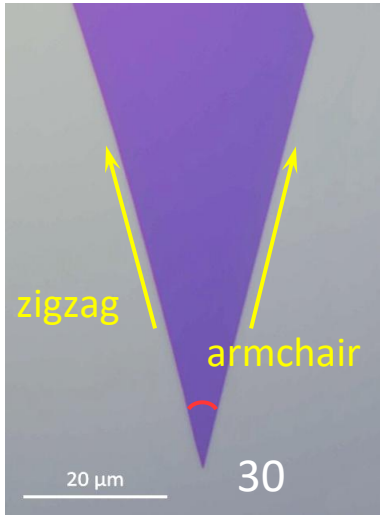


15% of exfoliated flakes contain ABC component



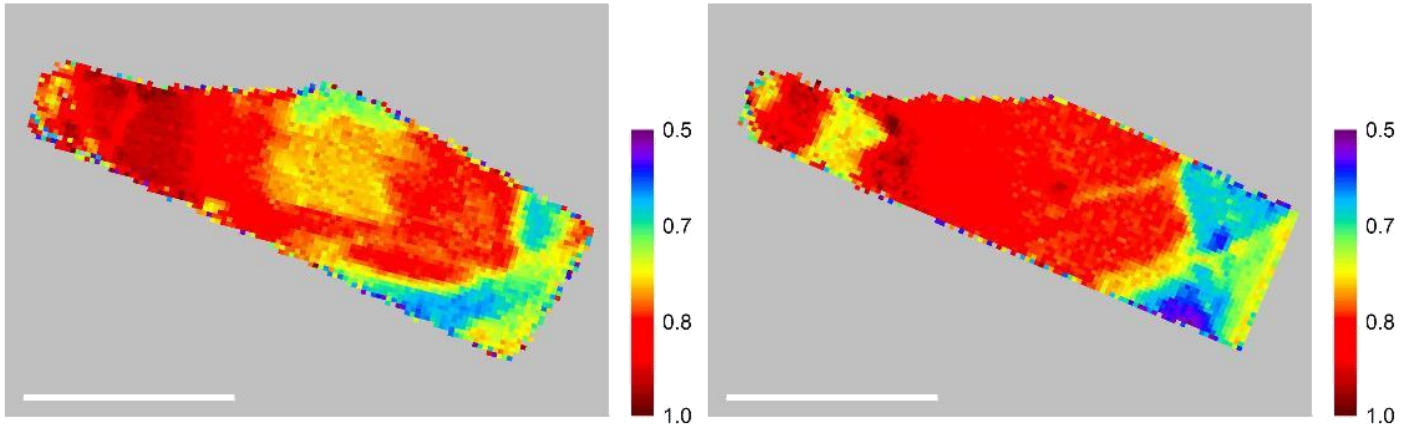


高精度转移平台

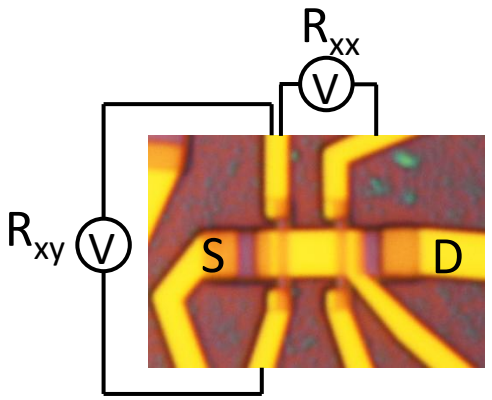


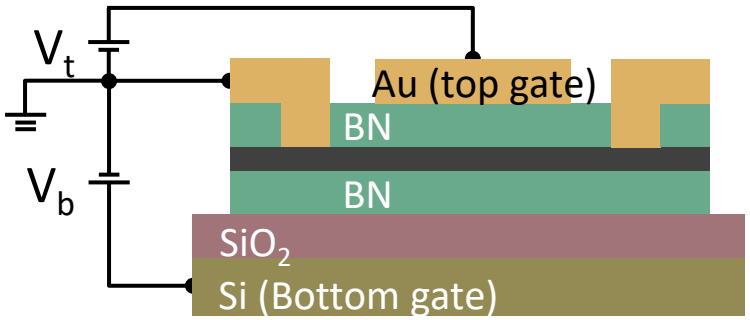
Before encapsulation

After encapsulation



电输运测量





载流子浓度:

$$n = (C_t V_t + C_b V_b)/2 - n_0$$

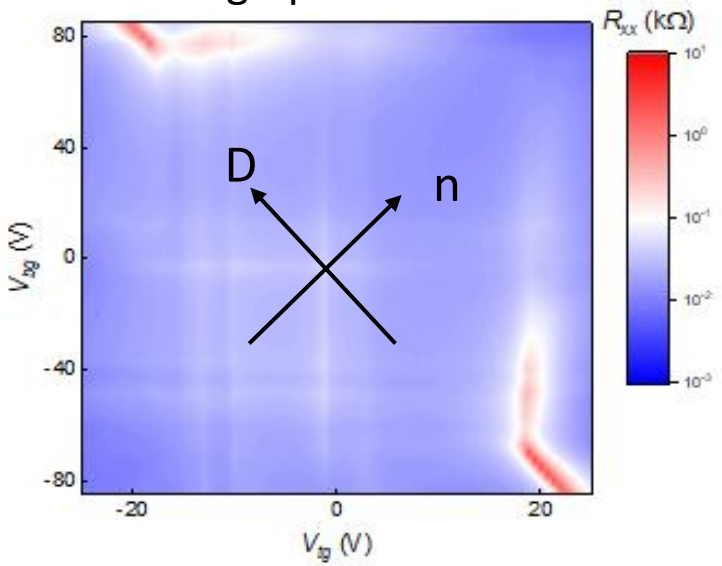
垂直电场:

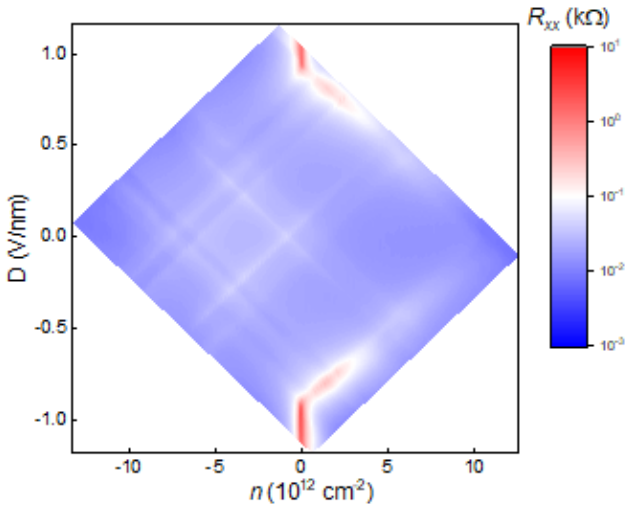
$$D = (C_t V_t - C_b V_b)/2\varepsilon_0 - D_0$$

C_t:top gate capacitance per area

C_b:back gate capacitance per area

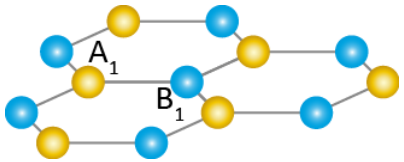
ABC graphite ≈16nm





石墨堆垛方式： 六方(ABA)堆垛

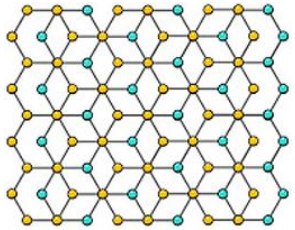
单层石墨烯

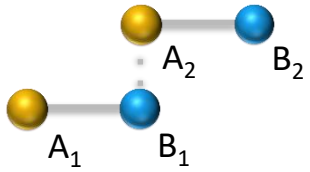


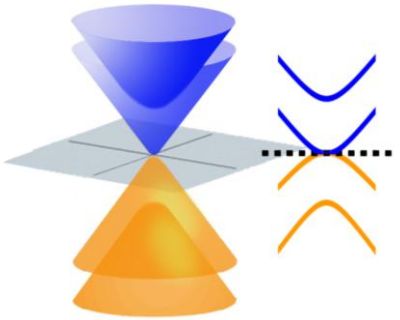
$\varepsilon \sim k$

$m^* = 0$

双层石墨烯



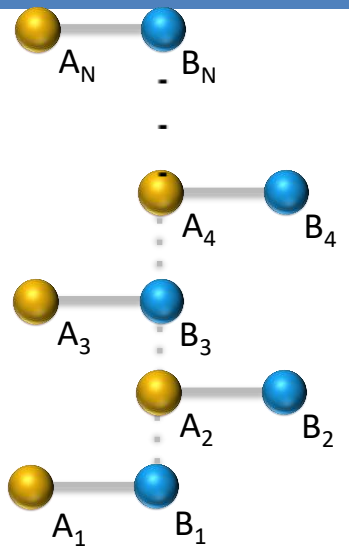


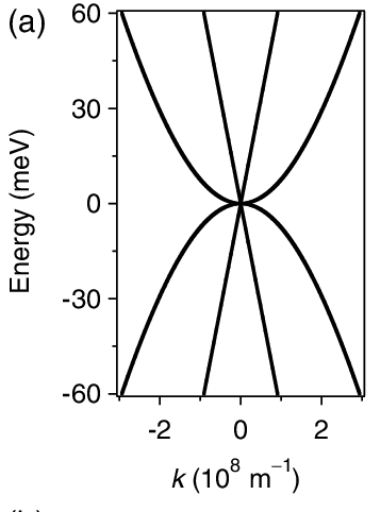


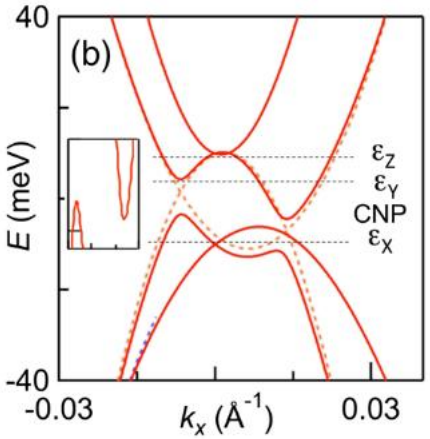
$\varepsilon \sim k^2$

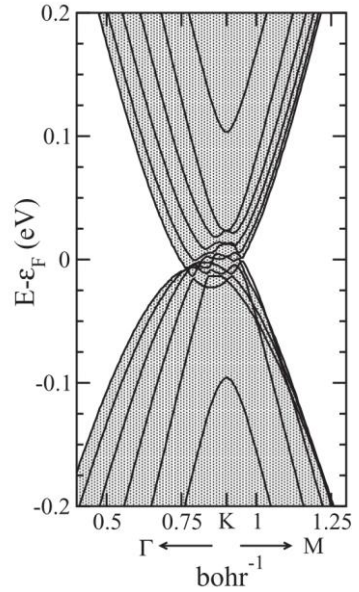
$m^* \sim 0.03 m_e$

六方/ABA堆垛 (HG)









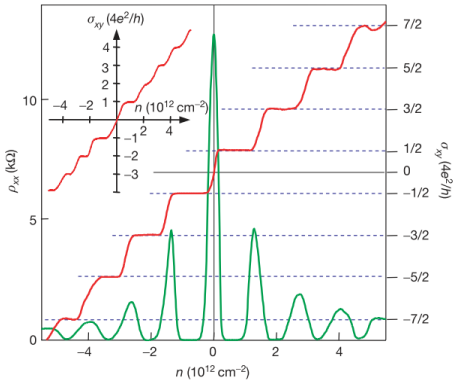
Y. Shi *et al* PRL(2016)

Ho, C.-H., *et al.* PRB(2016)

六方(ABA)堆垛石墨烯中的量子输运性质

K.Novoselov, *et al*, Nature (2005)
Y.Shi, *et al*, PRL (2016)
P. S., *et al*, PRL (2016)

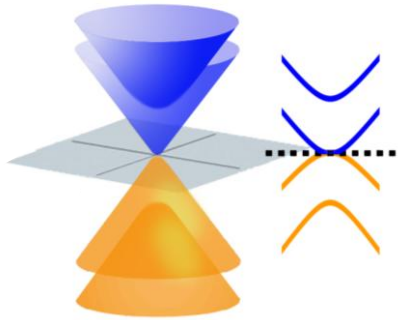
单层石墨烯

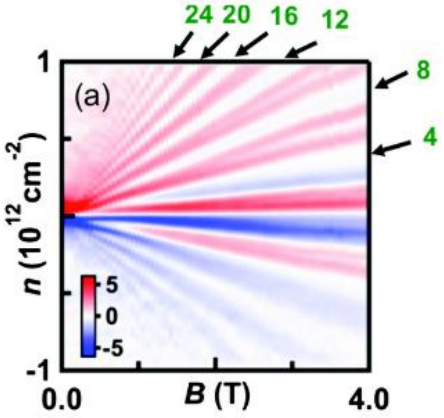


$$\varepsilon_N = \pm v_F \sqrt{2e\hbar BN}$$

半整数量子霍尔效应

双层石墨烯

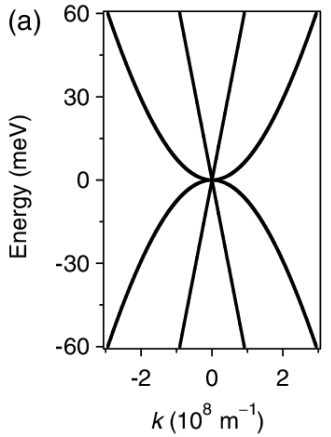


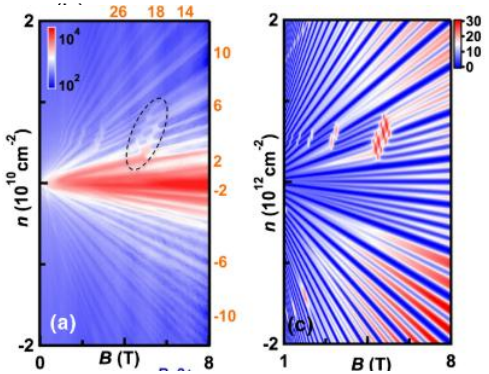


$$\varepsilon_N = \pm \hbar\omega_c \sqrt{N(N-1)}$$

最低朗道能级8重简并

ABA三层石墨烯



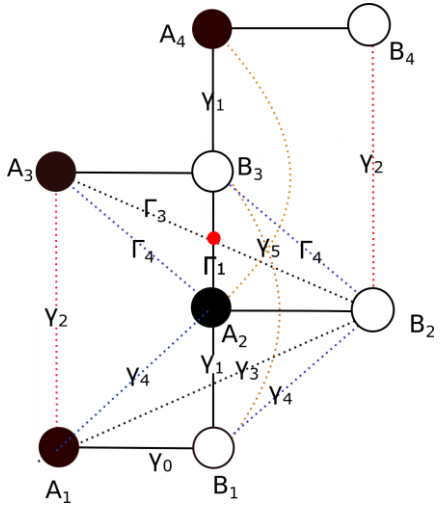


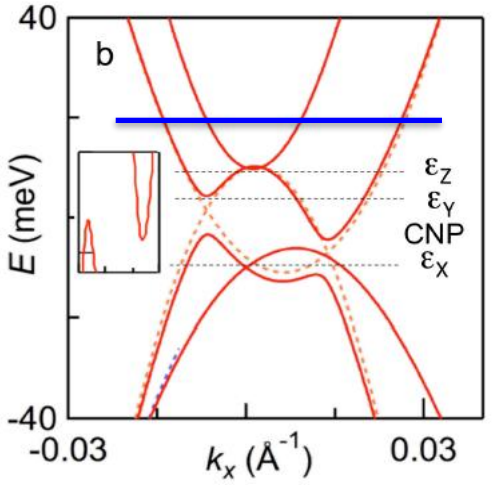
单层与双层支的叠加

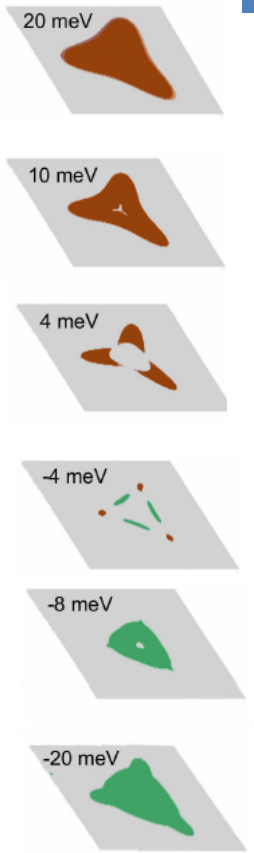
ABA堆垛四层石墨烯： Tunable Lifshitz Transitions

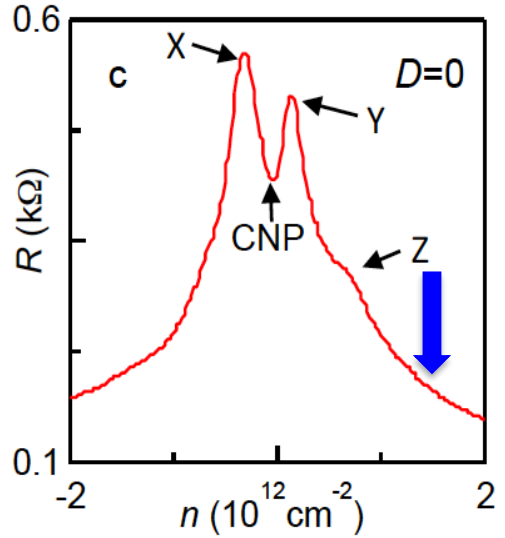
Y.Shi, *et al*, PRL (2018)

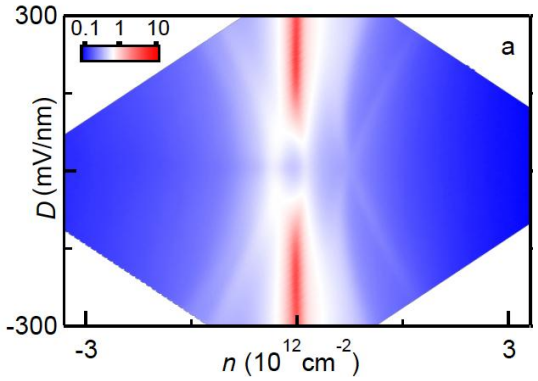
Bernal-stacked tetralayer graphene

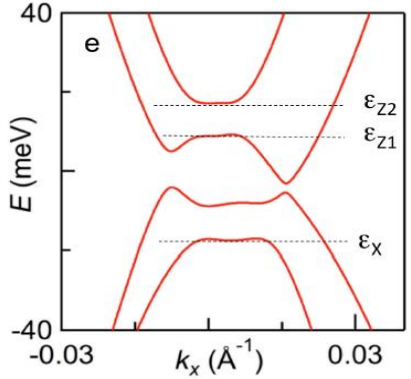


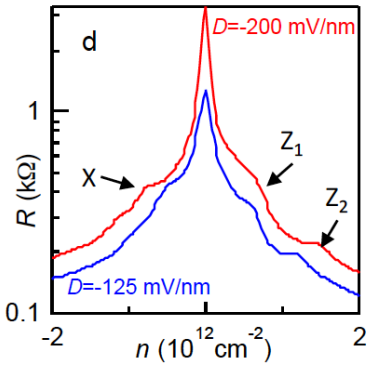








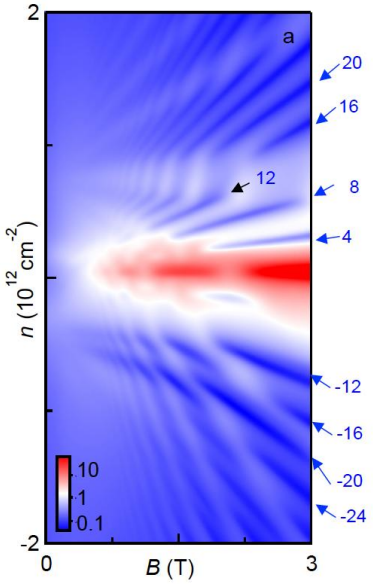


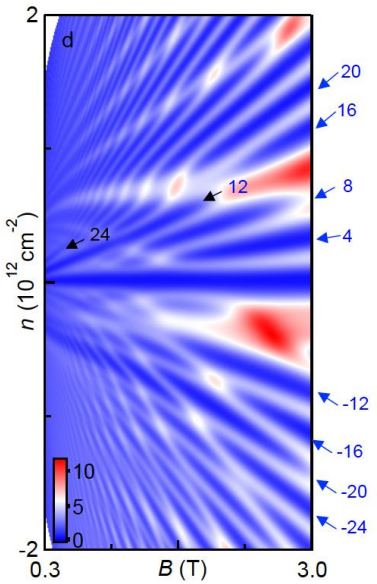


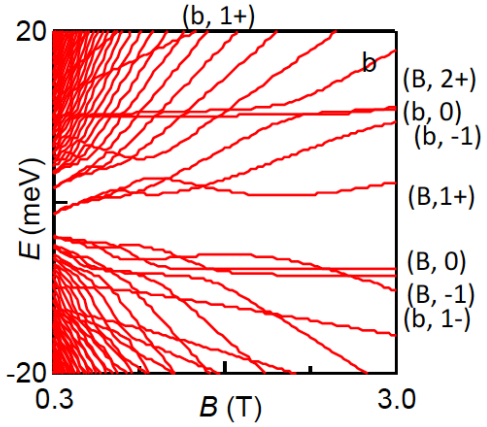
ABA堆垛四层石墨烯：量子霍尔效应

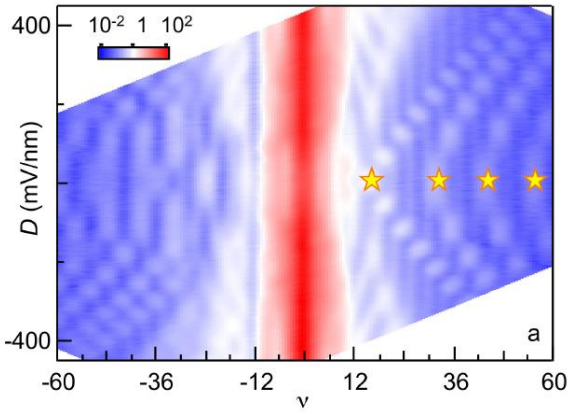
Y.Shi, *et al*, PRL (2018)
S. Che, *et al*, PRL (2020)

低磁场：2套BLG朗道能级交叉

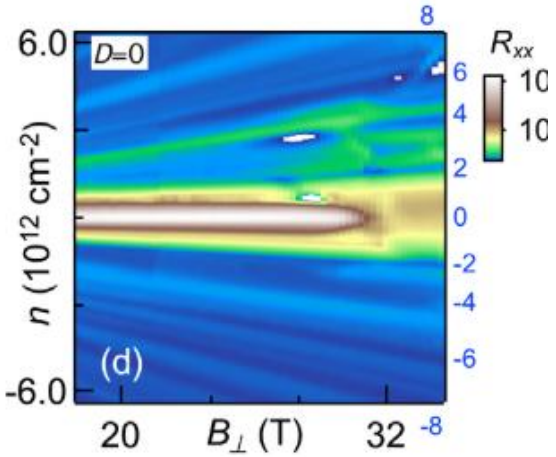


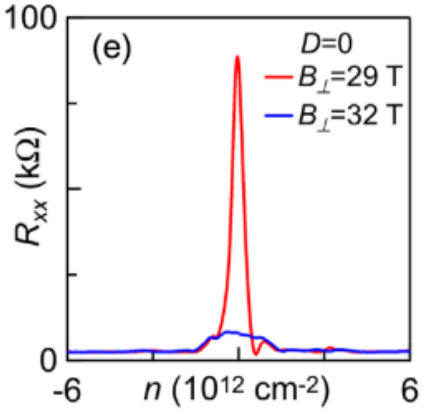


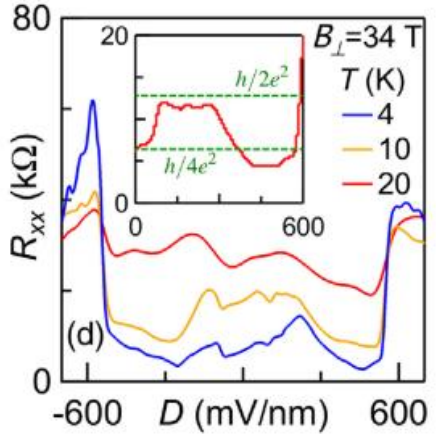


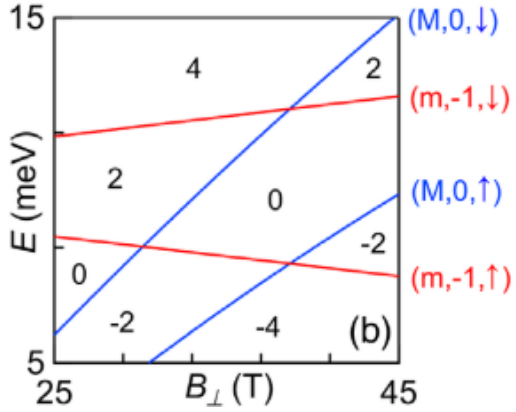


高磁场：BLG朗道能级交叉引起的Helical Edge States





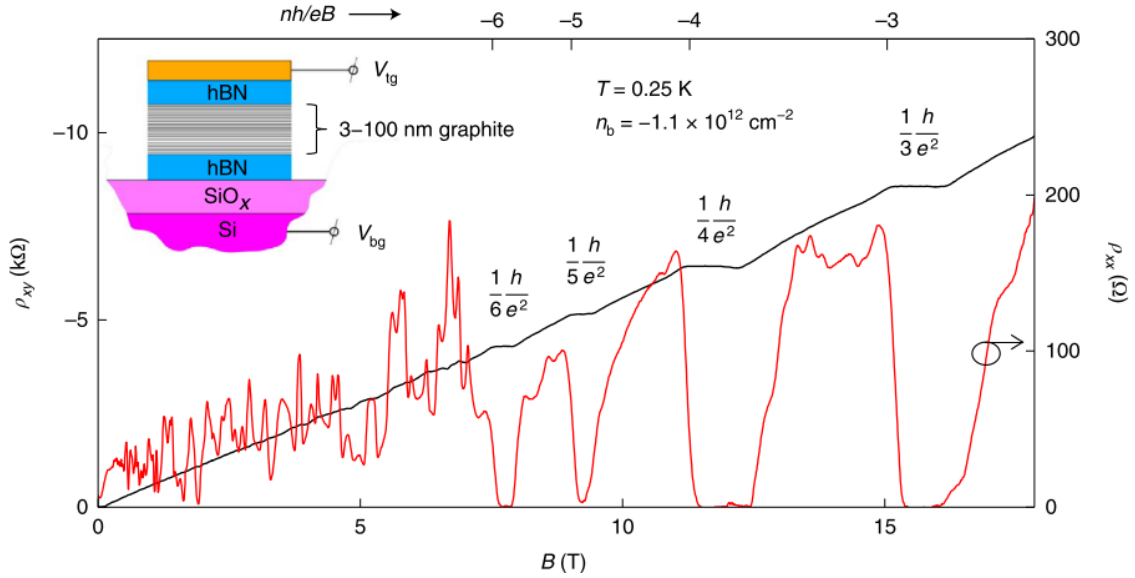


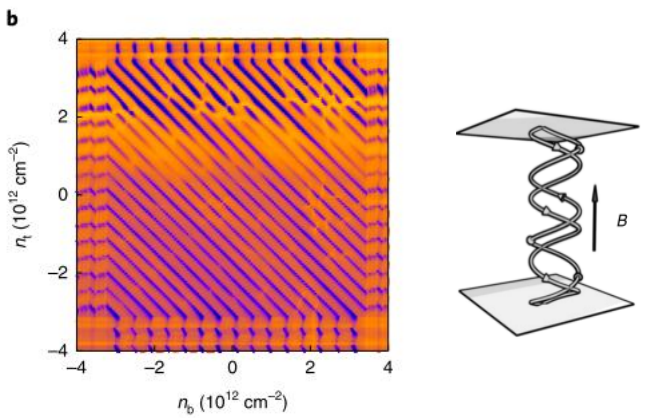


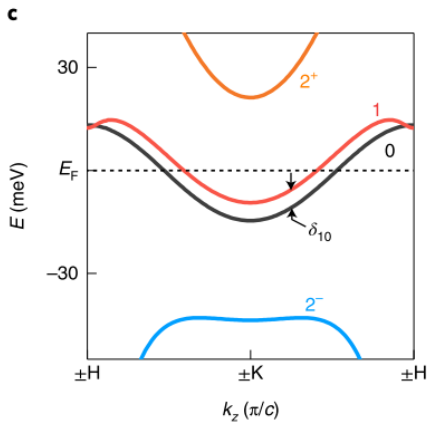
六方(ABA)堆垛石墨薄膜中的量子输运

J. Yin, *et al*, Nat. Phys. (2018)
C. Mullan, *et al*, Nature (2023)
D. Waters, *et al*, Nature (2023)

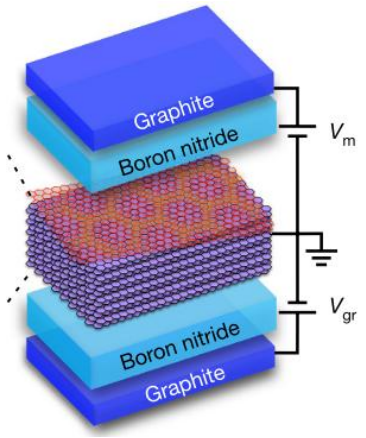
石墨薄膜：2.5维量子霍尔效应！

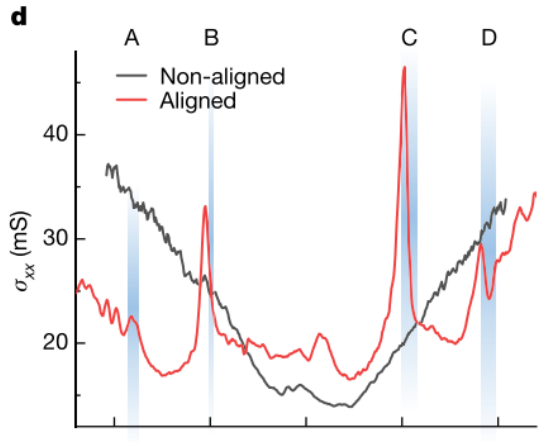


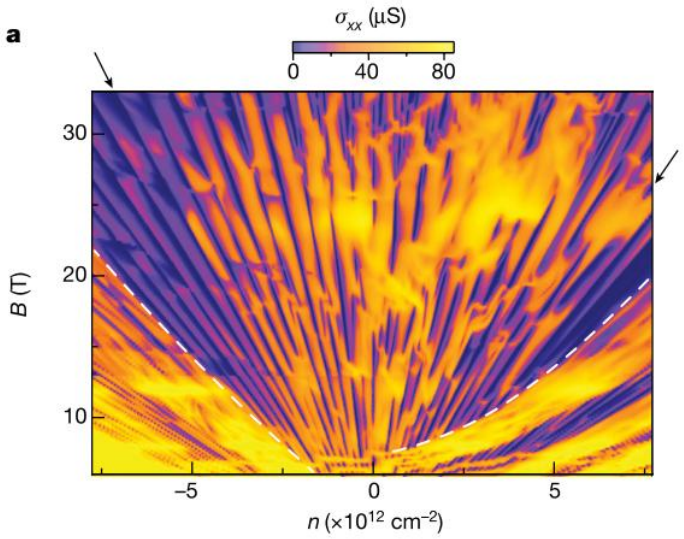




表面莫尔势对Bulk State的调控

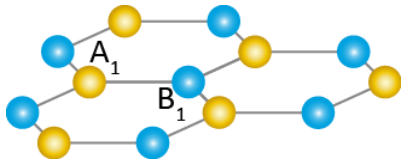






石墨堆垛方式： 菱面(ABC)堆垛

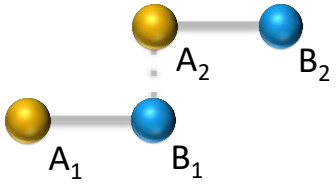
单层石墨烯

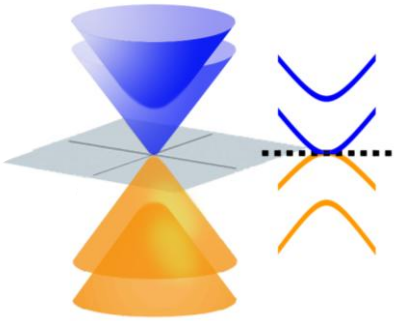


$\varepsilon \sim k$

$m^* = 0$

双层石墨烯

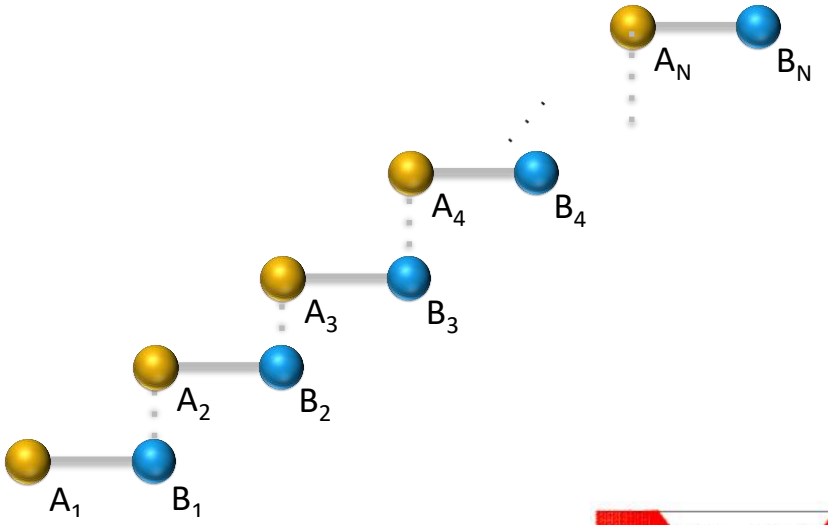


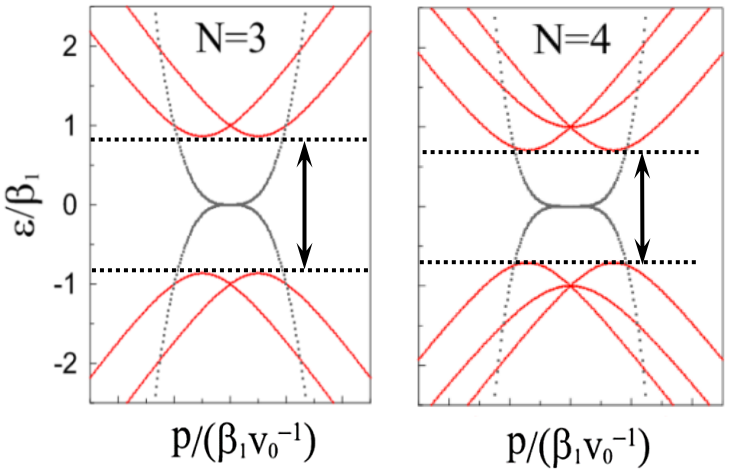


$\varepsilon \sim k^2$

$m^* \sim 0.03 m_e$

菱面/ABC
堆垛 (RG)

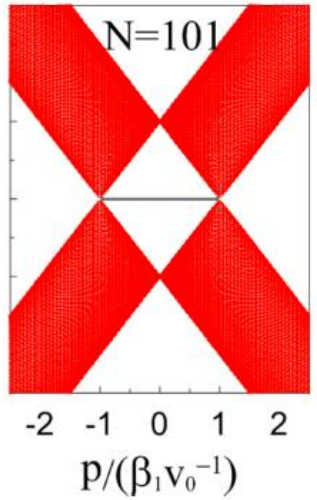




$\varepsilon \sim k^3$

$\varepsilon \sim k^4$

. . .



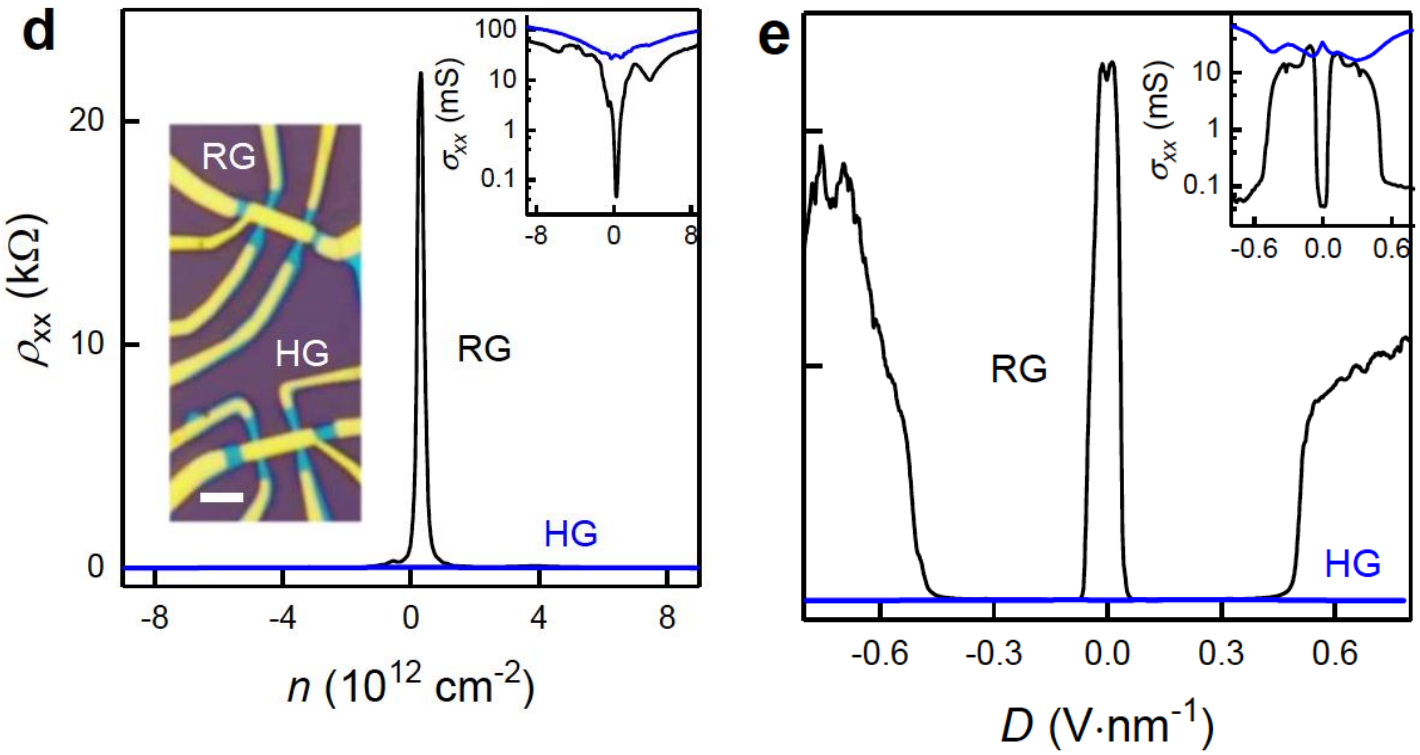
$\varepsilon \sim k^N$

ABC堆垛石墨烯具有天然的平能带

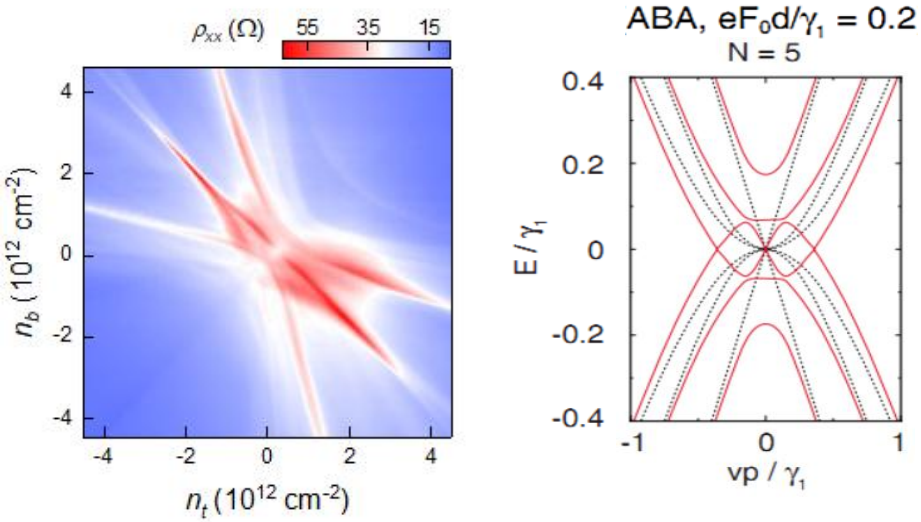
Ho, C.-H., *et al.* PRB(2016)

ABA堆垛 vs ABC堆垛

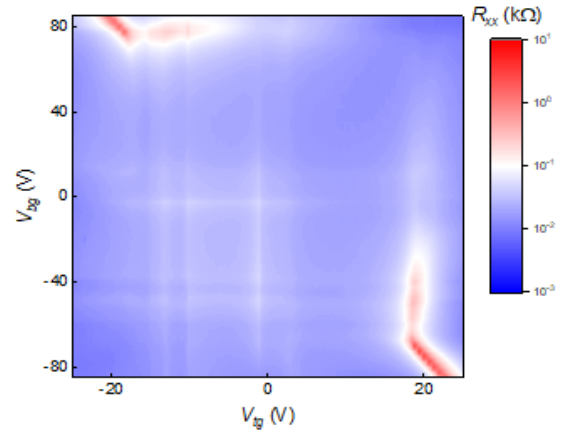
Ho, C.-H., *et al.* PRB(2016)
B. Pamuk, PRB (2017)
M. Koshino, PRB (2010)



ABA graphite



ABC graphite ≈16nm

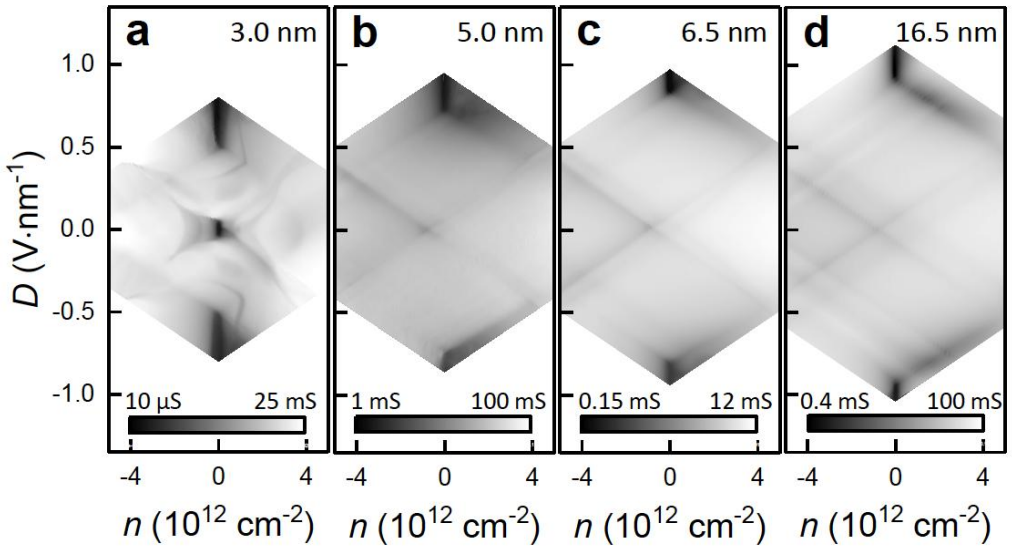


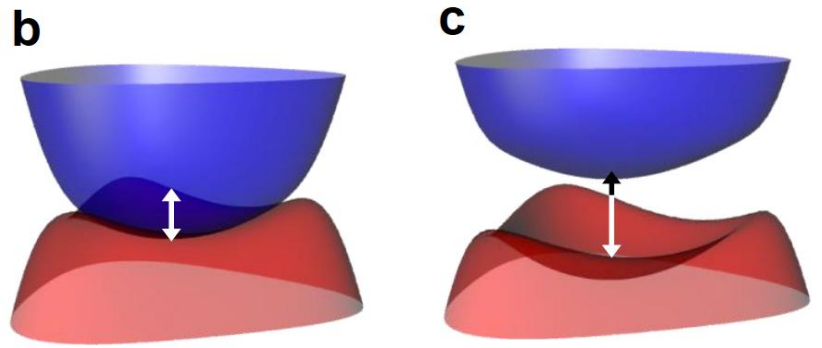
RG is much more tunable than HG

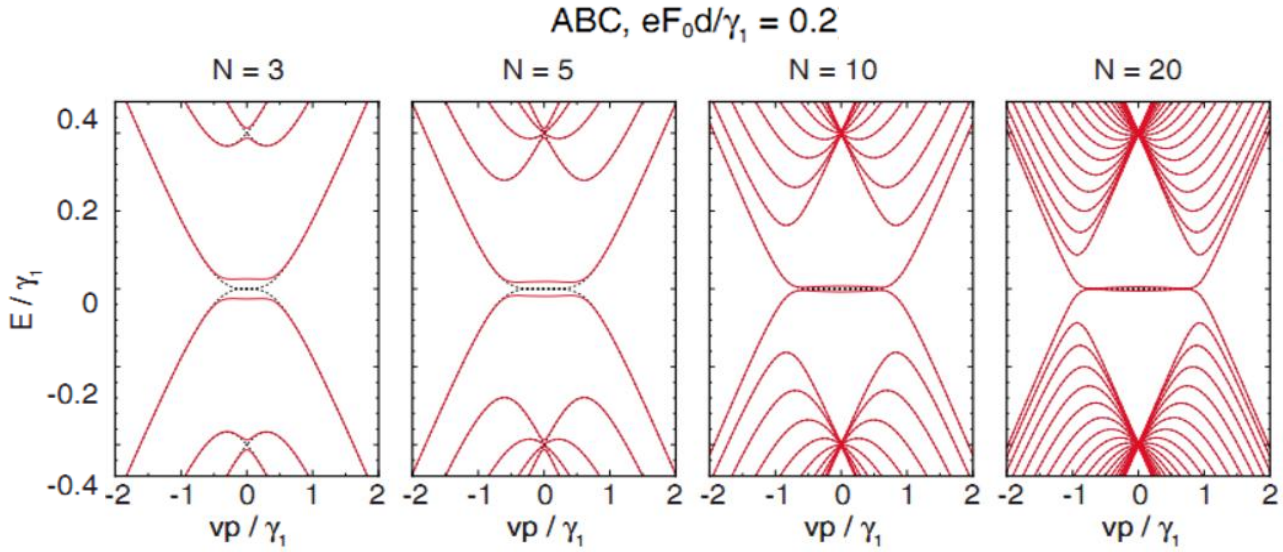
Nature **584**, 210–214 (2020)

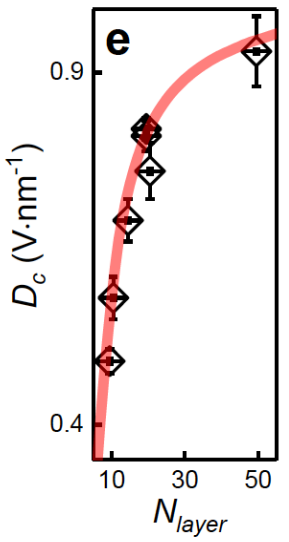
电场调控的半导体能隙

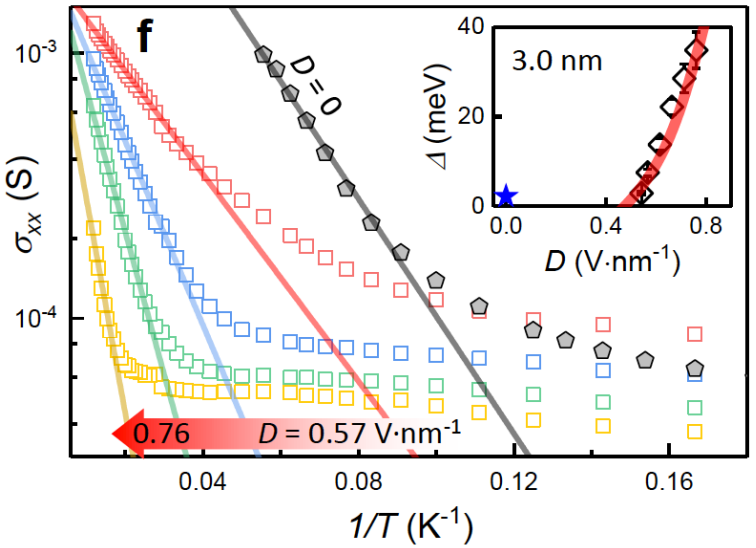
Ho, C.-H., *et al.* PRB(2016)
B. Pamuk, PRB (2017)
M. Koshino, PRB (2010)





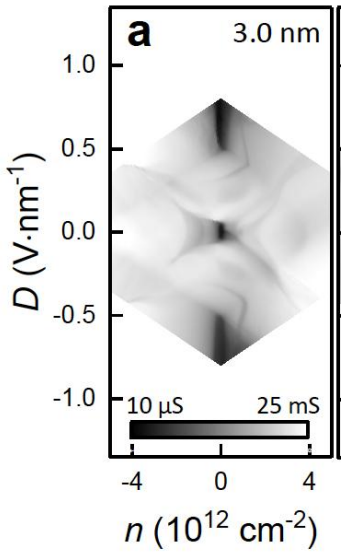


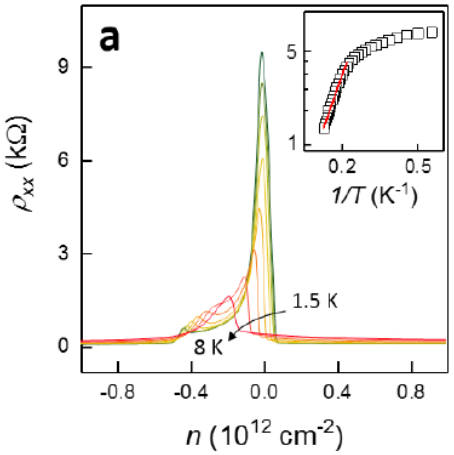


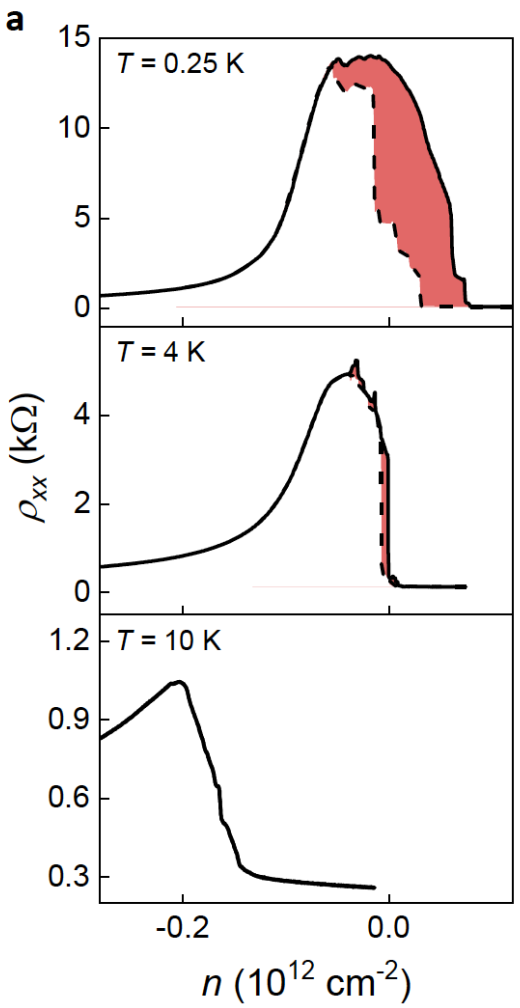


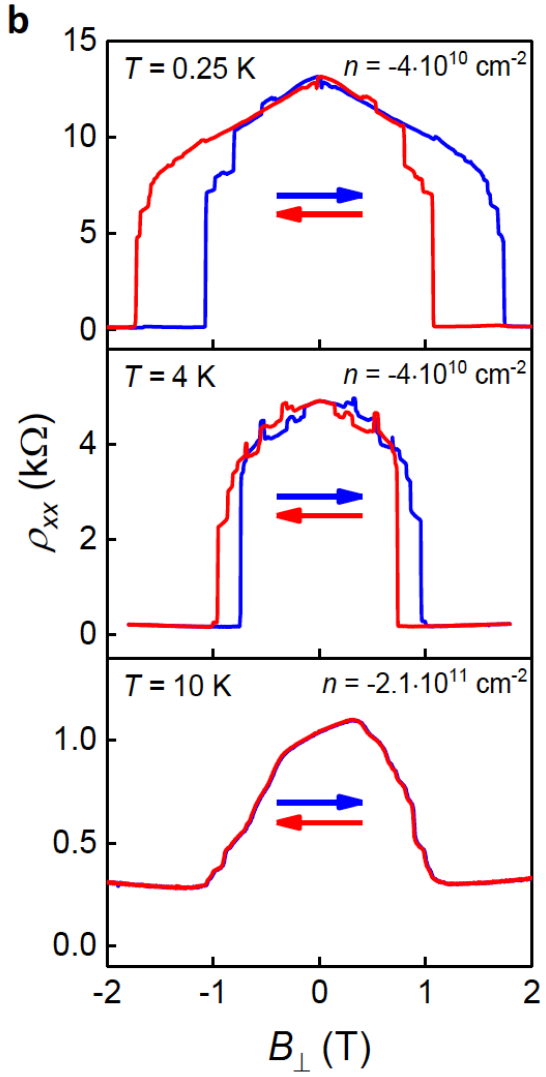
电子关联态回滞现象

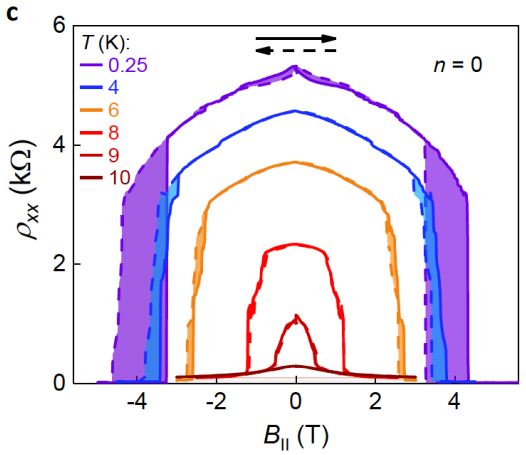
Nature **584**, 210–214 (2020)

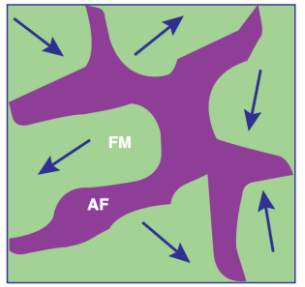










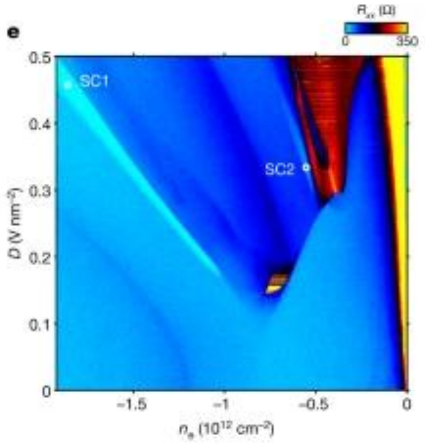


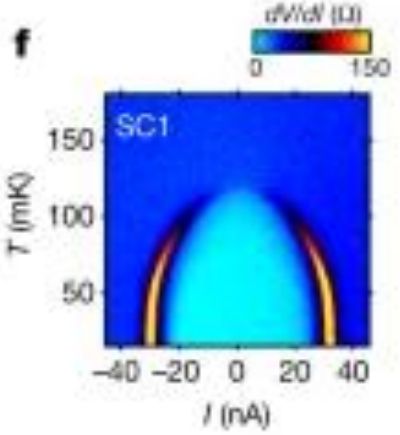
- 电子相的分离
- 随电场和磁场的回滞现象表明其中蕴含多铁现象

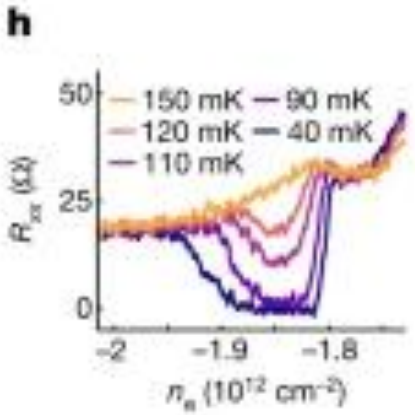
最新研究进展：菱面堆垛少层石墨烯

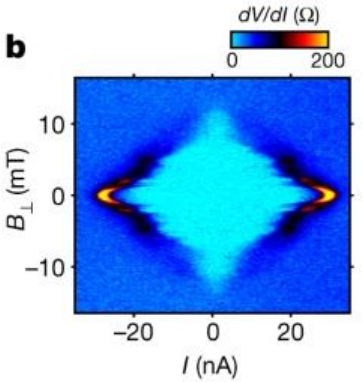
H. Zhou, Nature(2021)
H. Zhou, Nature(2021)

非常规超导态

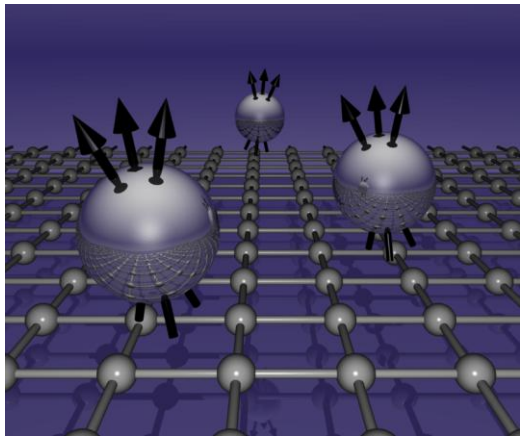


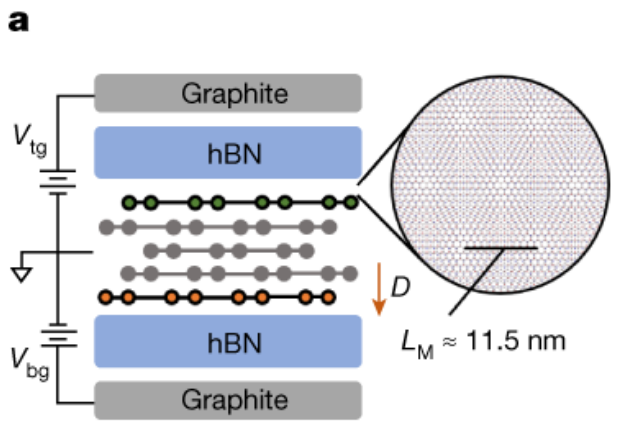


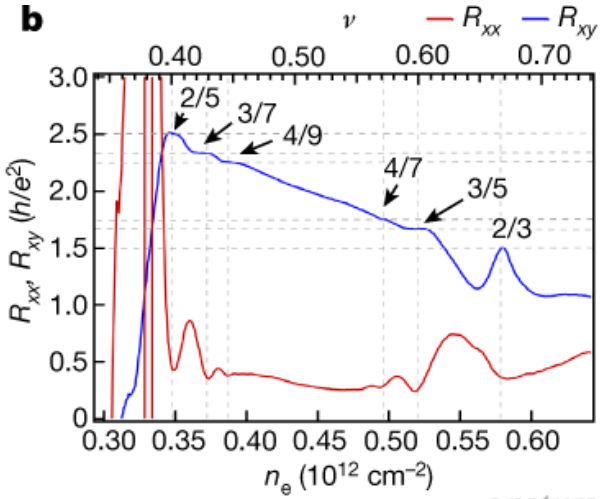




分数量子反常霍尔效应







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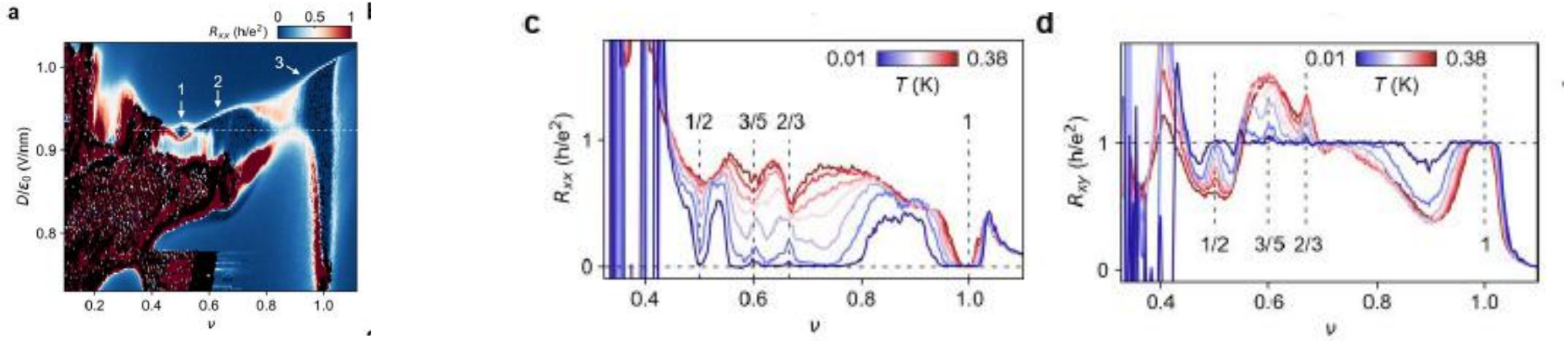
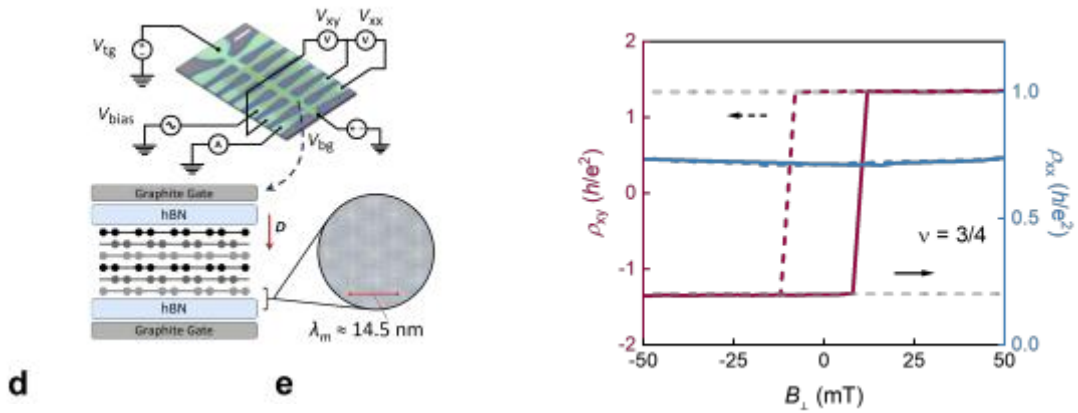
Extended Quantum Anomalous Hall Effect

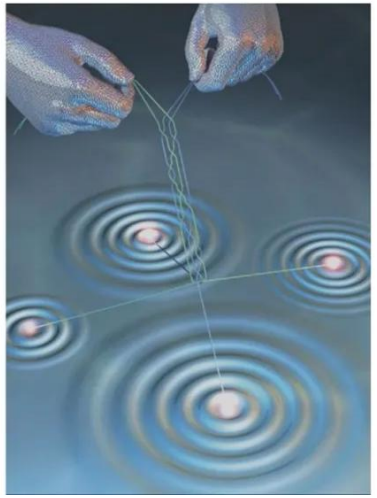
FQAHE vs Wiger crystal?



arXiv:2408.10203

偶数分母分数量子反常霍尔效应



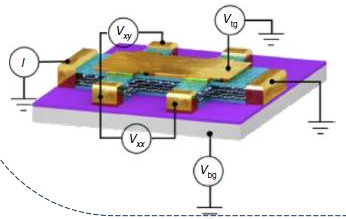


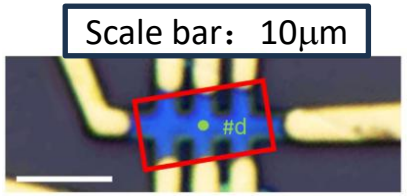
arXiv:2405.16944

研究方向概况

微纳加工

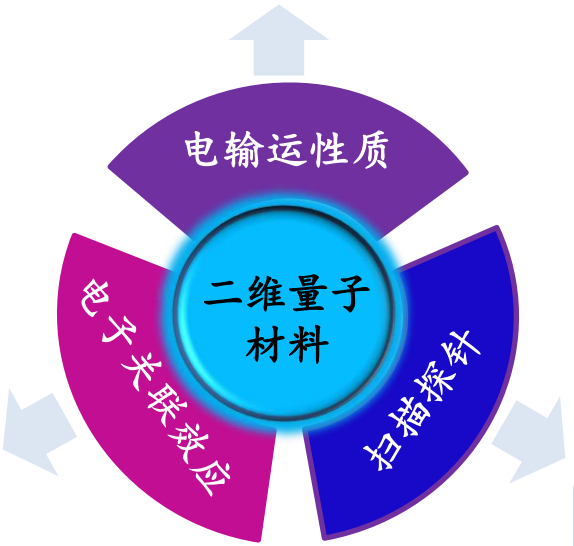
电子束曝光　　刻蚀　　金属蒸镀

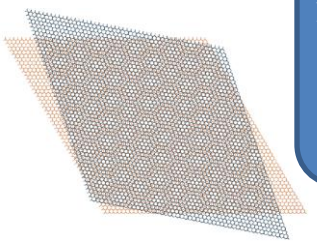




方向一：层状材料的电学性质、量子霍尔效应等及其物态调控机制。

Phys. Rev. Lett.,125(3), 036803(2020)
Phys. Rev. Lett.,120(9), 096802(2018)
Phys. Rev. Lett., 116(5), 056601(2016)



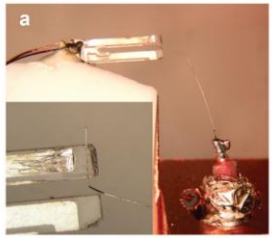


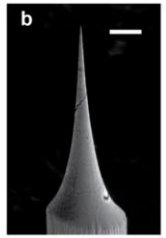
方向二：构筑具有强电子关联效应体系，研究各种衍生的新奇量子物态。

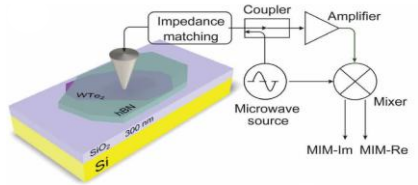
Nat. Phys.,17,619-626(2021)
Nature, 584, 210-214(2020)

电学测量

低温： 0.3K
强磁场： 14T







方向三：低温强磁场环境下的原子力显微镜（AFM）和扫描微波阻抗显微镜（sMIM）。

Sci. Adv., 5(2), eaat8799(2019)