中国科学院半导体研究所
Institute of Semiconductors,Chinese Academy of Sciences

重金属磁性异质结中自旋-轨道输运研究

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中国科学院半导体研究所
半导体芯片物理与技术全国重点实验室

2025-06-22 国科大

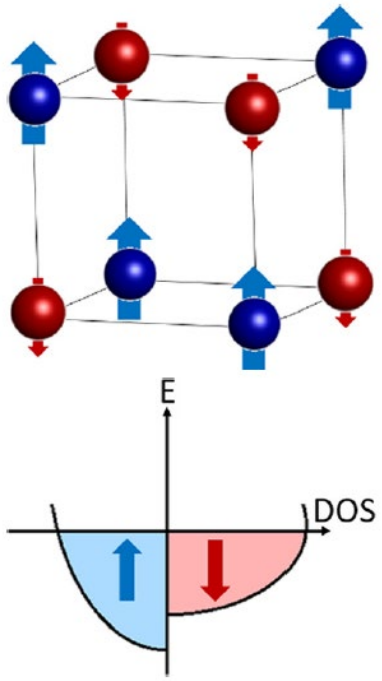
Outlines

1. 亚铁磁自旋电子材料中的自旋输运

2. 重金属/铁磁异质结中轨道流的分离与调控

1、亚铁磁自旋电子材料中的自旋输运

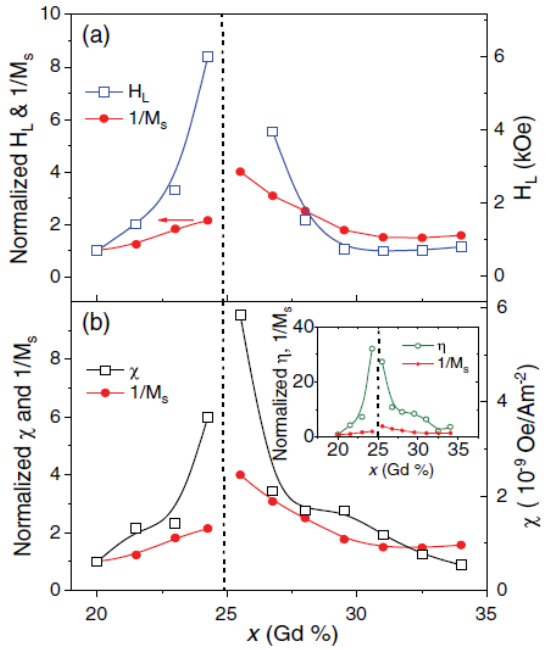
过渡-稀土亚铁磁合金



Finley *et al*. APL.116,110501 (2020)

丰富的磁结构

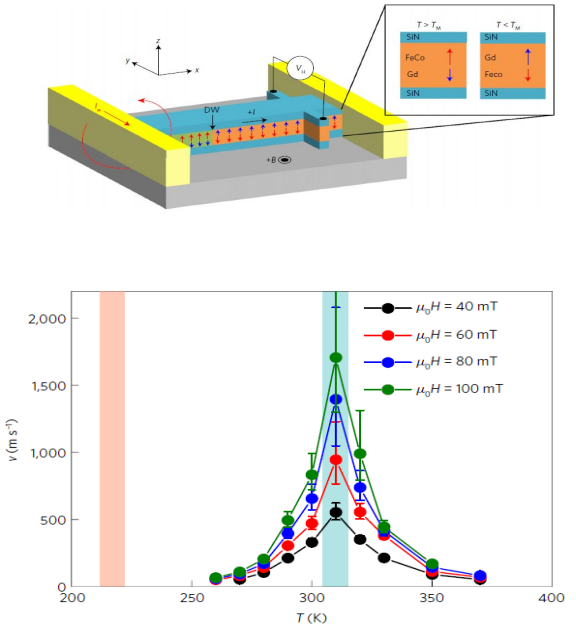
净磁矩较小，翻转能耗低



Mishra *et al*. PRL. 118.167201 (2017)

磁矩翻转效率很高

快速自旋动力学



Kim *et al*. Nat. Mater.16, 1187 (2017)

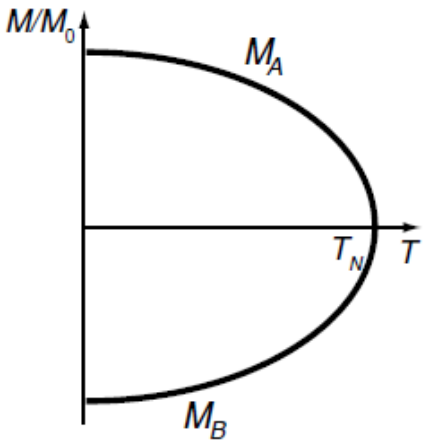
畴壁的移动速度达到最大值

过渡-稀土亚铁磁中的磁矩、角动量补偿行为

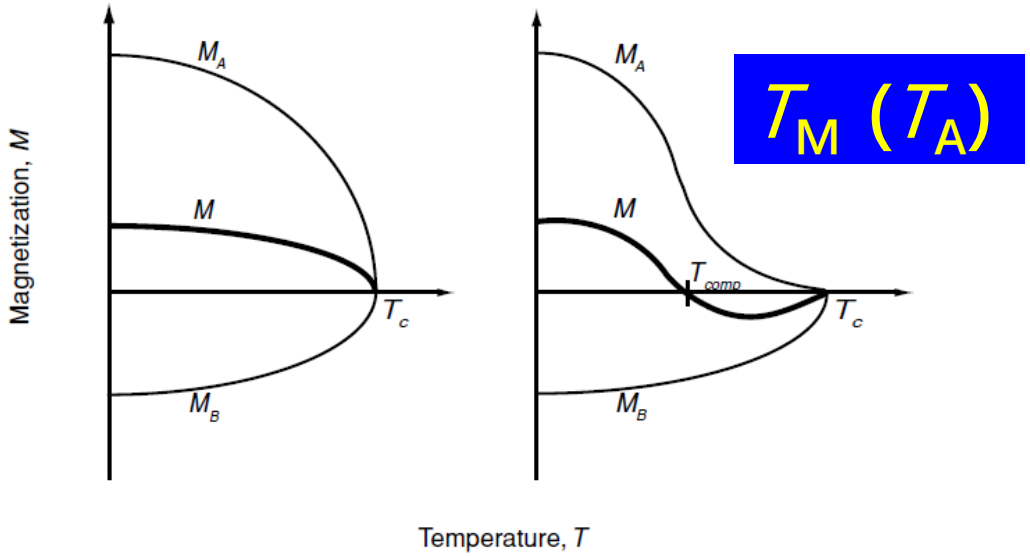
- Negative exchange coupling of antiferromagnetism (AFM)
- Ferrimagnets

  two unequal magnetic sublattice

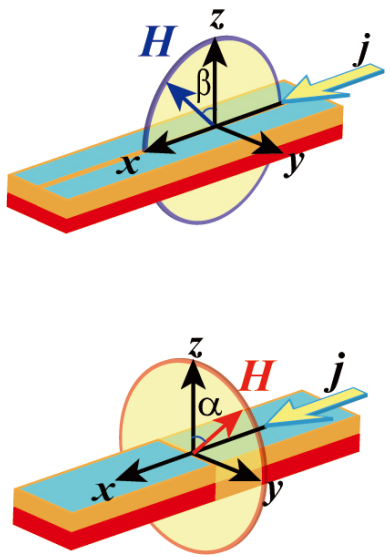
  compensation point for net **magnetization** and **angular momentum**

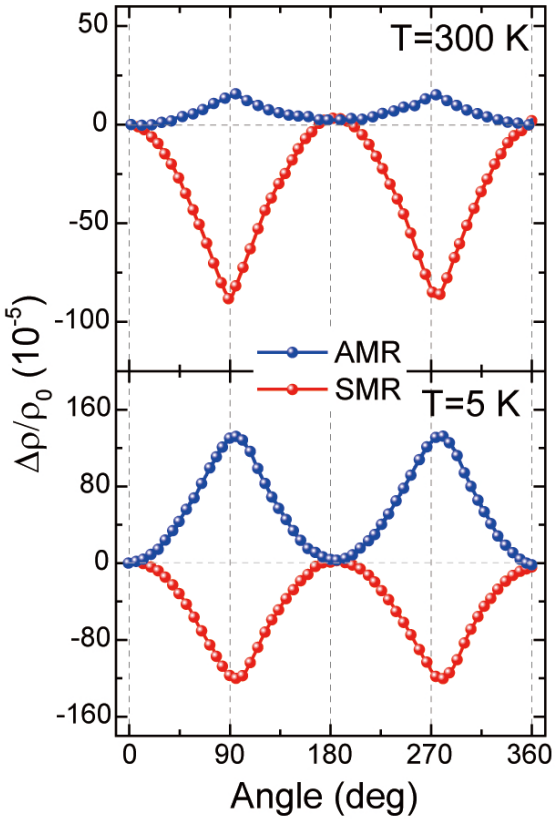


Sublattice magnetization of an antiferromagnet. T_N is the Néel temperature.



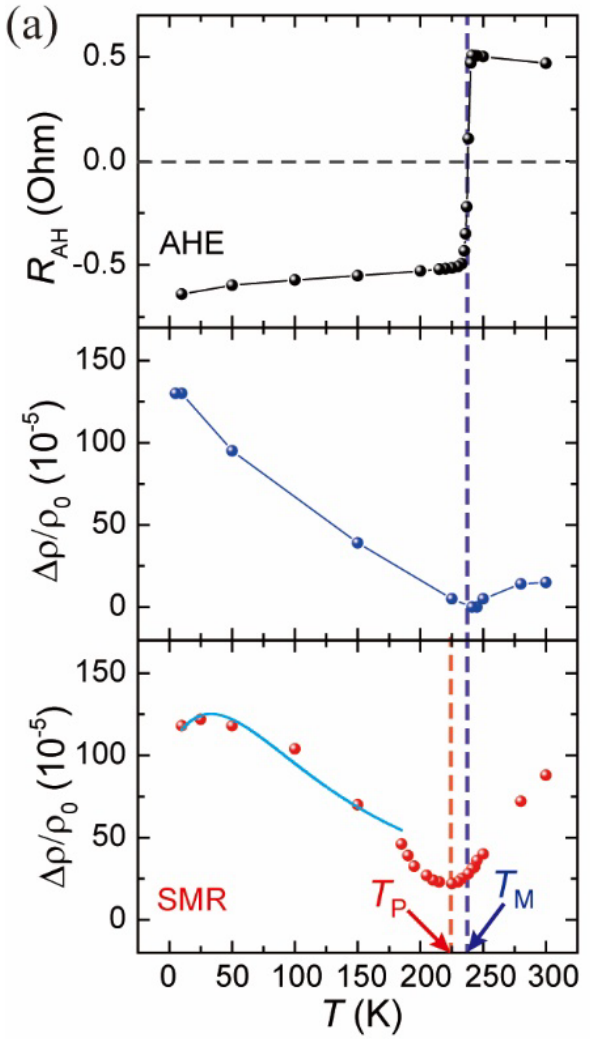
过渡-稀土亚铁磁CoTb合金中的自旋极化补偿

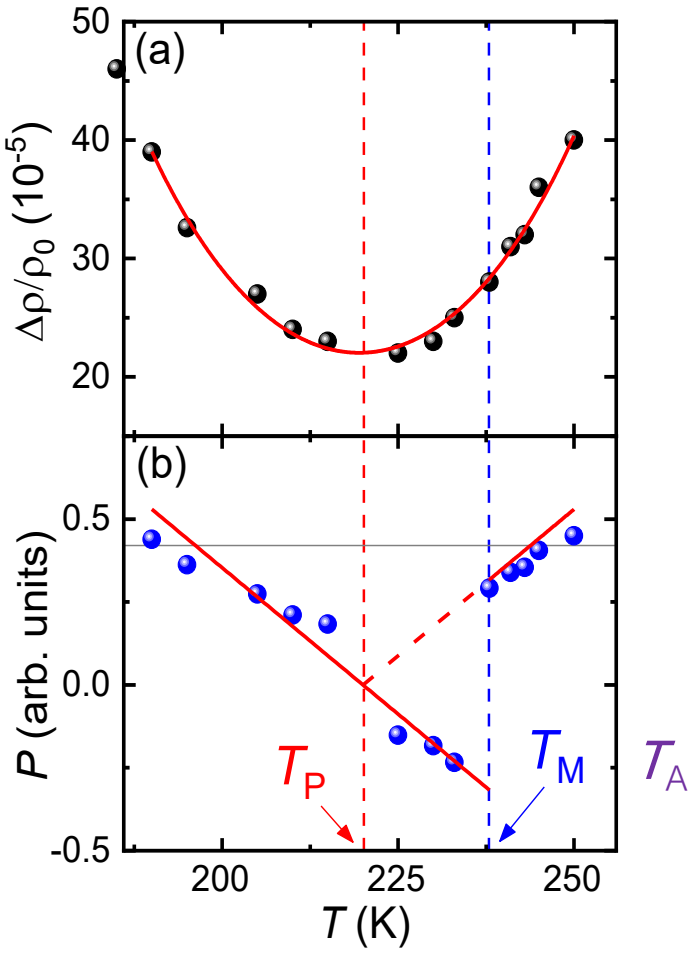




$$\rho_{AMR} = (\rho_{\parallel} - \rho_{\perp}) \sin^2 \beta$$

$$\rho_{SMR} = -(\rho_{\perp} - \rho_{T}) \sin^2 \alpha$$

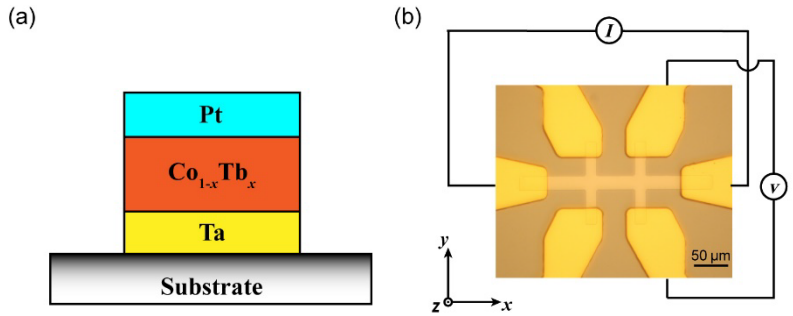


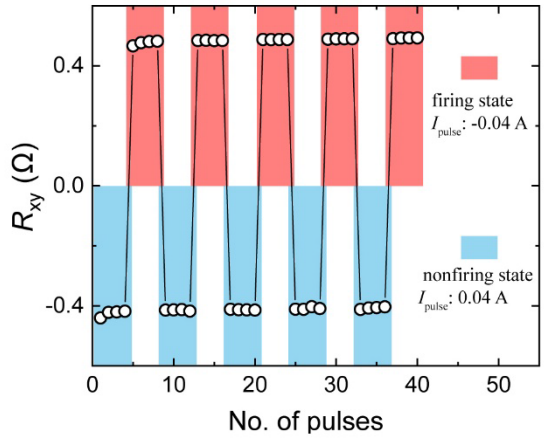


$T_M\,(238\ K) - T_P\,(220\ K)$ = 18 K

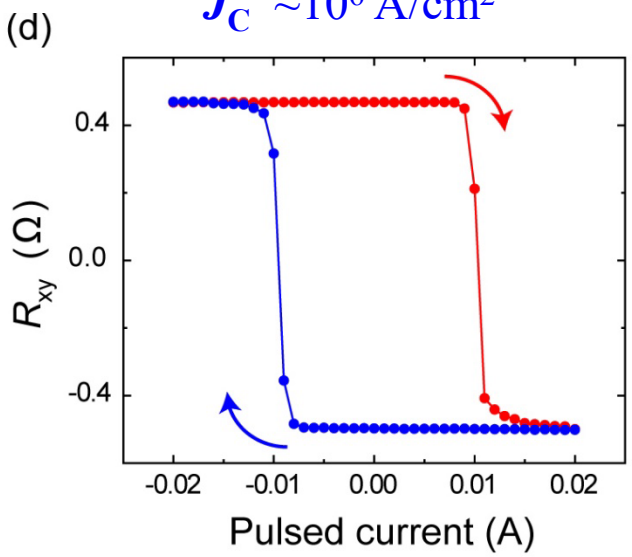
徐瑶函，魏大海，赵建华 et al., Phys. Rev. Appl., 14, 034064 (2020)

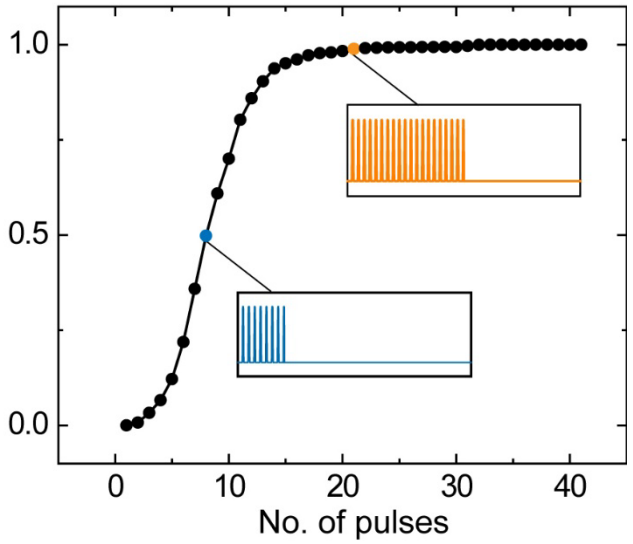
过渡-稀土亚铁磁CoTb/Pt的类突触翻转

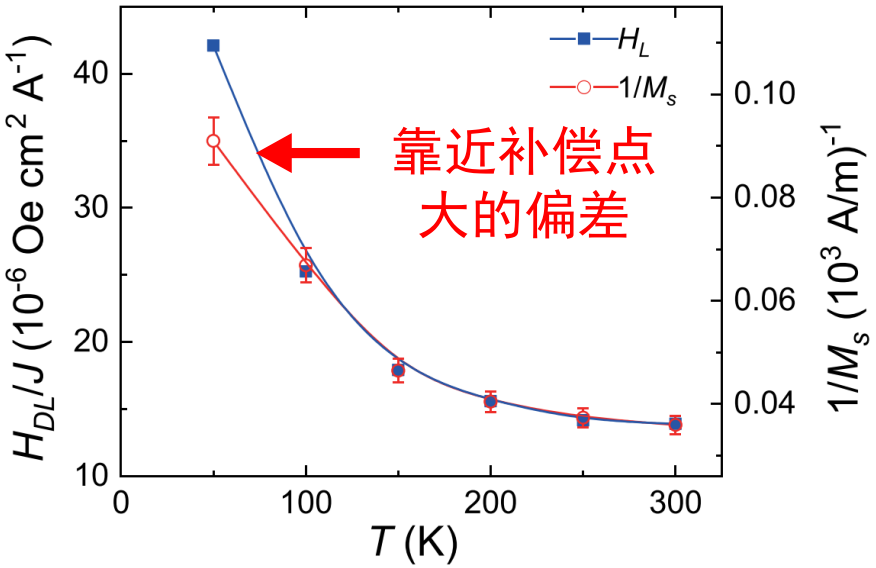


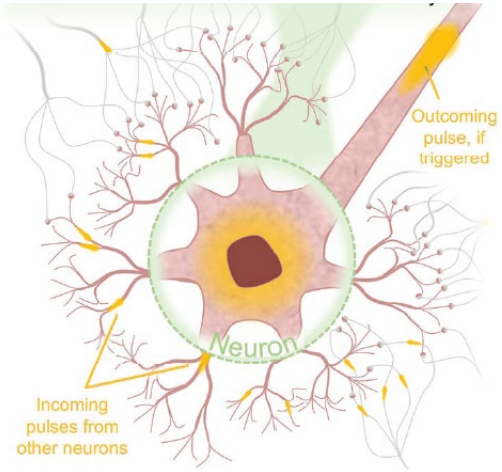


J_C ~10^6 A/cm^2







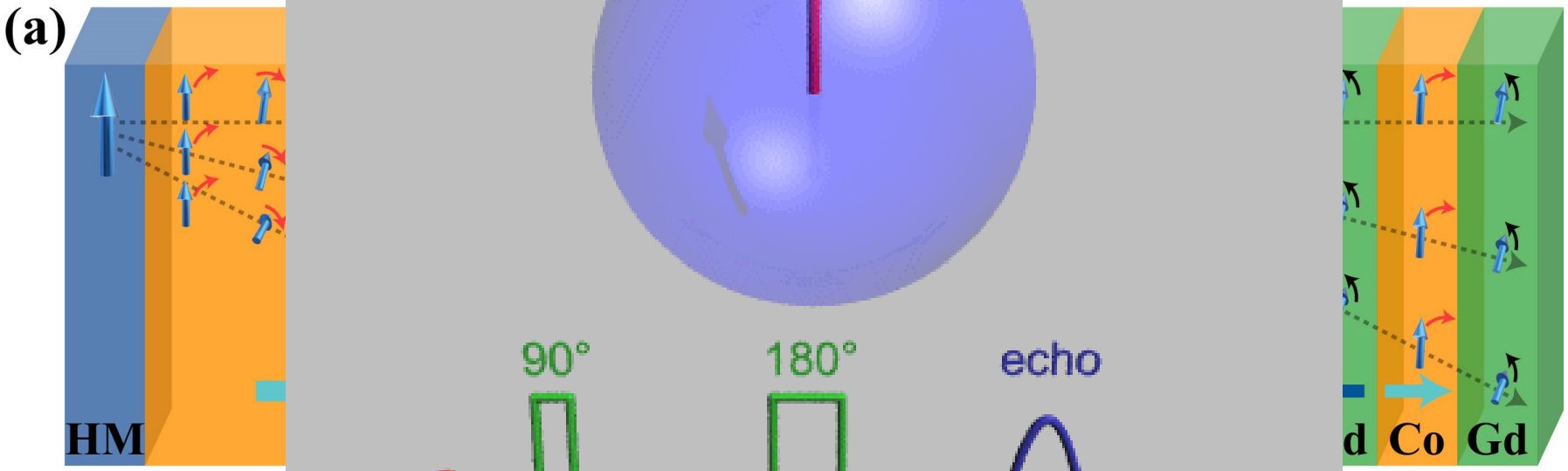


徐瑶函，魏大海，赵建华 et al., Appl. Phys. Lett., 118, 252405 (2021)

交错磁矩对自旋退相位（Spin dephasing）的抑制

- 加和当前系综内所有电子
  自旋，将
- 伴随额外
- 强自旋退
- 热稳定性差

- 反铁磁序能有效抑制自旋
  读取
  SOT效率高
  ✓ 高热稳定性

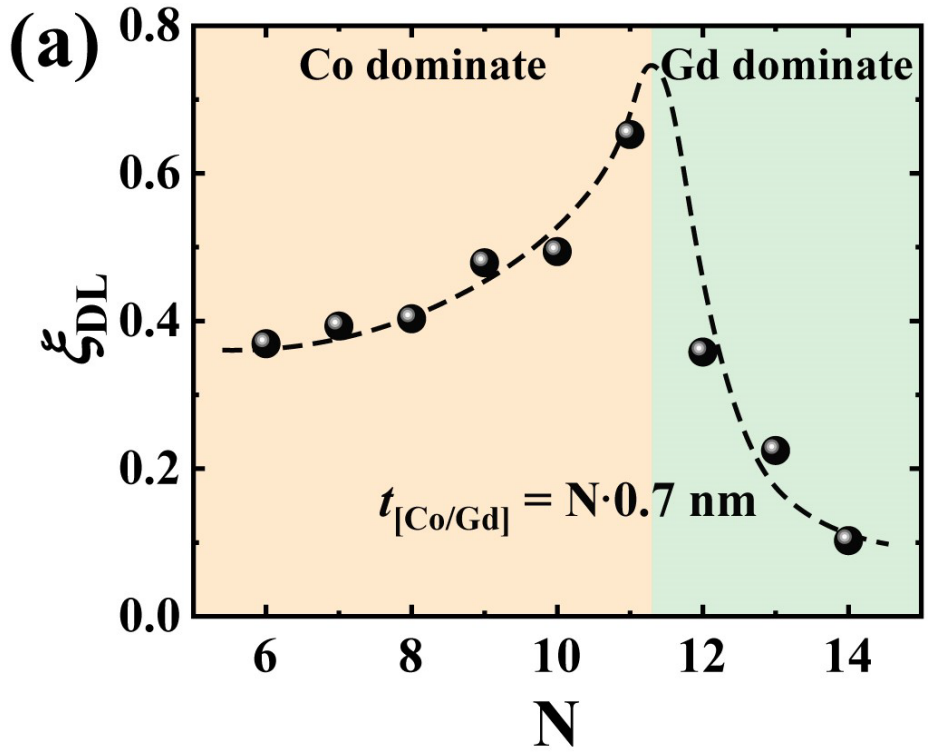


谢志成，魏大海 et al., ACS Appl. Mater. Interfaces 16, 27944 (2024)

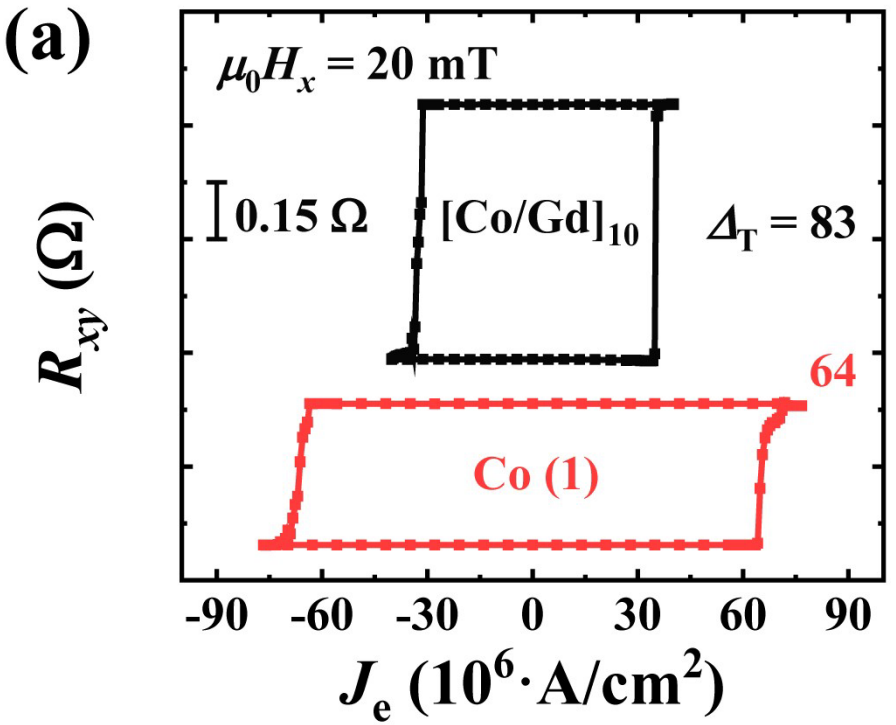
交错磁矩对自旋退相位（Spin dephasing）的抑制

$[Co/Gd]_N/Pt$

◆ 更厚的厚度，更高的热稳定性，更低的J_C



◆ ξ_{DL}非单调变化，最大值0.66

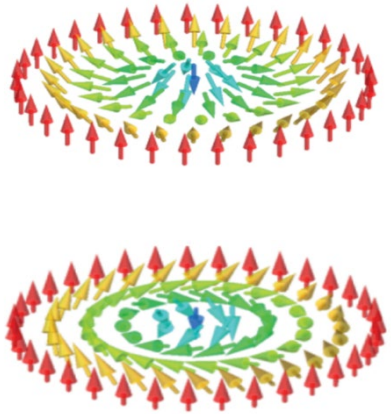


✓ 受益于增大的ξ_{DL}

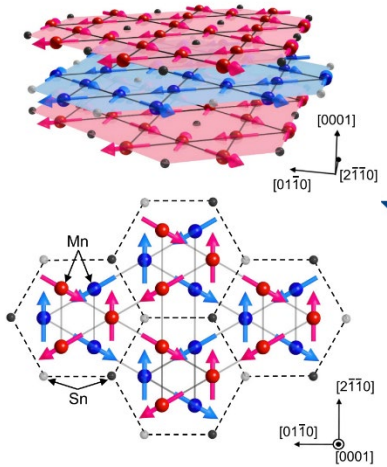
非共线磁结构与过渡-稀土亚铁磁

非共线磁结构

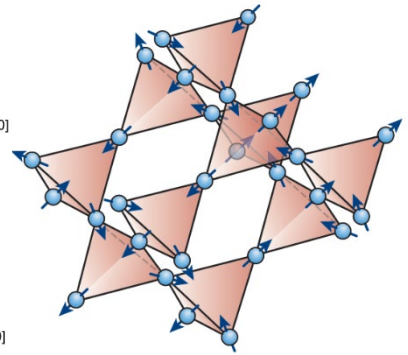
磁斯格明子



非共线反铁磁

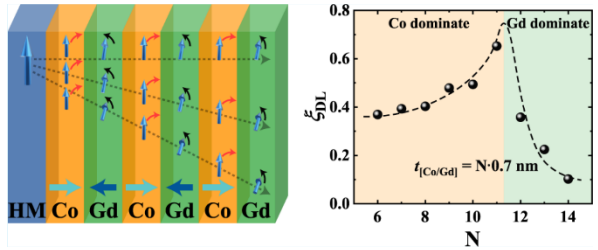


自旋阻挫

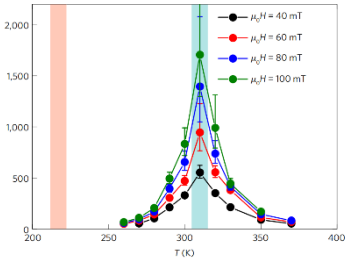


RE-TM亚铁磁

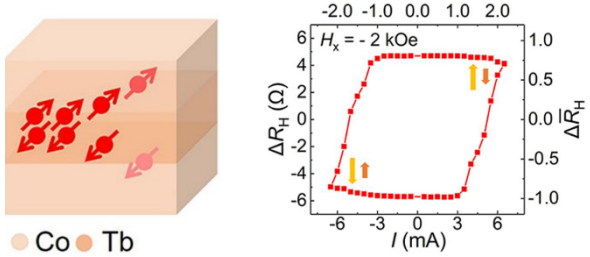
补偿特性



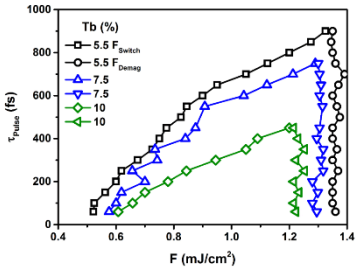
畴壁移动



SOT翻转



超快动力学



RE-TM亚铁磁补偿点附近的非共线磁结构及其调控

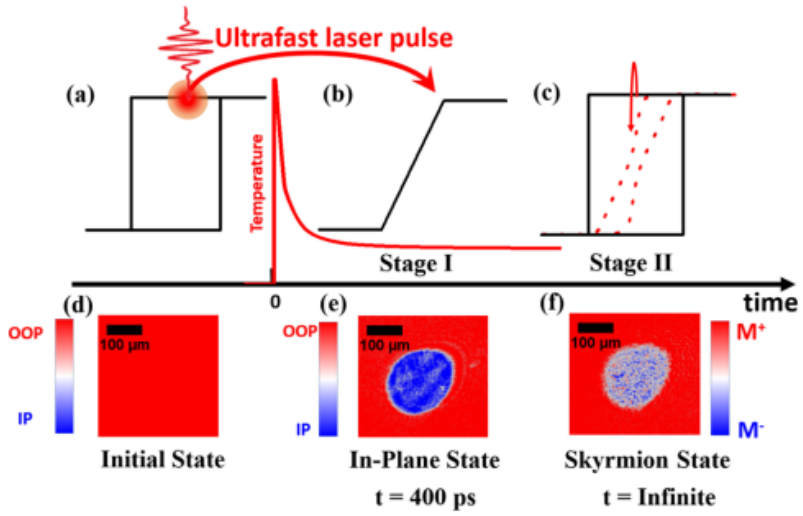
A. Fert *et al.*, Nature Reviews Materials 2, 17031 (2017)
T. Higo *et al.*, Appl. Phys. Lett. 113, 202402 (2018)
L. Balents, Nature 464, 199 (2010)

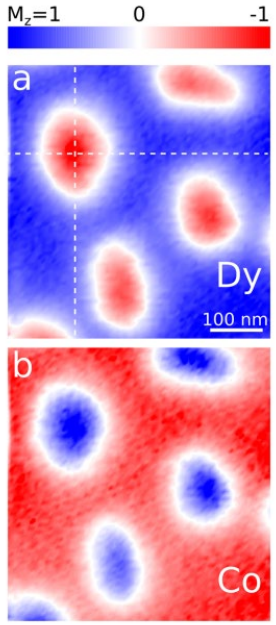
Z. Xie *et al.*, ACS Appl. Mater. Interfaces 16, 27944 (2024)
K.-J. Kim *et al.*, Nat. Mater. 16, 1187 (2017)
R. Q. Zhang *et al.*, Phys. Rev. B 101, 214418 (2020)
W. Zhang *et al.*, Phys. Rev. B 105, 054410 (2022)

过渡-稀土亚铁磁的非共线磁结构

RE-TM亚铁磁斯格明子

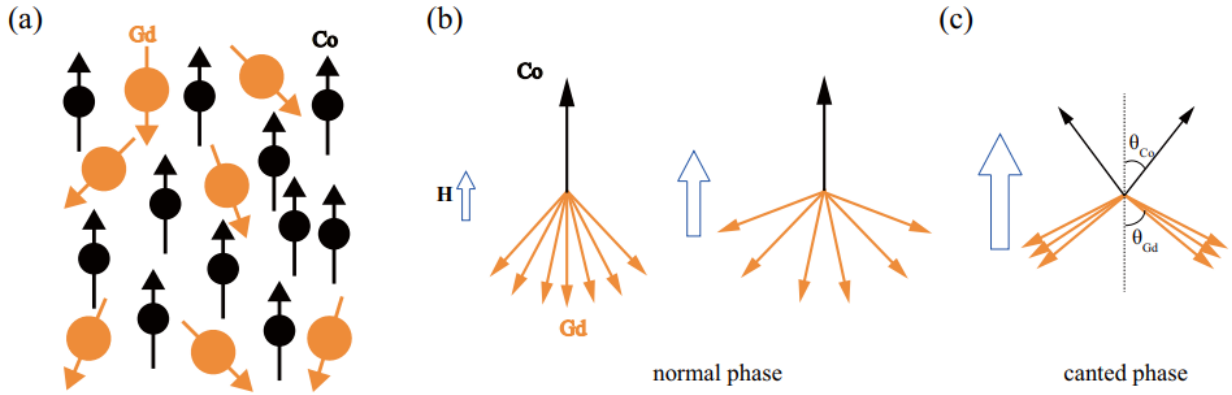
- 远离补偿点





散磁性与 spin flop

- 在补偿点附近共存

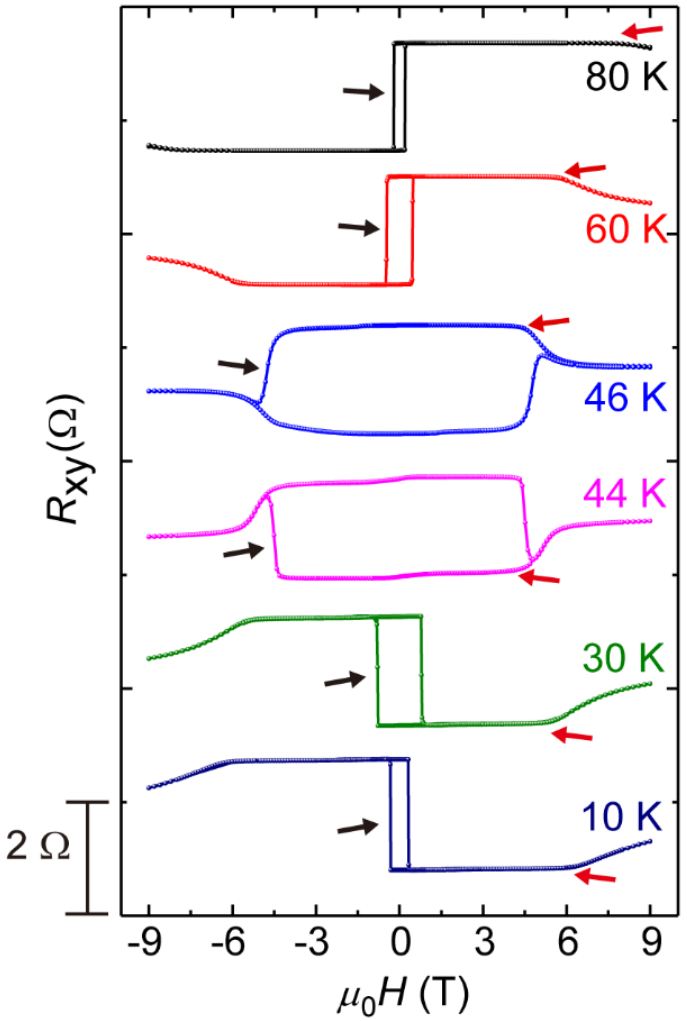


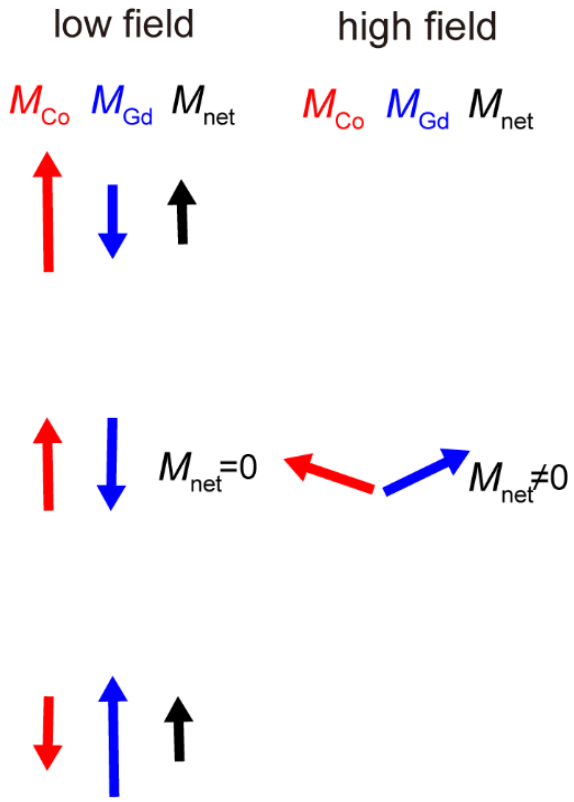
散磁性与 spin flop 共存时的非共线磁结构变化

C. Luo *et al*., Communications Physics 6, 218 (2023)
W. Zhang *et al*., ACS Appl. Mater. Interfaces 15, 5608 (2023)

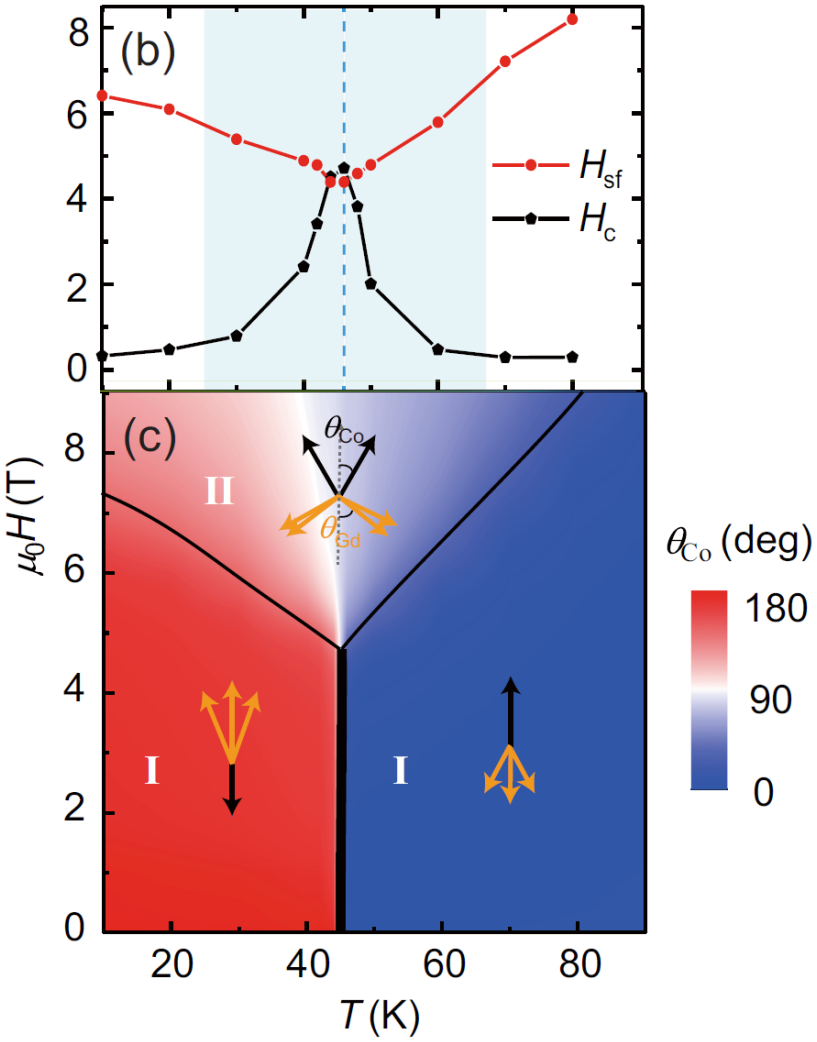
D. D. Chen *et al*., Physical Review Materials 6, 014402 (2022)

过渡-稀土亚铁磁CoGd合金的非共线磁结构



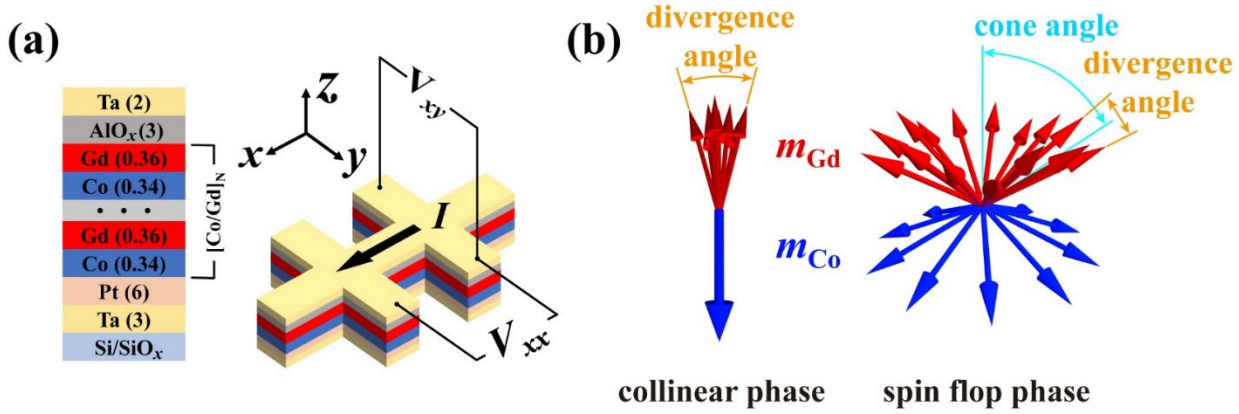


高场下，磁矩发生spin-flop相变



陈冬冬，魏大海，赵建华 et al., Phys. Rev. Matt., 6, 014402 (2022)

过渡-稀土亚铁磁$[Co/Gd]_N$超晶格的新奇磁结构

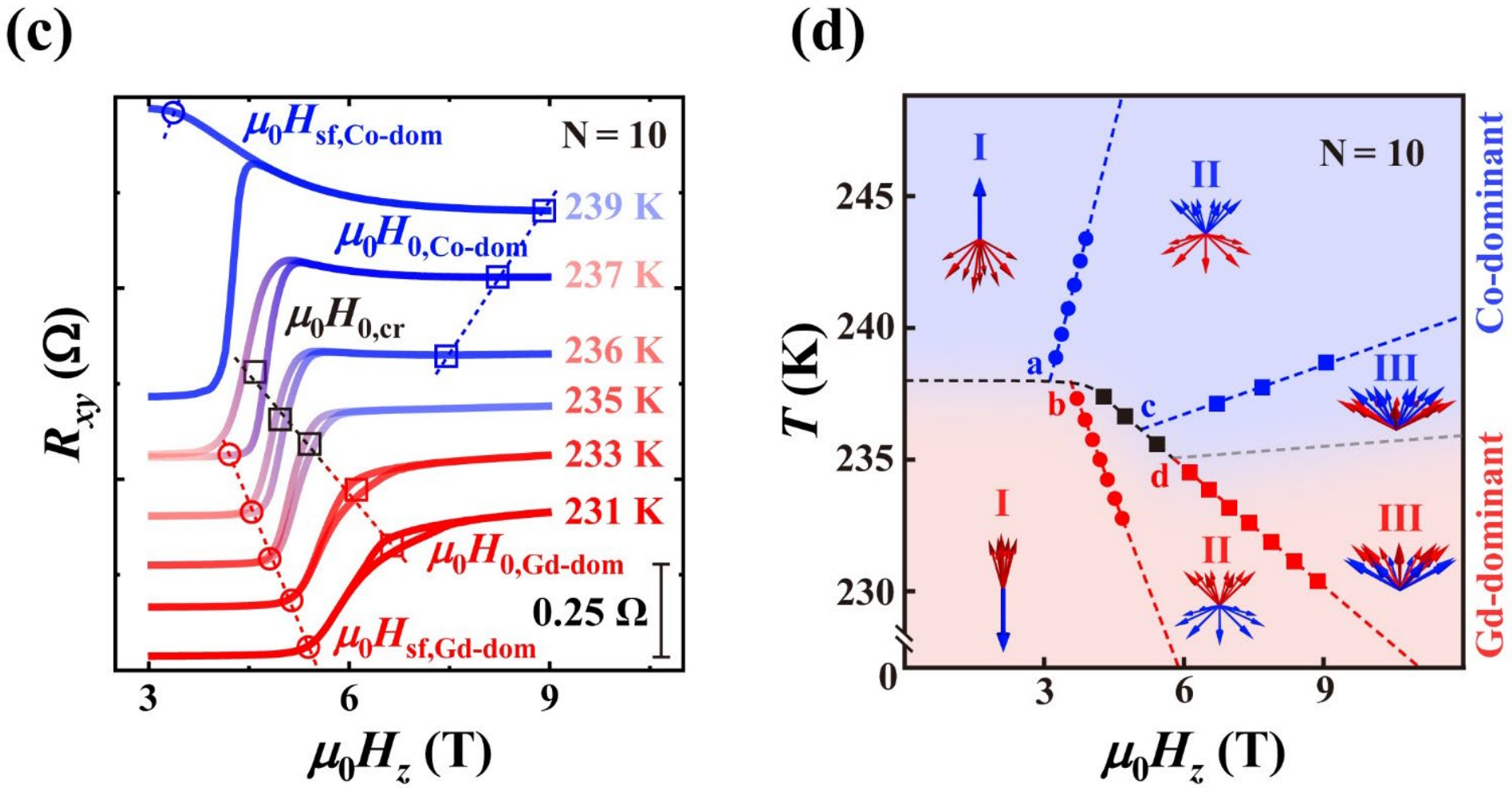


- 不同外磁场下的两类磁矩排列
- AHE由Co主导
- AHE回线弯曲，发生spin flop

改变层数N@室温

孟庚辰，魏大海 et al., Adv. Funct. Mater. (2025) accepted, DOI: 10.1002/adfm.202501767

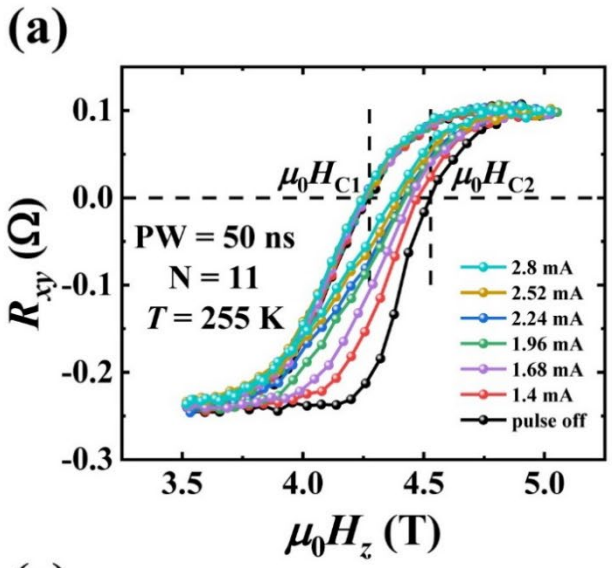
过渡-稀土亚铁磁$[Co/Gd]_N$超晶格的新奇磁结构

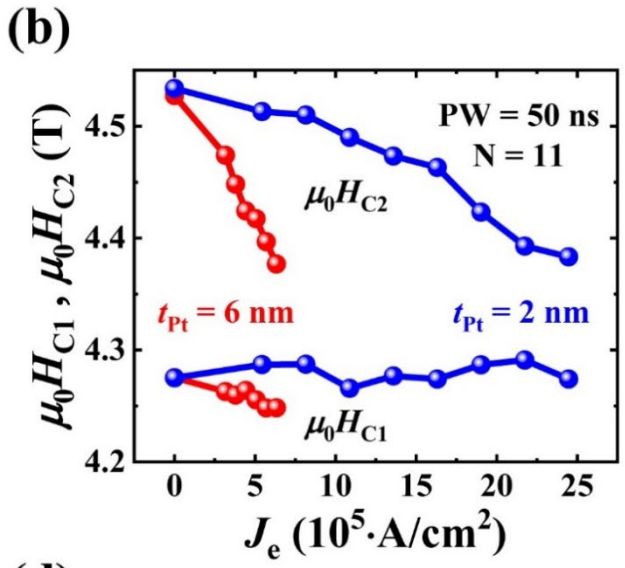


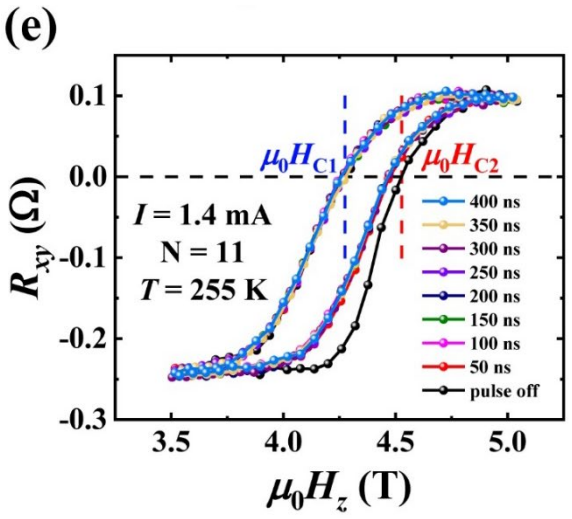
- 磁结构相图

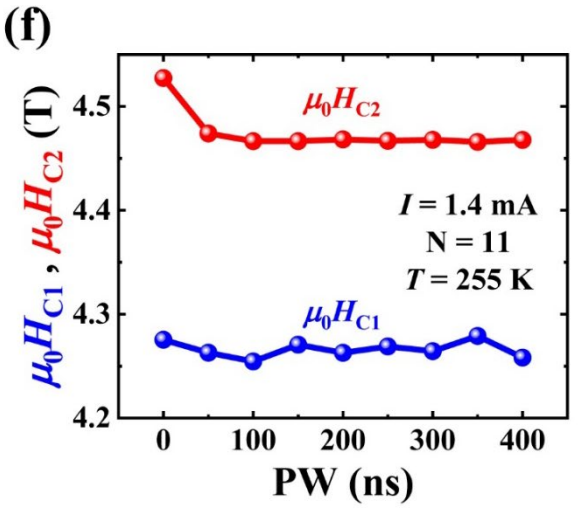
孟庚辰，魏大海 et al., Adv. Funct. Mater. (2025) accepted, DOI: 10.1002/adfm.202501767

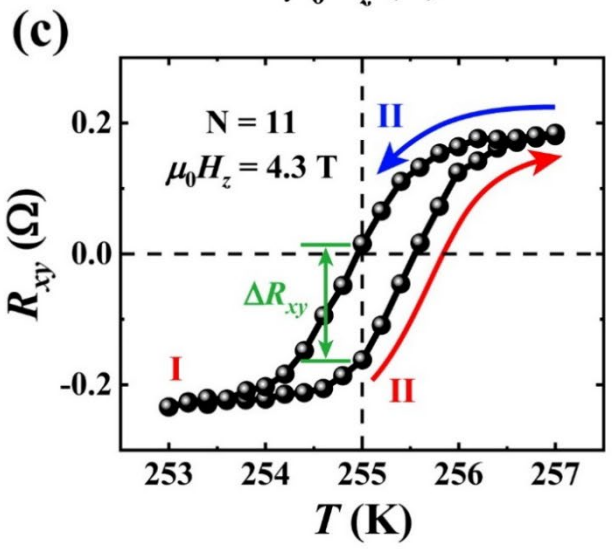
Pt-[Co/Gd]$_N$超晶格的SOT驱动

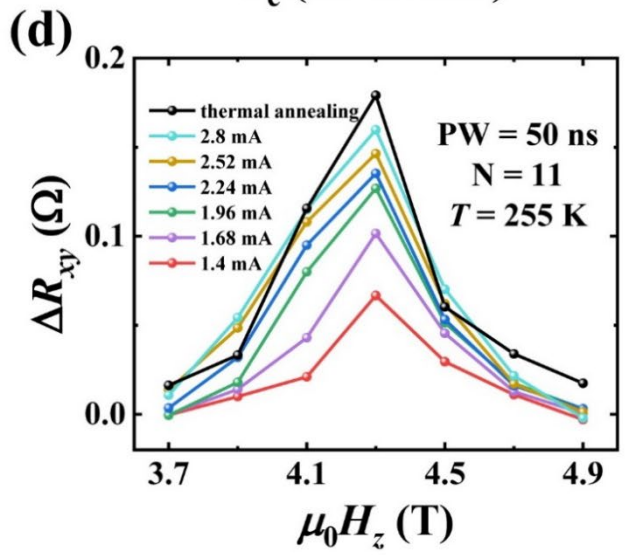












- 电流调控非共线磁结构
- 小回线随脉冲电流增大而减小
- $\mu_0 H_{C1}$ 和 $\mu_0 H_{C2}$ 非对称地减小
- 排除热效应，可能由SOT引起

孟庚辰，魏大海 et al., Adv. Funct. Mater. (2025) accepted, DOI: 10.1002/adfm.202501767

Outlines

1. 亚铁磁自旋电子材料中的自旋输运

2. 重金属/铁磁异质结中轨道流的分离与调控

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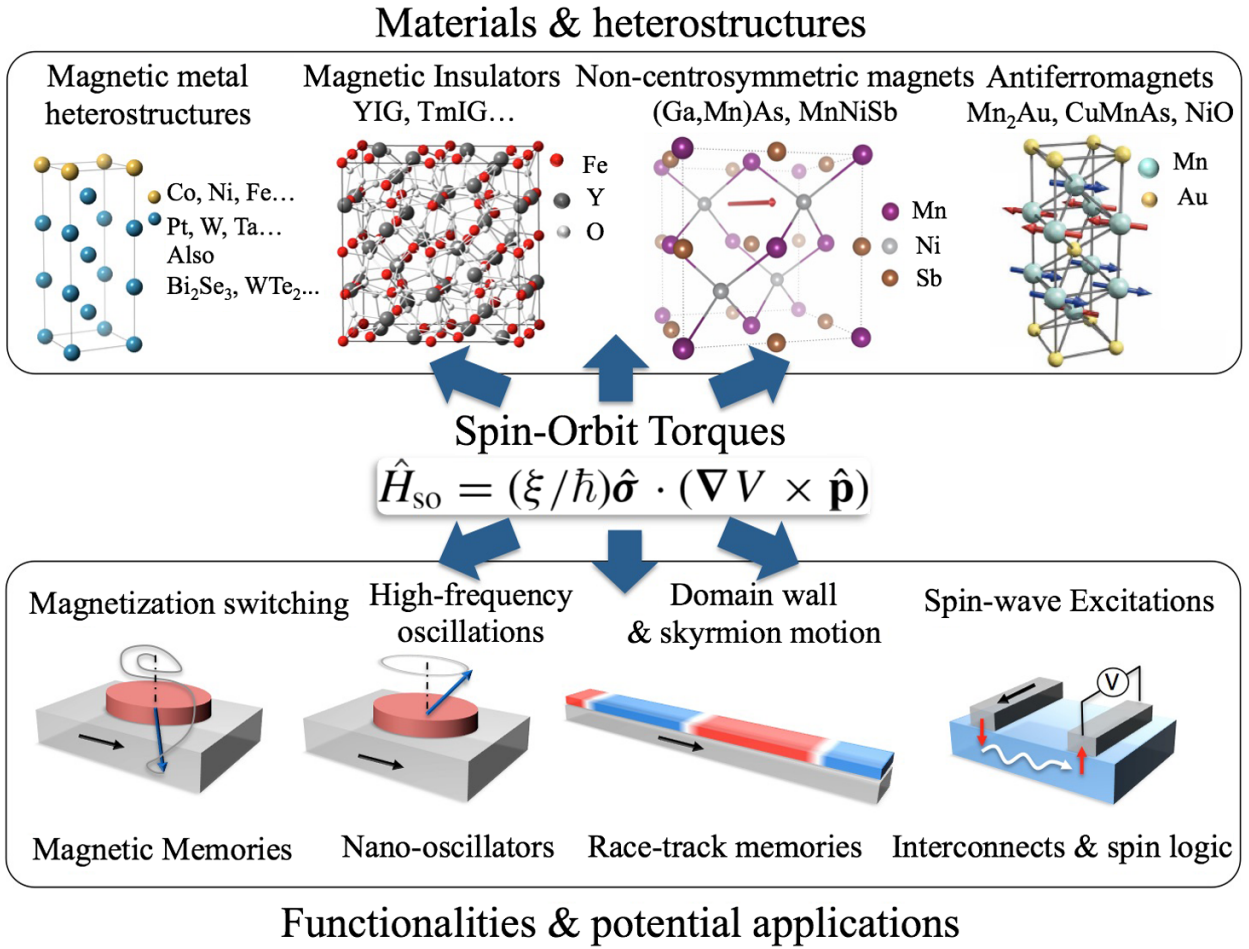
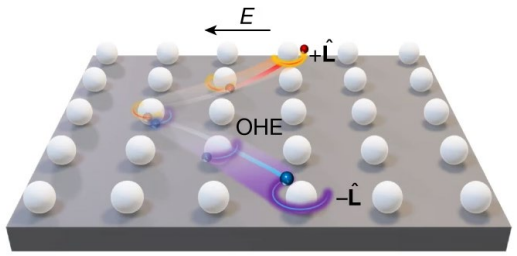
“自旋电子学”主要聚焦于自旋相关效应

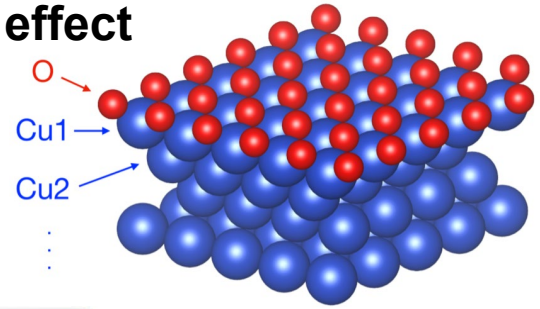


Manchon, A. *et al.*, Rev. Mod. Phys., 91, 035004 (2019)

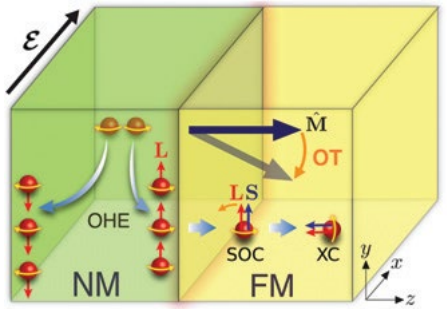
近年提出了轨道角动量相关效应



Orbital Hall effect



Orbital Rashba effect

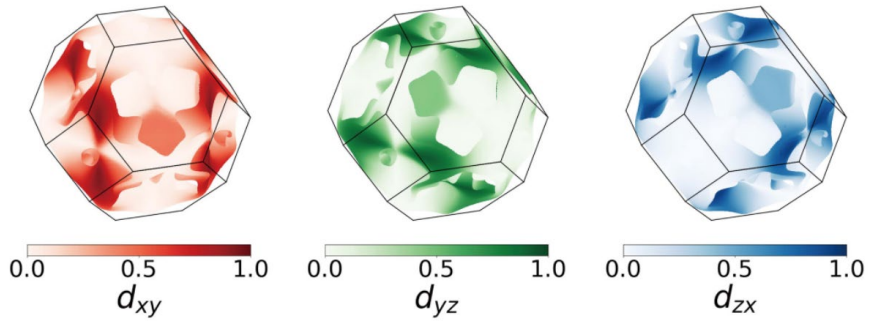


Orbital torque

轨道霍尔效应诱导的SOT

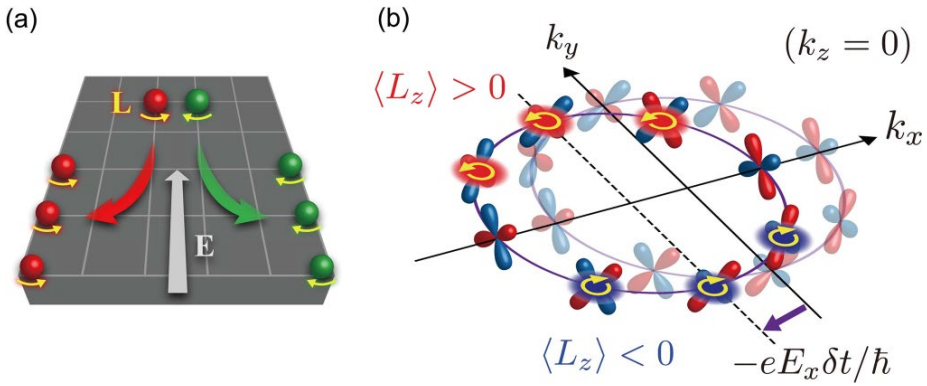
Orbital Texture

轨道角动量动量在空间中的不均匀分布



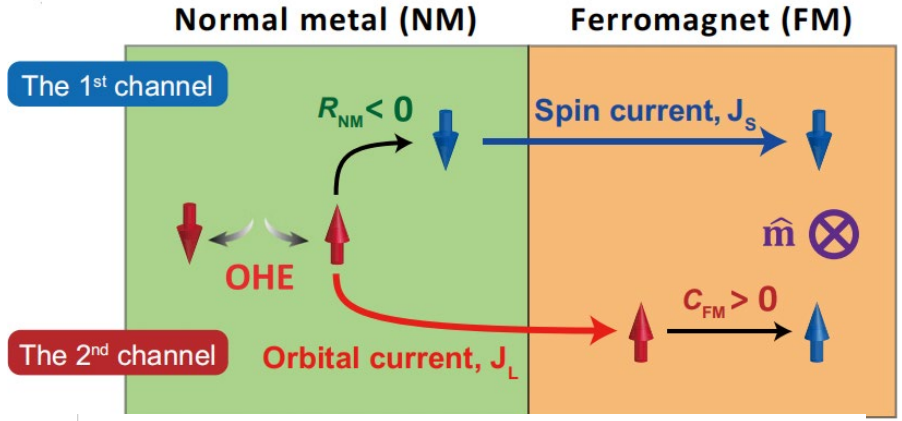
Orbital distribution of Pt

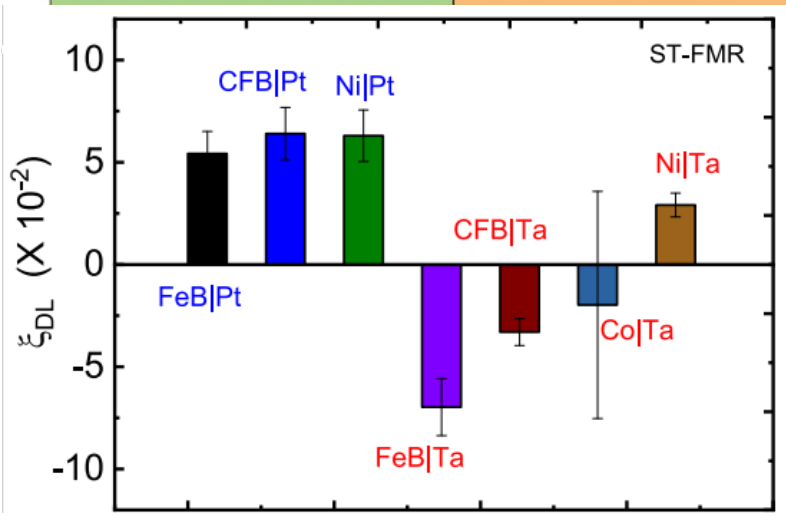
电流诱导轨道角动量累积



Go, D. *et al.*, Phys. Rev. Lett., 121, 086602 (2018)
Jo, D. *et al.*, Phys. Rev. B, 98, 214405 (2018)

Ta/Ni双层异质结中，轨道矩超过自旋矩导致反常的SOT反号

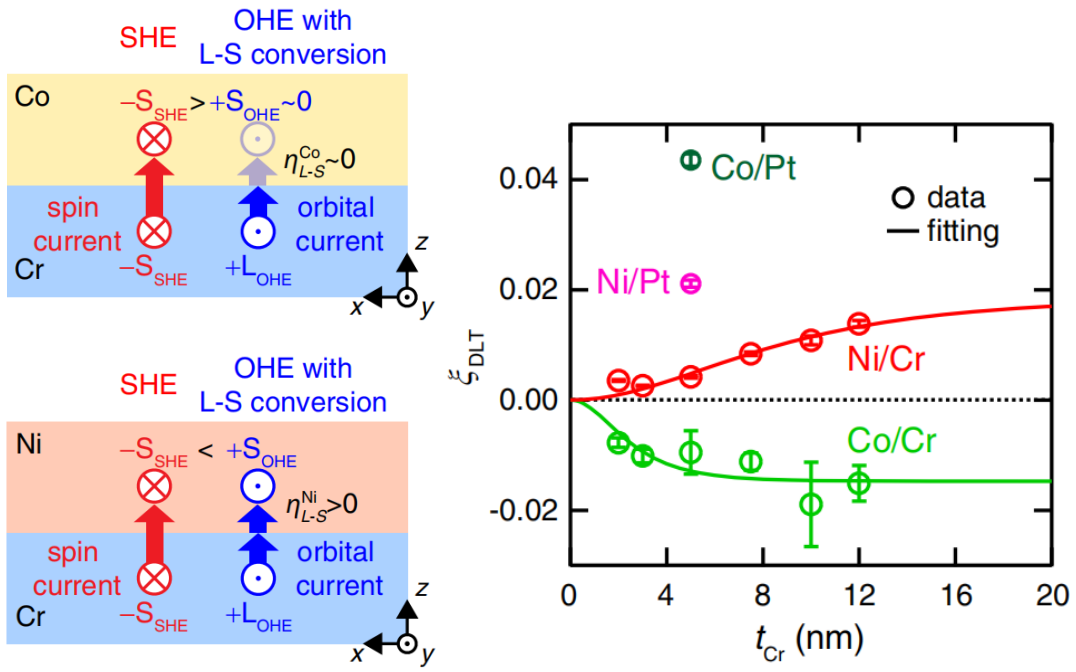




Lee, D. *et al.*, Nat. Commun., 12, 6710 (2021)

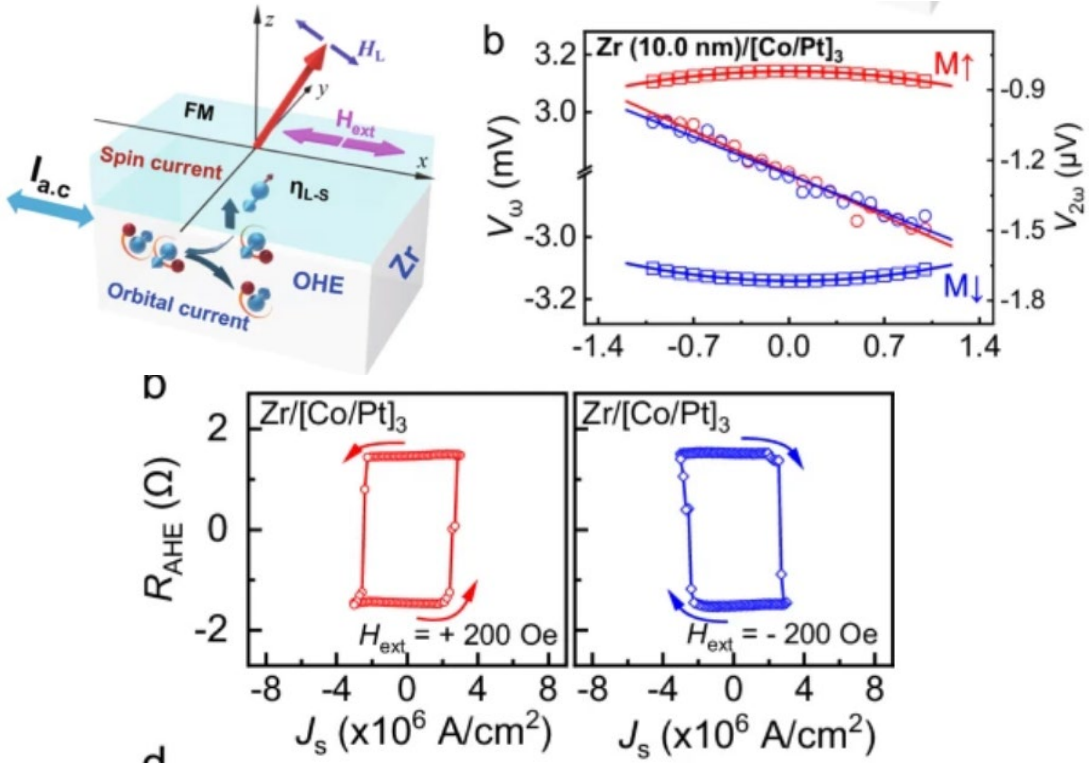
轨道霍尔效应诱导的SOT

由于金属Ni可以产生较强的轨道矩，Cr/Ni异质结同样产生正的SOT而Cr/Co异质结中SOT为负



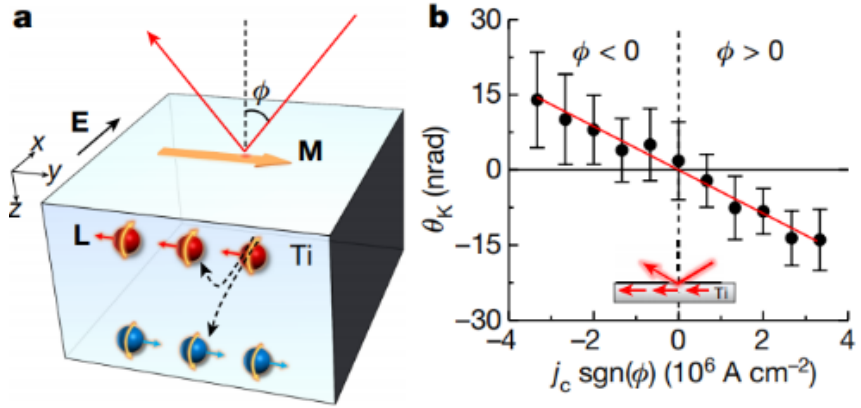
Lee, S. *et al.*, Commun. Phys. 4, 234 (2021)

Zr/[Co/Pt]$_3$中轨道矩诱导的SOT翻转

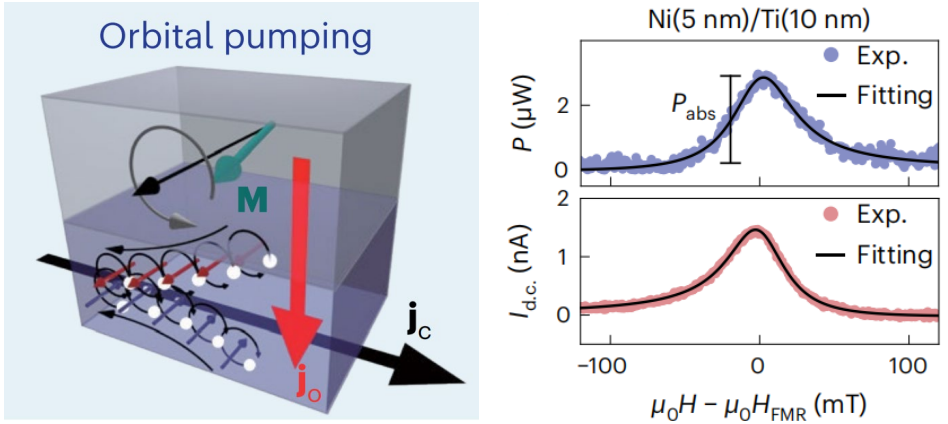


Yang, Y. *et al.*, Nat. Commun. 15, 8645 (2024)

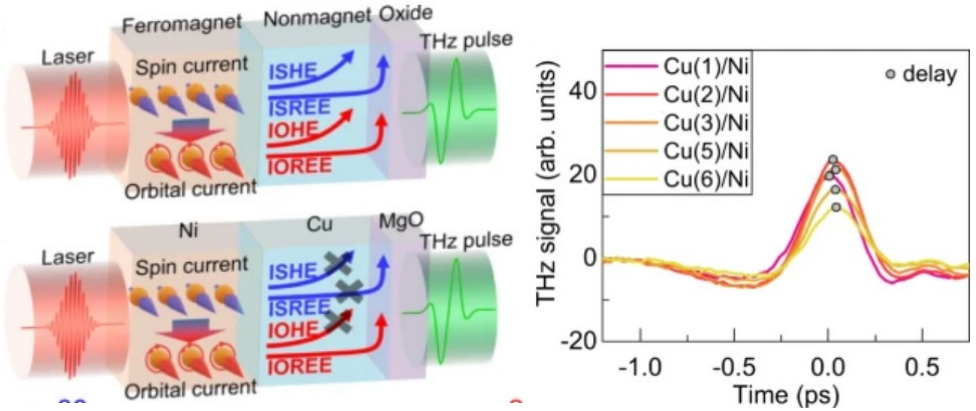
其他轨道相关效应



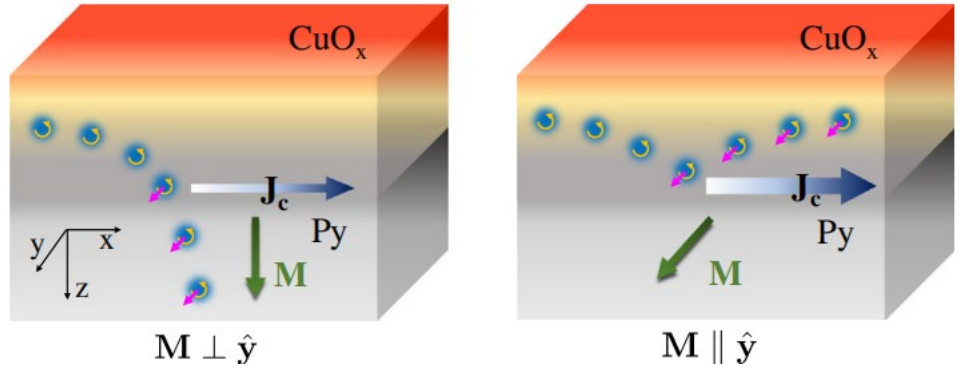
OHE observation via MOKE
Choi, Y. G. *et al.*, Nature, 619, 52–56 (2023)



Orbital pumping and inverse OHE
Hayashi, H. *et al.*, Nat. Electron., 7, 646–652 (2024)



Inverse OHE and THz emission
Xu, Y. *et al.*, Nat. Commun., 15, 2043 (2024)



Orbital magnetoresistance
Ding, S. *et al.*, Phys. Rev. Lett., 128, 067201, (2022)

自旋与轨道的协同作用

自旋相关研究

Material

Pt, W, Ta…

Effect

SHE, RRE…

自旋与轨道并不冲突

轨道相关研究

Material

Ti, Cr, Zr, Ru…

Effect

OHE, ORRE…

自旋+轨道

Motivation

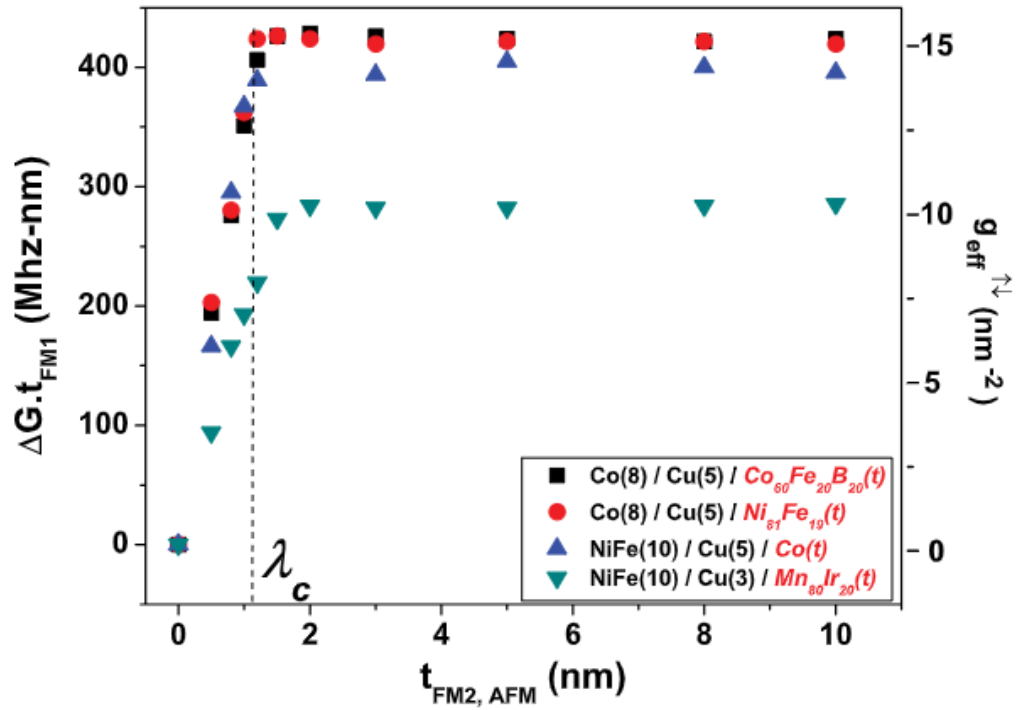
- Harnessing the OHE in heavy metal
- The synergy of spin and orbital torque
- Higher SOT efficiency

Challenges

- Distinguish spin and orbital contributions
- Manipulate spin and orbital torque in heavy metal system

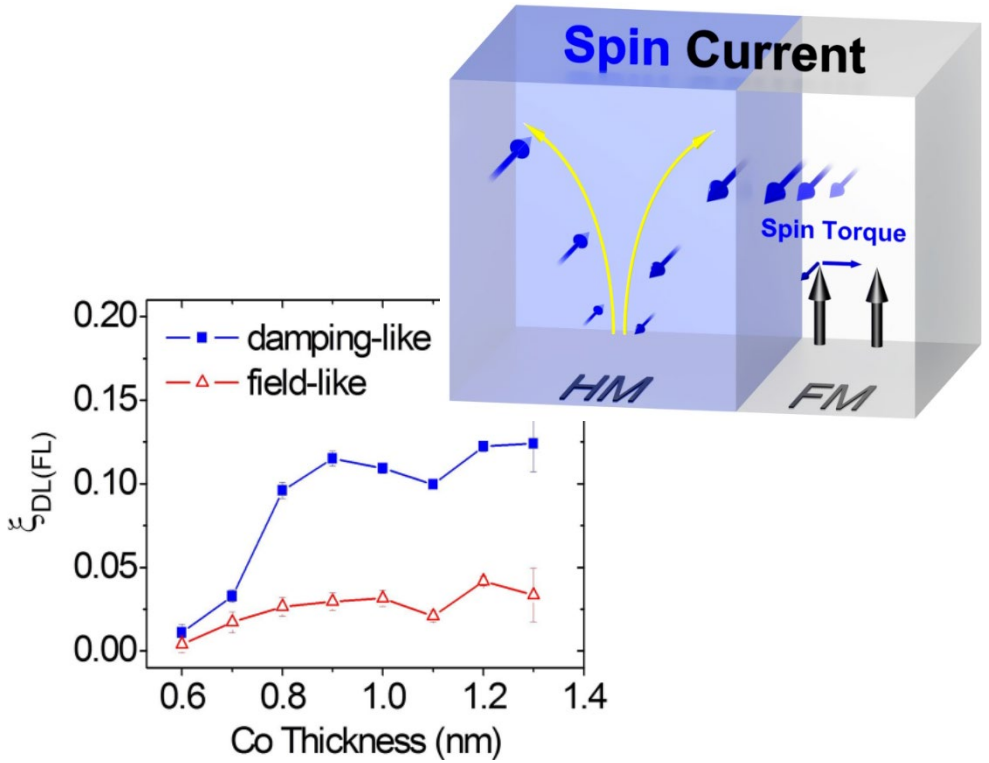
铁磁材料中的自旋输运与自旋矩

- 自旋输运长度小于1 nm
- 非指数衰减行为



Spin-mixing conductance of FM1/Cu/FM2 and FM/Cu/NM
Ghosh, A. *et al.*, Phys. Rev. Lett., 109, 127202, (2012)

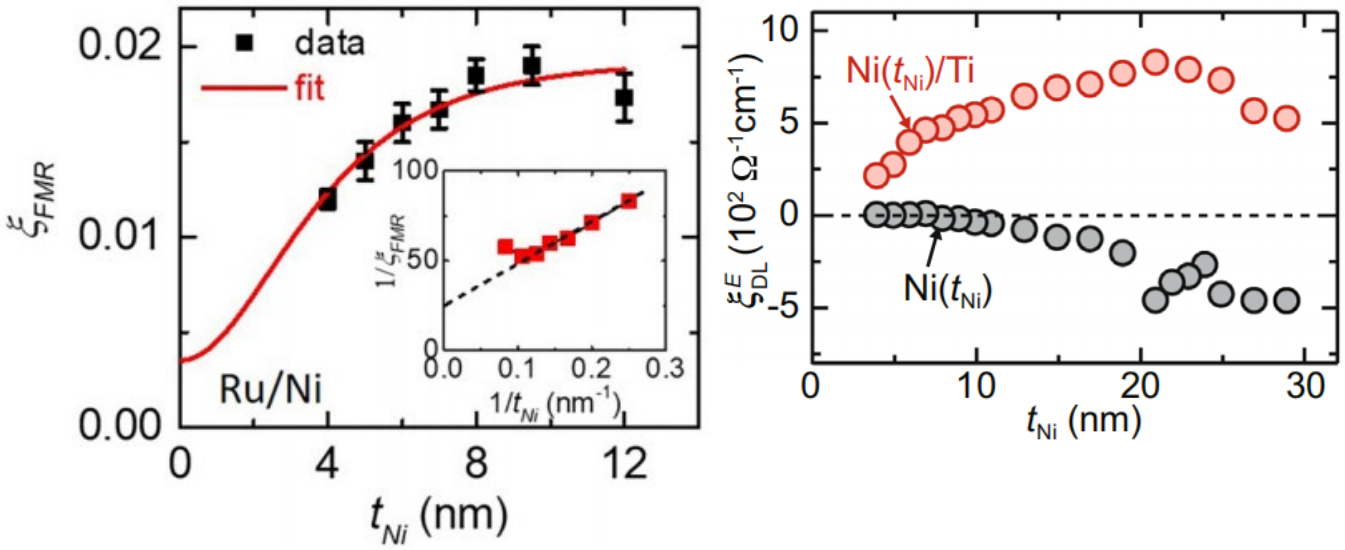
- 自旋流在HM/FM界面处产生自旋矩
- SOT效率与铁磁厚度无关



Pt/Co SOT vs. Co thickness
Pai, C. *et al.*, Phys. Rev. B, 92, 064426, (2015)

铁磁材料中的轨道输运与轨道矩

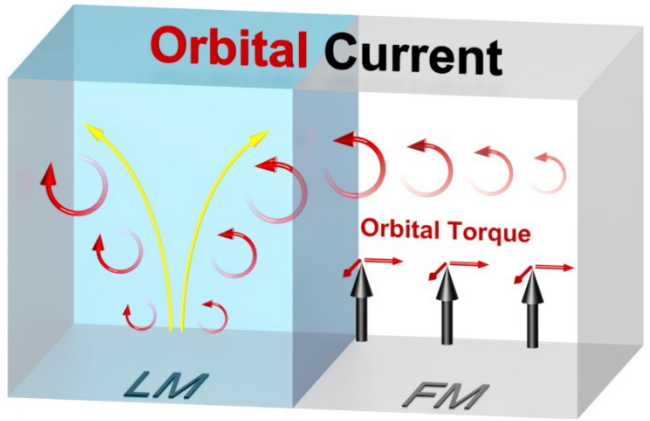
- 轨道输运在铁磁材料中具有长程特性
- 轨道矩的产生与铁磁材料的SOC有关
- 铁磁材料厚度影响轨道矩效率



Orbital torque vs. Ni thickness

Bose, A. *et al.*, Phys. Rev. B, 107, 134423, (2023)

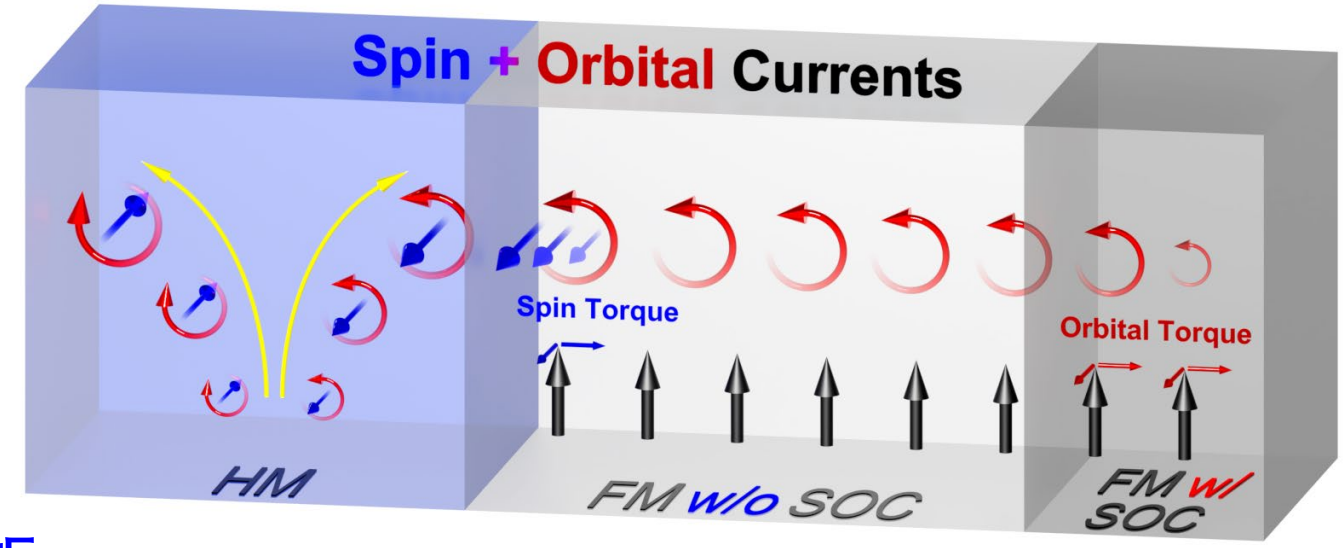
Hayashi, H. *et al.*, Commun. Phys. 6, 32 (2023)



Compared with spin torque, orbital torque is more like a "bulk effect".

自旋矩与轨道矩的区分

Spin and orbital transport in HM/FM/FM^{SOC} multilayers



自旋矩

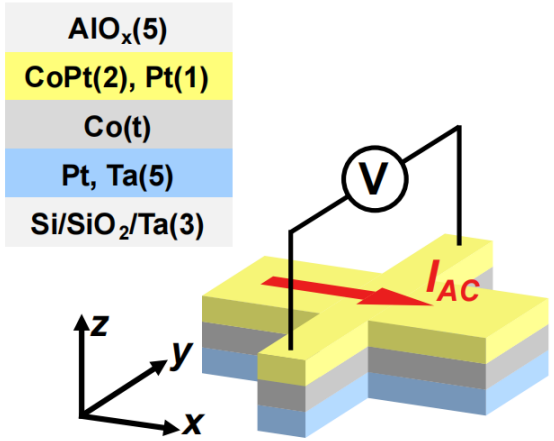
- 自旋流在FM中**快速衰减**
- 自旋流在**HM/FM界面**产生**恒定的SOT**

轨道矩

- 轨道流不与磁矩直接相互作用
- 轨道流穿过FM并在其中**缓慢衰减**
- 轨道流在**FM^{SOC}**中产生产生SOT，并且**SOT随FM厚度变化**

自旋矩与轨道矩的区分

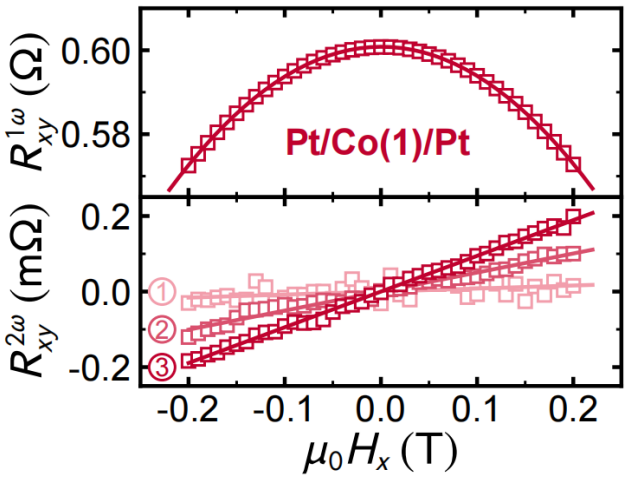
HM/FM/FM^{SOC}多层的结构



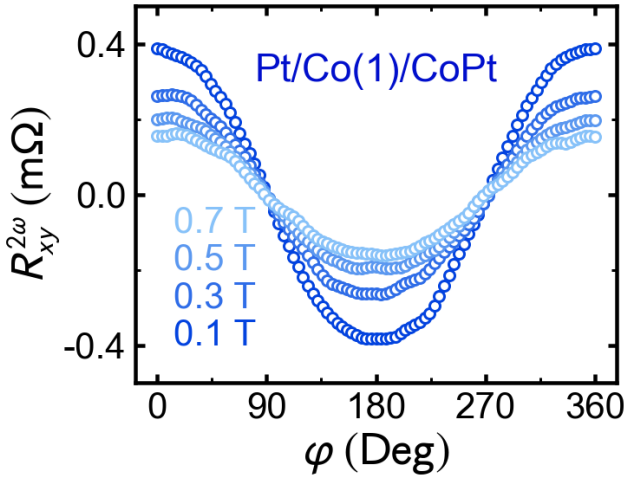
- **HM:** 5nm Pt or Ta, **sources** of spin and orbital current
- **FM:** Co with different thickness, **spin current filter**, generating spin torque
- **FM^{SOC}:** 2nm CoPt alloy or 1nm Pt with strong SOC, **orbital current detector**, generating orbital torque

二次谐波方法测量SOT有效场

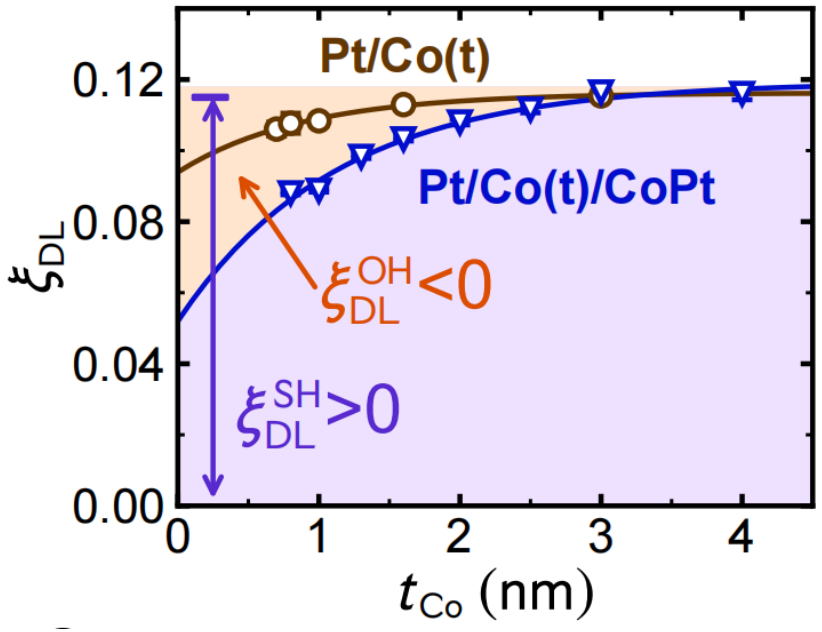
Sweeping-field method for out-of-plane

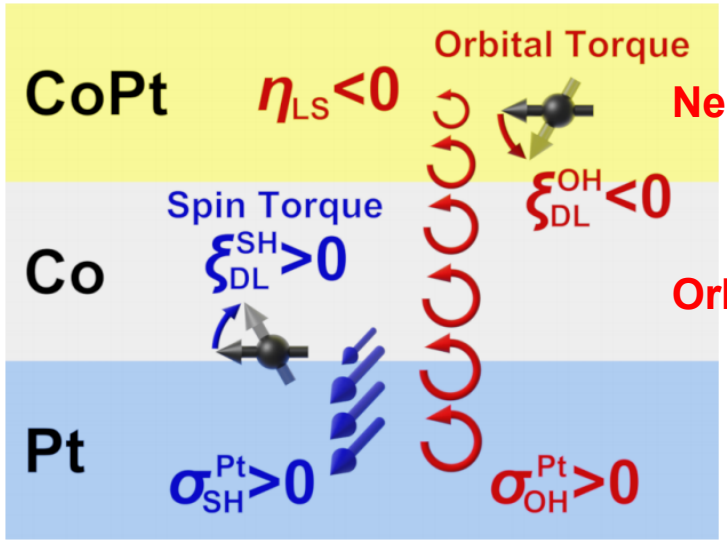


Rotating-angle method for in-plane



Pt/Co和Pt/Co/CoPt中的SOT贡献





Negative orbital torque in CoPt

Orbital current passes through Co

Positive spin torque at Pt/Co interface
Spin current decay in Co

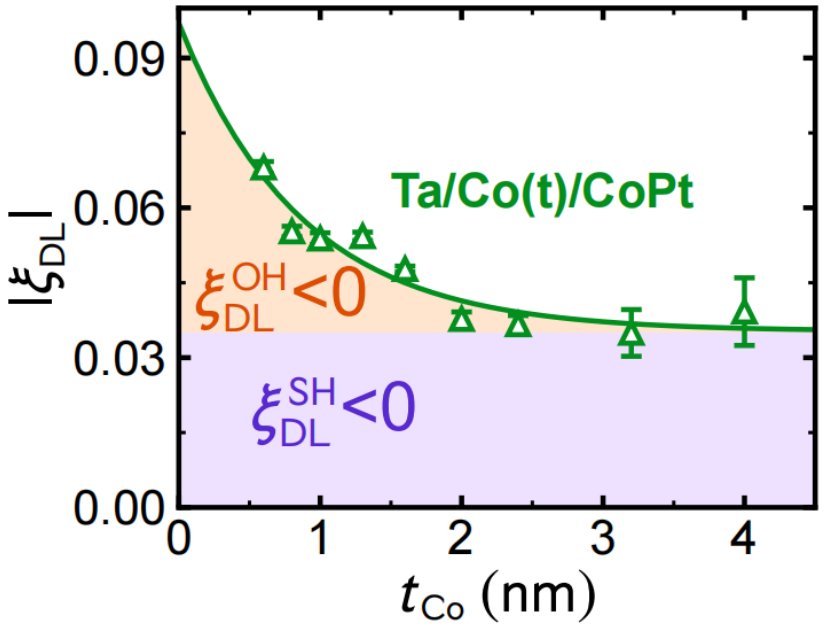
Pt(5)/Co(t)

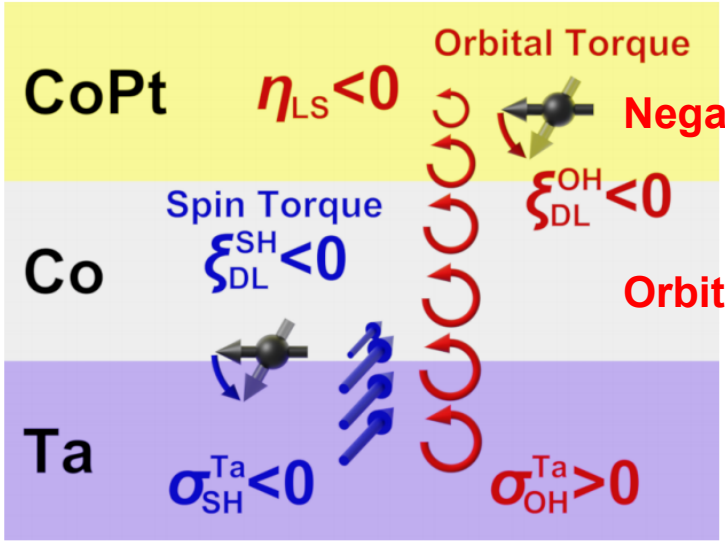
- ξ_{DL}基本**保持不变**，自旋矩贡献

Pt(5)/Co(t)/CoPt(2)

- ξ_{DL}随Co厚度**增加**
- ξ_{DL}在t = 3 nm处**饱和**，饱和后与Pt(5)/Co(t)一致
- **正的自旋矩**贡献(Pt/Co界面)和**负的轨道矩**贡献(CoPt合金)

Ta/Co/CoPt中的SOT贡献





Negative orbital torque in CoPt

Orbital current passes through Co

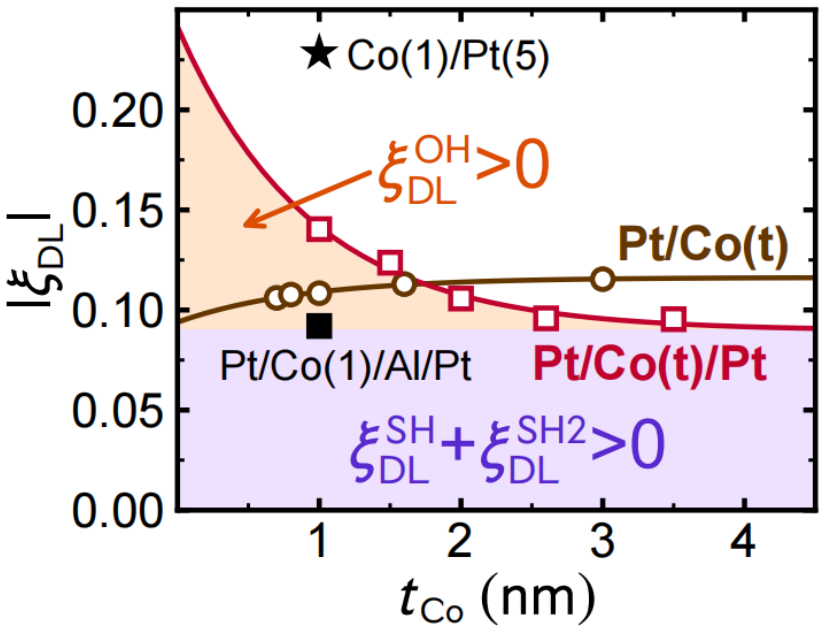
Negative spin torque at Ta/Co interface

Spin current decay in Co

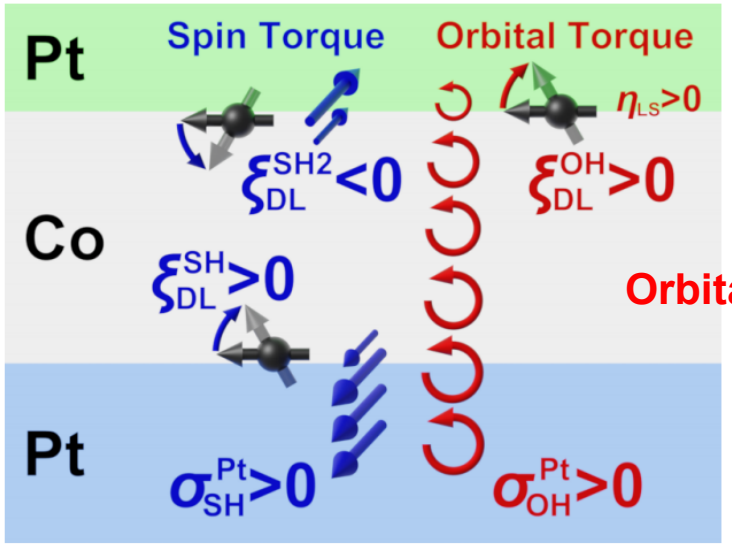
Ta(5)/Co(t)/CoPt(2)

- Ta产生负的自旋流和正的轨道流
- ξ_{DL}随Co厚度**降低**
- ξ_{DL}在t = 3 nm处**饱和**
- **负的自旋矩**贡献(Ta/Co界面)和**负的轨道矩**贡献(CoPt合金)
- 轨道矩**增强**SOT

不对称Pt/Co/Pt中的SOT贡献



Pt(5)/Co(t)/Pt(1)



Positive orbital torque at upper Co/Pt interface

Orbital current passes through Co

Spin torque at lower and upper interface
Spin current decay in Co

- 自旋矩之和为正，轨道矩为正，轨道矩**增强**SOT
- ξ_{DL}随Co厚度**降低**
- 尽管顶部Pt(1)产生负的自旋流，**Pt(5)/Co(1)/Pt(1)** 的ξ_{DL}仍然**超过Pt(5)/Co(1)**
- 当轨道矩衰减后，顶部Pt(1)产生的负自旋流导致Pt(5)/Co(t)/Pt(1)的ξ_{DL}Pt(5)/Co(t)
- **破坏Co/Pt界面**后轨道矩消失
- **110%的SOT效率提高**

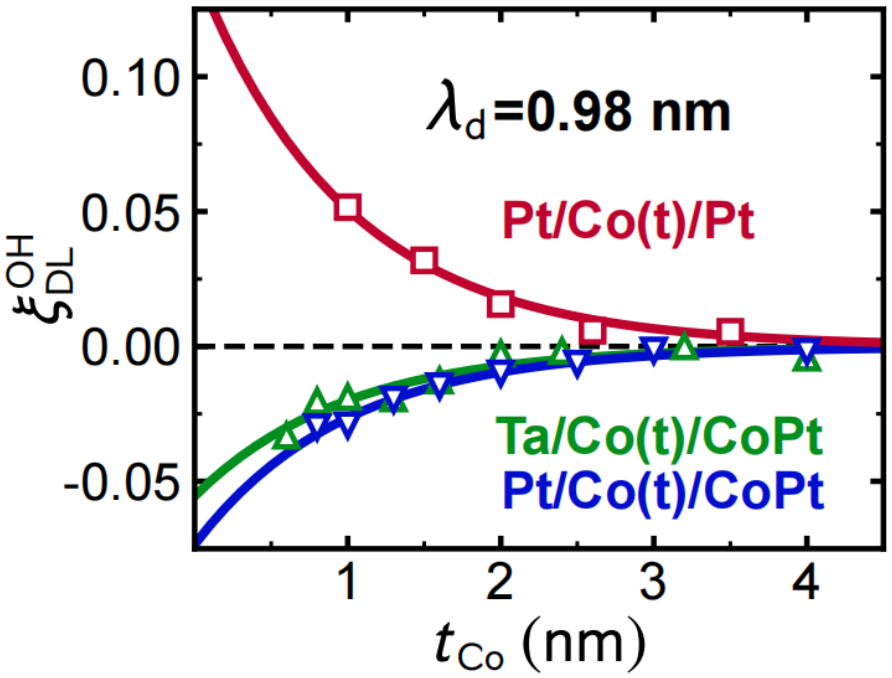
轨道流的扩散输运

Orbital torque contribution can be descript by a diffusion model

$$\xi_{\mathrm{DL}} = \xi_{\mathrm{DL}}^{\mathrm{SH}} + \xi_{\mathrm{DL}}^{\mathrm{OH}} \mathrm{e}^{-t_{\mathrm{Co}}/\lambda_{\mathrm{d}}}$$

Series Name	$\lambda_{\mathrm{d}}^{\mathrm{Co}}$	$\xi_{\mathrm{DL}}^{\mathrm{OH}}$	$\xi_{\mathrm{DL}}^{\mathrm{SH}}$
Pt(5)/Co(t)/CoPt(2)	1.13 nm	-0.067	0.119
Ta(5)/Co(t)/CoPt(2)	0.87 nm	-0.062	-0.035
Pt(5)/Co(t)/Pt(1)	0.93 nm	0.152	0.090

Fitting by average λ_{d}



- Pt的轨道霍尔电导超过自旋霍尔电导
- 自旋矩与轨道矩的协同作用可以增强SOT

重金属/铁磁异质结中轨道流的分离与调控

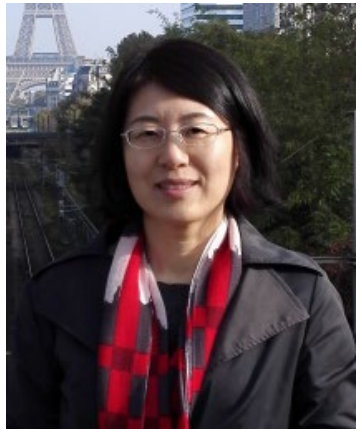
- 利用**HM/FM/FM^{SOC}**多层结构在**空间上分离**自旋流和轨道流
- 分离并量化HM/FM多层中轨道矩的效率 **(ξ_{OH} ~0.15)**，并超过自旋矩的效率 **(ξ_{SH} ~0.1)**
- 通过良好的结构设计可以实现**自旋矩和轨道矩的协同作用**，和SOT效率的显著增强

Multilayer Structure	ξ_{OT}	ξ_{ST}	Total	Reference
Pt(5)/Co(1)/Pt(1)	0.15	0.090	0.24	★This work
Pt(5)/Co(t)/CoPt(2)	-0.067	0.119	0.05	★This work
Pt(5)/Co(1)	-	0.11	0.11	Phys. Rev. Lett. 116, 126601, 2016
Ti(60)/Ni(8)	0.06	-	0.06	Commun. Phys. 6, 32, 2023
Ru(4)/Pt(1)/CFB(5)/Pt(1)	0.03		0.03	Phys. Rev. B 107, 134423, 2023

Harnessing synergy of spin and orbital torque can enhance SOT

杨雨民，雷娜，魏大海，赵建华 et al., Commun. Phys. 7, 336 (2024)

感谢合作者：



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