固体物理A

2021年秋

USTC

Instructor

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Syllabus

- 4学分，80学时
- 5406，周三(3,4),周五(6,7)
- 每隔一两周会有一个Quiz
- 期末考试
- 期末小论文
- 成绩=作业(20%)+quiz(15%)
  +期末成绩(55%)+小论文(10%)
- Absolutely no cell phone!

Knowledge prerequisites

- 经典力学
- 量子力学
    - 理解波函数的意义
    - 薛定谔方程
    - 求解一维方势阱，简谐势
    - 微扰
- 统计力学
    - 费米统计,玻色统计
- 数量方程基础

绪论：固体物理的昨天，今天

0.1　固体物理的研究对象

0.2　固体物理的发展历程

0.3　固体物理的研究方法

0.4　固体物理的相关教材

主要回答：什么是固体物理学？

如何学习固体物理学？

0.1 固体物理学的研究对象

顾名思义，固体物理学是研究固态物质物理性质的学科。

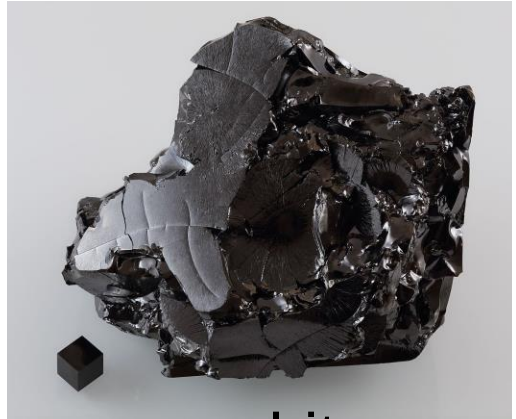
但和普通物理不同，它的重点不在于描述固体的宏观物理性质，而是去**阐明**和**理解**固体的宏观性质。**解释**形成这些性质的原因，从而找出**控制、利用、改善**这些性质的方法。

例如：普通物理使我们知道了欧姆定律，固体物理将说明固体电阻的来源并从理论上推导出欧姆定律，分析出不同固体导电性能不同的原因。

固体物理研究的不是单个原子的性质，而是大量原子组成在一起形成固体后所表现出来的集体性质。

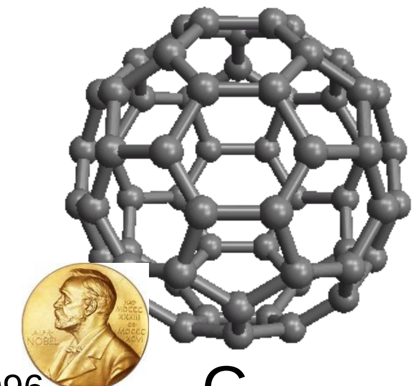
固体是由大量原子和分子组成的，固体的性质虽然也和组成固体的原子、分子种类有关，但更主要的是和这些原子采用什么方式结合在一起，他们的空间排列方式、相互作用力类型，特别是和原子形成固体后其价电子的运动状态有关。

amorphous carbon

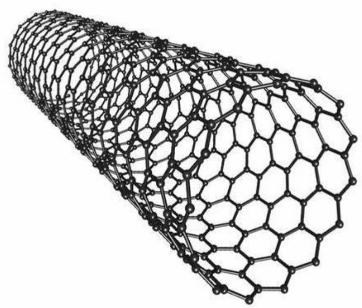


graphite

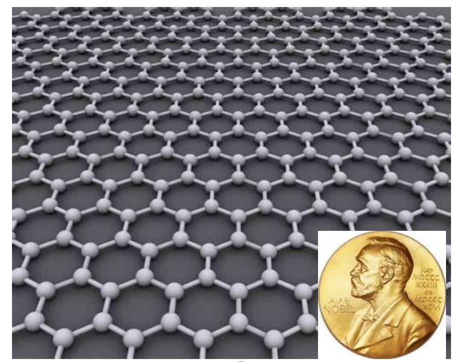
diamond



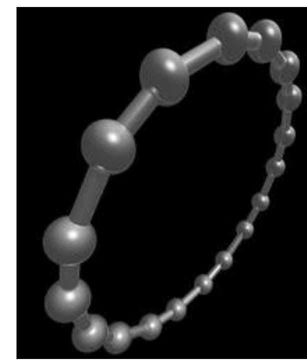
1996 C_{60}



carbon nanotube



graphene 2010



cyclocarbon

　　例如：性质完全不同的无定形碳、石墨和金刚石都是由相同的碳原子组成的，是碳原子空间排列和结合方式的差异带来了其物理性质的极端不同。

　　因此只有通过对**固体微观结构**和组成固体**微观粒子之间的相互作用及运动机制**的研究才能理解固体的性质。

自然界中的固体，按其构成原子空间排列的特点大致可以分为**晶体**和**非晶体**。

固体物理的研究首先是从晶体开始的：

1. 在自然界的矿物中，晶态物质占到98％以上，人类最早研究和使用的材料也大都是晶态物质，是各类晶态物质特有的性质引起了研究兴趣和开发利用。

2. 晶态物质原子排列的周期性使的固体理论得以顺利进行，**如今已经成熟并获得巨大成功的固体理论只是建立在对晶体研究的基础上。严格说来应该叫做晶体物理学**。但基于上述原因，过去很长一段时间里，人们把“固体”与“晶体”看成同义词，并不区别它们间的差别，所以早期Kittel说：固体物理研究 **晶体和晶体中的电子**。

固体物理和四大力学也不同，后者分别研究物质特定的运动形态，研究对象是理想条件下的特定运动的规律，如理论力学研究物体的机械运动等，固体物理则不同，它研究的对象是一类物质——固体，它既是力学系统、又是热学系统和电磁系统，而组成固体的微观粒子又必须服从量子力学规律，所以**固体物理是一门综合科学**，需要我们综合运用各种理论工具，从不同角度、不同侧面去研究**实际固体**的各种运动形态，从而全面地解释固体的**各种**性质，所以四大力学都是固体物理的理论基础课。

The scope of solid state physics

Solid state physics studies physical properties of materials

Material	Structure	Shape	Properties
metal	crystal	bulk	electrical
semiconductor	amorphous	surface	optical
insulator	… etc	interface	thermal
superconductor		nano-cluster	mechanical
magnetic		… etc	… etc
… etc			

Solid state physics = $\{A\} \times \{B\} \times \{C\} \times \{D\}$

Always try to understand a physical phenomenon from the microscopic point of view (atoms plus electrons)!

0.2 固体物理学的发展历程

Max von Laue
Nobel prize in 1914
“for his discovery of the diffraction of X-rays by crystals”

固体物理学作为一门近代科学始于20世纪初，虽然晶体学的研究有着悠久的历史，19世纪末就已经建立起了完整的对称性理论，但只是在1912年*Laue发现了晶体的X射线衍射现象后，晶体结构的研究才得以证实，并从此具备了实验研究固体微观结构的条件。

20世纪初量子论，特别是量子力学的逐步建立使正确解释已经发现的关于固体性质的规律成为可能。

自此之后的几十年是创立固体理论的辉煌时期：

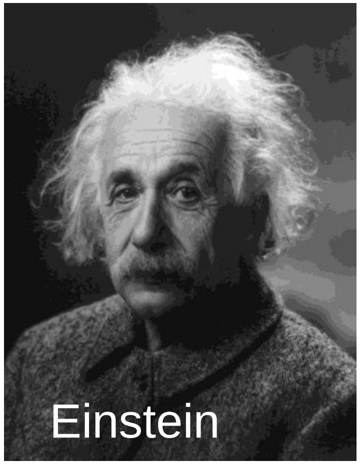
*Einstein 1907 和Debye 1912,建立了固体比热的量子理论，解释了低温比热为什么低于Dulong-Petit 值。

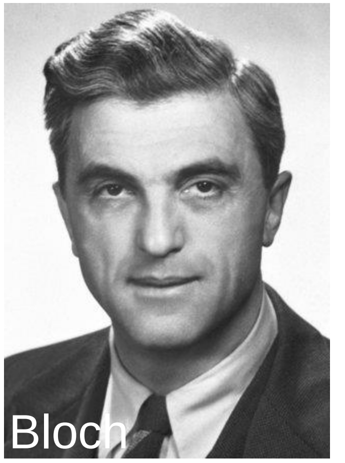
*Born和Karman 1912首次采用周期性边界条件处理了三维晶格振动问题，建立了晶格动力学理论。

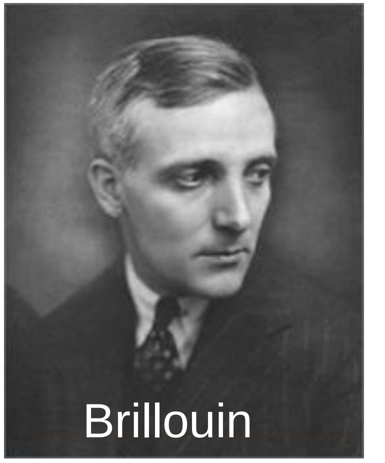
Sommerfeld 1928 采用Fermi统计，用量子论的观点修正了经典电子论。

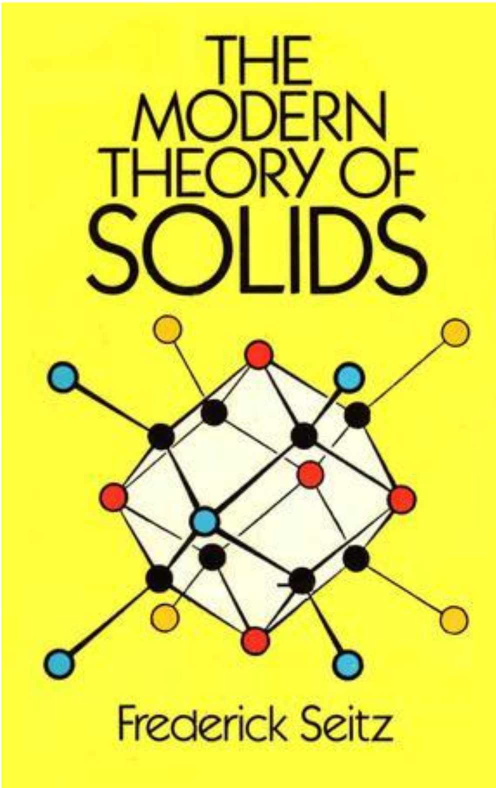
*Bloch 1928 近似求解周期势场中的Schödinger方程，引入了能带的概念。Wilson 1931利用能带观点解释了半导体的导电现象，提出了空穴的概念。Brillouin , Seitz, Slater等人相继进行研究，从而逐步完善了能带论。

与此同时，* Heisenberg, *Wigner, *Mott, *朗道，夫伦克尔，佩尔斯，*肖特基，*范弗莱克等当时一流的理论物理学家都曾投入到固体理论的研究中并取得了丰富的成果。









McGraw-Hill 1940

赛兹1940年出版的《现代固体理论》一书,标志着固体物理的成熟并形成了固体物理理论的第一个范式。（建立在对晶体认识的基础上）

这本书是固体物理学作为独立学科出现的奠基性著作，目前我们固体物理课程所讲述的固体理论依然处在该书建立的体系中，**它处理问题的基本方法取得了辉煌的成就，并一直普遍使用到今天，而且还将会继续使用下去，**因此**理解并掌握好这种方法是学好固体物理课的关键之处。**(适用条件，使用方法，局限性等），

固体理论的第一个范式：固体物理研究周期结构中波的传播问题，无论是弹性波、电磁波，de-Broglie波相关理论的共同点是：**充分利用了晶体结构中的平移对称性，使问题得到简化，因此作为实空间Fourier变换而得到的波矢空间的重要性就被突出出来，波矢空间的基本单位是布里渊区，因此了解布里渊区内部和边界上的能量波矢关系就成为解决具体问题的关键。**

有人（Hall）比喻：

倒易空间和布里渊区是固体物理的

Maxwell方程

该理论体系研究的主要成果：

弹性波在周期势场中的传播——**晶格动力学**；

X射线在周期势场中的传播——**X射线衍射学；**

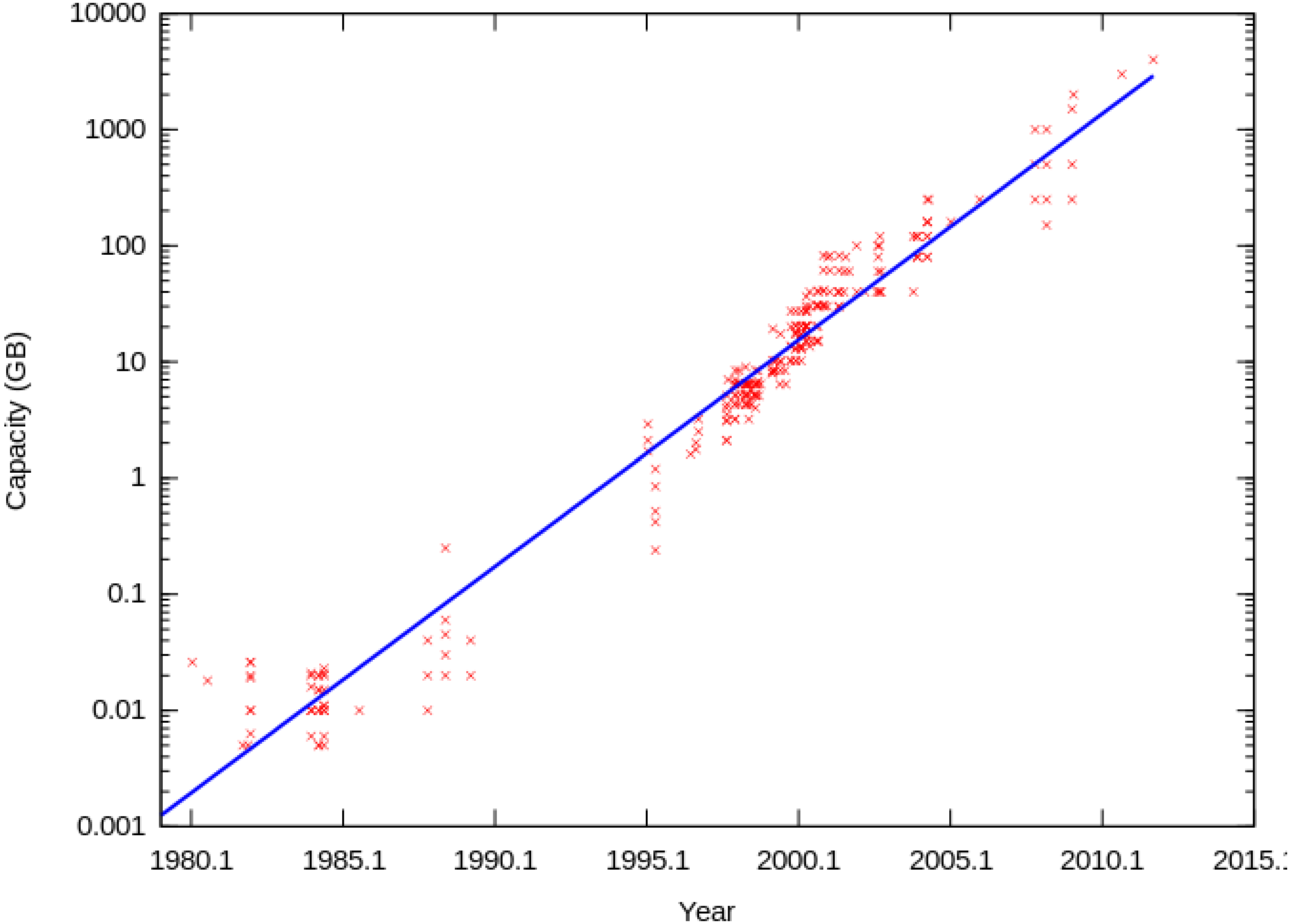
电子在周期势场中的传播—— **能带论；**

应用上述理论可以正确地阐明晶体的电性质、磁性质、光学性质，热性质、超导性等各种物理性质，并开启了晶体材料在各种新技术中，特别是信息技术中的应用，使固体物理在二十世纪后半叶得到了飞速的发展。

今天可以毫不夸大地说：已经成为当代科学重要支柱、高科技源泉的固体物理学是二十世纪物理学中**发展最快、影响最大、领域最广**的一门学科。统计表明，现今四分之一的物理工作者从事固体物理研究，每年发表的物理科学论文中三分之一属于固体物理领域。

Shockley,*Bardeen,Brattain1947年12月23日发现了半导体晶体管的放大效应，由此带来的巨大影响是固体物理和高科技发展关系的最典型的说明。1950年晶体三极管，1954年硅晶体管，1959年集成电路，之后大规模集成电路，超大规模集成电路相继问世，极大地推动了计算机的发展，促成了人类历史上的第3次技术革命。

固体物理促进高技术发展的实例：硬磁盘的发展



2013年

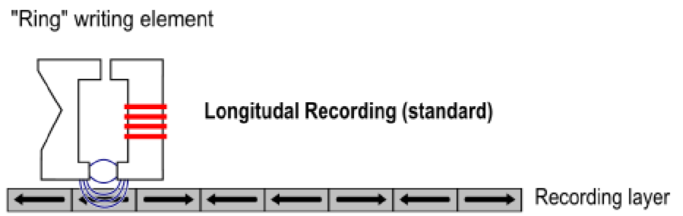
存储密度>
1 Tbit/in^2

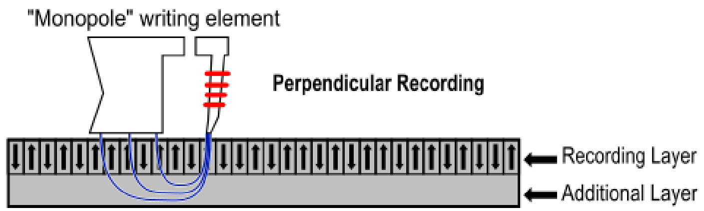
1G = 10^9

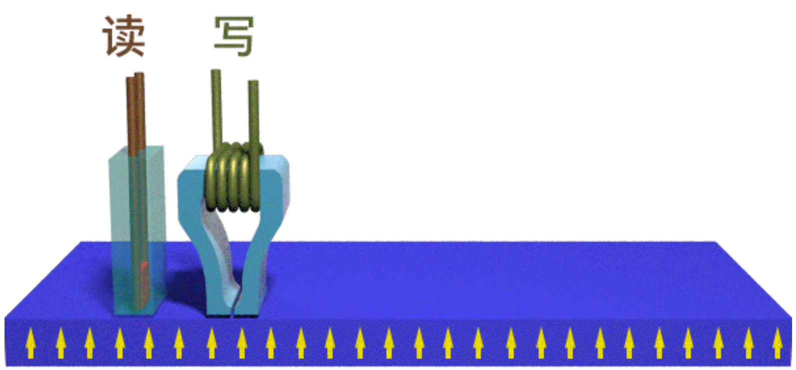
1T = 10^{12}

in = 2.54cm

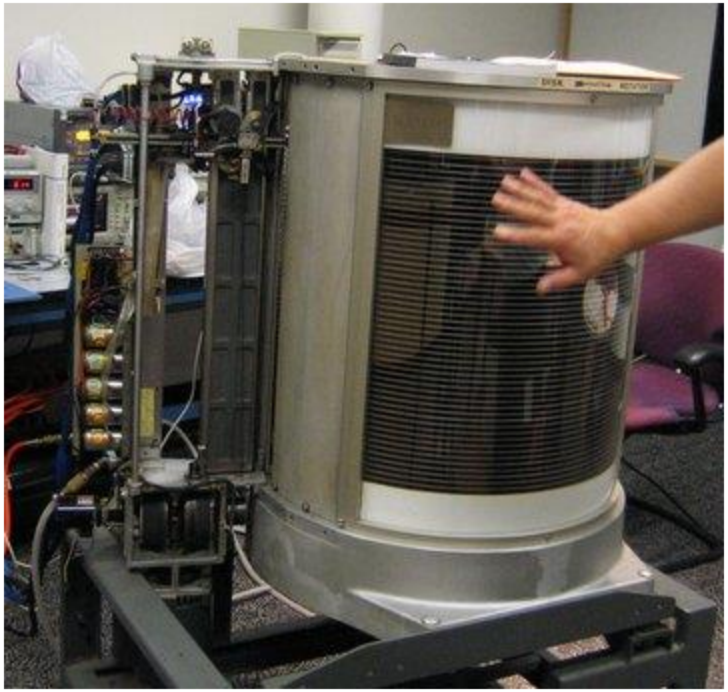
数字磁记录原理图







magnetic recording

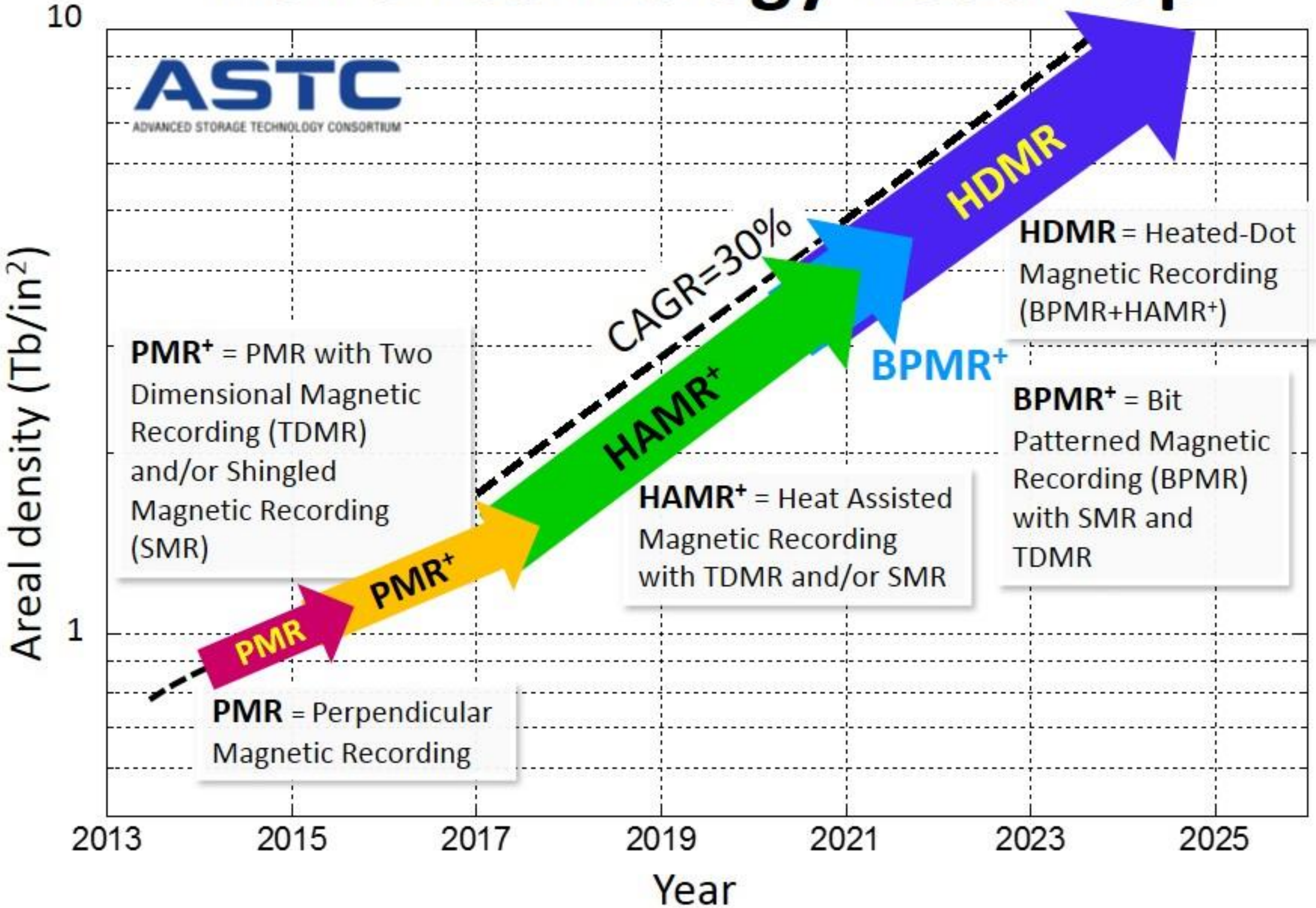


1956: IBM 350, 5 MB

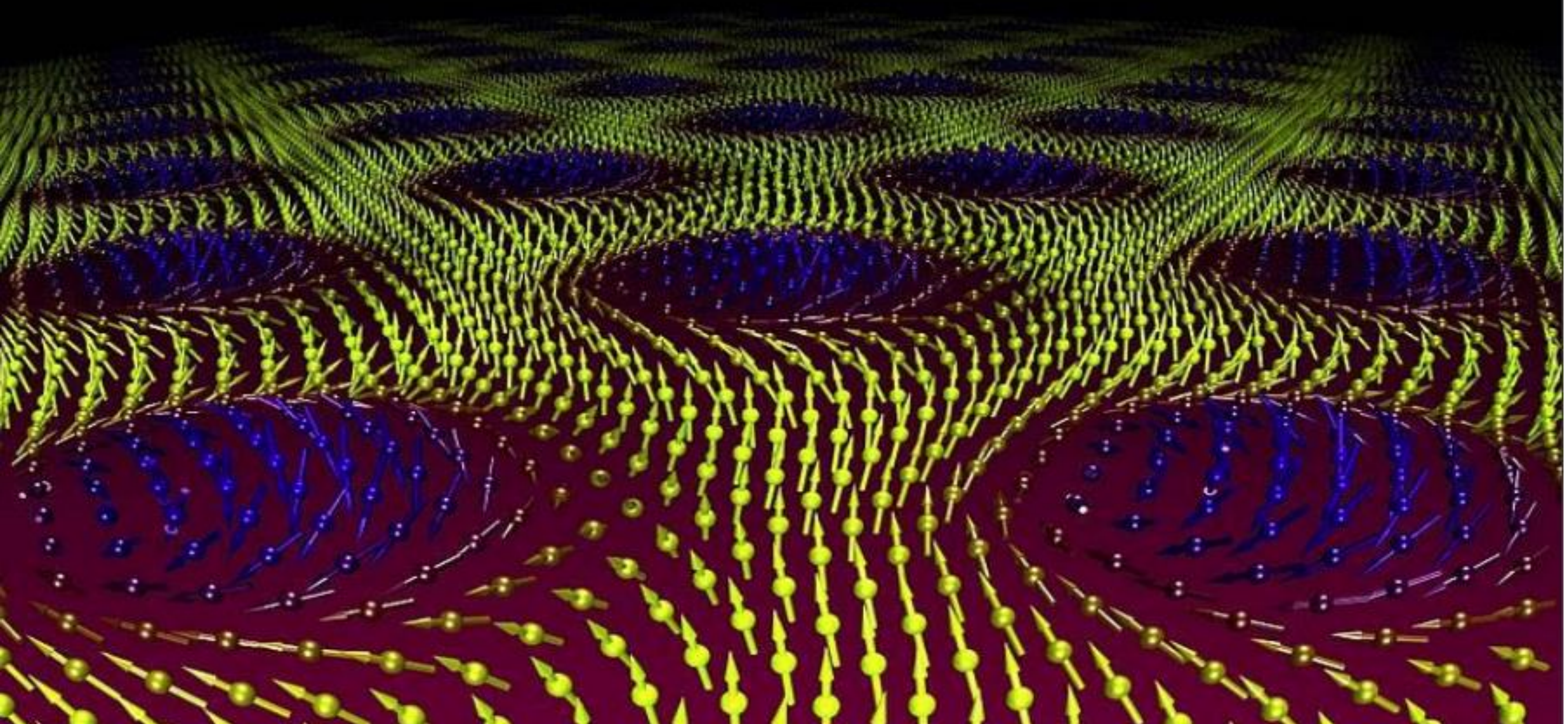
Ultrastar He硬盘: 18 TB

2021

ASTC Technology Roadmap

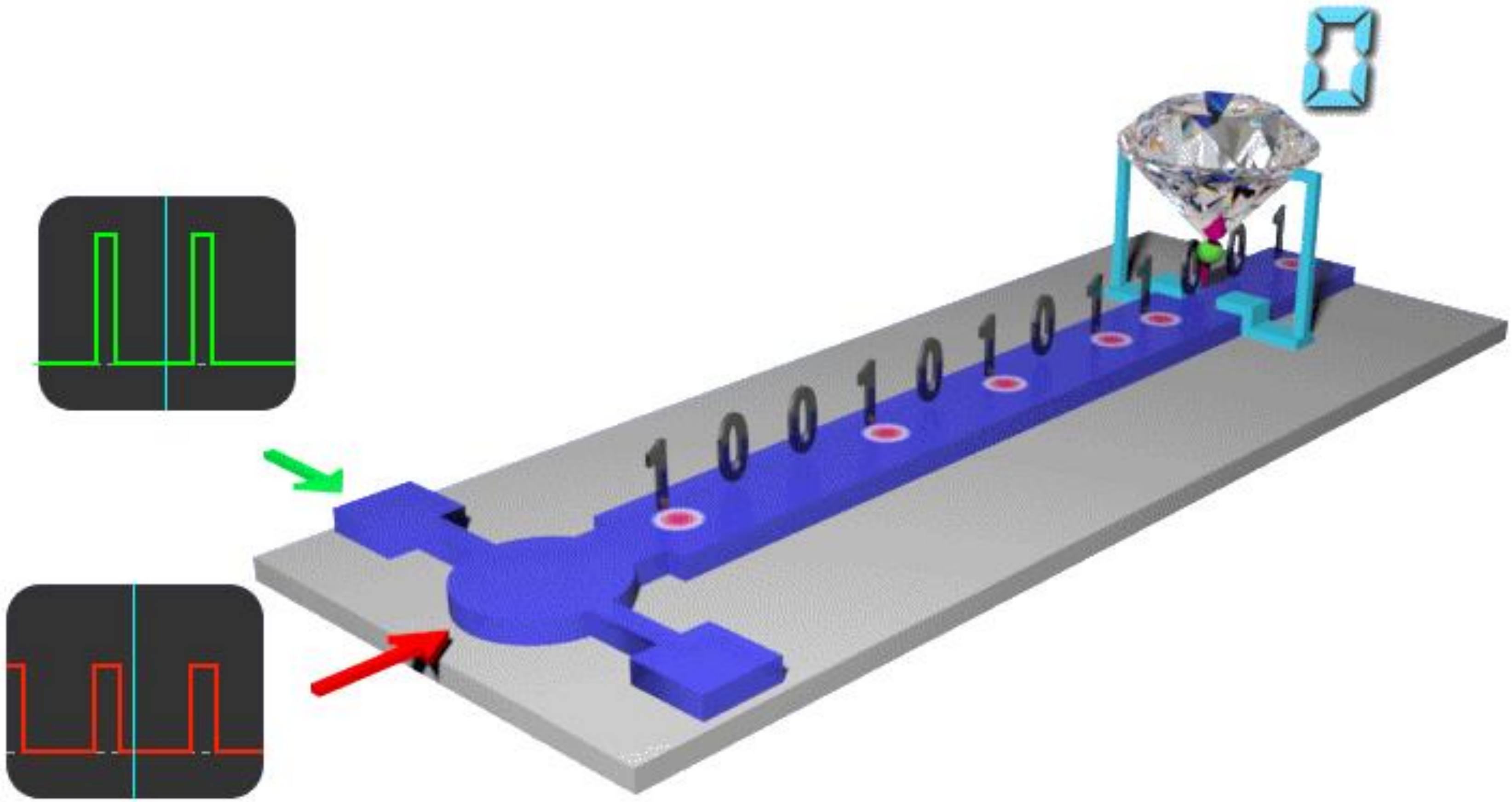


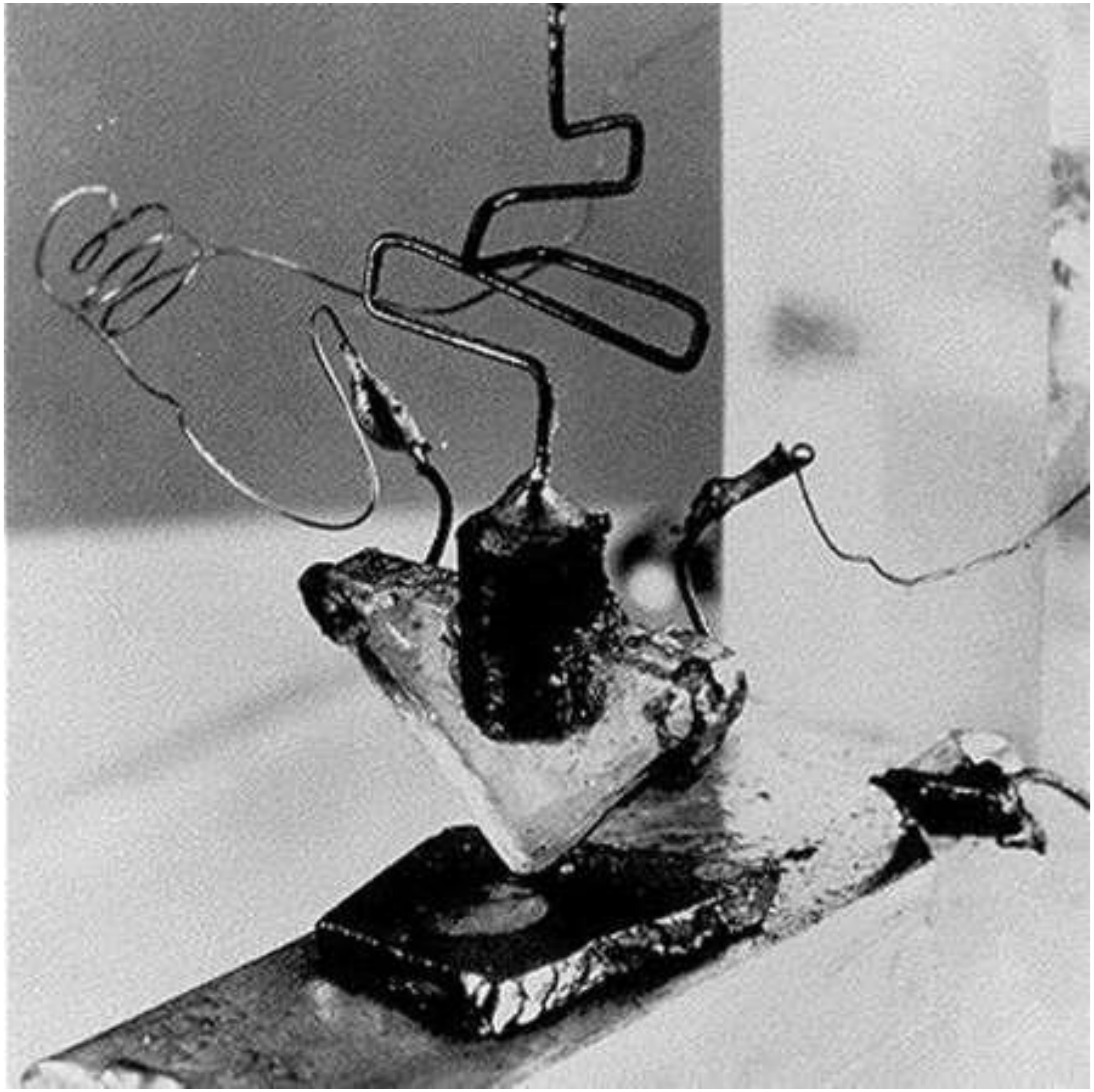
Skyrmion-斯格明子



Mühlbauer et al., (2009)

Skyrmion-race track model

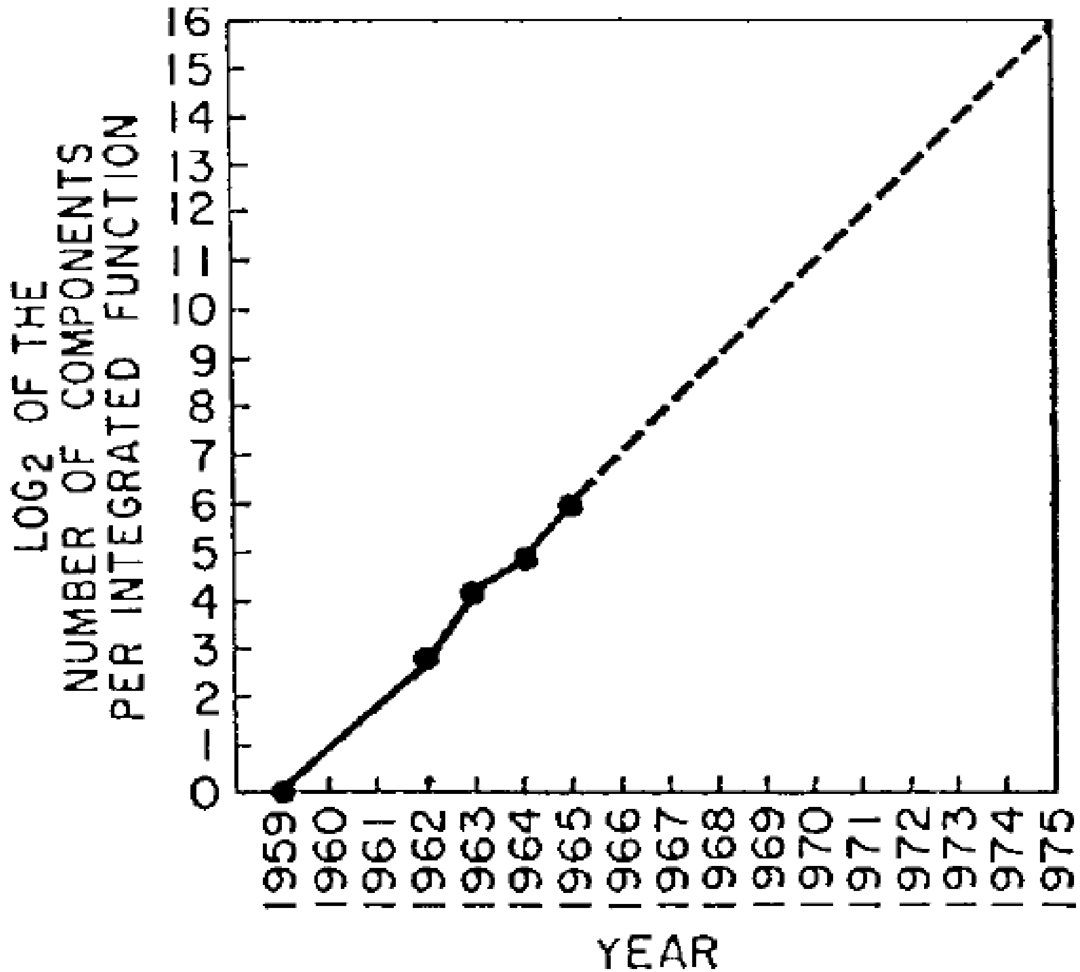




The first solid-state transistor
(Bardeen, Brattain & Shockley, 1947)

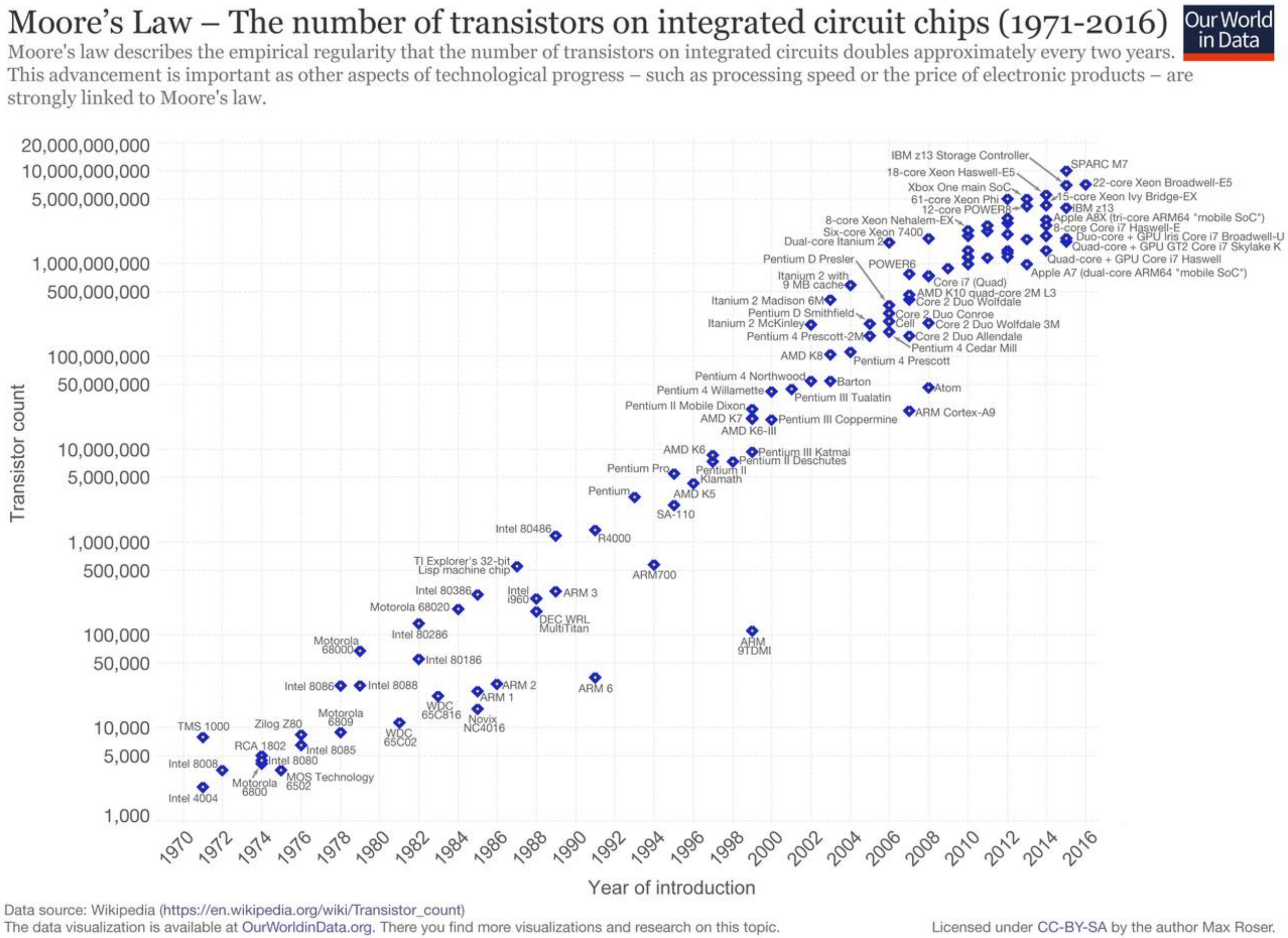
Cramming More Components onto Integrated Circuits

GORDON E. MOORE, LIFE FELLOW, IEEE



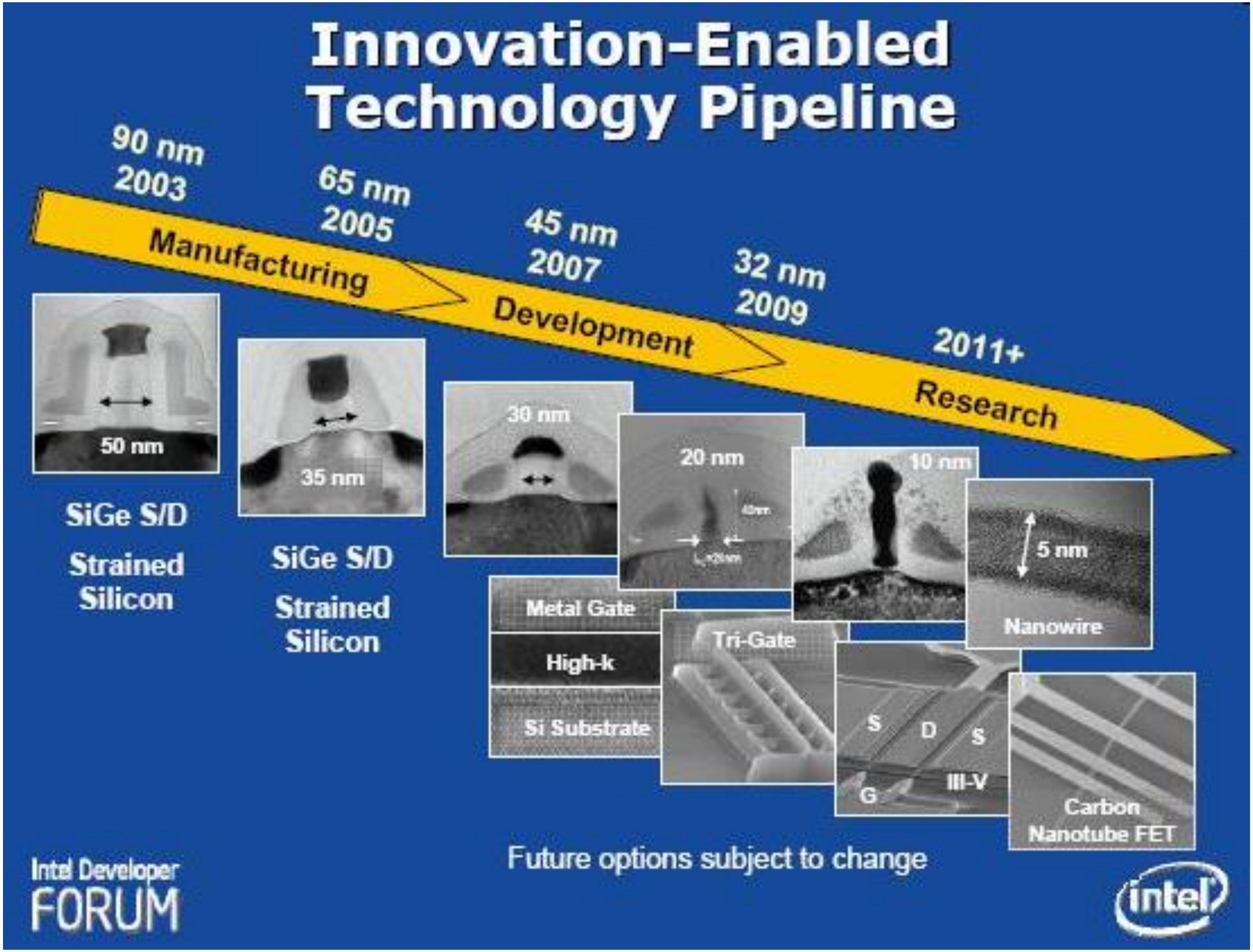
Electronics 1965

Moore's Law

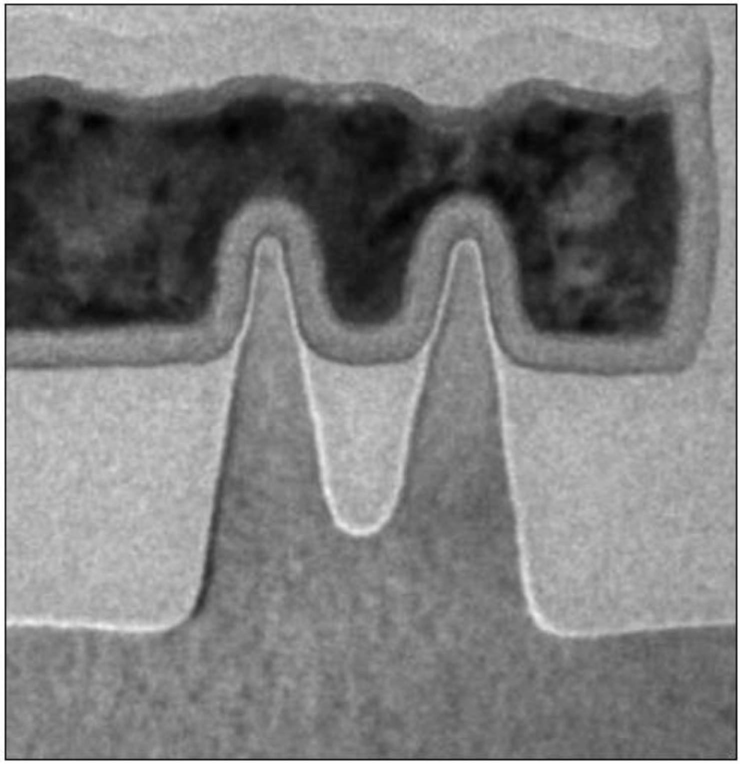


Moore's Law – The number of transistors on integrated circuit chips (1971-2016)
Our World in Data
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.
Transistor count
20,000,000,000
10,000,000,000
5,000,000,000
1,000,000,000
500,000,000
100,000,000
50,000,000
10,000,000
5,000,000
1,000,000
500,000
100,000
50,000
10,000
5,000
1,000
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
Year of introduction
IBM z13 Storage Controller
SPARC M7
18-core Xeon Haswell-E5
22-core Xeon Broadwell-E5
Xbox One main SoC
15-core Xeon Ivy Bridge-EX
61-core Xeon Phi
IBM z13
12-core POWER8
Apple A8X (tri-core ARM64 "mobile SoC")
8-core Xeon Nehalem-EX
8-core Core i7 Haswell-E
Six-core Xeon 7400
Duo-core + GPU Iris Core i7 Broadwell-U
Dual-core Itanium 2
Quad-core + GPU GT2 Core i7 Skylake K
Pentium D Presler
POWER6
Quad-core + GPU Core i7 Haswell
Itanium 2 with 9 MB cache
Apple A7 (dual-core ARM64 "mobile SoC")
Core i7 (Quad)
AMD K10 quad-core 2M L3
Itanium 2 Madison 6M
Core 2 Duo Wolfdale
Pentium D Smithfield
Core 2 Duo Conroe
Itanium 2 McKinley
Cell
Core 2 Duo Wolfdale 3M
Pentium 4 Prescott-2M
Core 2 Duo Allendale
Pentium 4 Cedar Mill
AMD K8
Pentium 4 Prescott
Pentium 4 Northwood
Barton
Atom
Pentium 4 Willamette
Pentium III Tualatin
Pentium II Mobile Dixon
AMD K7
Pentium III Coppermine
ARM Cortex-A9
AMD K6-III
AMD K6
Pentium III Katmai
Pentium II Deschutes
Pentium Pro
Pentium II
Klamath
Pentium
AMD K5
SA-110
Intel 80486
R4000
TI Explorer's 32-bit Lisp machine chip
ARM700
Intel 80386
Intel i960
ARM 3
Motorola 68020
DEC WRL MultiTitan
Intel 80286
ARM 9TDMI
Motorola 68000
Intel 80186
Intel 8086
Intel 8088
ARM 2
ARM 1
ARM 6
WDC 65C816
Novix NC4016
TMS 1000
Zilog Z80
Motorola 6809
WDC 65C02
RCA 1802
Intel 8085
Intel 8008
Intel 8080
MOS Technology 6502
Motorola 6800
Intel 4004
Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.
Licensed under CC-BY-SA by the author Max Roser.

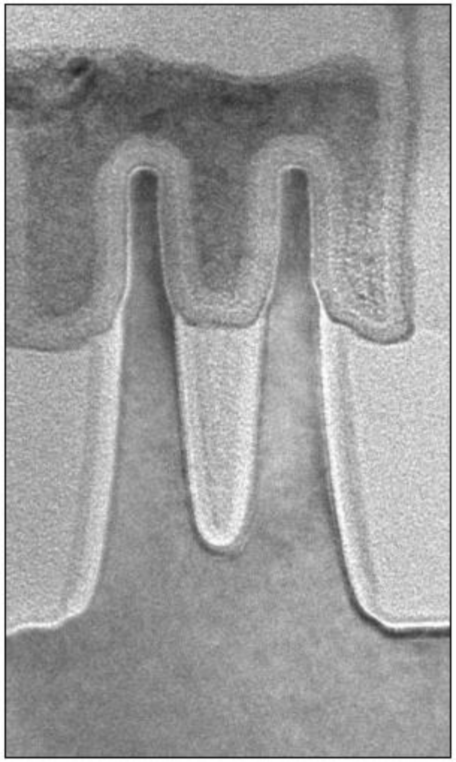
Moore's Law


Innovation-Enabled Technology Pipeline
90 nm 2003
65 nm 2005
45 nm 2007
32 nm 2009
2011+
Manufacturing
Development
Research
50 nm
35 nm
30 nm
20 nm
10 nm
5 nm
SiGe S/D
Strained Silicon
SiGe S/D
Strained Silicon
Metal Gate
High-k
Si Substrate
Tri-Gate
S
D
S
G
III-V
Nanowire
Carbon Nanotube FET
Future options subject to change
Intel Developer FORUM
intel

Transistor Fin Improvement



22 nm 1st Generation
Tri-gate Transistor

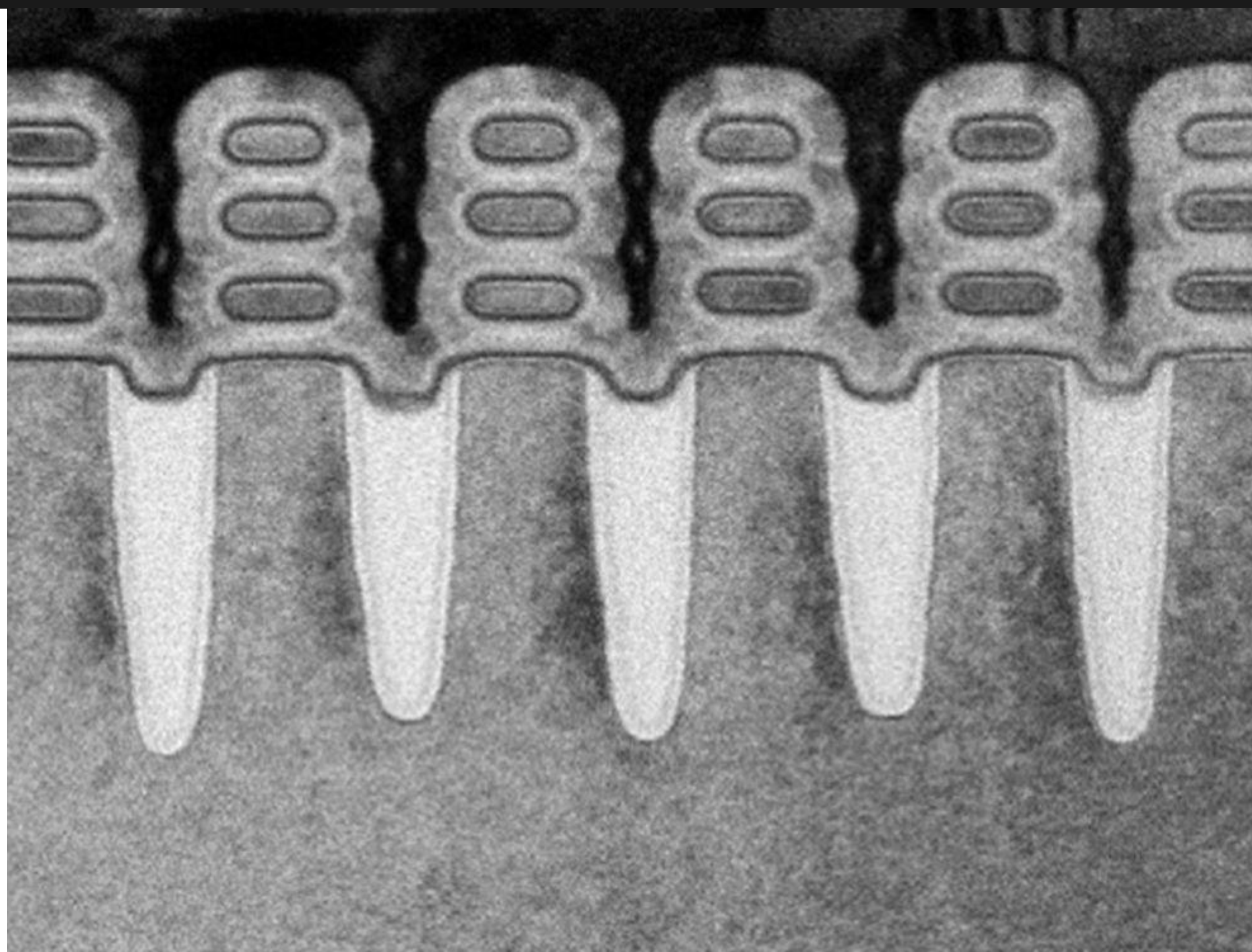


14 nm 2nd Generation
Tri-gate Transistor

FEATURE SEMICONDUCTORS

THE NANOSHEET TRANSISTOR IS THE NEXT (AND MAYBE LAST) STEP IN MOORE'S LAW

Nanosheet devices are scheduled for the 3-nanometer node as soon as 2021



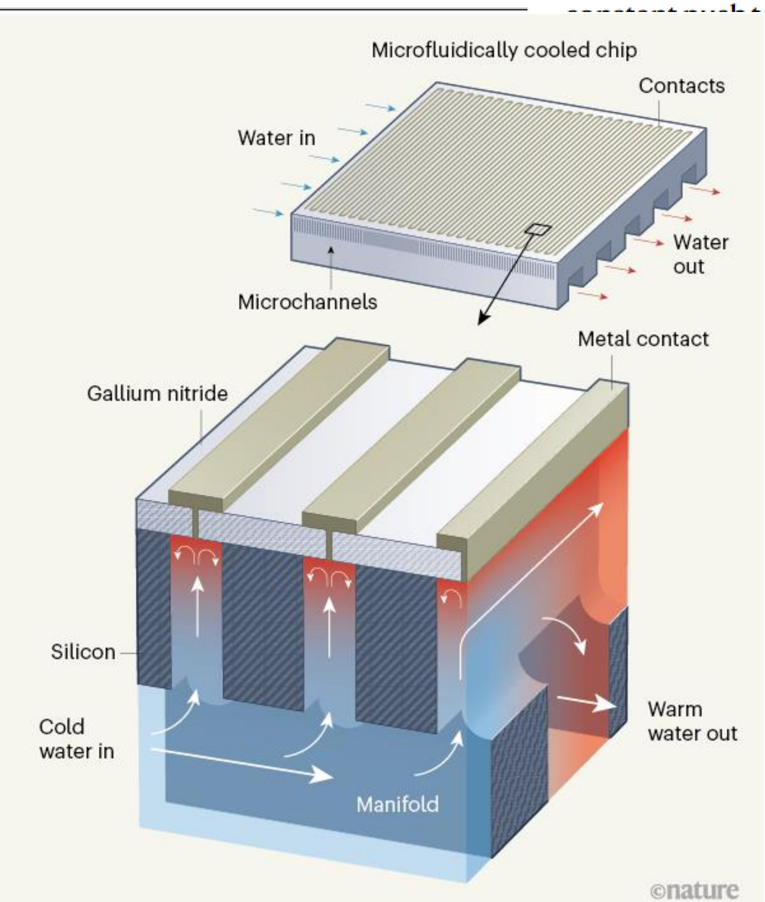
Co-designing electronics with microfluidics for more sustainable cooling

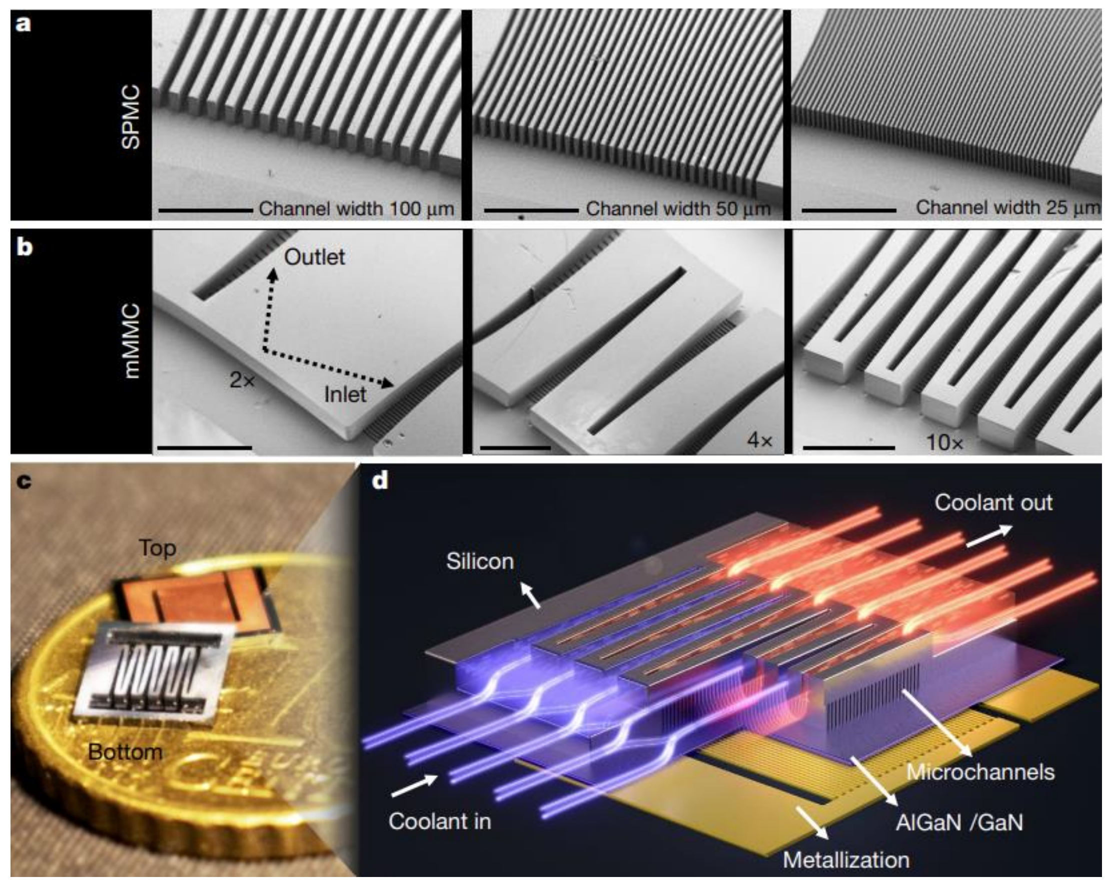
微流管冷却芯片

https://doi.org/10.1038/s41586-020-2666-1
Received: 4 March 2020
Accepted: 10 July 2020
Published online: 9 September 2020

Remco van Erp[1], Reza Soleimanzadeh[1], Luca Nela[1], Georgios Kampitsis[1] & Elison Matioli[1]✉

Thermal management is one of the main challenges for the future of electronics[1–5]. With the ever-increasing rate of data generation and communication, as well as the





MORE THAN MOORE

BY M. MITCHELL WALDROP

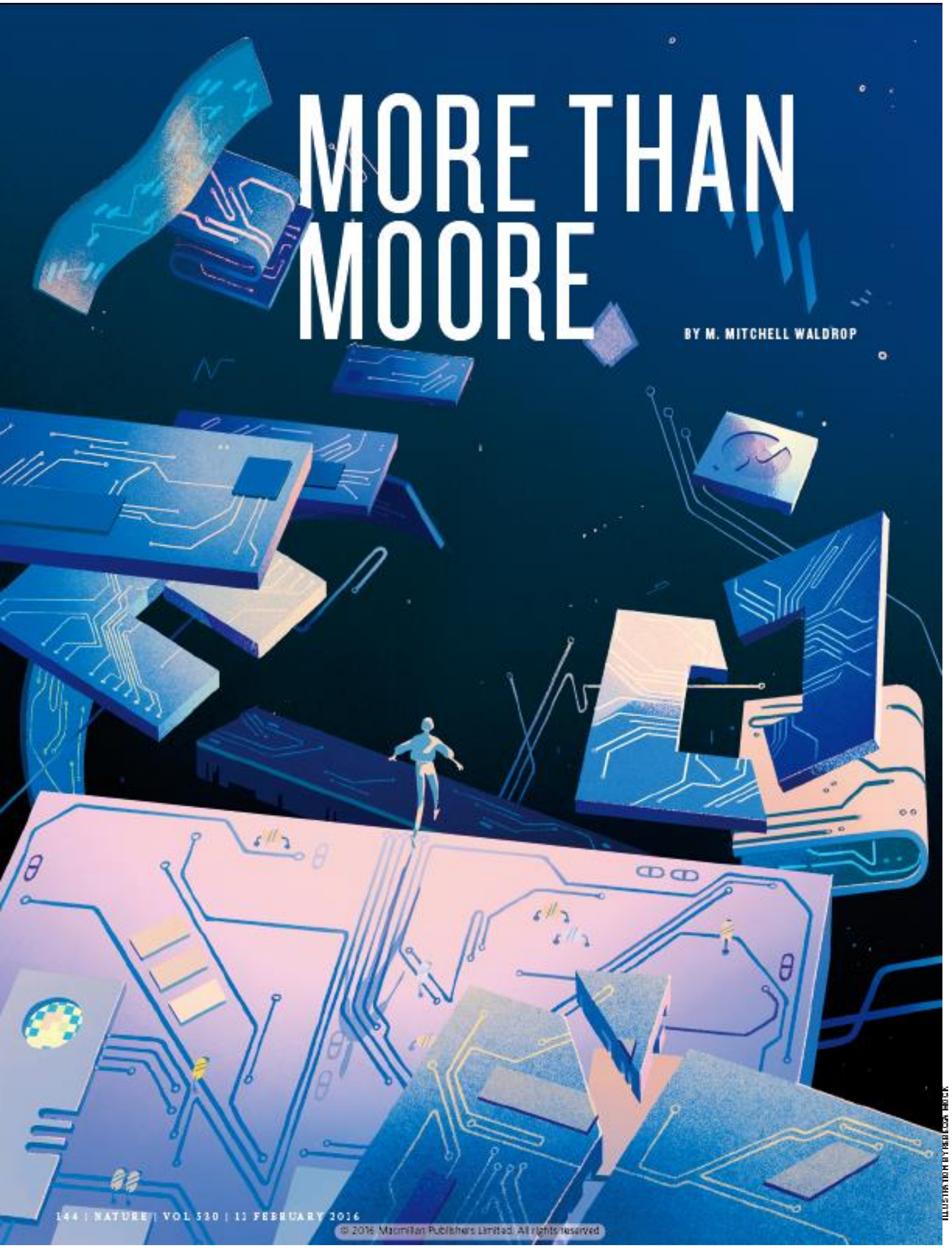


ILLUSTRATION BY REBECCA MOCK

THE SEMICONDUCTOR INDUSTRY WILL SOON ABANDON ITS PURSUIT OF MOORE'S LAW. NOW THINGS COULD GET A LOT MORE INTERESTING.

Next month, the worldwide semiconductor industry will formally acknowledge what has become increasingly obvious to everyone involved: Moore's law, the principle that has powered the information-technology revolution since the 1960s, is nearing its end.

A rule of thumb that has come to dominate computing, Moore's law states that the number of transistors on a microprocessor chip will double every two years or so — which has generally meant that the chip's performance will, too. The exponential improvement that the law describes transformed the first crude home computers of the 1970s into the sophisticated machines of the 1980s and 1990s, and from there gave rise to high-speed Internet, smartphones and the wired-up cars, refrigerators and thermostats that are becoming prevalent today.

None of this was inevitable: chipmakers deliberately chose to stay on the Moore's law track. At every stage, software developers came up with applications that strained the capabilities of existing chips; consumers asked more of their devices; and manufacturers rushed to meet that demand with next-generation chips. Since the 1990s, in fact, the semiconductor industry has released a research road map every two years to coordinate what its hundreds of manufacturers and suppliers are doing to stay in step with the law — a strategy sometimes called More Moore. It has been largely thanks to this road map that computers have followed the law's exponential demands.

Not for much longer. The doubling has already started to falter, thanks to the heat that is unavoidably generated when more and more silicon circuitry is jammed into the same small area. And some even more fundamental limits loom less than a decade away. Top-of-the-line microprocessors currently have circuit features that are around 14 nanometres across, smaller than most viruses. But by the early 2020s, says Paolo Gargini, chair of the road-mapping organization, "even with super-aggressive efforts, we'll get to the 2–3-nanometre limit, where features are just 10 atoms across. Is that a device at all?" Probably not — if only because at that scale, electron behaviour will be governed by quantum uncertainties that will make transistors hopelessly unreliable. And despite vigorous research efforts, there is no obvious successor to today's silicon technology.

The industry road map released next month will for the first time lay out a research and development plan that is not centred on Moore's law. Instead, it will follow what might be called the More than Moore strategy: rather than making the chips better and letting the applications follow, it will start with applications — from smartphones and supercomputers to data centres in the cloud — and work downwards to see what chips are needed to support them. Among those chips will be new generations of sensors, power-management circuits and other silicon devices required by a world in which computing is increasingly mobile.

The changing landscape, in turn, could splinter the industry's long tradition of unity in pursuit of Moore's law. "Everybody is struggling with what the road map actually means," says Daniel Reed, a computer scientist and vice-president for research at the University of Iowa in Iowa City. The Semiconductor Industry Association (SIA) in Washington DC, which represents all the major US firms, has already said that it will cease its participation in the road-mapping effort once the report is out, and will instead pursue its own research and development agenda.

Everyone agrees that the twilight of Moore's law will not mean the end of progress. "Think about what happened to airplanes," says Reed. "A Boeing 787 doesn't go any faster than a 707 did in the 1950s — but they are very different airplanes", with innovations ranging from fully electronic controls to a carbon-fibre fuselage. That's what will happen with computers, he says: "Innovation will absolutely continue — but it will be more nuanced and complicated."

LAYING DOWN THE LAW

The 1965 essay[1] that would make Gordon Moore famous started with a meditation on what could be done with the still-new technology of integrated circuits. Moore, who was then research director of Fairchild Semiconductor in San Jose, California, predicted wonders such as home computers, digital wristwatches, automatic cars and "personal portable communications equipment" — mobile phones. But the heart of the essay was Moore's attempt to provide a timeline for this future. As a measure of a microprocessor's computational power, he looked at transistors, the on–off switches that make computing digital. On the basis of achievements by his company and others in the previous few years, he estimated that the number of transistors and other electronic components per chip was doubling every year.

Moore, who would later co-found Intel in Santa Clara, California, underestimated the doubling time; in 1975, he revised it to a more realistic two years[2]. But his vision was spot on. The future that he predicted started to arrive in the 1970s and 1980s, with the advent of microprocessor-equipped consumer products such as the Hewlett Packard hand calculators, the Apple II computer and the IBM PC. Demand for such products was soon exploding, and manufacturers were engaging in a brisk competition to offer more and more capable chips in smaller and smaller packages (see 'Moore's lore').

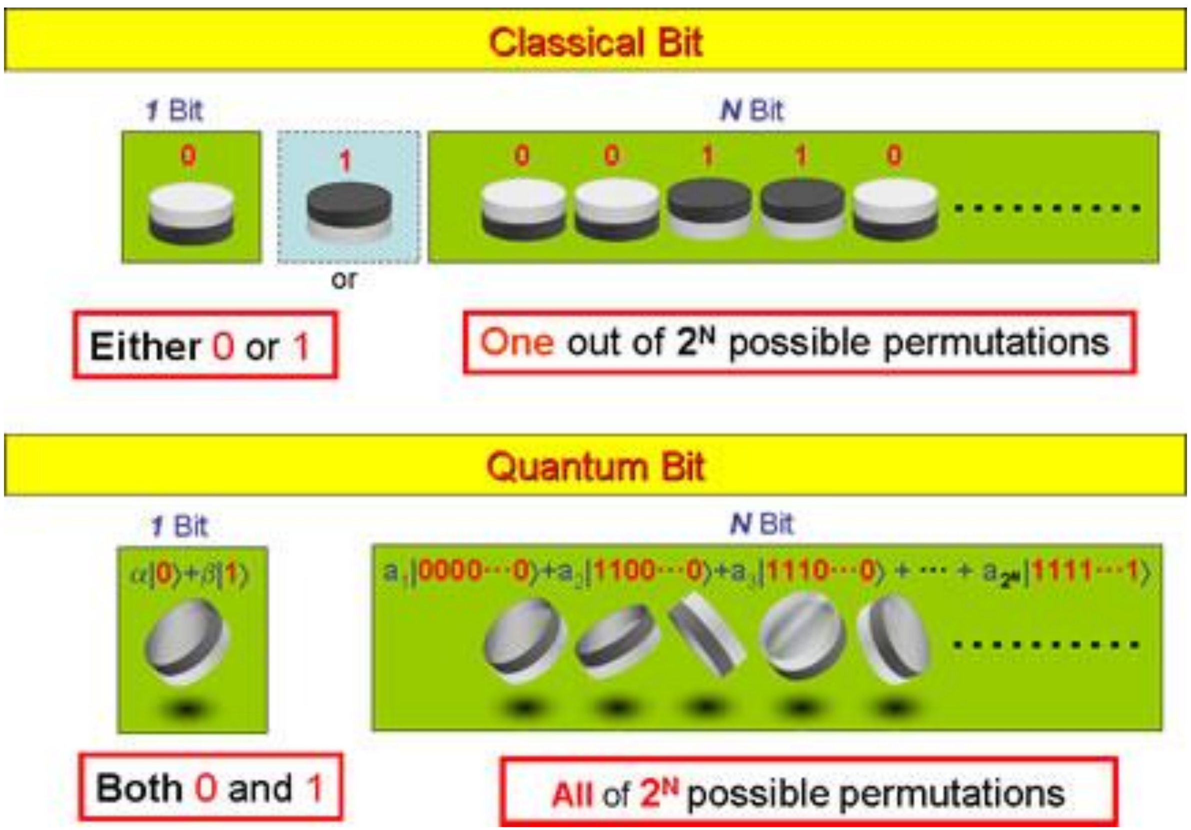
This was expensive. Improving a microprocessor's performance meant scaling down the elements of its circuit so that more of them could be packed together on the chip, and electrons could move between them more quickly. Scaling, in turn, required major refinements in photolithography, the basic technology for etching those microscopic elements onto a silicon surface. But the boom times were such that this hardly mattered: a self-reinforcing cycle set in. Chips were so versatile that manufacturers could make only a few types — processors and memory, mostly — and sell them in huge quantities. That gave them enough cash to cover the cost of upgrading their fabrication facilities, or 'fabs', and still drop the prices, thereby fuelling demand even further.

Soon, however, it became clear that this market-driven cycle could not sustain the relentless cadence of Moore's law by itself. The chip-making process was getting too complex, often involving hundreds of stages, which meant that taking the next step down in scale required a network of materials-suppliers and apparatus-makers to deliver the right upgrades at the right time. "If you need 40 kinds of equipment and only 39 are ready, then everything stops," says Kenneth Flamm, an economist who studies the computer industry at the University of Texas at Austin.

To provide that coordination, the industry devised its first road map. The idea, says Gargini, was "that everyone would have a rough estimate of where they were going, and they could raise an alarm if they saw roadblocks ahead". The US semiconductor industry launched the mapping effort in 1991, with hundreds of engineers from various companies working on the first report and its subsequent iterations, and Gargini, then the director of technology strategy at Intel, as its chair. In 1998, the effort became the International Technology Roadmap for Semiconductors, with participation from industry associations in Europe, Japan, Taiwan and South Korea. (This year's report, in keeping with its new approach, will be called the International Roadmap for Devices and Systems.)

➲ NATURE.COM
To hear more about what will come after Moore's law, visit:
go.nature.com/appjyx

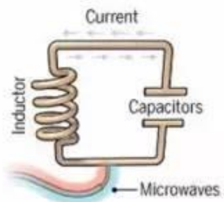
经典计算 → 量子计算


Classical Bit
1 Bit
N Bit
0
1
or
0 0 1 1 0
Either 0 or 1
One out of 2^N possible permutations
Quantum Bit
1 Bit
N Bit
$\alpha|0\rangle+\beta|1\rangle$
$a_1|0000\cdots0\rangle+a_2|1100\cdots0\rangle+a_3|1110\cdots0\rangle+\cdots+a_{2^N}|1111\cdots1\rangle$
Both 0 and 1
All of 2^N possible permutations

实用量子计算的可能实现技术

中国科学技术大学
University of Science and Technology of China

超导回路(superconducting loops)



一束无电阻的电流绕一个电路回路来回振荡。一束被注入的微波信号可以激励该电流进入叠加态。

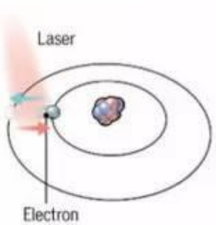
寿命 0.00005秒
逻辑成功率 99.4%
纠缠数量 9

支持该技术的公司
谷歌、IBM、Quantum Circuits

优点
快速起效。可适应已有半导体工业

缺点
容易坍缩，而且必须保持低温

囚禁离子（trapped ions)



带电原子（即离子）的量子能量取决于电子的位置。使用调谐的激光冷却和囚禁离子，并将它们置于叠加态。

寿命 >1000秒
逻辑成功率 99.9%
纠缠数量 14

支持该技术的公司
ionQ

优点
非常稳定，已知实现最高的逻辑本保真度

缺点
操作慢，需要很多激光

硅量子点（silicon quantum dots）

这些「人造原子（artificial atoms）」是通过向一小片纯硅上加入一个电子而制成的。微波控制该电子的量子态。

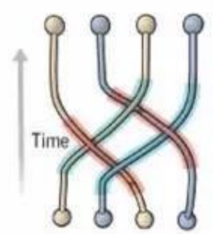
寿命 0.03秒
逻辑成功率 ~99%
纠缠数量 2

支持该技术的公司
英特尔

优点
稳定，可用已有的半导体工业开发

缺点
只有一点点纠缠，必需低温

拓扑量子比特（topological qubits）



可以在通过半导体结构引导的电子的行为中看到准粒子（quasiparticles）。它们交织的路径（braided paths）可以编码量子信息。

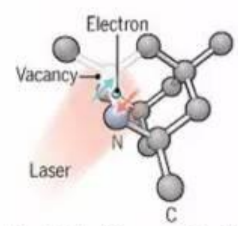
寿命 N/A
逻辑成功率 N/A
纠缠数量 N/A

支持该技术的公司
微软、贝尔实验室

优点
极大减少误差

缺点
还不确定是否存在这种技术

金刚石空位（diamond vacancies）



一个氮原子和一个空位为一个金刚石晶格加入一个电子。其量子自旋状态及其附近的碳原子核的量子自旋状态可以使用光进行控制。

寿命 10秒
逻辑成功率 99.2%
纠缠数量 6

支持该技术的公司
Quantum Diamond Technologies

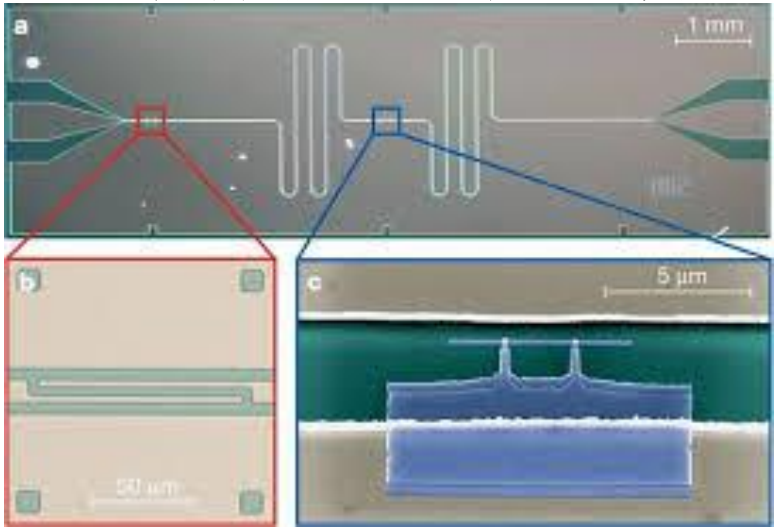
优点
可以在室温下操作

缺点
难以纠缠

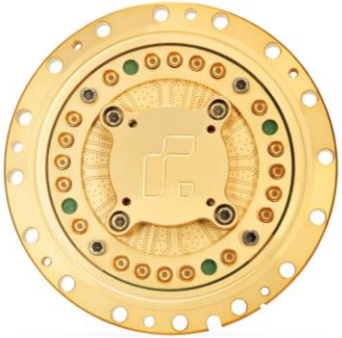
注：寿命（longevity）是指记录中单个量子比特叠加状态的相干时间；逻辑成功率是指记录中最高的在 2 个量子比特上的逻辑运算的逻辑门保真度（gate fidelity）；纠缠数量（number entangled）是指纠缠的和能够执行 2 量子比特运算的量子比特的最大数量。

超导量子计算

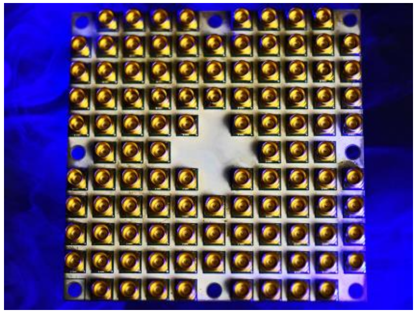
- 利用超导电路作为量子比特



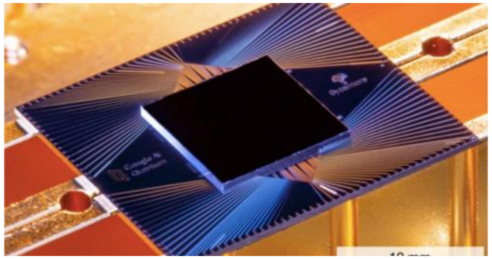
Transmon 量子比特



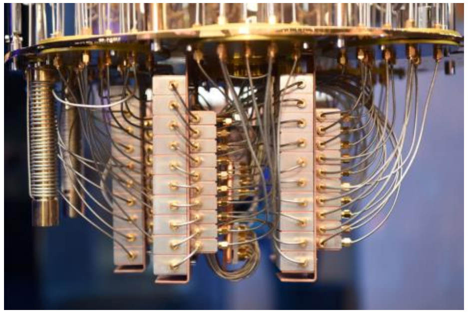
Rigetti 31 比特



英特尔 49 比特

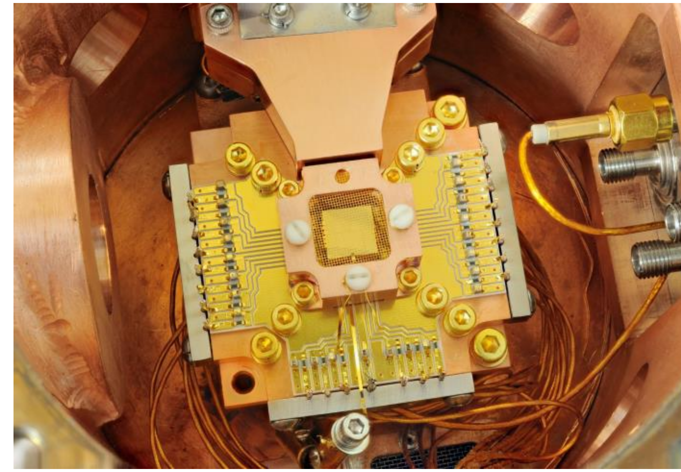


Google 54比特

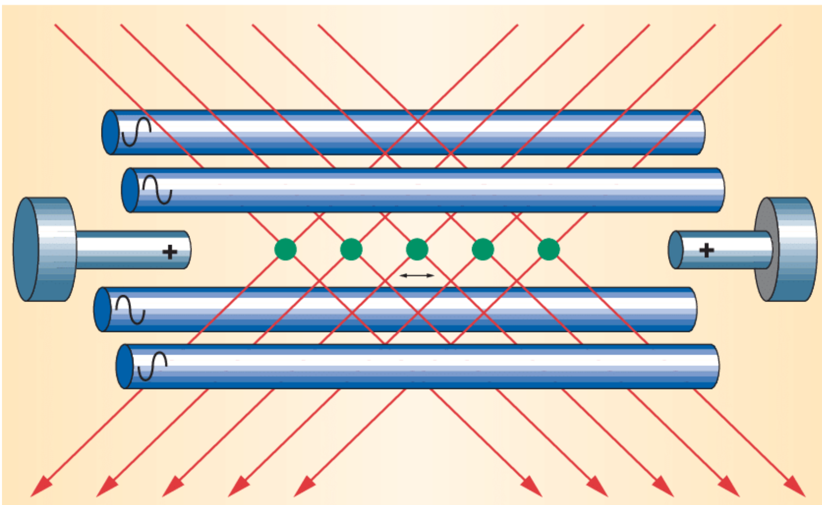


IBM 65比特

离子阱量子计算



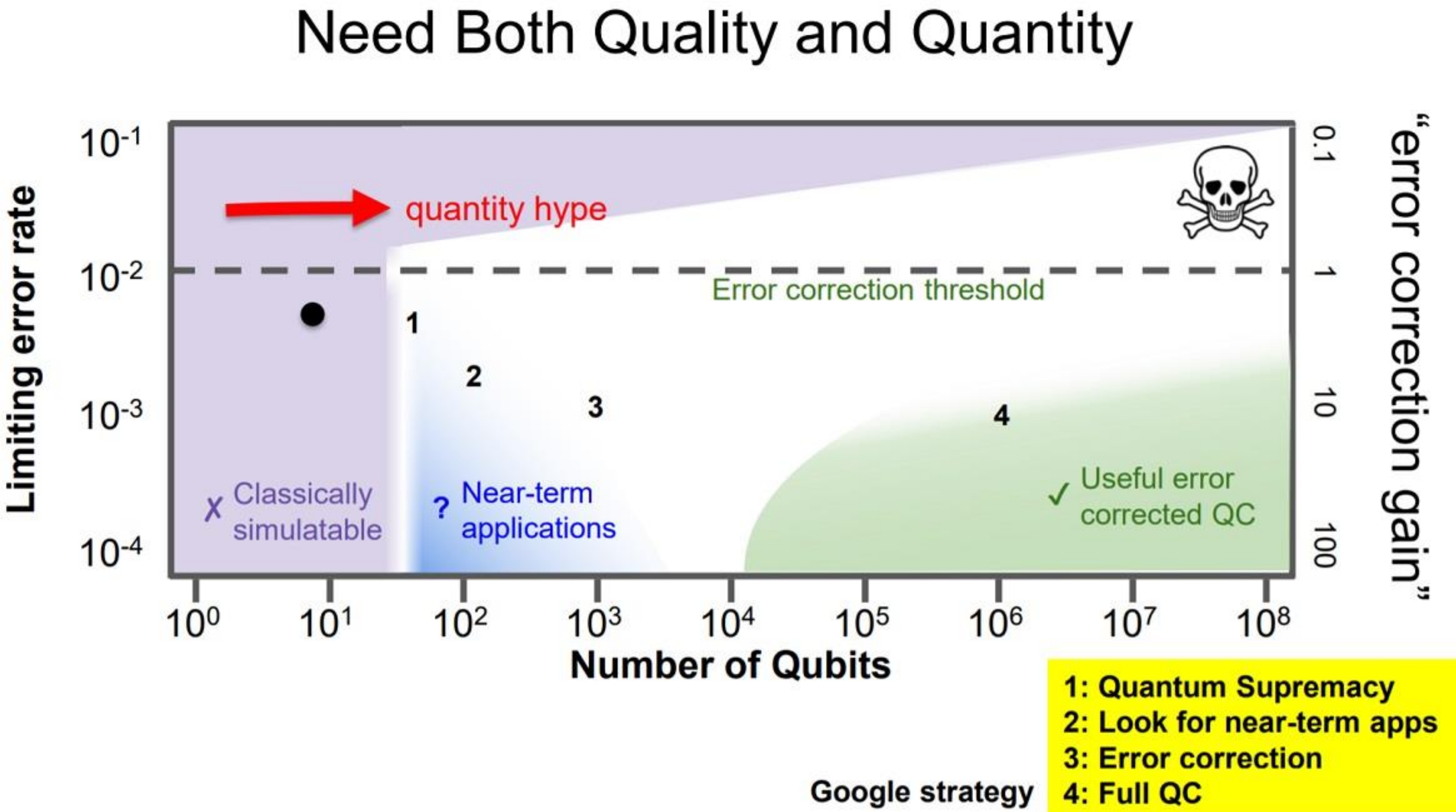
NIST，2011



- 利用微波囚禁离子作为量子比特

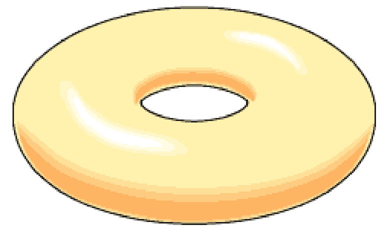
IONQ

量子纠错

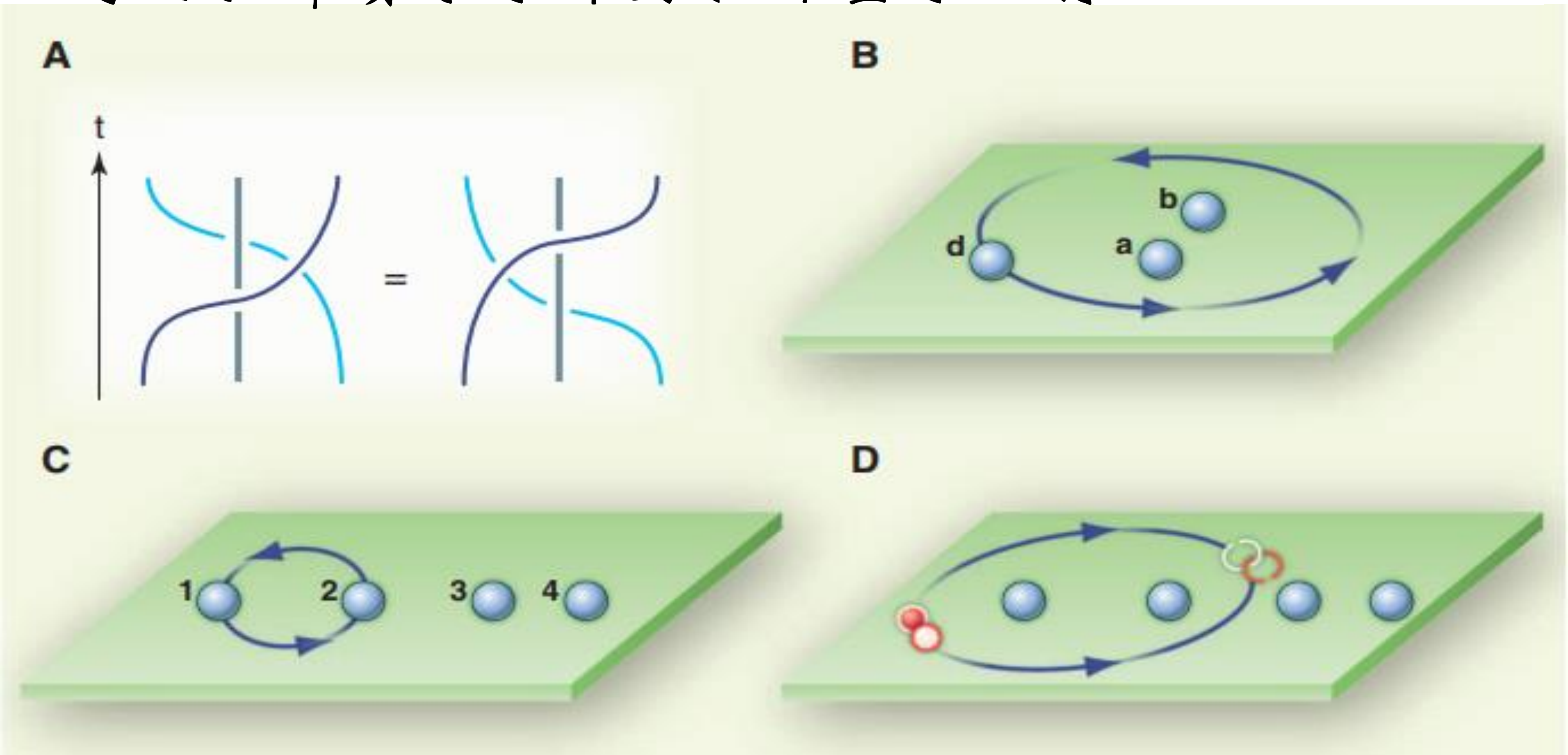


Need Both Quality and Quantity
quantity hype
Error correction threshold
1
2
3
4
Classically simulatable
Near-term applications
Useful error corrected QC
Limiting error rate
10-1
10-2
10-3
10-4
"error correction gain"
0.1
1
10
100
100
101
102
103
104
105
106
107
108
Number of Qubits
Google strategy
1: Quantum Supremacy
2: Look for near-term apps
3: Error correction
4: Full QC

拓扑量子计算

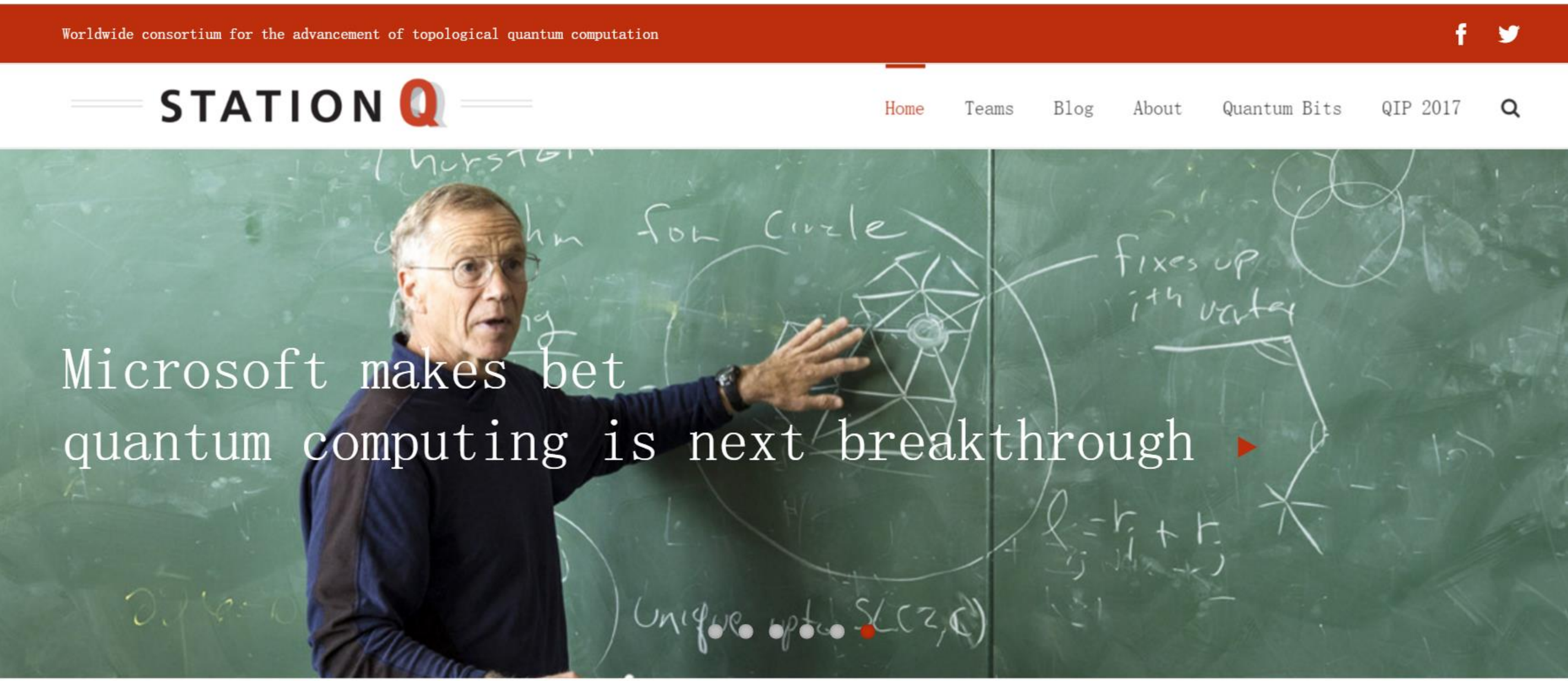


• 马约拉那费米子作为拓扑量子比特



不同方式交换拓扑量子比特会产生不同结果

微软公司的量子计算梦想



上世纪六七十年代后，固体物理的发展更为迅速，不但晶体材料的研究更加完美，而且逐渐走出大块晶体的范畴，开始了对微细材料和无序固体的开发和利用，新发现、新进展接踵而来，

1973年**非晶**态金属薄膜商品化；

1982年在人工合成材料中发现**准晶体**；

1985年发现了以C_{60}为代表的**团簇**化合物；

1986年新型**高温超导**材料的发现；

1988年发现**巨磁电阻**效应(GMR)；

1991年发现碳纳米管；

1994年发现**庞磁电阻**效应(CMR)；

1995年**隧穿磁阻(TMR)** 的发现；

2004年发现**石墨烯**(graphene)

2007年发现**拓扑绝缘体**(topological insulator)

2008年发现**铁基超导体**(pnictide superconductors)

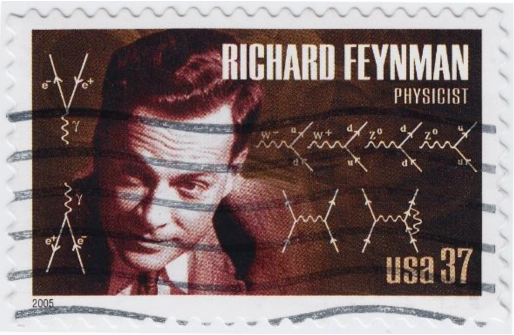
还应特别指出：这个期间中，人工微结构材料和微器件研究取得重大进展，过去，新材料制造方面的工作虽然也包括人工合成、人工提纯和人工拉制单晶等，但所得到的材料还是自然界中可能存在的，只是通过人工条件得到比自然条件下某种性能更优异的材料。20世纪70年代开始的人工超晶格材料的研究，则开创了完全由人工设计和制备全新材料的新纪元，这些材料的性能往往可以从理论上预先估计，从而有目的的进行研究。它得到的是全新的材料——人类智能的结晶，一维量子势阱和巨磁电阻效应就是在超晶格材料中发现的。

1959年，著名的诺贝尔奖得主费曼（Richard Feynman）就设想：

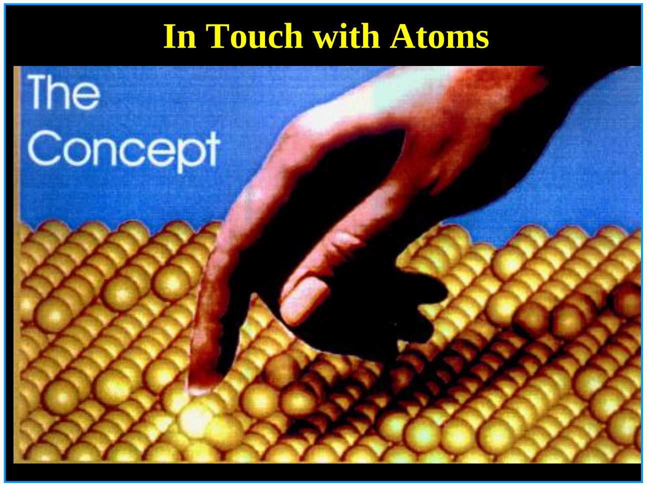
“如果有一天人们可以按照自己的意志排列原子和分子，那会产生什么样的奇迹！”，

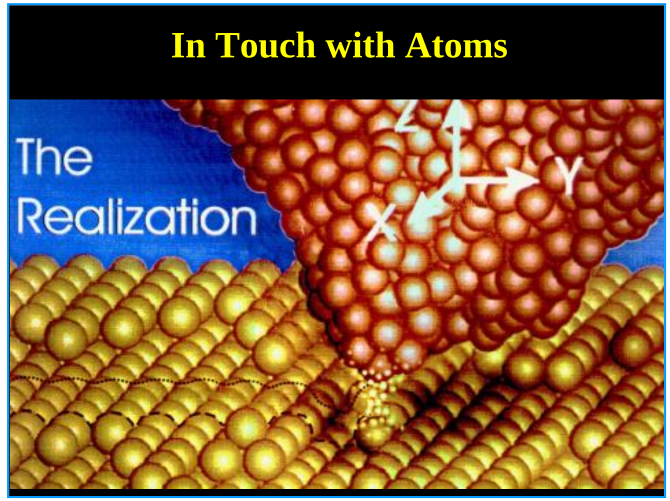
“毫无疑问，如果我们对细微尺度的事物加以控制的话，将大大扩充我们可以获得物性的范围”，

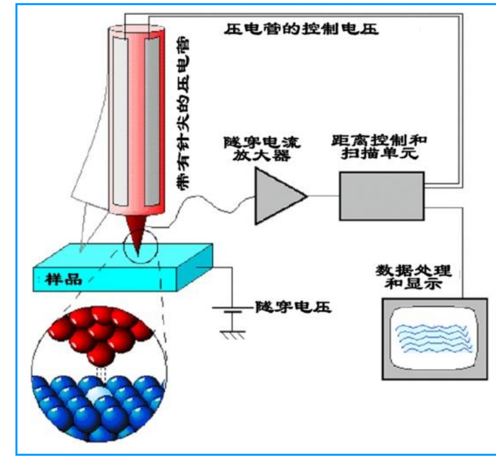
如今，费曼的预言已经初步实现：我们已能够制备包括几十个到几万个原子的纳米粒子，并把它们作为基本构成单元，适当排列成一位量子线、二维量子面和三维纳米固体。

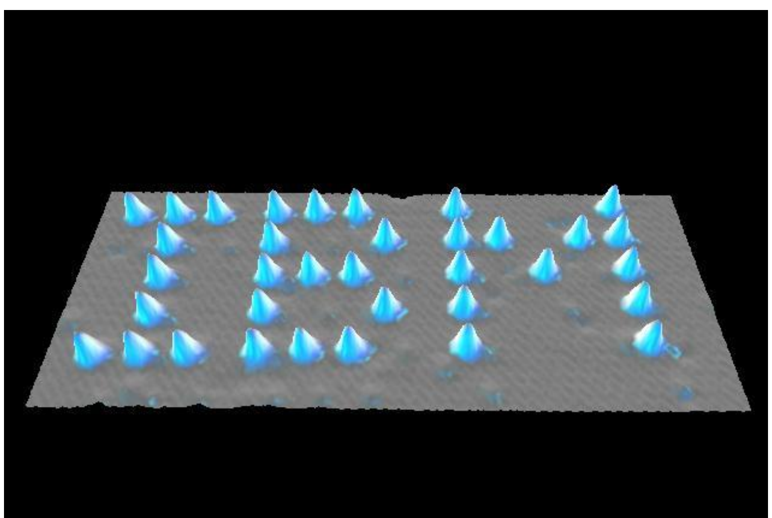


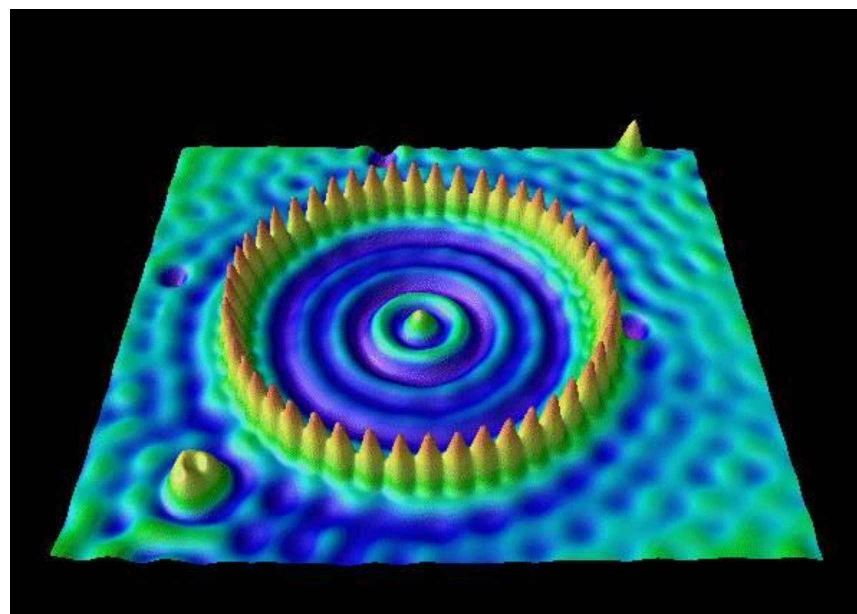
操纵原子

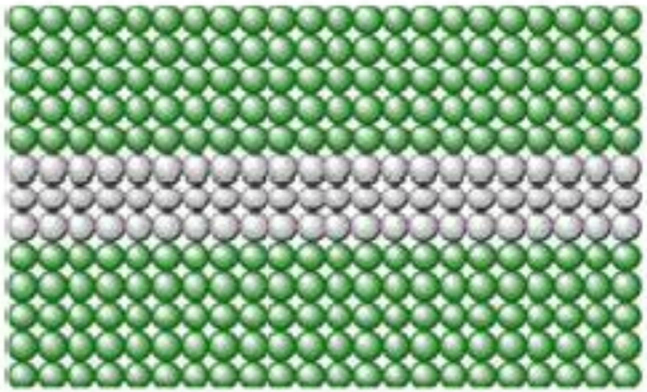

In Touch with Atoms
The Concept


In Touch with Atoms
The Realization
Z
Y
X


压电管的控制电压
带有针尖的压电管
隧穿电流放大器
距离控制和扫描单元
数据处理和显示
样品
隧穿电压



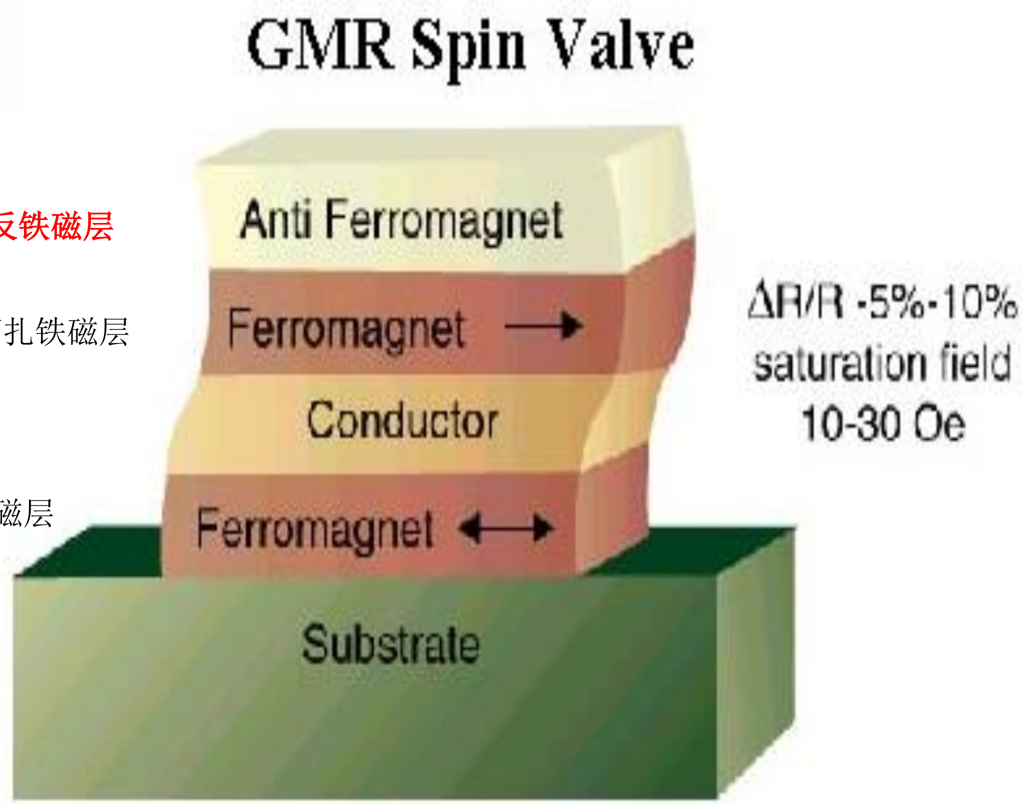




反铁磁层

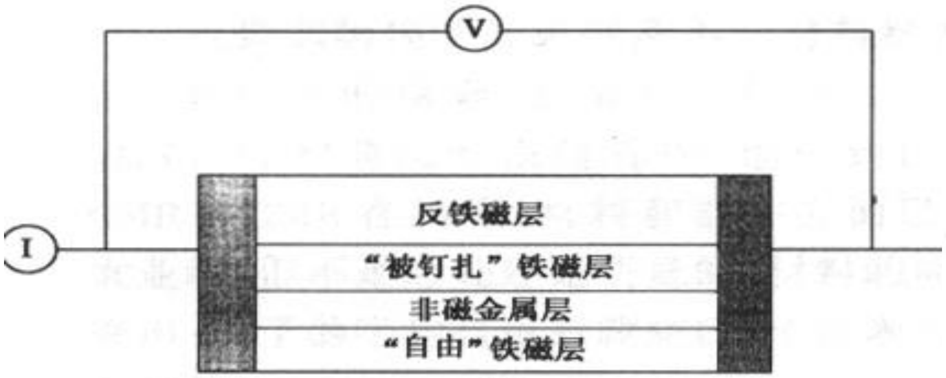
钉扎铁磁层

自由铁磁层

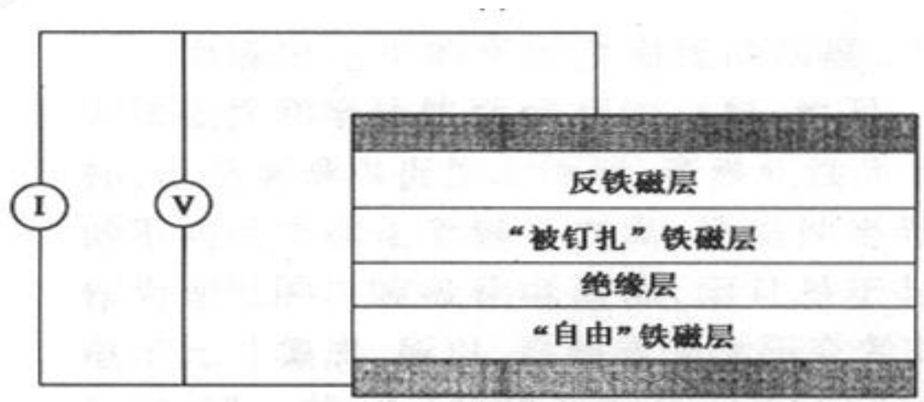


GMR

TMR



(a)

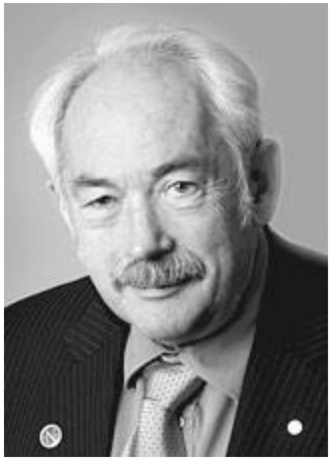


(b)

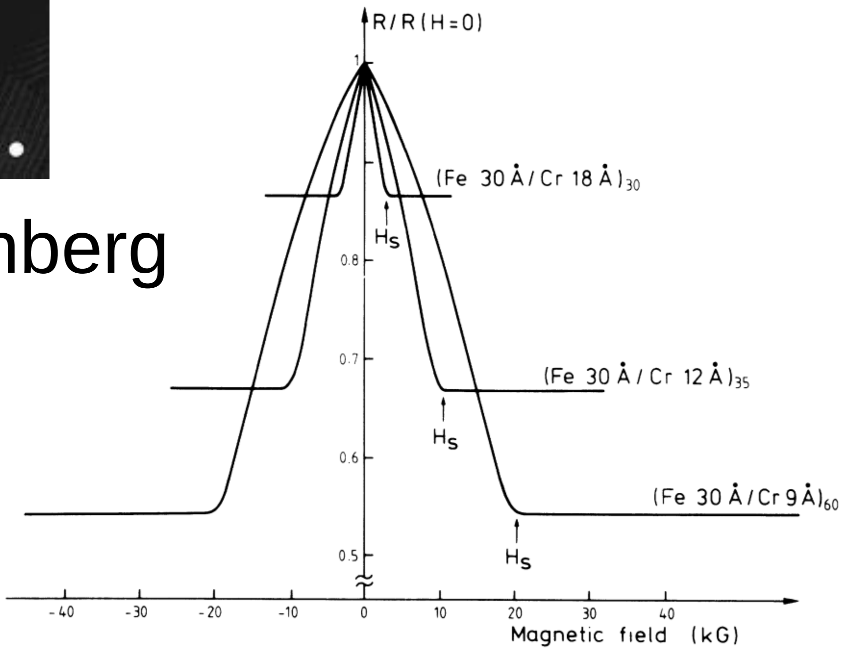
Technology	Current (mA)	Size (mm)	Sensitivity (mV/V/Oe)	Dynamic Range (Oe)	Resolution(mOe)	Operating Temperature (℃)
Hall	5 - 20	1×1	0.05	1 - 1000	500	< 150
AMR	1 - 10	1×1	1	0.001 - 10	0.1	< 150
GMR	1 - 10	2×2	3	0.1 - 30	2	< 150
TMR	0.001 – 0.01	0.5×0.5	20	0.001 - 200	0.1	< 200

巨磁电阻效应(GMR):
1988年发现，2007年获诺贝尔物理学奖

Albert Fert

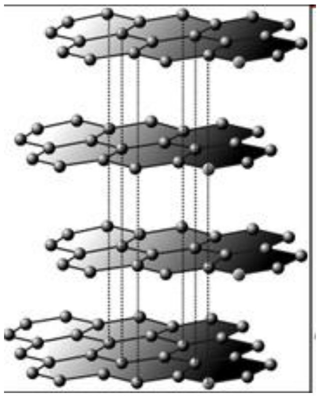


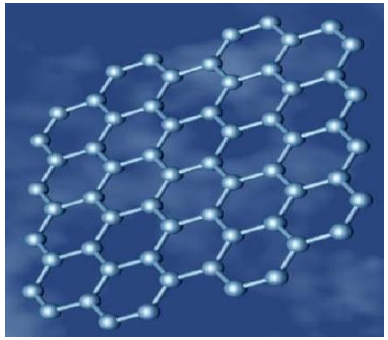
Peter Grünberg

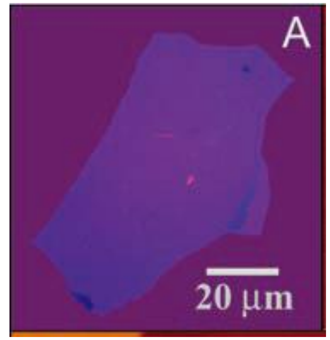


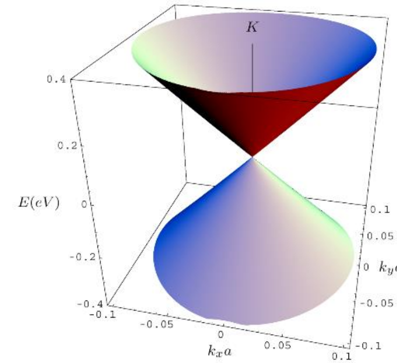
Phys. Rev. Lett. 61, 2472 (1988), Fert et al.

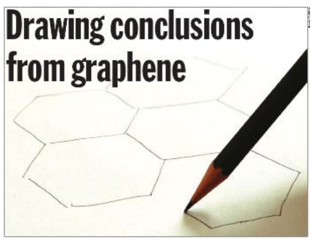
石墨烯(graphene):
2004年制备成功，2010年获诺贝尔物理学奖



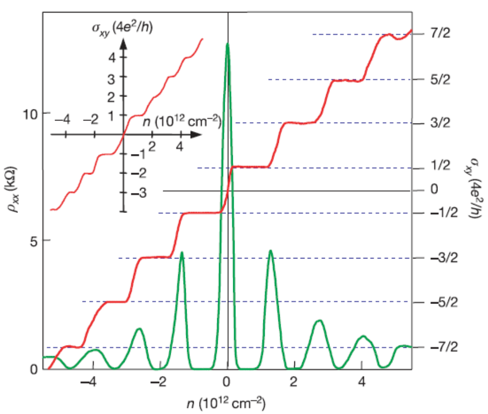








用铅笔和胶带制作graphene的视频：
http://v.youku.com/v_show/id_XMjI4NDI0MDE2.html



Andre Geim and Konstantin Novoselov

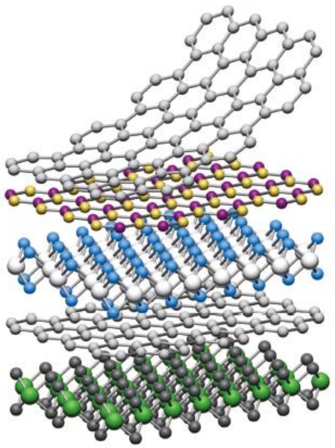
新兴量子材料

中国科学技术大学 University of Science and Technology of China

硅基微电子学

新材料载体：新兴量子材料体系

- 石墨烯、黑磷、过渡金属硫族化合物等二维体系
- 拓扑量子材料（拓扑绝缘体等等）
- 氧化物异质结

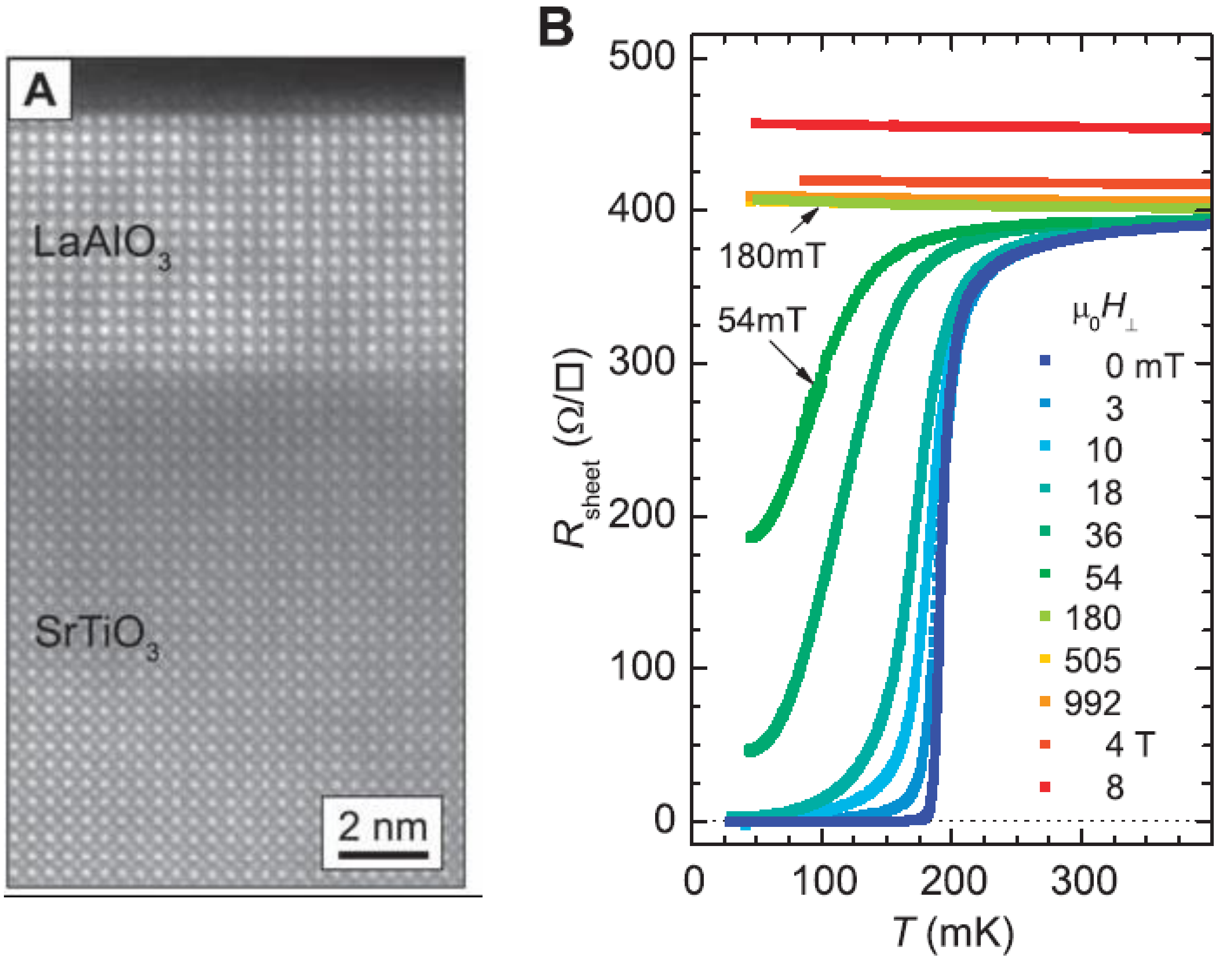


A revolution of nanoscale dimensions

Mildred S. Dresselhaus

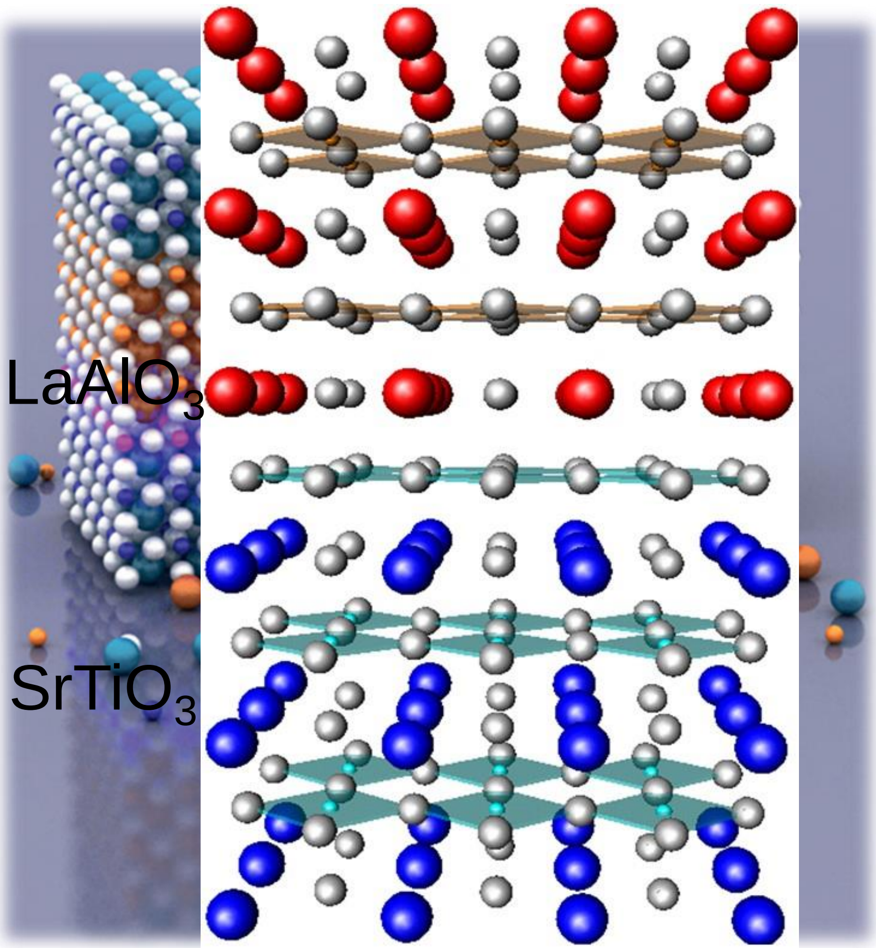
The continued drive to shrink the size and increase the functionality of electronic devices has seen the influence of nanotechnology strengthen as it offers materials with a layer thickness of one or a few atoms. Technological changes, awaited by computational scientists, are afoot.

氧化物量子材料



Science 317, 1169 (2007)

Quantum Lego and Nanoscale Programming

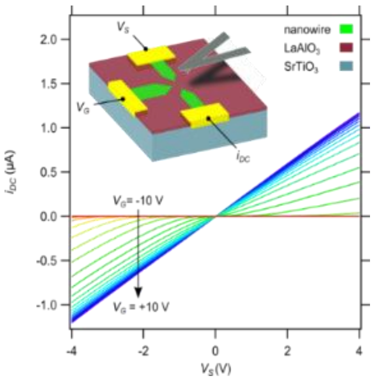


Different oxide materials can be coherently put together, giving rise to a dizzying array of emergent phenomena at the resulting interfaces.

A sharp (~10 nm) atomic force microscope tip could ”write” and ”erase” conductive structures, effectively programming all the novel properties to a nanoscale.

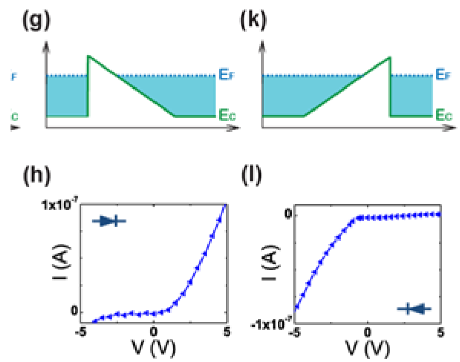
Functional Devices

SketchFET Transistors



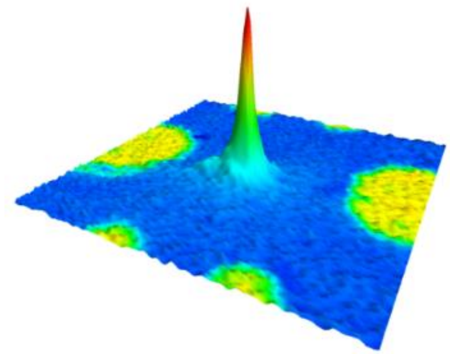
Cen et al., Science **6**, 343 (2009)

Nanoscale Diodes



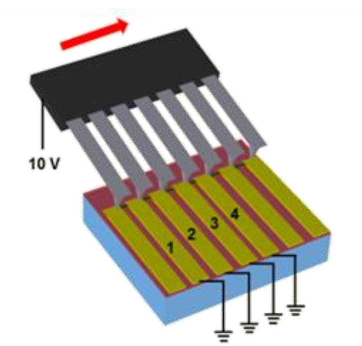
Bogorin et al., APL ***97***, 013102 (2010)

Nanoscale Photodetector



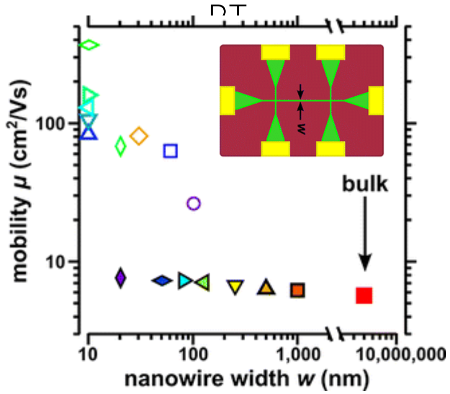
Irvin et al, Nature Photonics ***4***, 849 (2010)

Multiple Tip Lithography



Li et al., IEEE Trans. Nano. ***12***, 518 (2013)

Anomalous High Mobility @ RT



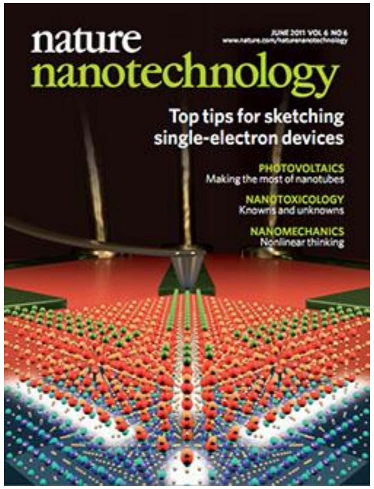
Irvin et al., Nano Letters ***13***, 364 (2013)

Molecular-Scale THz Spectroscopy

Ma et al., Nano Lett ***13***, 2884 (2013)
Jnawali et al., APL **106**, 211101 (2015)

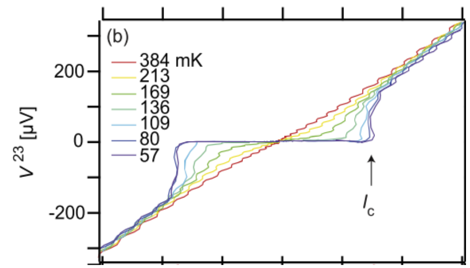
Quantum Devices

Single Electron Transistor



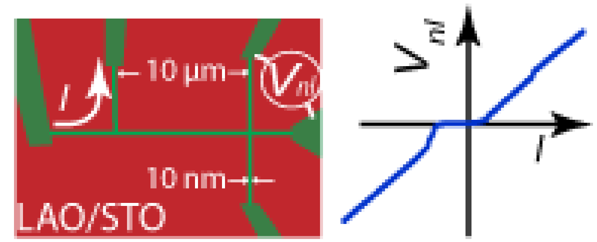
Cheng et al, Nature Nano **6**, 343 (2011)

Reconfigurable Superconducting Nanoelectronics



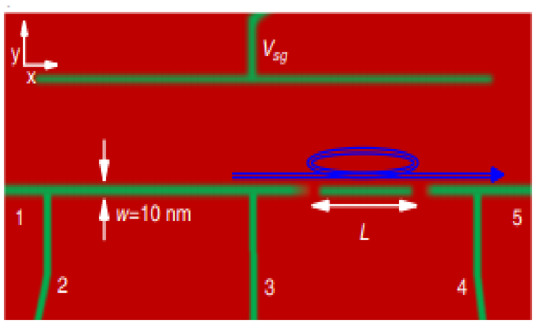
Nanotechnology ***24***, 375201 (2013)
PRL 120, 147001 (2018)

Reconfigurable Superconducting Nanoelectronics



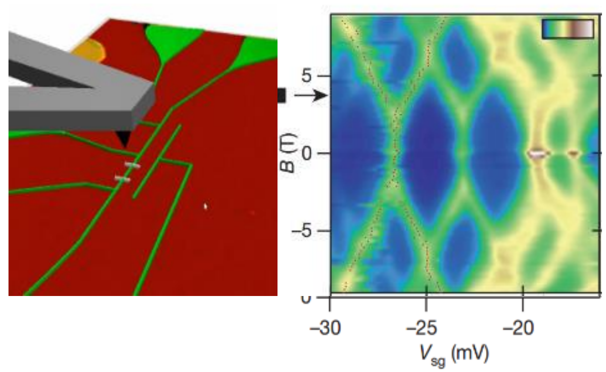
Cheng et al, PRX ***3***, 011021 (2013)
Veazey et al, EPL ***103***, 57001 (2013)

Electron Fabry-Perot resonator



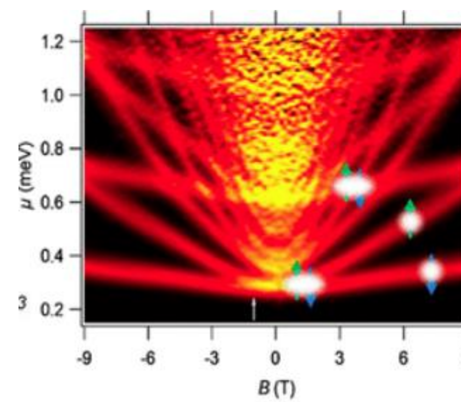
PRL ***117***, *096801 (2016)*

Electron Pairing without Superconductivity



Cheng et al, Nature **521**, 196 (2015)
PRX, **6**, 041042 (2016)

Electron Waveguide

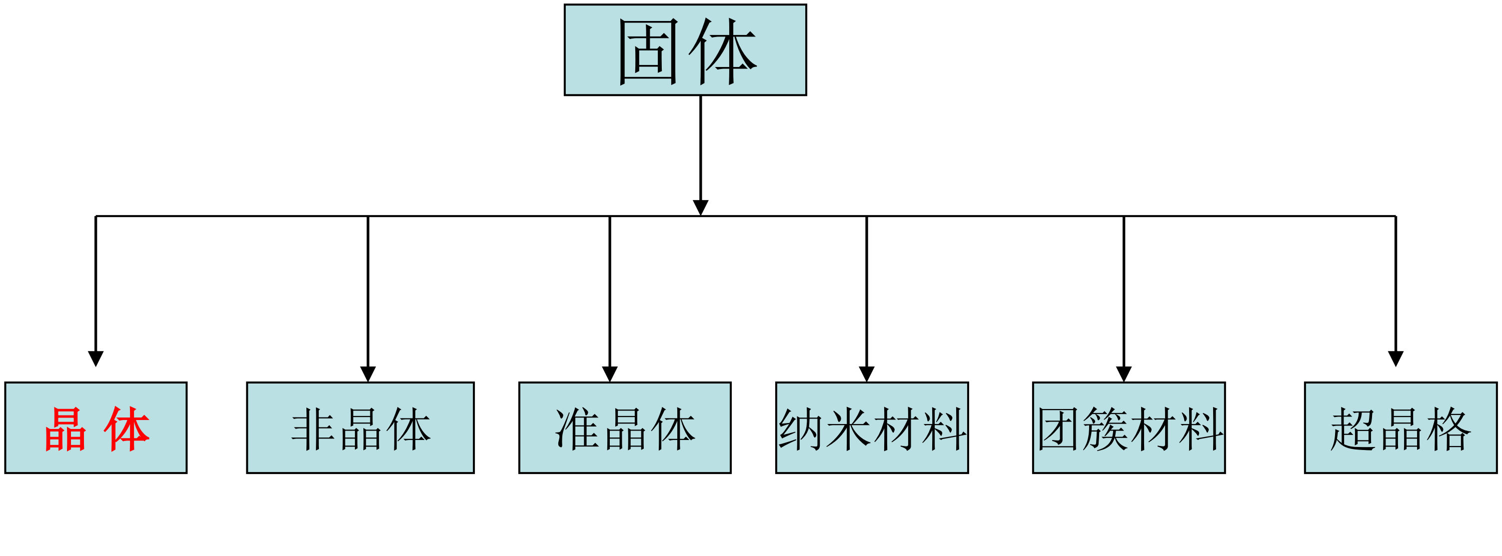


Nano Lett. **18**, 4473 (2018)

从二十世纪固体物理发展中得到的几点认识：

1. 固体物理正在向凝聚态物理的范畴扩展。
2. 固体物理的基本概念和实验技术已在非固体学科中得到广泛应用，成为众多学科的共同财富。
3. 固体物理是物质结构中最丰富的层次，因而构成了对于人类智力的巨大挑战，60多年来的新发现不断涌现，使之对高新技术发展的推动势头不但不减，在世纪交接之际反而变得更加突出。

固体物理正在向凝聚态物理的范畴扩展



目前固体物理的研究已经从传统的晶状固体拓展到非晶固体、薄膜和细小粒子体系、以及**量子流体**，这一更宽的研究领域人们称之为**凝聚态物理学**

Solid State Physics　　Condensed matter Physics

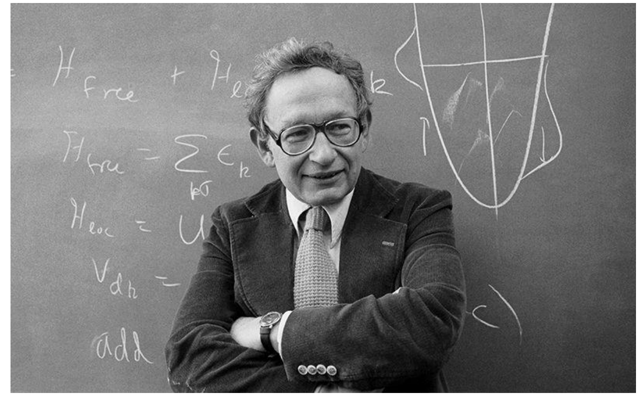
上世纪六七十年代后的发展，极大地扩展了固体物理的研究对象和研究领域，丰富了固体理论的内容。 这时再使用已经当作晶体同义词的“固体”一词表述该领域显然是不妥当的，人们提出了“凝聚态物理”的概念。然而至目前为止，已经成熟并获得巨大成功的固体理论体系仍然还是建立在对晶体研究的基础上，只完全适用于对**晶态块状**物质的讨论。无序、纳米体系材料物理性质的理论研究显然不能沿用上述理论体系，它们的理论研究仍处在起步和发展阶段，其理论体系尚在建立之中，因此至目前为止，虽已有凝聚态物理的论著，但真正建立起**对所有固体普遍适用的统一理论还有很大困难**。

从固体物理到凝聚态物理一方面是传统固体物理的向外扩展，使研究对象不再局限于晶体，还包括非晶态、超晶格、液态物质如：液氦，液晶，液态金属，电解液等，另一方面这种扩展也是**传统固体物理学中一些基本概念深化的结果，这些深化了的概念对传统固体物理学的内容做了更高度的概括，可以推广应用于比晶态物质更复杂的体系中**，因此我们不能认为由于研究范围的扩展，传统固体物理的方法就过时了，恰恰相反，**只有学好传统固体物理的内容，才能进入凝聚态物理的研究中**。

0.3 固体物理的研究方法

1. 固体物理是一门“横向”科学；
2. 是一门理论与实践密切结合的科学；
3. 固体理论中充满了各种近似方法：1立方厘米中含有10^{23}个原子，相互作用是极其复杂的多体问题，只能近似求解。
4. 固体物理中的两类问题：
   理想完整晶体； 近完整晶体；
   基态问题； 低激发态问题；

*Phil Anderson：



一个简化模型对于自然界实际状况的见解，远胜于个别情况的从头计算，这些计算即便是对的，也往往包含了过多的细节，以至于掩盖了而不是显示了现实，计算或测量的过于精细有时不一定是优点，反而可能是缺点，因为人们精确测量或计算出的结果往往是与机制无关的事情，总之，完美的计算可以重视自然，但不能解释它。

元激发是传统固体物理给出的最重要的概念，并在凝聚态物理得到推广应用。它有两层含义：1. 基态的总结合能并不是一个很重要的物理量，和物理系统的行为没有很大关系，物理上重要的是**相对于基态的低激发态行为**，这些态可以在相对低的温度和微弱的外场下就会被激发，是它们决定着固体的性质；2. 这些低激发态往往（几乎确是如此）具有特别简单的性质，比起其他状态来说，数学上可以做严格处理，而且物理上也容易被理解。所以原子振动的格波和晶体中运动的电子都可以归结为元激发，即声子和准电子。——摘自冯端文章

光子 ——————— 电磁波

固体中的元激发（excitation)

Bloch电子——————周期势场中的电子

声子 ——————— 弹性波

等离子激元—————集体电子波

磁振子———————自旋波

极化子———————电子＋弹性波

激子 ———————— 电极化强度波

轨道子——————— 轨道波

http://en.wikipedia.org/wiki/List_of_quasiparticles#

Quasiparticle_	Signification_
Bipolaron	A bound pair of two polarons
Chargon	A quasiparticle produced as a result of electron spin-charge separation
Composite fermion	Bound state of an electron and magnetic flux quanta
Configuron	An elementary configurational excitation in an amorphous material which involves breaking of a chemical bond
Electron hole (hole)	A *lack* of electron in a valence band
Electron quasiparticle	An electron as affected by the other forces and interactions in the solid
Exciton	A bound state of an electron and a hole
Fracton	A collective quantized vibration on a substrate with a fractal structure.
Holon	A quasi-particle resulting as a result of electron spin-charge separation
Libron	A quasiparticle associated with the librational motion of molecules in a molecular crystal.
Magnon	A coherent excitation of electron spins in a material
Majorana fermion	A quasiparticle equal to its own antiparticle, emerging as a midgap state in certain superconductors
Phason	Vibrational modes in a quasicrystal associated with atomic rearrangements
Phonon	Vibrational modes in a crystal lattice associated with atomic shifts
Plasmon	A coherent excitation of a plasma
Polariton	A mixture of photon with other quasiparticles
Polaron	A moving charged quasiparticle that is surrounded by ions in a material
Roton	Elementary excitation in superfluid Helium-4
Soliton	A self-reinforcing solitary excitation wave
Spinon	A quasiparticle produced as a result of electron spin-charge separation

0.4 固体物理国内通用教材

1. **阎守胜，固体物理基础**＊ 北大出版社 2000
2. **黄 昆，韩汝琦，国体物理学** 高等教育出版社 1988第1版，
   （根据黄 昆，固体物理学 人民教育出版社 1966版扩充改编）
3. 方俊鑫，陆栋，固体物理学（上，下两册） 上海科技出版社
   1980，1981
   （根据谢希德，方俊鑫，固体物理学 1965版扩充改编）

4. 顾秉林，王喜坤，固体物理学 清华大学出版社 1990
5. 陈长乐，国体物理学 西北工大出版社 1998
6. 王矜奉， 固体物理教程 （4版） 山东大学出版社 2004
   （1999年初版）
7. 朱建国等 固体物理学 科学出版社 2005 （四川大学）

国外最有影响的通用教材

Kittel C. **Introduction to Solid State Physics**, 8th ed.
John Wiley ＆ Sons Inc.,2005
（作者是在固体物理研究领域有过重要贡献的美国加州大学Bekeley分校物理学教授，该书1953年首次出版后受到广泛重视，后于1956，1966，1971，1976，1986，1996年不断修订再版，成为大学固体物理的标准教材之一，2005年是第8版。我国曾先后翻译出版了1956年的第2版和1976年的第5版。）固体物理导论 化学工业出版社，2005

Busch G. Schade H. 固体物理学讲义 高等教育出版社 1987
(原文为德文，瑞士联邦技术学院教材，1972)

M A Omar Elementary Solid State Physics: Principle and Applications
中译本：固体物理学基础 北京师范大学出版社 1987

H E Hall Solid State Physics John Wiley ＆ Sons Ltd 1974
(英国曼彻斯特大学教材)

Ashcroft, Mermin **Solid State Physics** 1976
（康乃尔大学，公认为世界最权威的固体物理教材）

Blakemore , Solid State Physics, Cambridge University Press,1986

更深入的教材

1. **冯 端，金国钧， 凝聚态物理学**（上卷） 高等教育出版社 2003
2. **冯 端，金国钧， 凝聚态物理学**（下卷） 高等教育出版社 2012
3. J Callaway, Quanyum Theory of The Solid State 1976
   中译本： **固体量子理论** 科学出版社 1984
4. O Madelung, Introduction to Solid State Theory Springer 1978
5. J M Ziman, Principles of the Theory of Solid
   Cambridge University Press 1972
6. William Jones, Norman H March, Theoretical Solid State Physics,
   Vol 1: The equilibrium properties of perfect crystalline solid
   Vol 2；The non-equilibrium properties and Disorder
   John Wiley ＆ Sons Ltd 1973
7. **李正中, 固体理论** 高等教育出版社 1985

课程大纲：

0. 绪论
1. 晶体结构
1.1 晶体结构的周期性，晶体点阵
1.2 晶体的对称性
1.3 典型的晶体结构，晶向、晶面的表示
1.4 倒易点阵和布里渊区
1.5 晶体结构的实验研究
2. 晶体结合
2.1 晶体中的结合力和结合能
2.2 元素和化合物晶体结合的规律性
2.3 弹性应变和晶体中的弹性波
3. 晶格振动
3.1 晶格振动的经典理论
3.2 晶格振动的量子化－声子
3.3 固体热容的量子理论
3.4 离子晶体的红外光学性质
3.5 非简谐效应
3.6 晶格振动的实验研究
4. 能带论
4.1 周期场中单电子状态的一般特征
4.2 一维周期场中电子运动的近自由近似
4.3 三维周期场中电子运动的近自由电子近似
4.4 紧束缚近似
4.5 Kronig-Penny模型
4.6 能带结构的计算方法
4.7 晶体能带的对称性
4.8 能态密度和费米面
5. 晶体中电子运动
5.1 晶体中电子的运动特征
5.2 在恒定电场作用下电子的运动
5.3 导体、绝缘体和半导体的能带论解释
5.4 在恒定磁场中电子的运动
5.5 能带结构的实验研究
6. 金属电导理论
6.1 分布函数和Boltzmann方程
6.2 驰豫时间近似和电导率公式
6.3 金属电阻率的微观机制