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

后摩尔硅器件半导体前沿物理

骆军委

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

中国科学院大学物院青年教师线上论坛第11期，2025年5月11日

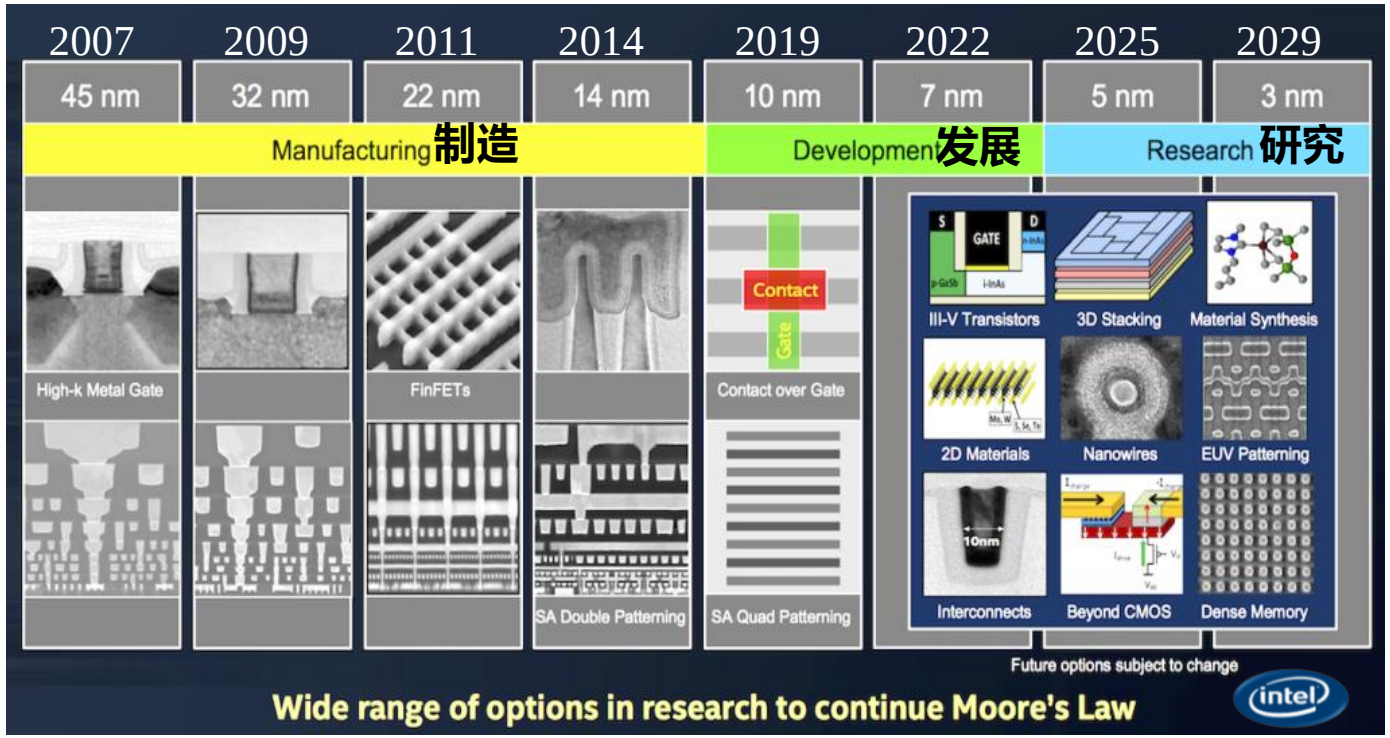
骆军委 --- 半导体物理

中国科学院半导体研究所研究员，党委委员，所务委员

- 半导体芯片物理与技术全国重点实验室主任
- 中国科学院首批稳定支持青年团队负责人（2021）
- 担任国家重点研发计划“物态调控”专项总体专家组成员
- 担任基金委十四五和中长期物理学科战略规划秘书组成员
- 国家杰出青年基金获得者（2019）、海外高层次人才青年项目（2014）
- 美国可再生能源国家实验室博士后、研究员（2007-2014）
- 2007年中科院半导体所获得博士学位（导师：李树深 院士）
- 浙江大学物理系获得学士、硕士学位（2000、2003）

- 长期从事半导体物理与器件物理研究，在后摩尔时代硅基半导体理论研究取得系统性创新成果，至今已发表论文130余篇，包括以第一或通讯作者发表在**Nature**（1篇）、**Nature Physics**（1篇）、**Nature Nanotechnology**（1篇）、**Nature Communications**（5篇）、**PRL**（7篇）等。
- 2023年在中科院院刊上发表《加强半导体基础能力建设点亮半导体自立自强发展的灯塔》得到**习近平总书记批示**和高度关注，美国彭博社以“中国顶级科学家勾画出绕过美国芯片制裁的计划”为题进行专题报道，收到《纽约时报》、《时代周刊》和《经济学人》等的采访邀约。
- 2024年在《改革内参.综合版》发表《实施专利战略反制美国芯片霸权》并获得发改委领导关注。
- 受邀在国家发改委、国务院发展研究中心、兵器工业集团等做半导体基础研究现状方面的讲座。

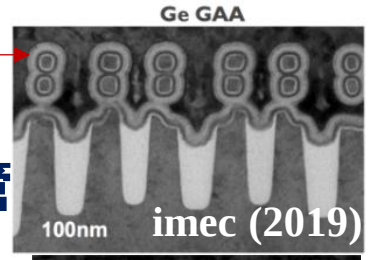
后摩尔时代半导体技术创新：新结构、新材料、新原理

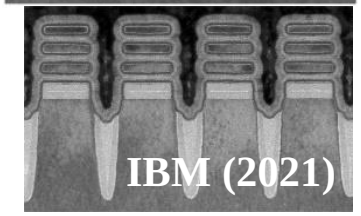


更小尺寸
More Moore

锗纳米线

锗晶体管
III-V/Si晶体管
纳米线晶体管
纳米片晶体管
二维材料



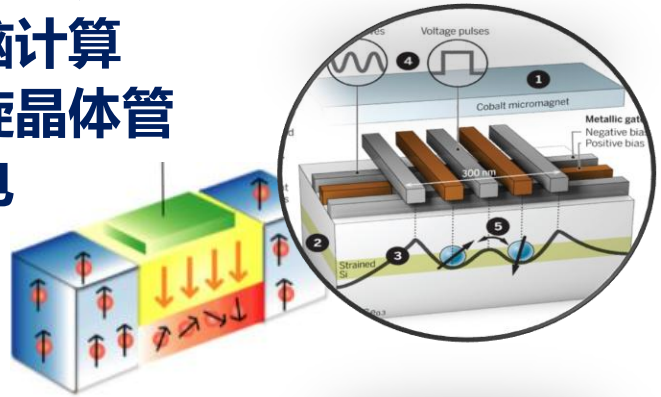


更多功能
More than Moore

3D异构异质集成
光电子集成
存算一体
感算一体

超越CMOS
Beyond Moore

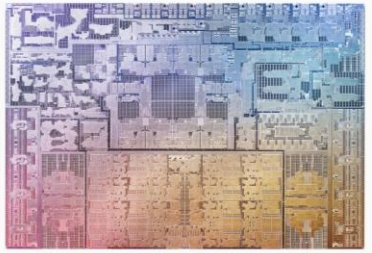
量子计算
类脑计算
自旋晶体管
铁电



160亿

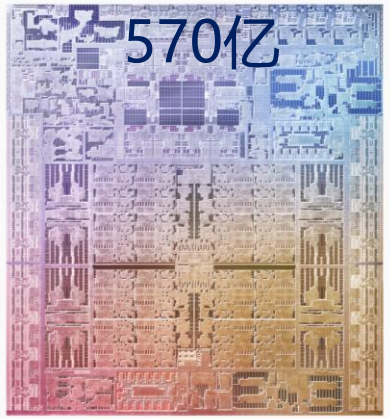
M1

337亿晶体管



M1 Pro

570亿

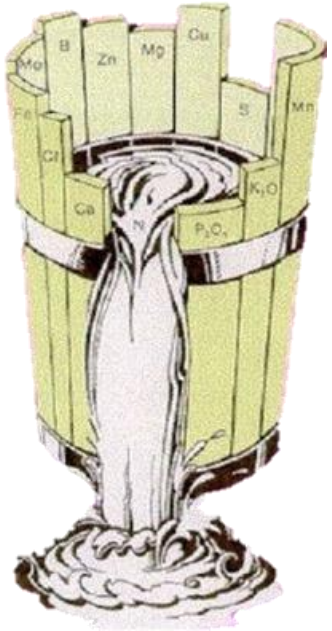


M1 Max

摩尔定律已经失效，但硅基生命还很长?

硅是半导体工业的基础材料（短板理论）：

- ✓ 硅具有储量丰富、化学稳定性好、无环境污染、大单晶、高纯度、可掺杂、高传导率、高度匹配本征氧化物等优点；
- ✓ 硅工艺非常成熟，形成强大的产业能力；
- ✓ 拥有高度兼容的高质量本征氧化物SiO_2是硅打败包括GaAs和Ge在内所有半导体材料的决定性因素（界面即器件）。



人类的第一个晶体管是锗晶体管

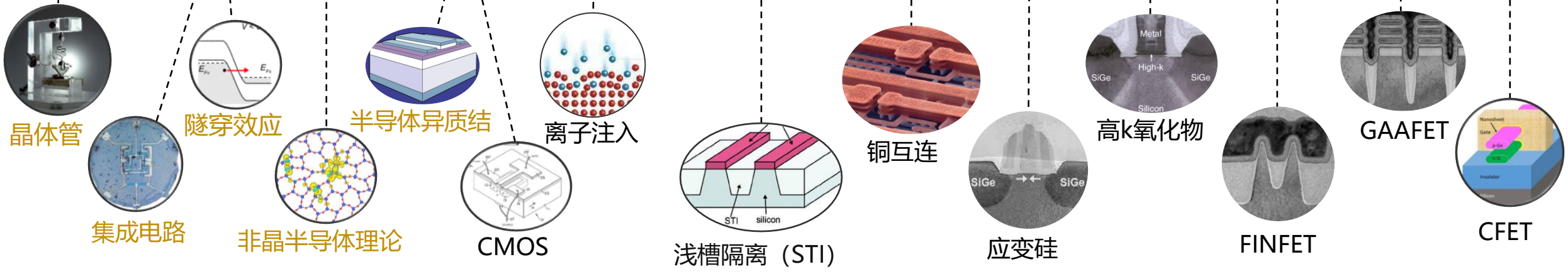
巴丁、肖克利、布拉顿

摩尔定律的延续依赖半导体物理的突破

第一次量子革命

第二次量子革命(超越摩尔)

1947 Transistor
1958 IC TE
1960 DM
1963 SHS CMOS
1970 II
1993 STI
1998 Cu
2003 Strain
2007 HKMG
2011 FinFET
2022 GAAFET
2030 CFET

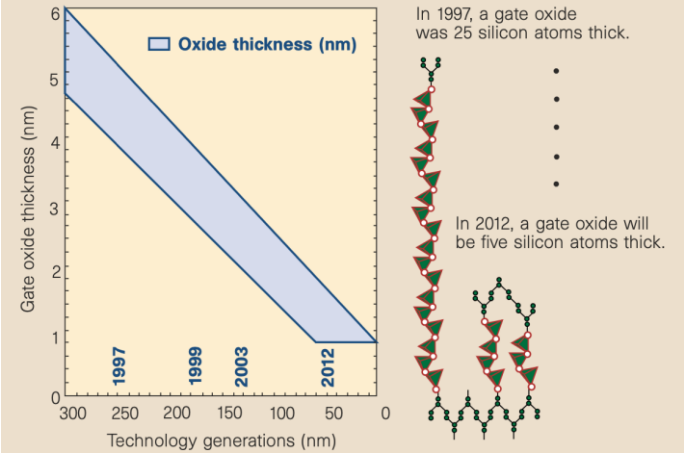


NATURE | VOL 399 | 24 JUNE 1999 | www.nature.com

The end of the road for silicon?

Max Schulz

Computer chips continue to shrink. But the discovery that a layer of silicon dioxide must be at least four to five atoms thick to function as an insulator suggests that silicon-based microchips will reach the physical limits of miniaturization early next century.



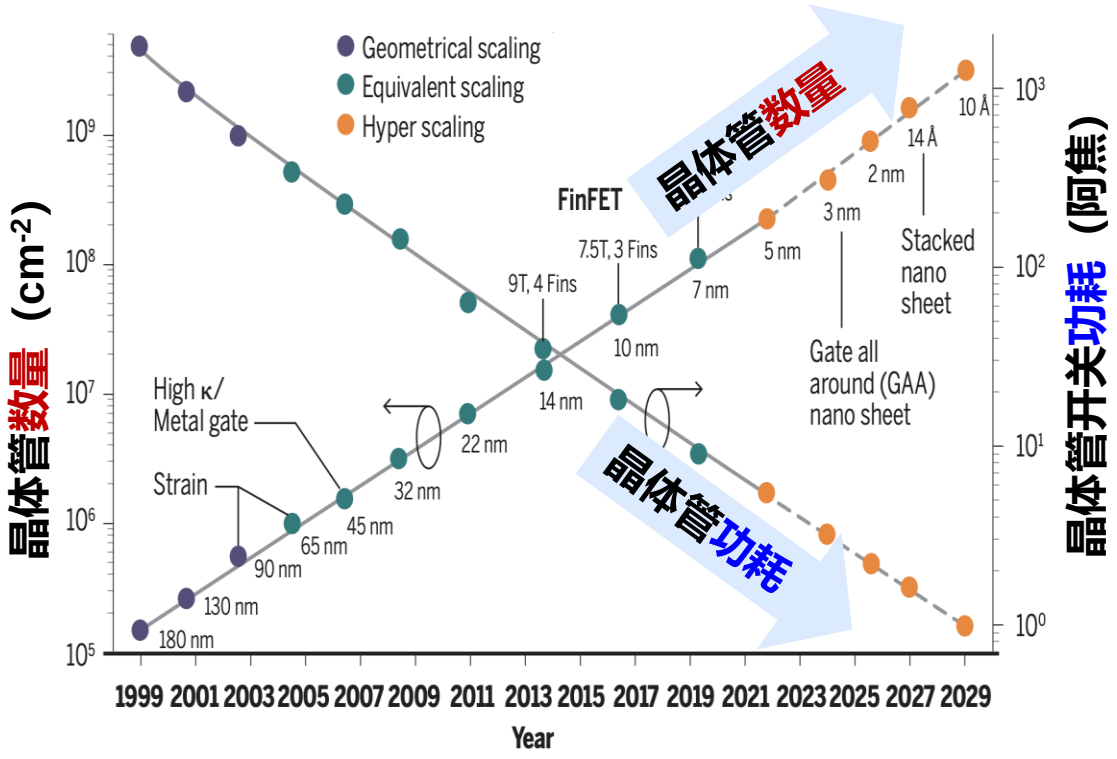
迁移率cm^2/V-sec	平面晶体管
电子	200
空穴	63

延续摩尔技术路线：亟需物理上的真正突破

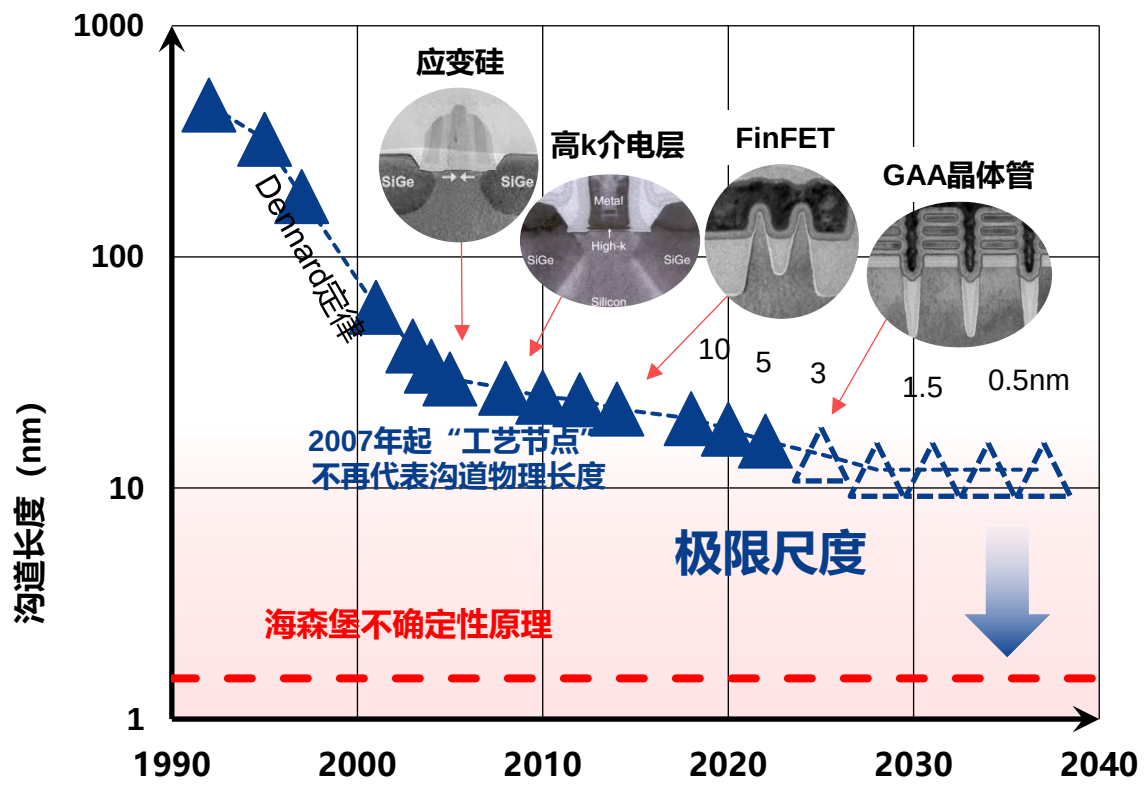
- 功耗是限制芯片集成度和性能的主要因素，延续摩尔定律需要器件功耗等比例降低
- 硅沟道晶体管沟道长度将停滞在12nm极限尺寸，亟需突破极限尺度半导体器件的关键物理瓶颈

摩尔定律：集成晶体管数量每18个月翻一番

Datta et al., Science 378, 733 (2022)



器件与系统国际路线图（IRDS 2022）



极限尺度晶体管物理瓶颈

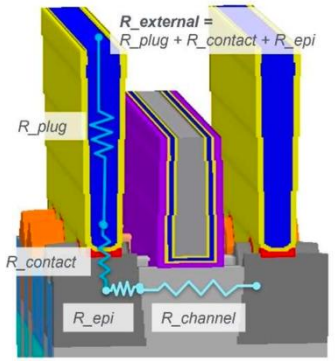
国际半导体技术路线图 IRDS 2022

4.2. PERFORMANCE BOOSTERS

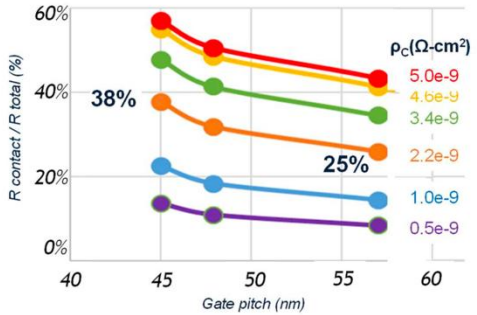
In order to maintain the scaling at low voltages, scaling in recent years focused on additional solutions to boost the performance such as the use of introducing strain to channel; stress boosters; high-κ metal gate; lowering contact resistance, and improving electrostatics. This was all done in order to compensate the gate drive loss while supply voltage needs to be scaled down for high-performance mobile applications.

总功耗 =接触功耗+沟道功耗 + 栅极功耗

接触电阻成为先进节点关键瓶颈

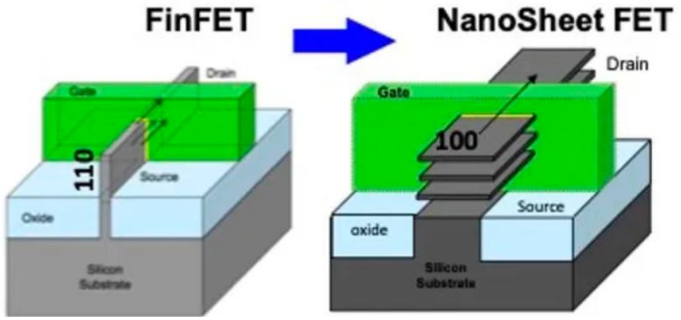


$$R_c \approx \rho_c / A_c$$



Nicolas Breil@AMAT, IEEE IITC (2021)
S. Datta et al., Science 378, 733 (2022)

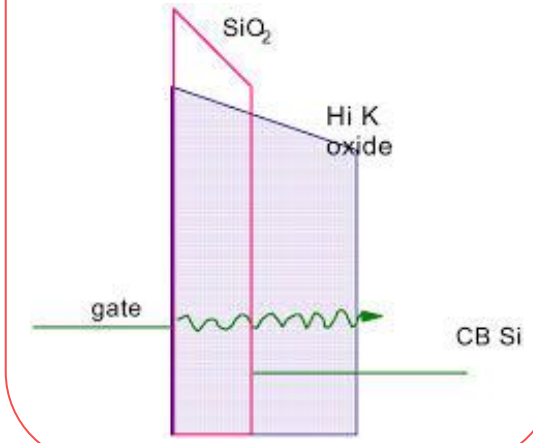
迁移率退化严重



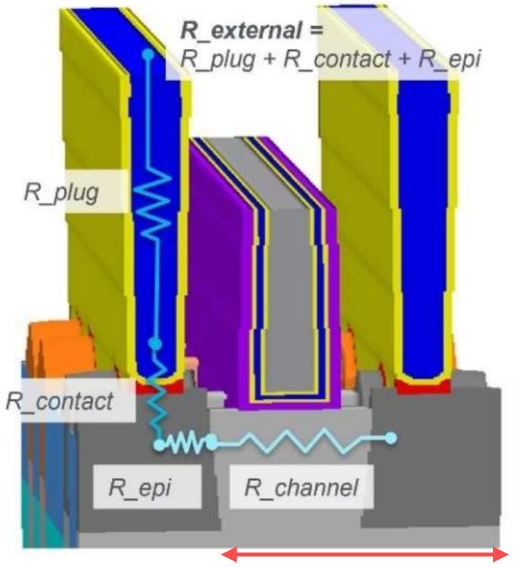
Mobility cm²/V-sec	Planar MOSFET	FinFET	GAAFET
electron	200	130	175
hole	63	238	78

K. Zhao, IBM/IEDM tutorial (2021)

高k介电层：隧穿漏电流与缺陷引起的可靠性



Contact resistance becomes a fundamental bottleneck



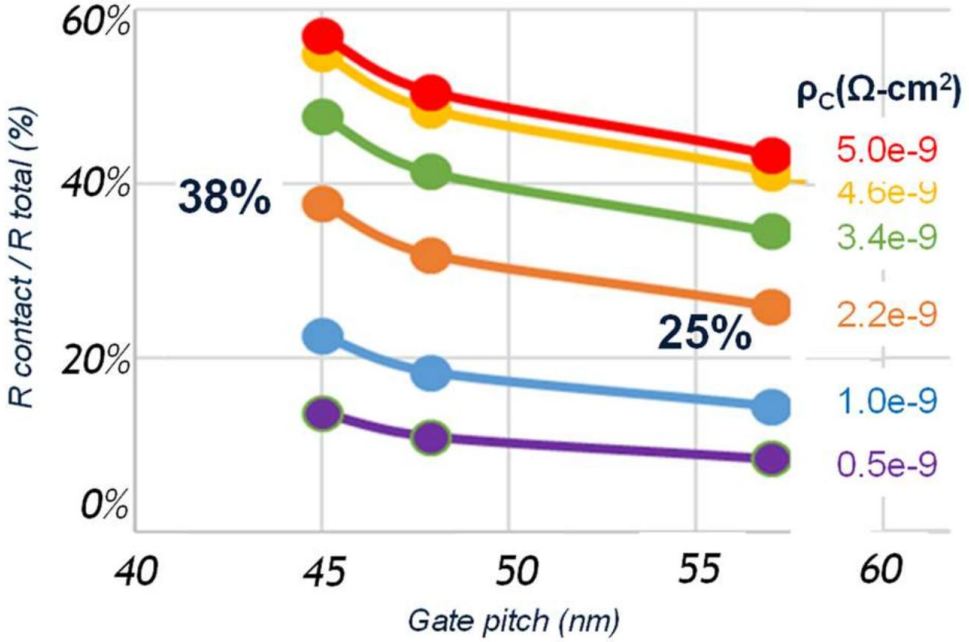
$$R_c \approx \rho_c / A_c$$

Power consumption (thermal energy)

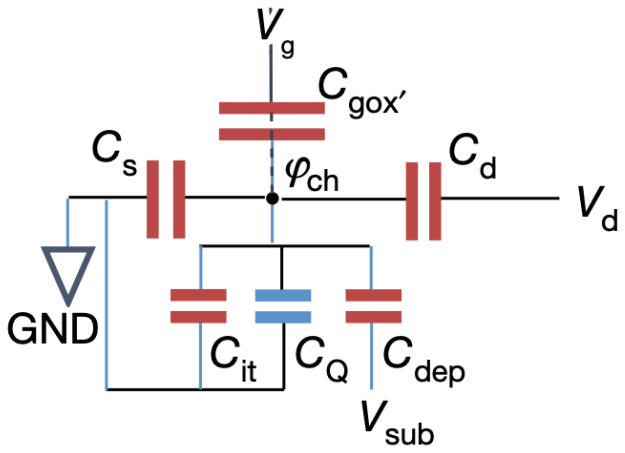
$$P_c = R_c \times I_{on}^2$$

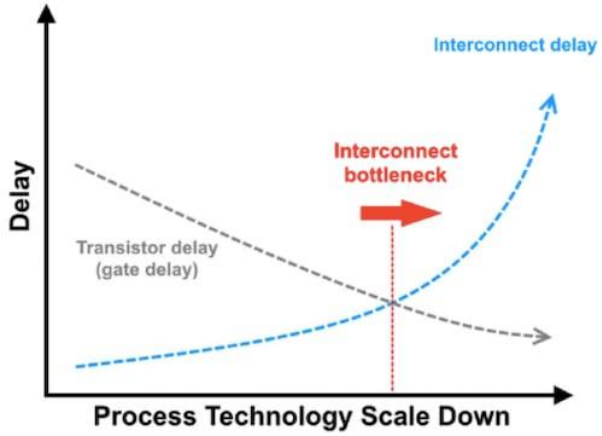
Interconnect delay

$$\tau_c = R_c \times C_{tot}$$

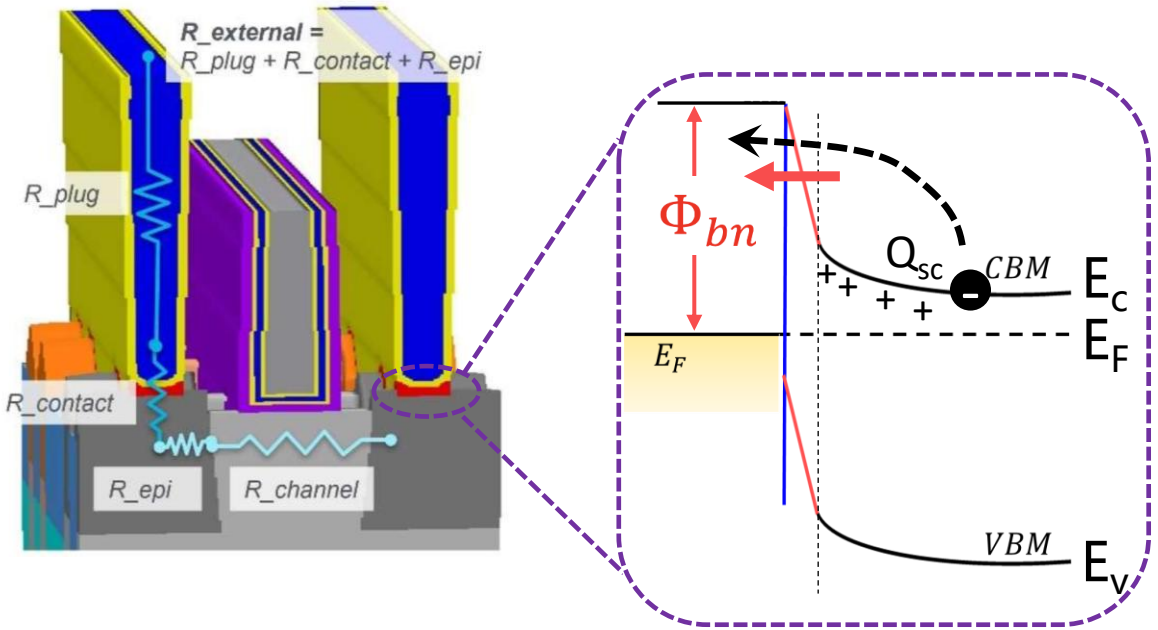


Nicolas Breil@AMAT, 2021 IEEE IITC





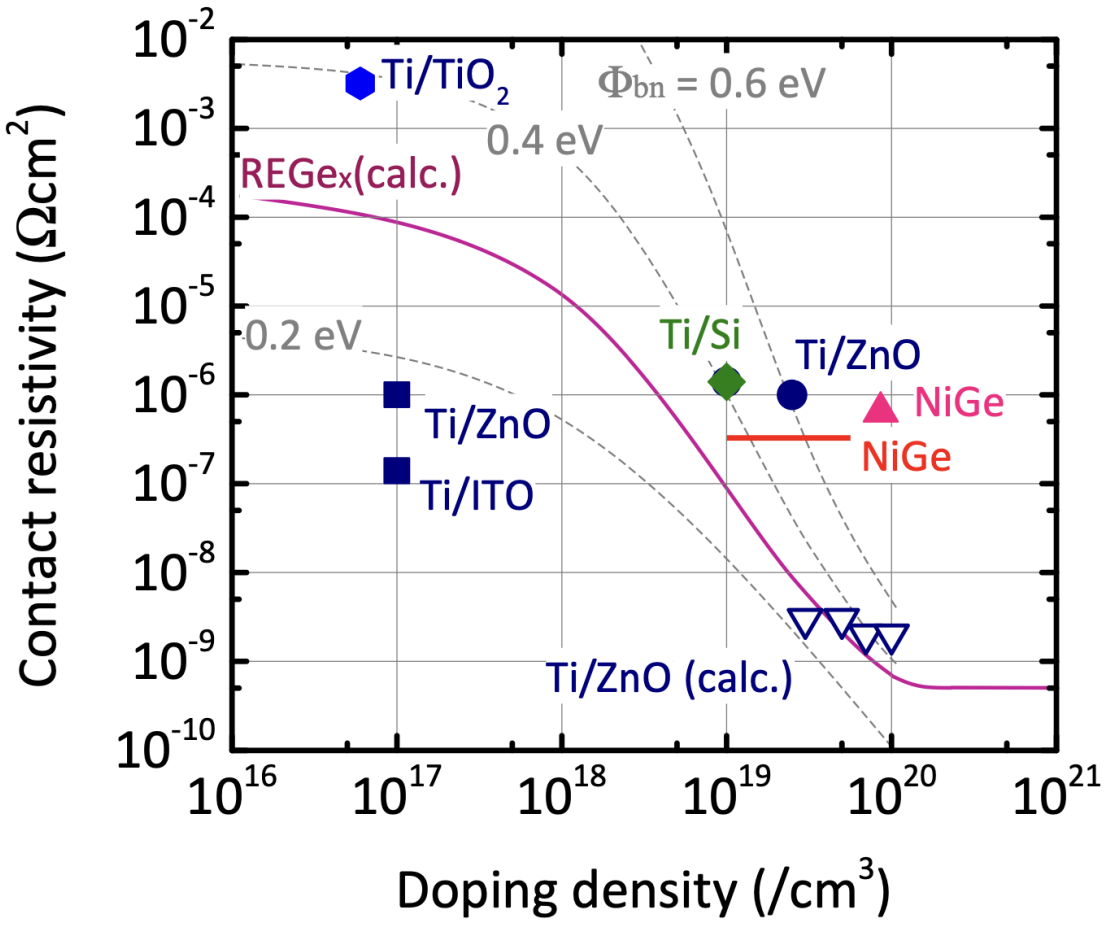
Schottky barrier height and dopant concentration



$$\rho_c \approx exp\left(\frac{C \cdot \phi_b}{\sqrt{N_d}}\right)$$

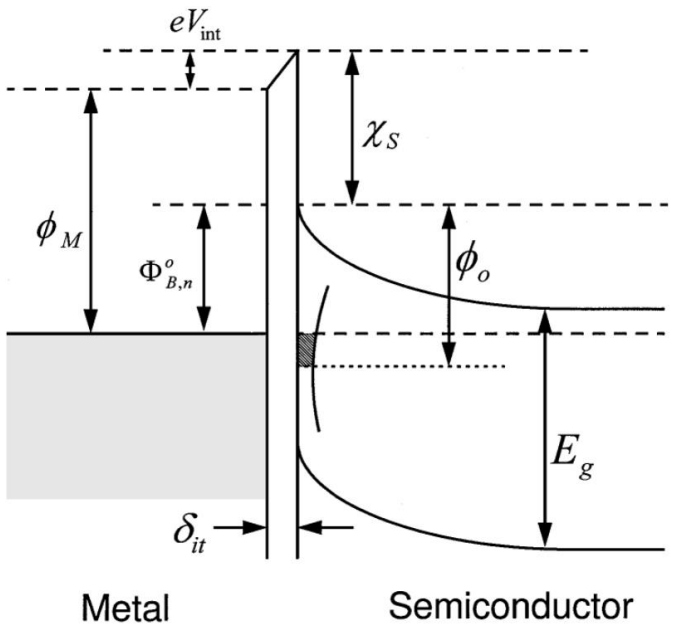
Schottky barrier height Φ_{bn}

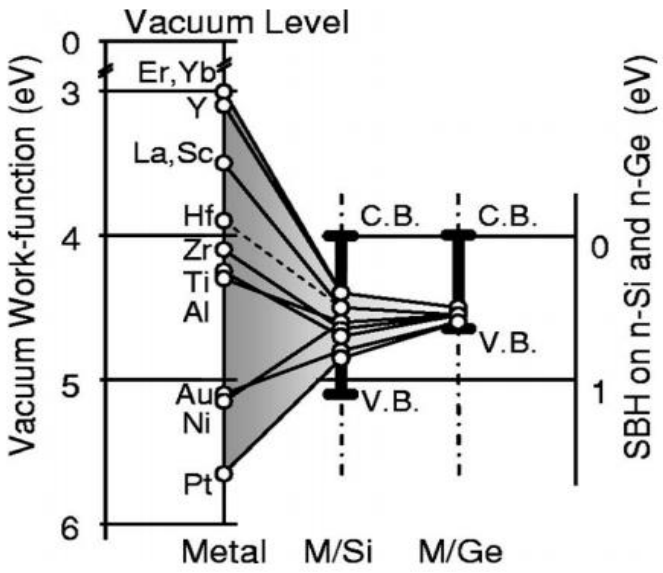
Active dopant concentration N_d -> (E_F)



Nishimura, Electronics 11, 2419 (2022)

Femi level pinning





n-type Si and n-type Ge contacts exhibit strong Femi level pinning

Nishimura et al., APL 91, 123123(2007)

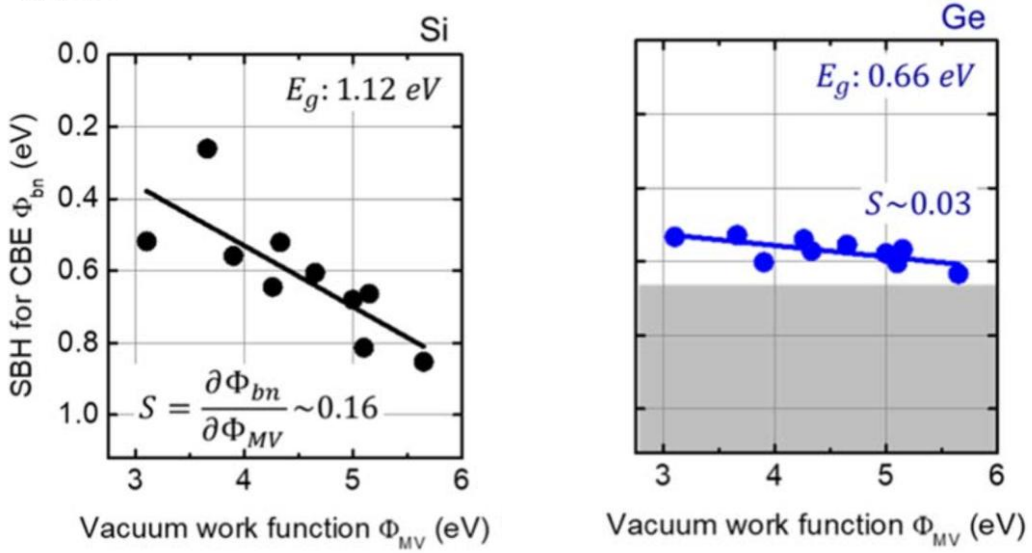
Schottky-Mott relationship

$$\Phi^0_{B,n} = \phi_M - \chi_S$$

Interface dipole:

$$\Phi^0_{B,n} = \phi_M - \chi_S + eV_{\text{int}},$$

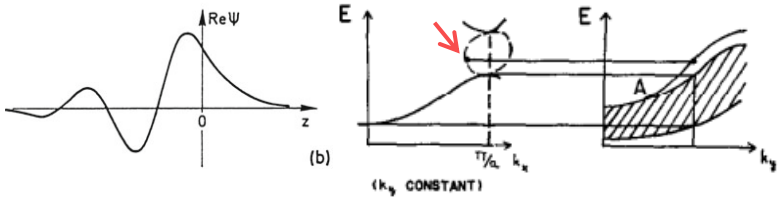
Tung, PRL 84, 6078 (2000)



Nishimura et al., Applied Physics Express 13, 031003 (2020)

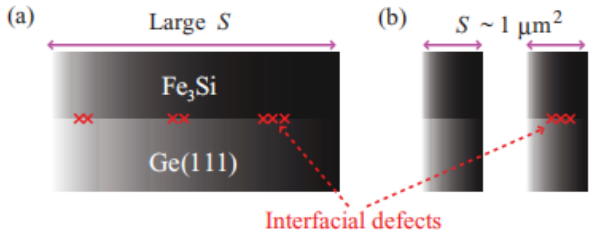
The Fermi level pinning mechanisms are under debate

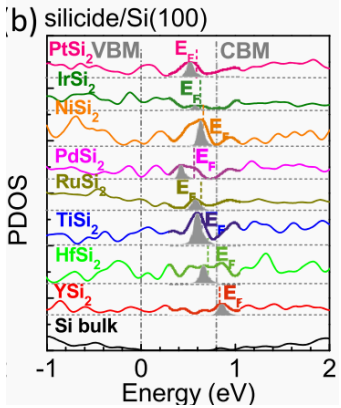
Dangling Bond

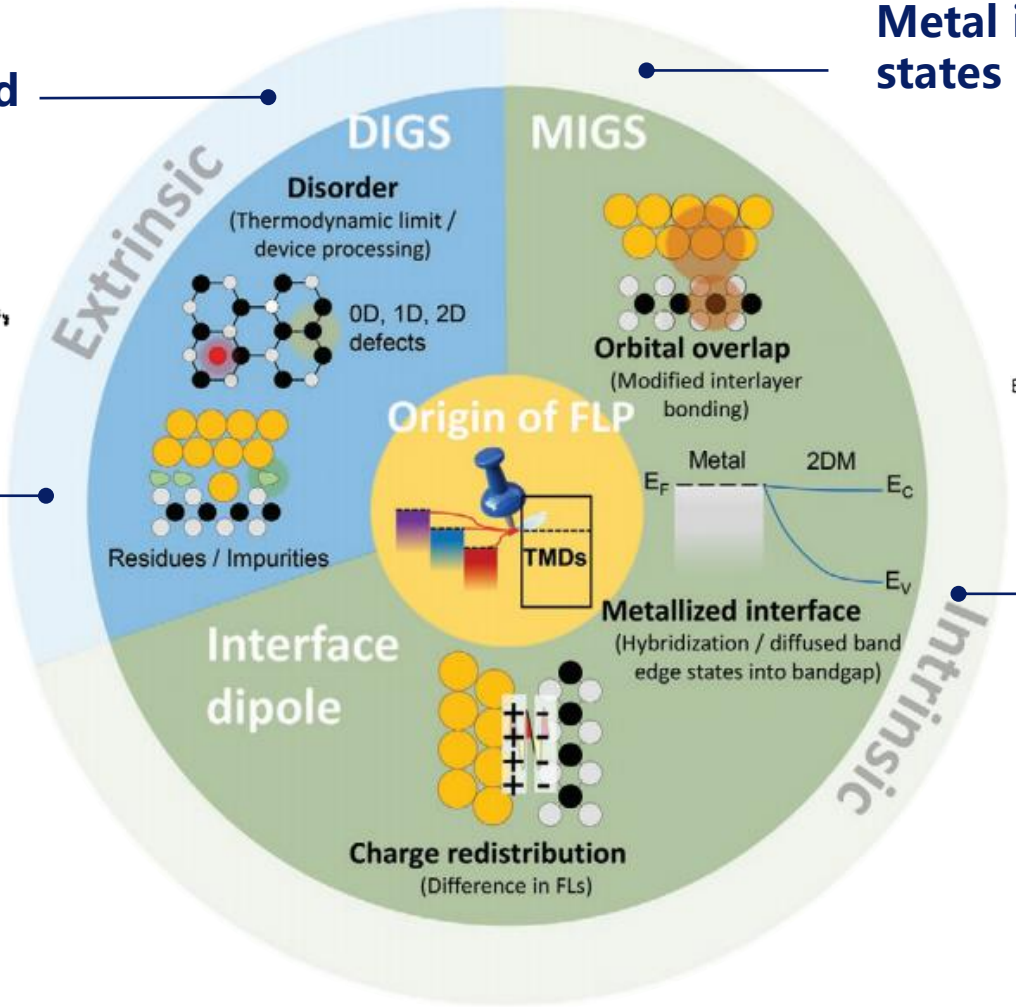


J. Bardeen, Phys. Rev. (1947)

Defect States

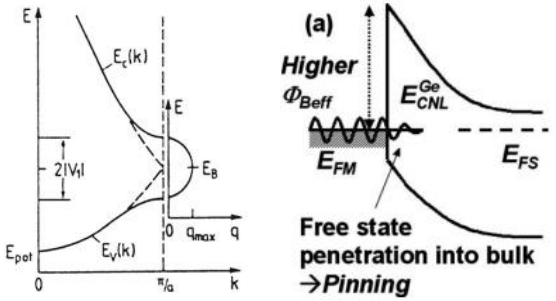






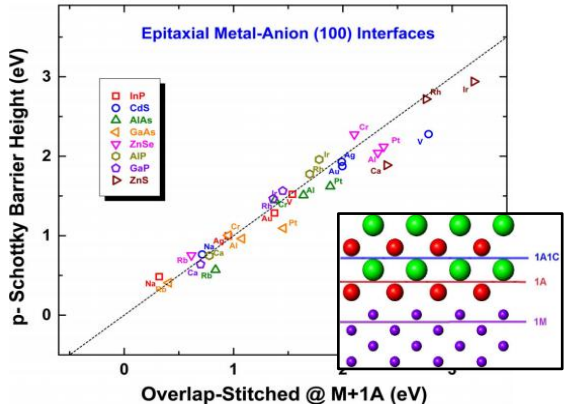
K. Kasahara et al, PRB (2011).
Z. Zhang et al, J. Phys. Chem. (2020).

Metal induced gap states (MIGS)



V. Heine, Phys. Rev. (1965)

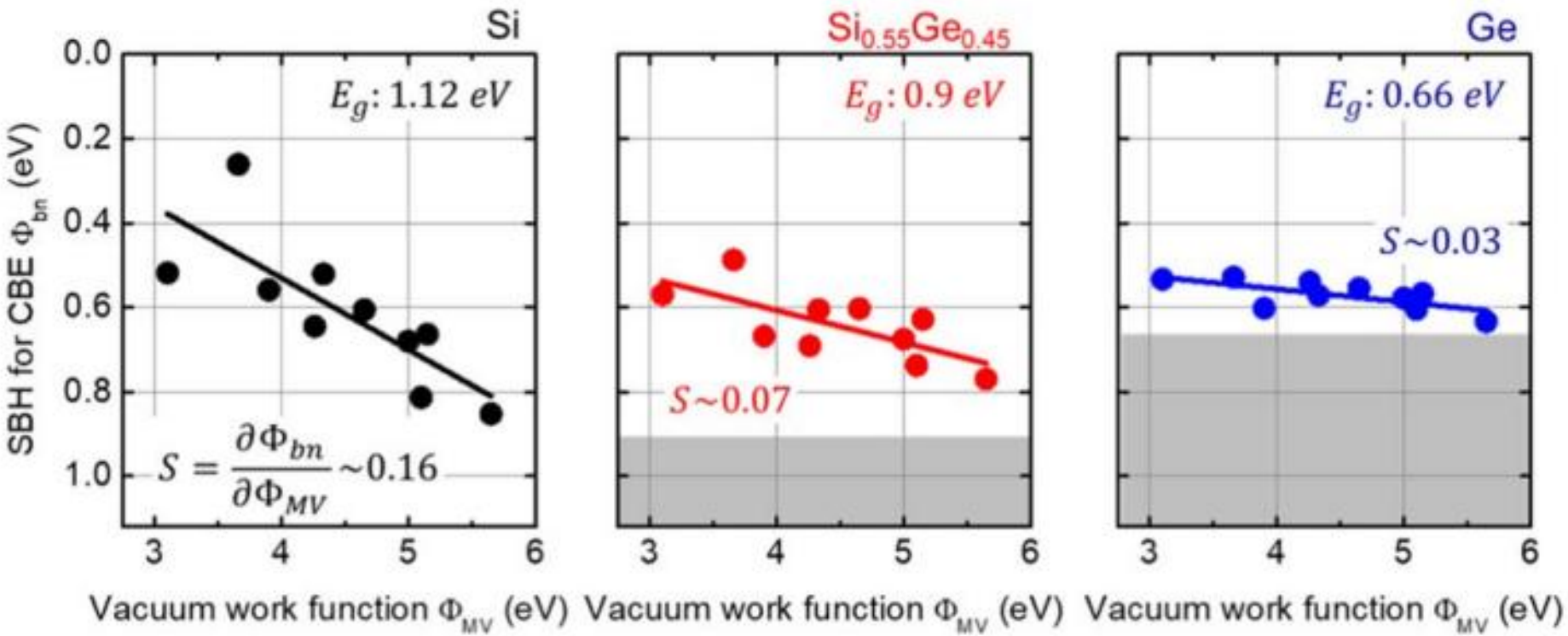
Interface Chemical bonds



R. T. Tung, PRL (2000)
R. T. Tung et al., PRB (2021).

Interface dipole arising from MIGS

Metal- induced gap states (MIGS)

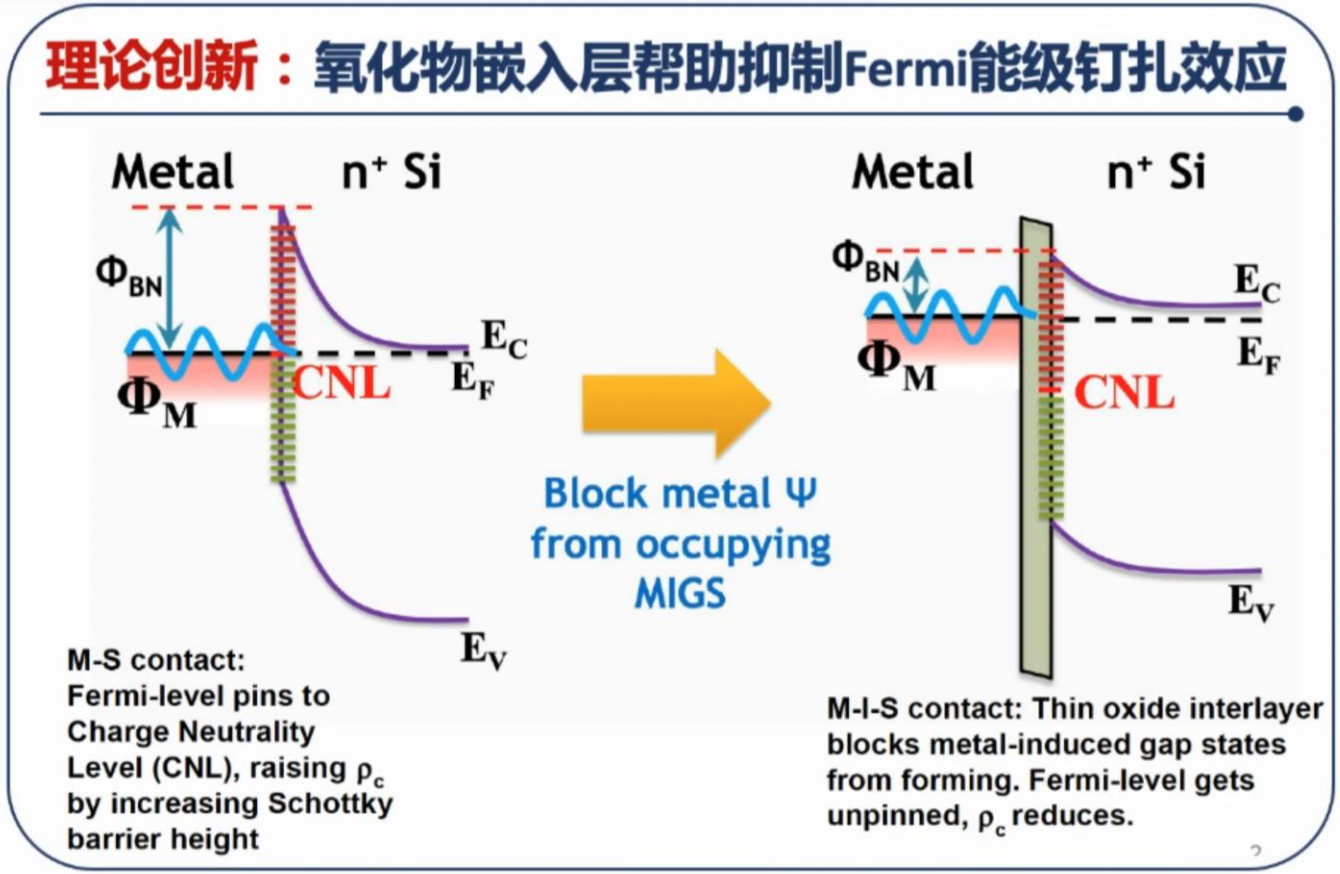


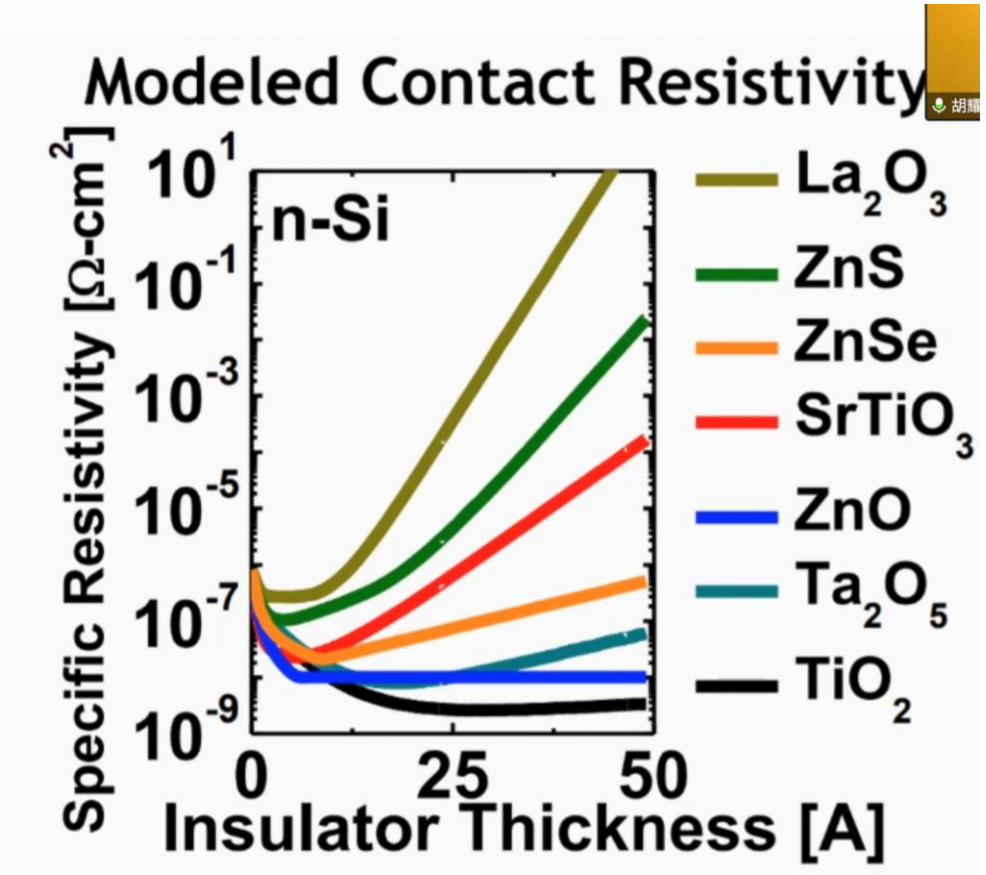
Independent on interface bonding details!

Assuming that the total number of MIGS is the same for all semiconductor/metal contacts, thus the density of MIGS around the Femi level is inversely proportional to bandgap of semiconductors.

Nishimura et al., Applied Physics Express 13, 031003 (2020)

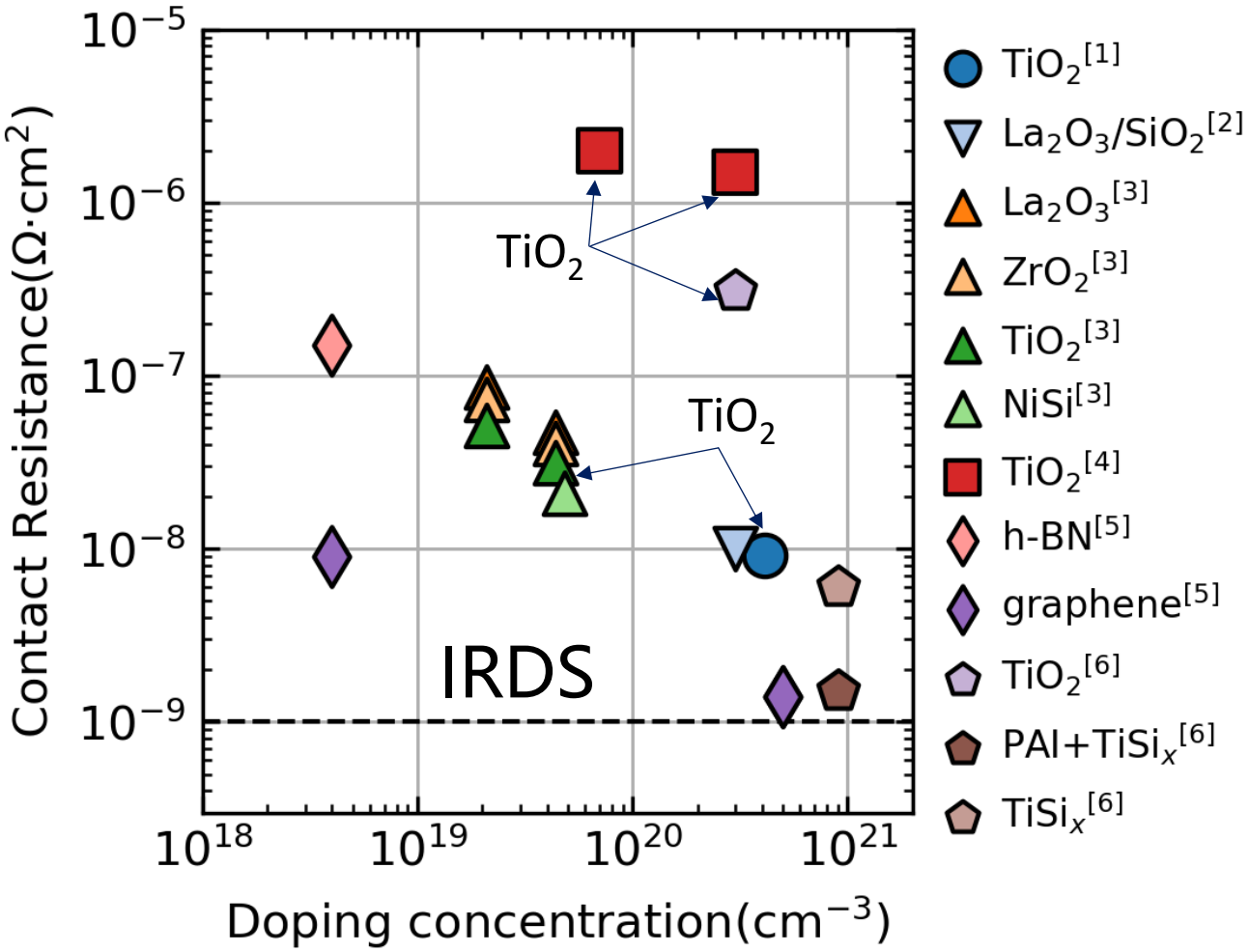
插入超薄介质层削弱费米能级钉扎：Intel主推TiO_2插入层

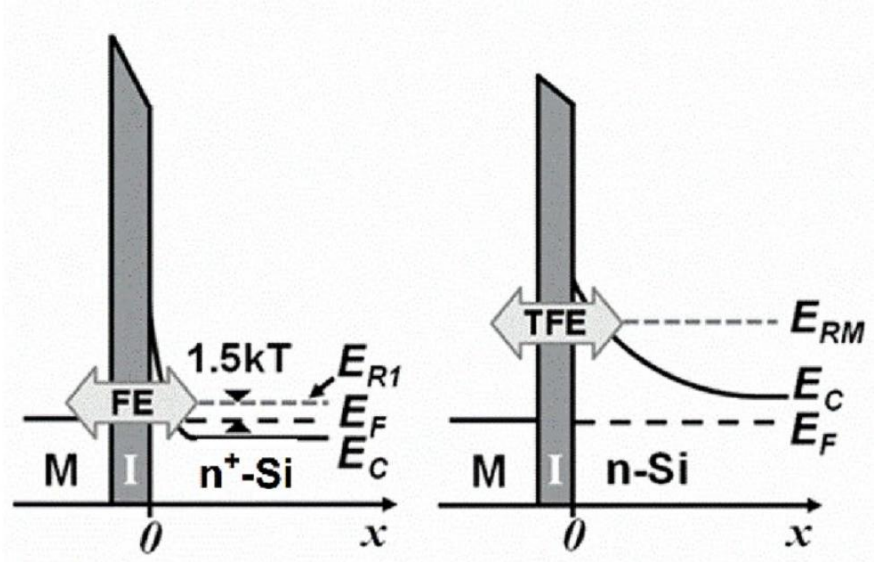


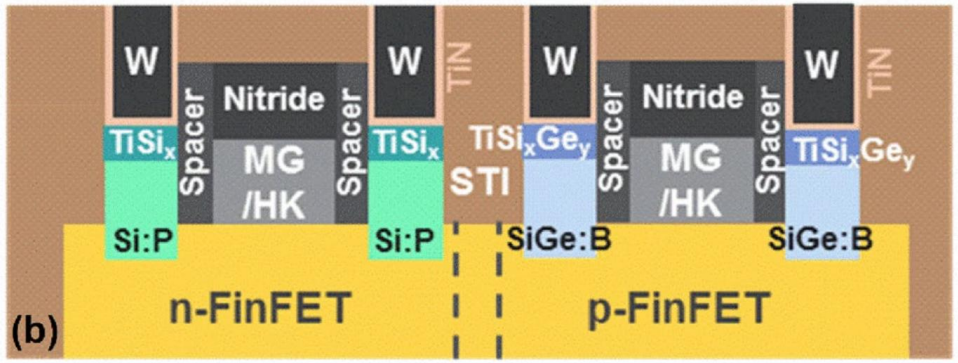


成果 提出用TiO_2嵌入层改善接触电阻的方法，Intel和DARPA正在引入这项技术

但是，TiO_2插入层的实际接触电阻高1个数量级以上



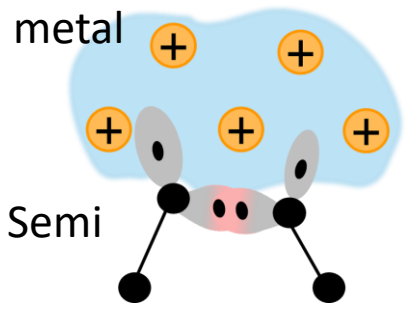




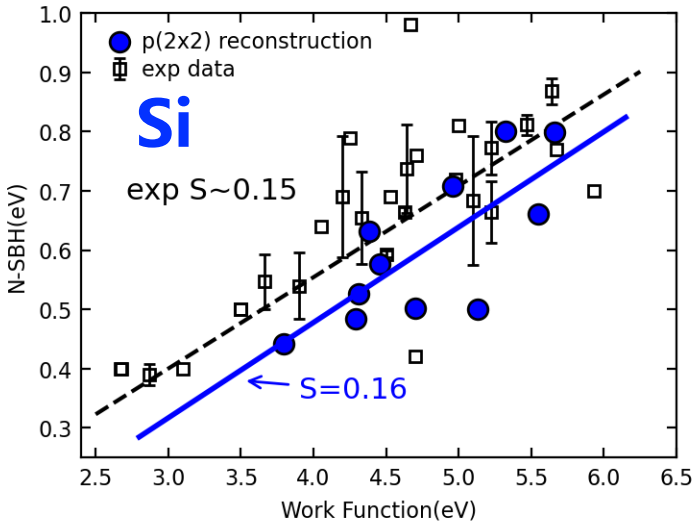
Hao Yu et al., MRS Advances 7, 1369 (2022)

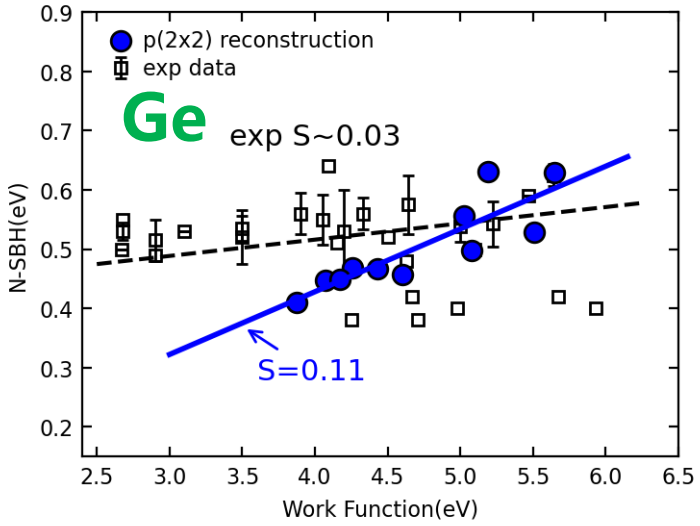
Si has p(2x2) interface and Ge has c(1x1)

p(2x2) reconstruction

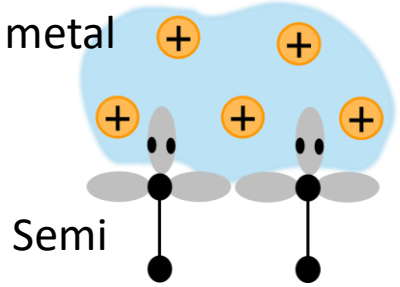


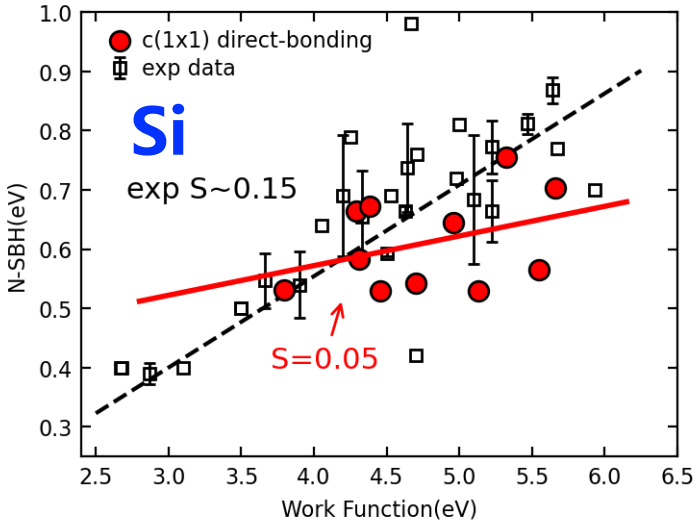
Kruger and Pollmann, PRL 74, 1155 (1995)

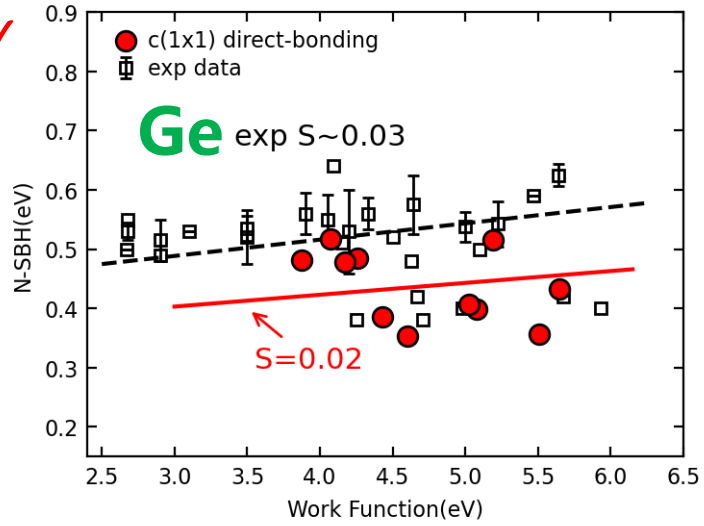




Ideal c(1x1) structure

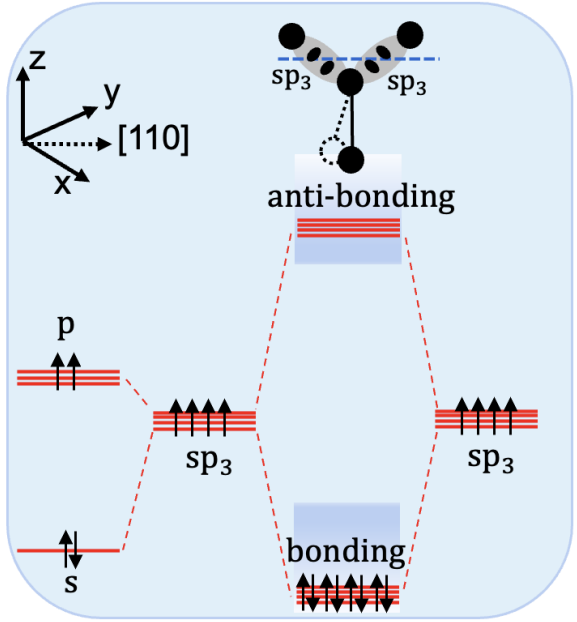




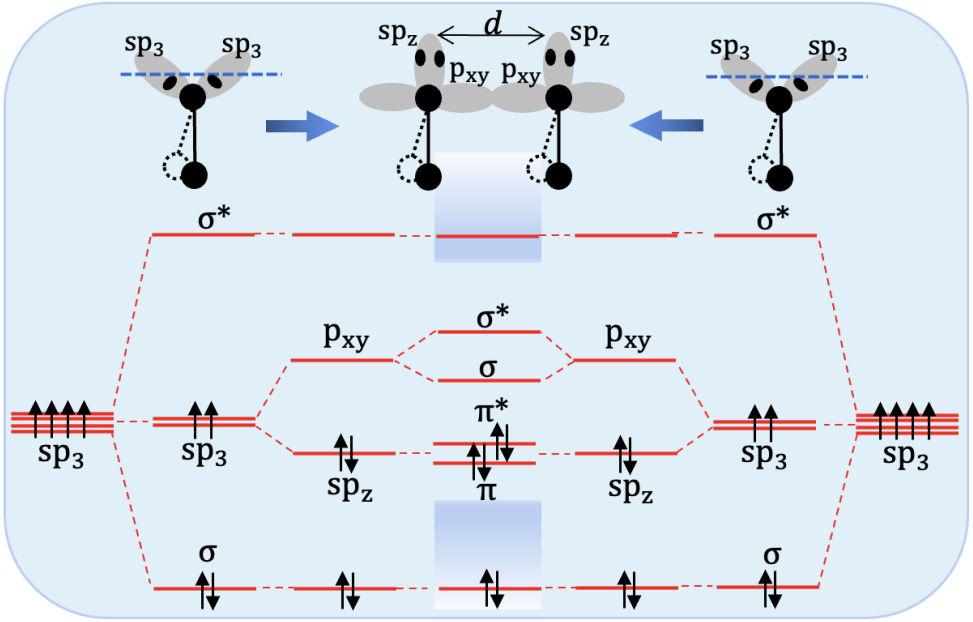


Z.Y. Xiang, **J.W. Luo***, S.S. Li, Nature Comm. (under revision)

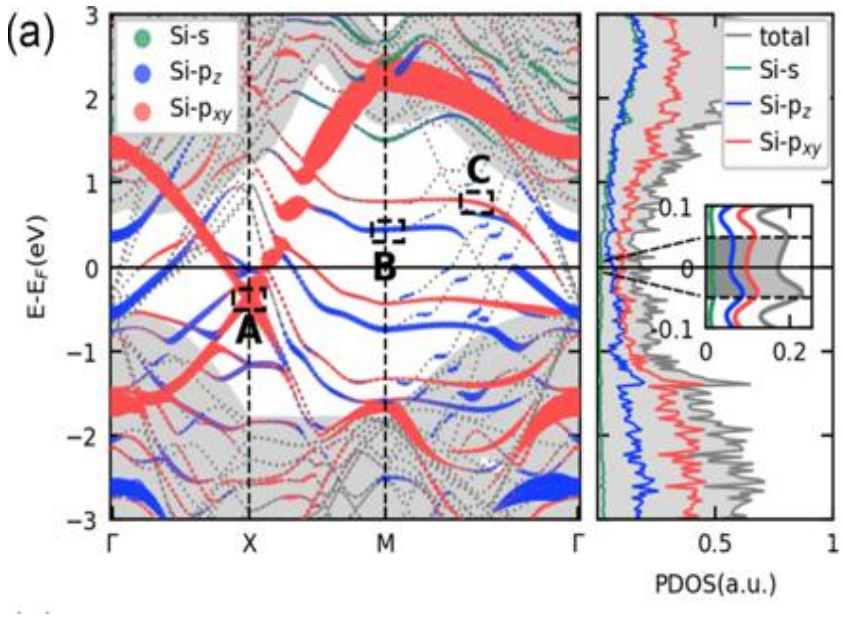
Ideal c(1x1) has a larger density of interface states



Re-hybridization



Ideal c(1x1)

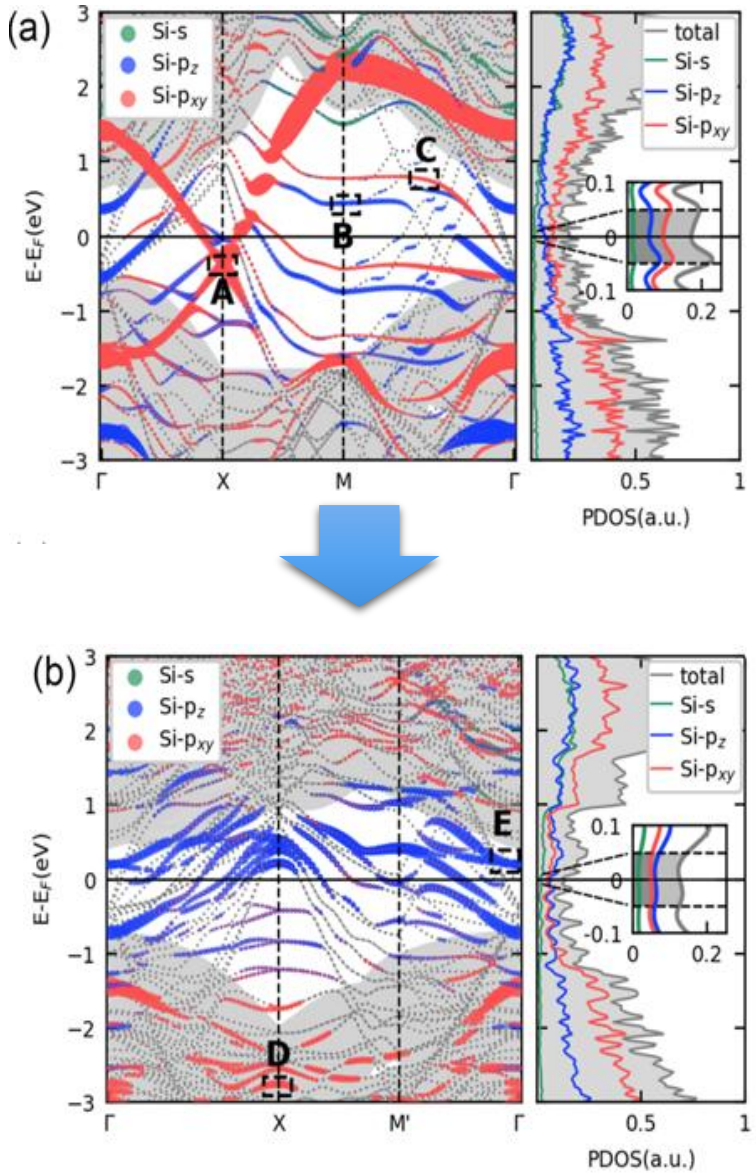


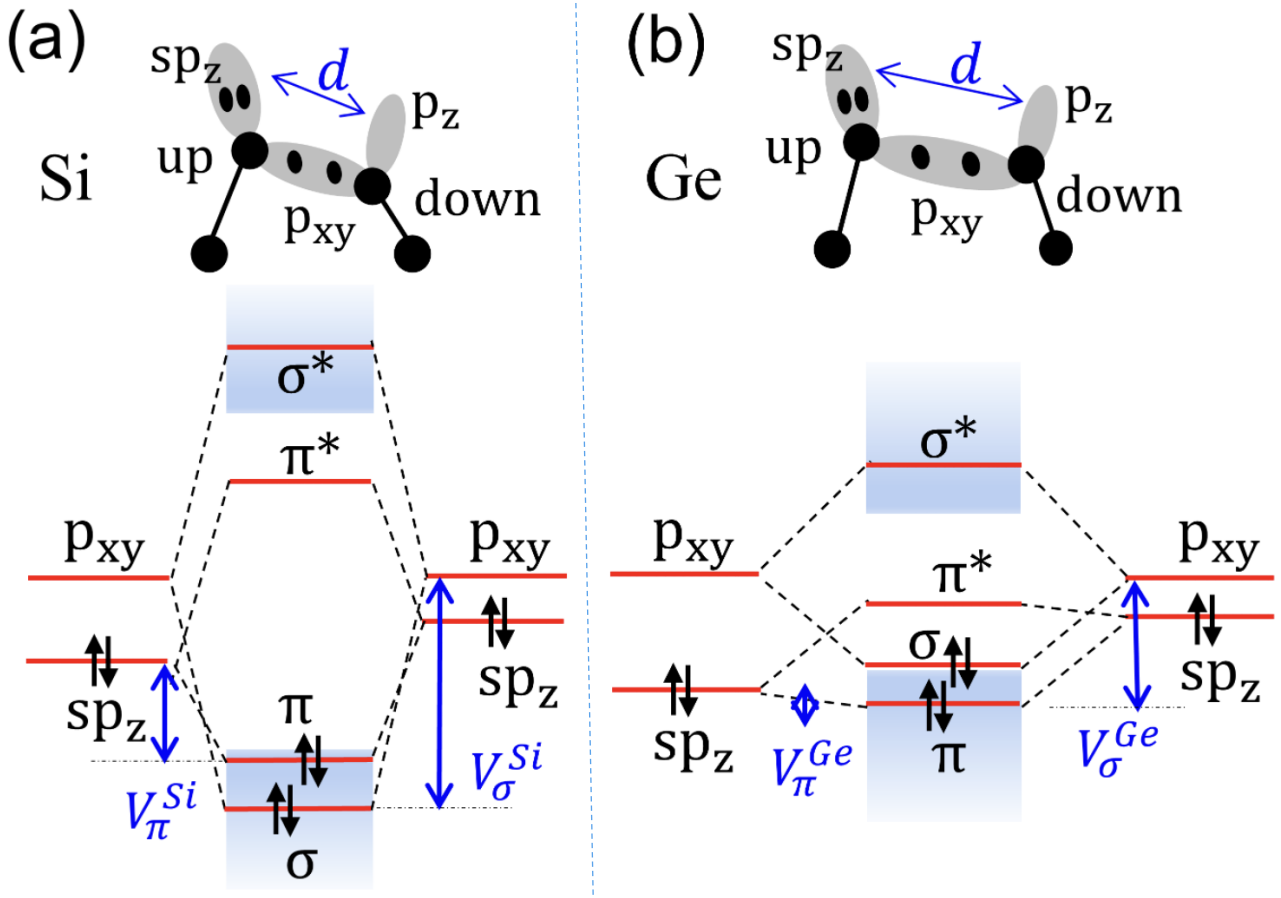
Z.Y. Xiang, **J.W. Luo***, S.S. Li, Nature Comm. (under revision)

Self-passivation in the p(2x2) interface structure

Ideal c(1x1)

p(2x2)

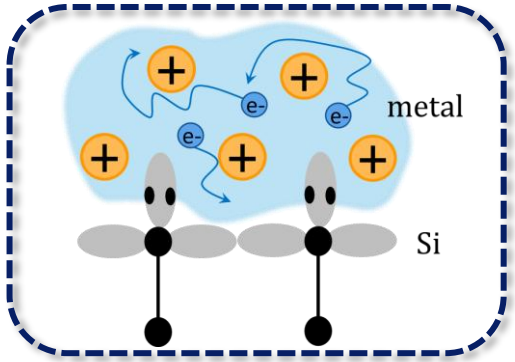




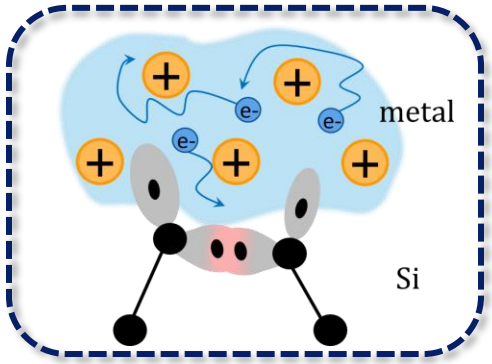
Z.Y. Xiang, **J.W. Luo***, S.S. Li, Nature Comm. (under revision)

Design principle I: dangling bonds passivation

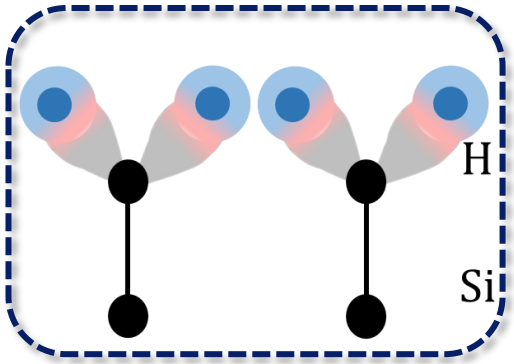
c(1x1)



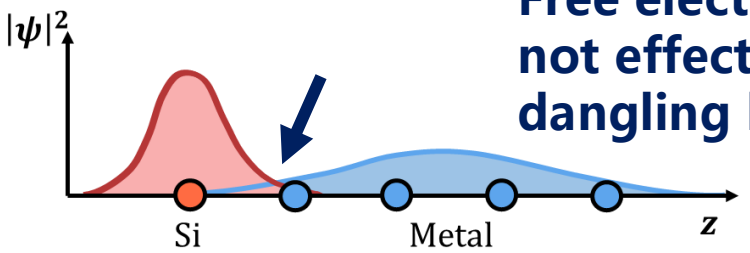
p(2x2)



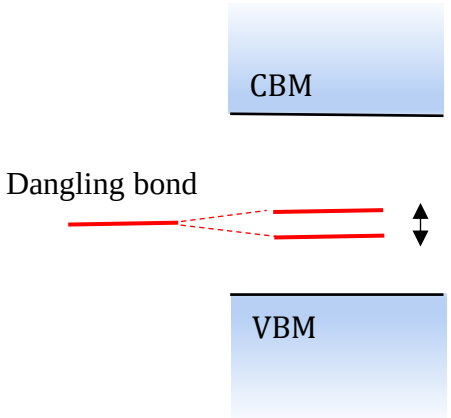
H passivation



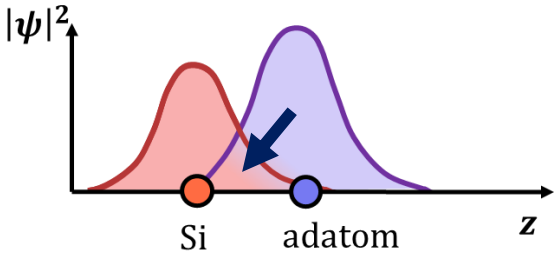
E. Cartier et al., Passivation and depassivation of silicon dangling bonds at the Si/SiO2 interface by atomic hydrogen, APL(1993)

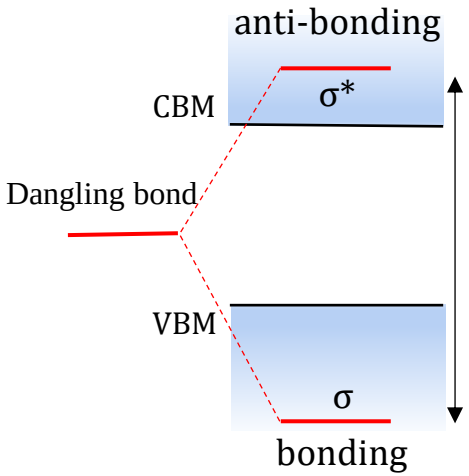


Free electrons in metal can not effectively passivate Si dangling bonds



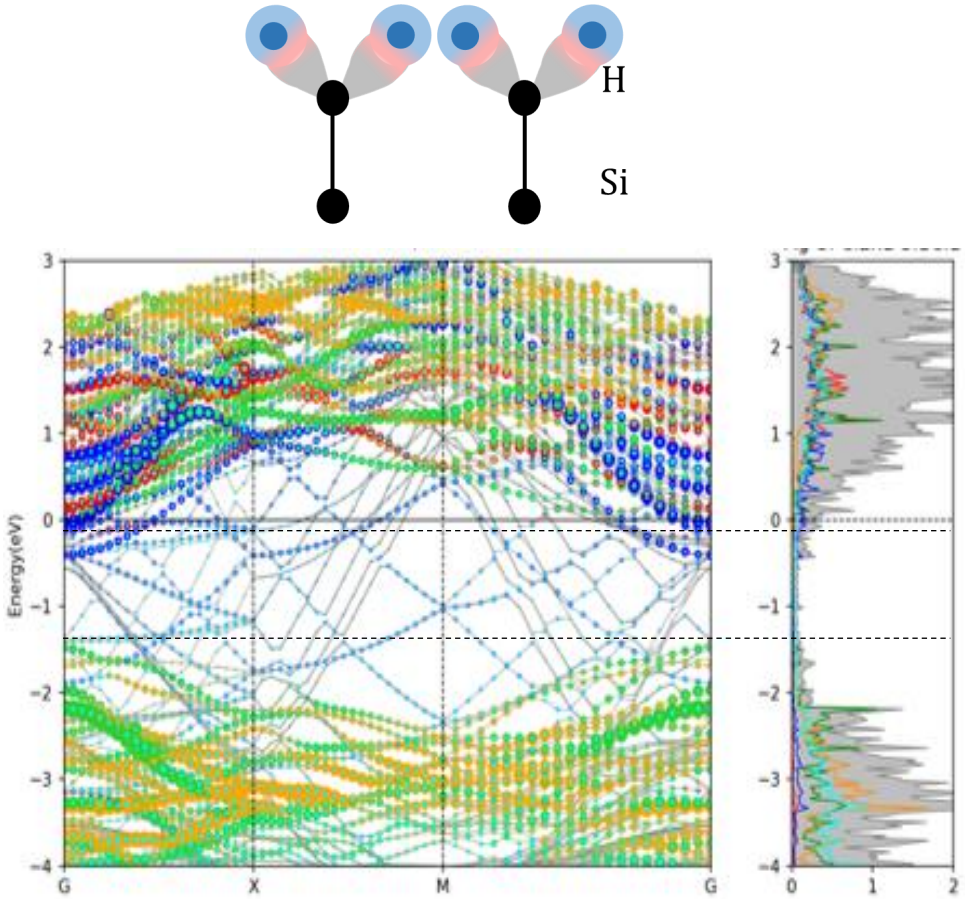
$$\langle \varphi_S | H | \varphi_M \rangle \rightarrow \int \varphi_S^* H \varphi_M dr$$

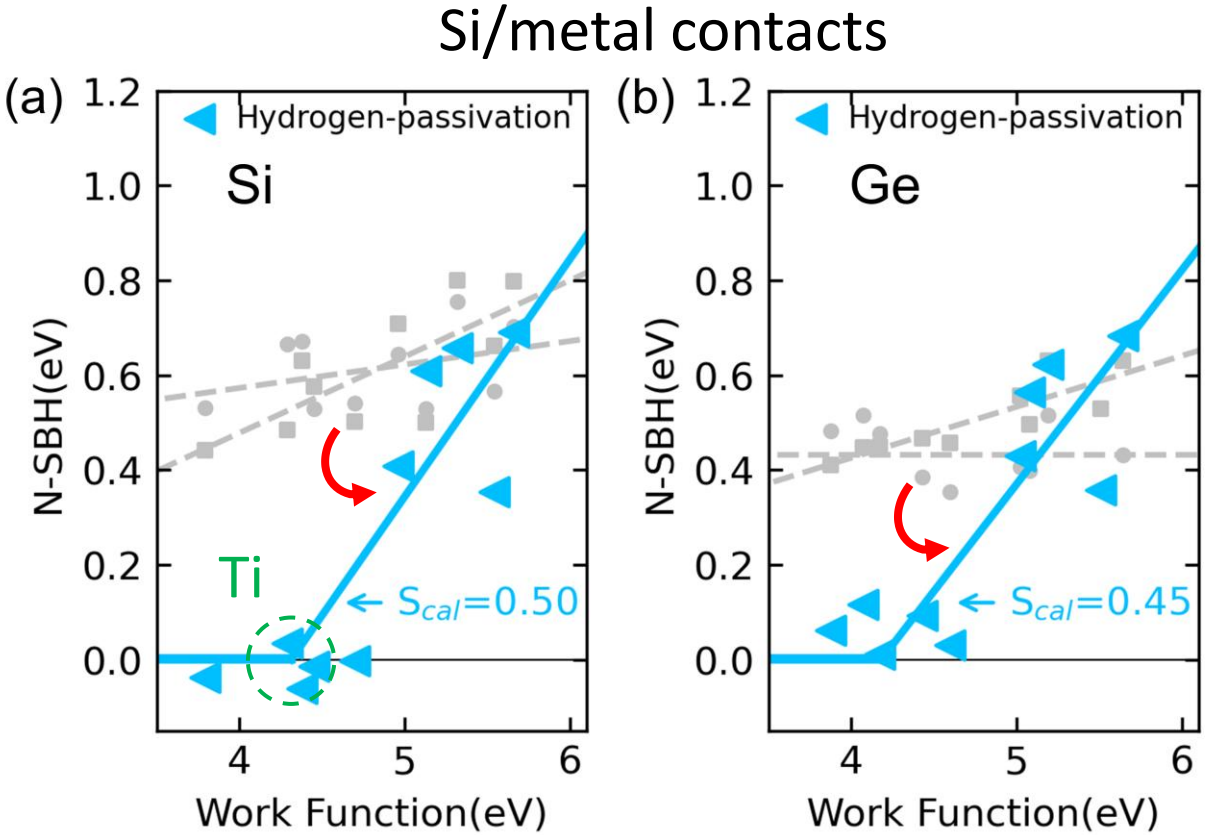




$$\langle \varphi_S | H | \varphi_{\mathrm{ad}} \rangle \rightarrow \int \varphi_S^* H \varphi_{ad} dr$$

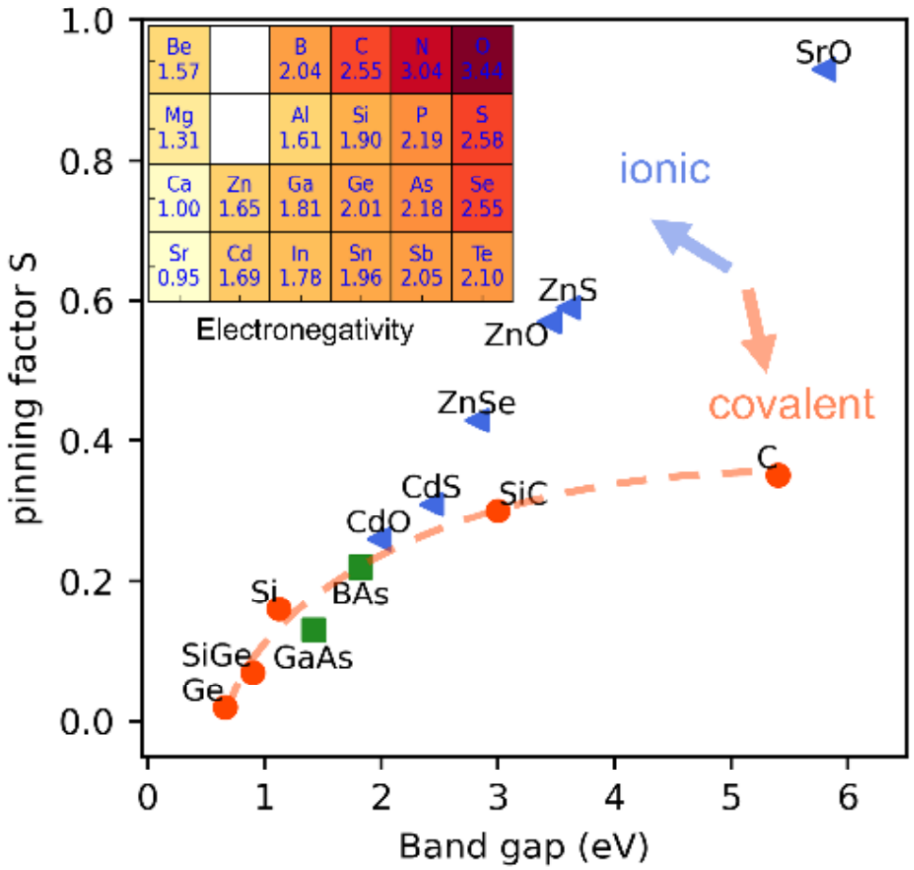
H-passivation induced depinning of FLP

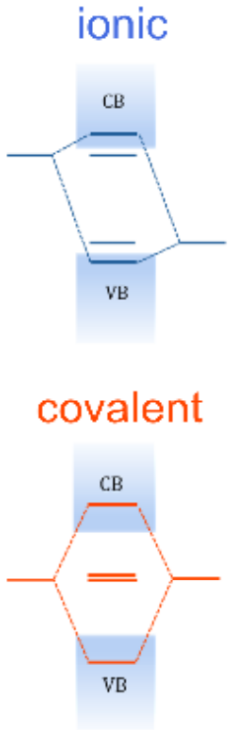


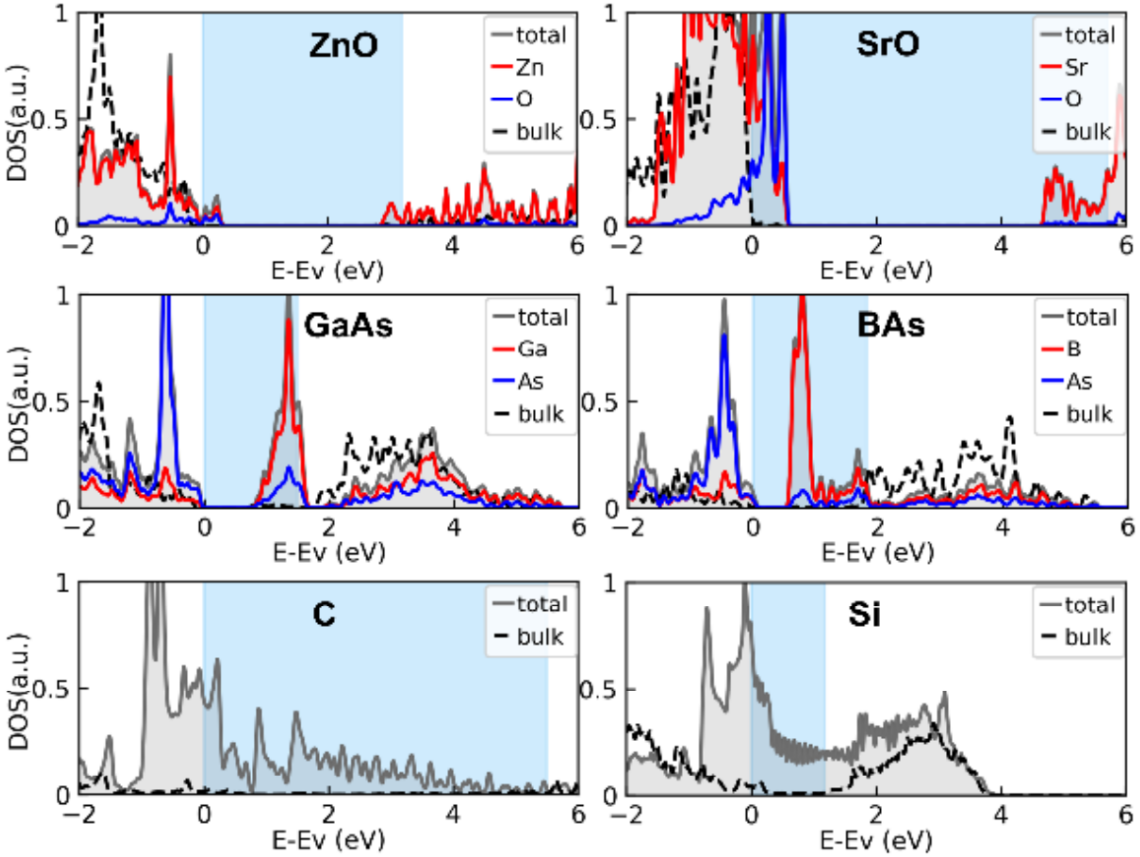


Z.Y. Xiang, **J.W. Luo***, S.S. Li, Nature Comm. (under revision)

Go ionicity to lower the Fermi leveling pinning effect



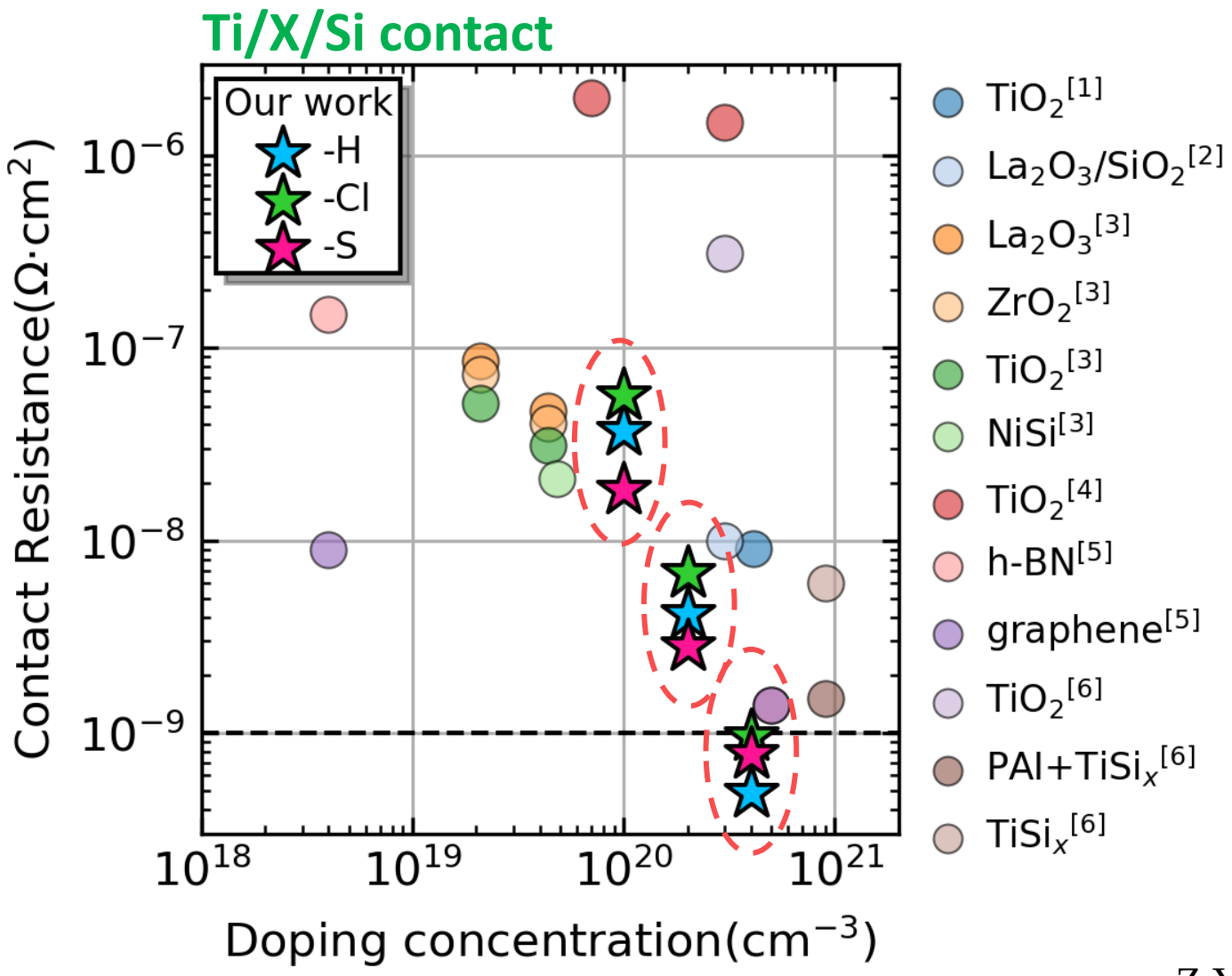




Z.Y. Xiang, **J.W. Luo***, S.S. Li, Nature Comm. (under revision)

Achieving contact resistance <10^{-9} Ω cm^2

unpublished confidential data



The depinning mechanism is different from the scheme of ultrathin insulator layers

A. Agrawal et al., Appl. Phys. Lett. (2014).
K.-W. Ang et al., IEEE IEDM (2012).
K. Majumdar et al., VLSI-Technology (2014).

H. Yu et al, Appl. Phys. Lett. (2016).
M. H. Lee et al., Nano Lett. (2018).
H. Yu et al., IEEE IEDM (2015).

Z.Y. Xiang and J.W. Luo, manuscript in preparation

极限尺度晶体管物理瓶颈

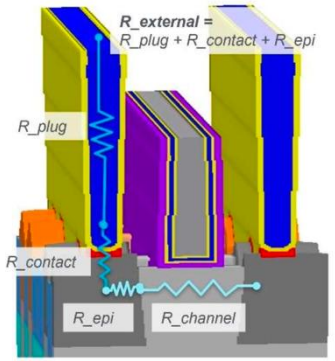
国际半导体技术路线图 IRDS 2022

4.2. PERFORMANCE BOOSTERS

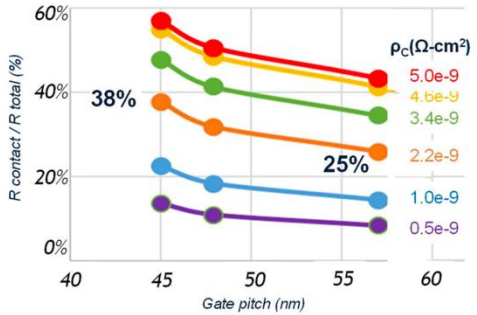
In order to maintain the scaling at low voltages, scaling in recent years focused on additional solutions to boost the performance such as the use of introducing strain to channel; stress boosters; high-κ metal gate; lowering contact resistance, and improving electrostatics. This was all done in order to compensate the gate drive loss while supply voltage needs to be scaled down for high-performance mobile applications.

总功耗 =接触功耗+沟道功耗 + 栅极功耗

接触电阻成为先进节点关键瓶颈

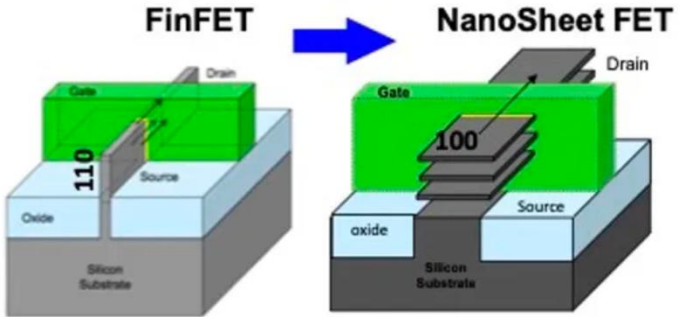


$R_c \approx \rho_c / A_c$



Nicolas Breil@AMAT, IEEE IITC (2021)
S. Datta et al., Science 378, 733 (2022)

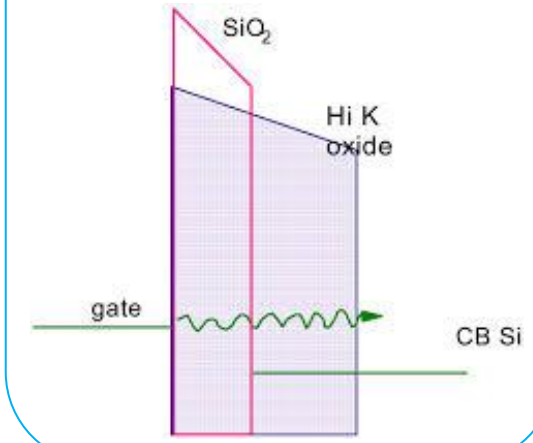
迁移率退化严重



Mobility cm²/V-sec	Planar MOSFET	FinFET	GAAFET
electron	200	130	175
hole	63	238	78

K. Zhao, IBM/IEDM tutorial (2021)

高k介电层：隧穿漏电流与缺陷引起的可靠性



提出免于退极化效应光学声子软化新理论

- 随着器件持续缩微栅介电层必须等比例减薄，导致栅极隧穿漏电流指数增高，高k介电材料可以确保在不改变栅控能力的情况下拥有更厚的栅介电层，遏制栅极隧穿漏电流，从而拯救了摩尔定律
- 高k介电层材料面临的难题：难以同时兼顾大介电常数和大带隙

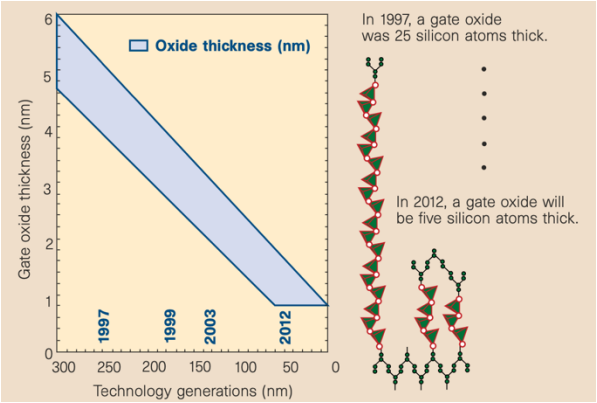
摩尔定律第一次接近物理极限

NATURE | VOL 399 | 24 JUNE 1999 | www.nature.com

The end of the road for silicon?

Max Schulz

Computer chips continue to shrink. But the discovery that a layer of silicon dioxide must be at least four to five atoms thick to function as an insulator suggests that silicon-based microchips will reach the physical limits of miniaturization early next century.

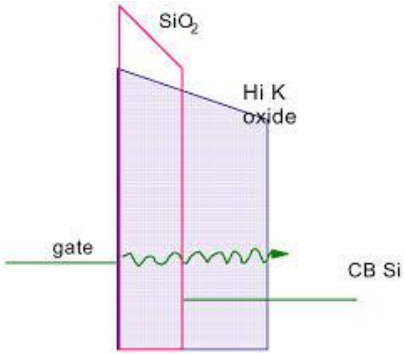


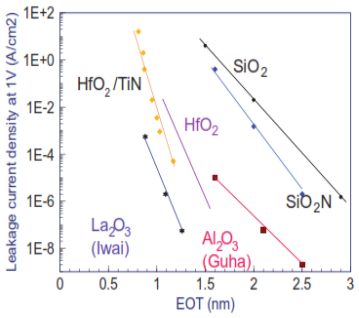
M. Schulz, Nature 399, 729 (1999)

高k介电层拯救了摩尔定律

$$t_{ox} = \mathrm{EOT} = (3.9/K)t_{HiK}$$

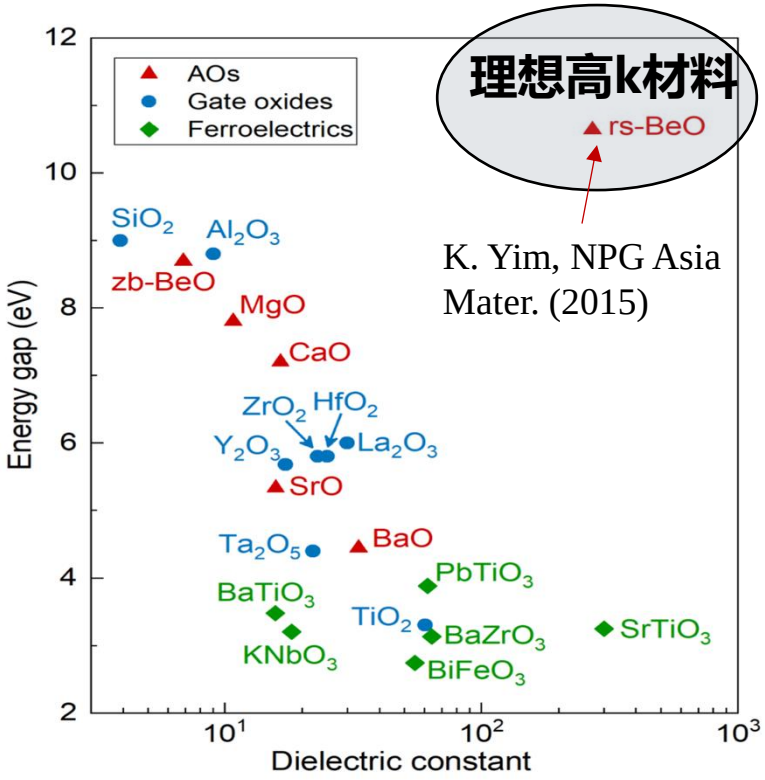
5倍厚的HfO_2（K=22）栅介电层与SiO_2栅介电层拥有相同的等效栅氧化层厚度





EOT：等效栅氧化层厚度

高k介电层难题：难以兼顾大介电常数和大带隙

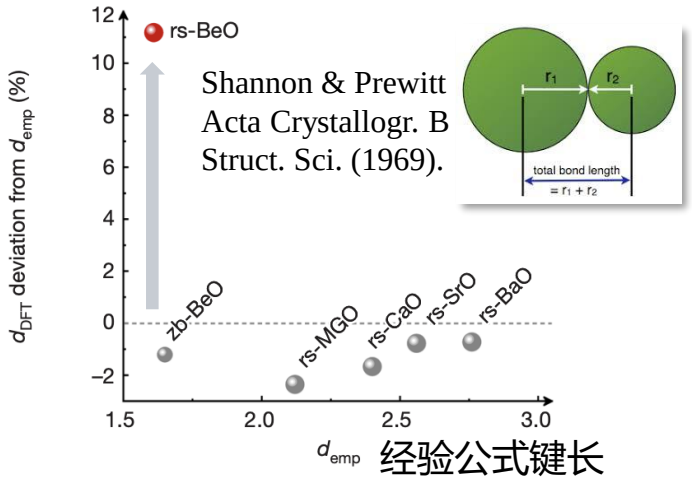


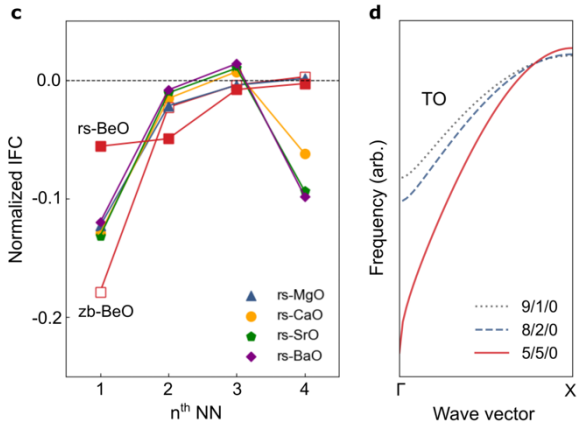
K. Yim, NPG Asia Mater. (2015)

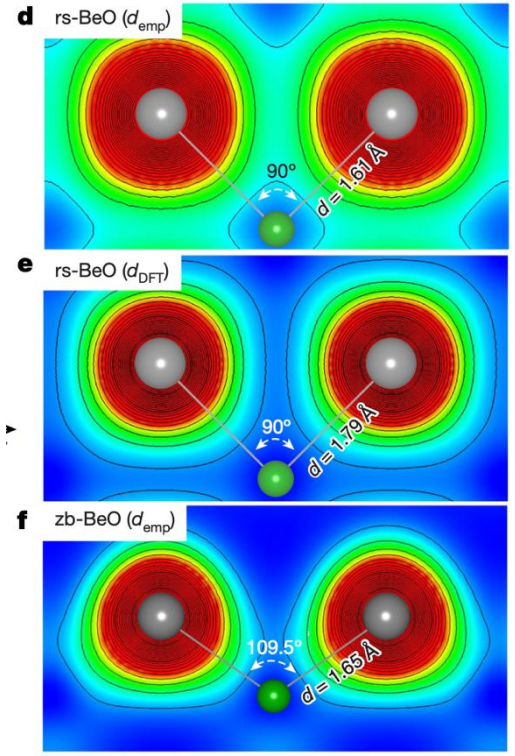
J. Robertson, Eur. Phys. J. Appl. Phys. (2004)

提出免于退极化效应光学声子软化新理论

➢ **rs-BeO的键长比经验公式大11%： rs-BeO在采用经验公式键长时，最近邻氧原子间的电子云高度重叠，产生非常强的库伦排斥力，把键长拉升11%达到第一性原理预测的键长，大幅降低短程原子力导致TO声子软化，显著增强了晶格贡献的介电常数。一般认为TO软化来自异常强的长程库伦力，带隙也变小**





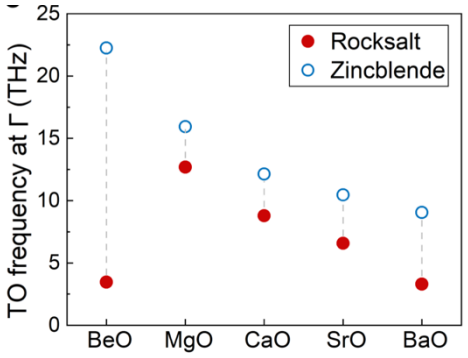


TO声子频率：

W. Cochran, PRL 3, 412 (1959)

短程原子力　　长程库伦力

$$\mu\omega_T^2 = R_0' - 4\pi(\epsilon+2)(Z'e)^2/9v,$$



氧化物介电常数：

J. Robertson, Eur. Phys. J. Appl. Phys. 28, 265 (2004)

$$\kappa = n^2 + \frac{Ne^2 Z*_T^2}{m\omega_{TO}^2}.$$

R. Cao, …, **Jun-Wei Luo***, **Nature** 634, 1080-1085 (2024)

提出免于退极化效应光学声子软化新理论

➢ **光学声子完全软化导致铁电相变，铁电发现100年来由于存在界面退极化效应始终无法实用化**

Letter | Published: 09 July 1992

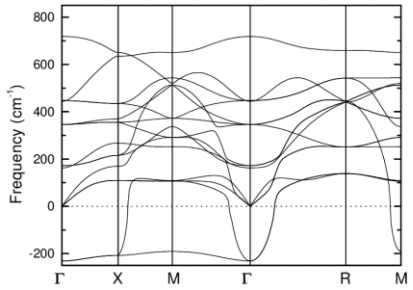
Origin of ferroelectricity in perovskite oxides

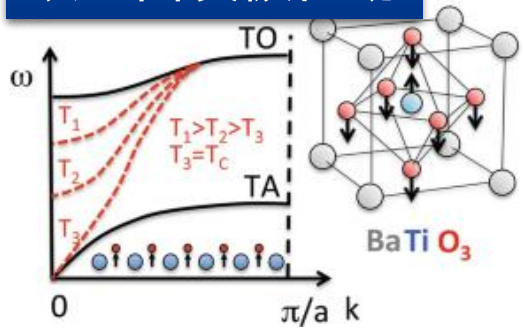
Ronald E. Cohen

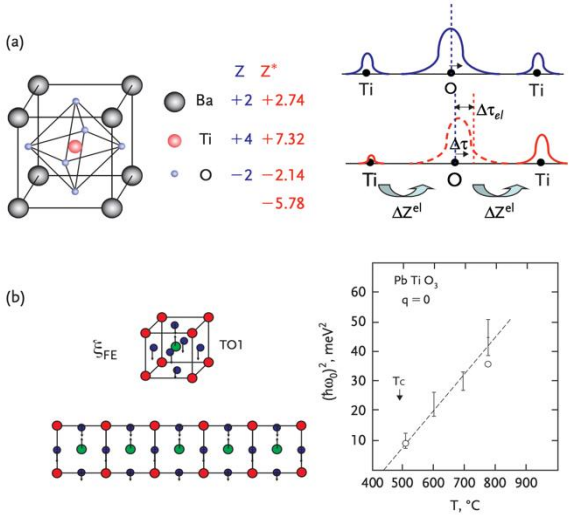
Nature **358**, 136–138 (1992) | Cite this article

22k Accesses | **2653** Citations | **3** Altme

铁电自发极化场







Born有效电荷Z*依赖Ti 3d-O 2p 的耦合强度

Crystal Stability and the Theory of Ferroelectricity

W. Cochran
Phys. Rev. Lett. **3**, 412 – Published 1 November 1959

$$\mu\omega_T^2 = R_0' - 4\pi(\epsilon+2)(Z'e)^2/9v,$$

Letter | Published: 03 April 2003

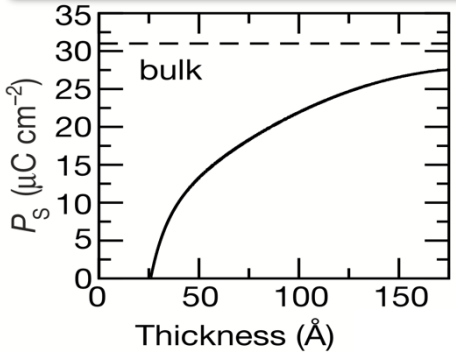
Critical thickness for ferroelectricity in perovskite ultrathin films

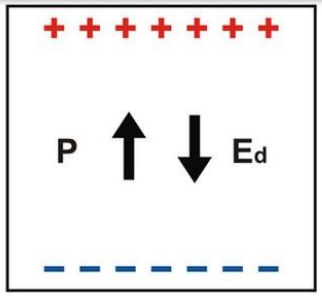
Javier Junquera & Philippe Ghosez

Nature **422**, 506–509 (2003) | Cite this article

21k Accesses | **1411** Citations | **6** Altmetric | Metrics

Born有效电荷 -》界面退极化场 -》临界尺寸Tc



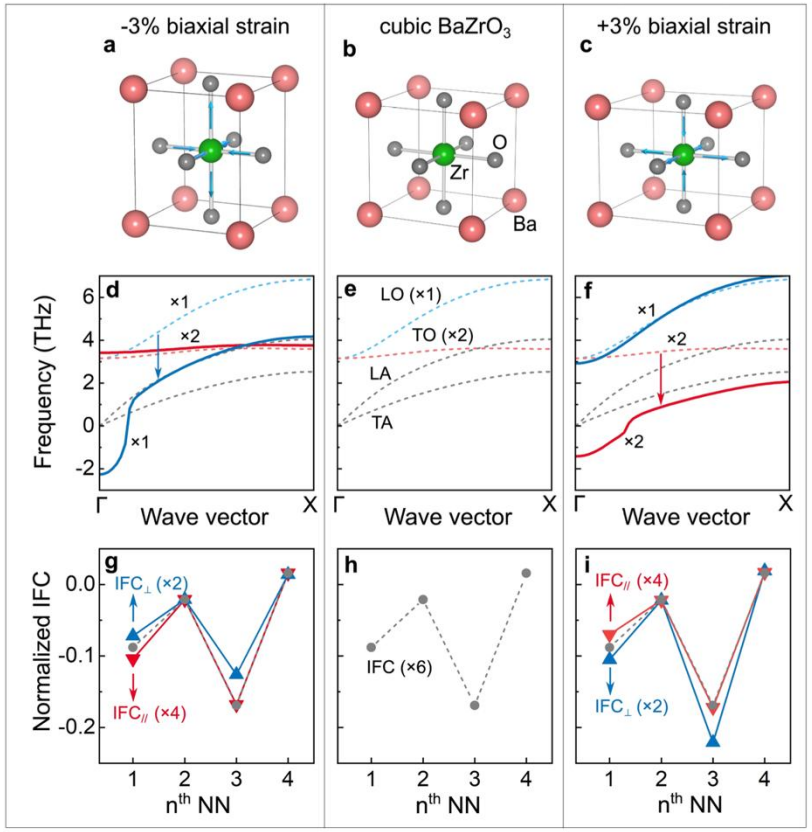


Stengel & Spaldin, Nature 443, 679 (2006)

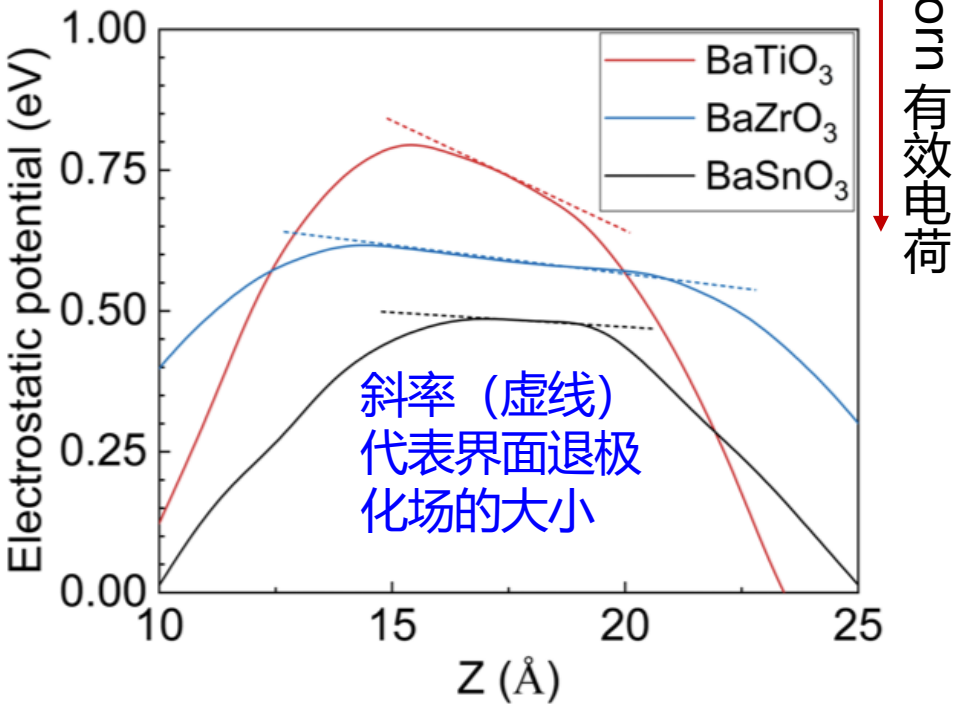
提出免于退极化效应光学声子软化新理论

➢ **由于界面退极化场随Born有效电荷减小而降低，在Born有效电荷比较小的情况下，通过降低短程原子力也可以实现TO光学声子软化和铁电相变，从而避免传统铁电材料所面临的界面退极化效应**

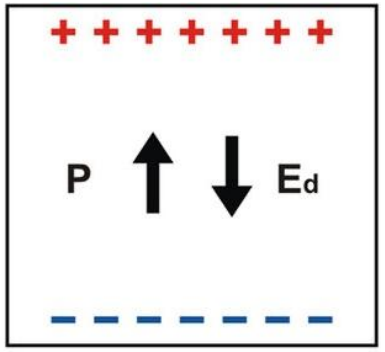
$$\mu\omega_T^2 = R_0' - 4\pi(\epsilon+2)(Z'e)^2/9v,$$



随Born有效电荷降低
界面退极化场依此减小



Born 有效电荷

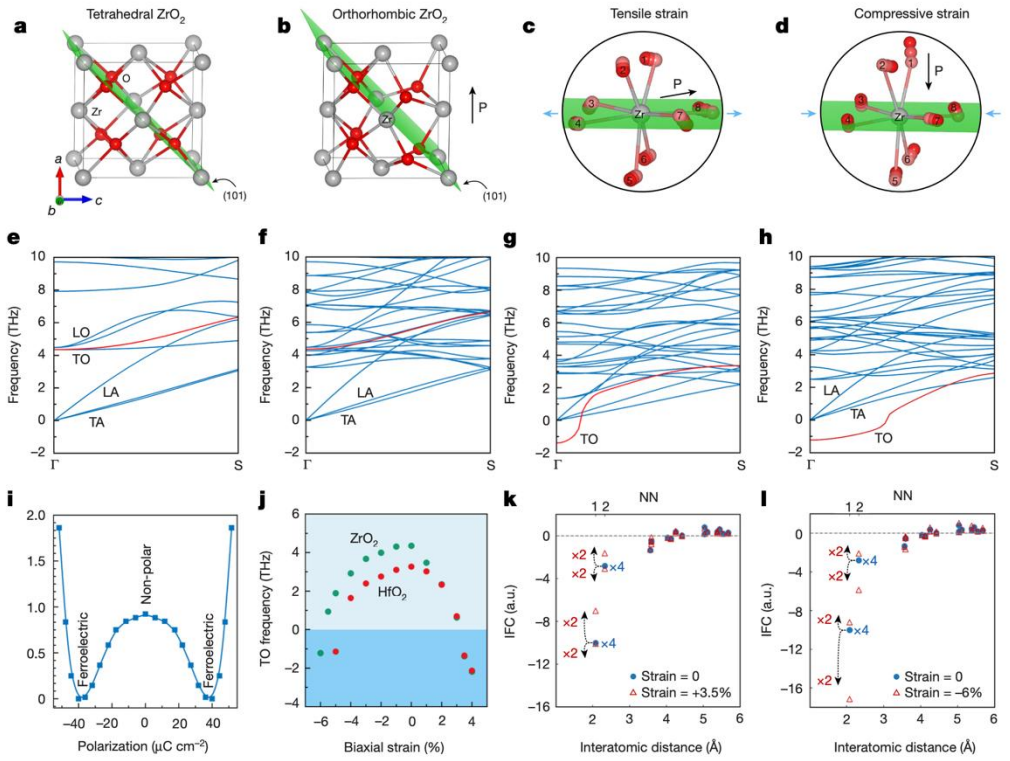


R. Cao, …, **Jun-Wei Luo***, **Nature** 634, 1080-1085 (2024)

提出免于退极化效应光学声子软化新理论

- 2011年发现晶体管高k介电材料HfO_2具有铁电性引起了巨大轰动
- 基于光学声子软化新理论解释清楚硅上外延HfO_2铁电薄膜减薄至2-3nm才出现铁电的逆尺寸效应

T. S. Boscke, et al., **APL** 99, 102903 (2011)
U. Schroeder et al., **Nature Reviews Materials** 7, 653 (2022)



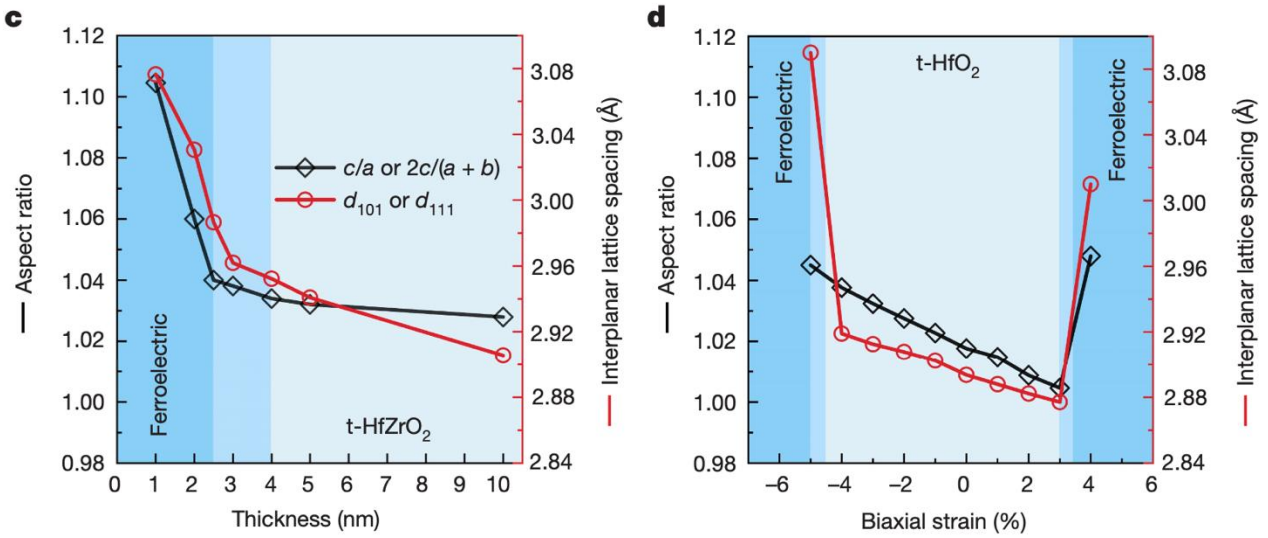
R. Cao, …, **Jun-Wei Luo***, **Nature** 634, 1080-1085 (2024)

实验
减薄到2-3nm铁电相变

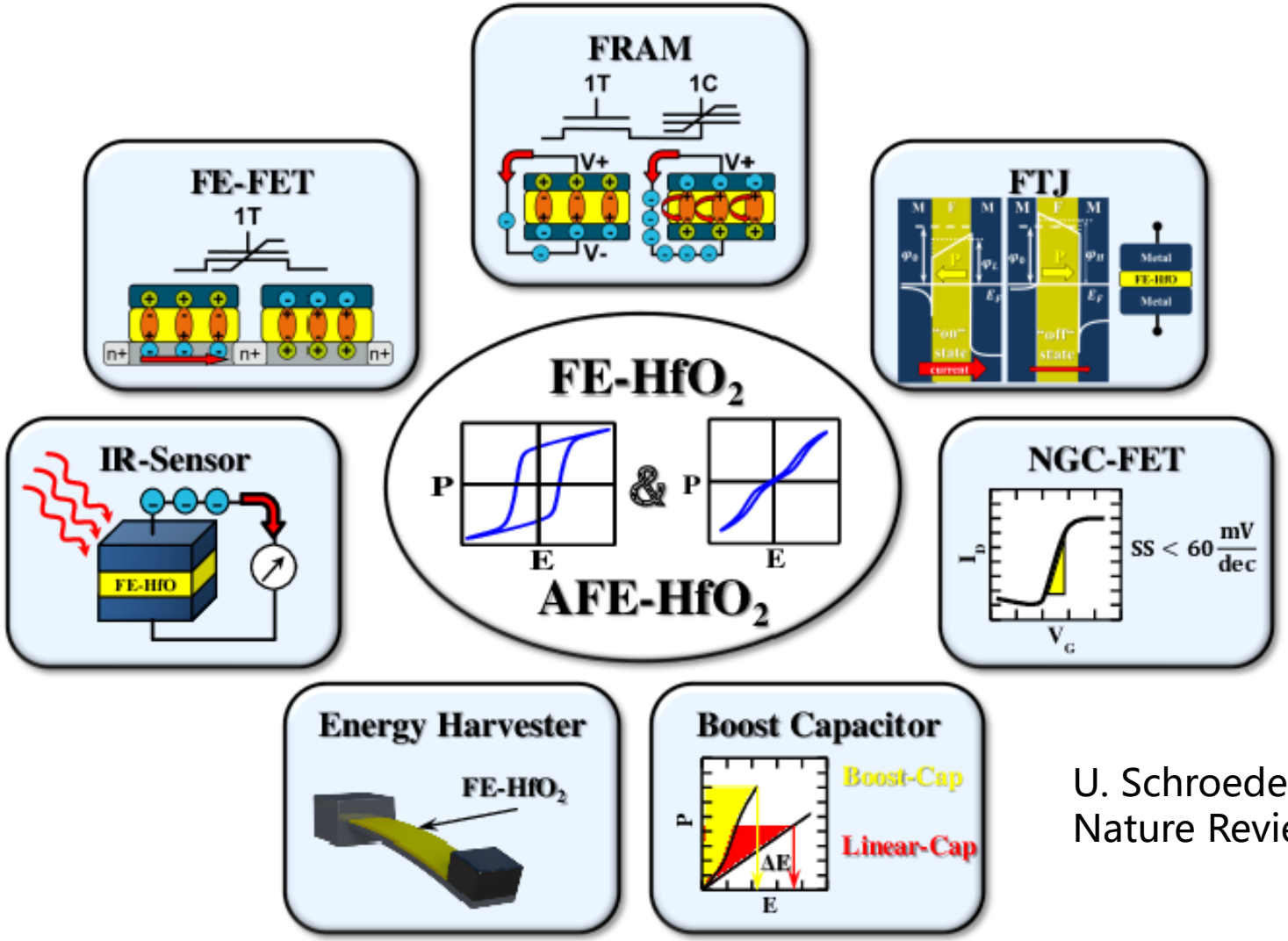
S. S. Cheema et al.,
Nature 478, 580 (2020)

理论
-5%双轴应变铁电相变

R. Cao, …, **Jun-Wei Luo***,
Nature 634, 1080-1085 (2024)



Applications of ferroelectric HfO2



U. Schroeder et al.,
Nature Reviews Materials 7, 653 (2022)

Fig. 1 System on Chip application potential of a CMOS-compatible ferroelectric

提出免于退极化效应光学声子软化新理论

➢ **国际同行认为这项成果对铁电材料在微电子器件中的应用将有关键影响，打开了创造一大类新铁电材料的大门；该成果入选2024年度中国半导体十大研究进展**

nature > news & views > article

NEWS AND VIEWS | 30 October 2024

Strain could enable energy-saving computer memories

Materials called ferroelectrics are being used to build energy-efficient electronics, but their benefits diminish when their size is scaled down. A proposed solution using mechanical strain could transform computer microelectronics.

By Chiara Gattinoni

The team's work has key implications for the future use of ferroelectric materials in microelectronic devices. The findings offer a robust explanation of the nanoscale ferroelectricity observed previously[6,7] in zirconium oxide and hafnium oxide, the experimental measurements of which are consistent with Cao and colleagues' theory. Even more crucially, the authors' study opens an avenue to creating a large class of ferroelectric materials by making use of the mechanism they propose.

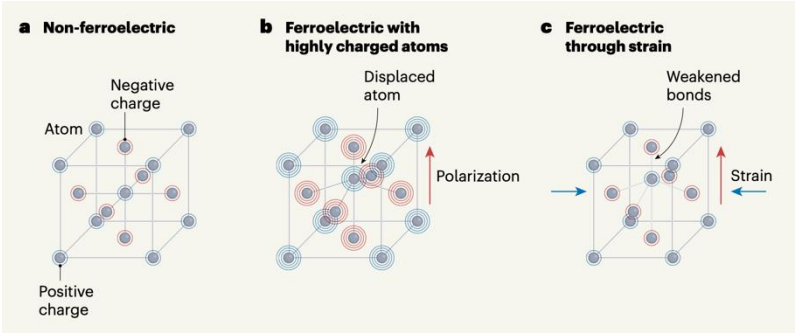
"2024年度"半导体十大研究进展"

（点击成果名称即可查看详情；排名不分先后）

01 光学声子软化新理论：突破半导体器件功耗瓶颈新希望

中国科学院半导体研究所骆军委团队联合宁波东方理工魏苏淮教授创新性地提出通过拉伸原子键降低化学键强度实现光学声子软化的新理论，可以克服高*k*介栅电材料难以同时拥有大介电常数和宽带隙，以及传统铁电材料因界面退极化效应难以应用于纳米器件等难题。为发展晶体管高*k*介电层和铁电晶体管等降低器件功耗提供了新思路。

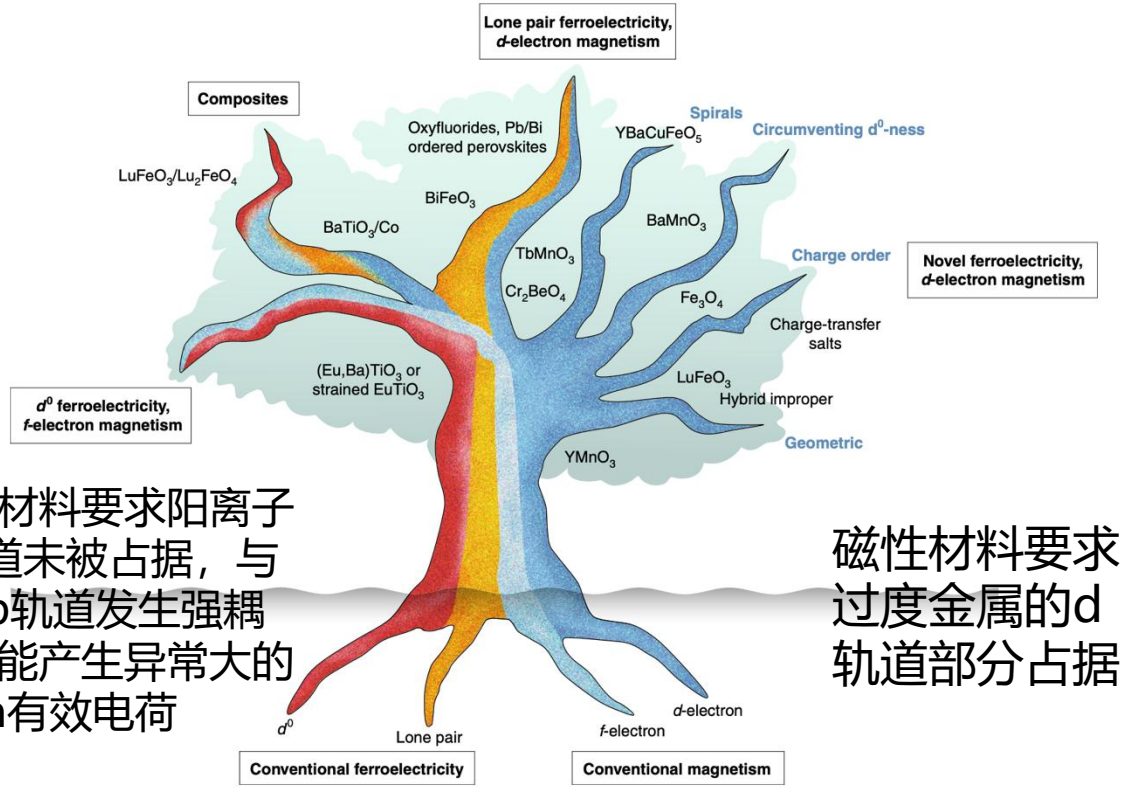
该纯理论的成果发表于《自然》杂志（*Nature*, 2024, 634: 1080–1085）。



提出免于退极化效应光学声子软化新理论

➢ **提出的免于退极化效应光学声子软化新理论为突破多铁材料面临的难题（磁性要求拥有部分占据的d轨道和铁电性要求的未占据d轨道），以及提升热电材料性能（小热导大电导）提供了新思路**

Multiferroics = magnetism + ferroelectricity



铁电材料要求阳离子d轨道未被占据，与O 2p轨道发生强耦合才能产生异常大的Born有效电荷

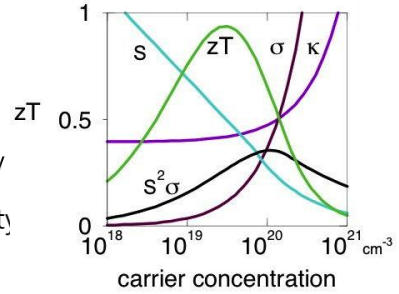
磁性材料要求过度金属的d轨道部分占据

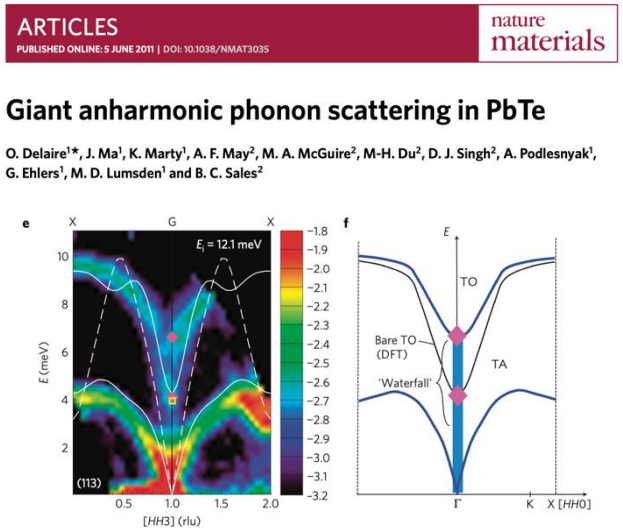
Cheong and Mostovoy, **Nature Materials** 6, 13 (2007)
Spaldin and Ramesh, **Nature Materials** 18, 203 (2019)

降低TO模频率提升热电材料性能

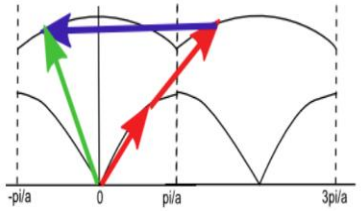
$$ZT = \left(\frac{S^2\sigma}{\lambda}\right)T$$

λ = thermal conductivity
S = Seebeck coefficient
σ = electrical conductivity
T = temperature





Umklapp phonon-phonon scattering



研究计划的执行情况：半导体物理与器件物理

- 半导体是中美科技战的主战场，后摩尔时代半导体技术创新是抢占中美科技战制高点的关键
- 后摩尔时代半导体技术已经从单纯追求器件尺寸微缩提升集成密度，扩展到同时追求功能性集成；技术路线按照“延续摩尔”、“扩展摩尔”和“超越摩尔”3个不同维度继续演进

降低器件功耗

受华为核心芯片部门邀请在华为2024年度战略与技术大会上作《**半导体界面与应力对器件性能的影响**》主题报告

超越摩尔
硅量子计算机
新概念

研究内容一：半导体自旋轨道耦合效应
进展/成果：发现硅锗量子阱的空穴存在新型线性Rashba效应，是锗空穴量子比特实现**全电EDSR快速操控的物理根源**；**发现“交错磁”**(altermagnetism)。

圆满完成

扩展摩尔
硅光电子集成芯片
新功能

研究内容二：硅基发光材料与器件
进展/成果：提出掺杂应变锗直接带隙发光**硅基发光原创方案**，**揭示激光退火新机制**，**研制出**发光强度媲美III-V族直接带隙半导体**硅基发光材料**。

圆满完成

延续摩尔
硅微电子芯片
新材料

新增**研究内容三：晶体管摩尔定律物理瓶颈**（面向国家急迫需求）
进展/成果： 高k介电层缺陷导致良品率和漏电流功耗，**提出免于退极化效应光学声子软化新理论**为发展低功耗器件提高新希望。

新增任务

时间

超越摩尔：半导体自旋轨道耦合效应（方向一）

➢ **从发现隐藏自旋极化提出隐藏物理概念到发现交错磁和隐藏的类Zeeman自旋极化**

- 2014年发现**硅**等中心对称晶体中存在**隐藏自旋极化效应**

X.W. Zhang, Q.H. Liu, **Jun-Wei Luo***, A. Freeman, and A. Zunger*, “Hidden spin polarization in inversion-symmetric bulk crystals”, **Nature Physics** 10, 387 (2014).

- 2019年揭示**隐藏Rashba效应**的物理根源与对称性要求

L.D. Yuan, Q. Liu, X. Zhang, **Jun-Wei Luo***, Shu-Shen Li, and Alex Zunger*, Uncovering and tailoring hidden Rashba spin-orbit splitting in centrosymmetric crystals, **Nature Communications** 10, 906 (2019)

- 2020年发现**反铁电**晶体中存在**电场可调的隐藏自旋极化**

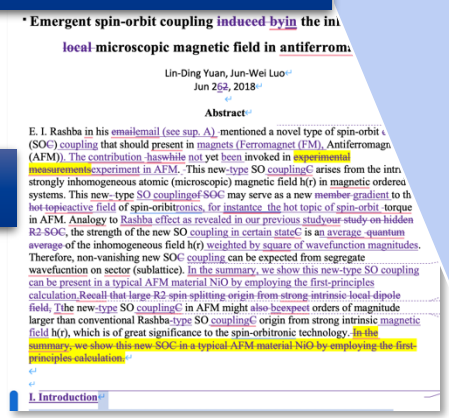
S. Guan and **Jun-Wei Luo***, Electrically switchable hidden spin polarization in antiferroelectric crystals, **Phys. Rev. B** 102, 184104 (2020) （第一标注）

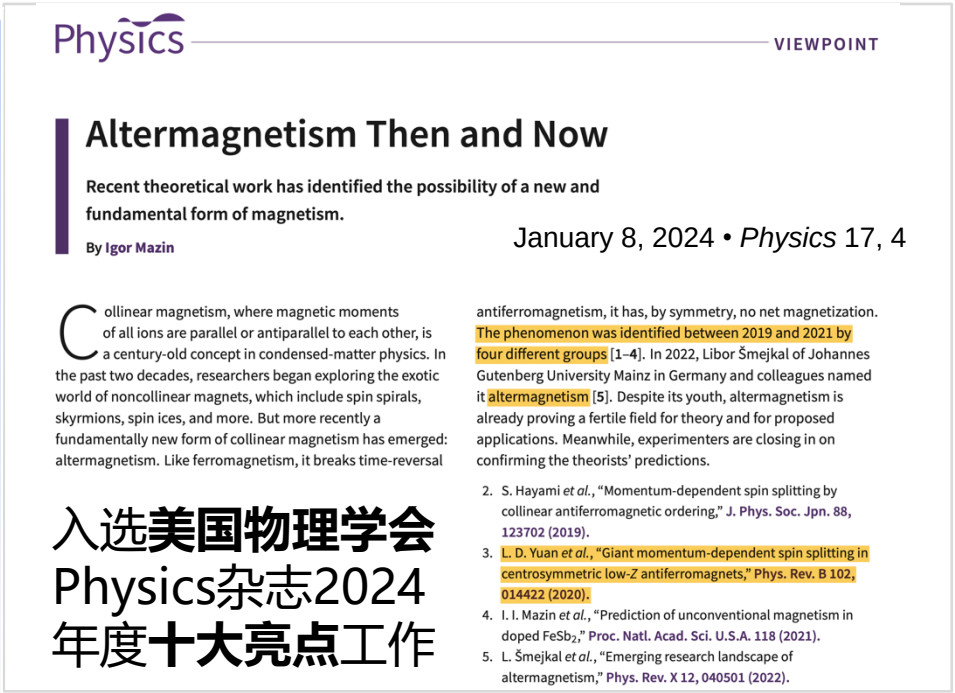
- 2020年发现**反铁磁**晶体中存在**隐藏的**与自旋轨道耦合无关的**新型自旋极化效应（交错磁）**

L.D. Yuan, Z. Wang, **Jun-Wei Luo**, E. I. Rashba* and A. Zunger*, Giant momentum-dependent spin splitting in centrosymmetric low-Z antiferromagnets, **Phys. Rev. B** 102, 014422 (2020).

- 2023年发现**隐藏的类Zeeman自旋极化**

S. Guan, **Jun-Wei Luo***, Shu-Shen Li and Alex Zunger, Hidden Zeeman-type spin polarization in bulk crystals, **Phys. Rev. B** 107, L081201 (2023)（第一标注）


Emergent spin-orbit coupling induced byin the in
local microscopic magnetic field in antiferrom
Lin-Ding Yuan, Jun-Wei Luo
Jun 262, 2018
Abstract
E. I. Rashba in his emailemail (see sup. A) mentioned a novel type of spin-orbit
(SOC) coupling that should present in magnets (Ferromagnet (FM), Antiferromagn
(AFM)). The contribution haswhile not yet been invoked in experimental
measurementsexperiment in AFM. This new-type SO couplingC arises from the intr
strongly inhomogeneous atomic (microscopic) magnetic field h(r) in magnetic ordered
systems. This new-type SO couplingof SOC may serve as a new member gradient to th
hot topicactive field of spin-orbitronics, for instance, the hot topic of spin-orbit torque
in AFM. Analogy to Rashba effect as revealed in our previous studyour study on hidden
R2 SOC, the strength of the new SO coupling in certain stateC is an average quantum
average of the inhomogeneous field h(r) weighted by square of wavefunction magnitudes.
Therefore, non-vanishing new SOC coupling can be expected from segregate
wavefucntion on sector (sublattice). In the summary, we show this new-type SO coupling
can be present in a typical AFM material NiO by employing the first-principles
calculation.Recall that large R2 spin splitting origin from strong intrinsic local dipole
field. The new-type SO couplingC in AFM might also beexpect orders of magnitude
larger than conventional Rashba-type SO couplingC origin from strong intrinsic magnetic
field h(r), which is of great significance to the spin-orbitronic technology. In the
summary, we show this new SOC in a typical AFM material NiO by employing the first-
principles calculation.
I. Introduction


Physics VIEWPOINT

Altermagnetism Then and Now

Recent theoretical work has identified the possibility of a new and fundamental form of magnetism.

By Igor Mazin

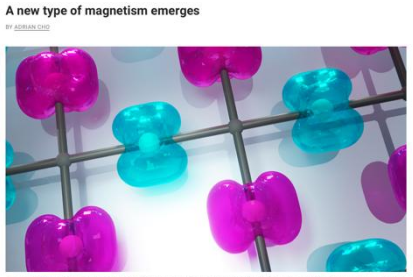
January 8, 2024 • *Physics* 17, 4

Collinear magnetism, where magnetic moments of all ions are parallel or antiparallel to each other, is a century-old concept in condensed-matter physics. In the past two decades, researchers began exploring the exotic world of noncollinear magnets, which include spin spirals, skyrmions, spin ices, and more. But more recently a fundamentally new form of collinear magnetism has emerged: altermagnetism. Like ferromagnetism, it breaks time-reversal antiferromagnetism, it has, by symmetry, no net magnetization. The phenomenon was identified between 2019 and 2021 by four different groups [1–4]. In 2022, Libor Šmejkal of Johannes Gutenberg University Mainz in Germany and colleagues named it altermagnetism [5]. Despite its youth, altermagnetism is already proving a fertile field for theory and for proposed applications. Meanwhile, experimenters are closing in on confirming the theorists’ predictions.

2. S. Hayami *et al.*, “Momentum-dependent spin splitting by collinear antiferromagnetic ordering,” J. Phys. Soc. Jpn. 88, 123702 (2019).
3. L. D. Yuan *et al.*, “Giant momentum-dependent spin splitting in centrosymmetric low-*Z* antiferromagnets,” Phys. Rev. B 102, 014422 (2020).
4. I. I. Mazin *et al.*, “Prediction of unconventional magnetism in doped $FeSb_2$,” Proc. Natl. Acad. Sci. U.S.A. 118 (2021).
5. L. Šmejkal *et al.*, “Emerging research landscape of altermagnetism,” Phys. Rev. X 12, 040501 (2022).

入选**美国物理学会**Physics杂志2024年度**十大亮点**工作

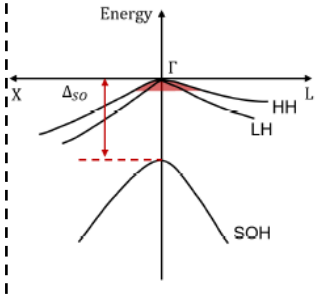
交错磁入选Science杂志2024年度**十大突破**



超越摩尔：半导体自旋轨道耦合效应（方向一）

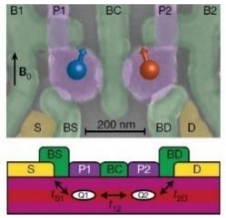
- 锗空穴自旋量子比特由于实现108MHz的全电EDSR快速操控，已经超越硅电子自旋量子比特成为发展硅量子计算的最佳平台，但是其物理根源还存在争议
- 我们发现**锗量子阱中存在新型线性Rashba效应，是**其实现全电EDSR快速操控的**物理根源**

锗空穴量子比特



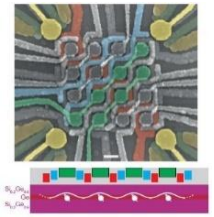
锗空穴

✓有效质量小
✓没有谷简并
✓强SOC



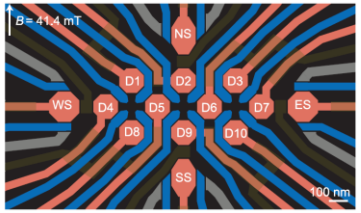
M. Veldhorst, Nature (2020)

Rabi频率108 MHz



M. Veldhorst, Nature Nano (2023)

4x4 QDs



M. Veldhorst, Science (2024)

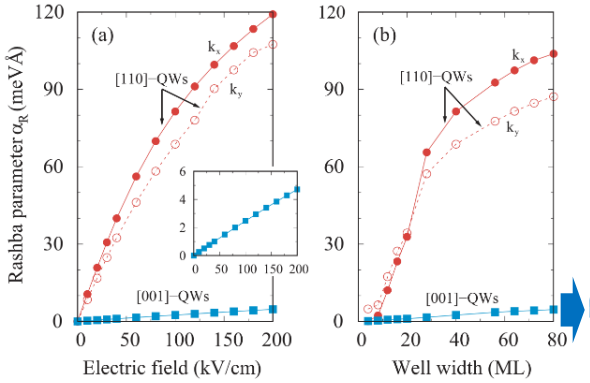
10 Qubits

操控速度

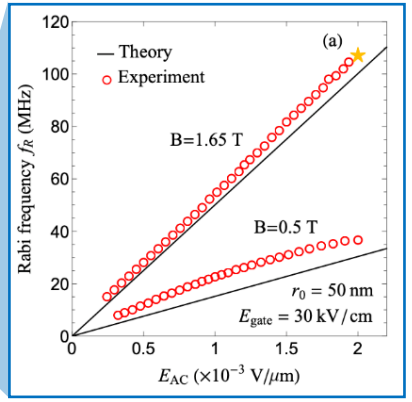
$$Q = 2 f_{Rabi} \cdot T_2$$

品质因子　退相干时间

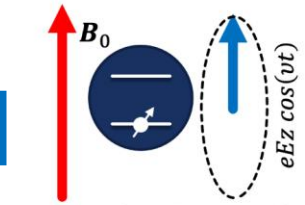
成果：发现锗量子阱空穴存在新型线性Rashba效应，并揭示该效应为锗空穴量子比特提供了EDSR快速操控（Rabi频率108MHz）



预测Rabi频率



- All electrical EDSR
Static B field + SOC + oscillating E field



$$H_{SO} = p(\alpha_R \sigma^z + \alpha_D \sigma^x)$$

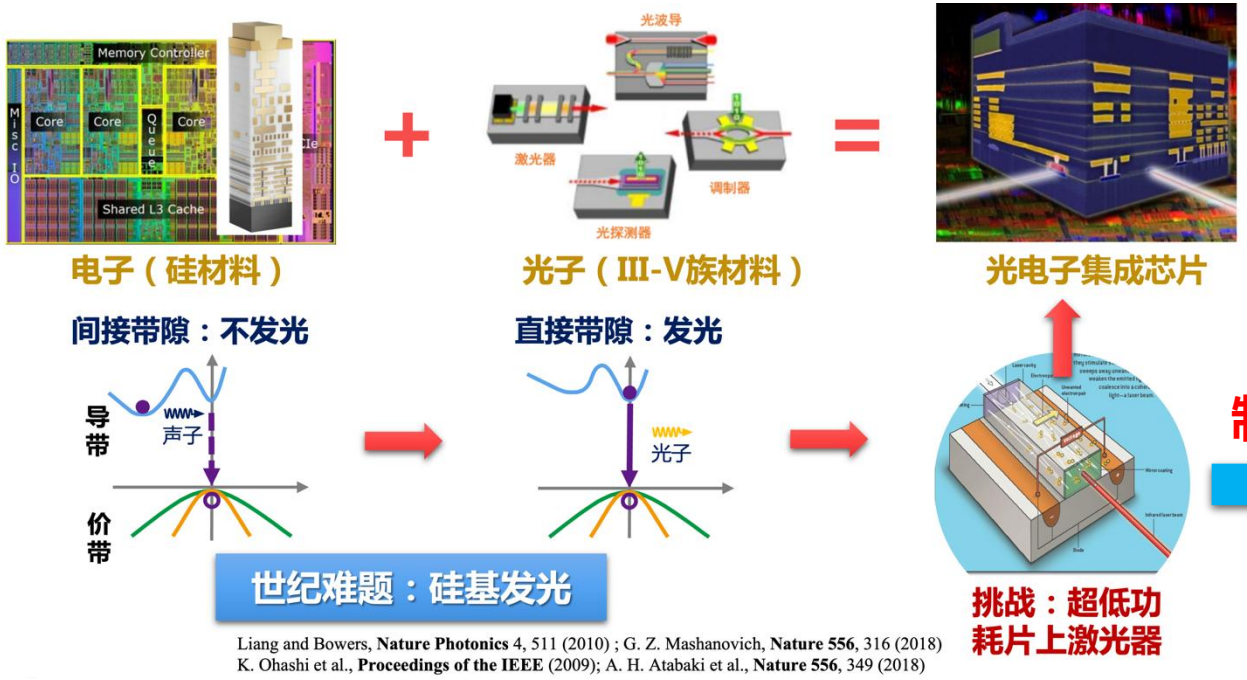
基于自旋轨道耦合效应的全电EDSR操控

J.X. Xiong, S. Guan*, **J.W. Luo***, and S.S Li, **PRB** 103, 085309 (2021) （第一标注）
J.X. Xiong, S. Guan*, **J.W. Luo***, and S.S. Li, **PRB** 105, 115303 (2022) （第一标注）
J.X. Xiong, Y. Liu, S. Guan*, **J.W. Luo***, and S.S. Li, **PRB** 106, 155421 (2022) （第一标注）

Expt.: M. Veldhorst et al., Nature 577, 487 (2020)
Theory: Y. Liu, … **J.W. Luo***, and S.S. Li, **PRB** 105, 075313 (2022) （第一标注）

扩展摩尔：硅基发光材料与器件（方向二）

- 硅光电子集成芯片可以解决延时、带宽、功耗等摩尔定律物理极限，将颠覆集成电路CMOS芯片技术，是美国重点部署的后摩尔芯片关键技术之一，相关技术已被美国列入禁运清单
- 除激光器外其他关键光学器件都已成功集成在硅CMOS芯片上，芯片上集成激光器成为制约硅光电子集成芯片的最后障碍，由于间接带隙硅不发光难以做出激光器，硅基发光成为世界难题

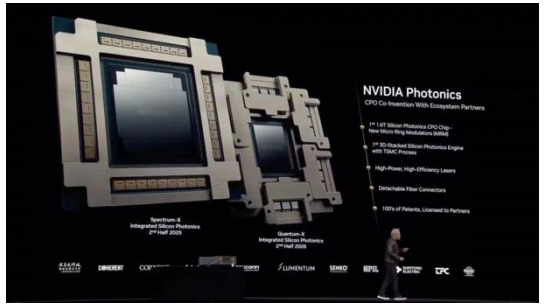


Liang and Bowers, **Nature Photonics** 4, 511 (2010) ; G. Z. Mashanovich, **Nature 556**, 316 (2018)
K. Ohashi et al., **Proceedings of the IEEE** (2009); A. H. Atabaki et al., **Nature 556**, 349 (2018)

主要竞争者：
英伟达、台积电、Intel、IBM、imec

2020年Nature报道六方锗直接带隙发光，**被评为2020年度世界最大突破**，但无法兼容CMOS工艺。
Fadaly et al., Nature 580, 205 (2020)

制高点



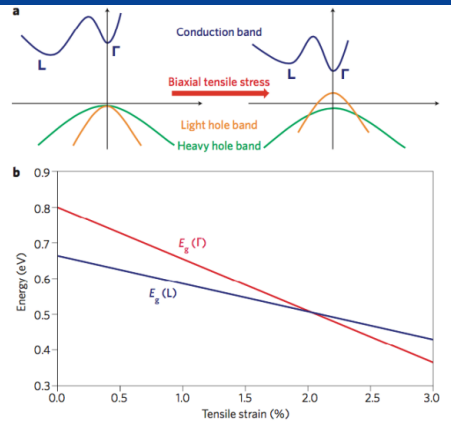
缺少片上激光器

- **英伟达**最近公布的**硅光交换机**使用了外置光源
- 2015年Nature报道了首个由7千万个晶体管和850个光子器件组成的硅光电子集成芯片，但缺乏片上集成光源，无法实用化

扩展摩尔：硅基发光材料与器件（方向二）

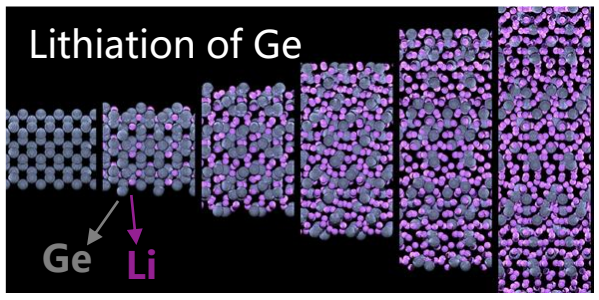
- 从锗充锂后体积急剧膨胀得到启发，提出掺杂应变锗直接带隙发光的硅基发光新方案
- 使用离子注入和超快激光退火技术，实现锗在Ar掺杂后发光强度提高40倍，接近直接带隙半导体

锗变成直接带隙只需2%的张应变



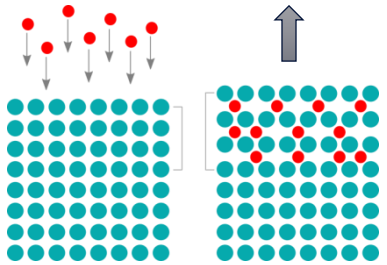
J. Michel, **Nature Photonics** (2010)

掺杂 **锂电池的挑战**：硅/锗阳极材料在充锂后体积膨胀最大可达400%



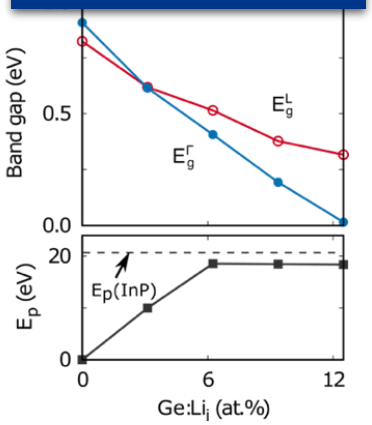
Tarascon & Armand, Nature **414**, 359 (2001)

单轴应变

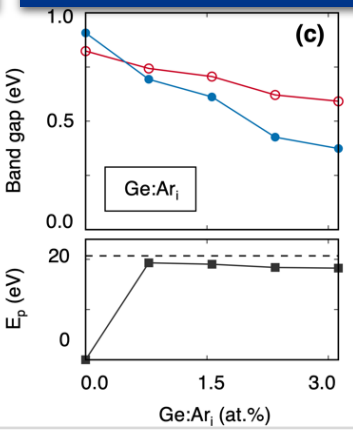


L.D. Yuan, S.S. Li, **J.W. Luo***, **Nature Communications** 15, 618 (2024) （第五标注，前四都是申请人的项目）

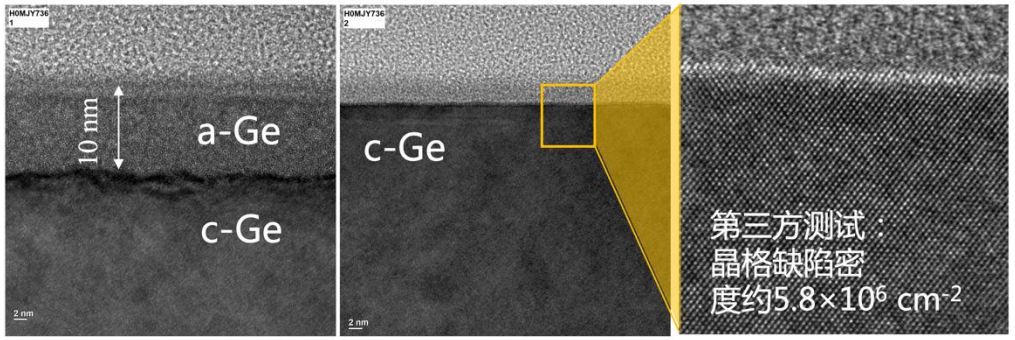
锂掺杂浓度>6%



Ar掺杂浓度>1%

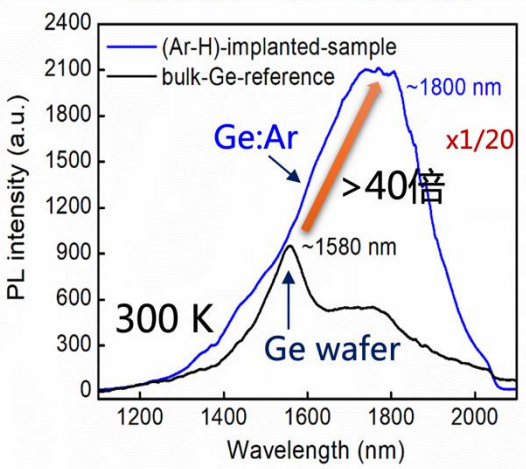


离子注入惰性气体掺杂技术路线



Ge:Ar激光退火前　Ge:Ar激光退火后（低倍）　Ge:Ar激光退火后（高倍）

锗掺杂Ar的PL发光谱



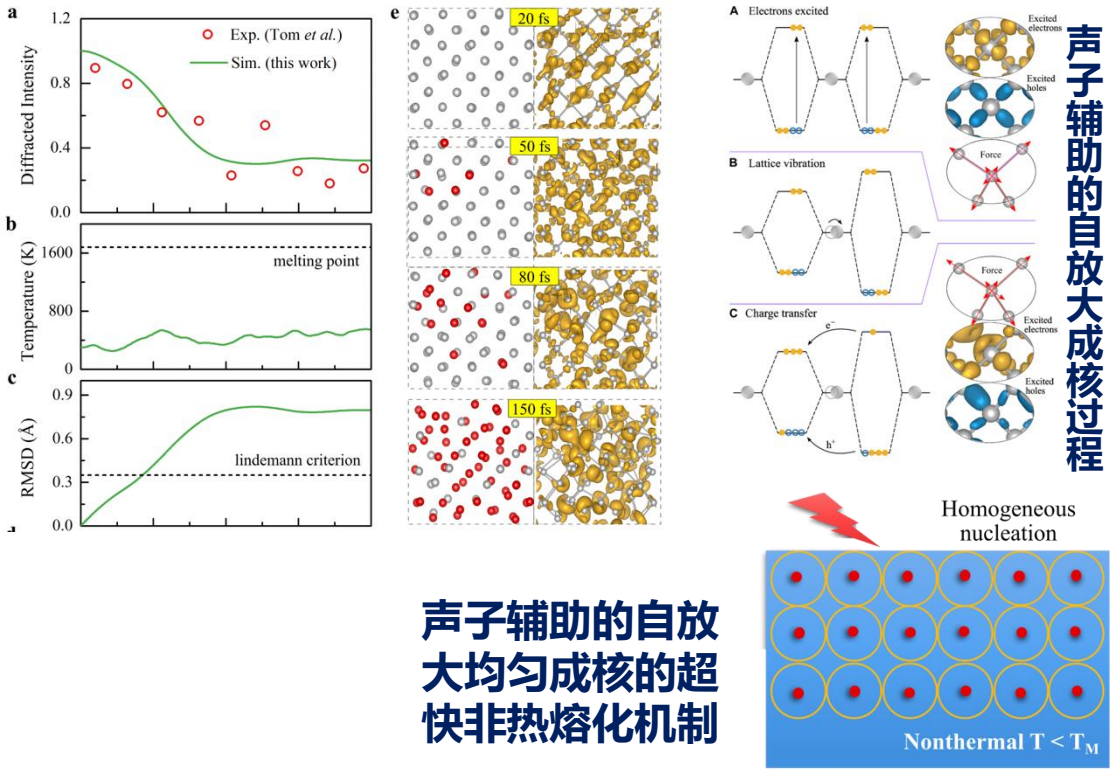
PL光谱：激光退火后的PL峰红移到1800nm，发光强度提高40倍。

但是，重复性很差！

扩展摩尔：硅基发光材料与器件（方向二）

- 硅等半导体材料的超快激光退火微观机制：声子辅助的自放大均匀成核超快非热熔化过程
- 光致相变新认识：光激发导致载流子在成键态与反成键态能带间重新分布，产生原子力驱动原子移动，导致周期晶格发生结构相变，而非普遍认为的光生相干声子驱动的相变

揭示激光退火非热熔化新机制

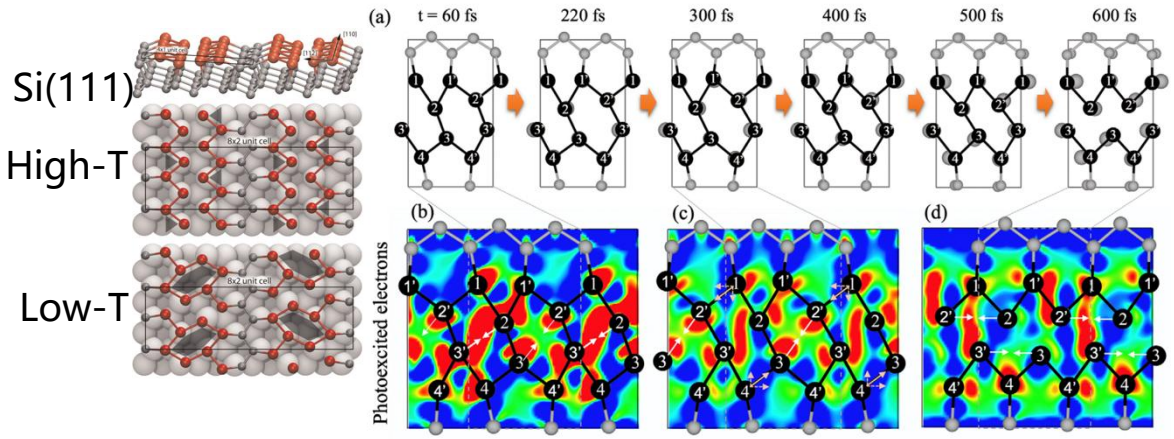


声子辅助的自放大均匀成核的超快非热熔化机制

W. Liu, **J.W. Luo***, et al., **Science Advances** 8, 4430 (2022) （第一标注）

提出光致相变由原子力驱动而非相干声子驱动

光激发导致载流子在成键态与反成键态间重新分布，这要求改变原子键长来降低总能量，从而产生原子力驱动原子定向移动，实现周期晶格的结构相变，并伴随产生相干声子。

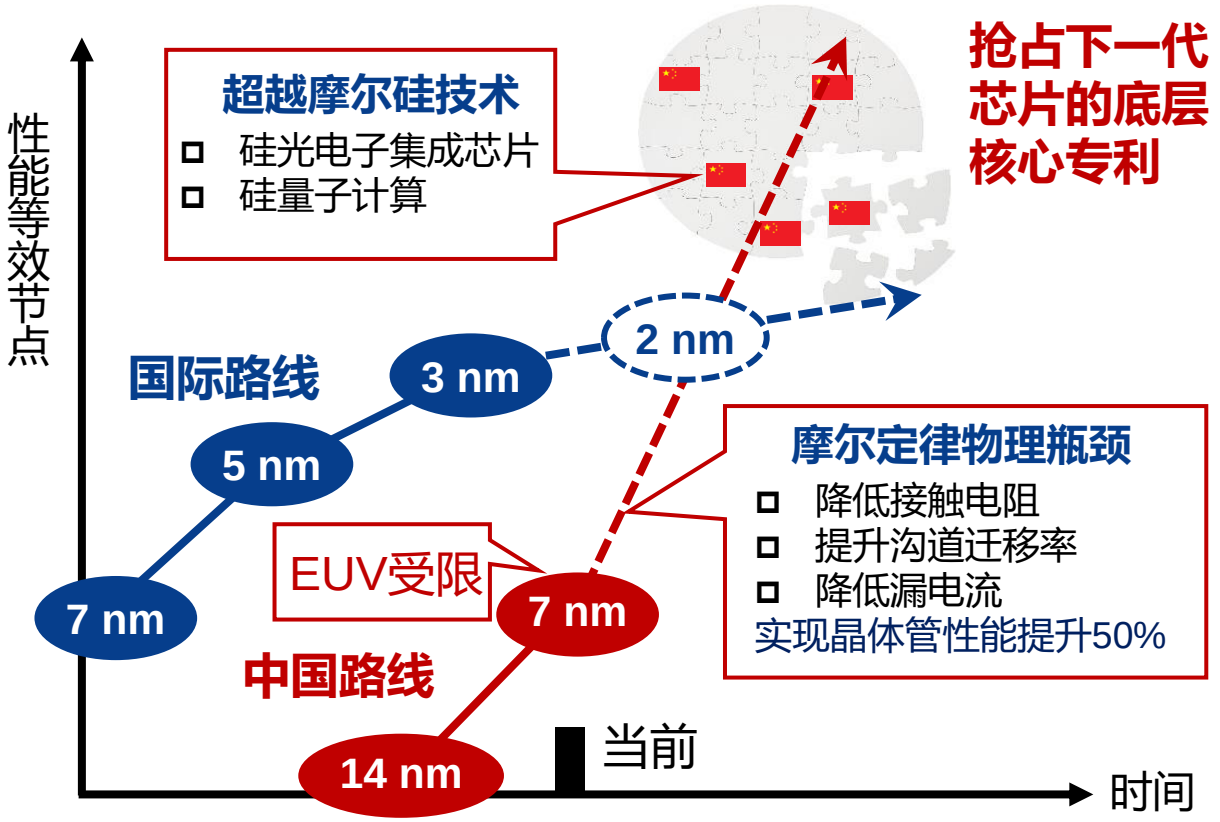


W. Liu, …, **J.W. Luo*, PRL** 130, 146901 (2023) （第一标注）
H. Liu, …, **J.W. Luo*,** L. Wang*, **PNAS** 119, e2122534119 (2022) （第一标注）
F. Guo,..., **J.W. Luo*, Nature Communications** 16, 94 (2025) （第一标注）

半导体物理：面向国家急迫需求 聚焦硅器件守正创新

- 习近平：我国面临“卡脖子”技术问题，根子是基础理论研究跟不上，源头和底层的东西没有搞清楚
- 华为在造出5G麒麟芯片后，制定了没有EUV光刻机情况下的芯片超越战略，提出通过一系列单点技术的突破，打开未来芯片的非EUV光刻制造路径，并向学术界发出了寻求理论指导的召唤

面临众多“没有已知解决方案”的基本物理问题挑战



科学观察
Scientific Focus

引用格式：骆军委, 李树深. 加强半导体基础能力建设 点亮半导体自立自强发展的“灯塔”. 中国科学院院刊, 2023, 38(2): 187-192, doi: 10.16418/j.issn.1000-3045. 20230130001.
Luo J W, Li S S. Strengthen the building of basic reach capacity for semiconductor research to light up the “beacon” towards realizing the self-reliance and self-improvement of semiconductors. Bulletin of Chinese Academy of Sciences, 2023, 38(2): 187-192, doi: 10.16418/i.issn.1000-3045.20230130001. (in Chinese)

骆军委　李树深*

中国科学院半导体研究所 半导体超晶格国家重点实验室 北京 100083

加强半导体基础能力建设 点亮半导体自立自强发展的“灯塔”

力加强半导体基础研究，围绕下一代晶体管的材料、器件、工艺等在欧洲和美国布局大量专利，就可以在芯片制造这个全球半导体产业链的“咽喉”部位设置“关卡”，形成反制手段，有望解决半导体关键核心技术“卡脖子”难题。

- ✓ 获得习近平总书记批示
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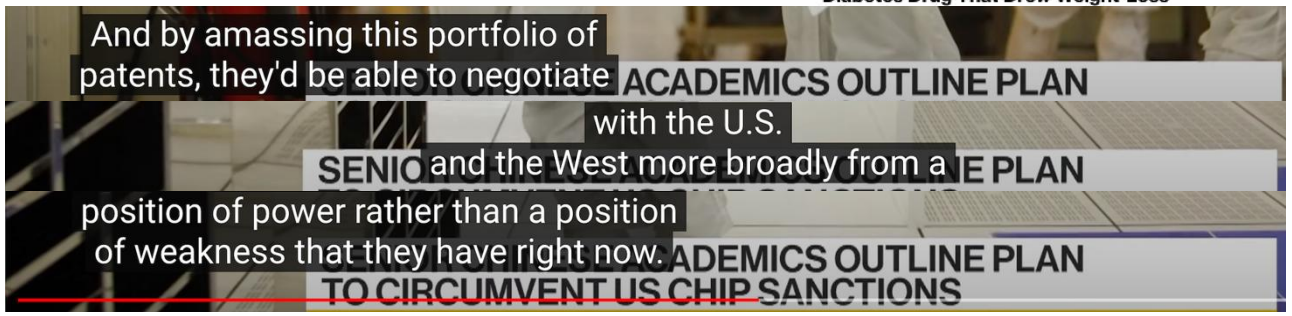
半导体物理的研究成果也可以反制美国芯片霸权

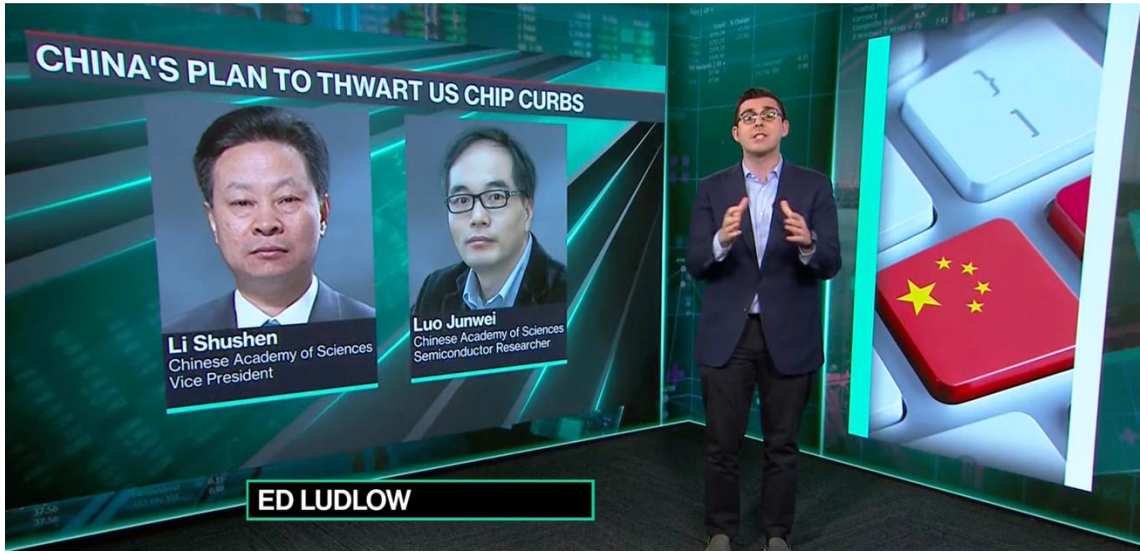
美国彭博社、纽约时报、泰晤士报等欧美主流媒体

Top Chinese Scientists Sketch Out Plans to Thwart US Chip Curbs

- US measures aim to cap China's chipmaking advancements
- Article gives a rare glimpse of how Beijing can counter-strike

China's Plan to Dodge US Chip Curbs





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收件箱

John Liu 2023/2/21
收件人：骆军委

纽约时报采访邀请

尊敬的骆军委研究员您好，

我是纽约时报报道科技领域的记者。我们关注到您近期在中国科学院院刊的关于加强国内半导体基础能力建设的文章，这篇文章在国内及国外都引起了相当大的讨论，我们对您提出来的观点也有极深的兴趣。不知道有没有机会能够跟您深入聊聊国内要怎么做才能反转半导体目前面临的困境，甚至如您文中所说来反制美方？只要您愿意的话，不管是具名（on the record）或是不具名的背景访谈（for background only）都可以。

谢谢您，期待您的回复。

Best regards,

John Liu 刘忠恩
The New York Times
Phone: +86 1056952817 / +86 17160420480
WeChat: jliu5214
Telegram: +86 17160420480

13:14

收件箱

发件人：Cecilia Wang
收件人：骆军委
2023年3月14日 16:42

《经济学人》杂志采访邀约

尊敬的骆老师：

您好！我是《经济学人》杂志的王歆悦。 我们正在策划撰写一篇关于美国对华《芯片法案》和107新规对我国产业影响的文章，我看这个主题与您的研究方向很契合，所以希望能够对您做个采访，就一些相关问题请教您。若您有兴趣，请随时来电来函与我联系。盼复！

《经济学人》（The Economist）介绍：
1843创办于伦敦的《经济学人》是全球最具影响力的政治商业期刊，致力于对全球政治、财经、科技、文艺等广泛领域提供权威洞见，拥有的政治、经济领导人读者远多于世界上其它任何一份杂志。《经济学人》的文章以英文刊发，发行量超150万份。目前，《经济学人》已推出旗下首款中英双语电子App《经济学人·商论》，专注全球经济领域的资讯新闻。

祝好！
--
王歆悦
Cecilia Wang
The Economist

12:20

Yaqi Yang 11:22
收件人：骆军委 抄送：Fabian

采访邀请-关于中国芯片行业现状及美国禁令对它的影响-德国《时代》周报

骆主任，

早上好！

我是杨雅琪，德国《时代》周报驻京分社的研究员。

记者 Fabian Kretschmer 正为我们报社撰写一篇关于中国芯片的文章。我们看到您近期发表在《中国科学院院刊》上的文章，特别想邀请您和我们聊聊：

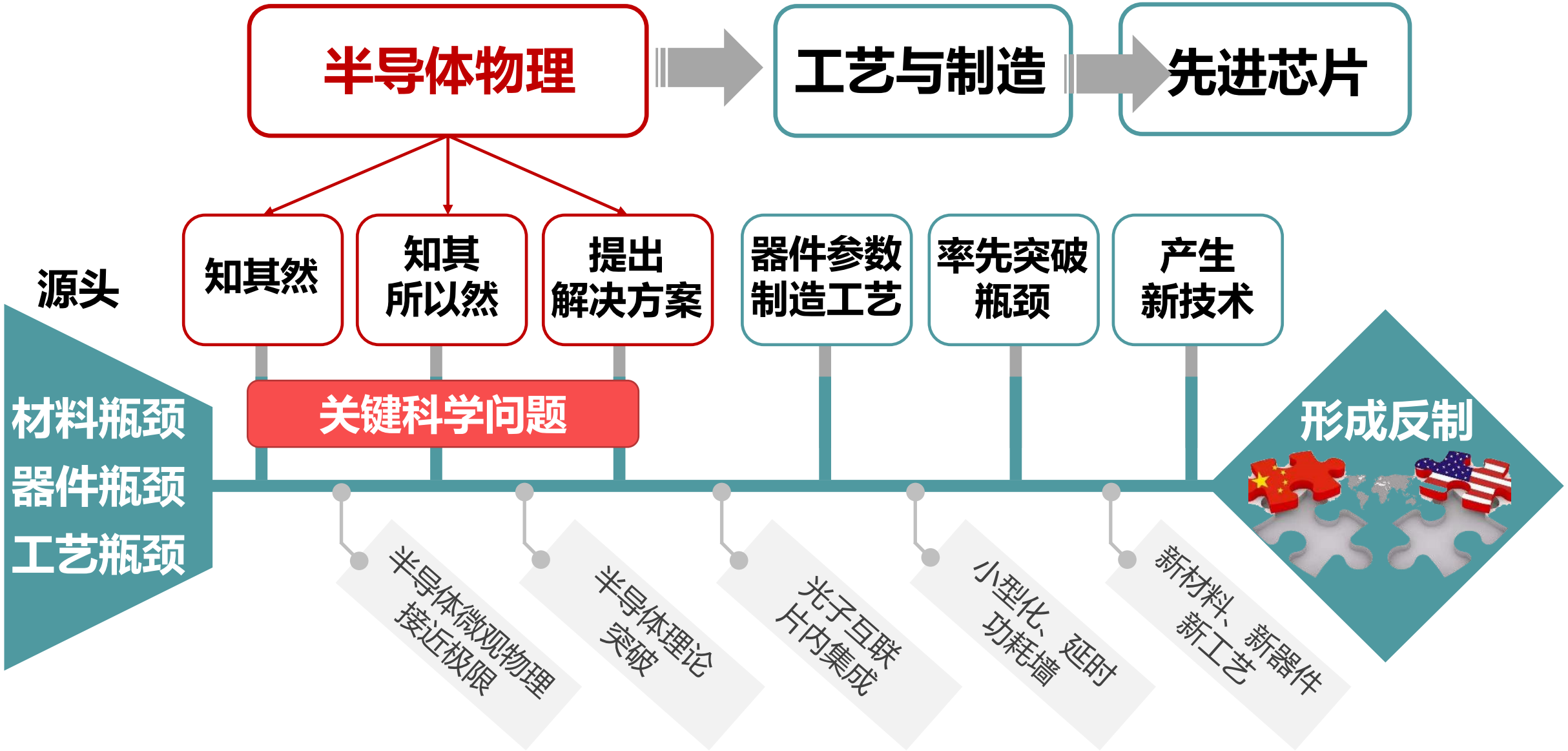
- 中国芯片行业的现状；
- 中国芯片行业在多大程度上会受到美国制裁的影响；
- 克服如此恶劣的地缘政治环境的策略。

请问您近期是否方便？

期待您的回复，另祝周末愉快！

祝好，
杨雅琪

敬请各位专家批评指正


半导体物理
工艺与制造
先进芯片
源头
知其然
知其所以然
提出解决方案
器件参数制造工艺
率先突破瓶颈
产生新技术
材料瓶颈
器件瓶颈
工艺瓶颈
关键科学问题
形成反制
半导体微观物理接近极限
半导体理论突破
光子互联片内集成
小型化、延时功耗墙
新材料、新器件新工艺