Nanoelectronics: Besides and Beyond Moore

Wilfred G. van der Wiel

MESA$^+$ Institute for Nanotechnology
University of Twente, The Netherlands

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Contents of this lecture

- A brief history of electronics
- Single-electron transistors and quantum dots
- Organic electronics
- Spintronics

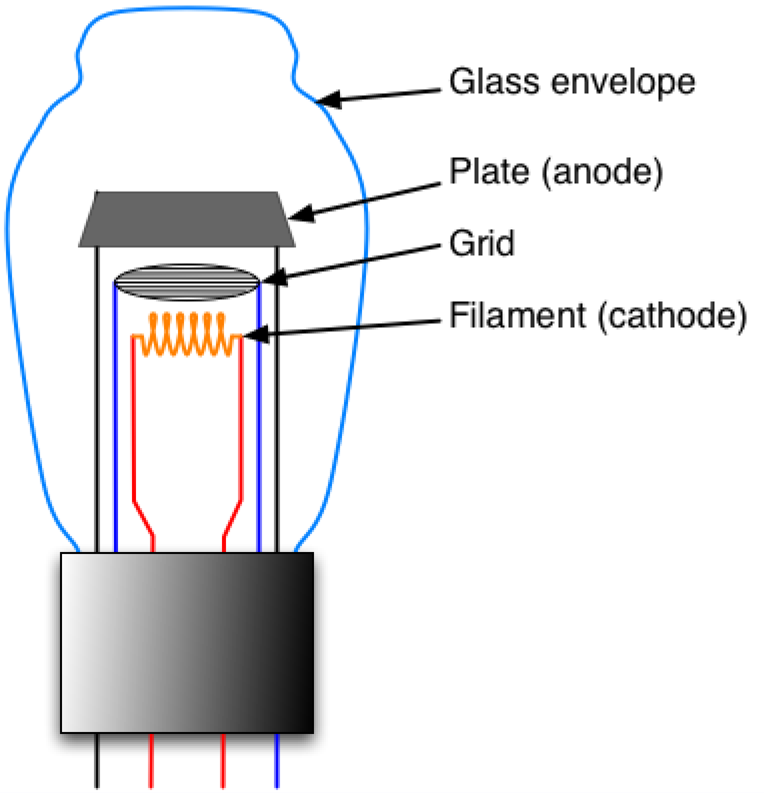
A brief history of electronics

Breakthroughs:

1920s:	semiconductor components ([photo]diodes)
1925:	idea of the field effect transistor (FET)
1947:	first working transistor
1959:	the integrated circuit (IC)
1960:	the first metal-oxide-silicon (MOS) transistor
1970:	solid state memories; the microprocessor
1980:	the PC
1990s:	ubiquitous internet and cellular phones

Electronic “work horses”

vacuum tube (end 19th century)

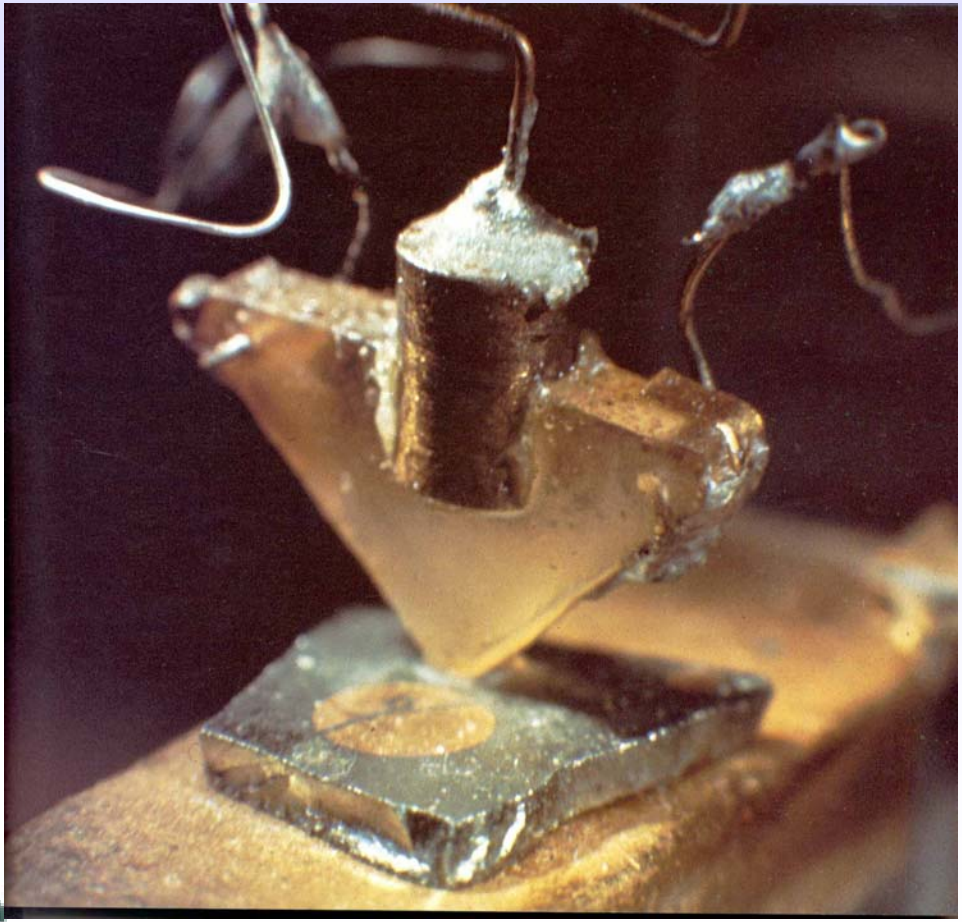


- slow
- bulky
- fragile
- consumes a lot of power

1947: first transistor

point contact transistor

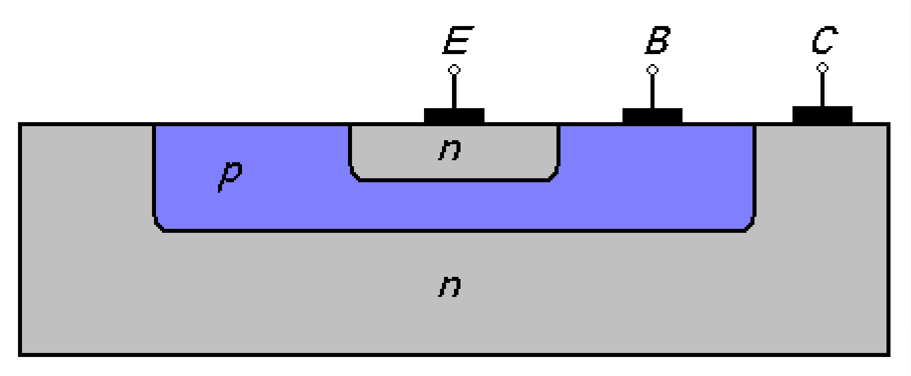
- 2 metal wires on n-Ge
- hard to make, not practical



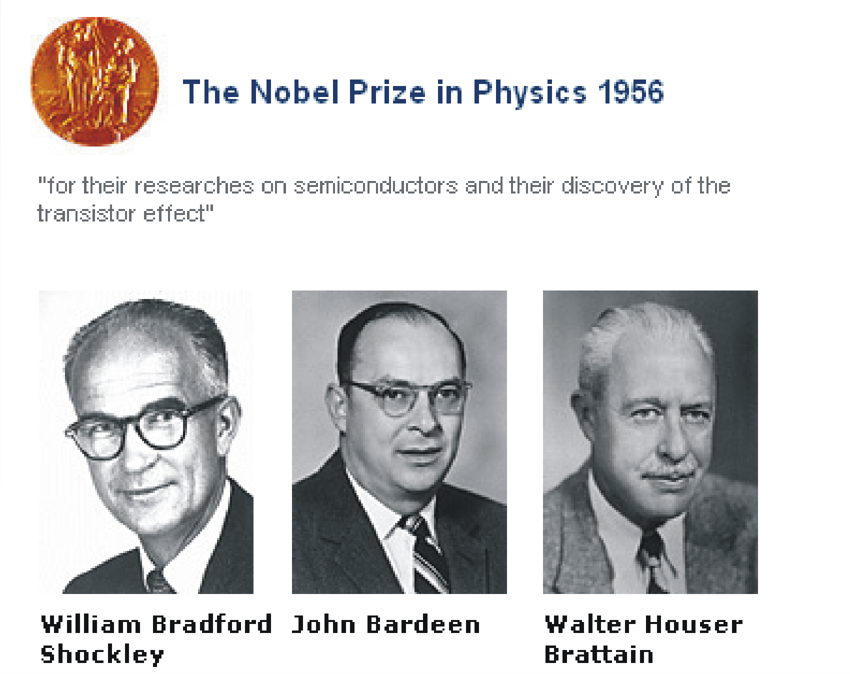
Electronic “work horses”

bipolar junction transistor (BJT)

- invented at Bell Labs in 1947
- bipolar: both holes and electrons carry the current
- now largely replaced by CMOS technology, but still used for specific applications (e.g. radio-frequency circuits)



cross section of an npn BJT



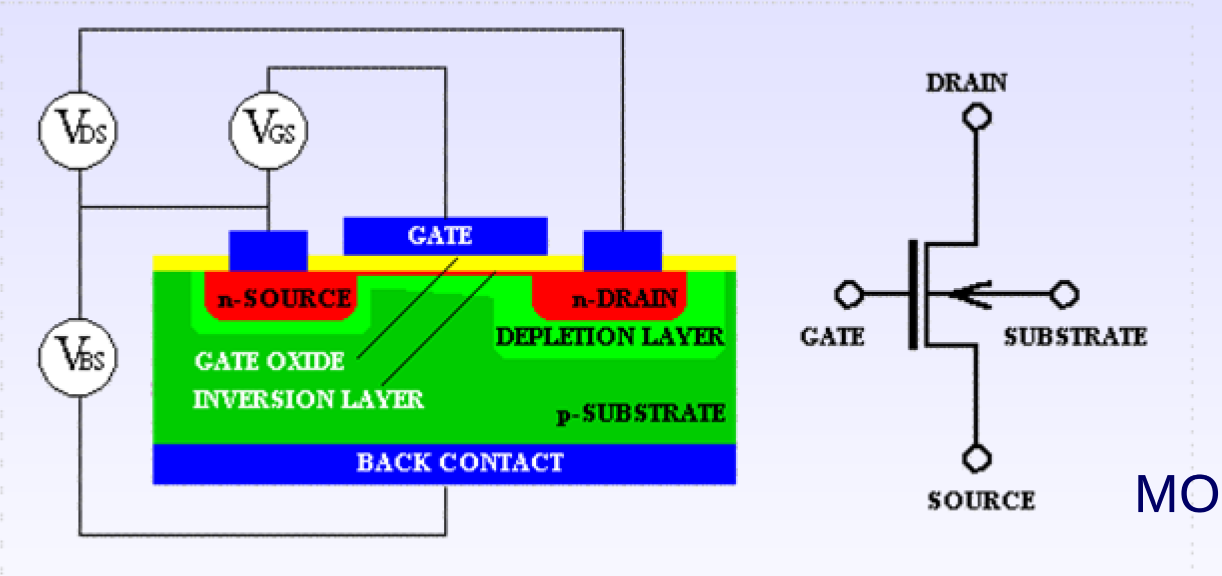
The Nobel Prize in Physics 1956

"for their researches on semiconductors and their discovery of the transistor effect"

William Bradford Shockley **John Bardeen** **Walter Houser Brattain**

Electronic “work horses”

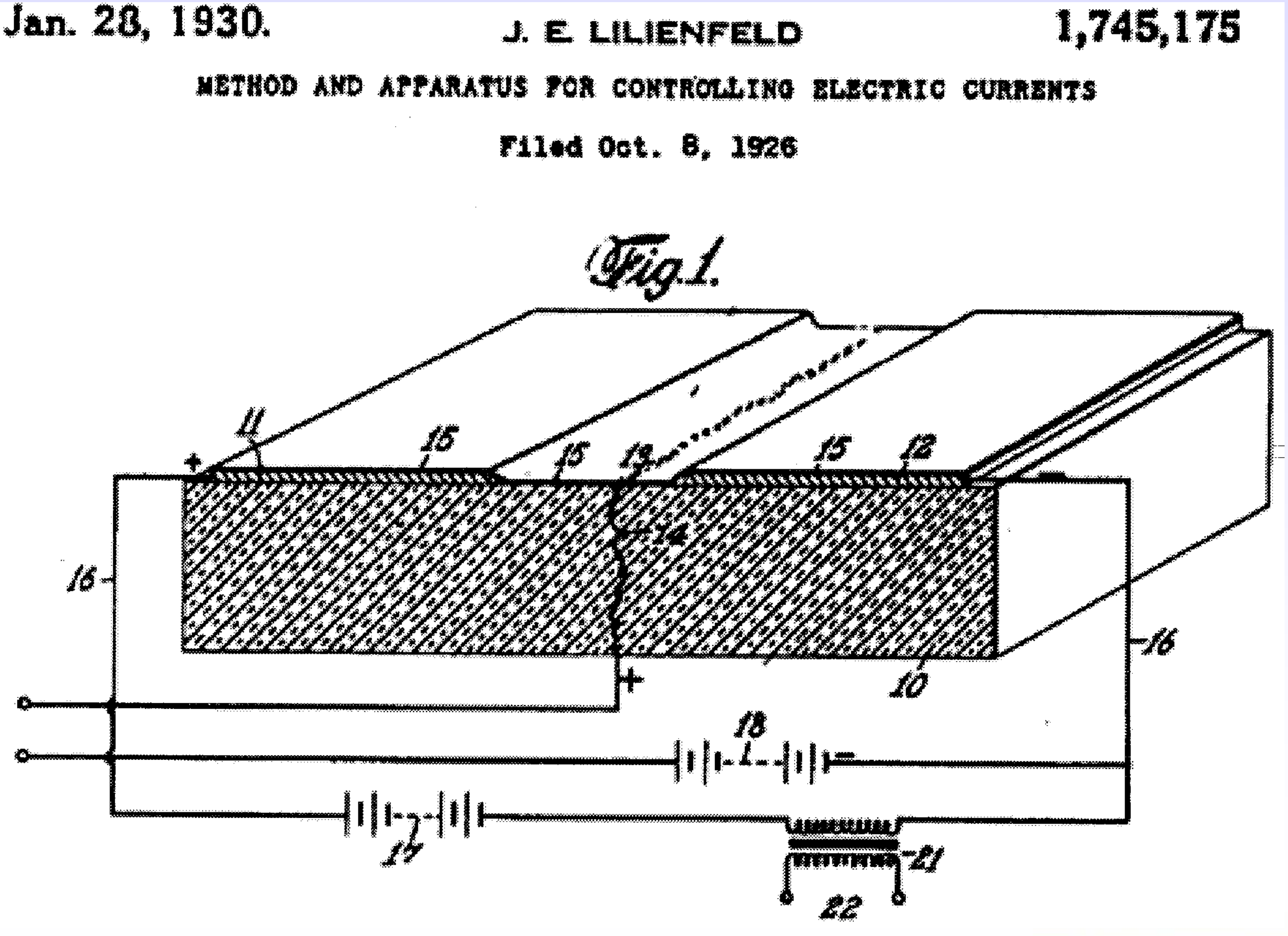
field effect transistor (idea: 1925, realized: 1960)



MOSFET

CMOS – *complementary* metal-oxide-silicon

- pairs of transistors for logic functions, only one of which is switched on at any time
- Simplicity and low power dissipation of CMOS circuits have allowed for integration densities not possible with BJTs



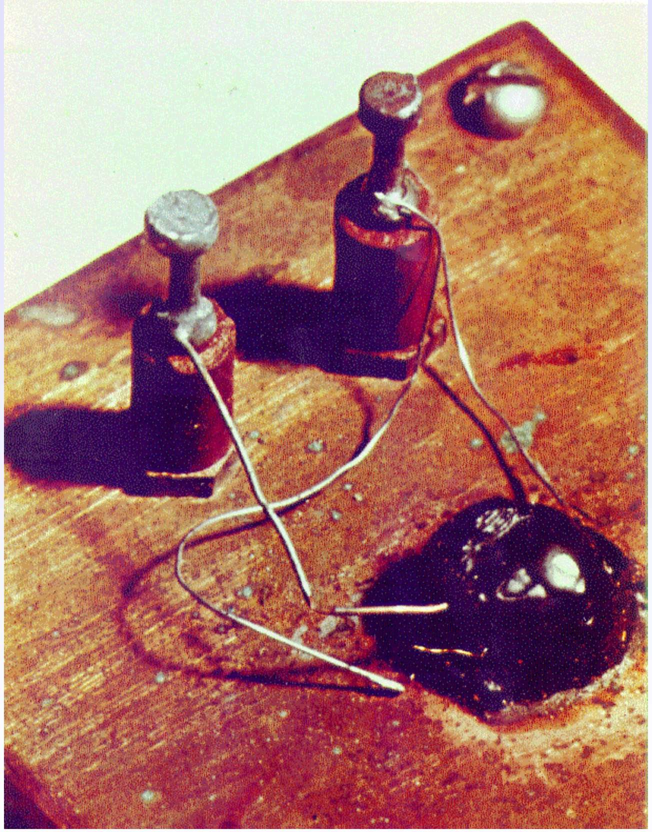
Jan. 28, 1930. **J. E. LILIENFELD** 1,745,175

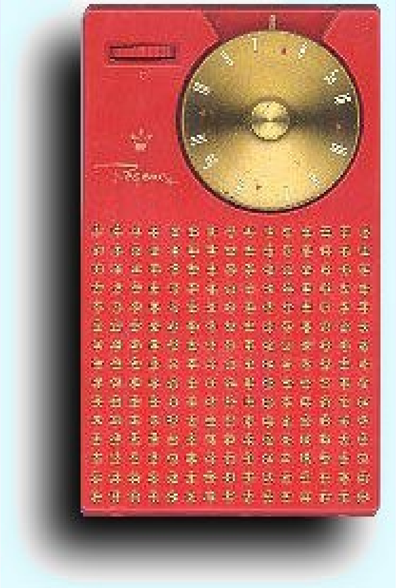
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926

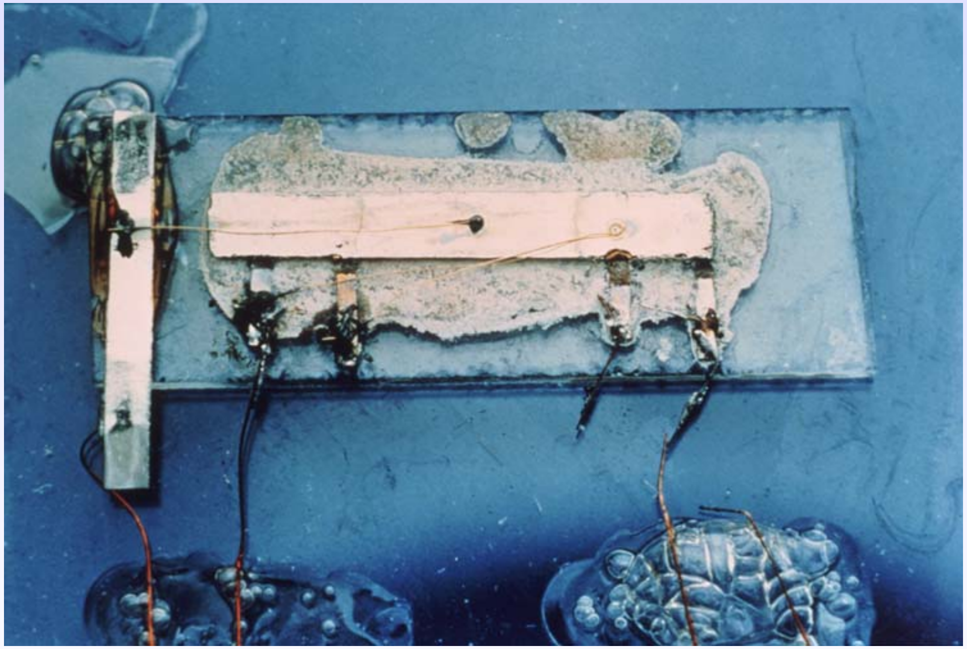
Fig. 1.

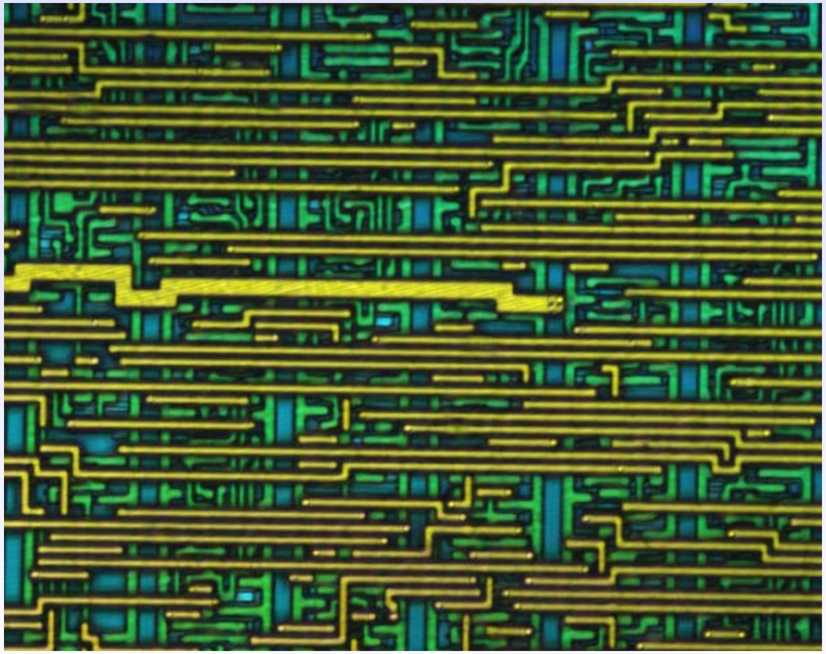
Transistor revolution





Integrated circuits - ICs





all components of a circuit on a piece of semiconductor

© 1992 Smithsonian Institution

1976: Apple I motherboard
1981: The first PC: IBM's 5150 PC
Intel microprocessor
DOS operating system

IBM stated in 1951: 'the world needs only 5 computers'

INTEL:
The microprocessor

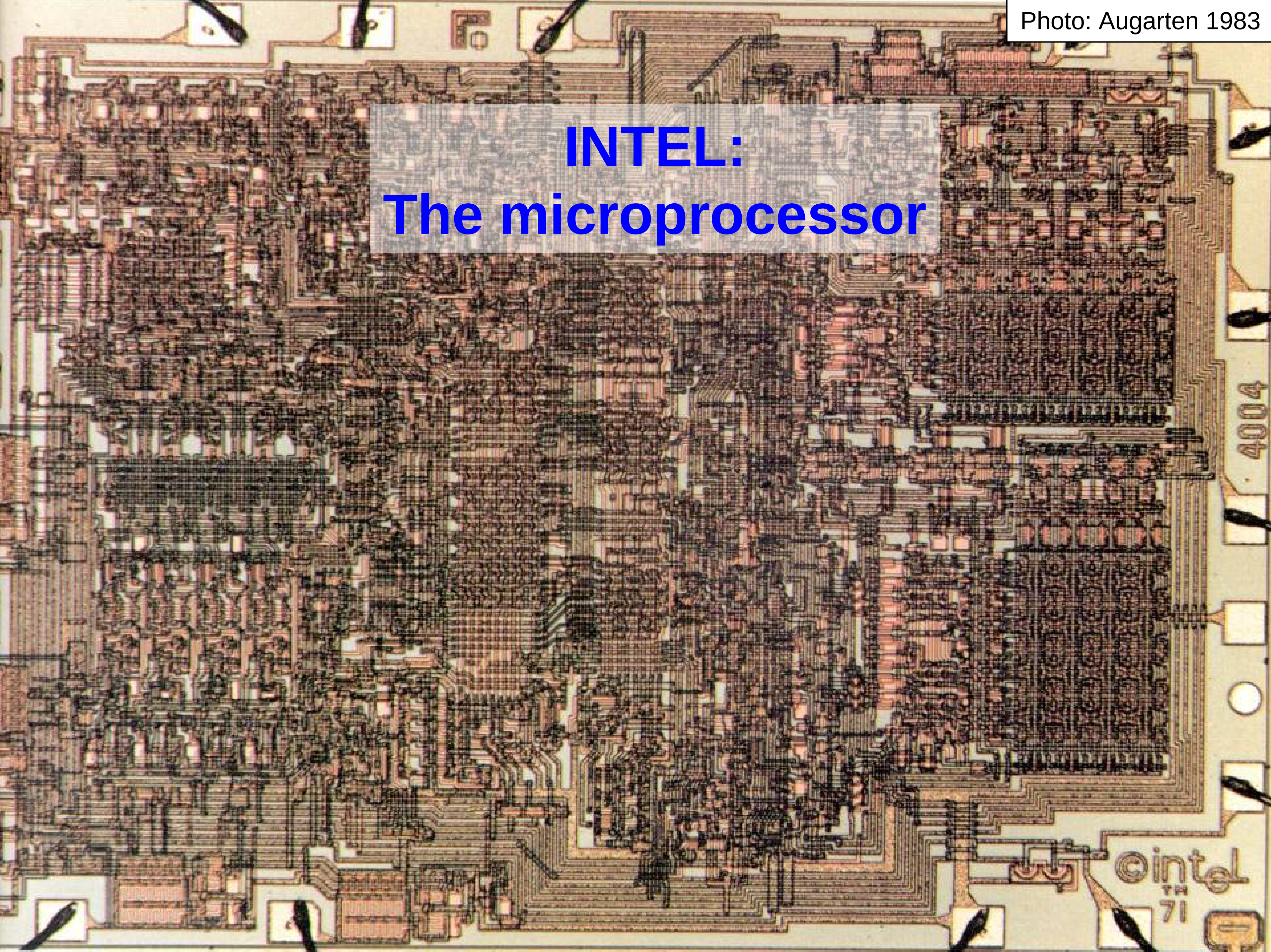
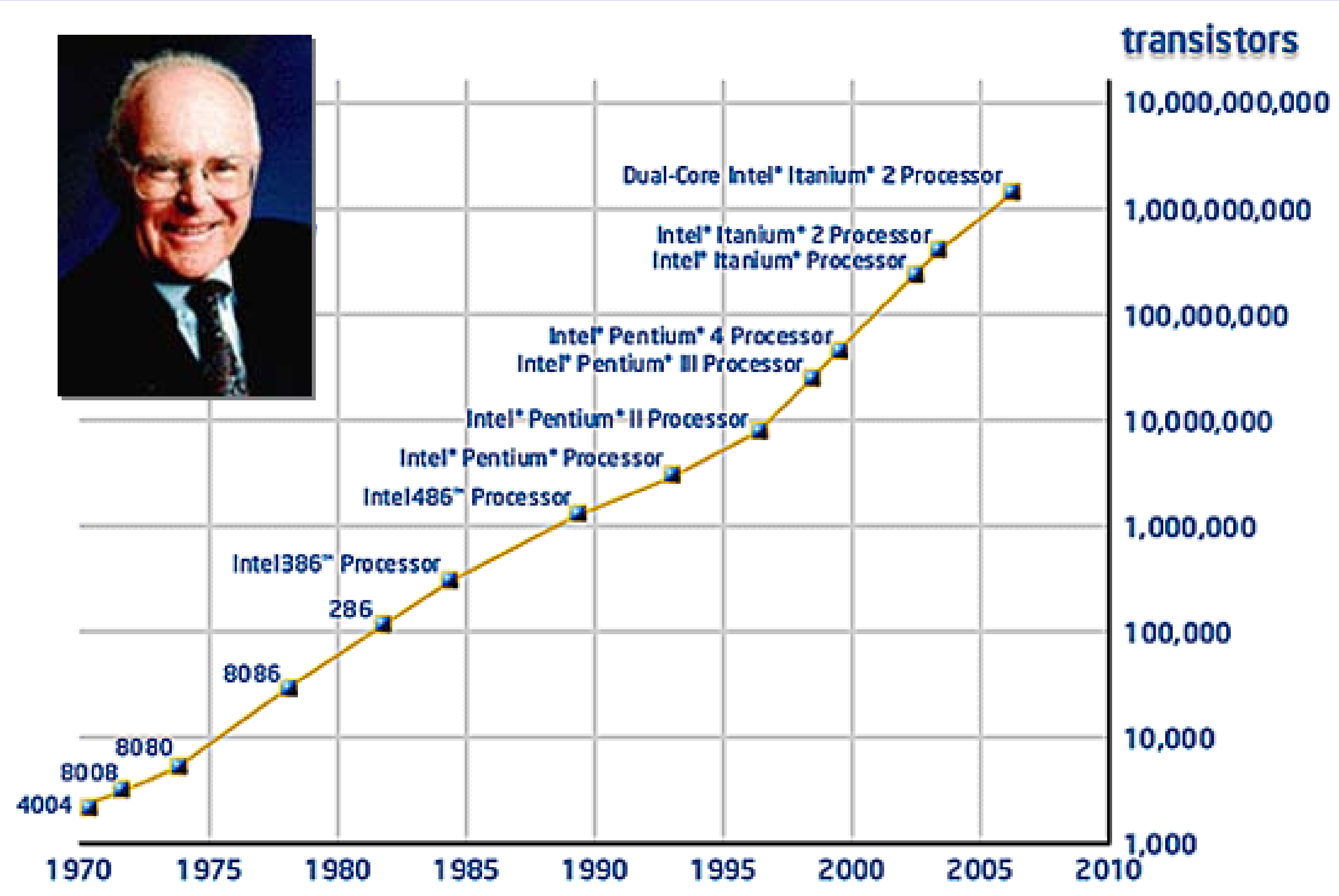


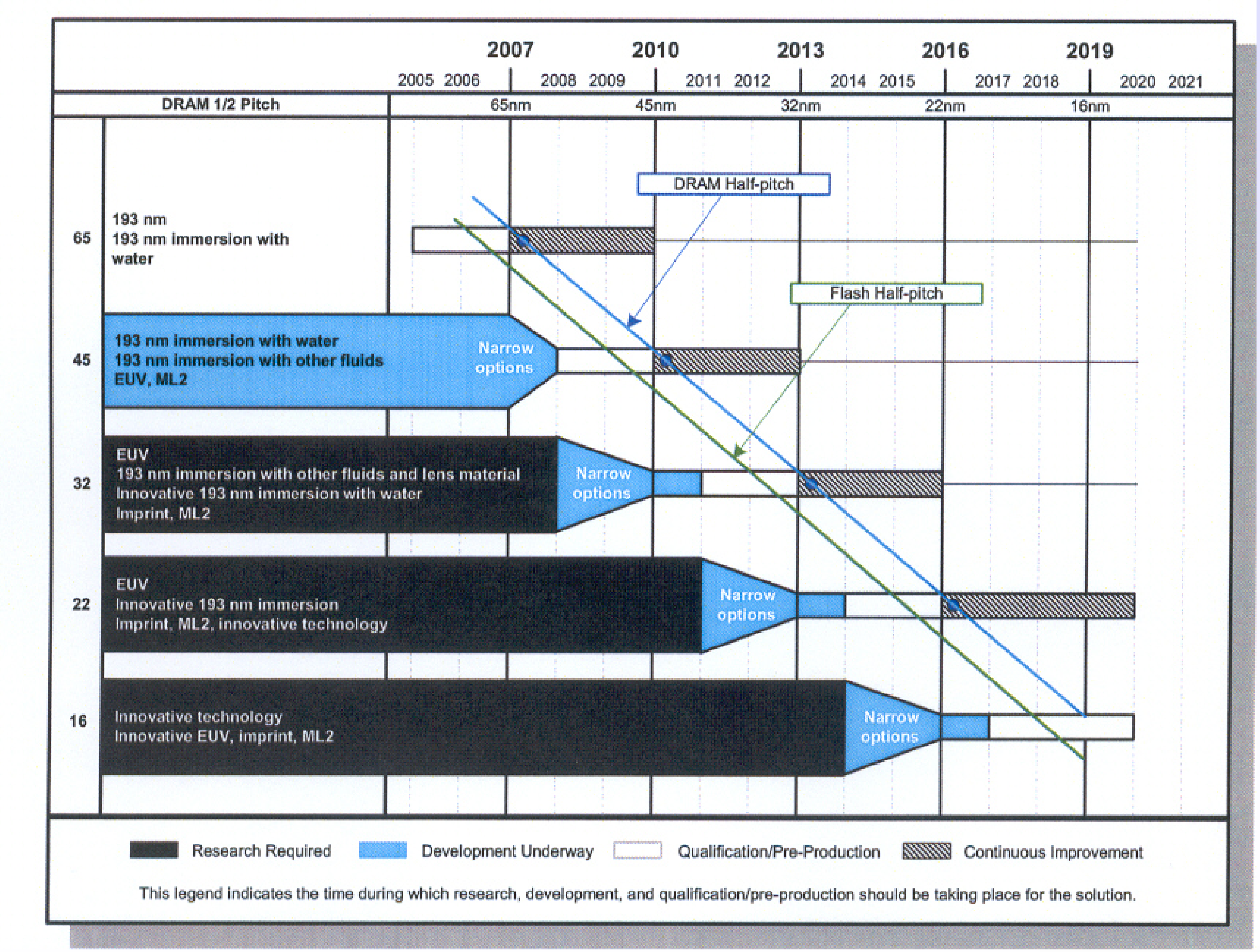
Photo: Augarten 1983

Moore’s Law



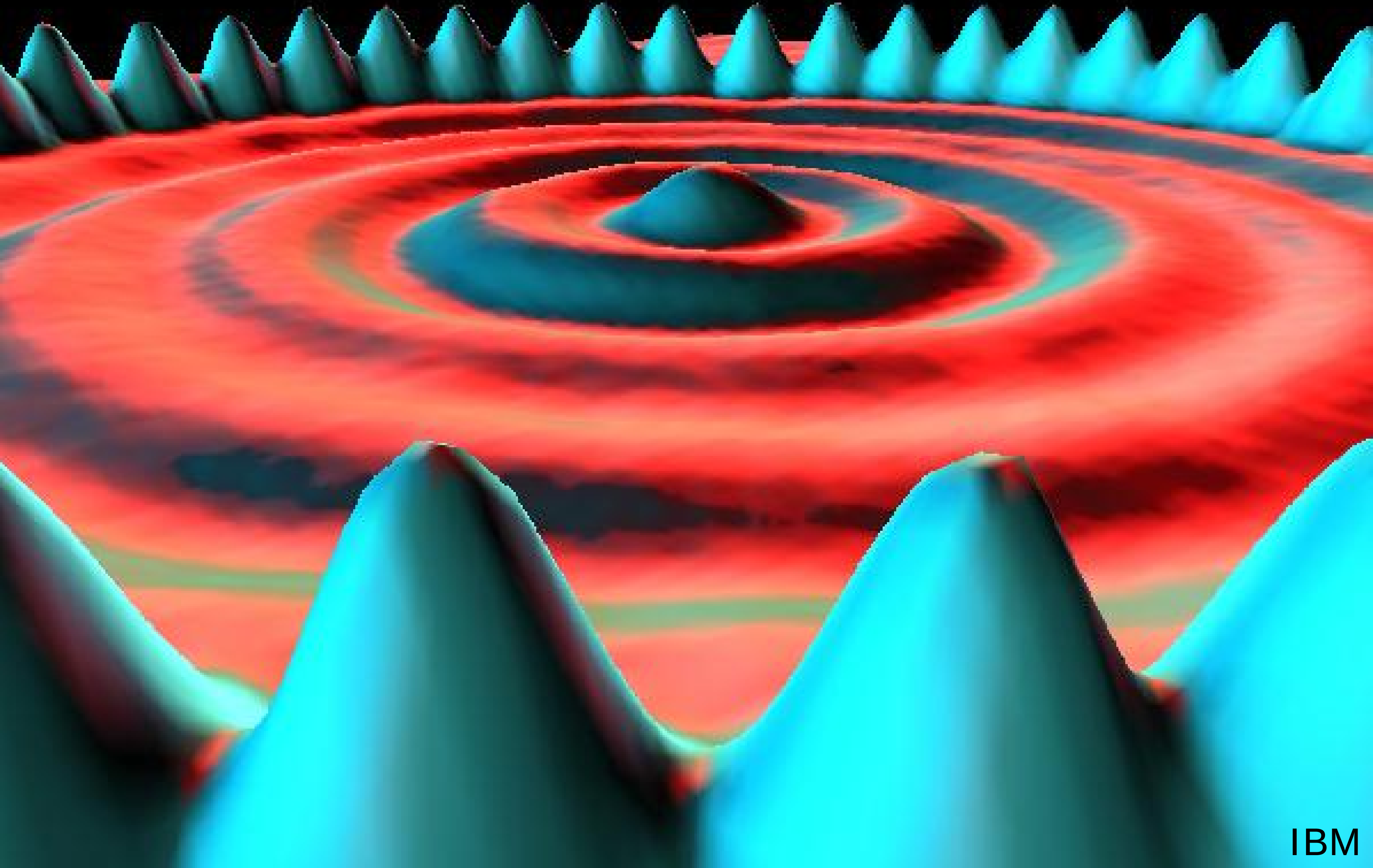
“number of transistors per square inch doubles every 18 months”

International Technology Roadmap for Semiconductors



This legend indicates the time during which research, development, and qualification/pre-production should be taking place for the solution.

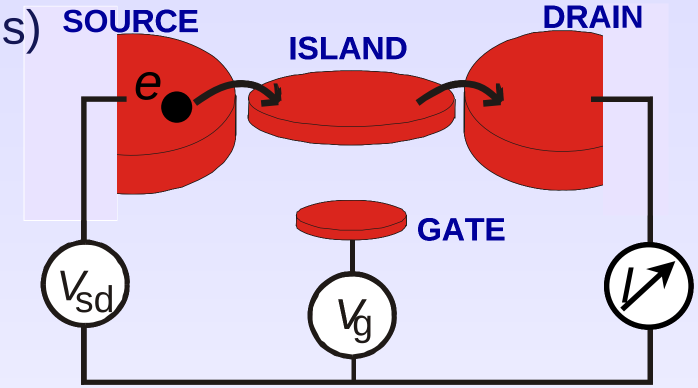
Moore’s law cannot continue forever...



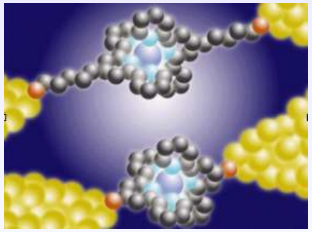
IBM

Single Electron Transistors (SETs) and Quantum Dots (QDs)

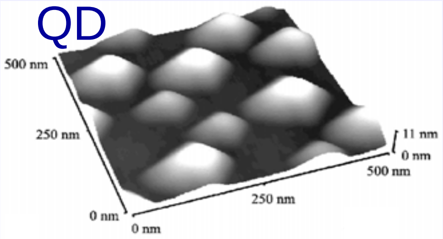
- Small box in solid-state occupied by electrons (holes)
- number of electrons 0 - ~1000
- Coupled via tunnel barriers to source and drain reservoirs
- Coupled capacitively to gate electrode(s)
- Discrete energy spectrum ⇒ **artificial atoms**



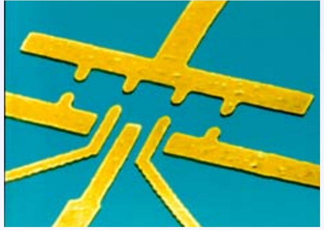
single molecule



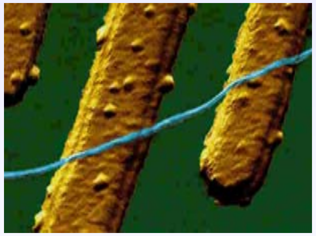
self-assembled QD



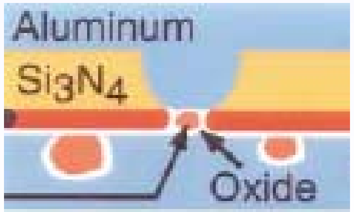
lateral QD



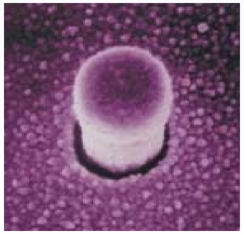
nanotube



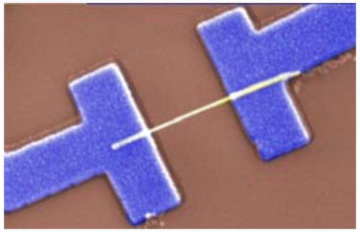
1 nm 10 nm 100 nm 1μm



nanoparticle



vertical QD

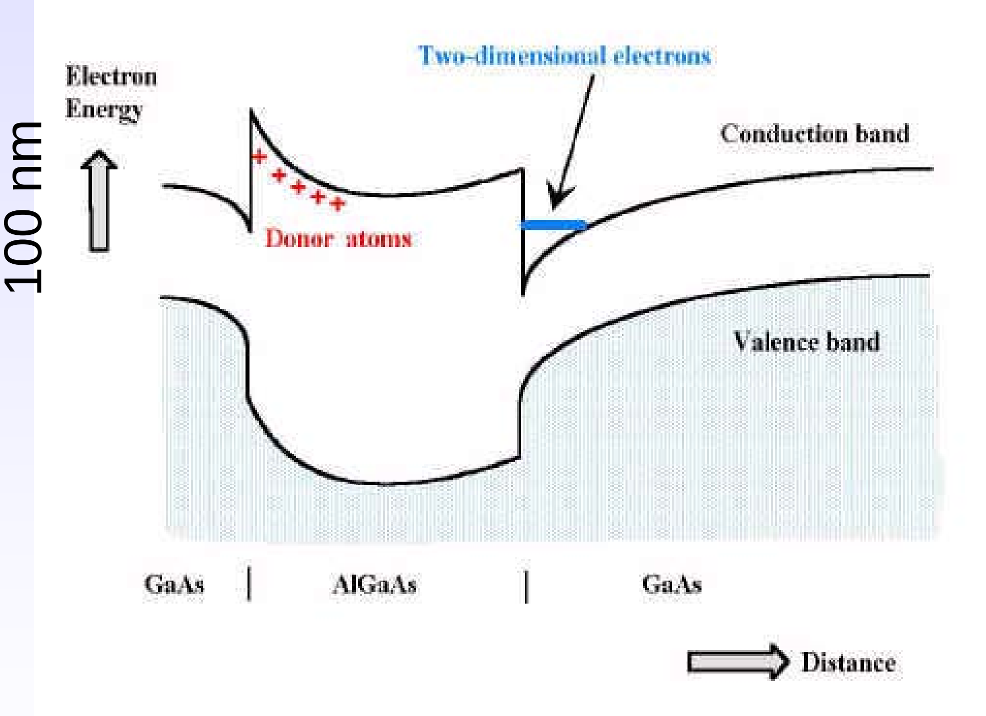


nanowire

2-dimensional electron gas

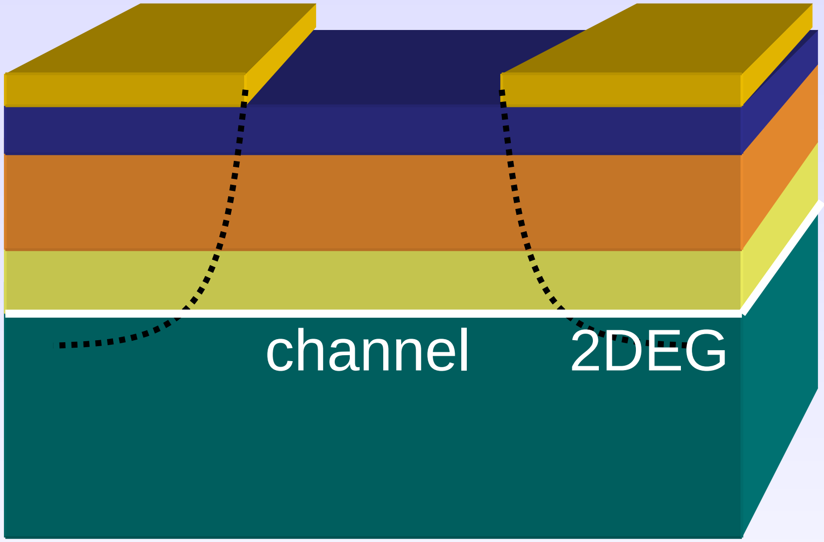
semiconductor heterostructure

band diagram



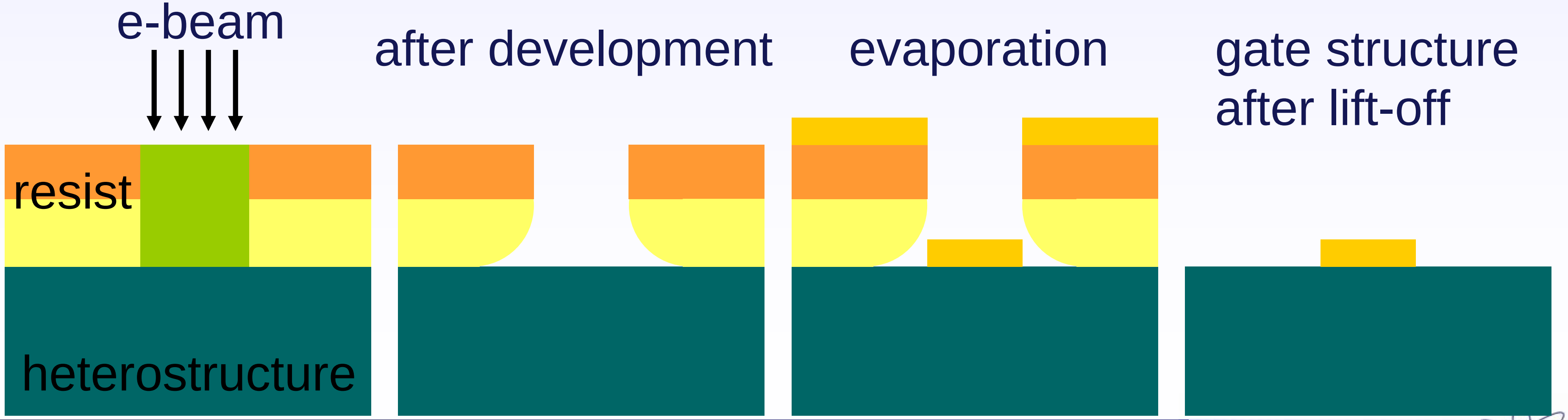
III-V semiconductors
Si n-dopant

heterostructure processing

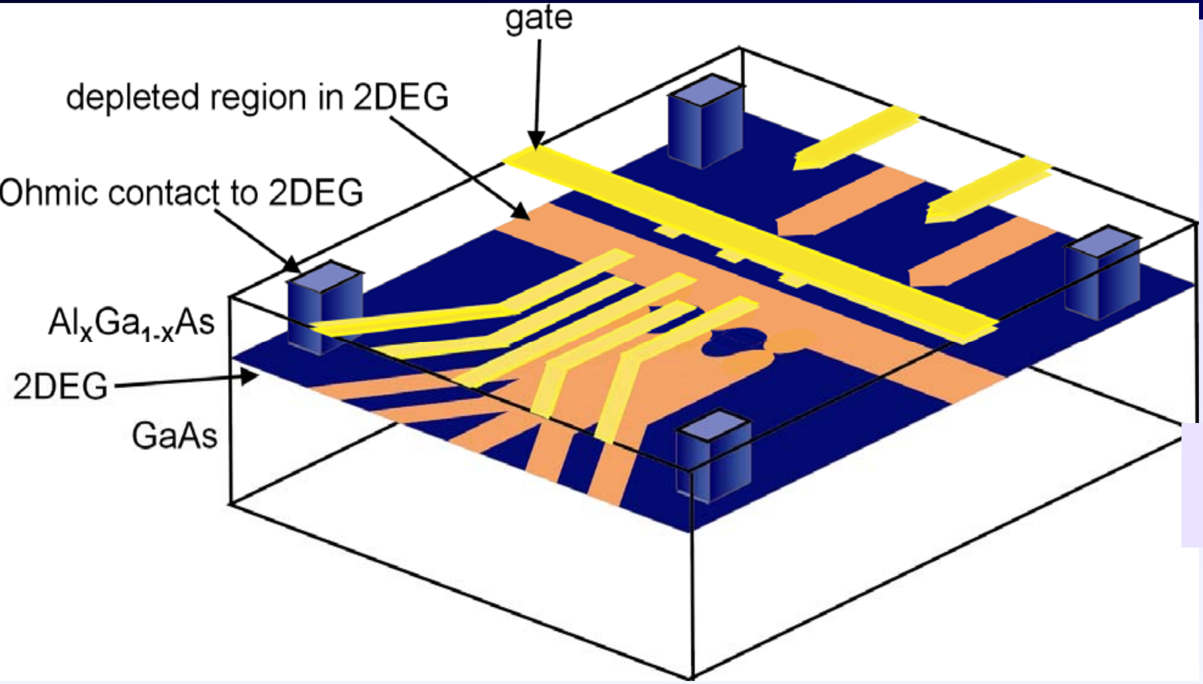


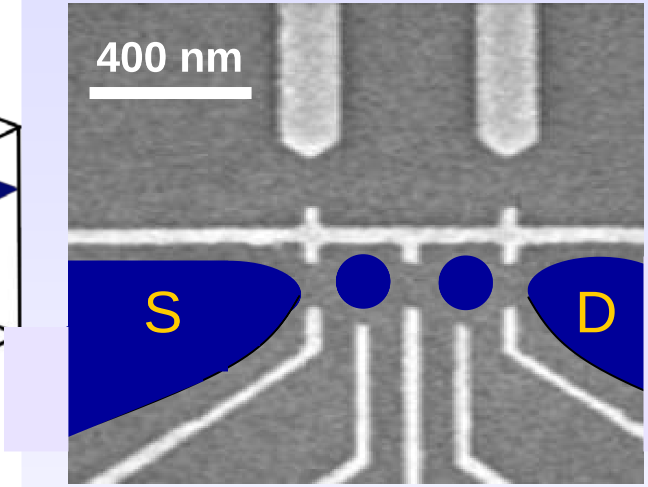
How to define nanostructures out of a 2DEG?

- applying (negative) voltages to gate electrodes on top
- wet etching
- dry etching (focused ion beam, electron cyclotron resonance, ...)



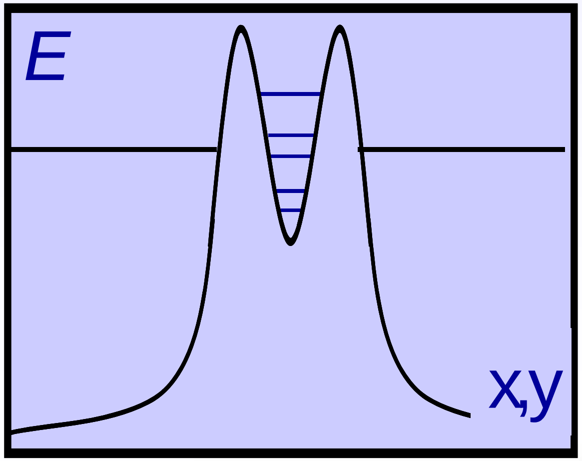
lateral quantum dots



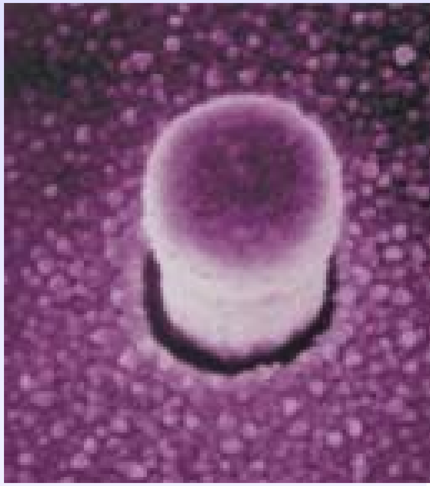


- High-mobility 2DEG (~10^6 cm^2/ Vs)
- Density ~10^{15} m^{-2} $\Rightarrow$ λ_F ~ 30 nm
- Resolution gate structure ~20 nm
- Dot size ~ 100 nm
- Comparable to electron wavelength

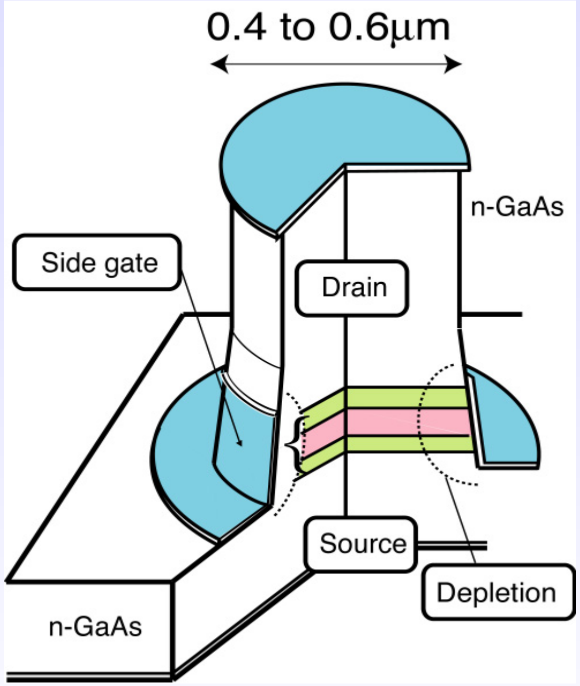
  $\Rightarrow$ discrete energy spectrum



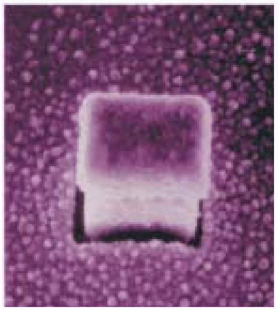
vertical quantum dots

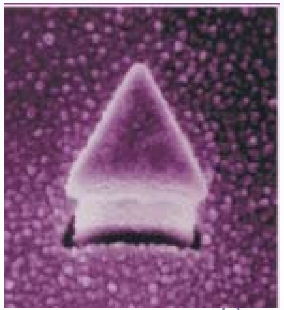


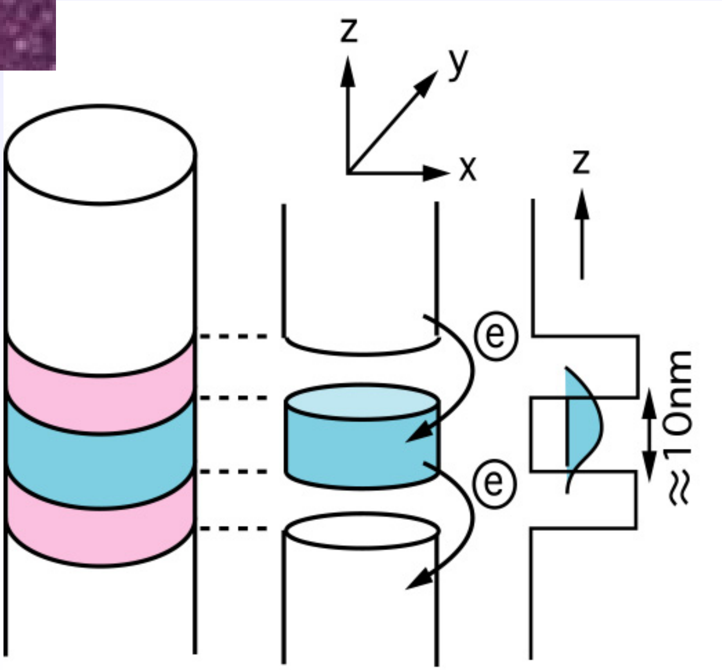
circular pillar made from double barrier structure by dry and wet etching



Other geometries possible







n-GaAs drain

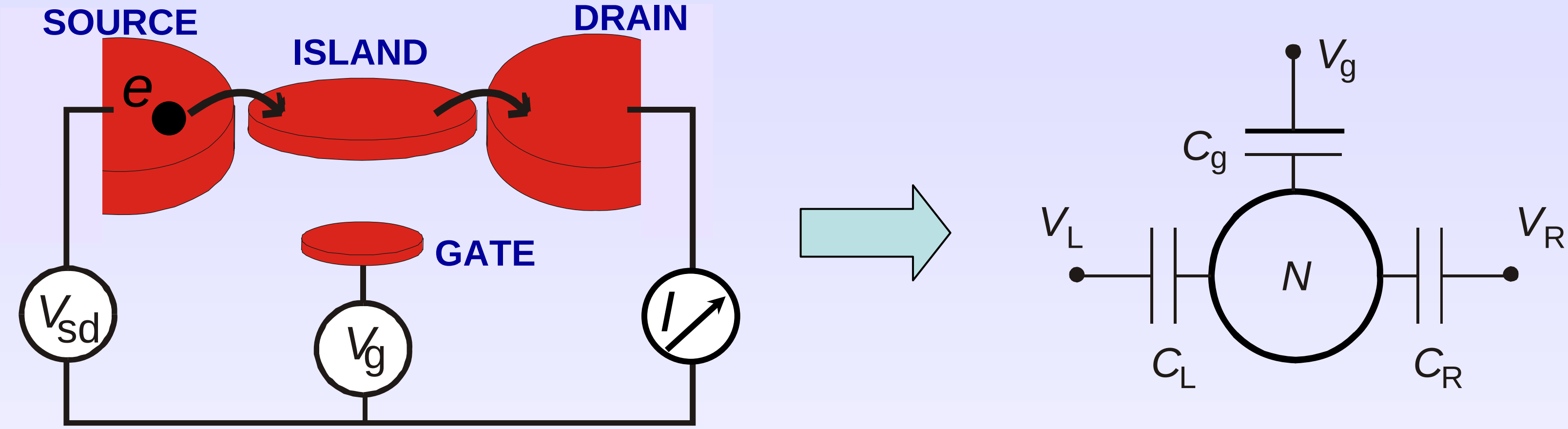
AlGaAs barrier

InGaAs well

AlGaAs barrier

n-GaAs source

constant interaction model



$$V_L \approx V_R \approx 0: \quad U(N) = \frac{\left[-N|e| + C_g V_g\right]^2}{2C} + \sum_{n=1}^{N} E_n(B)$$

classical

Q-mech.

Assumptions:

- all Coulomb interactions among electrons are parameterized by a single capacitance C ($C = C_L + C_g + C_R$)
- discrete energy spectrum is independent of the electron number N

electrochemical potential

minimum energy for adding the Nth electron to the dot

$$\mu_{dot}(N) \equiv U(N) - U(N-1) =$$

$$(N-\tfrac{1}{2})E_C - \frac{E_C}{|e|}C_g V_g + E_N$$

$$E_C = \frac{e^2}{C}$$

charging energy:
$E_C = e^2/C$

$C \propto R$,
R (radius) 100 nm
⇒ E_C ~ few meV

$$-|e|\varphi_N = (N-\tfrac{1}{2})E_C - \frac{E_C}{|e|}C_g V_g$$

electrostatic potential

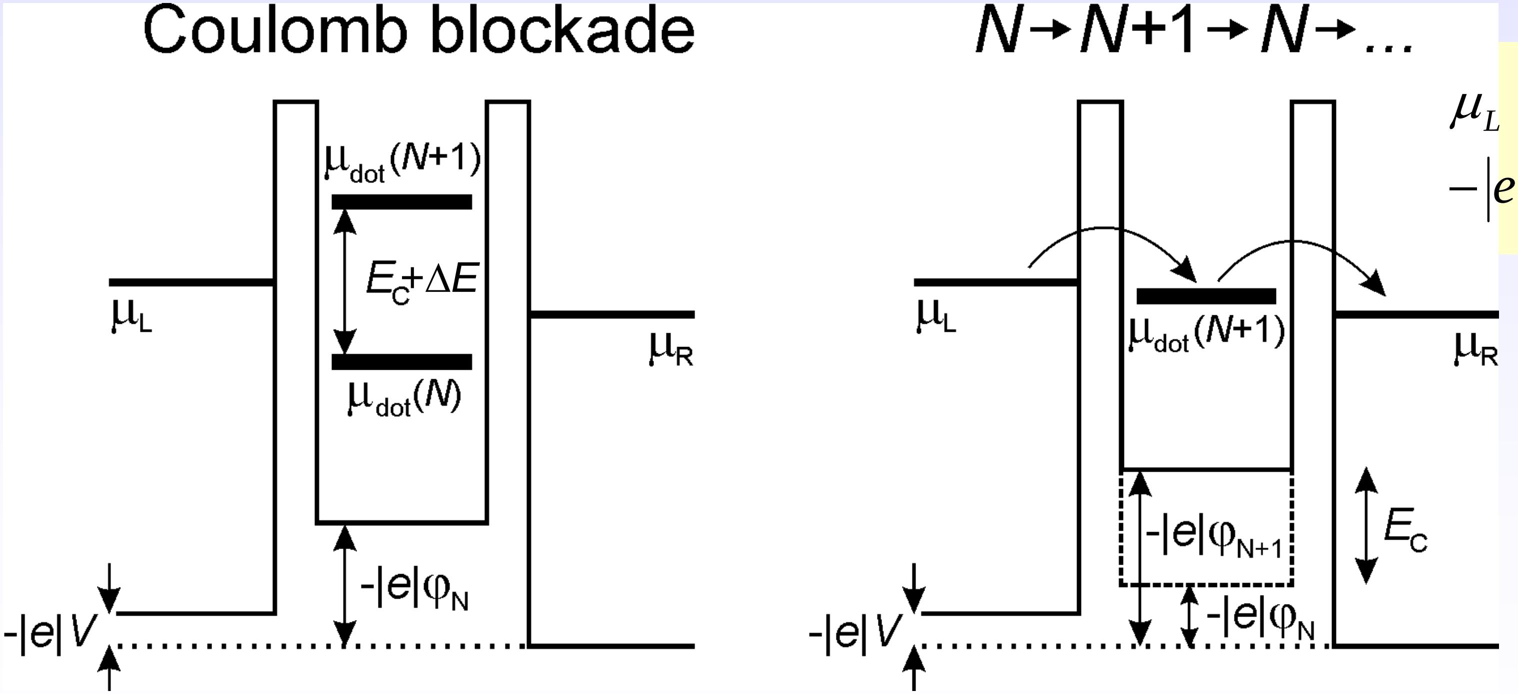
$$\mu_{ch}(N) = E_N$$

chemical potential

Coulomb blockade

$$\Delta\mu_{dot} = \mu_{dot}(N+1) - \mu_{dot}(N) = U(N+1) - 2U(N) + U(N-1)$$

$$= E_C + \Delta E$$ addition energy



$$\mu_L > \mu_{dot} > \mu_R$$

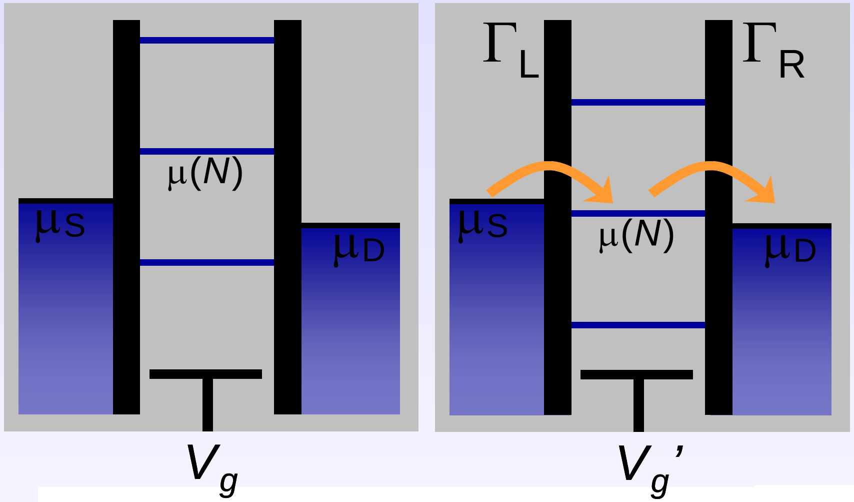
$$-|e|V = \mu_L - \mu_R$$

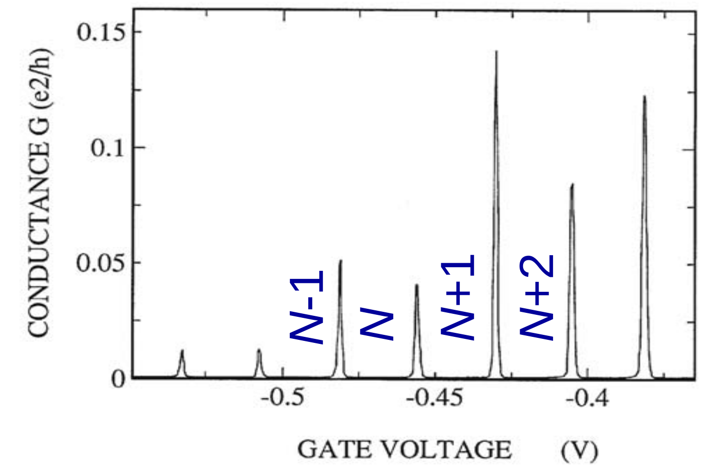
NO CURRENT

CURRENT

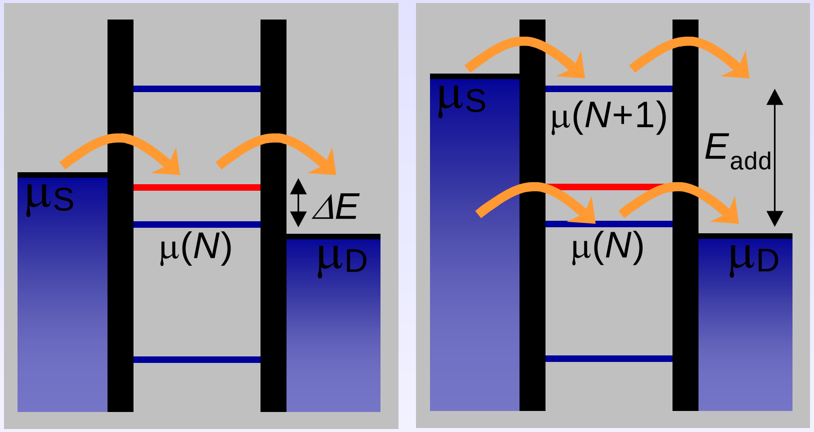
single-electron tunneling

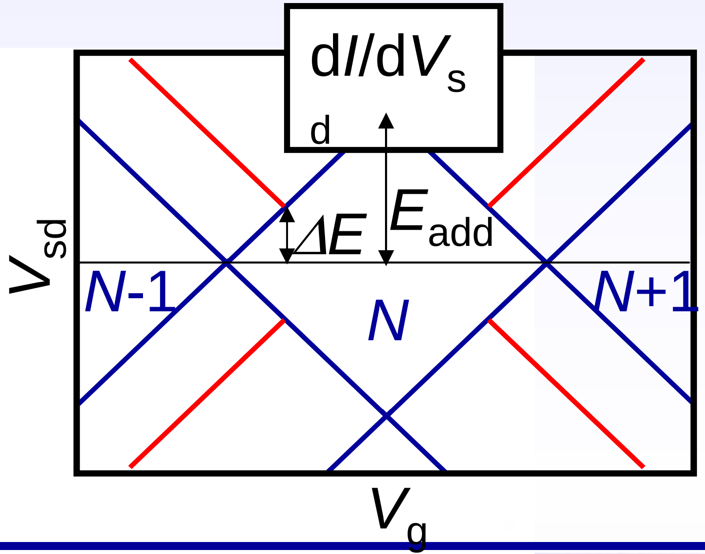
Linear response



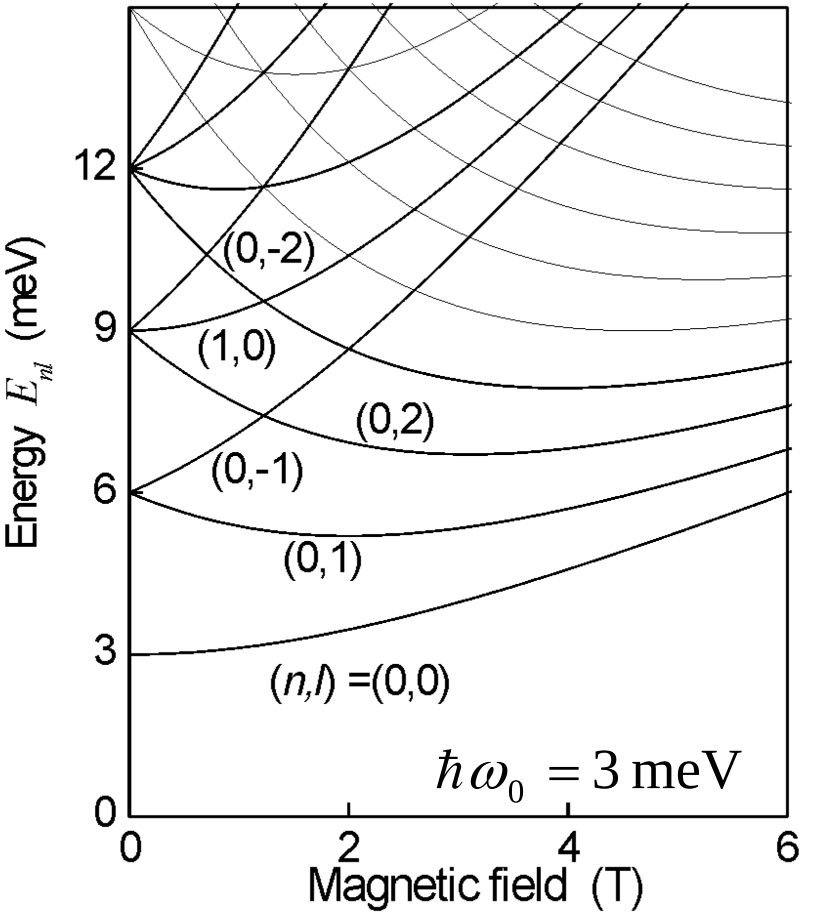


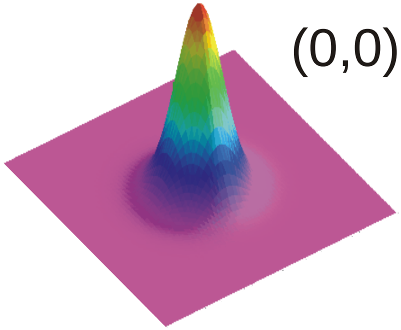
Non-linear transport

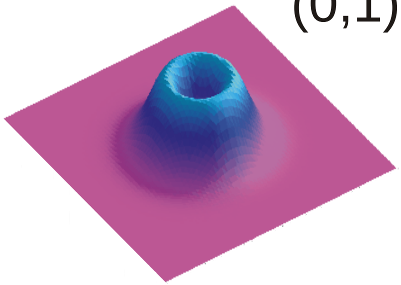


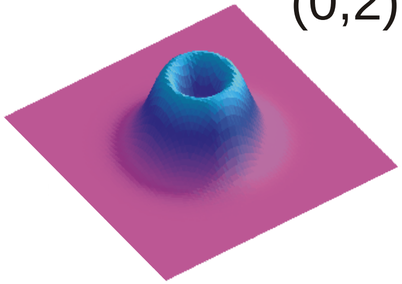


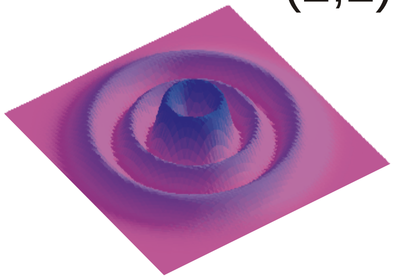
2D harmonic potential: Fock-Darwin states

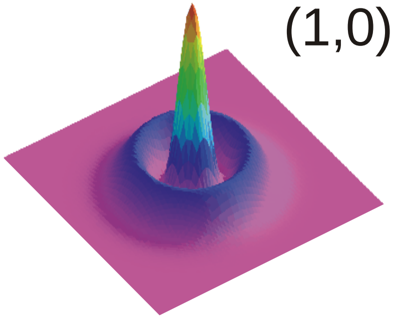


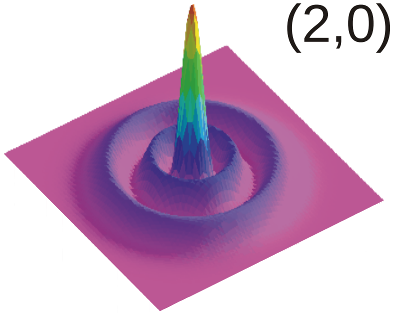

(0,0)


(0,1)


(0,2)


(2,2)


(1,0)

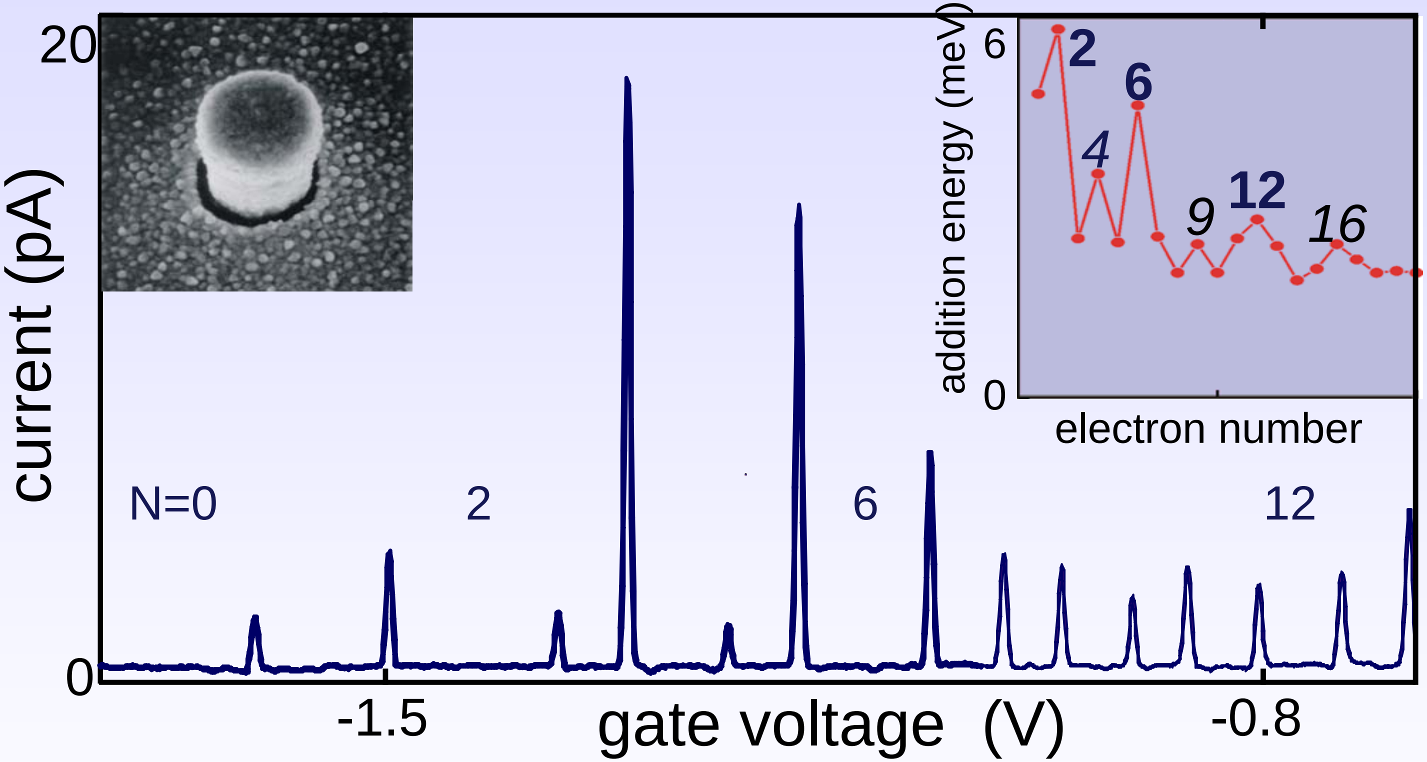

(2,0)

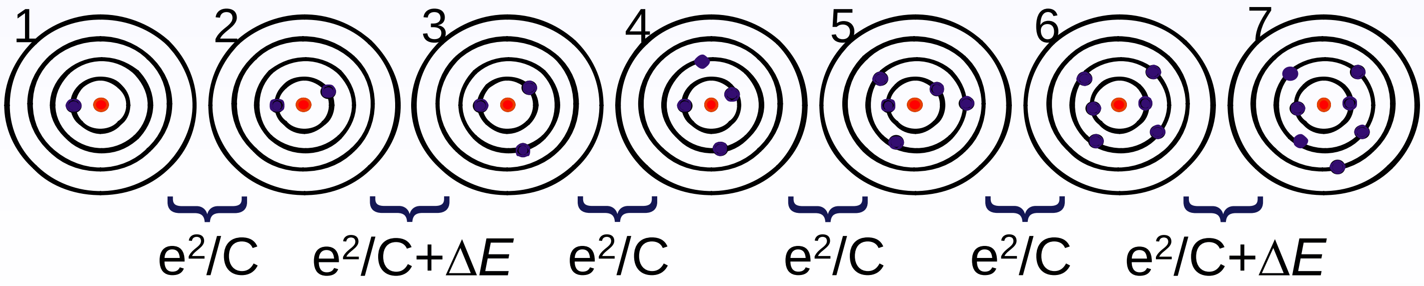
$$E_{nl} \equiv \left(2n+|l|+1\right)\hbar\tilde{\omega} - 1/2l\hbar\omega_c$$

$$\tilde{\omega}^2 \equiv \omega_0^2 + 1/4\omega_c^2 \qquad \omega_c = eB/m^*$$

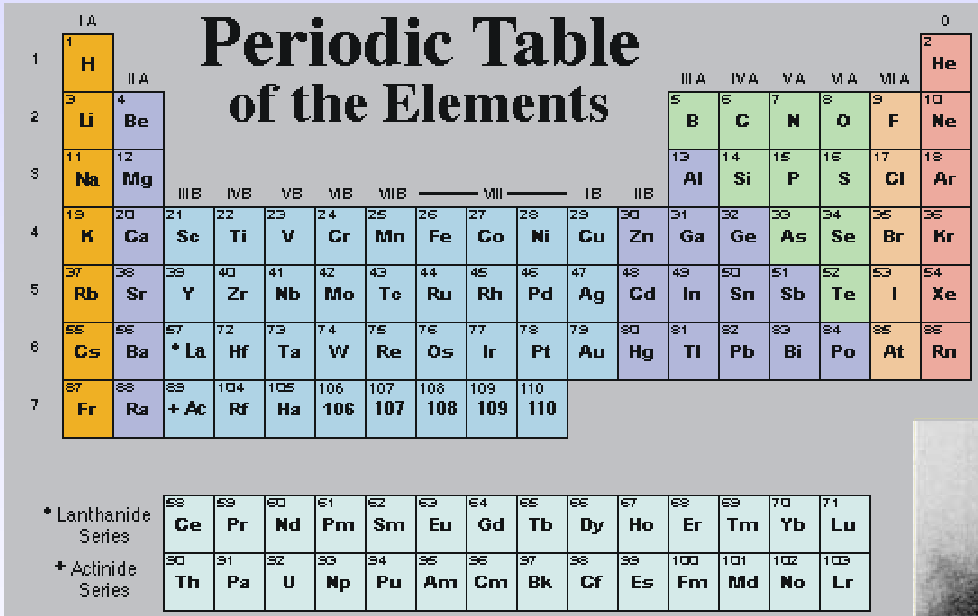
(cyclotron frequency)

Shell filling





Atoms

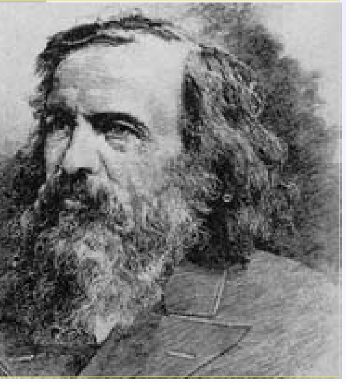


Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 * La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 + Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

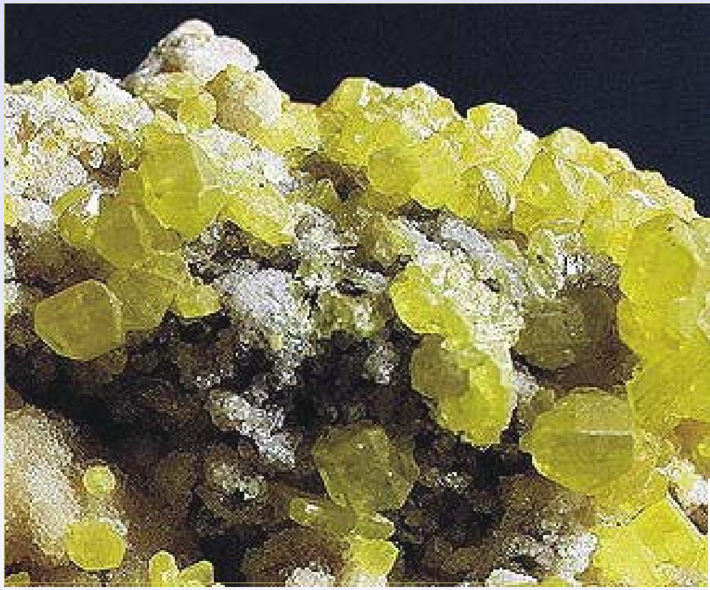
1869
Mendeleev arranges 63 known elements in a periodic table



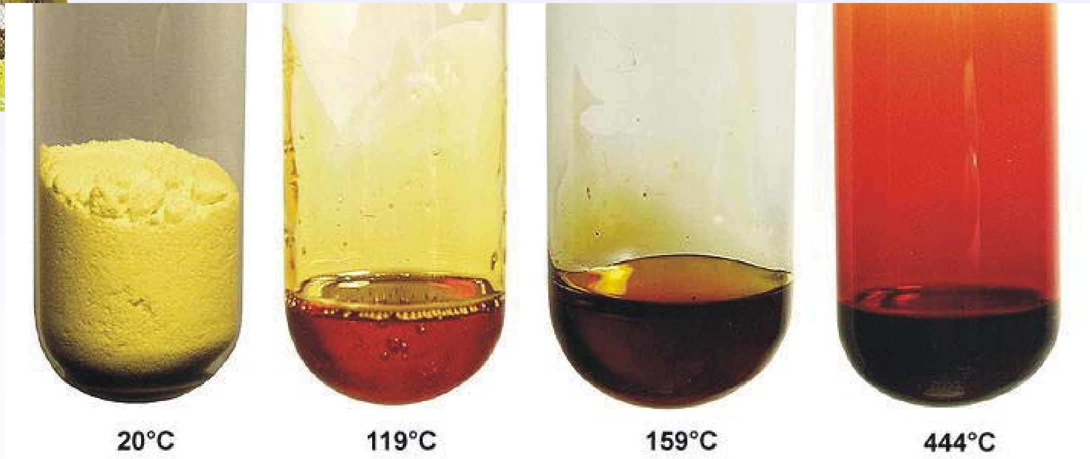
Dmitri Mendeleev
(1834-1907)

"The elements, if arranged according to their atomic weights, show a distinct periodicity of their properties..."

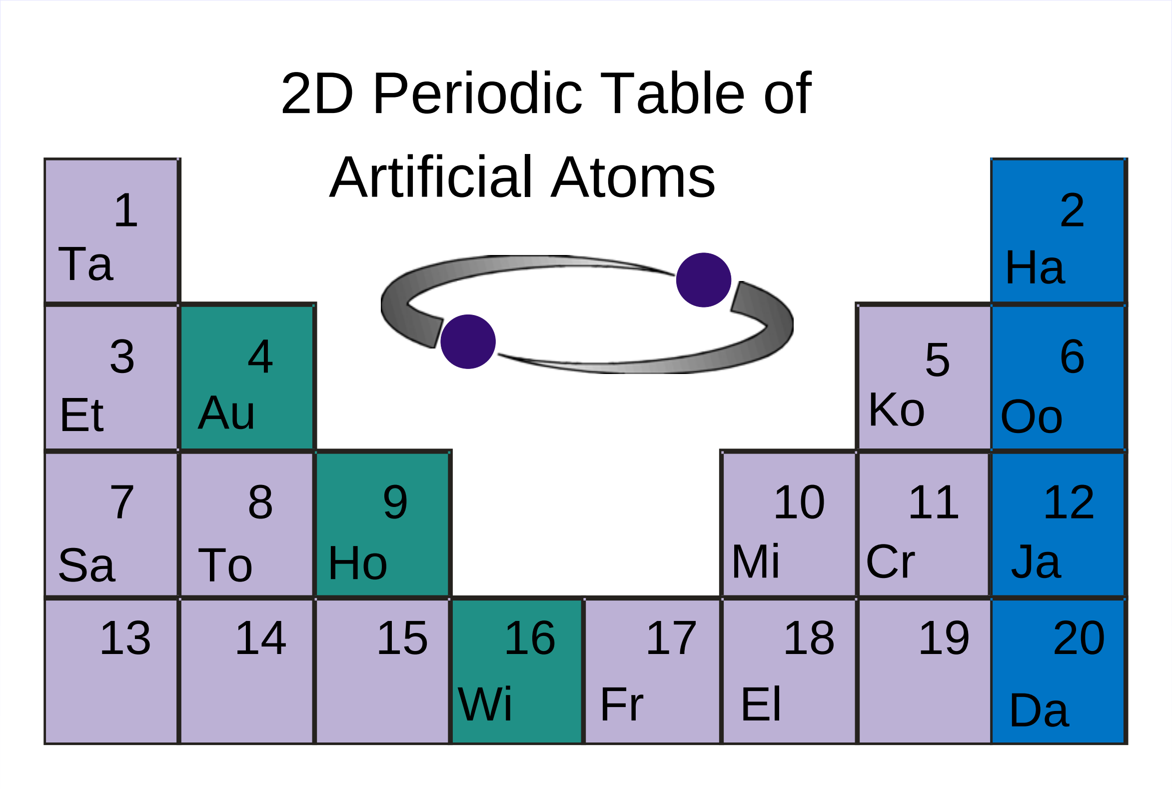
Atoms



Element number 16: Sulphur



artificial atoms

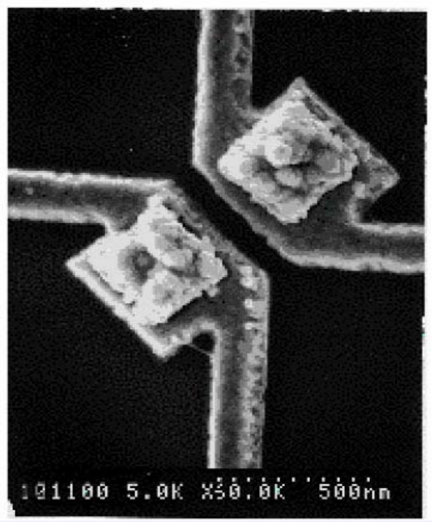


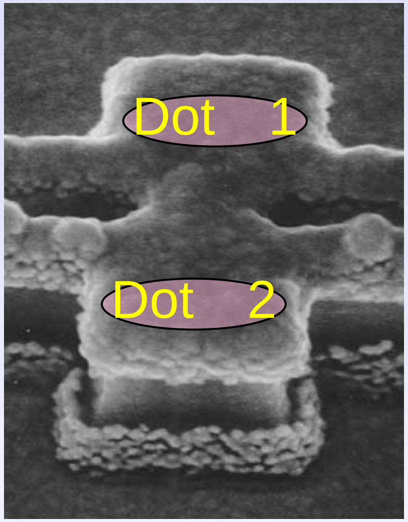
2D Periodic Table of Artificial Atoms

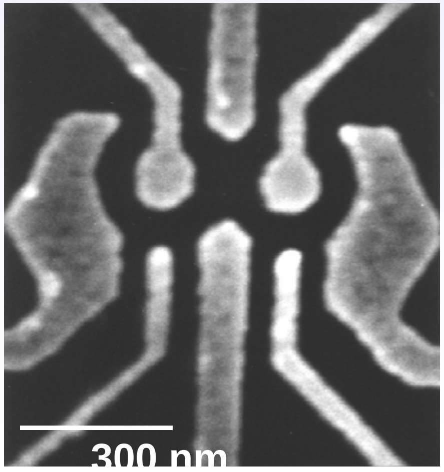
1 Ta							2 Ha
3 Et	4 Au					5 Ko	6 Oo
7 Sa	8 To	9 Ho			10 Mi	11 Cr	12 Ja
13	14	15	16 Wi	17 Fr	18 El	19	20 Da

Coupled quantum dots

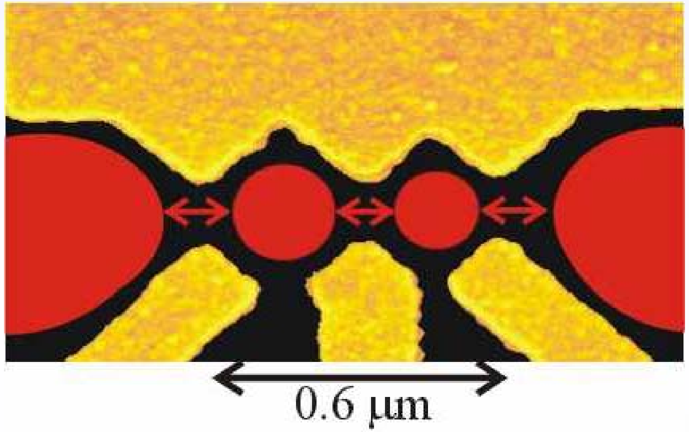
vertical,
laterally coupled
quantum dots



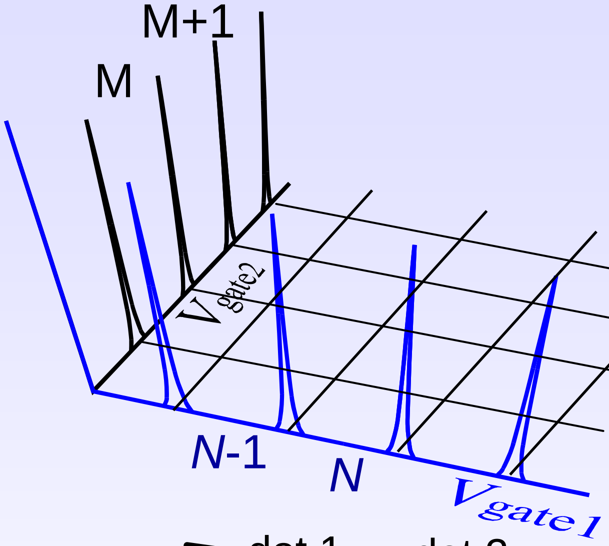


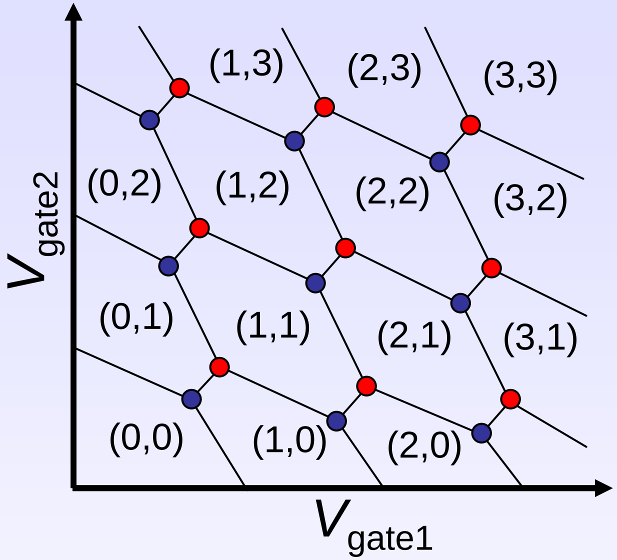


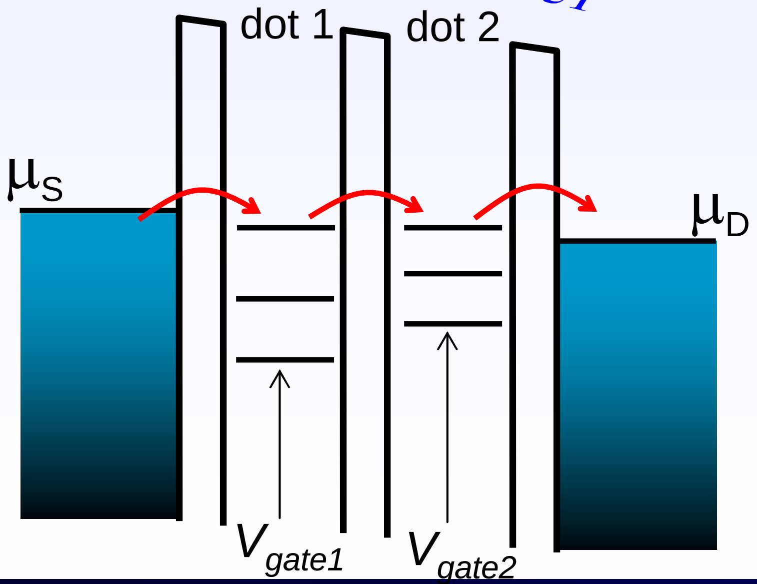
lateral, coupled quantum dots



Coupled quantum dots







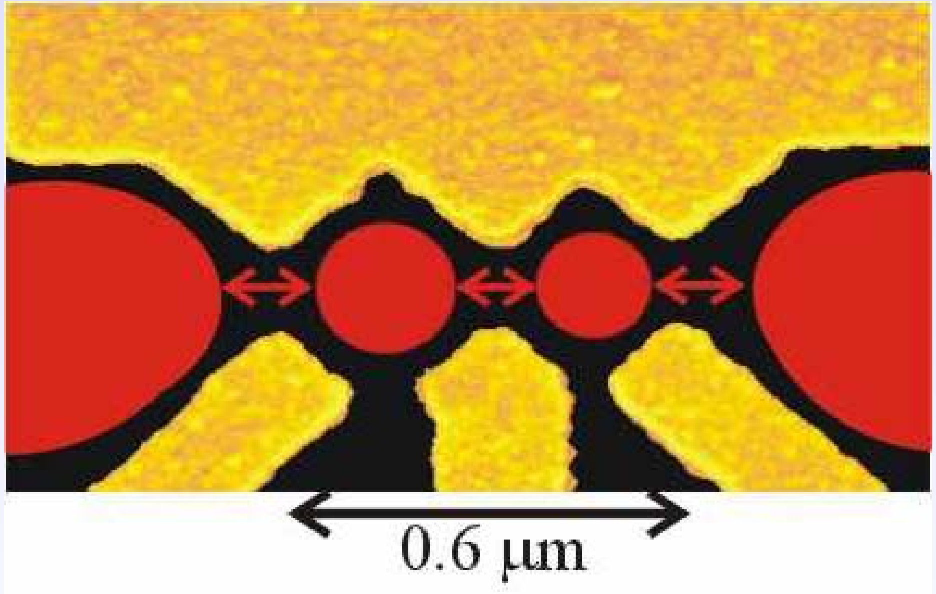
dots in series: transport at triple points only !!

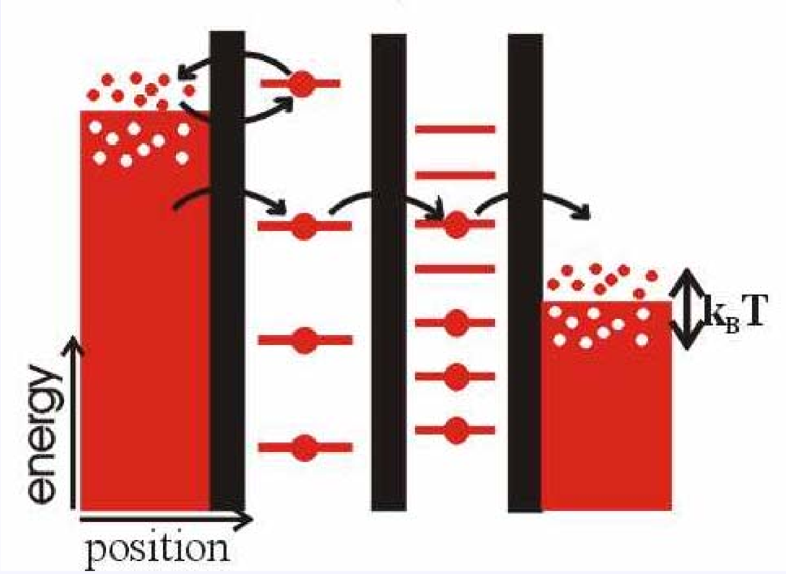
charge cycle I:
(N,M) → (N+1,M) → (N,M+1) → (N,M) → …

charge cycle II:
(N+1,M+1) → (N+1,M) → (N,M+1) → (N+1,M+1) → …

W.G. van der Wiel *et al*., Rev. Mod. Phys. **75**, 1 (2003)

“Temperature filter”



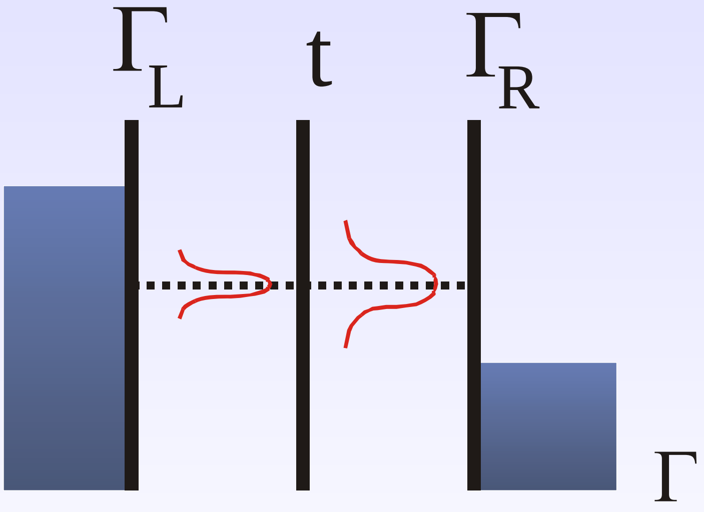


=> resonant current is determined by alignment of discrete states and **independent of temperature**

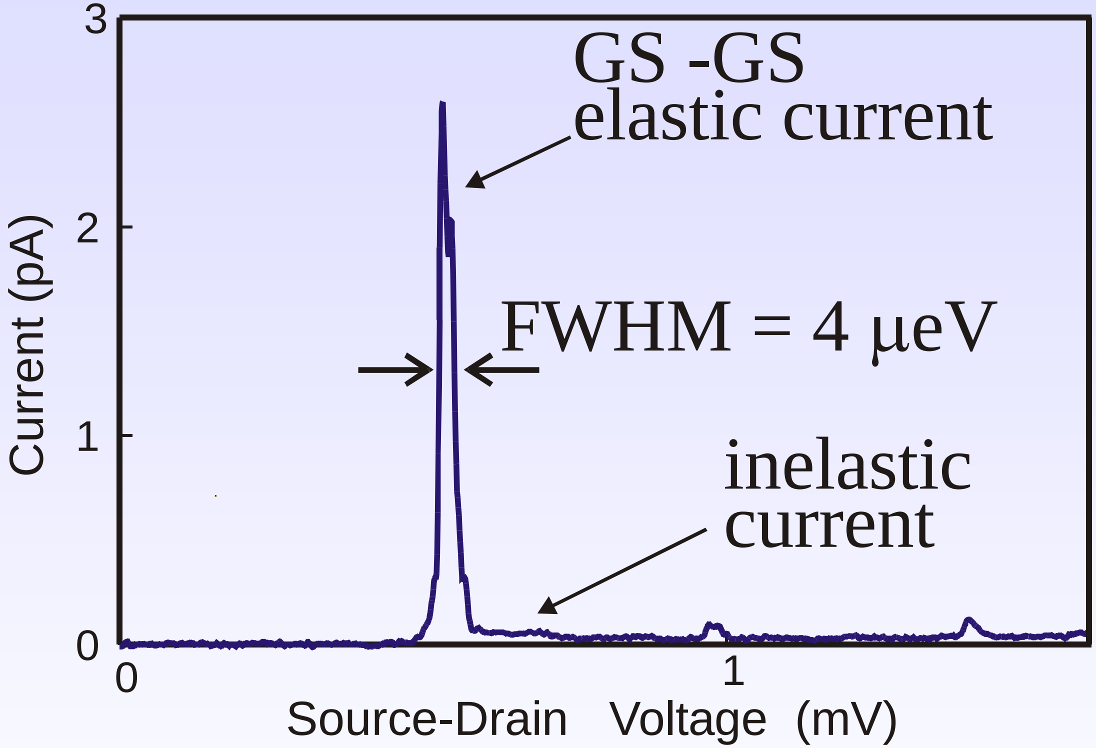
W.G. van der Wiel *et al.*, Rev. Mod. Phys. **75**, 1 (2003)

“Temperature filter”

elastic tunneling



$$\text{width} \approx \frac{h}{\text{lifetime}} \approx h$$



3.5 x 100 mK = 35 μeV

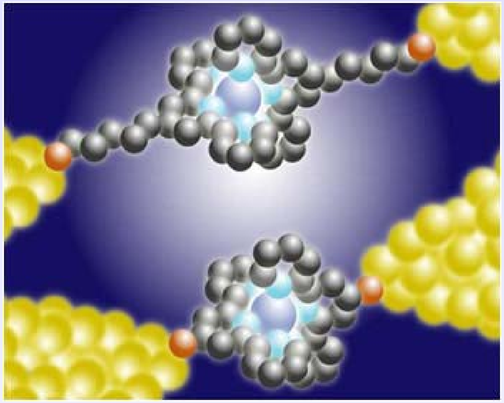
=> FWHM is an order of magnitude smaller than thermal energy

Organic electronics

Why organic electronics???

organic materials

- light and flexible
- easy to process → cheap
- additional functionalities
- interface with biological systems



molecular electronics

- essentially all electronic processes in nature occur in molecular structures (e.g. photosynthesis, signal transduction)
- size 1-100 nm → cost, efficiency, power dissipation
- self-assembly and recognition (switches & sensors)
- molecular synthesis allows great flexibility

Organic electronics

Organic electronics

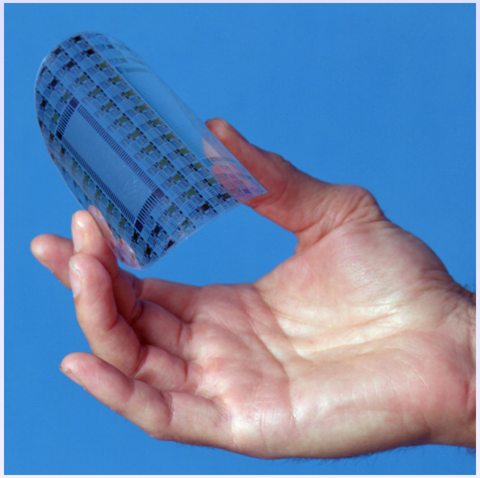
Single-molecule electronics

molecular rectifier proposed by
Aviram and Ratner 1974

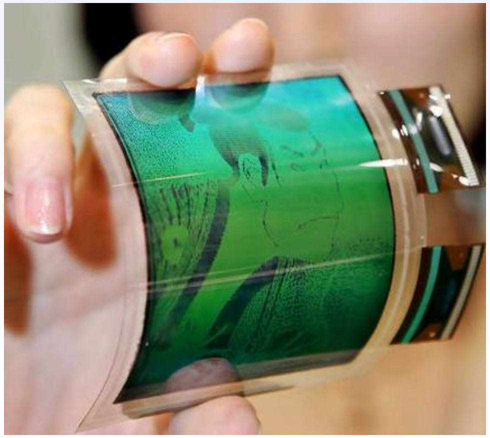
Organic thin-film electronics

- polymers (Nobel prize chemistry 2000)
- small molecules
- single-crystals

Organic electronics

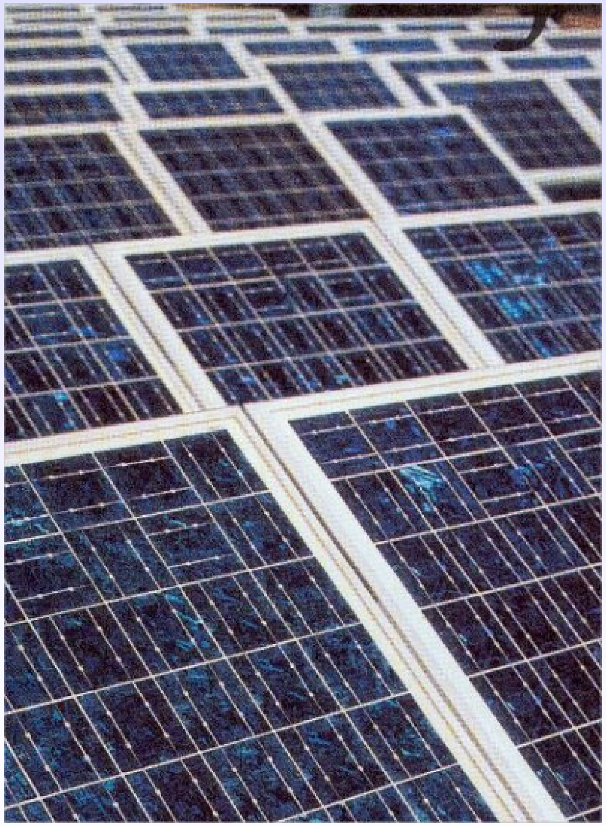


flexible circuitry



electronic paper

OLED



solar cells

Carrier mobility

μ is the constant of proportionality between the drift velocity v of the charge carriers and the electric field E that induces this drift velocity:

$$v = \mu E$$

material	mobility [cm^2/(Vs)]
Si (crystalline)	1350 (e)
InAs (bulk)	30,000 (e)
GaAs (quantum well)	up to ~10,000,000 (e) at low *T* (~ 1K)
CNT	100,000 (e)
Cu	42 (e)
pentacene (crystalline)	30 (h)
pentacene (thin film)	~1 (h)

When band transport occurs?

In general, an energy ΔE is required to move an electron from one molecule to the next.

Even at zero temperature, this energy can be provided by quantum fluctuations:

$$\Delta E \cdot \Delta t > \hbar$$

Heisenberg uncertainty relation

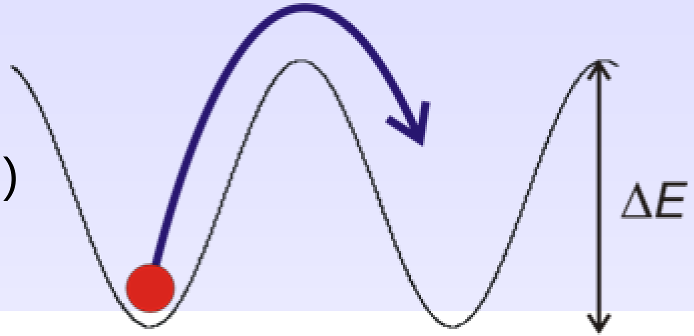
If the tunnel rate between molecules is much larger than $\Delta E / \hbar$ then the electron can delocalize over many molecules.

If the tunnel rate is much less than $\Delta E / \hbar$ then the electron is localized on one molecule and conduction takes place via (thermally activated) hopping.

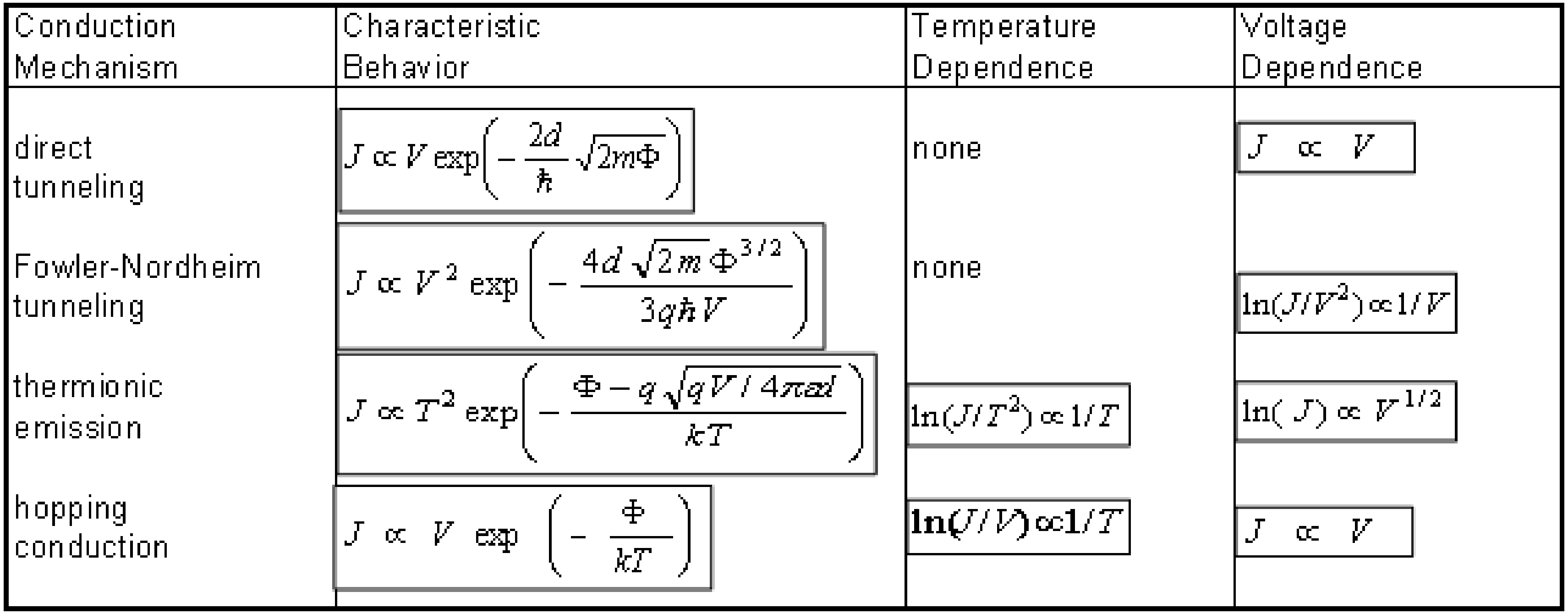
Conduction mechanisms

band-like conduction only occurs when the charge carriers are in sufficiently **delocalized** states

hopping
(thermally activated)



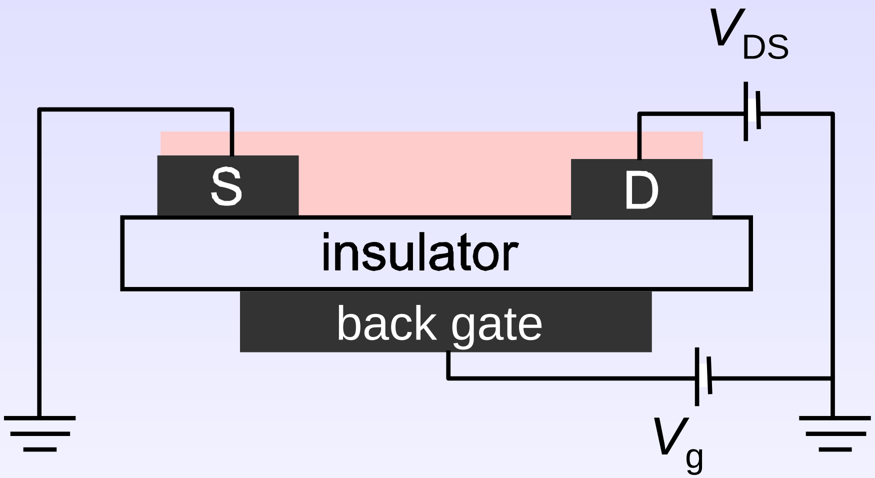
non-band-like conduction



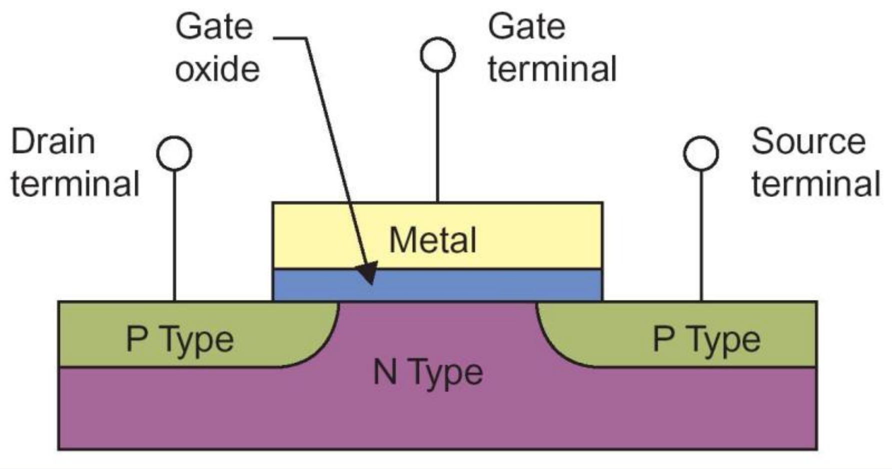
Conduction Mechanism	Characteristic Behavior	Temperature Dependence	Voltage Dependence
direct tunneling	$J \propto V \exp\left(-\frac{2d}{\hbar}\sqrt{2m\Phi}\right)$	none	$J \propto V$
Fowler-Nordheim tunneling	$J \propto V^2 \exp\left(-\frac{4d\sqrt{2m}\,\Phi^{3/2}}{3q\hbar V}\right)$	none	$\ln(J/V^2) \propto 1/V$
thermionic emission	$J \propto T^2 \exp\left(-\frac{\Phi - q\sqrt{qV/4\pi\varepsilon d}}{kT}\right)$	$\ln(J/T^2) \propto 1/T$	$\ln(J) \propto V^{1/2}$
hopping conduction	$J \propto V \exp\left(-\frac{\Phi}{kT}\right)$	$\ln(J/V) \propto 1/T$	$J \propto V$

Organic Thin-Film Transistors (OTFTs)

organic semiconductors: OTFT



inorganic semiconductors: MOSFET



- doping is difficult due to low purity
- conducting channel by accumulation
- predominantly hole transport (p-type)

- doping introduces carriers
- conducting channel by inversion
- both n-type and p-type channel (allows for CMOS architecture)

For a review of inorganic (silicon) FETs, see, e.g.:

S.M. Sze, *Physics of Semiconductor Devices*

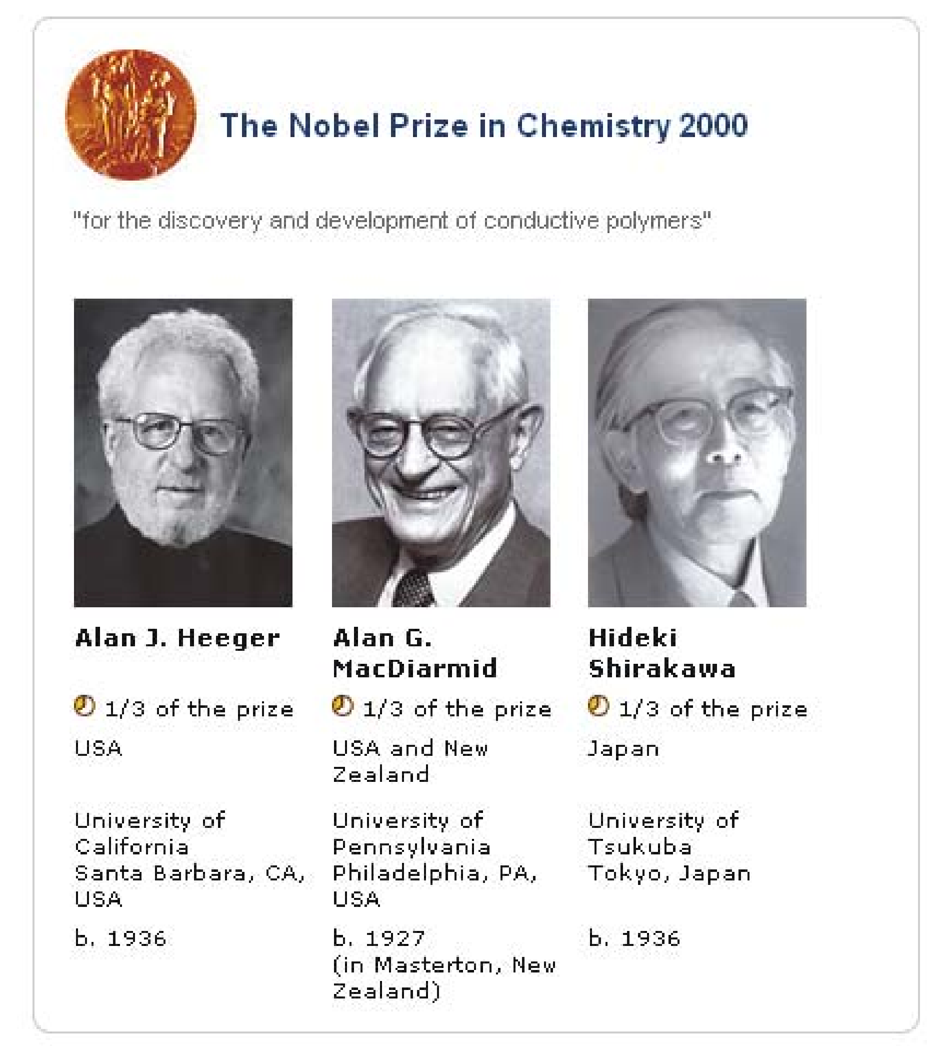
A.S. Sedra and K.C. Smith, *Microelectronic Circuits*, ISBN 0-03-053237-X

Organic Thin-Film Transistors (OTFTs)

organic semiconductors

	examples	typical mobility ($cm^2V^{-1}s^{-1}$)
polymers	polyacetylene poly(3-alkylthiophene) (P3AT)	0.1
small molecules	pentacene oligothiophenes	1
single-crystals	pentacene rubrene	10

Conductive polymers



The Nobel Prize in Chemistry 2000

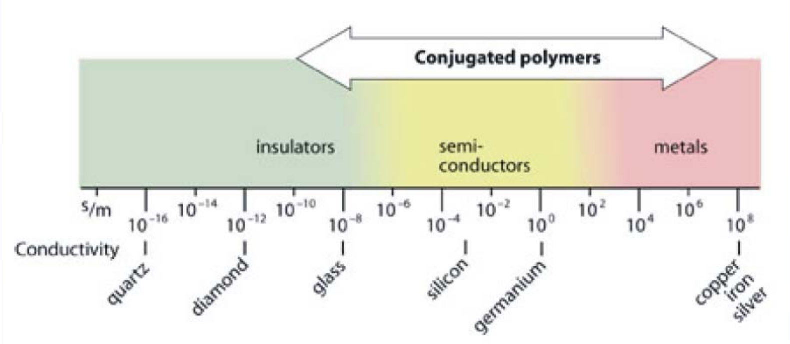
"for the discovery and development of conductive polymers"

Alan J. Heeger	**Alan G. MacDiarmid**	**Hideki Shirakawa**
1/3 of the prize	1/3 of the prize	1/3 of the prize
USA	USA and New Zealand	Japan
University of California Santa Barbara, CA, USA	University of Pennsylvania Philadelphia, PA, USA	University of Tsukuba Tokyo, Japan
b. 1936	b. 1927 (in Masterton, New Zealand)	b. 1936

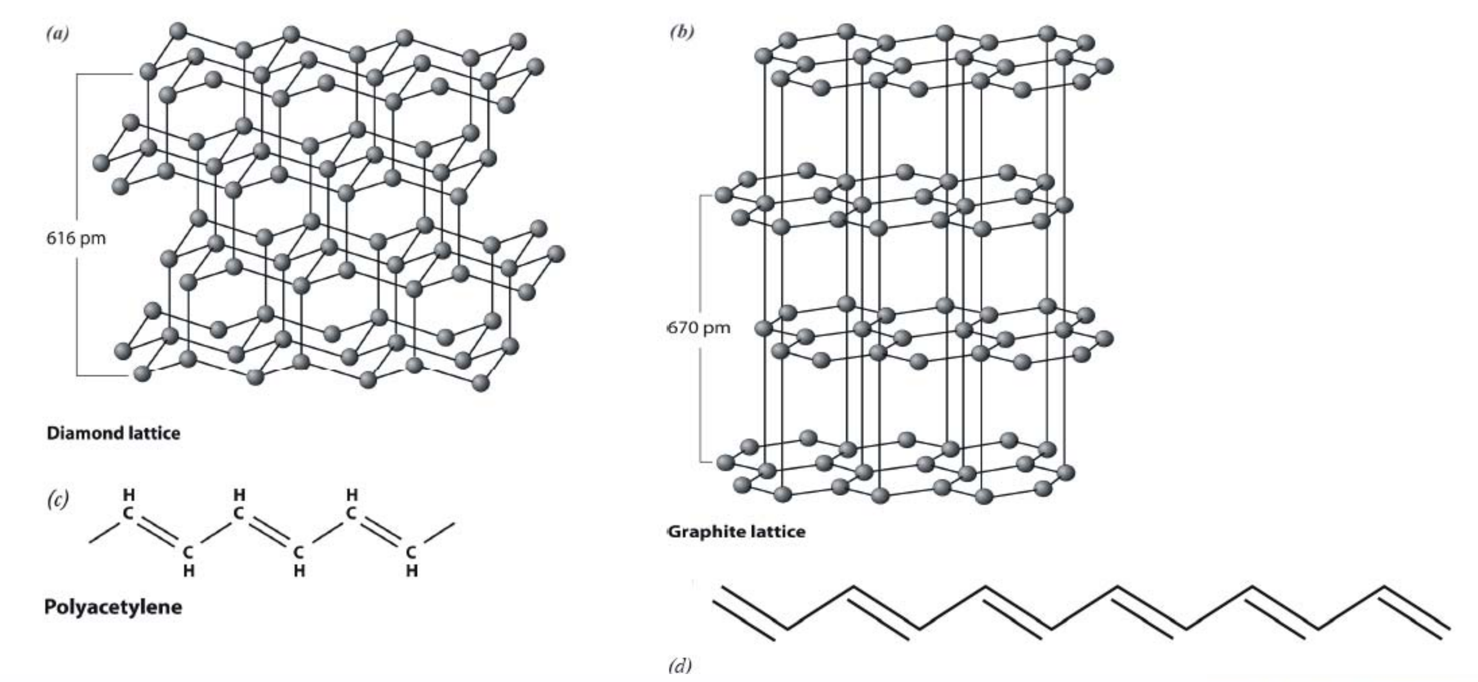
Conductive plastics are used in, or being developed industrially for, e.g. anti-static substances for photographic film, shields for computer screen against electromagnetic radiation and for "smart" windows (that can exclude sunlight).

In addition, semi-conductive polymers have recently been developed in light-emitting diodes, solar cells and as displays in mobile telephones and mini-format television screens.

Conductive polymers



polyacetylene: insulator
discovery: halogen (Cl, Br, I) doping makes polyacetylene 10^9 times more conductive:
$\sigma = 10^5\ \mathrm{Sm^{-1}}$
(teflon: $10^{-16}\ \mathrm{Sm^{-1}}$; copper: $10^8\ \mathrm{Sm^{-1}}$)



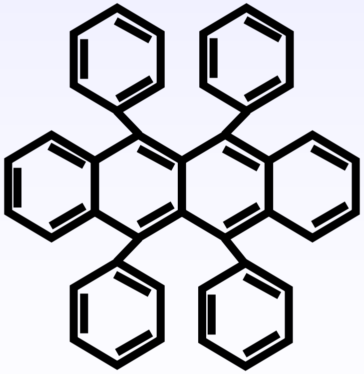
Organic single-crystals

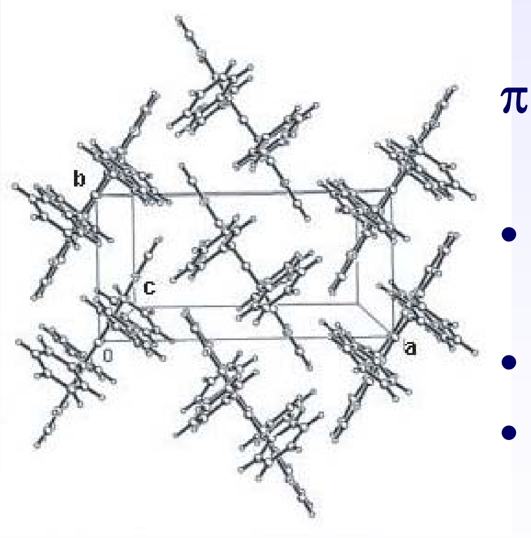
Polymers: no periodic structure (“spaghetti”)

Thin films of small molecules: defects (grain boundaries)

Single-crystals: low defect density (mobility independent of gate voltage)

rubrene





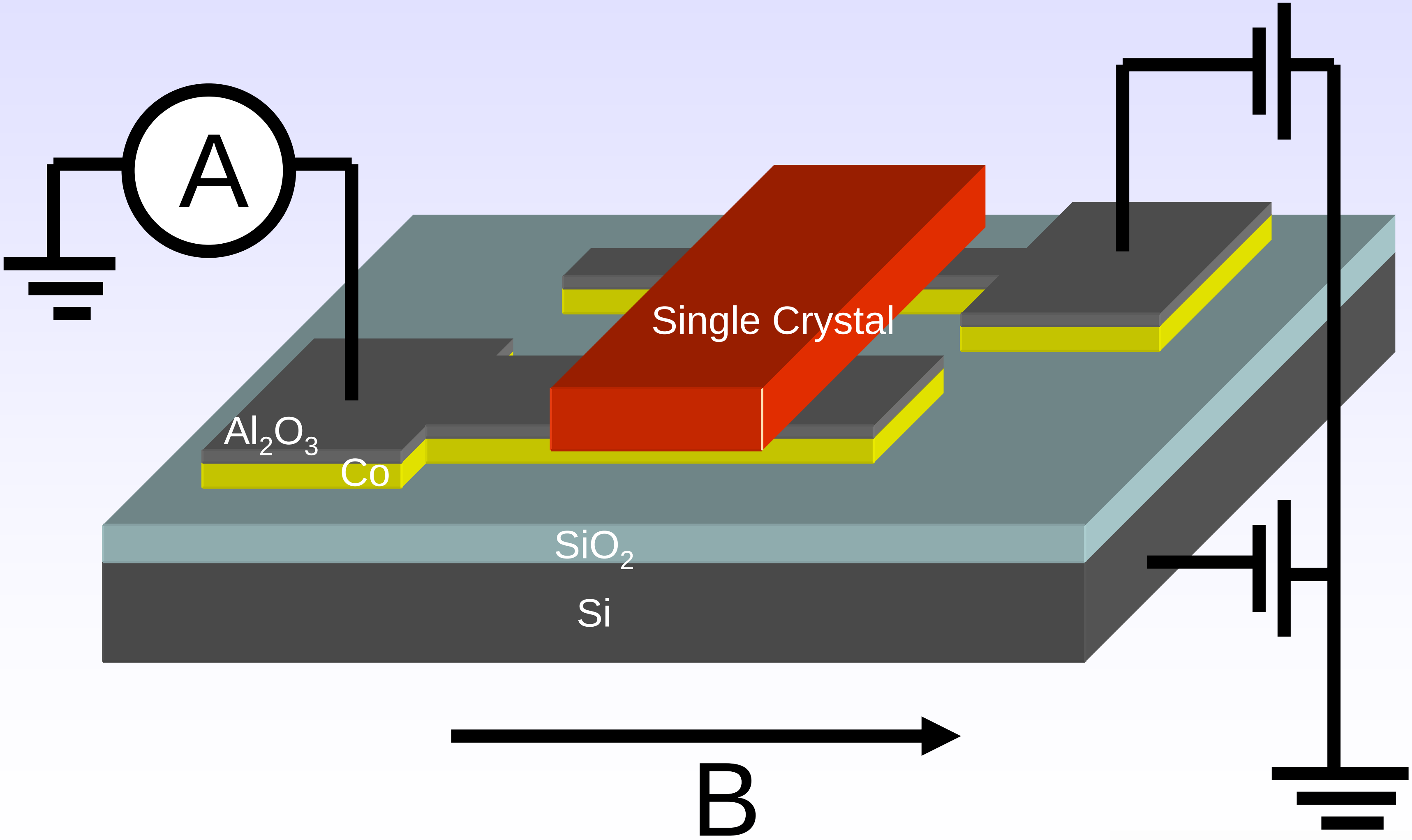
π-conjugated molecule (aromatic rings)

- High mobility due to strong orbital overlap (6 cm^2/Vs, up to 20 at RT)
- Stable in air
- Growth parameters known

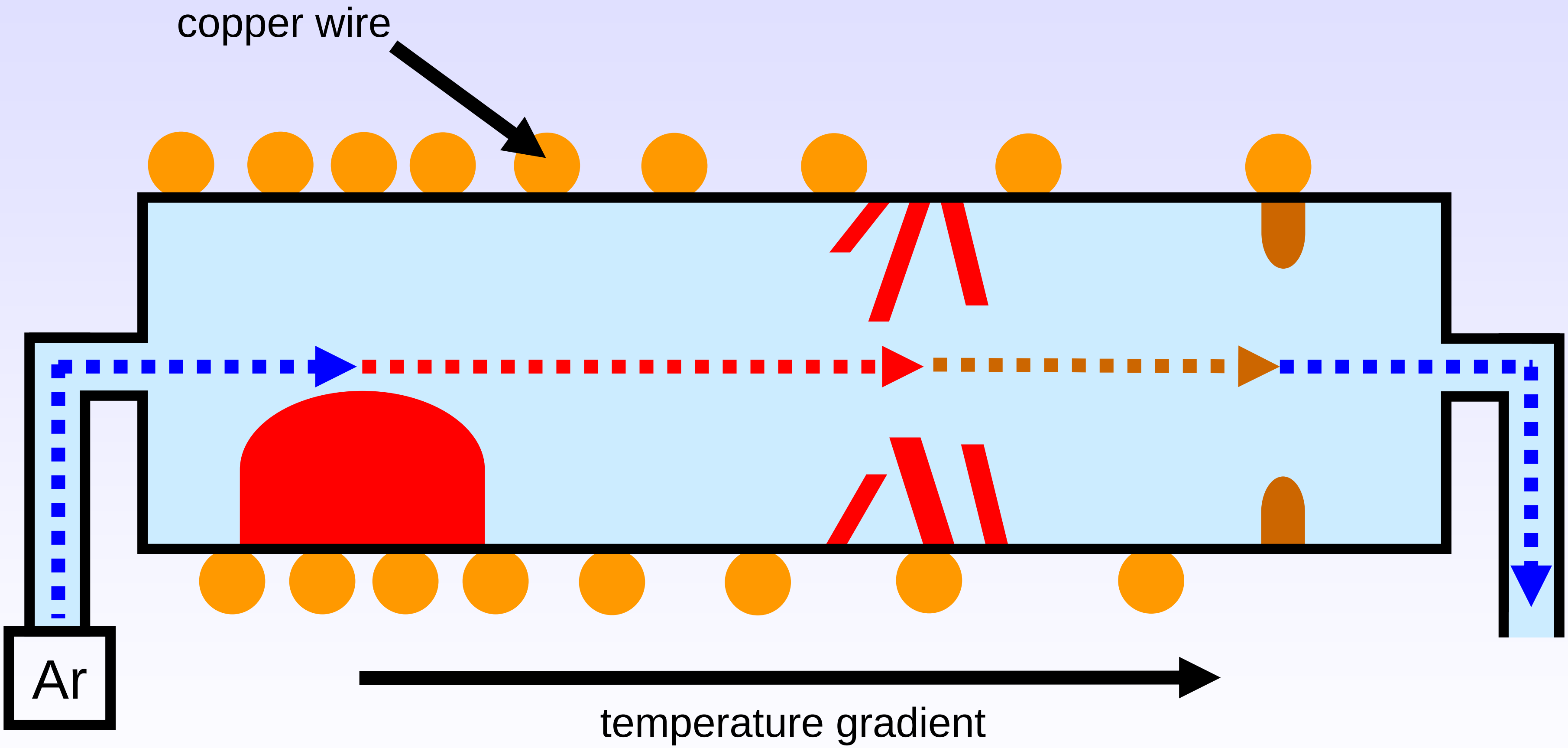
review:

R.W.I. de Boer, phys. stat. sol. (a) **201**, 1302 (2004)

Organic single-crystals

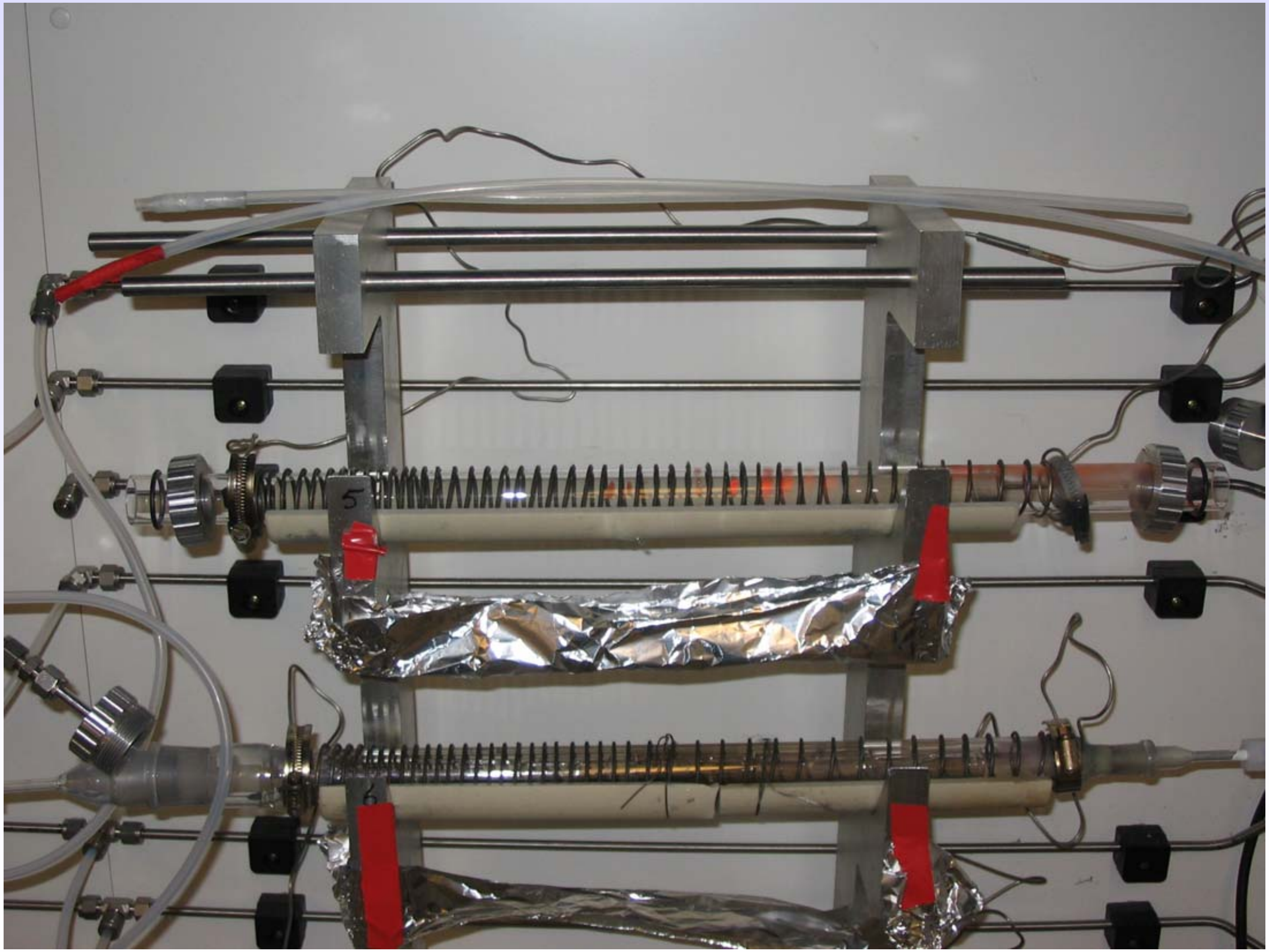


Organic single-crystals

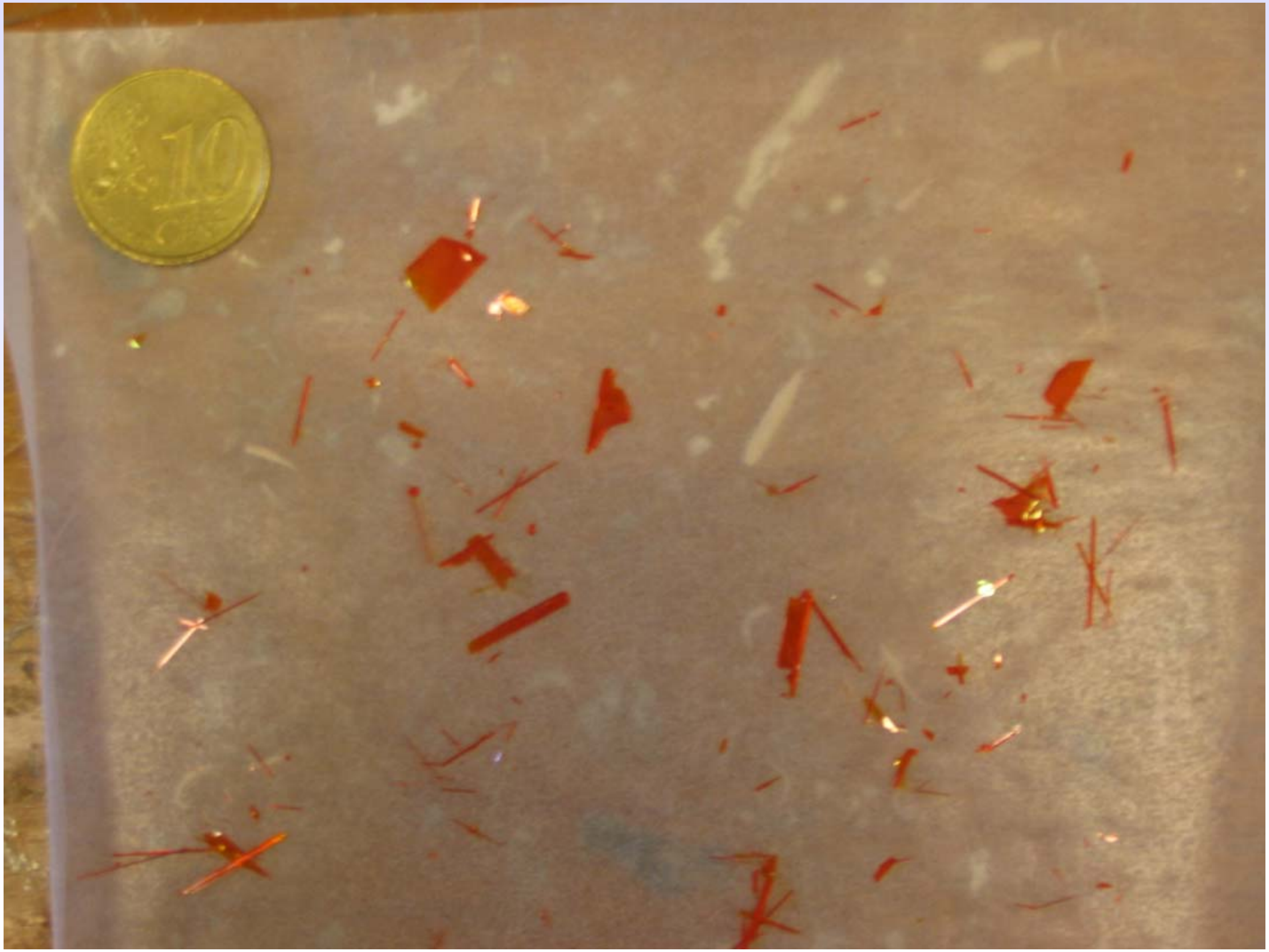


In collaboration with Anna Molinari, Alberto Morpurgo (TU Delft)

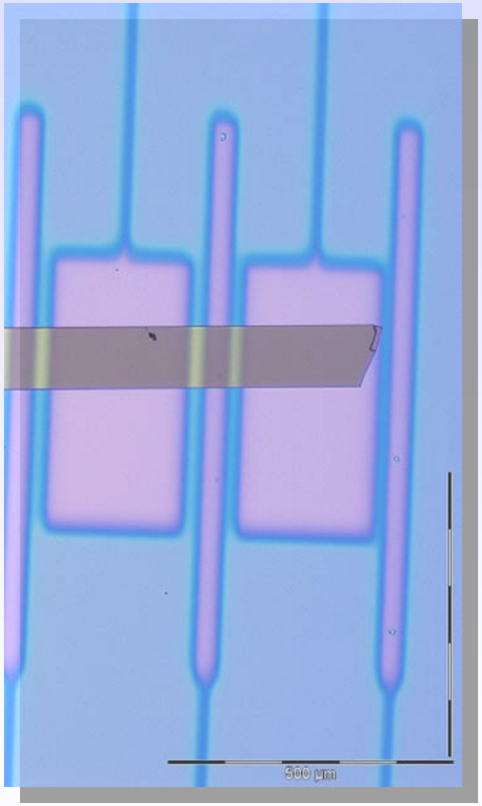
Organic single-crystals

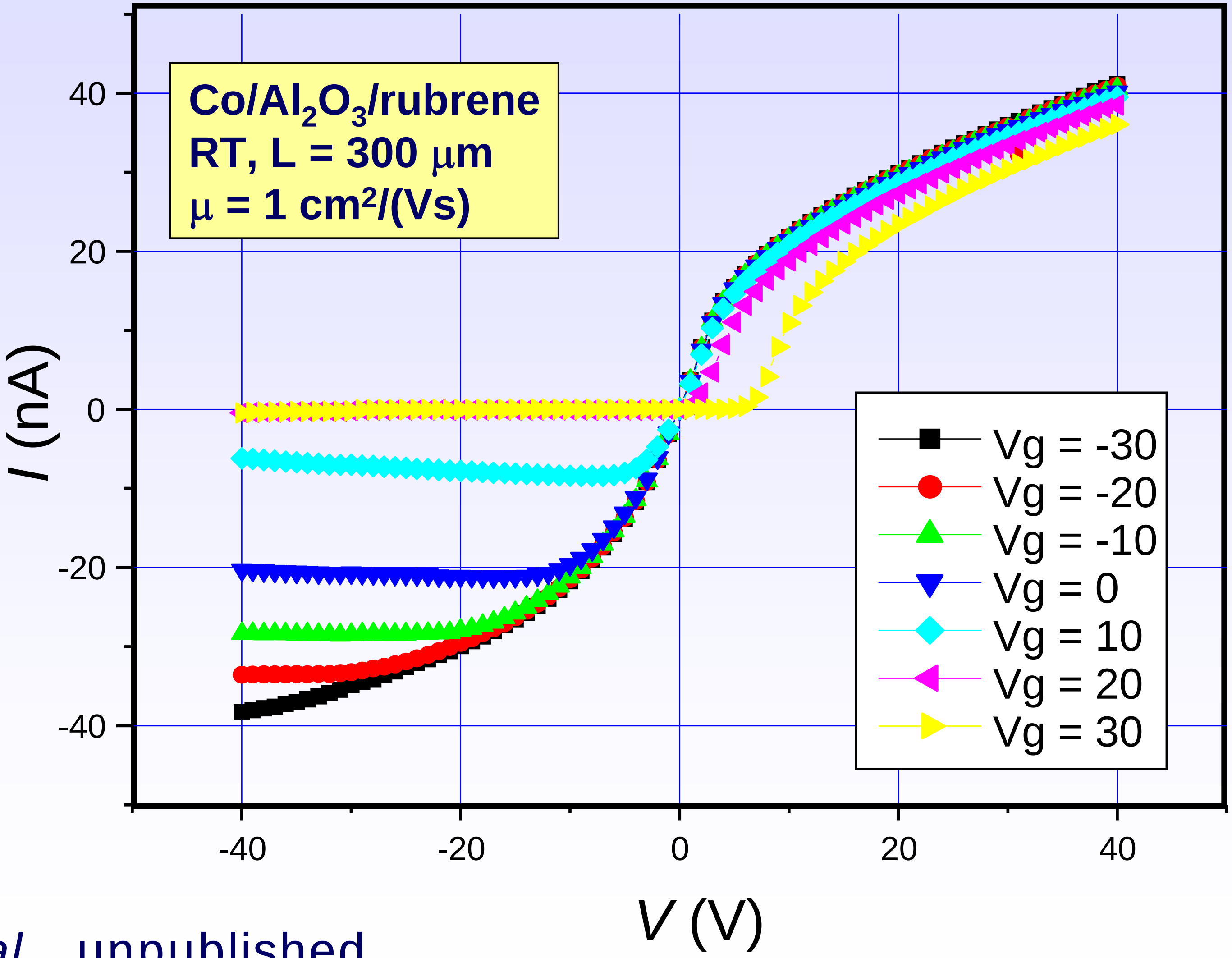


Organic single-crystals



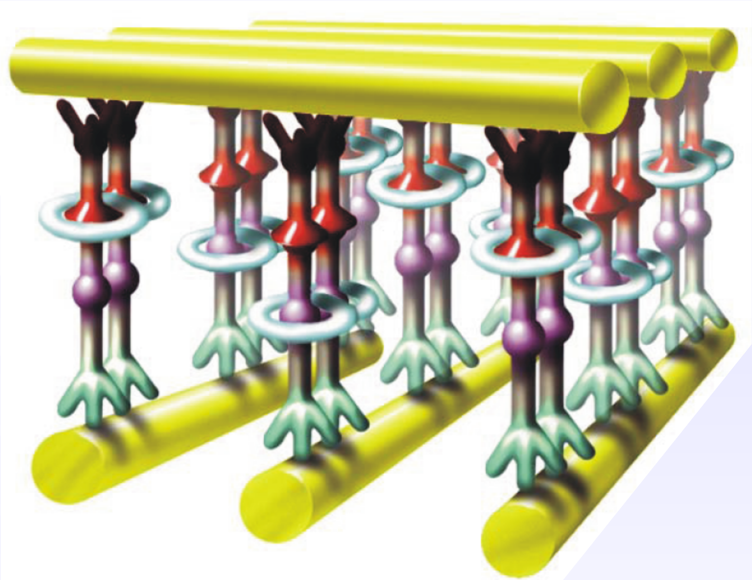
Organic single-crystals



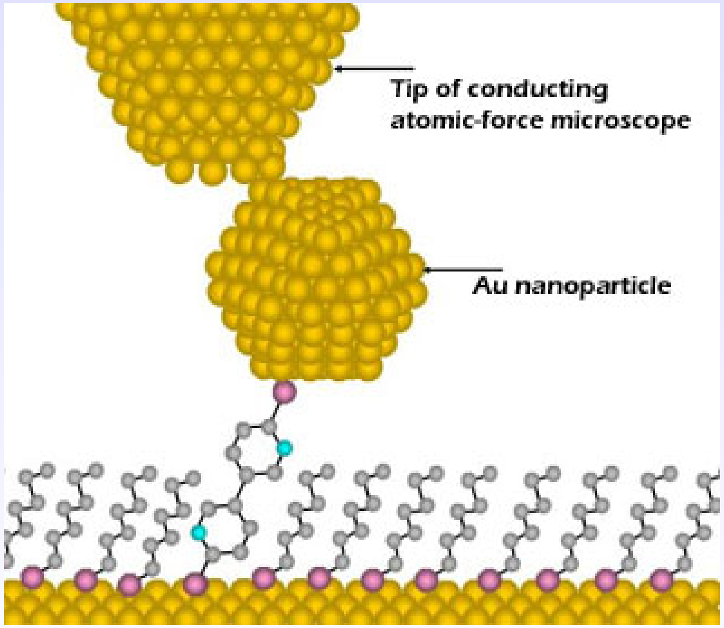


Wouter Naber *et al.*, unpublished

Molecular electronics

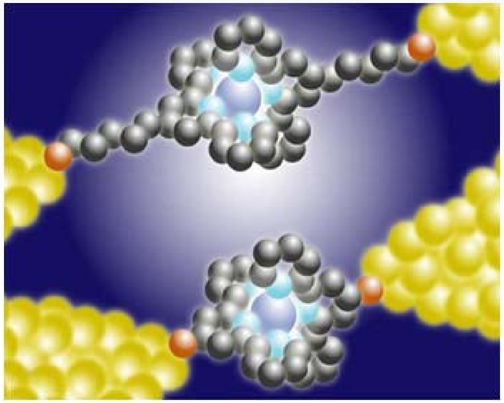


rotaxane – switching molecule

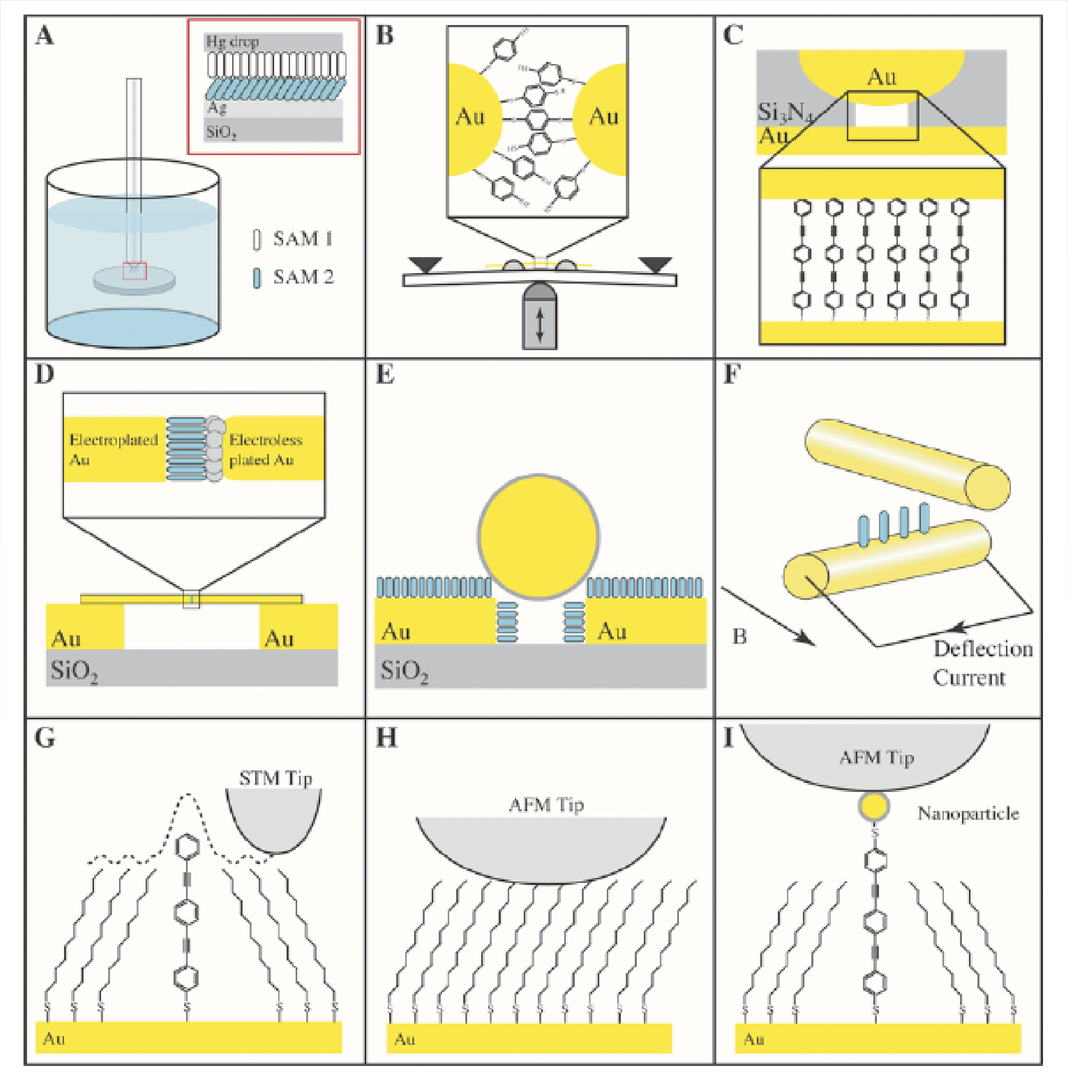


STM tip with nanoparticle

single
atom
transistor



Measuring electronic properties of molecules



A. Hg drop junction
B. Mechanical break junction
C. Nanopore
D. Nanogap in nanowire
E. Nanoparticle bridge
F. Crossed (nano)wires
G. STM
H. CP-AFM
I. Nanoparticle + CP-AFM

B.A. Mantooth and P.S. Weiss,
Proc. IEEE **91**, 11 (2003)

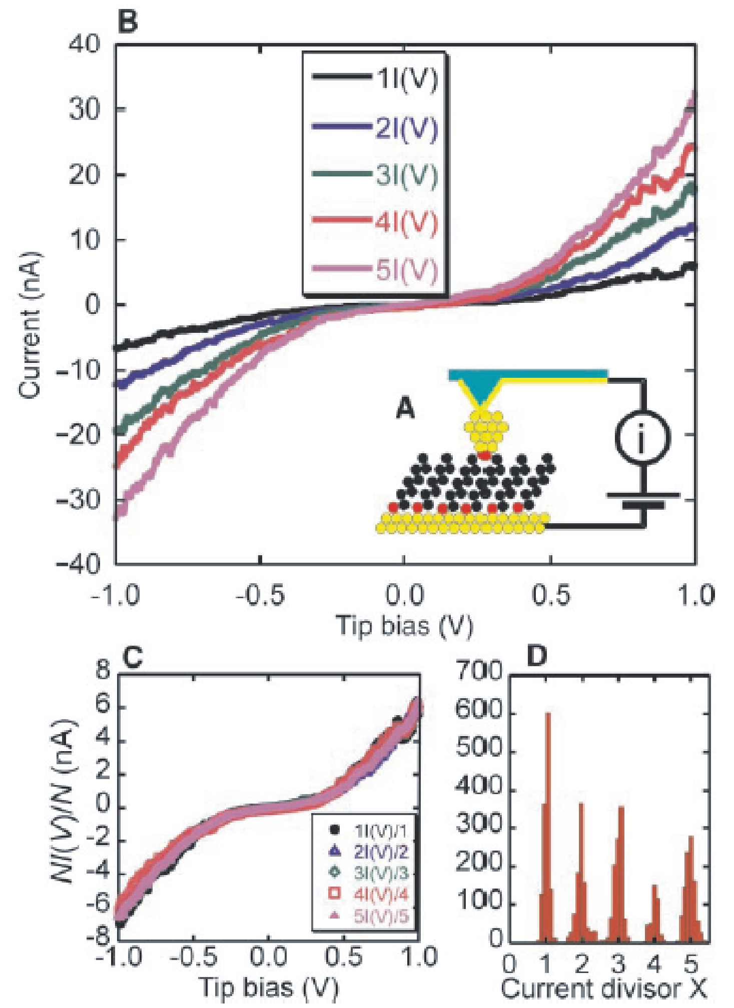
conducting AFM

single 1,8-octanedithiol molecules inserted in octanethiol monolayer

gold nanoparticles on top of the monolayer are contacted by gold-plated conducting AFM probe

octanedithiol: 900 ± 50 MOhm (based on 1000 single molecules)

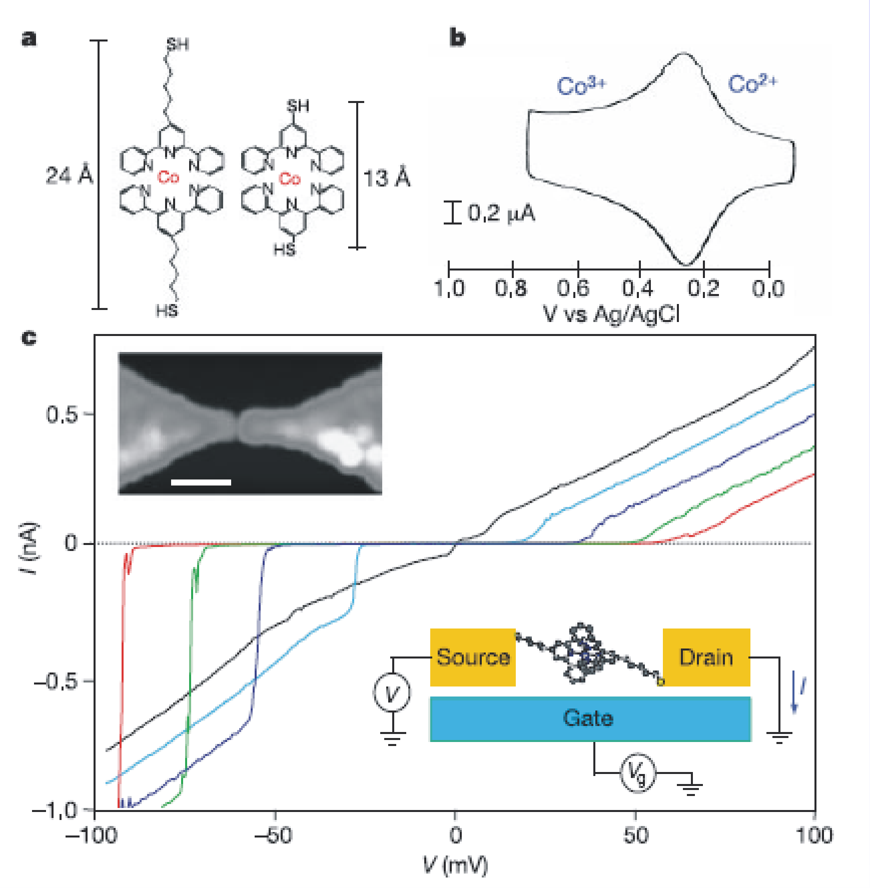
1, 2, 3, 4 or 5 molecules measured in parallel



X.D. Cui *et al.*, Science **294**, 571 (2001)

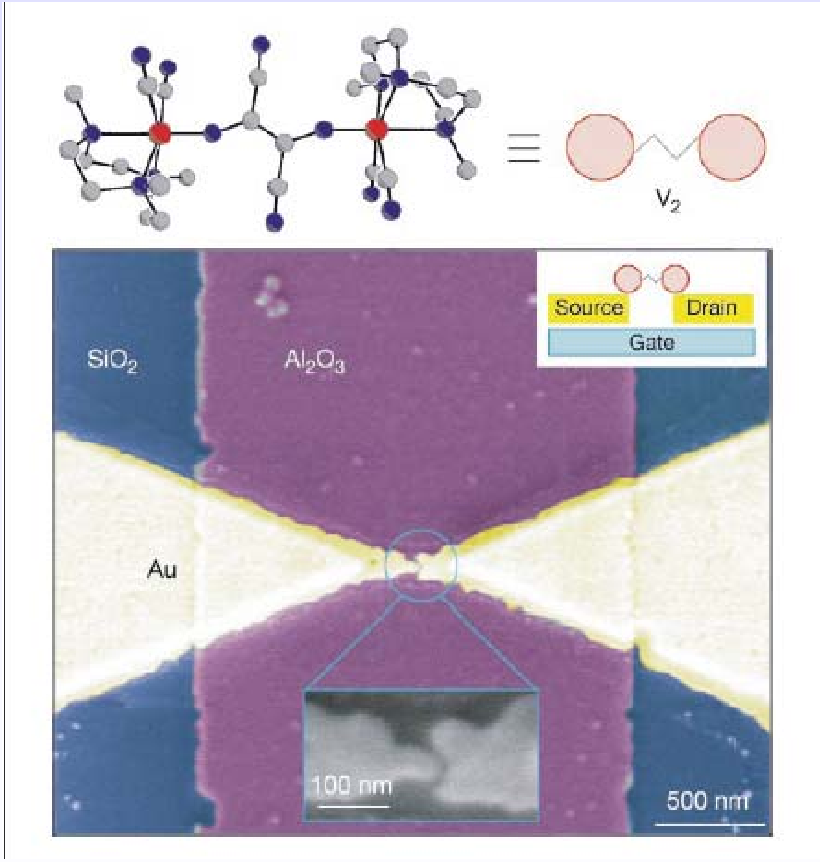
Single-molecule transistors

single Co-atom transistor



J. Park *et al*., Nature **417**, 722 (2002)

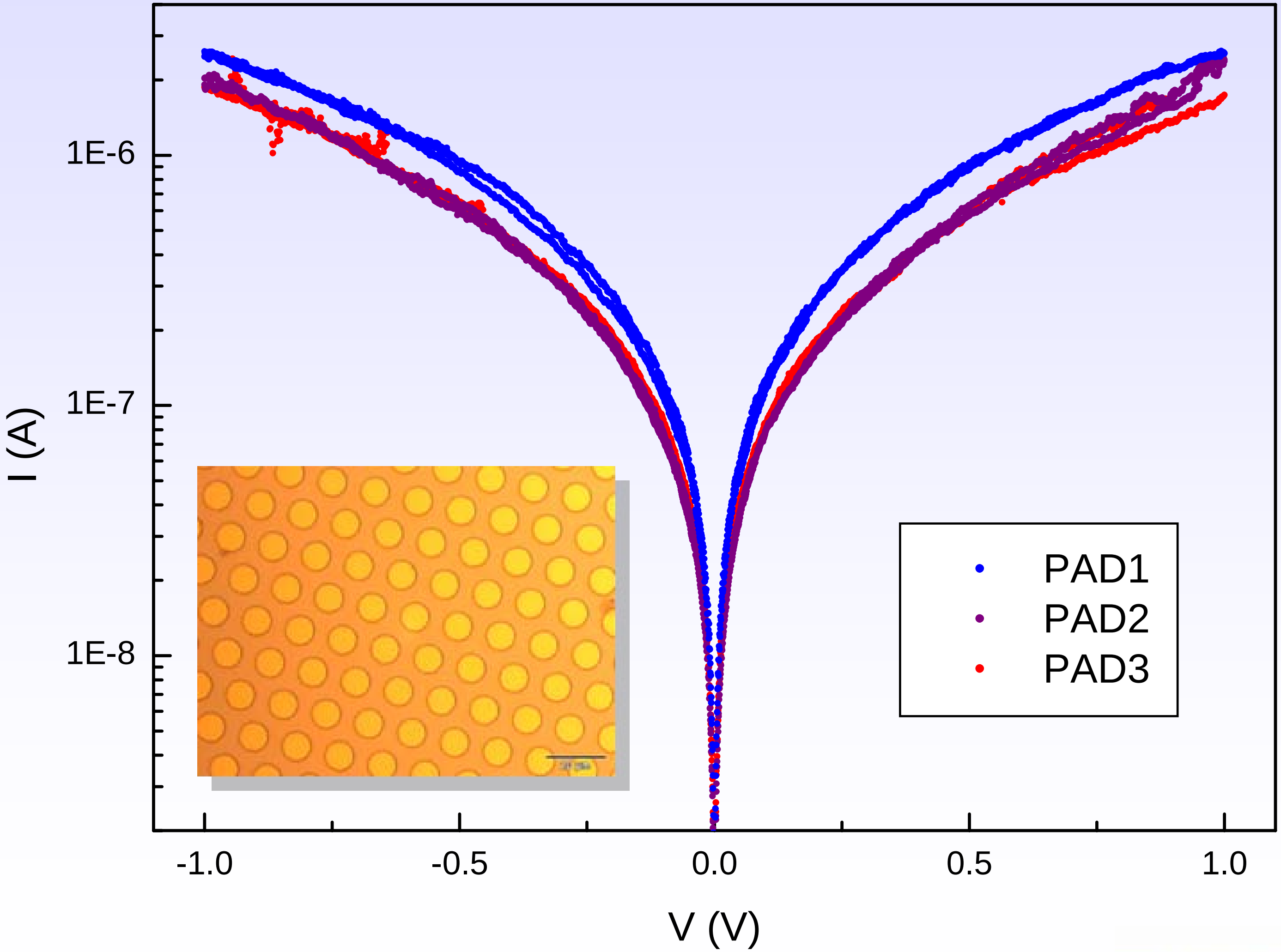
divanadium molecule as spin impurity



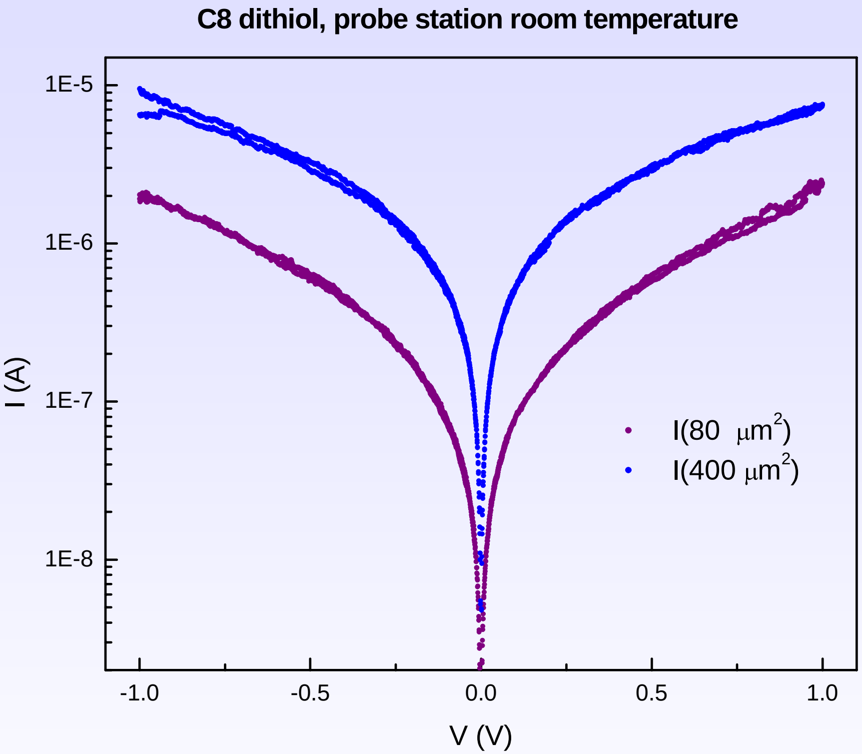
W. Liang *et al*., Nature **417**, 725 (2002)

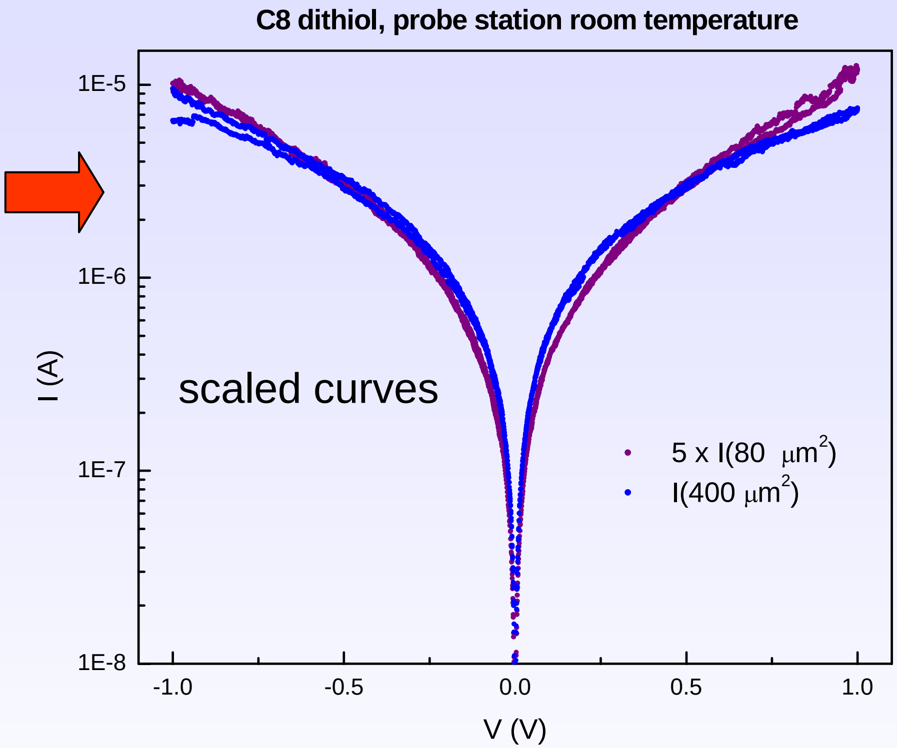
Tunneling through alkanedithiol SAMs

C8 dithiol, 10 micron circular pads, probe station room temperature

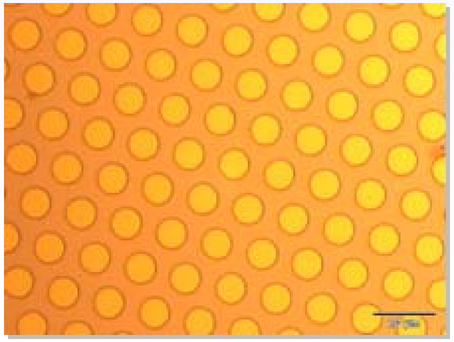


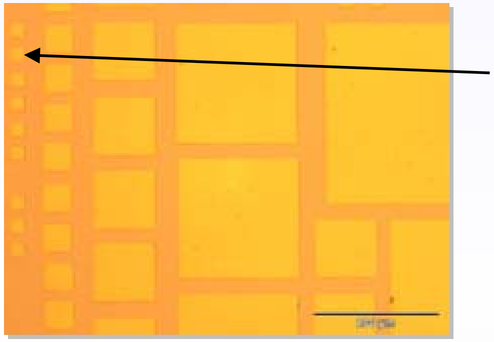
Tunneling through alkanedithiol SAMs





10 μm circles
(80 μm^2)





20 μm x 20 μm
(400 μm^2)

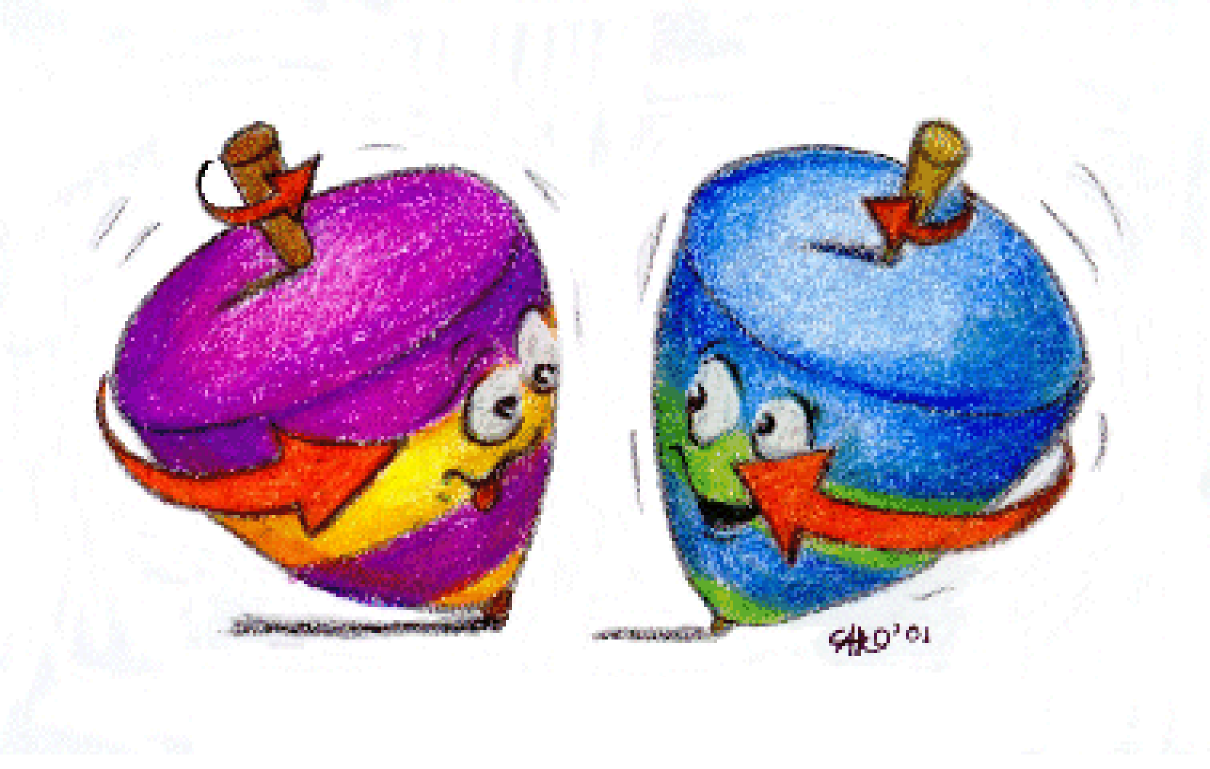
Organic electronics vs CMOS

Once it is possible to make transistors by chemical synthesis, more transistors will be made in one day that it will ever be possible by photolithography.

However, CMOS is still going strong! Dimensions of transistors have shrunk a factor 10,000 since the 1960s. The price of 1 gigabit of memory has decreased by a 1.5 million times.

Experts predict that CMOS will remain the mainstream technology for many years and that improvements will continue until at least 2016.

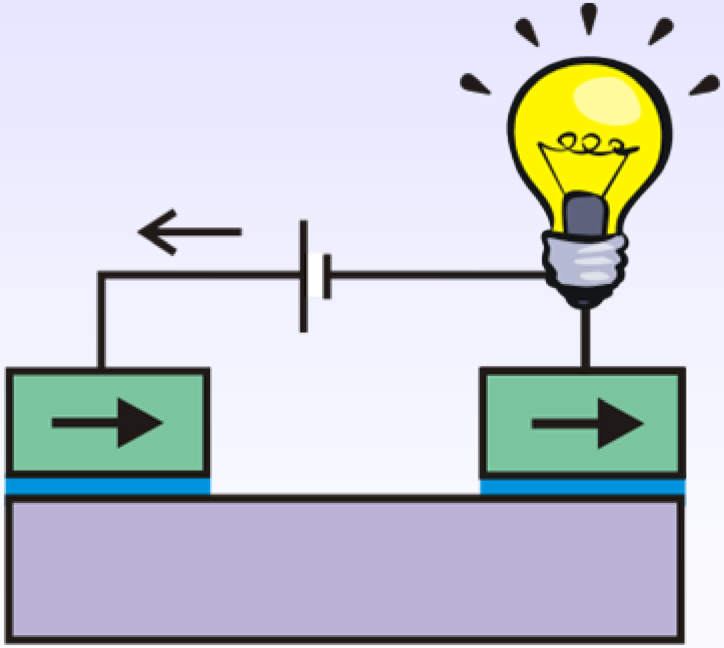
Spintronics



- non-volatality (no constant voltage required to ‘remember’ state)
- decreased electric power consumption
- increased data processing speed

Spintronics

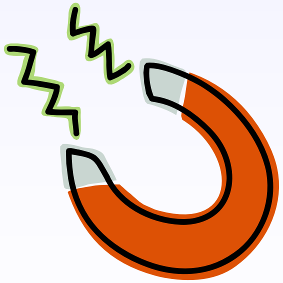
traditional electronics: **charge**
spin electronics: ***spin* and charge**



magnetic contacts

tunnel barriers

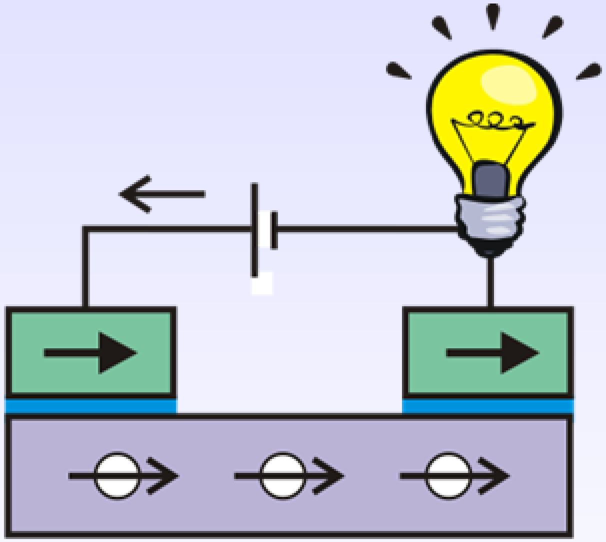
normal *metal* spacer



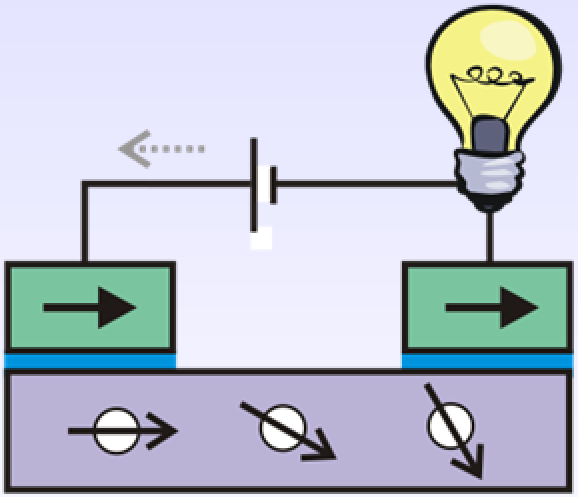
semiconductor spacers offer new possibilities

GaAs: X. Lou *et al.*, Nature Physics **3**, 197 (2007)

Spintronics



no spin relaxation

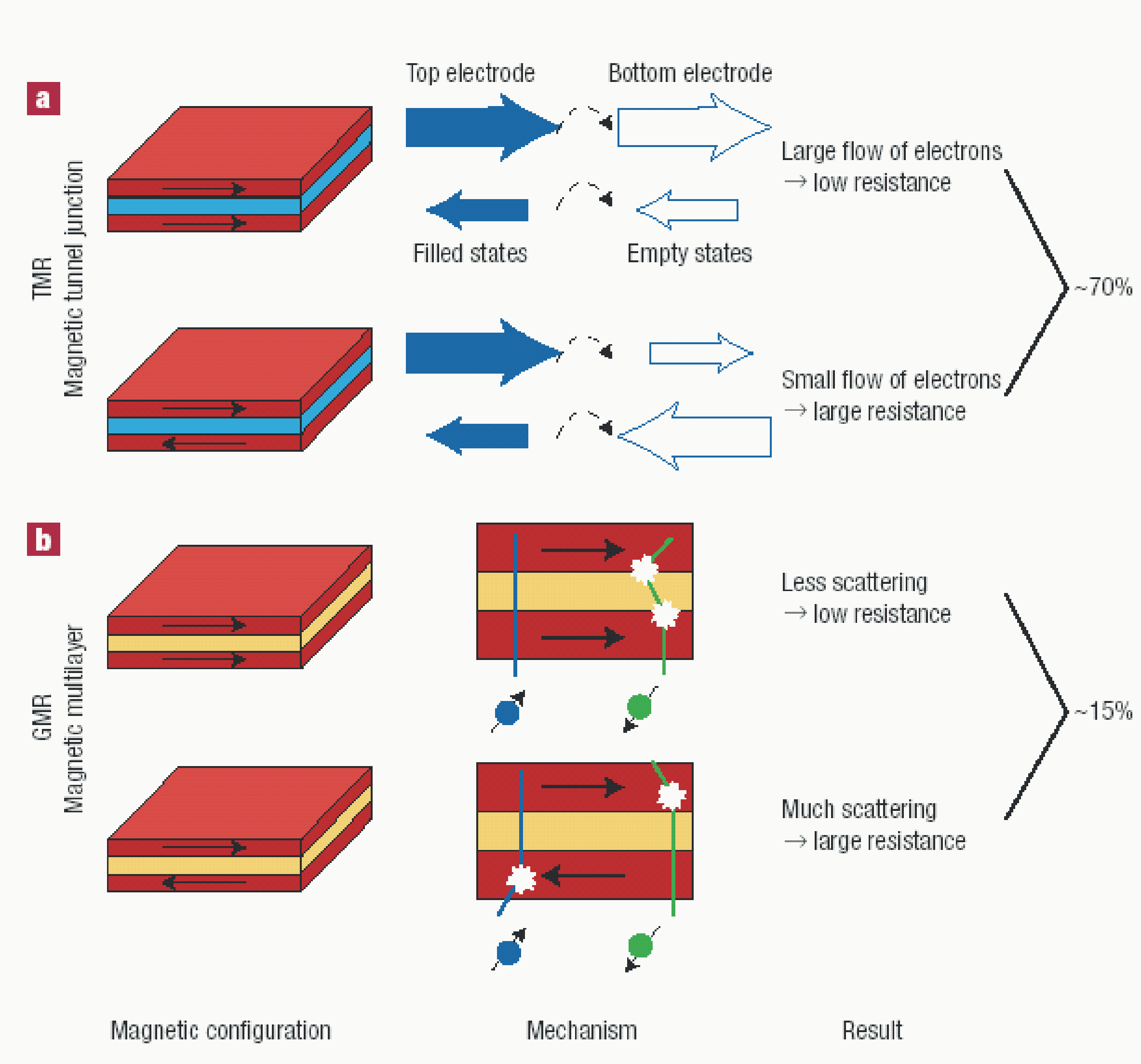


with spin relaxation

Spintronics

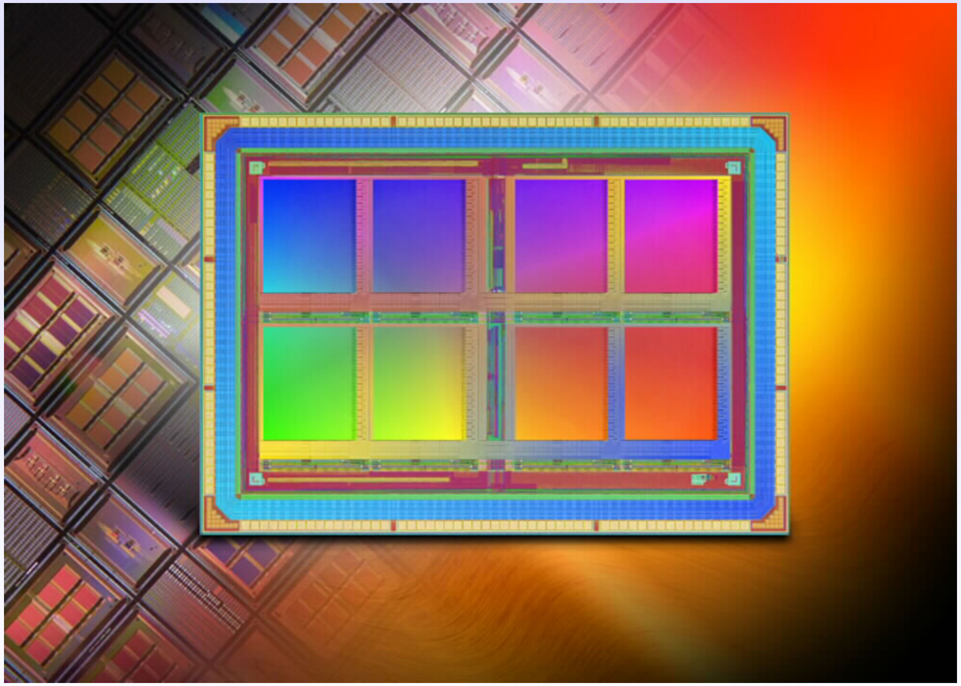
tunnel magneto resistance (**TMR**)
FM-insulator-FM

giant magneto resistance (**GMR**)
FM-metal-FM



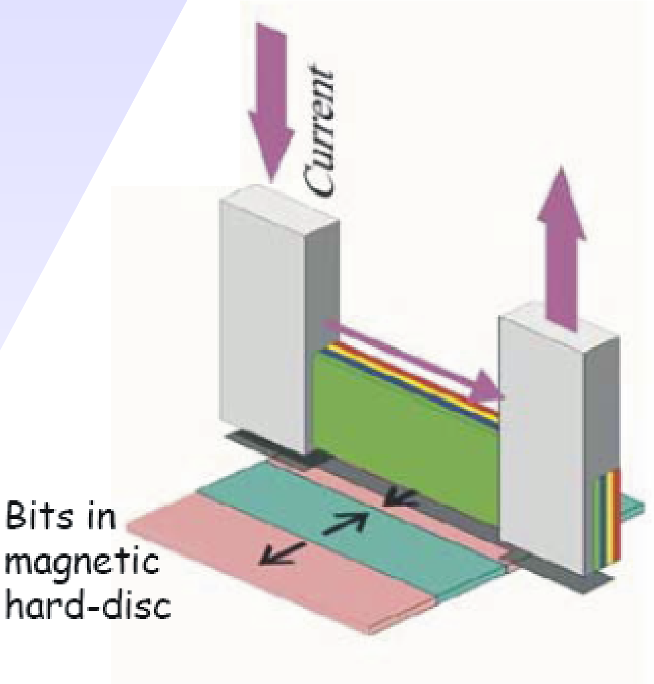
Spintronics

GMR head hard drive
Fujitsu

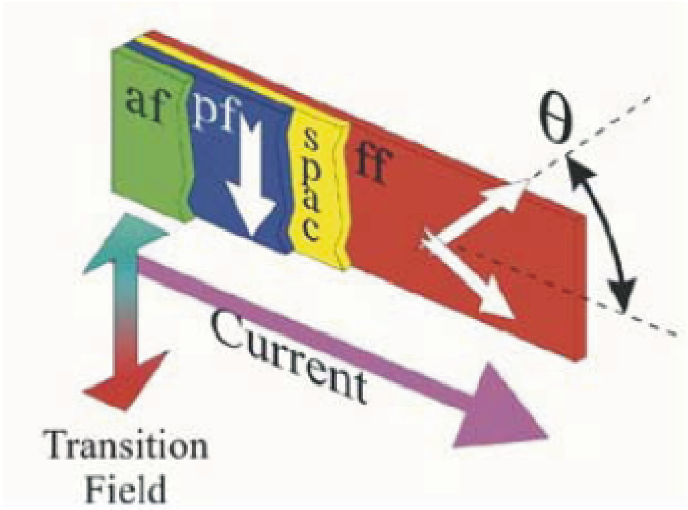


Magnetic Random Access Memory (MRAM)
Motorola

GMR hard disk read heads



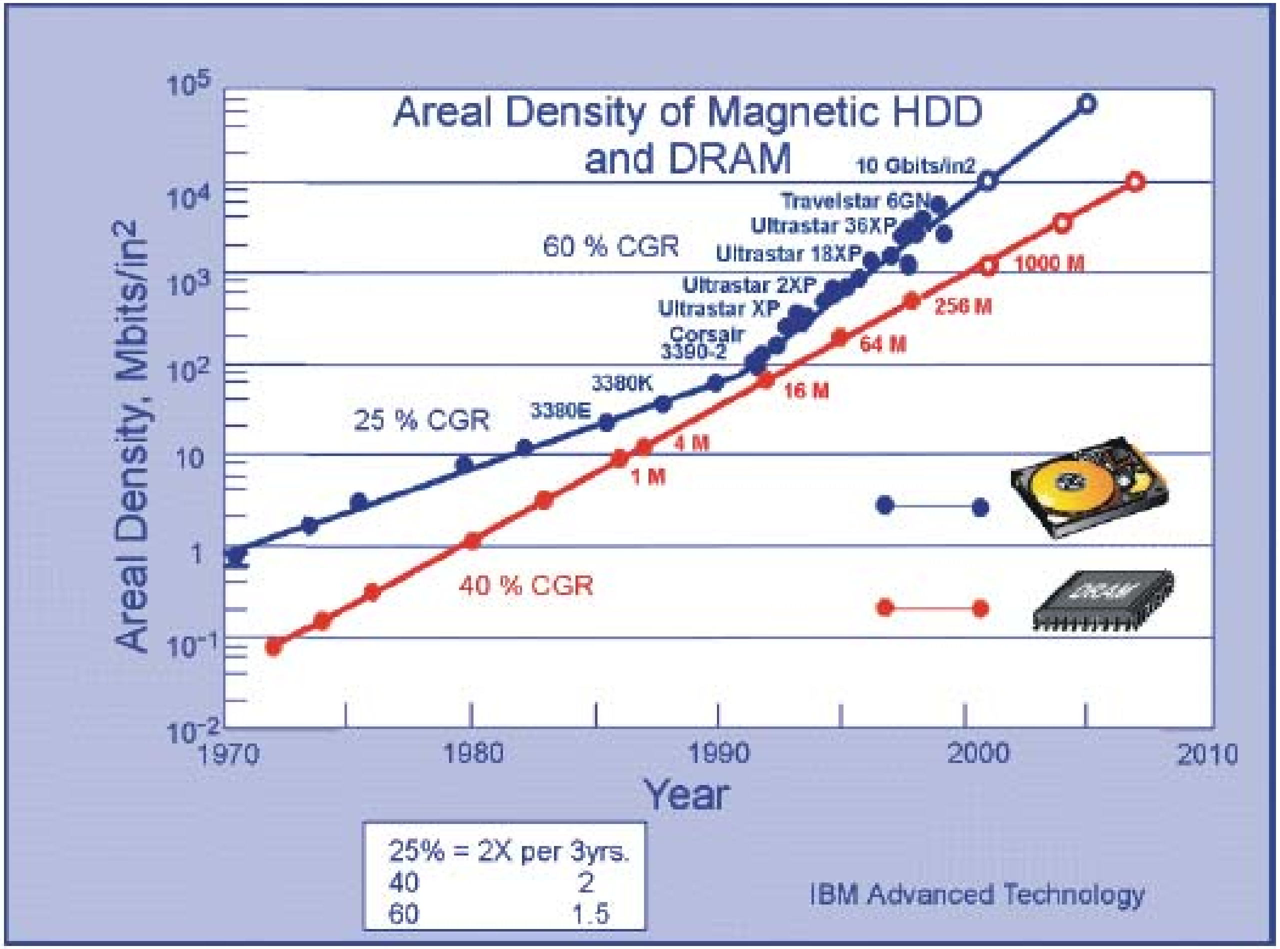
Layout of spin-valve type
GMR read head element



🟩 af = antiferromagnet
🟦 pf = pinned ferromagnet
🟨 spac = spacer layer
🟥 ff = free ferromagnet
🟦 sal = soft adjacent layer

Stray field from bits changes magnetization direction of one of the magnetic layers (red-ff), while the other (pf-blue) remains fixed. This changes the resistance of the spin valve.

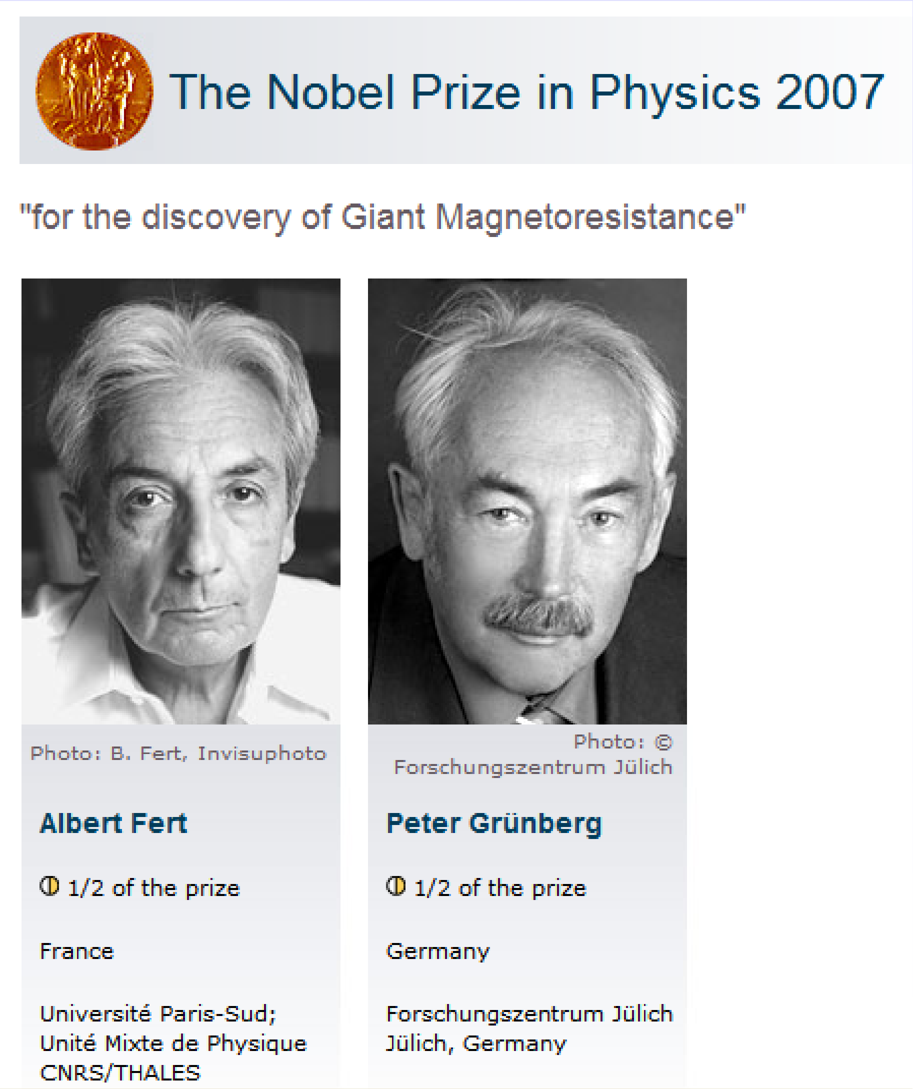
GMR hard disk read heads



Kink around 1992
for hard disc drives
(blue curve).

Due to replacement
of inductive sensor
by magnetoresistance
(MR) sensor with
much higher field
sensitivity.

Giant magnetoresistance



The Nobel Prize in Physics 2007

"for the discovery of Giant Magnetoresistance"

Photo: B. Fert, Invisuphoto

Albert Fert

◐ 1/2 of the prize

France

Université Paris-Sud;
Unité Mixte de Physique
CNRS/THALES

Photo: ©
Forschungszentrum Jülich

Peter Grünberg

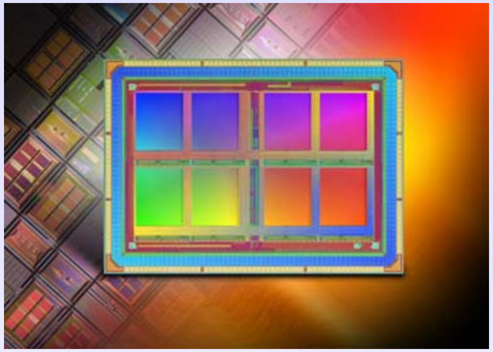
◐ 1/2 of the prize

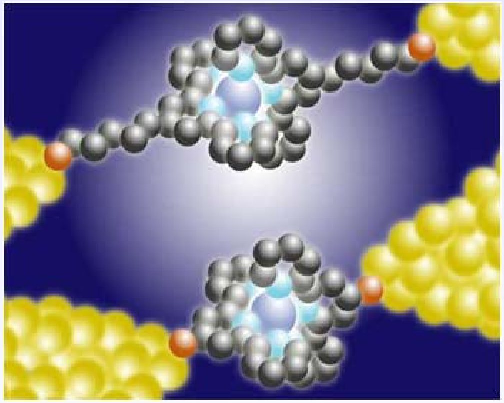
Germany

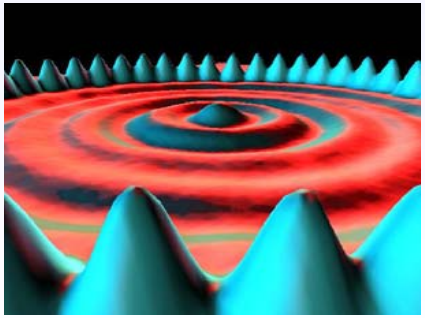
Forschungszentrum Jülich
Jülich, Germany

Nanoelectronics...

...is where physics, materials science, chemistry and electric engineering inevitably meet







Getting grip on the fundamental properties of nanoelectronic devices is of crucial importance, and a very exciting scientific challenge

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