Physics of the XXth century
Part 3

Condensed matter physics
and optics

Solid state physics originated as a distinct branch of physics only around 1940

Earlier: crystallography

studies of elasticity

studies of electrical conductivity

studies of thermal conductivity

.....

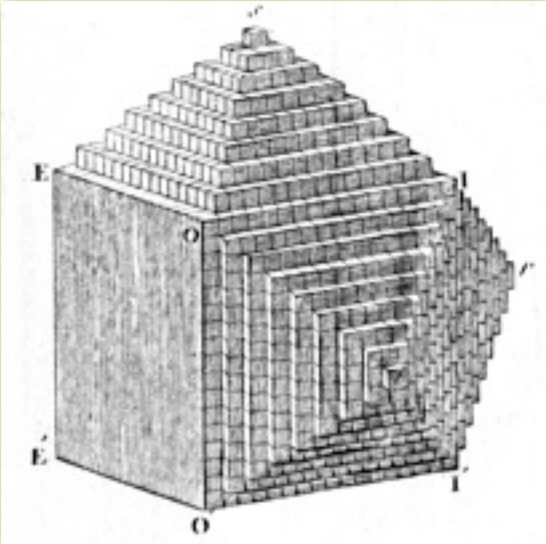
For example, interpretation of characteristic features of three different materials, say, copper, diamond and ordinary salt, depended on three very different pictures of their internal structure

The beginnings of crystallography

René Just Haüy (1743-1822): general rules of crystal structure, hypotheses concerning their parts

Further analysis of crystal symmetry:
Franz Neumann (1798-1895)
Johann Hessel (1796-1872)
Auguste Bravais (1811-1863)

Direct experimental studies since 1912 (Laue et al., diffraction of X rays)

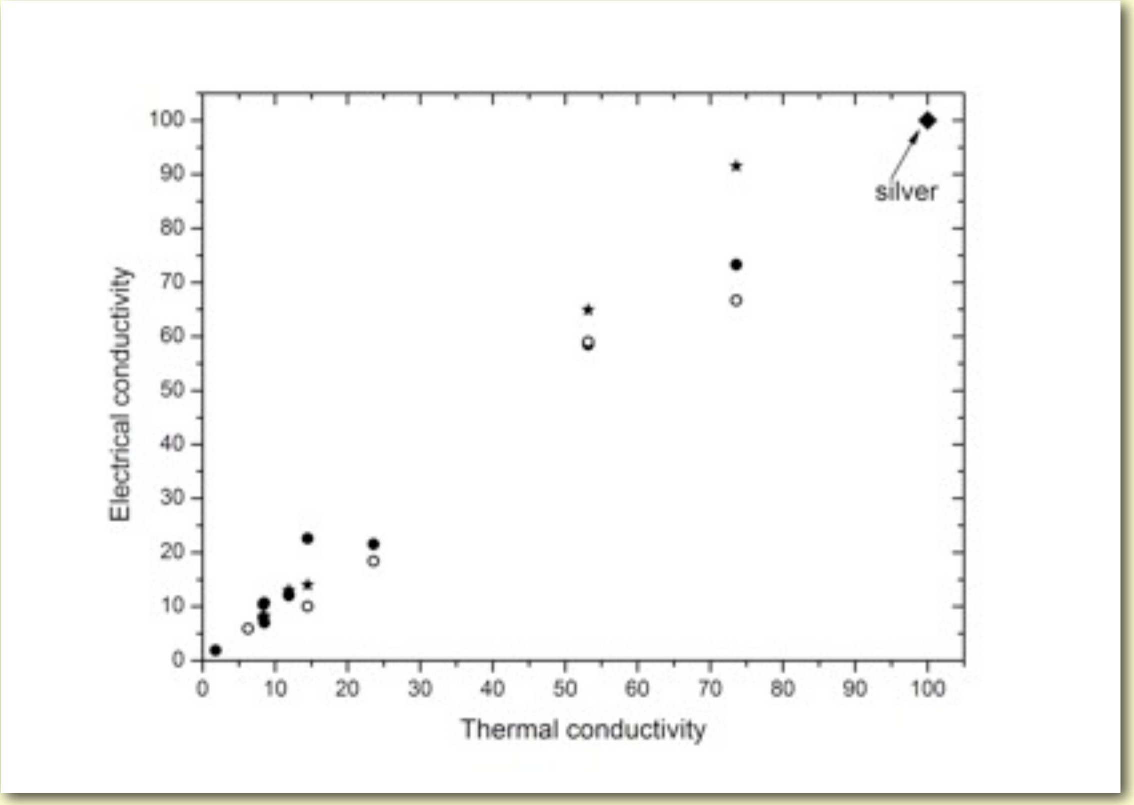


Haüy (1806)

Many unrelated observations

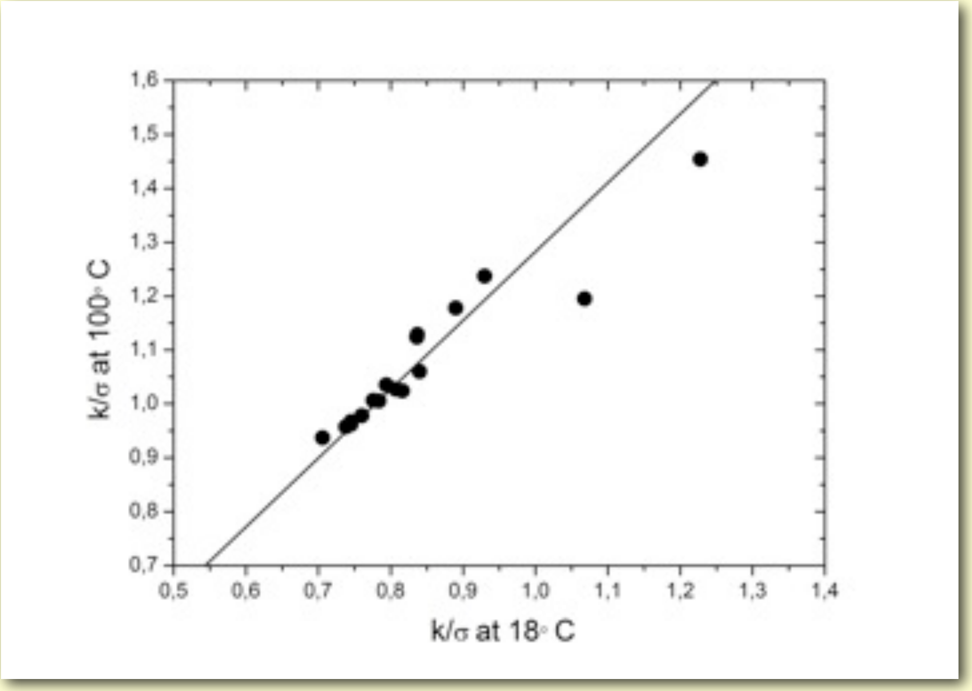
1821 Davy – electric resistance of metals increases with T
1833 Faraday – electric resistance of silver sulphide decreases with T (the same for several other substances)
1852 Hittorf – similar measurements; hypothesis of electrolitic conductivity
1839 Becquerel (Antoine César) – photovoltaic effect (illumination of electrodes produces a potential difference in the electrolite)
1873 Smith – photoconductivity of selenium
1874 Braun – rectifying property of selenium
1874 Schuster – rectifying property of copper oxide
1874 Pickard – rectifying property of silicon
1876 Adams & Day – photovoltage in selenium
1876 Fritts – photovoltage in selenium

Wiedemann-Franz law (1853) - the ratio of coefficients of thermal conductivity σ and electrical conductivity k is approximately constant for many metals

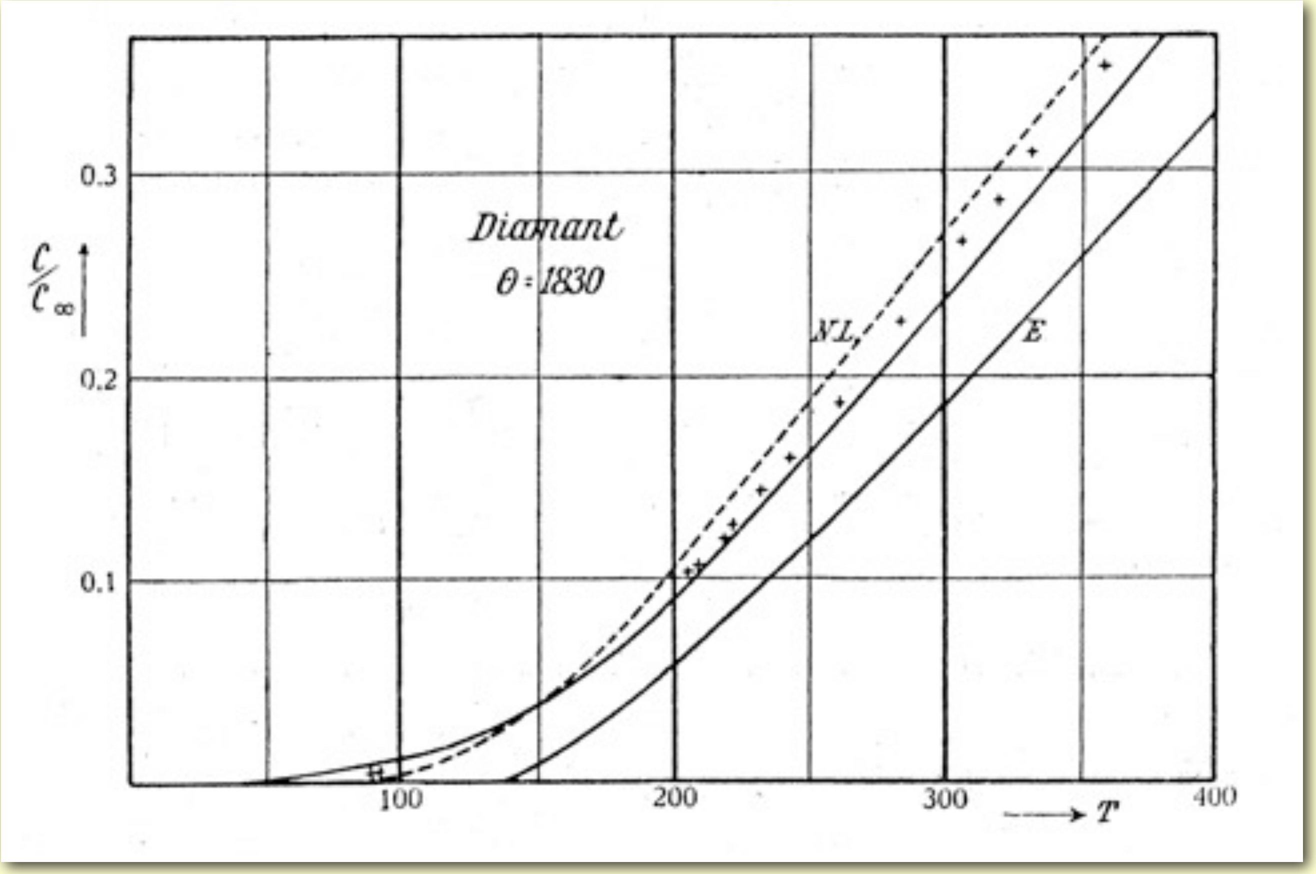


1898-1905 Paul Drude, Hendrik Lorentz - classic theory of electrical conductivity of metals (also Edouard Riecke, Owen Richardson, J. J. Thomson, Niels Bohr)

Drude (1900) – from the classical theory ($k/\sigma \sim T$)



1907-1912 Albert Einstein, Peter Debye
theory of specific heat of solid bodies



1908 – Johann Königsberger – the electrical resistivity of silicon, zirconium, titanium and other substances decreases with temperature to a certain minimum and then increases

1911 – Königsberger and J. Weiss introduced the term *Halbleiter* – semiconductor

1913 – Kurt Bädeker (1877-1914) – metallic layers on sheets of glass or mica produced by sputtering and exposed to vapours of sulphur, iodine, oxygen, selenium and arsenic to produce the respective compounds of copper, silver, cadmium, lead, and thallium; the electrical conductivity of CuI and AgS found to be extremely sensitive to the iodine content in the specimen.

1930 – Bernhard Gudden – a review article with an opinion that no chemically pure substance may be a semiconductor; the observed electrical conductivity must always be due to impurities

1926-1927 Wolfgang Pauli, Arnold Sommerfeld
the first use of Fermi-Dirac statistics
to study electrons in metals

1927-1928 Maximilian Strutt - bands of energy

1928-1930 Felix Bloch, Léon Brillouin
beginning of the band theory
(method of plane waves)

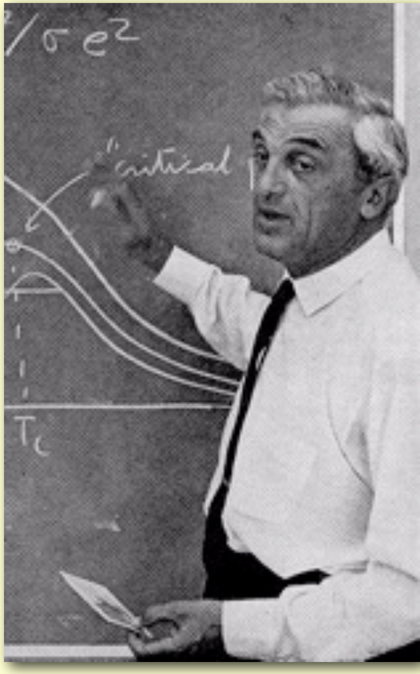
1928-1930 Bloch, Rudolf Peierls - quantum theory
of electrical conductivity of metals

1928 Peierls, Yakov Frenkel – ‘hole’ conduction

1931 Alan Wilson - classification of metals, dielectrics
and semiconductors according to their
band structure

”From the beginning I was convinced that the answer, if at all, could be found only in the wave nature of the electron...The fact that the periodicity of a crystal would be essential was somehow suggested to me by remembering a demonstration in elementary physics where many equal and equally coupled pendula were hanging at constant spacing from a rod and the motion of one of them was seen to ‘migrate’ along the rod from pendulum to pendulum. Returning to my rented room one evening in early January [1928], it was with such vague ideas in mind that I began to use pencil and paper and to treat the easiest case of a single electron in a one-dimensional potential. By straight Fourier analysis I found to my delight that the solutions of the Schrödinger equation differed from the de Broglie wave of a free particle only by a modulation with the period of the potential. The generalization to three dimensions was obvious...”

Bloch (1980)



Felix Bloch
(1905 - 1983)

Über die Quantenmechanik der Elektronen in Kristallgittern.

Von **Felix Bloch** in Leipzig.

Mit 2 Abbildungen. (Eingegangen am 10. August 1928.)

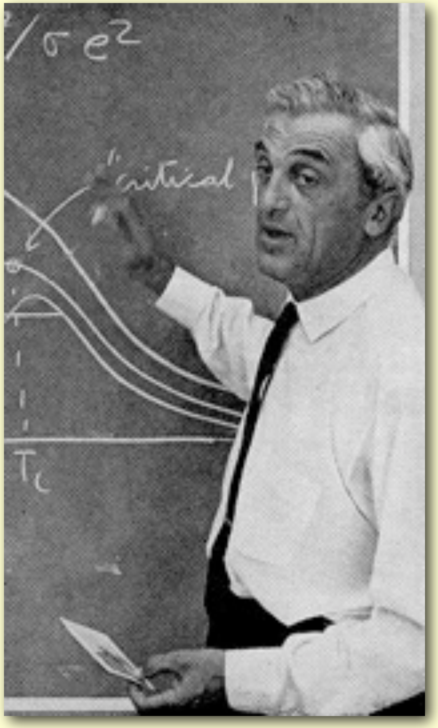
Die Bewegung eines Elektrons im Gitter wird untersucht, indem wir uns dieses durch ein zunächst streng dreifach periodisches Kraftfeld schematisieren. Unter Hinzunahme der Fermischen Statistik auf die Elektronen gestattet unser Modell Aussagen über den von ihnen herrührenden Anteil der spezifischen Wärme des Kristalls. Ferner wird gezeigt, daß die Berücksichtigung der thermischen Gitterschwingungen Größenordnung und Temperaturabhängigkeit der elektrischen Leitfähigkeit von Metallen in qualitativer Übereinstimmung mit der Erfahrung ergibt.

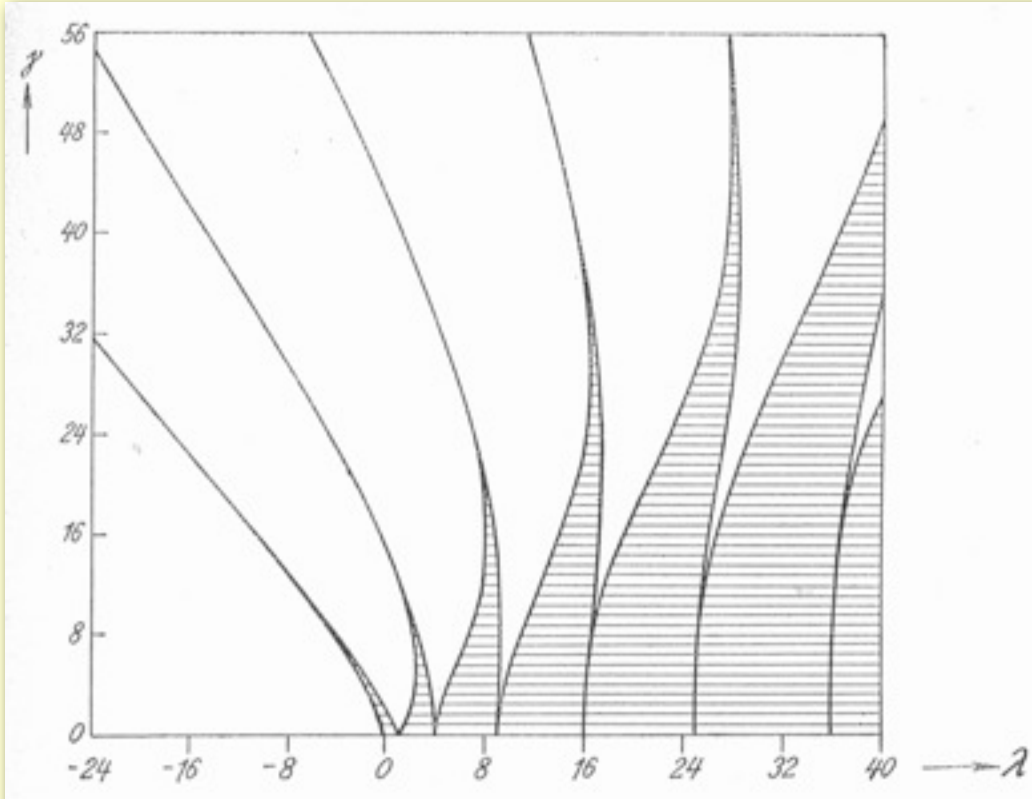
Einleitung. Die Elektronentheorie der Metalle hat seit einiger Zeit Fortschritte zu verzeichnen, die in der Anwendung quantentheoretischer Prinzipien auf das Elektronengas begründet sind. Zunächst hat Pauli* unter der Annahme, daß die Metallelektronen sich völlig frei im Gitter bewegen können und der Fermischen** Statistik gehorchen, den temperaturunabhängigen Paramagnetismus der Alkalien zu erklären vermocht. Die elektrischen und thermischen Eigenschaften des Elektronengases sind dann von Sommerfeld, Houston und Eckart*** näher untersucht worden. Die Tatsache freier Leitungselektronen wird von ihnen als gegeben betrachtet und ihre Wechselwirkung mit dem Gitter nur durch eine zunächst phänomenologisch eingeführte, dann von Houston**** strenger begründete freie Weglänge mitberücksichtigt. Schließlich hat Heisenberg† gezeigt, daß im anderen Grenzfall, wo zunächst die Elektronen an die Ionen im Gitter gebunden gedacht und erst in nächster Näherung die Austauschvorgänge unter ihnen berücksichtigt werden, das für den Ferromagnetismus entscheidende intermolekulare Feld seine Erklärung findet.

Hier soll ein Zwischenstandpunkt zwischen den beiden oben erwähnten Behandlungsweisen eingenommen werden, insofern, als der Austausch der Elektronen unberücksichtigt bleibt, sie dagegen nicht einfach

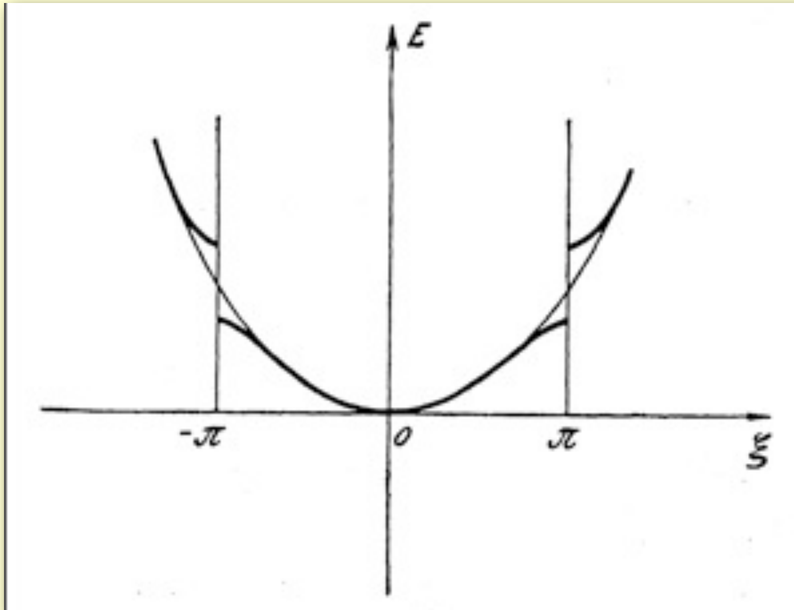
* W. Pauli, ZS. f. Phys. **41**, 81, 1927.
** E. Fermi, ebenda **36**, 902, 1926.
*** A. Sommerfeld, W. V. Houston, C. Eckart, ebenda **47**, 1, 1928.
**** W. V. Houston, ebenda **48**, 449, 1928.
† W. Heisenberg, ebenda **49**, 619, 1928.

Seminal article of Bloch
Zeit.f.Physik **52**, 555 (1928)





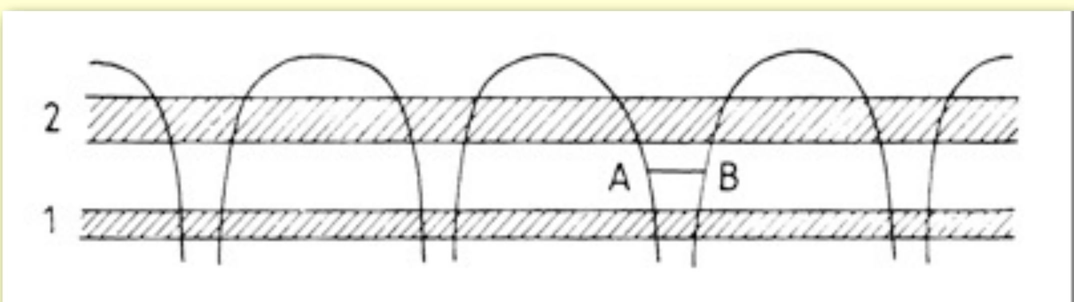
Maximilian Strutt: the Matthieu differential equation can describe the motion of a particle along the direction of sinusoidally changing potential energy (first attempt to solve the Schrödinger equation for a periodic potential)
Allowed solutions of the Matthieu equation fill certain finite areas in the plane of particle energy – potential amplitude
[*Zur Wellenmechanik des Atomgitters, Ann. Phys.* **86**, 319 (1928)]



First diagram showing electron energy as function of the wave-number *k* for motion in a periodic potential; the product $\xi = ka$, where *a* is the lattice constant, is plotted in the horizontal axis [Peierls, Ann. Phys. **4**, 121 (1930)]

First diagram of energy bands for an intrinsic semiconductor

[Alan Wilson, *The Theory of Electronic Semiconductors,* Proc. Roy. Soc. **133**, 458, **134**, 277 (1931)]



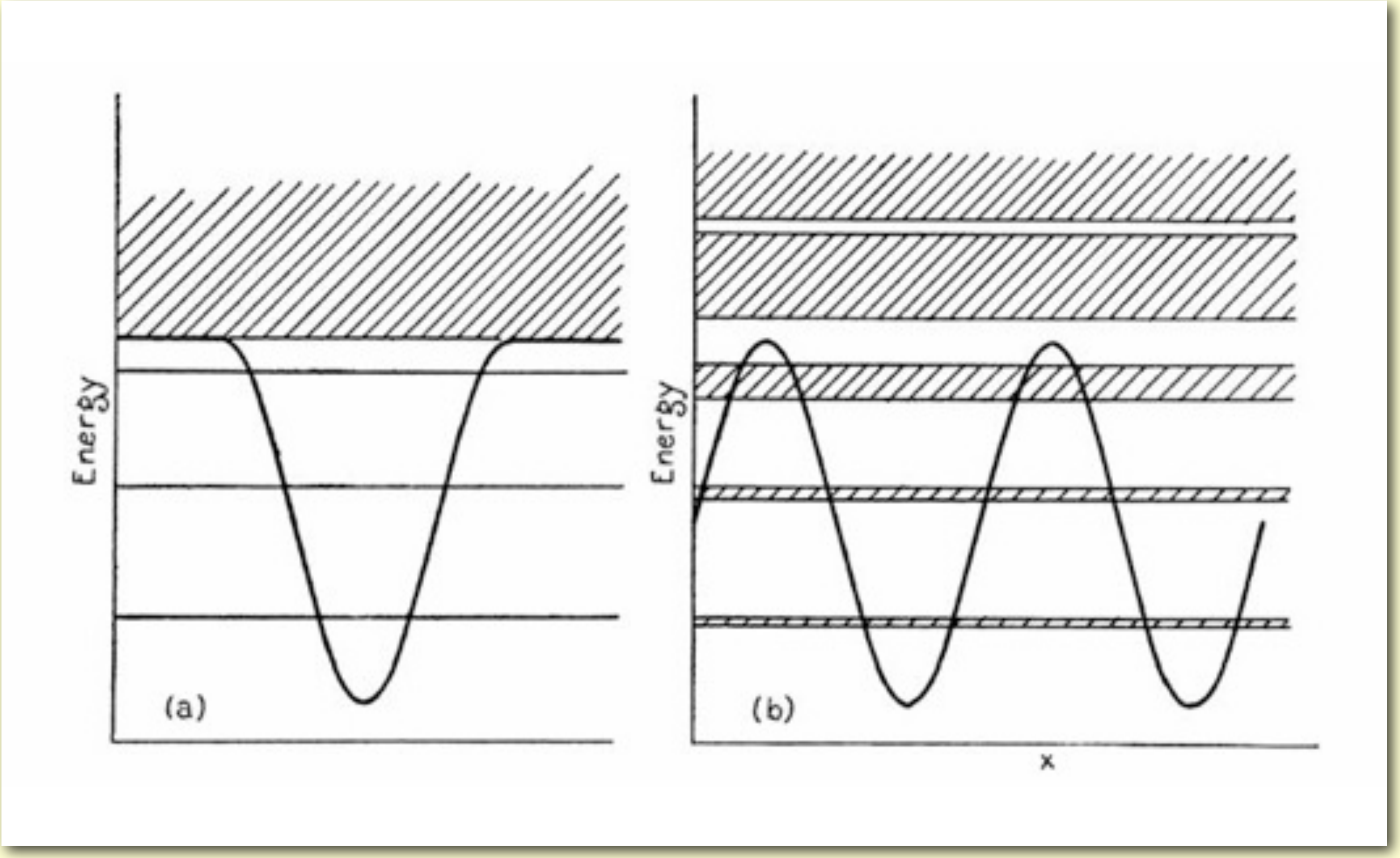
”The experimental results on semi-conductors are not easy to interpret. In the first place there are two main types of semi-conductors. The first type consists of ionic conductors in which heavy ions are transported through the crystal by a process akin to electrolysis. The second type consists of purely electronic conductors, while there is a third class in which the current is carried partly by ions and partly by electrons. The theory developed here only applies to electronic conductors. Further, we have considered the crystal to be atomic, and the theory must not be expected to apply to molecular crystals without considerable modification. The greatest difficulty in the interpretation arises, however, because there is no general agreement as to which substances are to be classified as metals and which as semi-metals...”

A. H. Wilson, *Theory of Electronic Semi-Conductors*, Proc. Roy. Soc. **A133**, 458 (1931).

”...Gudden is inclined to the view that no pure substance is ever a semi-conductor. This view is supported by the superconductivity of titanium and by the fact that a positive temperature coefficient has been found for silicon. Recent measurements by Meissner did not confirm the metallic character of silicon, though this is almost certainly due to the presence of oxygen in his single crystal. From the experimental side, therefore, the existence or non-existence of semi-conductors remains an open question, and neither the measurements not those of susceptibility are sufficiently accurate to supply additional evidence.

Theoretically there is no reason why semi-conductors should not exist, the main difference between semi-conductors and insulators being that for the former Θ_u is so small that the substance has a measurable conductivity at ordinary temperatures, while for the latter Θ_u is extremely large. Experimentally, however, the only substances which show undoubted semi-conducting properties are very impure, and it may be that they have no intrinsic conductivity...”

A. H. Wilson, *Theory of Electronic Semi-Conductors*, Proc. Roy. Soc. **A133**, 458 (1931).



Potential energy of an electron as function of the distance from the nucleus for a single ‘atom’ (left) and for a crystal of infinite extent (right); horizontal lines – discrete energy levels shaded areas – bands of allowed energy
[Philip M. Morse, Phys. Rev. **35**, 1310 (1930)]

”Periodic variation of potential inside the crystal creates bands of forbidden energies inside the crystal, even for electronic energies greater than the maximum potential energy, a somewhat surprising result. However, this only means that when electrons outside a crystal have energies such that their wave-number components are integral multiples of the reciprocal lattice spacing, they are reflected strongly back at the surface of the crystal. That this is true experimentally has been shown by Davisson and Germer.”

Philip M. Morse, Phys. Rev. **35**, 1310 (1930]

First calculations for real materials

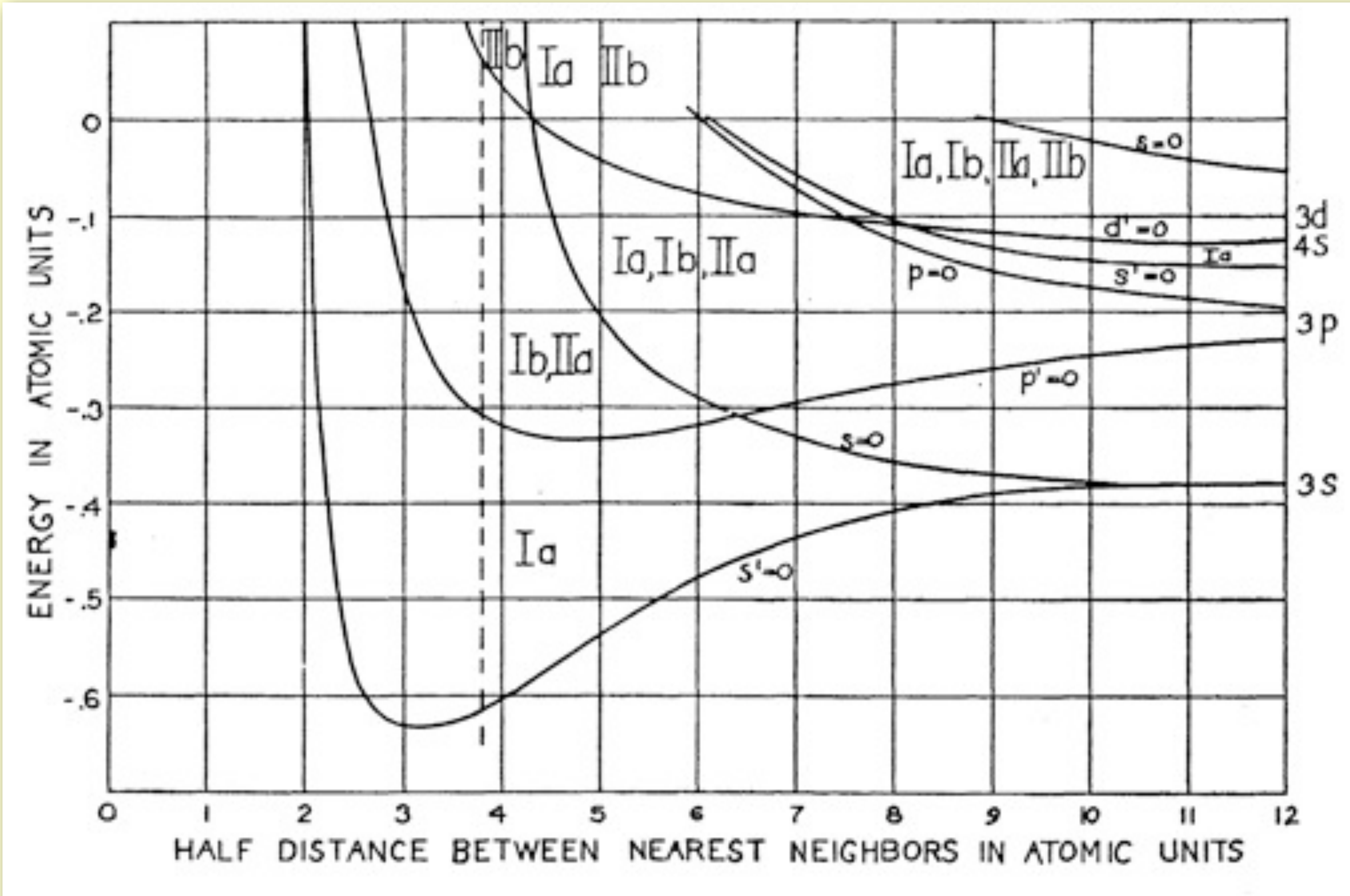
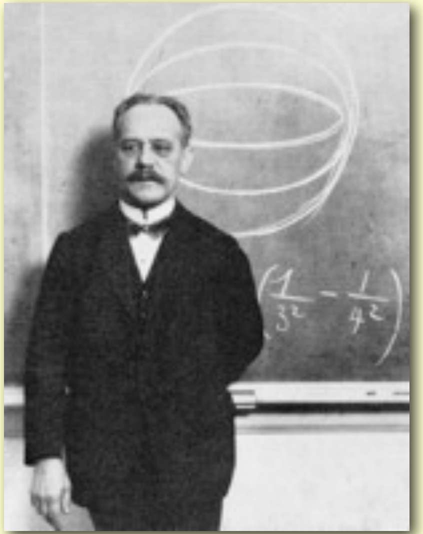


FIG. 1. Energy bands for sodium. Symbols Ia–IIb represent type of state allowed in each band.

Energy bands for sodium (J. Slater, Phys. Rev. **45**, 794 (1934))

A. Sommerfeld, H. Bethe –
Elektronentheorie der Metalle,
Handbuch der Physik
24, 333-622 (1933)

This review article helped to train
the new generation
of ”solid state physicists”



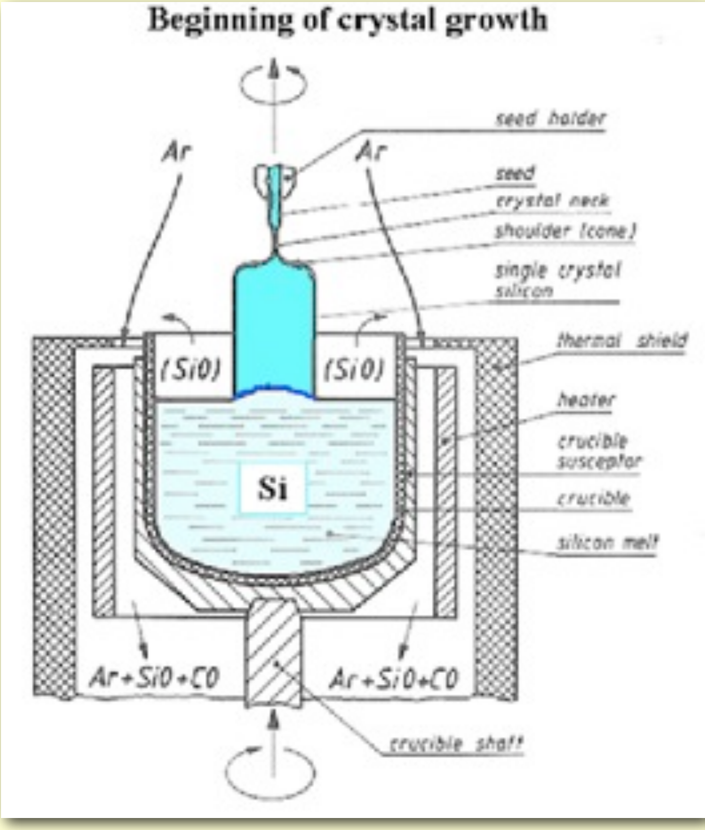
Some physicists, e.g. Pauli, tended to refer to solid state physics as ‘dirty physics’, which did not prevent the best minds to work in this field

”The history of semiconductor physics is not one of grand heroic theories, but one of painstaking intelligent labor. Not strokes of genius producing lofty edifices, but great ingenuity and endless undulation of hope and despair. Not sweeping generalizations, but careful judgement of the border between perseverance and obstinacy. Thus the history of solid-state physics in general, and of semiconductors in particular, is not so much about great men and women and their glorious deeds, as about the unsung heroes of thousands of clever ideas and skillful experiments - progress of a purposeful centipede rather than a sleek thoroughbred, and thus a reflection of an age of organization rather than of individuality.”

Ernest Braun, *Selected topics from the history of semiconductor physics and its applications* (1992)

Production of large and pure crystals

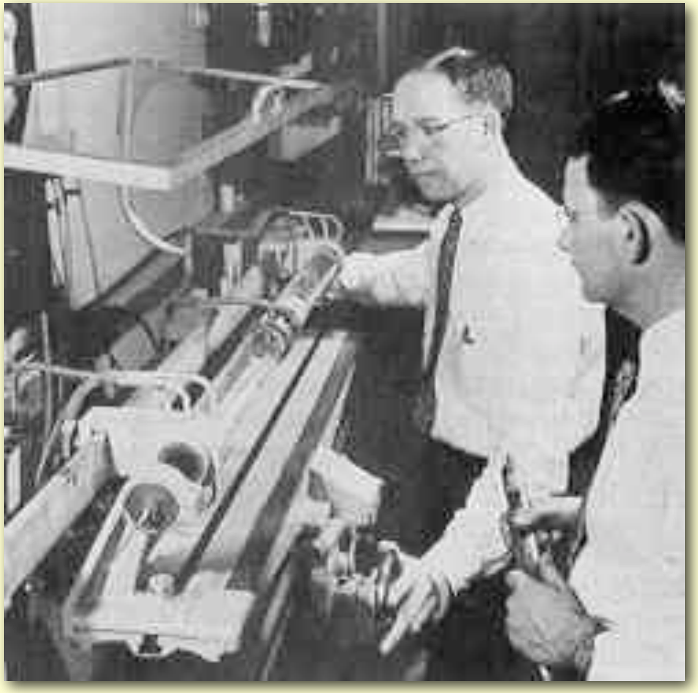
The most popular method of obtaining large monocrystals was proposed in 1916 by Jan Czochralski (1885-1953)



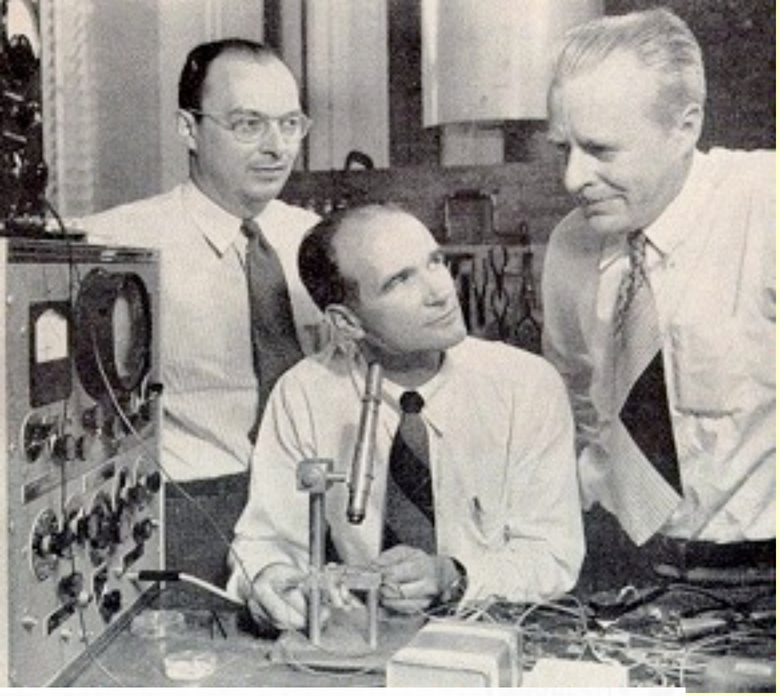
Production of large and pure crystals

1950-1951 - William Pfann
(Bell Labs)

- zone refining method



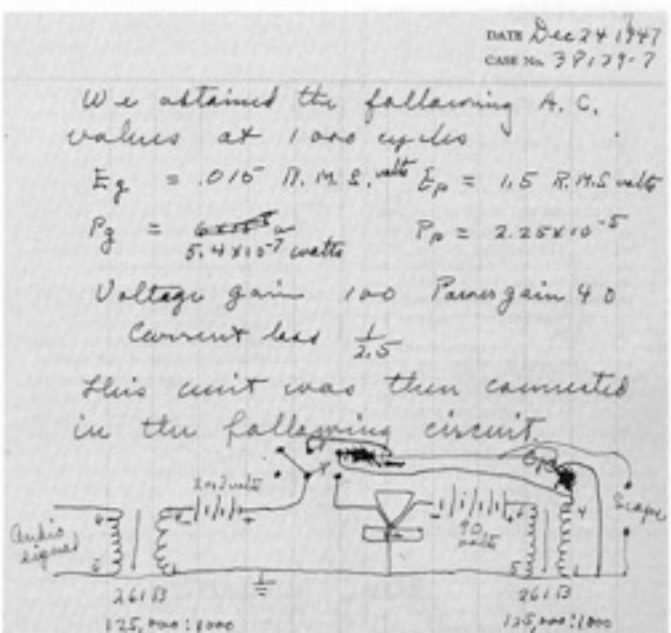
”less than a pinch of salt in 35 freight cars of sugar”

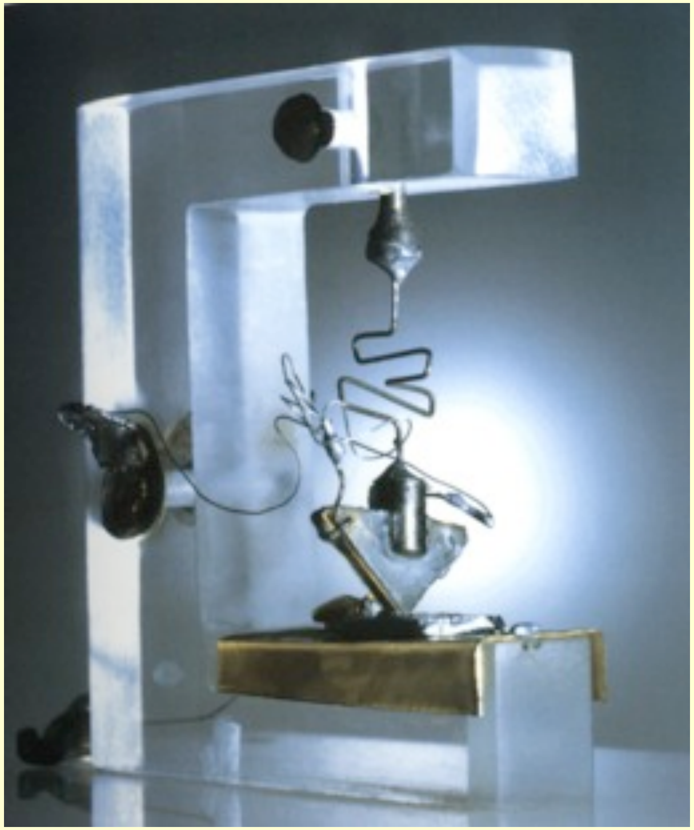


Discoverers of the transistor

John Bardeen
William Shockley
Walter Brattain

LABORATORY NOTEBOOK of Nobel laureate Walter H. Brattain records the events of 23 Dec. 1947, when the transistor was discovered at Bell Telephone Laboratories. The notebook continues: "This circuit was actually spoken over and by switching the device in and out a distinct gain in speech level could be heard and seen on the scope presentation with no noticeable change in quality."

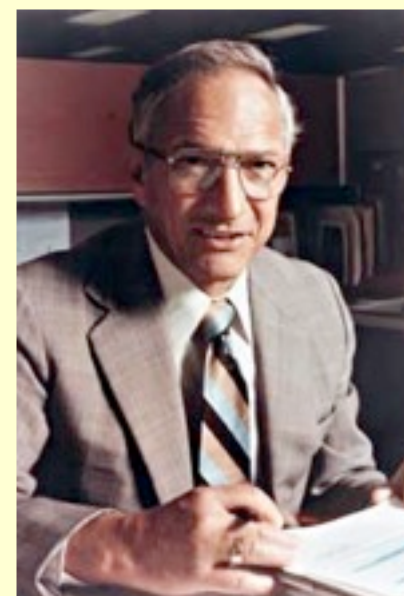




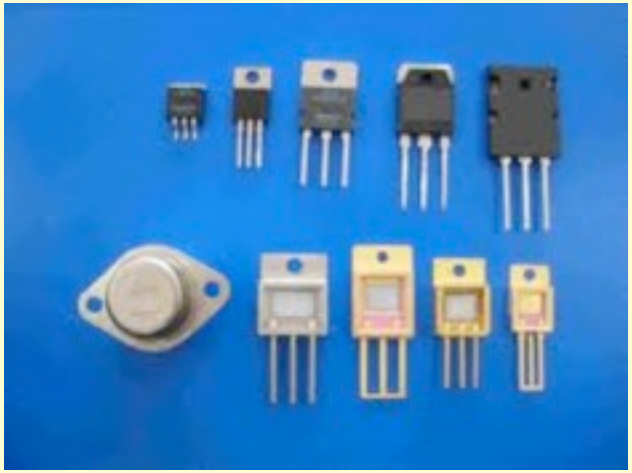
In 1959 Jack St. Clair Kilby (b. 1923) built the first integrated circuit. Four months after Kilby's patent application Robert Noyce (1927-1990) applied for patent for an almost identical device but constructed in a different process.
Integrated circuits of rapidly increased miniaturization made possible production of personal computers and other devices which play an essential role in everyday life.

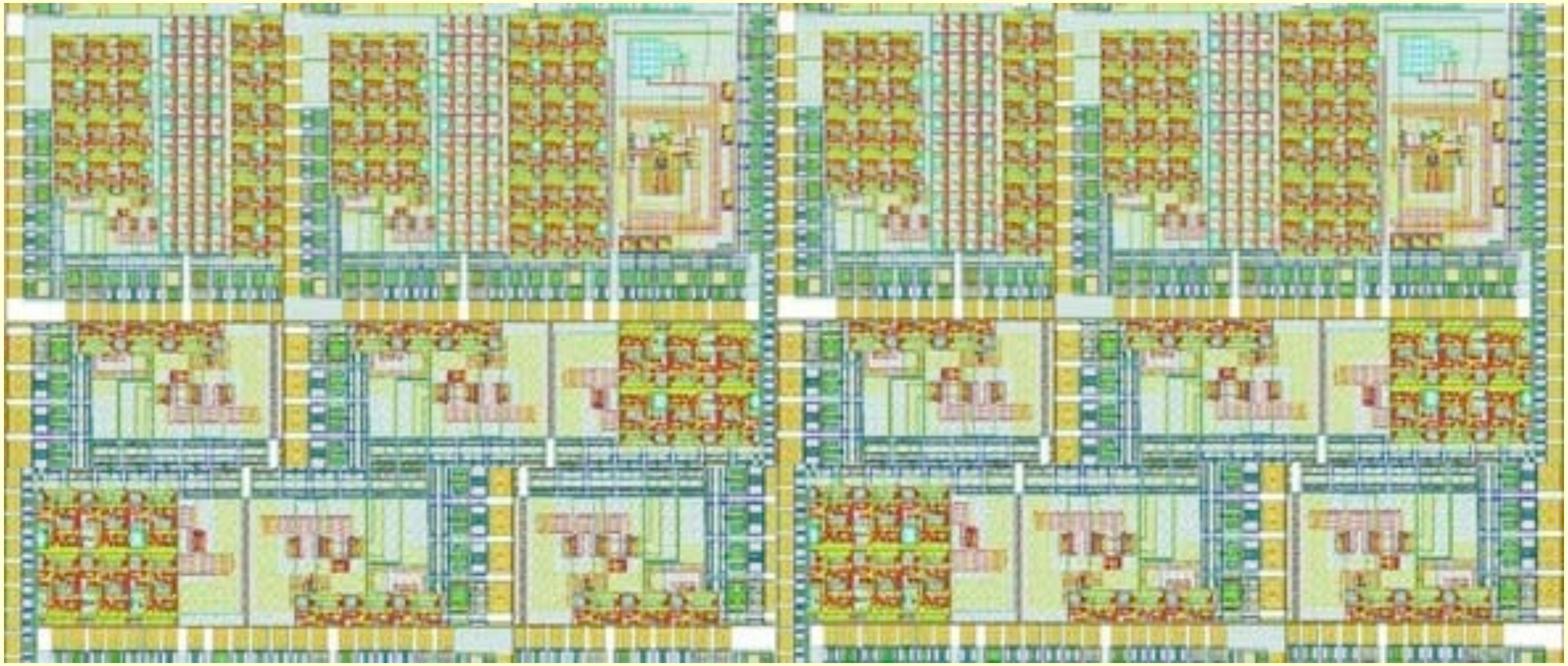
Kilby

Kilby's first integrated circuit



Noyce



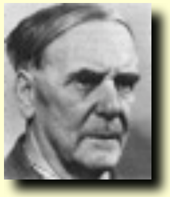



Integrated circuits

Selected discoveries in condensed matter physics

1911 Superconductivity - Kamerlingh-Onnes

1938 Supefluidity of helium II - Kapitsa



1947 Bardeen, Brattain, Shockley - transistor

1957 Bardeen, Cooper, Schrieffer - theory of superconductivity

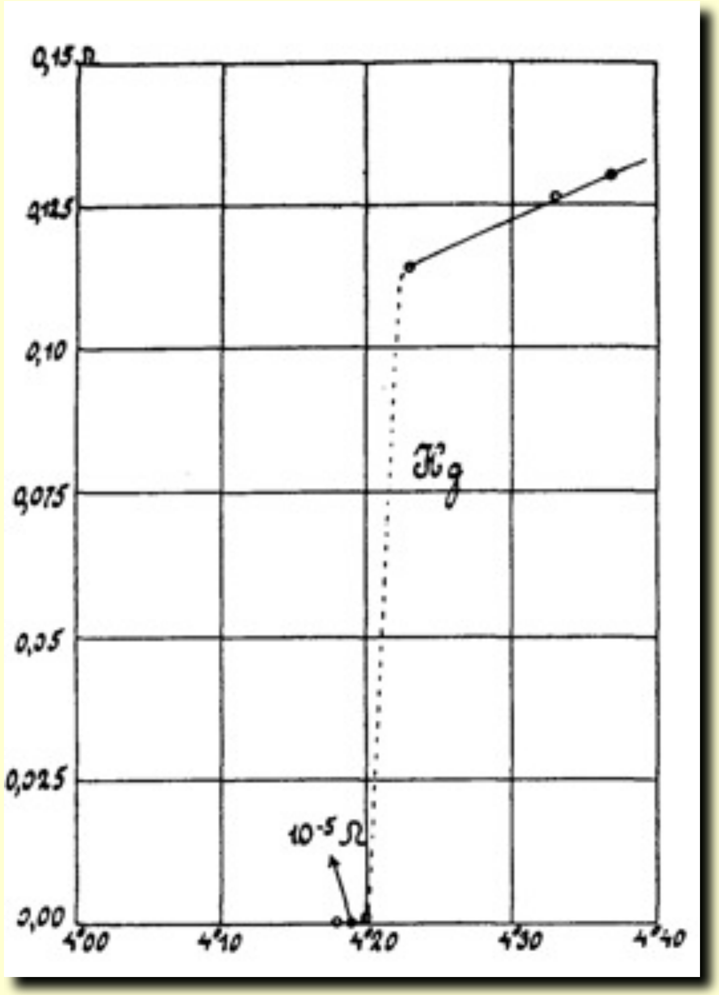
1958 Mössbauer effect

1962 Josephson effect

1980 Quantum Hall effect (von Klitzing, Dorda, Pepper)

1986 High T superconductivity (Bednorz, Müller)

Discovery of superconductivity (1911)



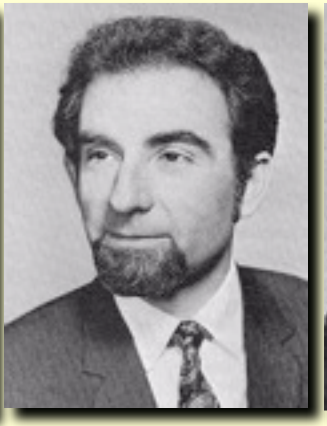
Heike Kamerlingh-Onnes (1853-1926)

Numerous attempts (Bethe, Bloch, Bohr, Born, Brillouin, Casimir, Feynman, Frenkel, Heisenberg, Landau, Pauli) to develop the theory of superconductivity were unsuccessful.

”I was so discouraged by my negative result that I saw no further way to progress and for a considerable time there was for me only the dubious satisfaction to see that others, without noticing it, kept on falling in the same trap. This brought me to the facetious statement that all theories of superconductivity can be disproved, later quoted in the more radical form of ‘Bloch theorem’: Superconductivity is impossible.”

Felix Bloch (1980)

John Bardeen



Leon Cooper

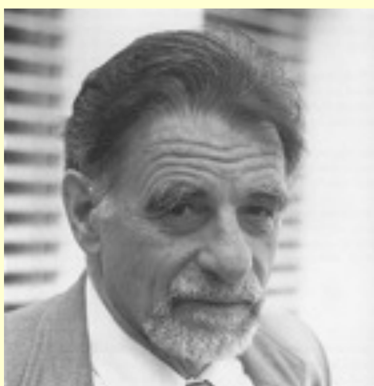
John Schreiffer

Finally, the breakthrough came in 1957, a when a new idea of ‘Cooper pairs’ appeared.

The ”BCS theory” was accepted as correct.

The discovery of superconductivity at high temperatures

J. Georg Bednorz



K. Alex Müller

J.G. Bednorz and K.A. Müller: Ba – La – Cu – O System

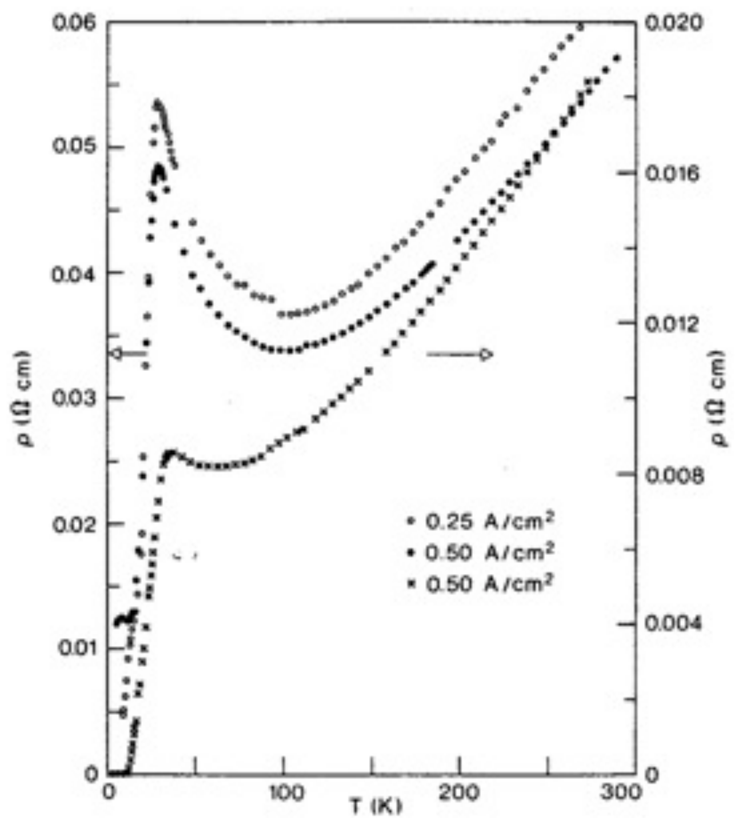
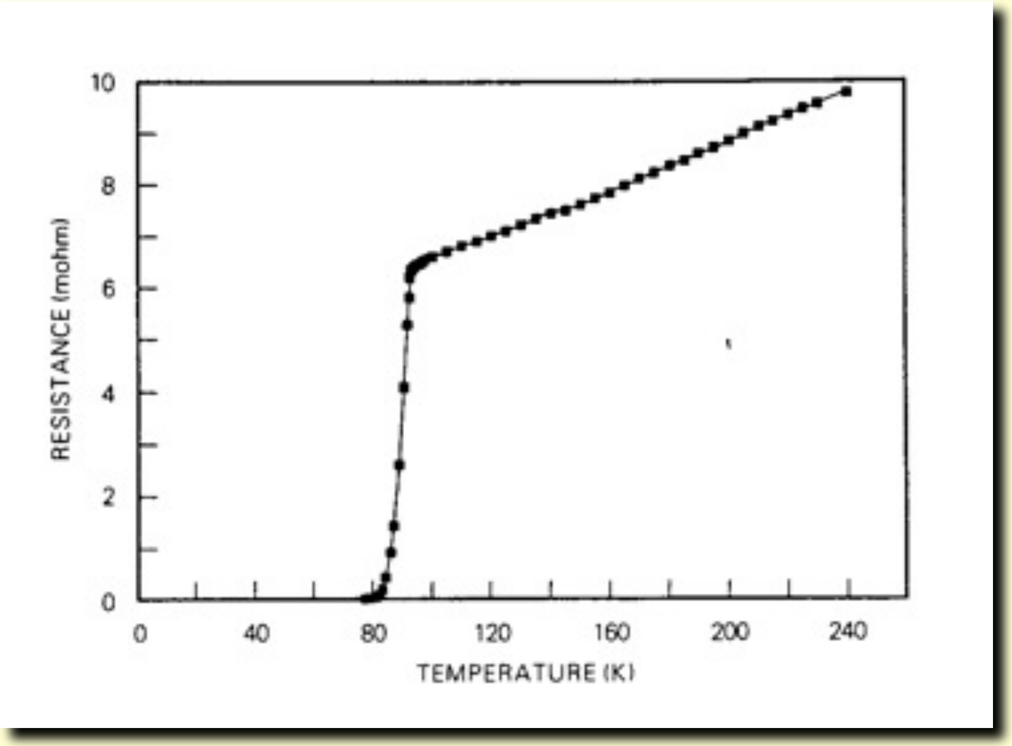


Fig. 1. Temperature dependence of resistivity in $Ba_xLa_{5-x}Cu_5O_{5(3-y)}$ for samples with $x(Ba) = 1$ (upper curves, left scale) and $x(Ba) = 0.75$ (lower curve, right scale). The first two cases also show the influence of current density

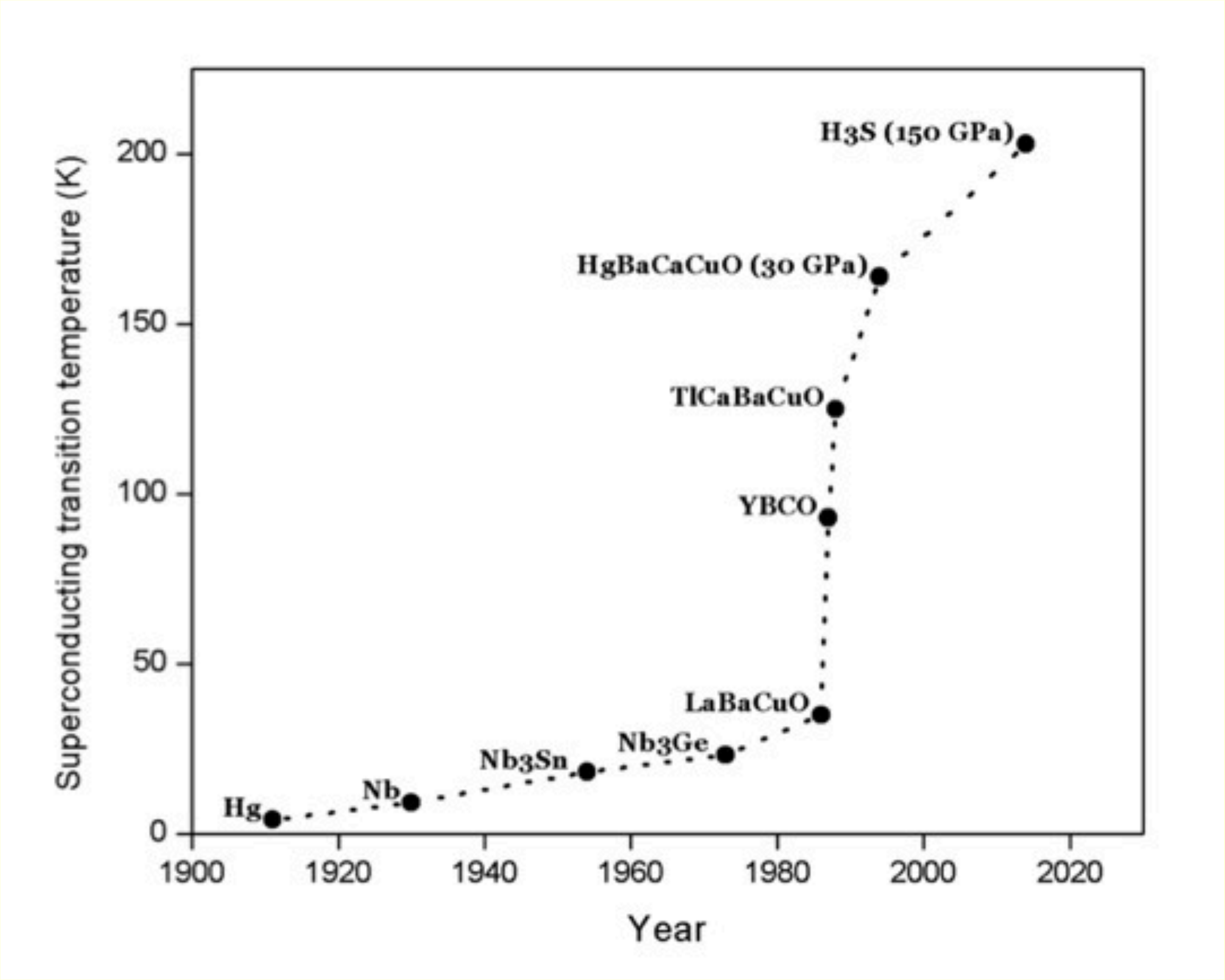
Z. Phys. **B64**, 189 (1986)

Superconductivity at high temperatures



First observation of superconductivity (in $YBa_2Cu_3O_7$) at temperatures above that of liquid nitrogen
M. K. Wu et al., Phys. Rev. **58**, 908 (1987)

Superconductivity at high temperatures

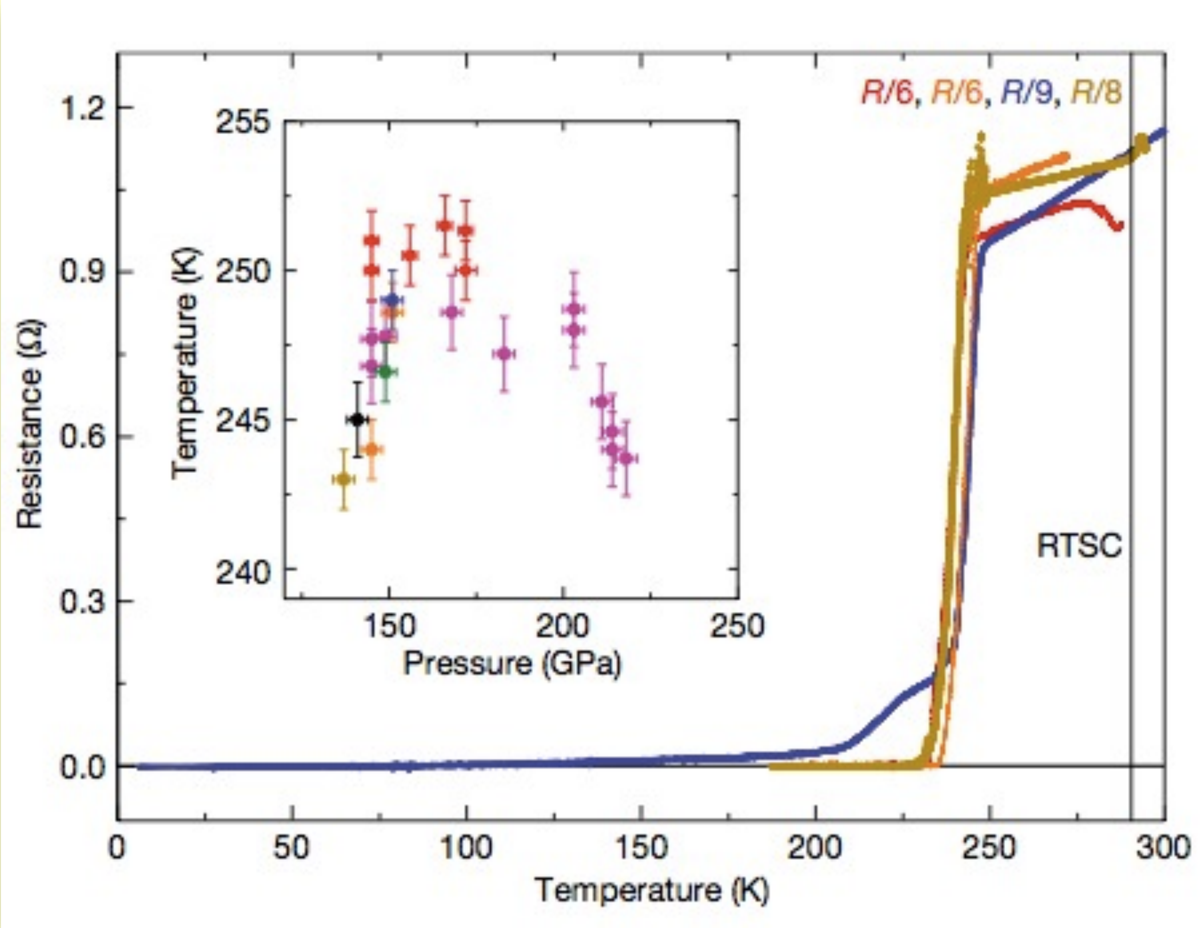


Superconductivity at high temperatures

Superconductivity at 250 K in lanthanum hydride under high pressures

A. P. Drozdov[1,7], P. P. Kong[1,7], V. S. Minkov[1,7], S. P. Besedin[1,7], M. A. Kuzovnikov[1,6,7], S. Mozaffari[2], L. Balicas[2], F. F. Balakirev[3], D. E. Graf[2], V. B. Prakapenka[4], E. Greenberg[4], D. A. Knyazev[1], M. Tkacz[5] & M. I. Eremets[1]*

Nature, May 23, 2019



Selected dates from the early history of magnetism studies

1895 P.Curie - Curie's law for paramagnetics,
Curie temperature

1905 Langevin - classic theory of paramagnetism
and diamagnetism

1907 Weiss – hypothesis of a molecular field

1907 Cotton & Mouton - birefringence in the magnetic field

1911 Bohr – falsification of the classic theory of diamagnetism

1911 Weiss - hypothesis of the (Weiss) magneton
- rejected only about 1930

1915 Barnett's effect, Einstein-DeHaas effect

1919 Barkhausen effect

Selected dates from the early history of magnetism studies

1925 Ising - ferromagnetic model

1926 Debye, Giauque - adiabatic demagnetisation of a paramagnetic

1927 Pauli - paramagnetism of electron gas (Pauli paramagnetism)

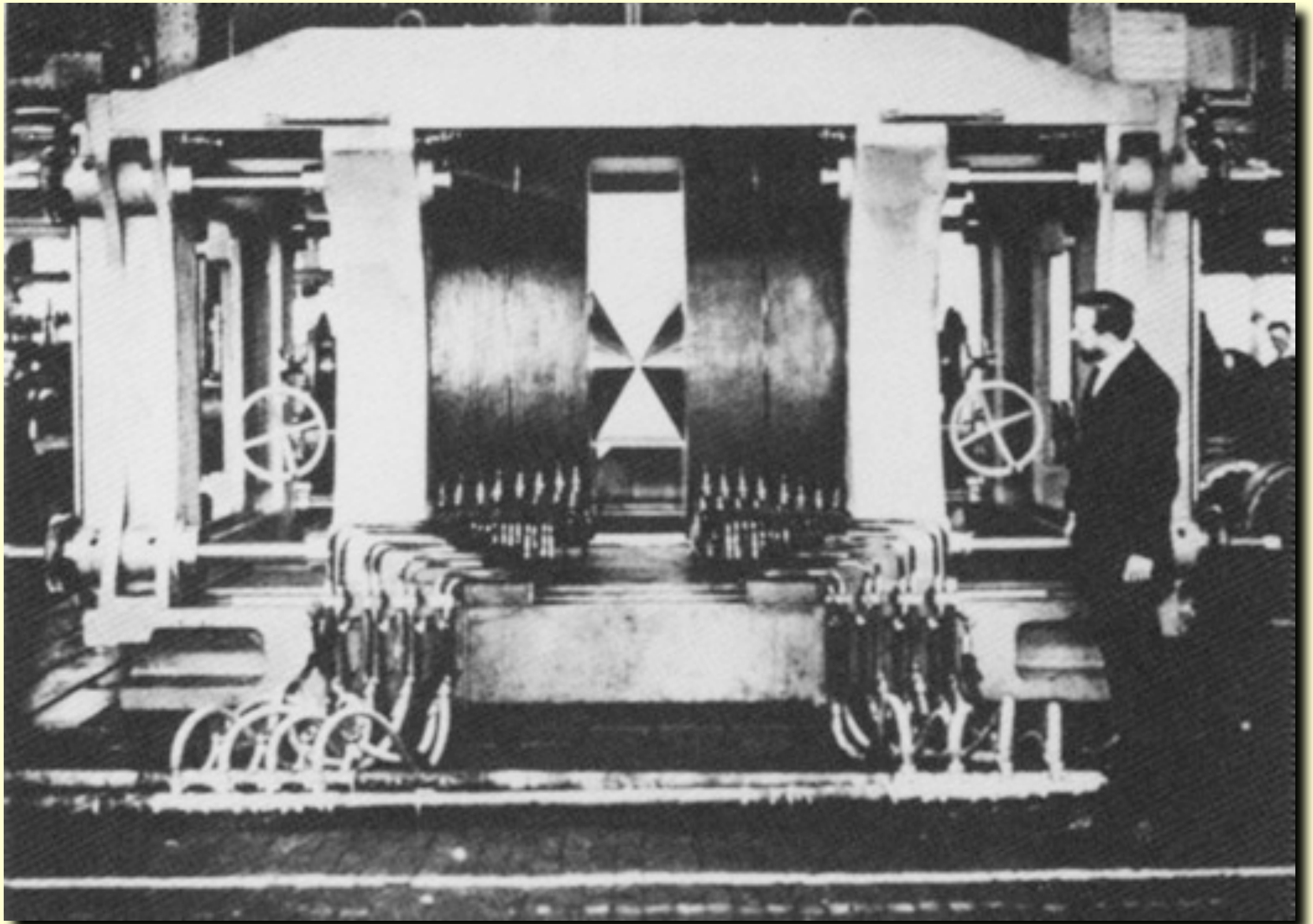
1927 Van Vleck - quantum theory of paramagnetism

1928 Heisenberg, Frenkel - first quantum theories of ferromagnetism

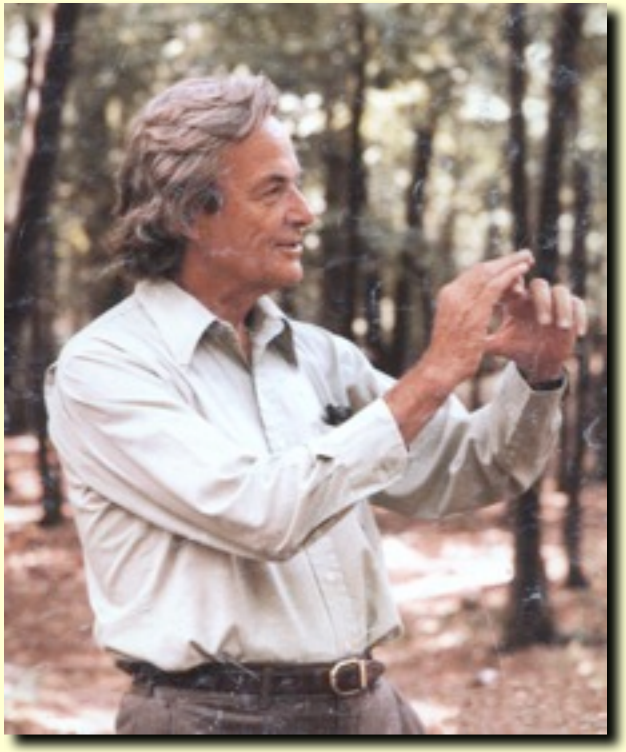
1930 Landau - quantum theory of diamagnetism of metals (Landau diamagnetism)

1932 Neél - antiferromagnetism, ferrimagnetism

The beginnings of ”Big Science”



Great magnet of Aimé Cotton (1920s)



„There's plenty of room at the bottom"

Richard Feynman (1959)

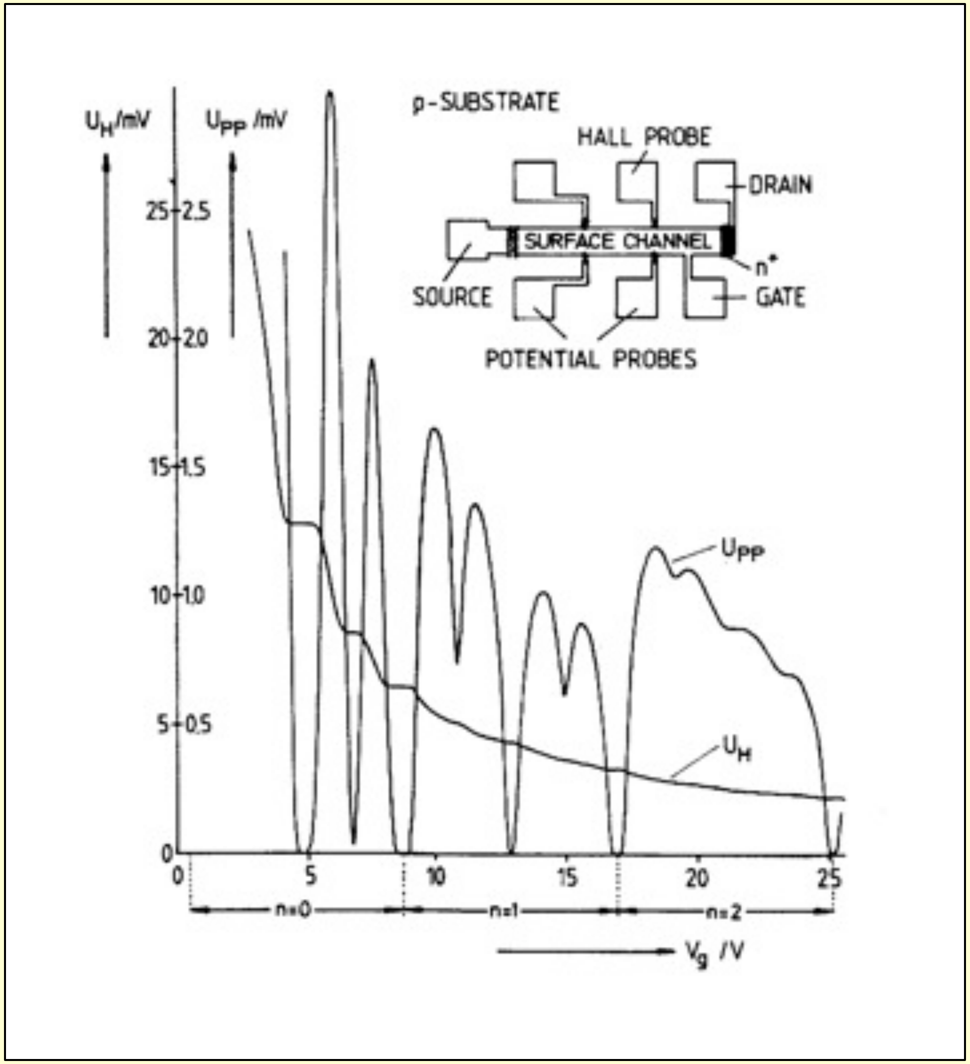
Low dimensional structures

- planar – semiconductor layers, electrons may move freely in two dimensions
- linear (**quantum wires**) – motion of electrons in one dimension only, along the quantum wire
- zero dimensional (**quantum dots**) – electrons are bound and cannot move

Important discoveries: quantum Hall effect (1980)
fractional quantum Hall effect (1982)

Great importance of nanophysics for technology of the XXIst century

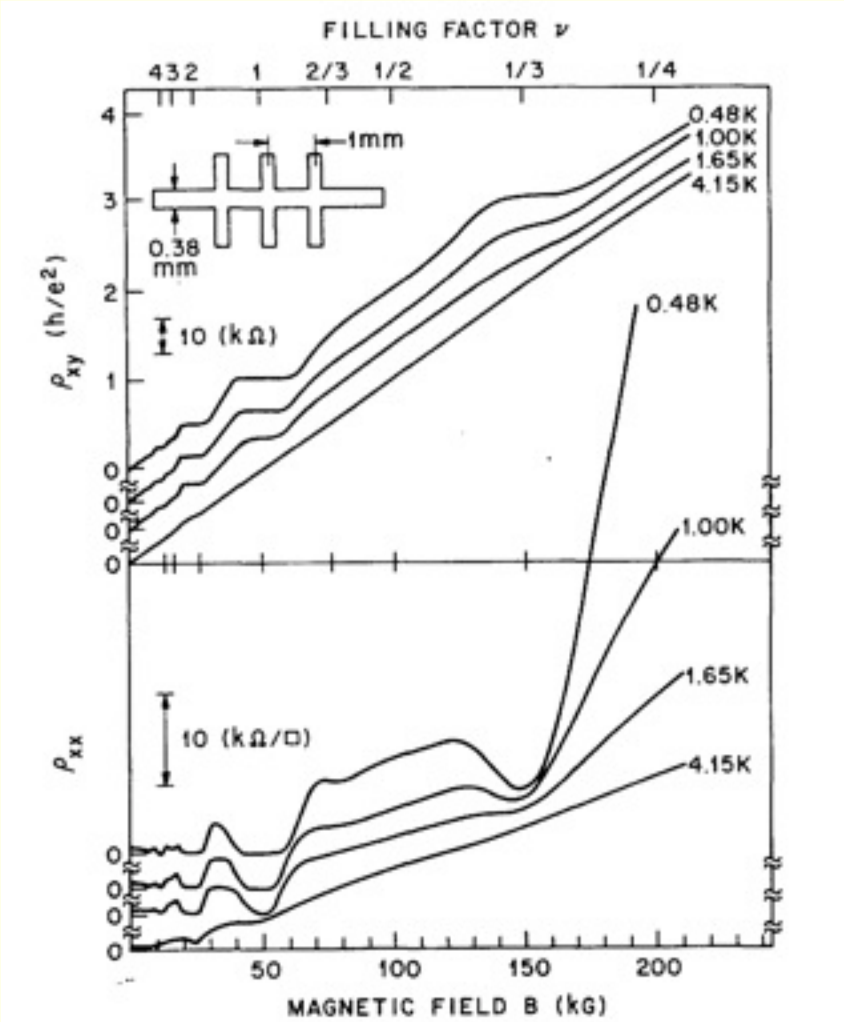
Quantum Hall effect



Klaus von Klitzing

K. v. Klitzing, G. Dorda, M. Pepper, Phys. Rev. Letters **45**, 494 (1980)

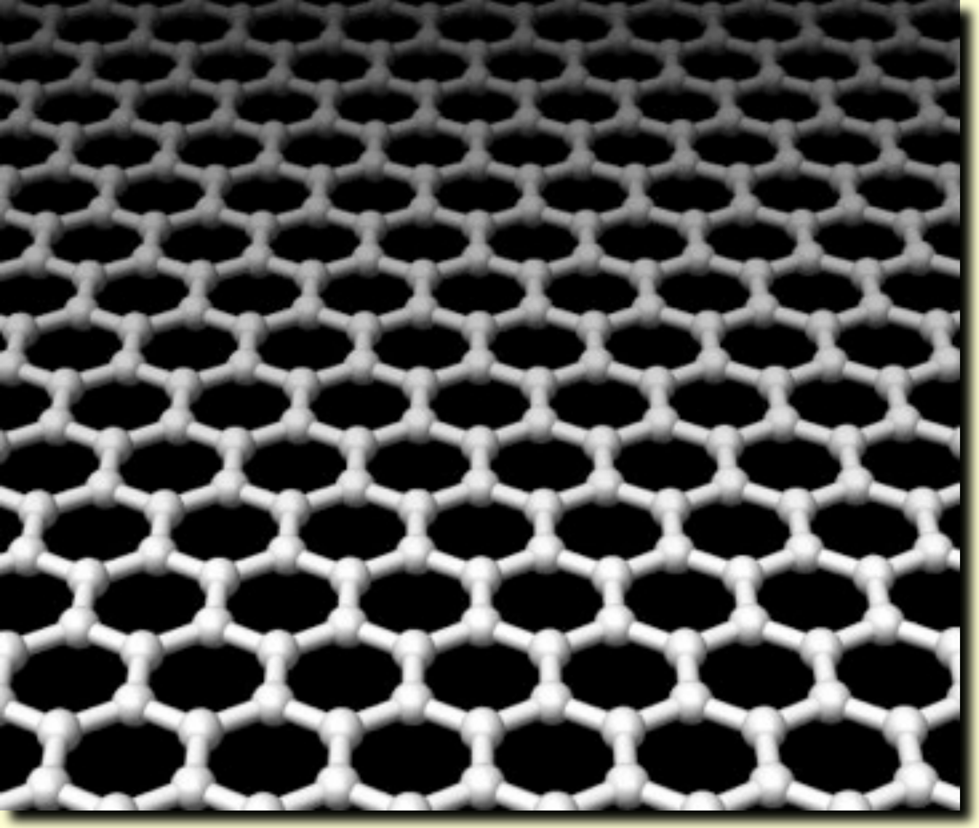
Fractional quantum Hall effect



Daniel Tsui

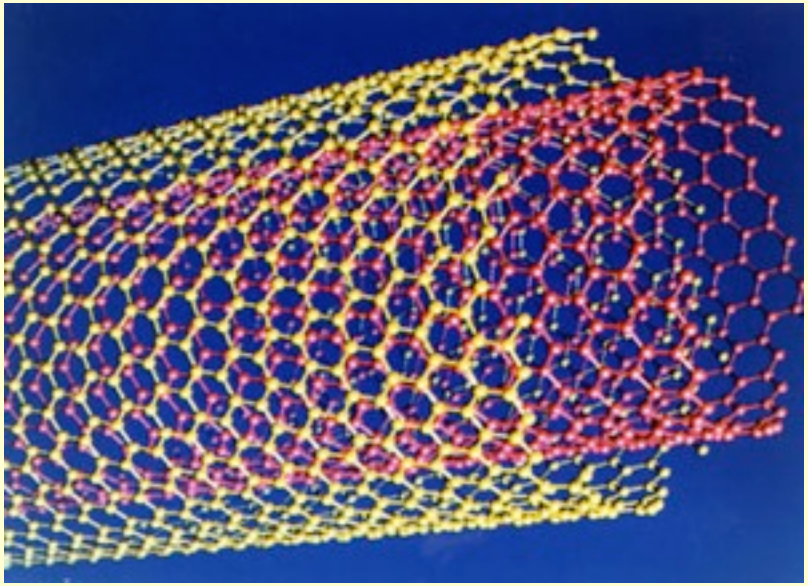
Horst Stormer

D. C. Tsui, H. L. Stormer, A. C. Gossard, Phys. Rev. Letters **48**, 1559 (1982)

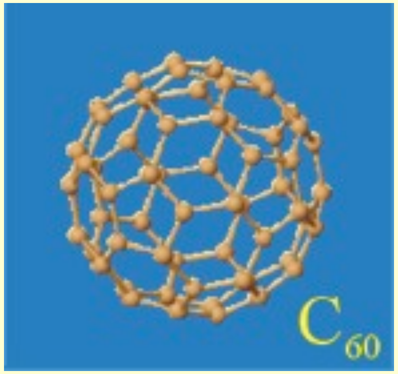


Graphene

Konstantin Novoselov & Andre Geim
Nobel Prize for Physics 2010



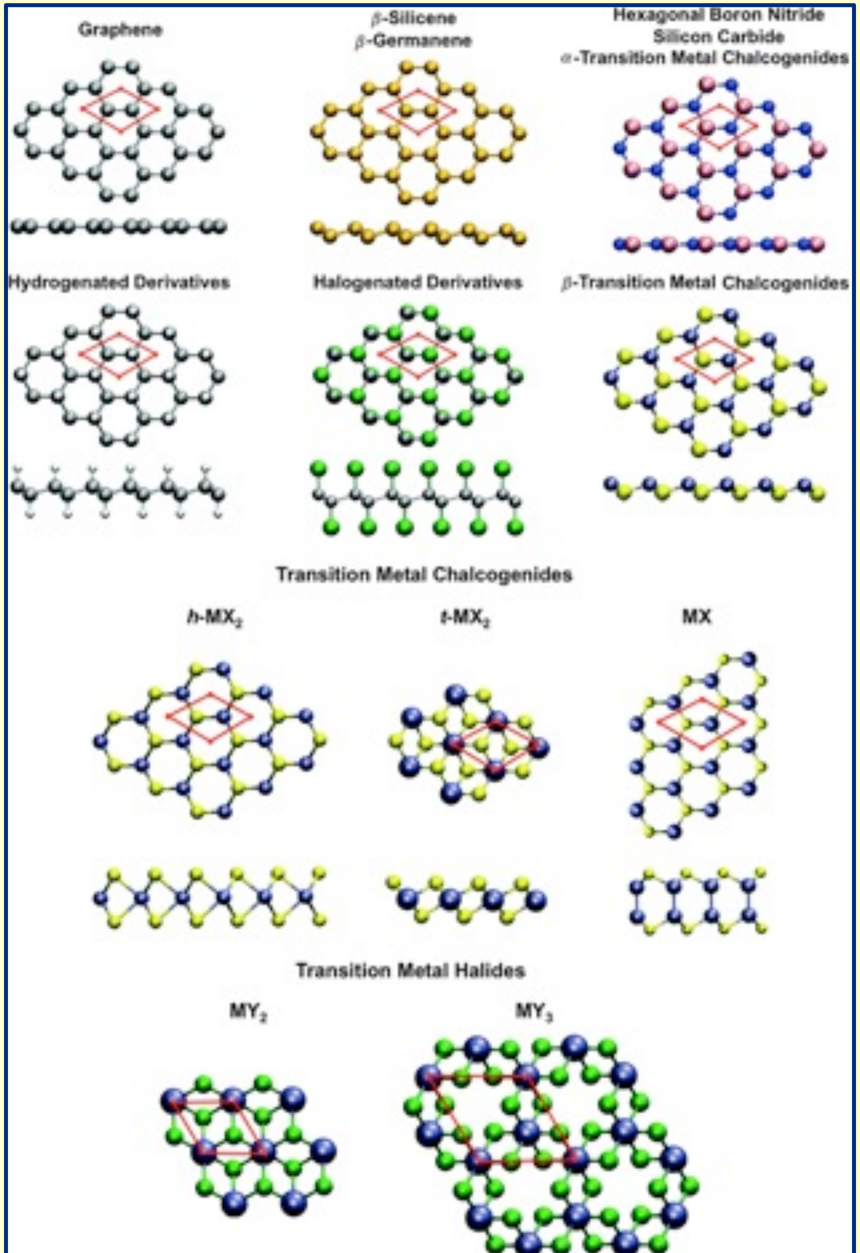
carbon nanotubes

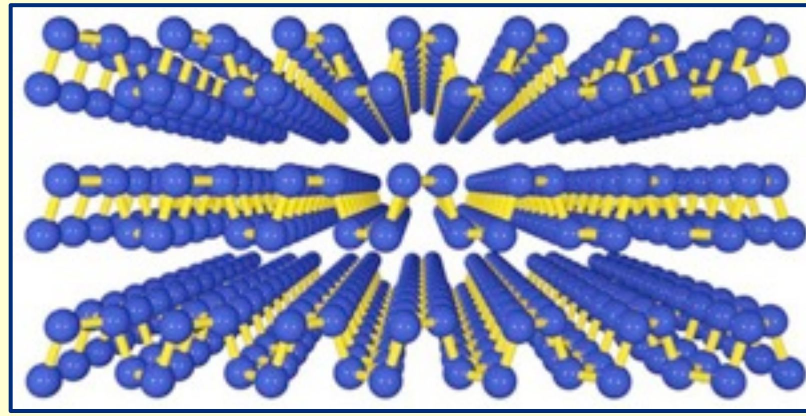


fullerene

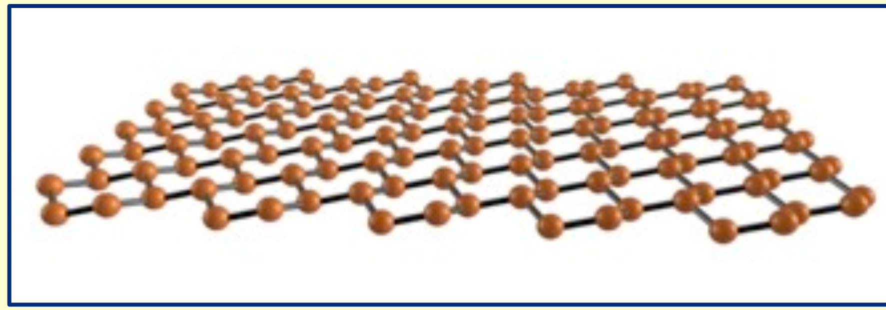
new discoveries: phosphorene, silicene.....

2D materials

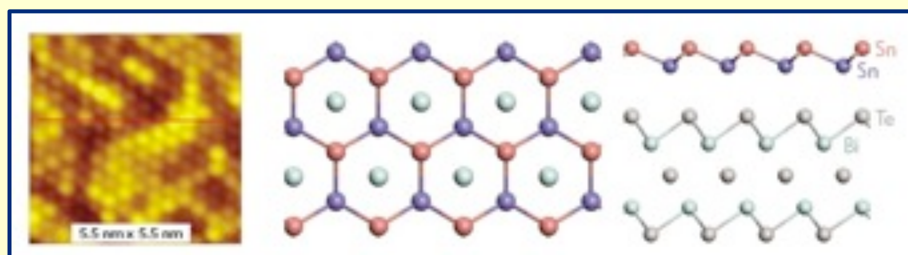




phosphorene

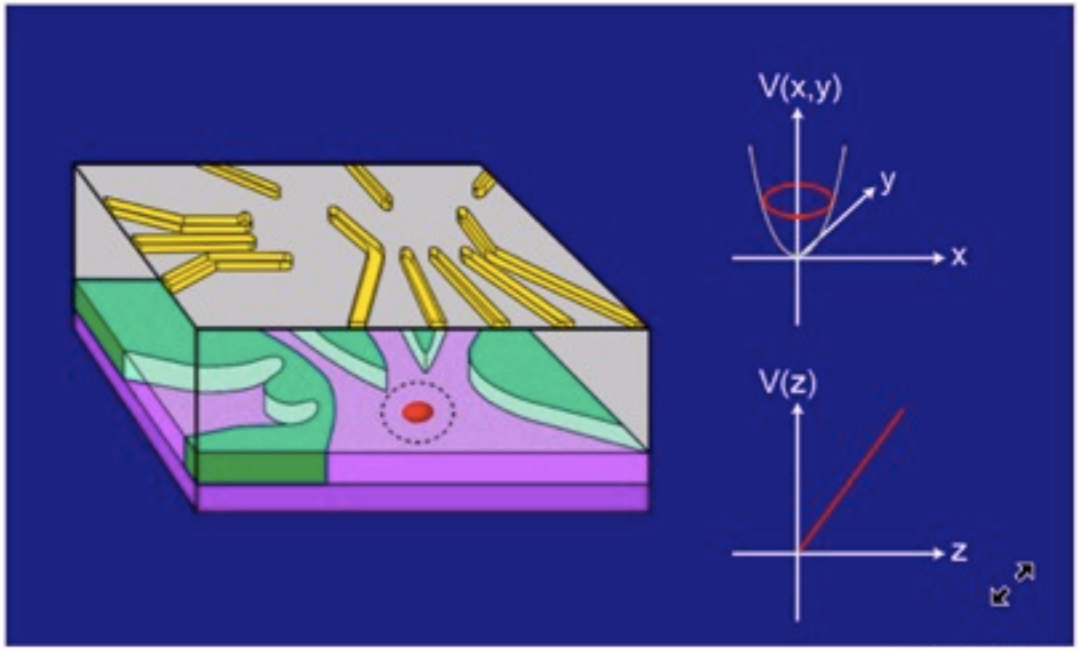


silicene



stanene

A new experimental method provides a way to determine the 3D confining potential of an electron in a quantum dot, allowing improved control over the electron's spin.



APS/Joan Tycko

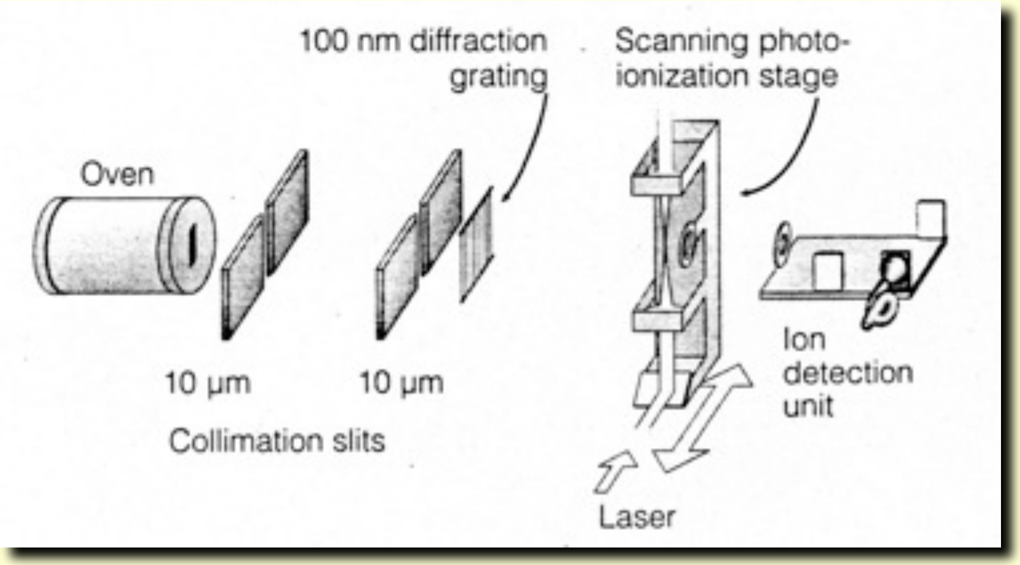
Figure 1: A sketch of the device used by Camenzind and colleagues to create a single-electron quantum dot (red ellipsoid inside dotted circle) [3]. The team demonstrated a technique for characterizing the confining potential of such a dot.

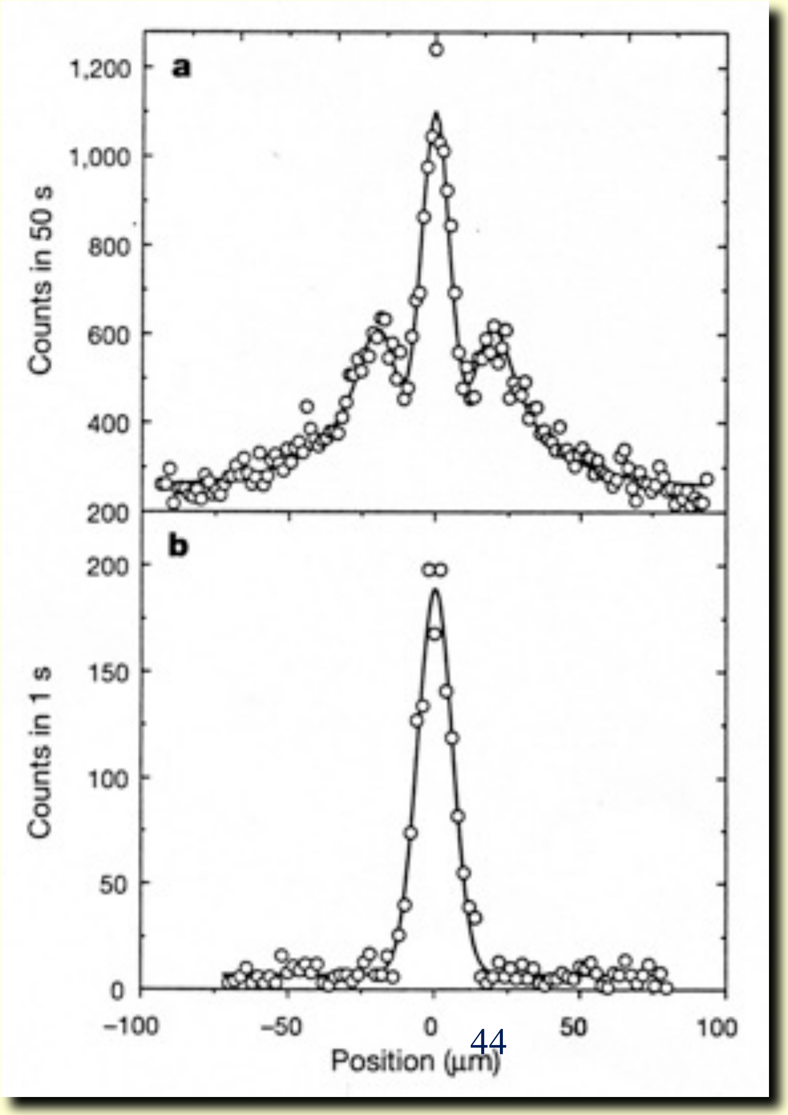
L. C. Camenzind, L. Yu, P. Stano, Zimmerman, A. C. Gossard, D. Loss, and D. M. Zumbühl, "Spectroscopy of quantum dot orbitals with in-plane magnetic fields," **Phys. Rev. Lett. 122, 207701 (2019)**.

May 22, 2019

Quantum mechanics in a macro-scale

Diffraction of C_{60} molecules

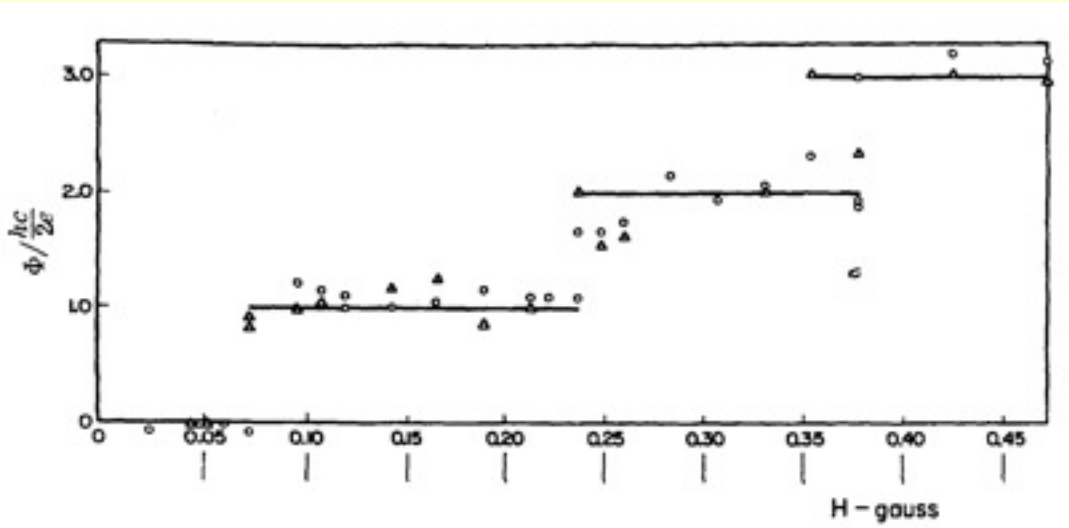




Nature (1999)

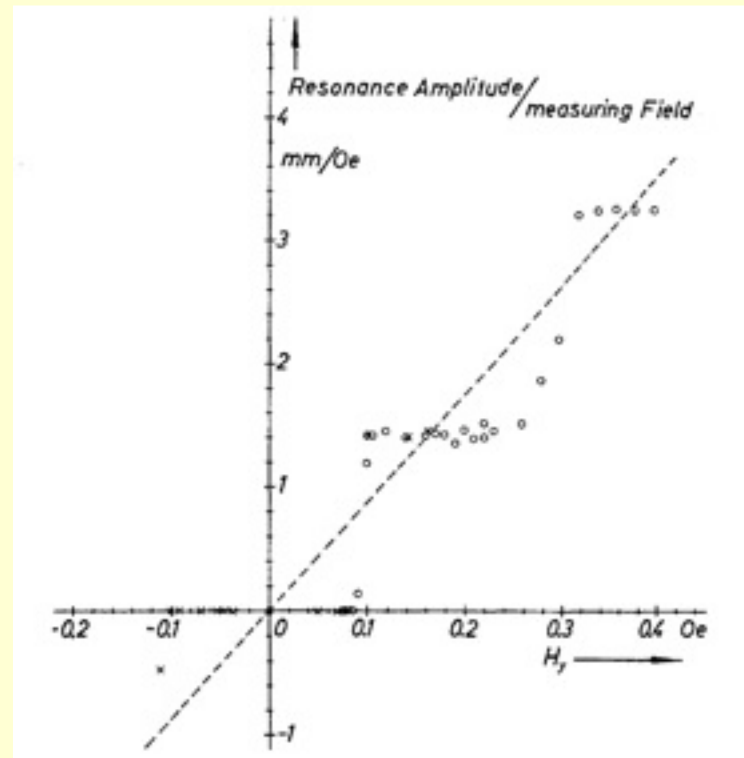
Quantum mechanics in a macro-scale

Quantization ot the magnetic flux in a superconducting cylinder



B. S. Deaver, W. M. Fairbank,
Phys. Rev. Lett. **7**, 43 (1961)

R. Doll, M. Näbauer,
Phys. Rev. Lett. **7**, 51 (1961)



Quantum mechanics in a macro-scale

Dependence of the Josephson current on the magnetic field

J. M. Rowell, Phys. Rev. Lett. **11**, 200 (1963)

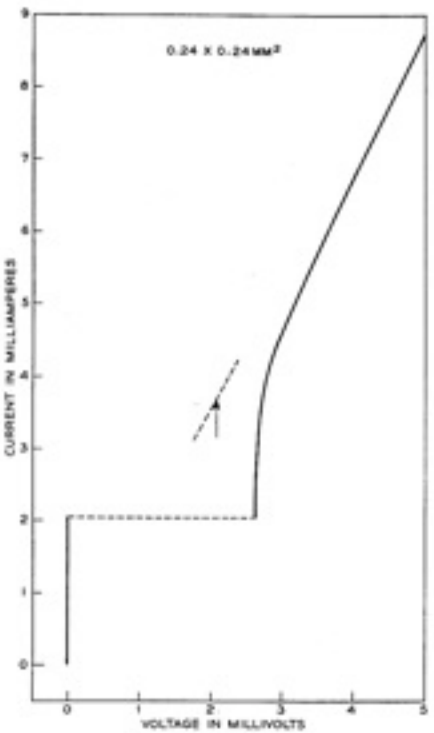


FIG. 1. Current-voltage characteristic for a Pb-I-Pb junction at 1.3°K. The arrow marks the predicted maximum magnitude of the Josephson current.

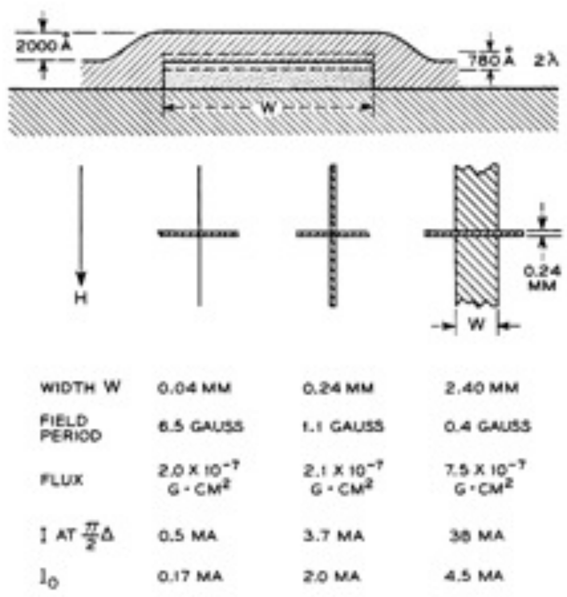


FIG. 2. Comparison of the dimensions of three junctions and the magnitude and field dependence of the Josephson current.

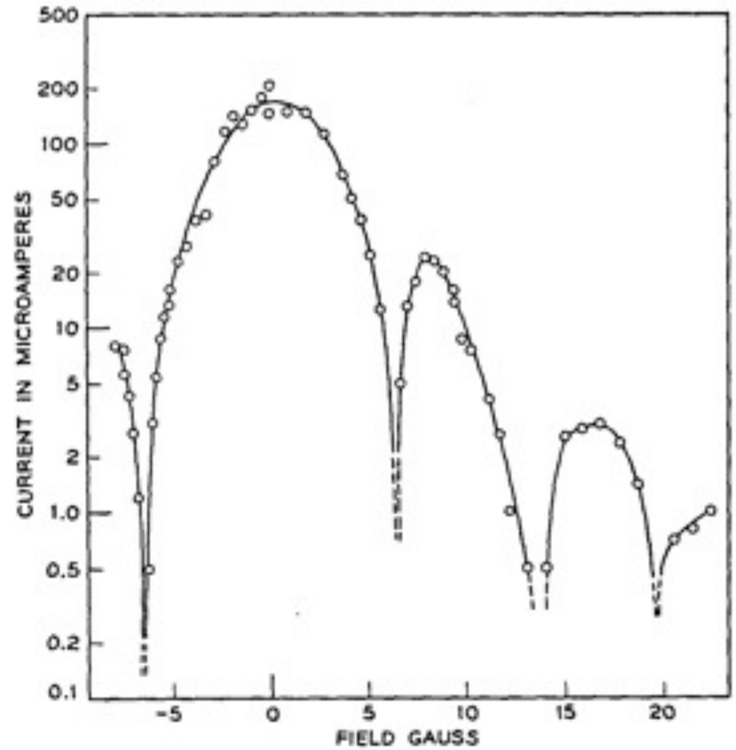
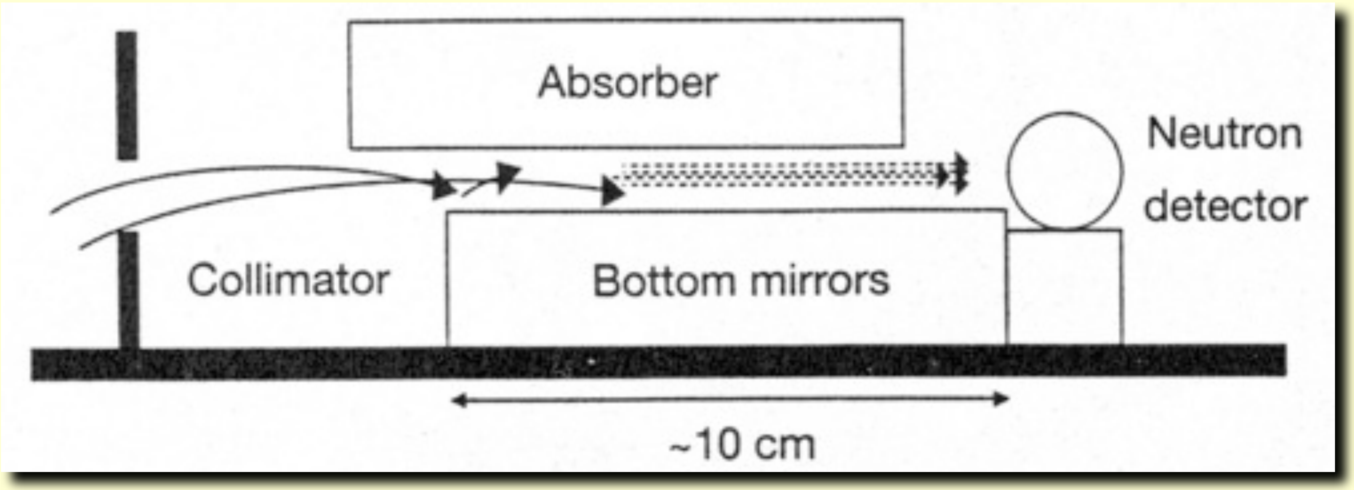
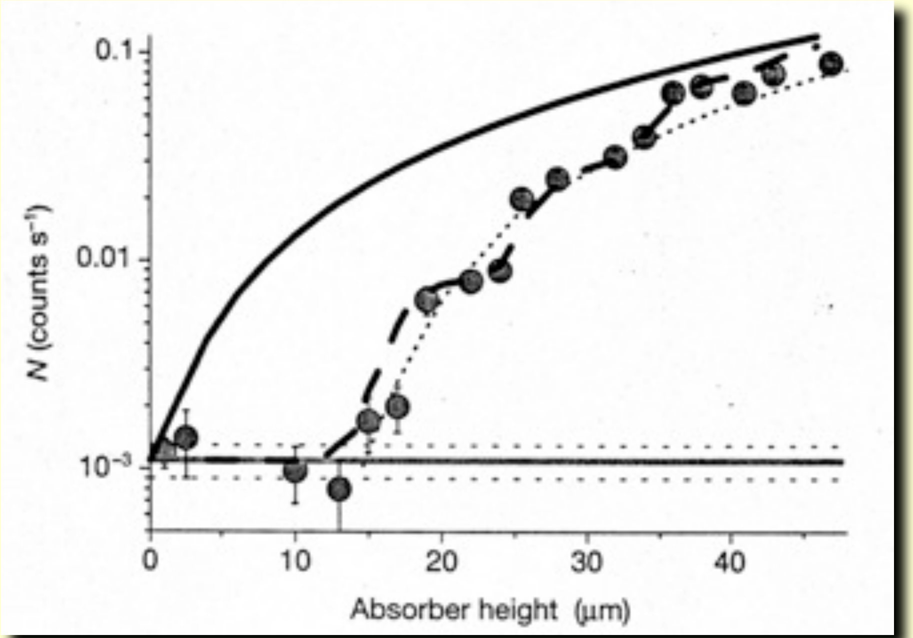


FIG. 3. The field dependence of the Josephson current in a Pb-I-Pb junction at 1.3°K.

Quantum mechanics in a macro-scale

Quantized energy states of neutrons in the gravitational field





Nature (2002)

Selected dates from the history of modern optics

1948 Principle of holography - Dennis Gabor

(the principle of two-step reconstruction was discovered and proposed already in 1920 by Mieczysław Wolfke [*Phys. Zeit.* **21**, 495 (1920)]

1950 Optical pumping method - Alfred Kastler

1954 First (ammonia) maser - Charles Townes,
James Gordon, Herbert Zeiger

1955 Three-level maser - Nikolai Basow, Alexandr Prokhorow

1958 Laser principle - Charles Townes, Arthur Schawlow

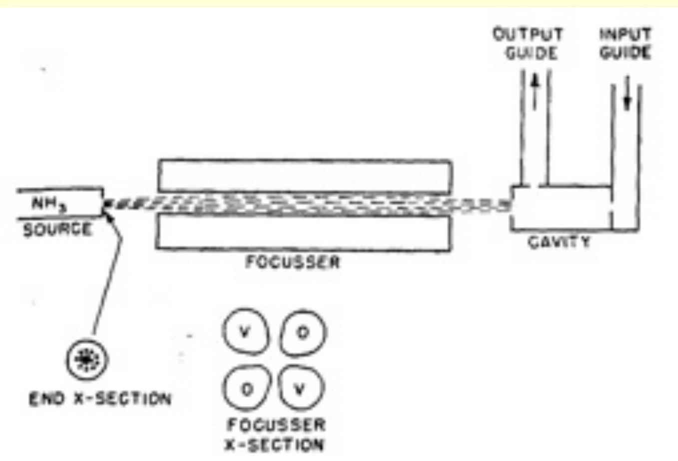
1960 First (ruby) laser - Theodore Maiman

1962 Optical holography realised with the use of lasers
- Emmett Leith, Juris Upatnieks

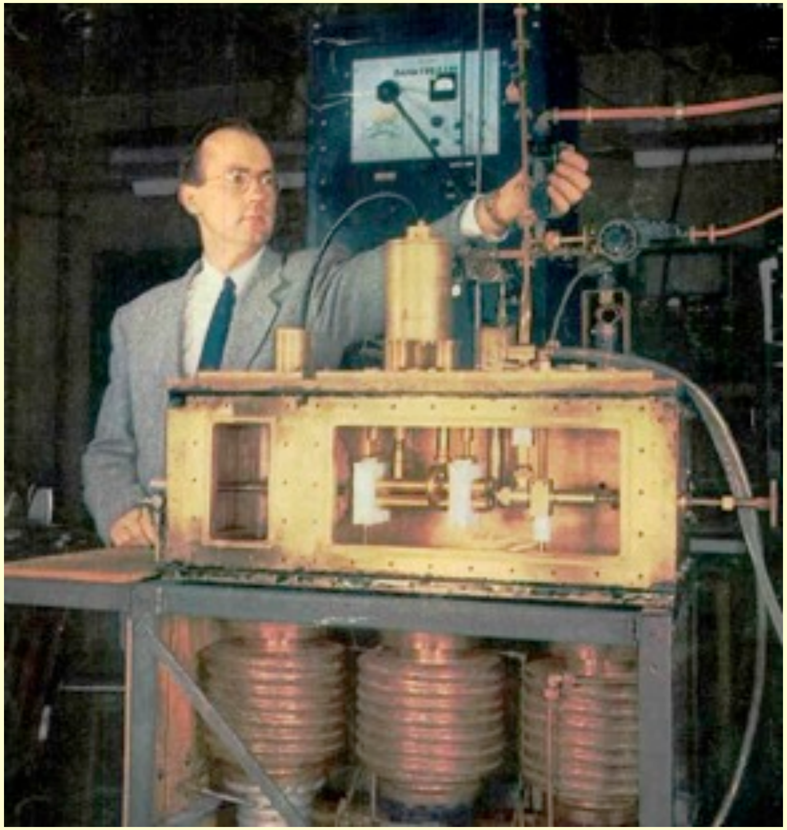
The first maser

(**M**icrowave **A**mplification by **S**timulated **E**mission of **R**adiation)

Charles Townes



Scheme of the first maser



J. P. Gordon, H. J. Zeiger, and C. H. Townes, Phys. Rev. **95**, 282 (1954)

”One day... Rabi and Kusch, the former and current chairmen of the department - both of them Nobel laureates for work with atomic and molecular beams, and both with a lot of weight behind their opinions – came into my office and sat down... ‘Look – they said – you should stop the work you are doing. It isn’t going to work. You know it’s not going to work. We know it’s not going to work. You are wasting money. Just stop!’ ...Llewelyn H. Thomas, a noted Columbia theorist, told me that the maser flatly could not, due to basic physics principles, provide a pure frequency with the perfomance I predicted. So certain was he that he more or less refused to listen to my explanations. After it did work, he just stopped talking to me. A younger physicist in the department, even after the first successful operation of the device, bet me a bottle of scotch that it was not doing what we said it would (he paid up).”

Charles Townes - *How the laser happened*

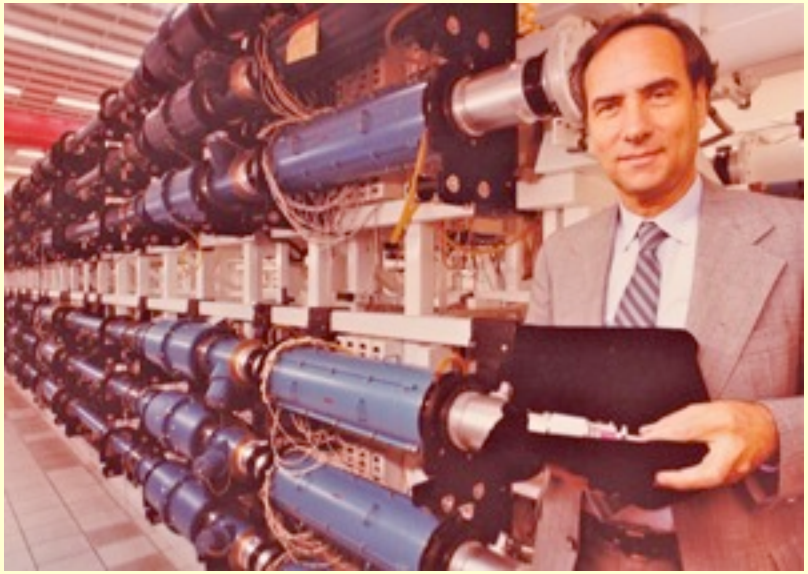
”Shortly after we built a second maser and showed that the frequency was indeed remarkably pure, I visited Denmark and saw Niels Bohr...As we were walking along the street together, he quite naturally asked what I was doing. I described the maser and its performance. ‘But that is not possible,’ he exclaimed. I assured him that it was. Similarly, at a cocktail party in Princeton, New Jersey, the Hungarian mathematician John von Neumann asked what I was working on. After I told him about the maser and the purity of its frequency, he declared, ‘That can’t be right’. But it was, I replied, and told him it was already demonstrated.”

Charles Townes - *How the laser happened*

The first laser

Light **A**mplification by **S**timulated **E**mission of **R**adiation

The first laser of Maiman



Theodore Maiman

T. Maiman, Nature **187**, 493 (1960)

Largest and smallest lasers

SHIVA Laser
(1977)

NOVA Laser (1984)
$15 \cdot 10^{12}$ W in $3 \cdot 10^{-9}$ s

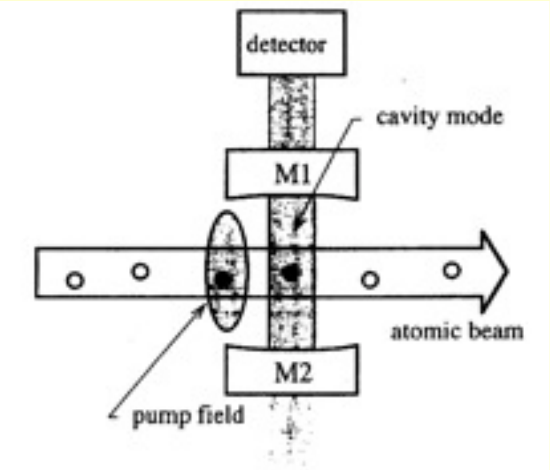
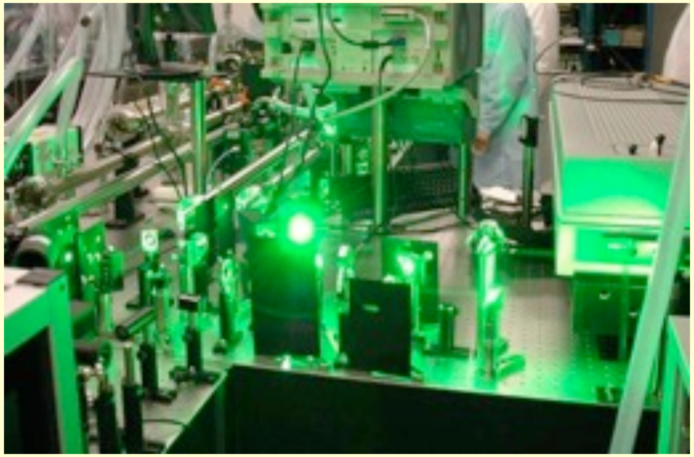


FIG. 1. Schematic of a microlaser experiment.

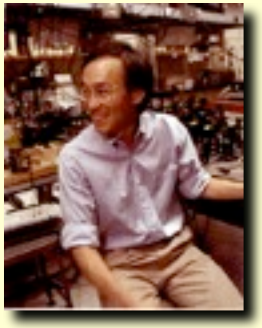
”Microlaser: A laser with one atom in an optical resonator”, Kyungwong An, James J. Child, Ramachandra R. Dasari, Michael S. Feld, *Phys. Rev. Lett.* **73**, 3375 (1994)

LFEX (Osaka)
$2 \cdot 10^{15}$ W in 10^{-12} s



Texas Petawatt Laser
10^{15} W in 10^{-12} s

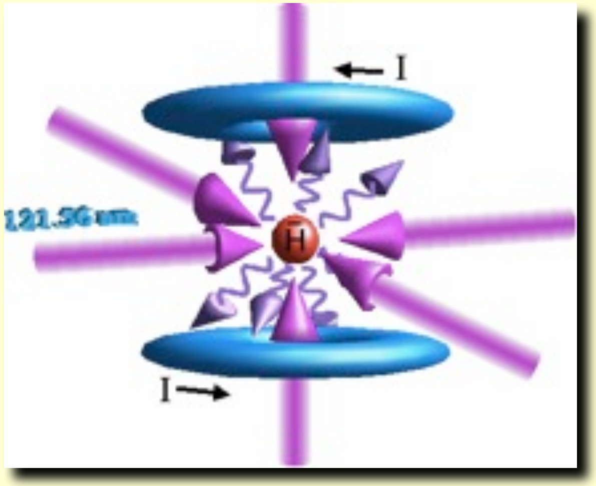
Nobel Prize for physics (1997): For developing methods of cooling and trapping atoms by laser light



Steven Chu (USA)

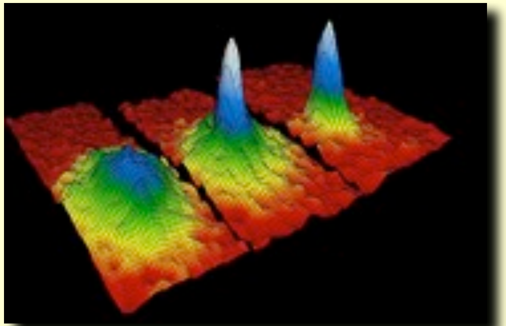
Claude Cohen-Tannoudji (France)

William D. Phillips (USA)

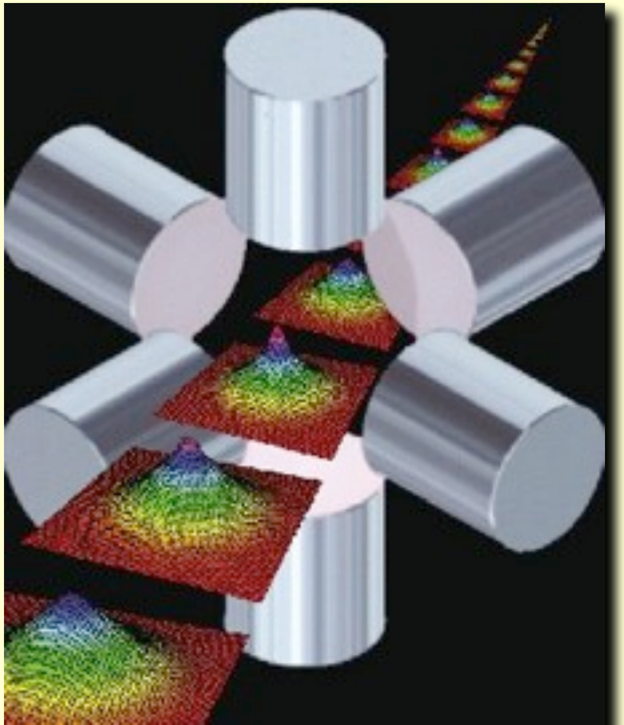


Nobel Prize for physics (2001): For creating Bose-Einstein condensate in ultra-cold rubidium gas

Eric A. Cornell (USA)



Wolfgang Ketterle (Germany)



Carl E. Wieman (USA)