Fundamentals of Nanomaterials

1. Introduction to nanoscale materia

- Four key words:
  - Macroscopic, mesoscopic, microscopic, nano

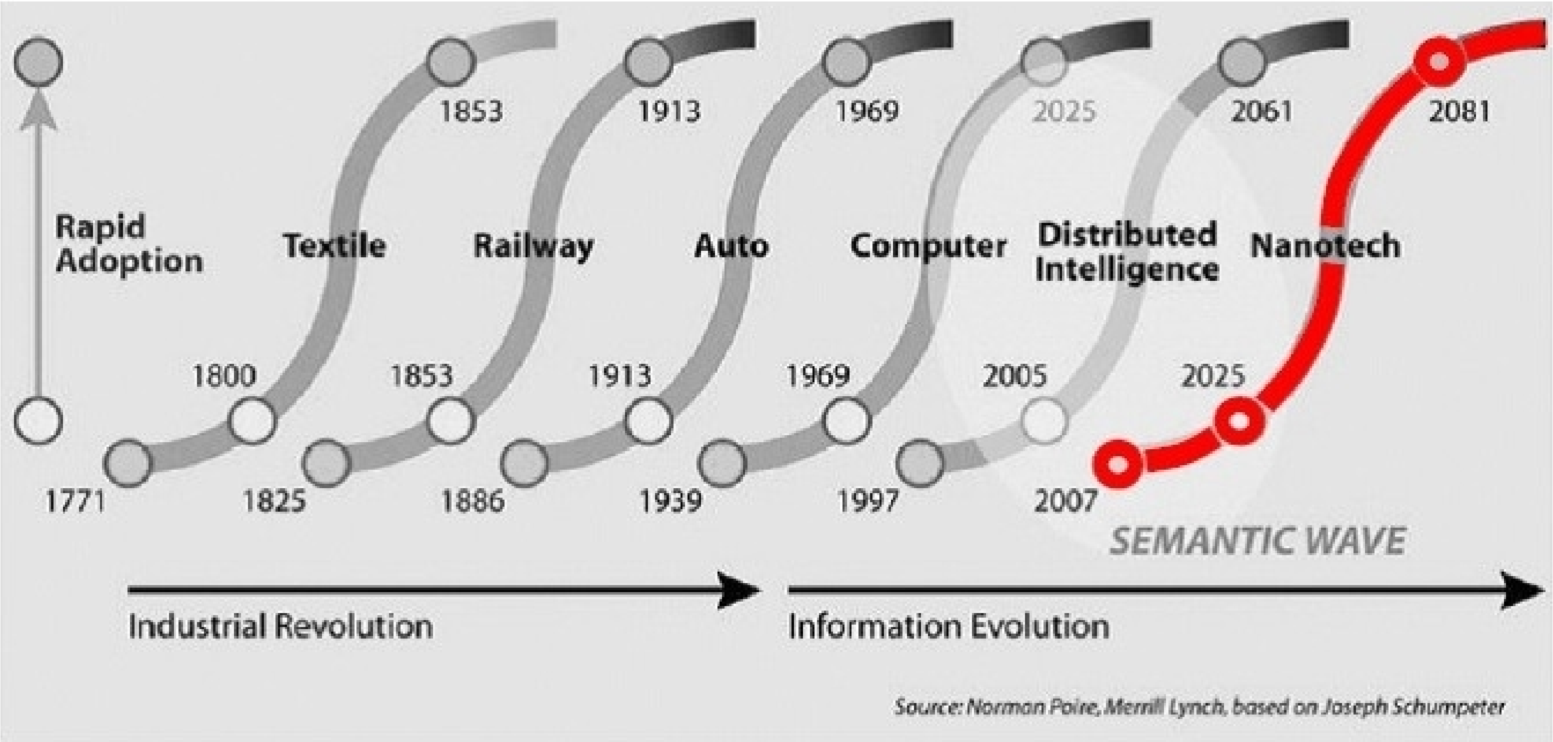
Macroscopic: has minimum limit (threshold), no top limit, such as the normal visible matter.

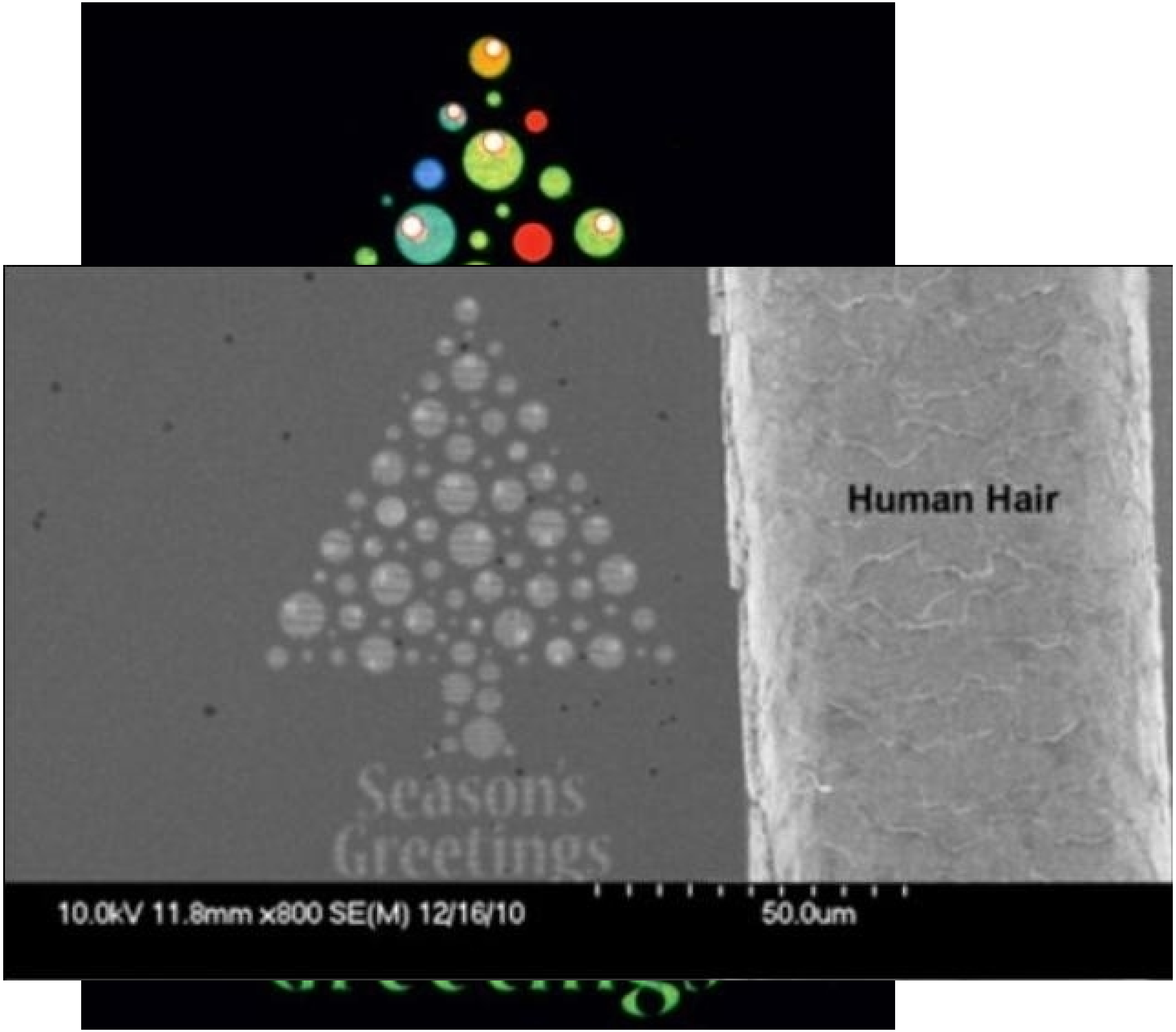
Mesoscopic: a intermediate length scale

Microscopic: has upper limit, no minimum limit, such as atom, molecule, nucleus

Nano: a new metrology, $1n=10^{-9}$.

Nano as next semantic revolution wave

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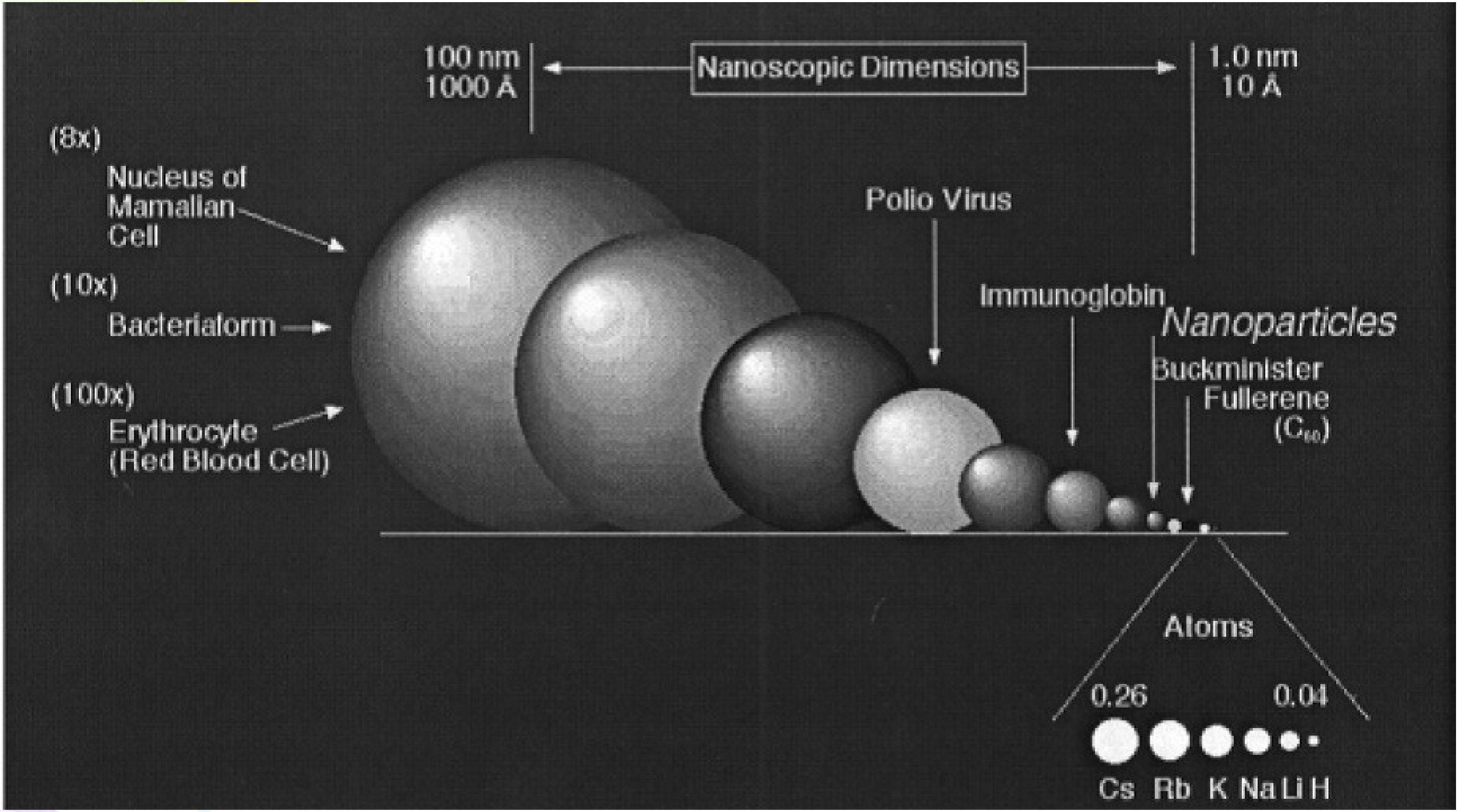
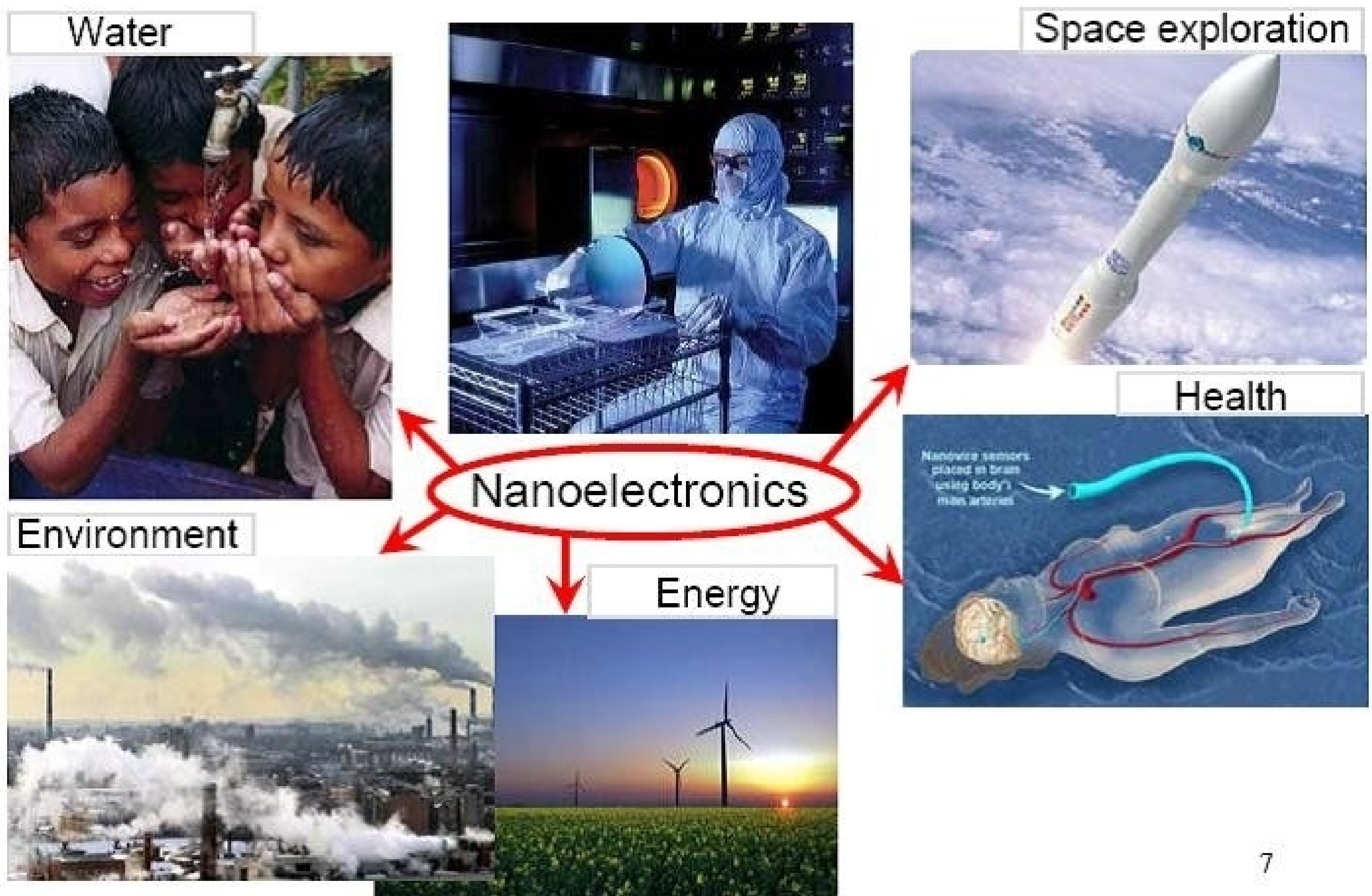
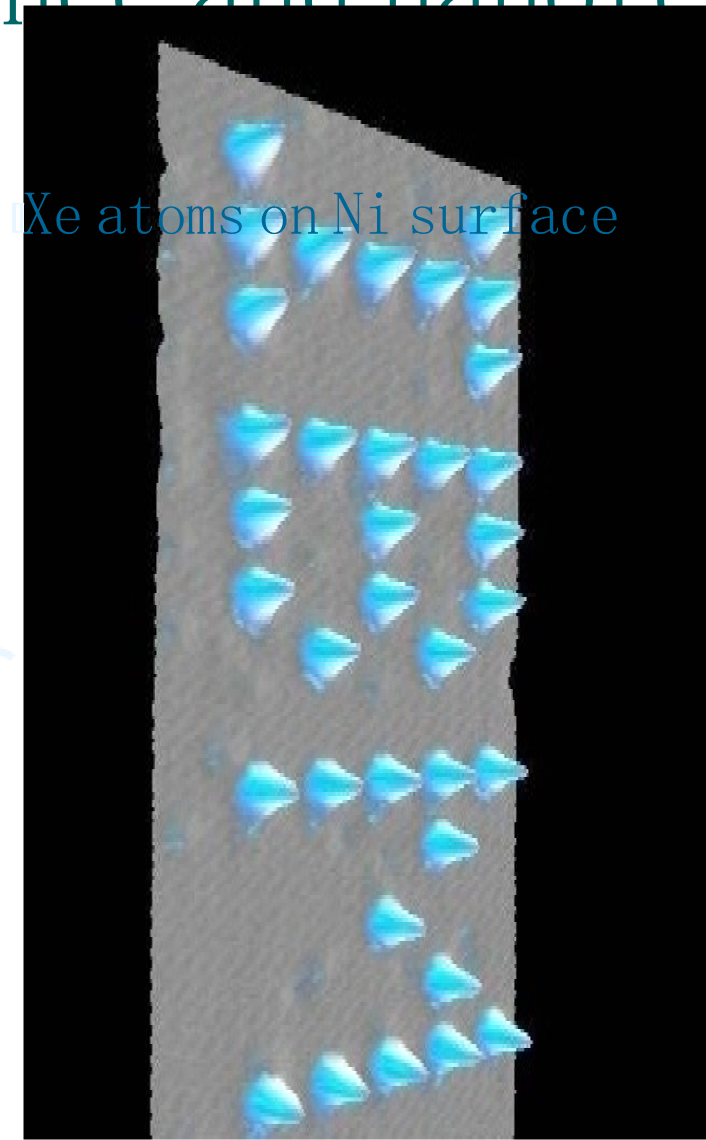


Size comparisons of nanocrystals with bacteria, viruses, and molecules.

Nano: serving society needs

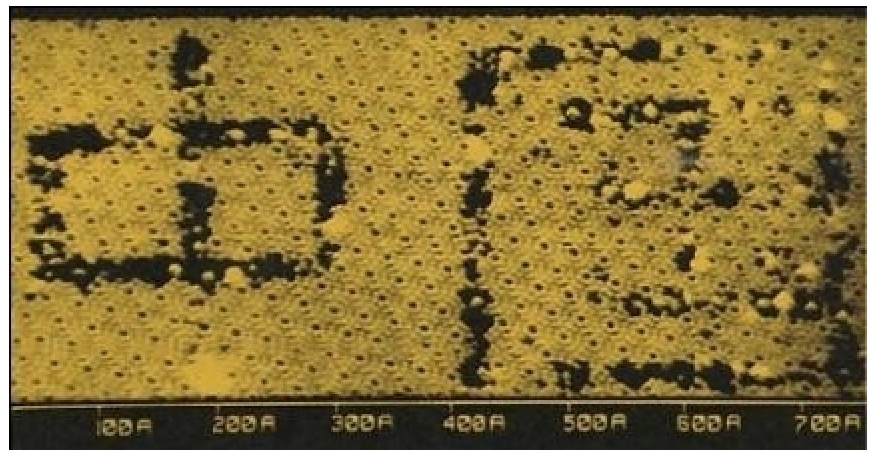


Nanoscience and nanotechnology



Xe atoms on Ni surface

Fe atoms on Cu surface



- **Nanotechnology** (sometimes shortened to "**nanotech**") is the study of manipulating matter on an atomic and molecular scale. Generally, nanotechnology deals with developing materials, devices, or other structures possessing at least one dimension sized from 1 to 100 nanometres. Quantum mechanical effects are important at this quantum-realm scale.

- Has the building blocks which has at least one dimension in the nanometer scale (1-100nm);
- Has the different characteristic comparing with the bulk materials

} Nanomaterial

Classification of nanoscale material

- According to the spatial dimension

Zero dimension: three dimensions are all in nanometer scale

One dimension: two dimensions are in nanometer scale

Two dimension: only one dimension is in nanometer scale

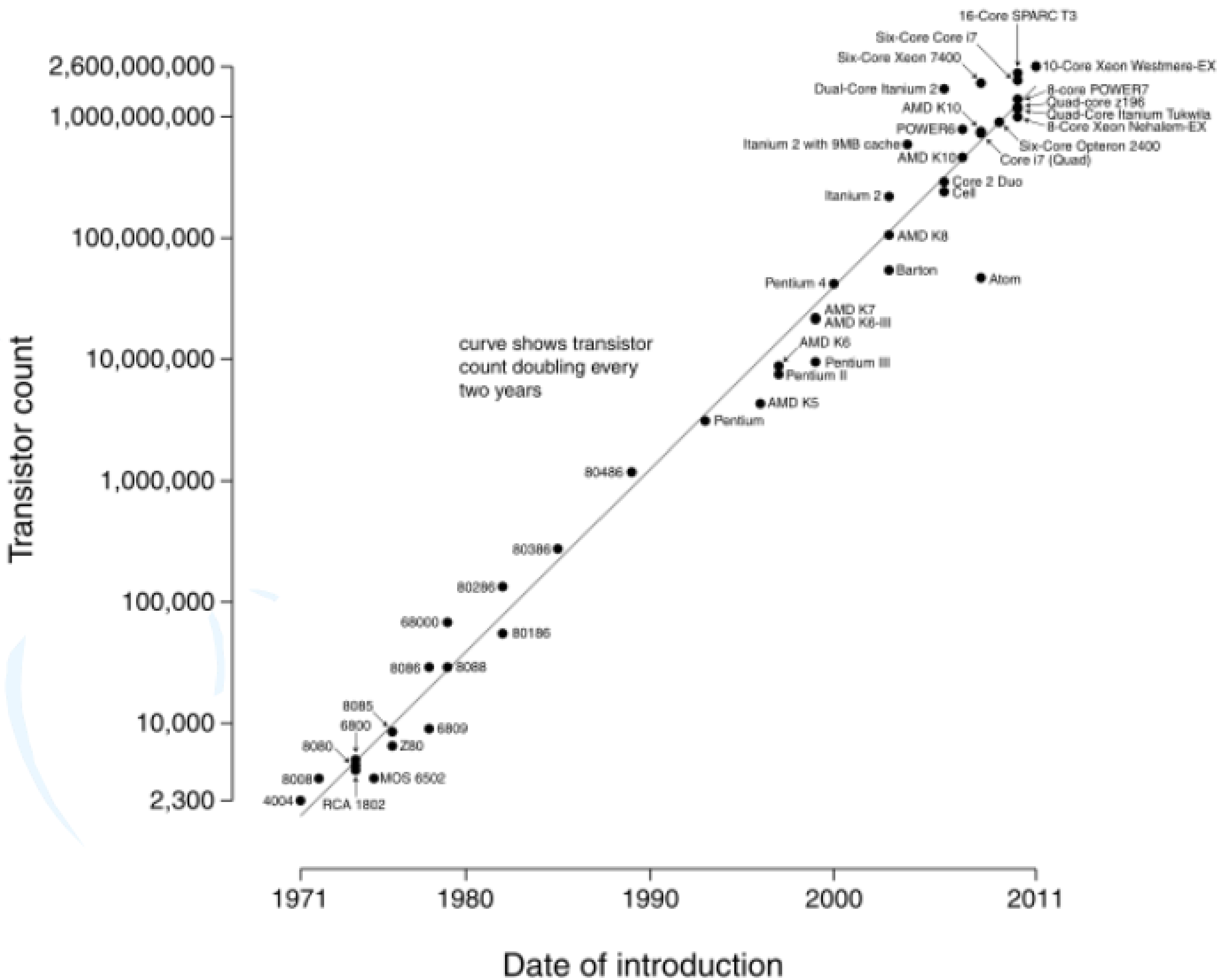
- According to quantum properties (P3-5)
  - Bulk material
  - Quantum wells
  - Quantum wires
  - Quantum dots

- According to the shape and chemical composition (P3-8)
  - Nanostructured materials
  - Nanostructures
  - Nanocomposites

Moore’ s Law

- **Moore"s law** describes a long-term trend in the history of computing hardware whereby the number of transistors that can be placed inexpensively on an integrated circuit doubles approximately every two years. The period often quoted as "18 months" is due to David House, an Intel executive, who predicted that period for a doubling in chip performance (being a combination of the effect of more transistors and them being faster).

Microprocessor Transistor Counts 1971-2011 & Moore's Law

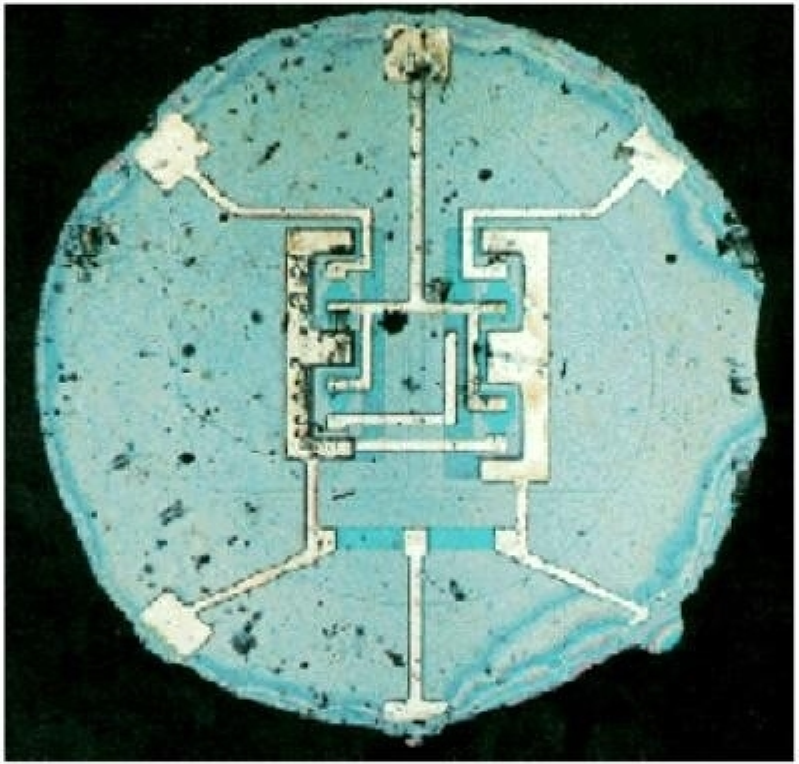


>40 years of Moore's law: 1965 – 2006

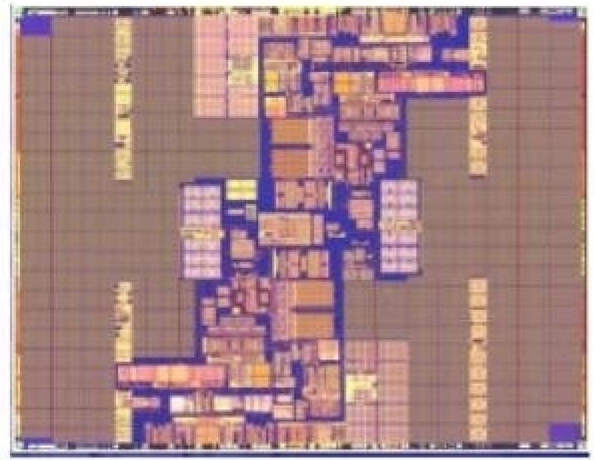
- 1965: a transistor cost more than a dollar
- 1975: cost of a transistor had dropped to less than a penny, almost 100'000 transistors on a single die
- 1979 to 1999, processor performance went from about 1.5 million instructions per second (MIPS) to over 1'000 MIPS on the Intel® Pentium® III
- Today's Intel® processors run at >3.2 GHz and higher, deliver >10'000 MIPS, and are manufactured with transistors that cost less than 1/10'000th of a cent

>40 years of Moore's law: 1965 – 2006

First planar integrated circuit (1961)

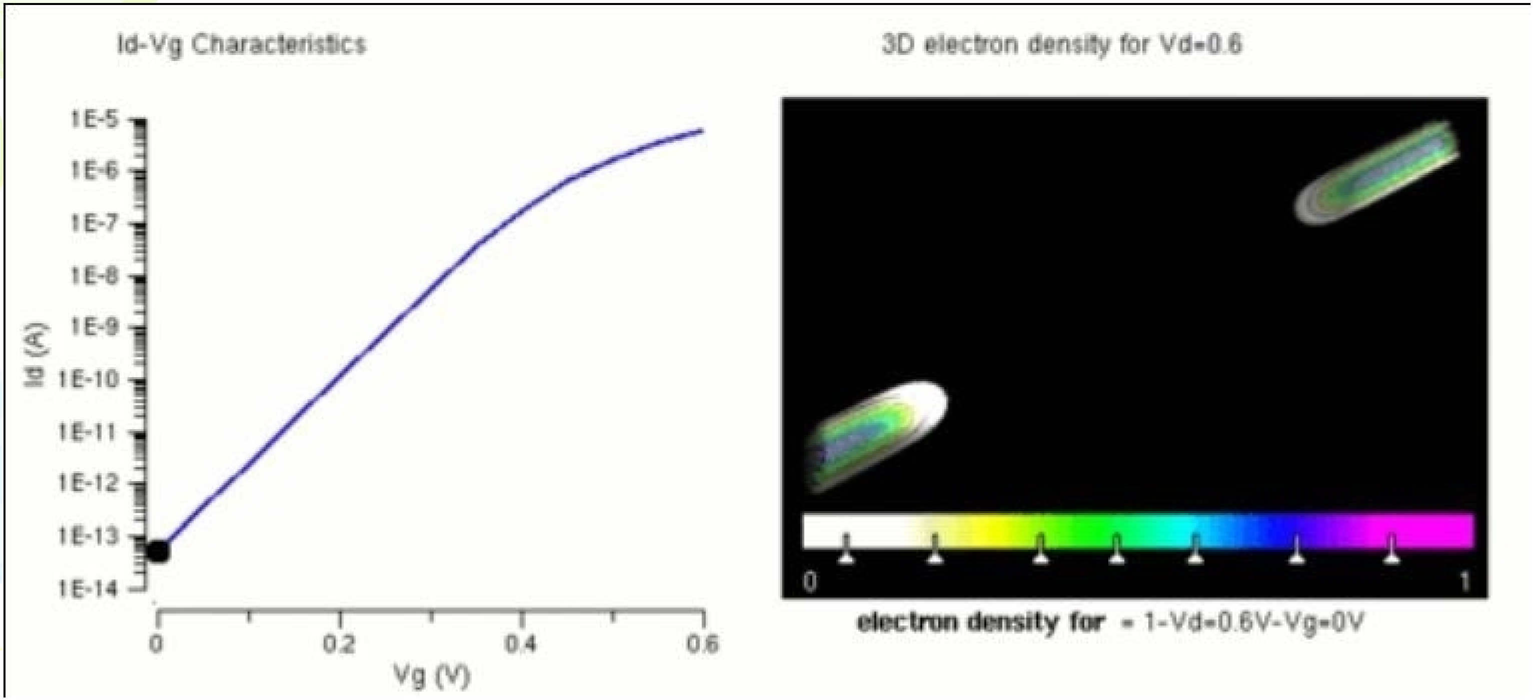


90 nm Intel's processor Montecito (2004) Itanium Processor Family



Transistors: 1.72 Billion
Frequency: >1.7GHz
Power: ~100W

Source: Intel Developer Forum, September, 2004



Atomistic simulation result for formation of inversion channel (electron density) and attainment of threshold voltage (IV) in a nanowire MOSFET. Note that the threshold voltage for this device lies around 0.45 V. Nanowire MOSFETs lie towards the end of the ITRS roadmap for scaling devices below 10 nm gate lengths.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2. Nanometer effects of nanoscale materials

- 2.1 Small size effect

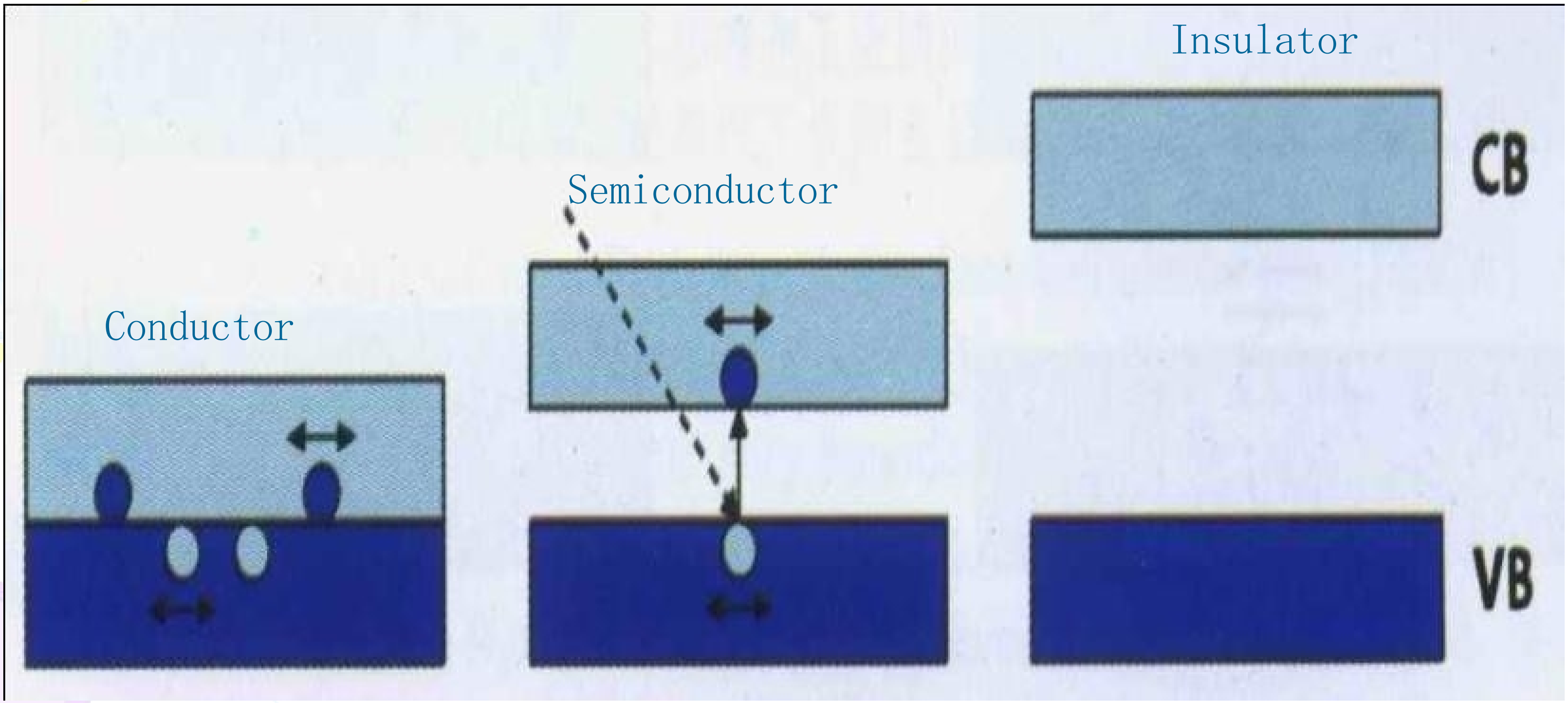
The size of the superfine particles is close to some characteristic length, the properties will be changed significantl

- Optical properties: all the superfine metal particles show BLACK.
- Thermodynamic properties: the melting point of the superfine particles decreases.
- Magnetic properties: superparamagnetism
- Mechanical properties: Ceramic can show good tenacity.

- 2.2 Quantum size effect

As the material is miniaturized in nano-scal
the energy spectrum becomes discrete.

As a result, the bandgap becomes size dependent. There is a small and finite separation between energy levels.


Insulator
CB
Semiconductor
Conductor
VB

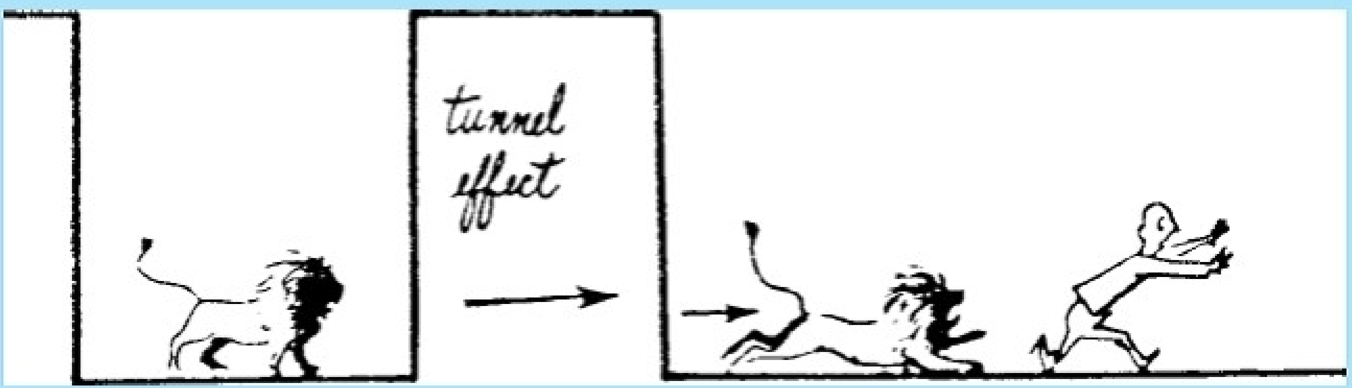
- 2. 3 Surface effect

Large specific surface area lead to the high surface energy. (P30. Fig. 2. 4)

- 2.4 Macroscopic quantum tunnel effect
  - 2.4.1 Ballistic transport

Ballistic transport is the transport of electrons medium with negligible electrical resistivity due t scattering. (P31 Fig. 2.5)

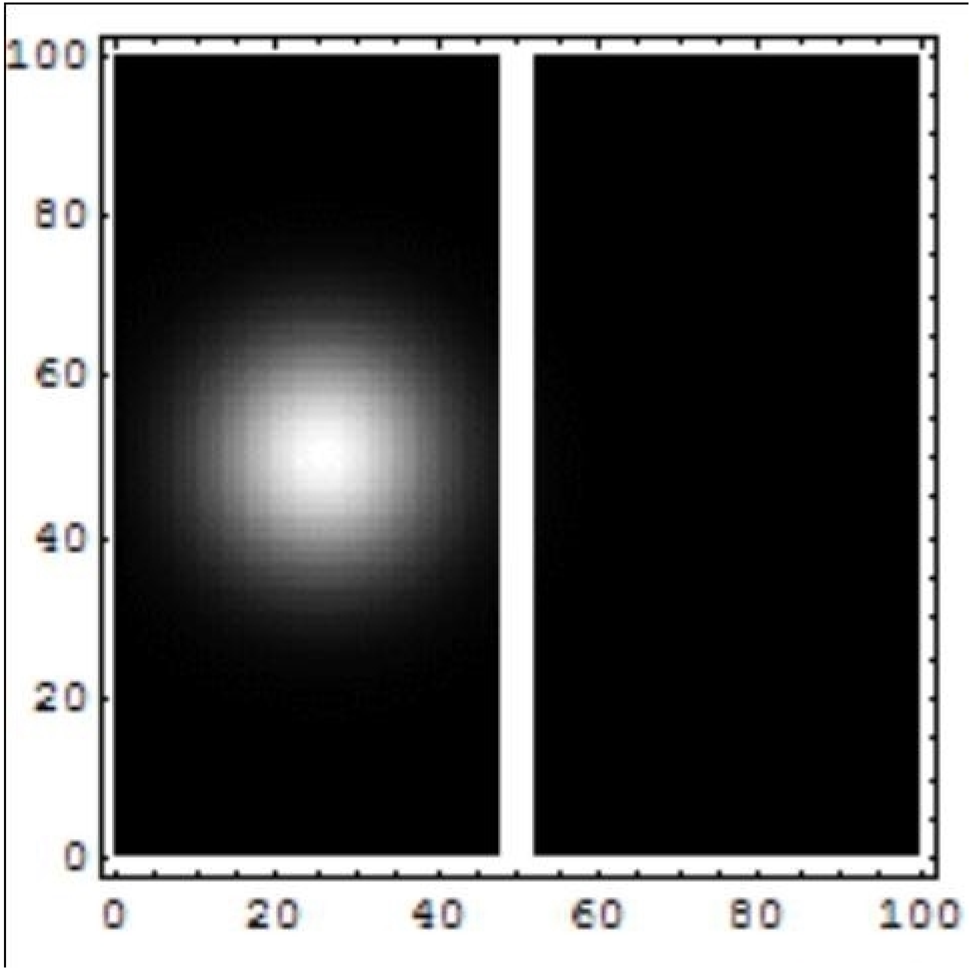
- 2. 4. 2 Tunneling

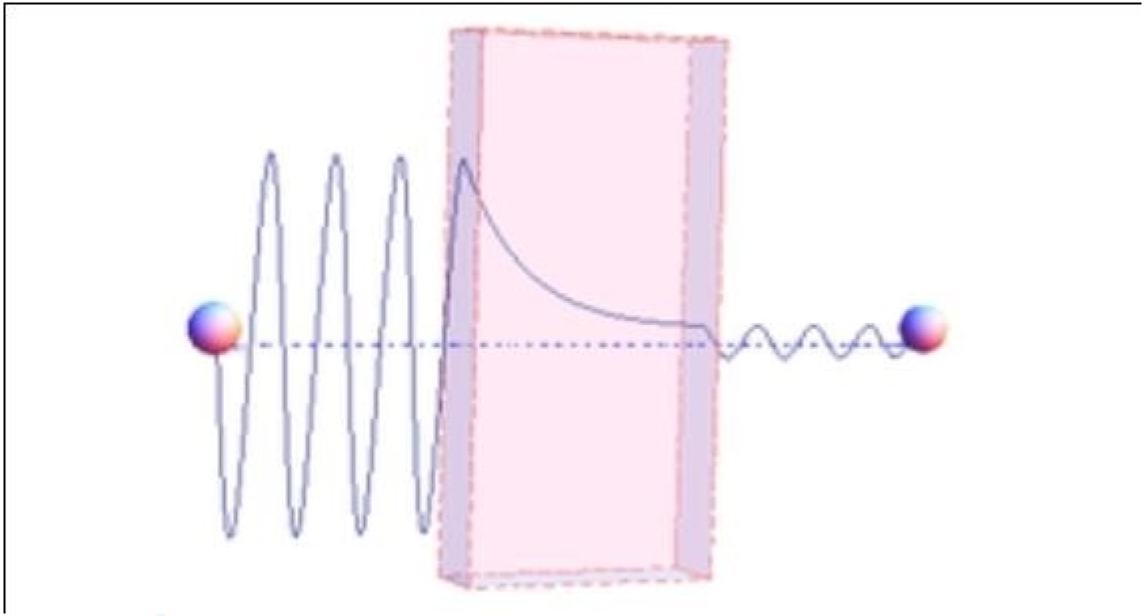


Van Vleck, 1979

Tunneling refers to phenomena of a particle"s ability to penetrate energy barriers within el structures.

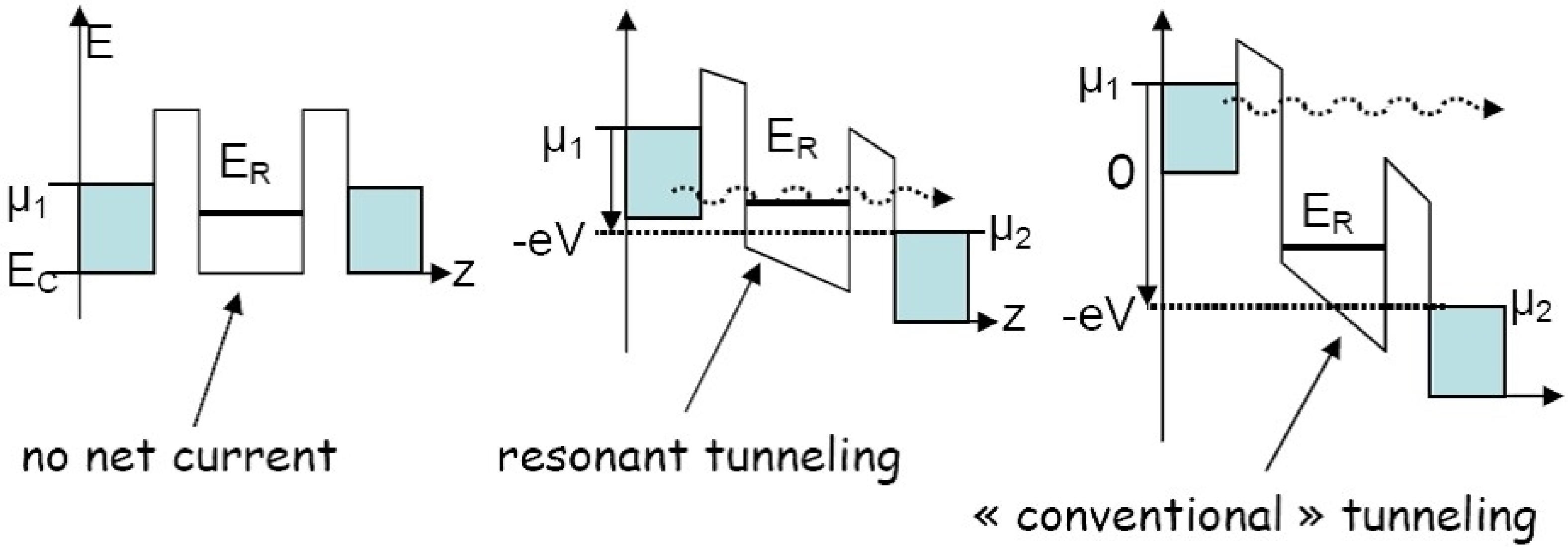
- An electron wavepacket directed at a potential barrier. Note the dim spot on the right that represents tunnelling electrons





Quantum tunnelling through a barrier. The energy of the tunnelled particle is the same but the amplitude is decreased.

- 2.4.3 Resonance tunneling



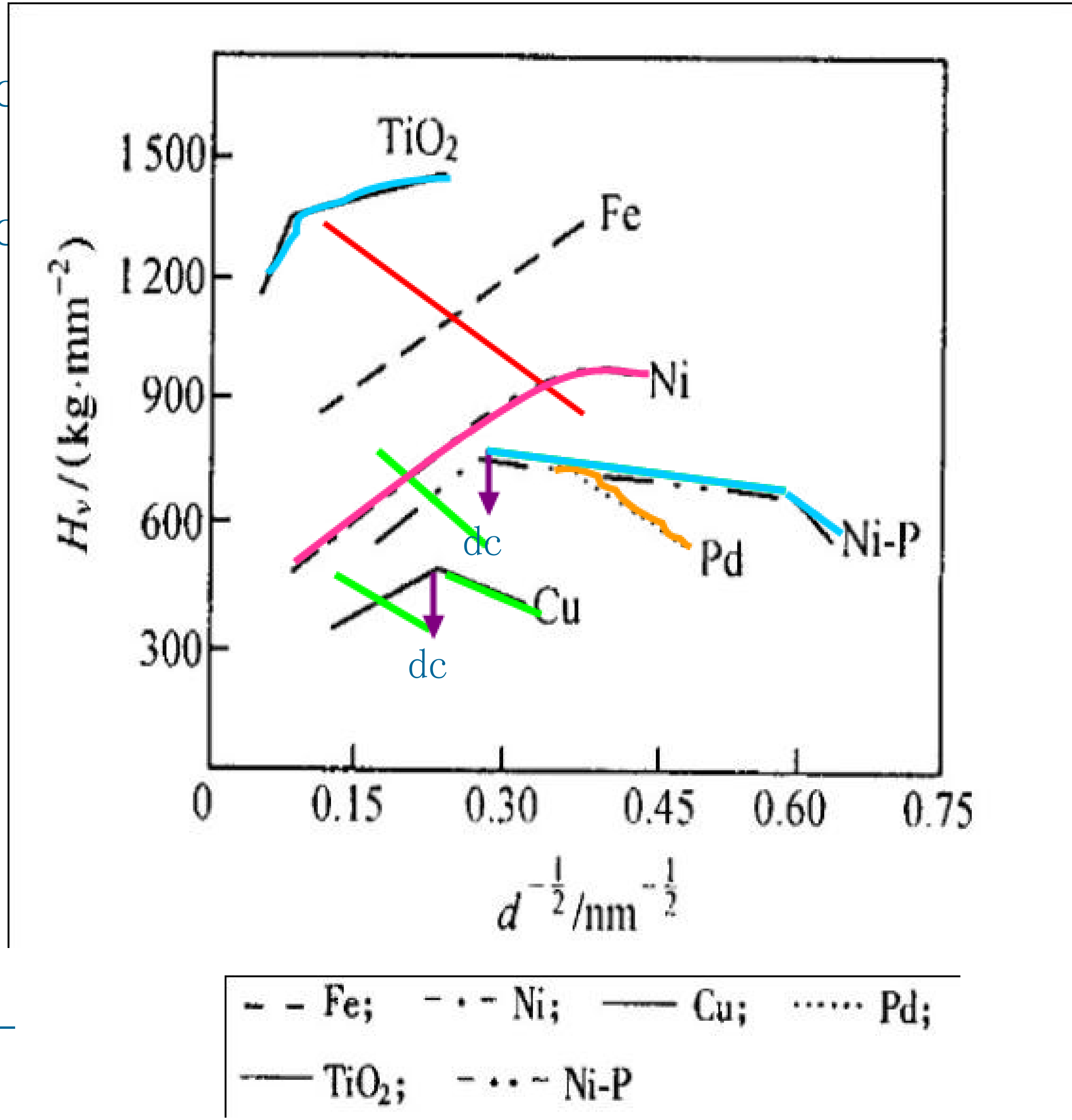
3. Properties of nanoscale materia

- 3. 1 Mechanical properties

In all case the Hall-Petch effect is relate the phenomena of dislocation generation and dislocation motion in materials.

Hardness typically increases with decreasing grain size as the grain size is reduced down to the nanoscale region.

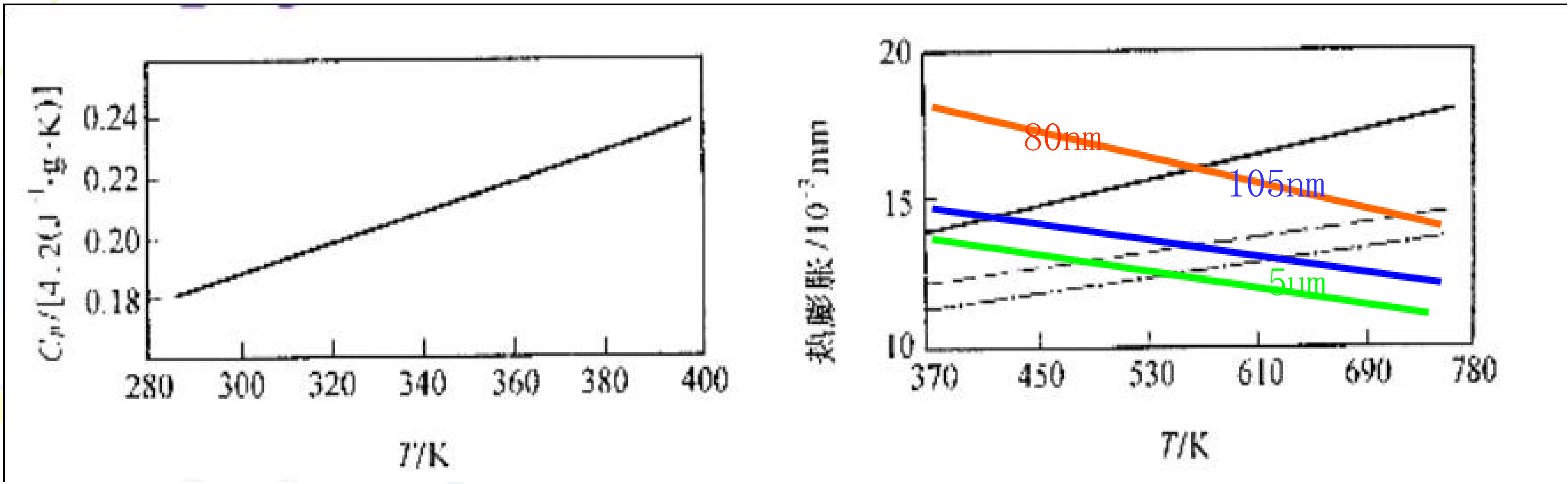
- Positive Hall-Petch slopes (K>0)
- Negative Hall-Petch slopes (K<0)
- Positive and negative Hall-Petch slopes
  - d > dc K>0
  - d < dc K<0
- K changes with d decreasing
  - K>0, K decreases
  - K<0, K increases
- Deviation of Hall-Petch (Nonlinear)



- 3.2 Thermal properties

Nanoparticles exhibit enhanced specific he
as compared to the bulk material.

Nanoparticles have higher coefficient of thermal expansion comparing with bulk material.



Nanoparticles of Al_2O_3

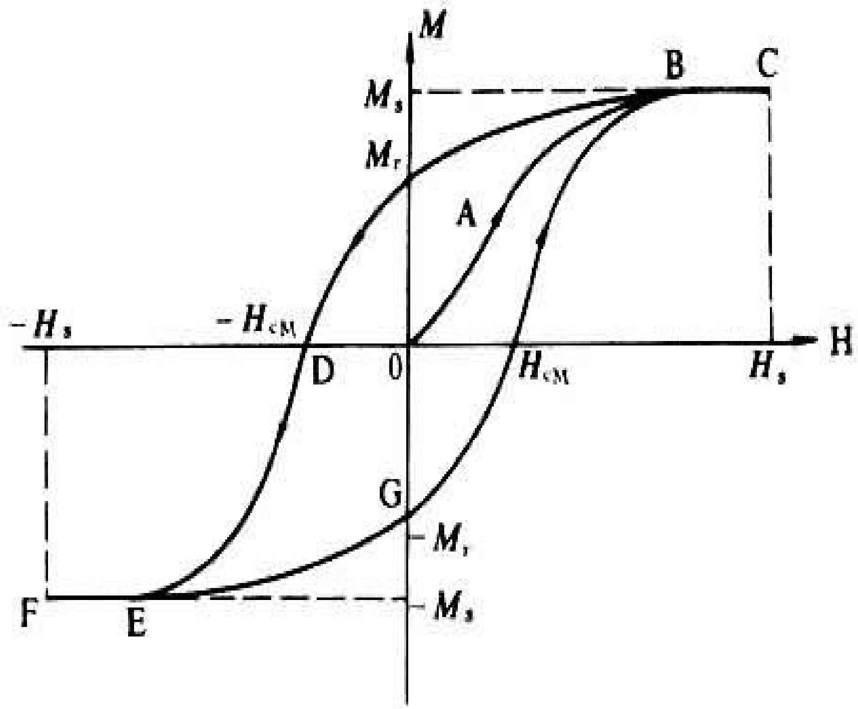
- 3.3 Magnetic properties

  Ferromagnetism

  Paramagnetism

  Diamagnetism

  Superparamagnetism



Hysteresis loop of ferromagnetic material

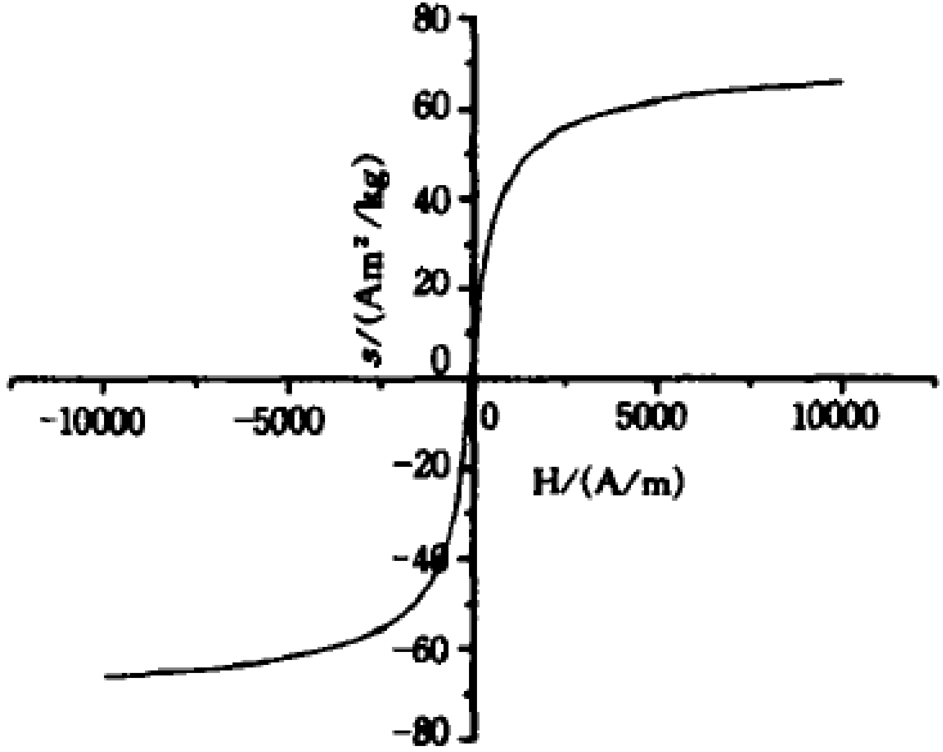
M: magnetization (intensity)

H: magnetic field intensity

B: magnetic induction (intensi

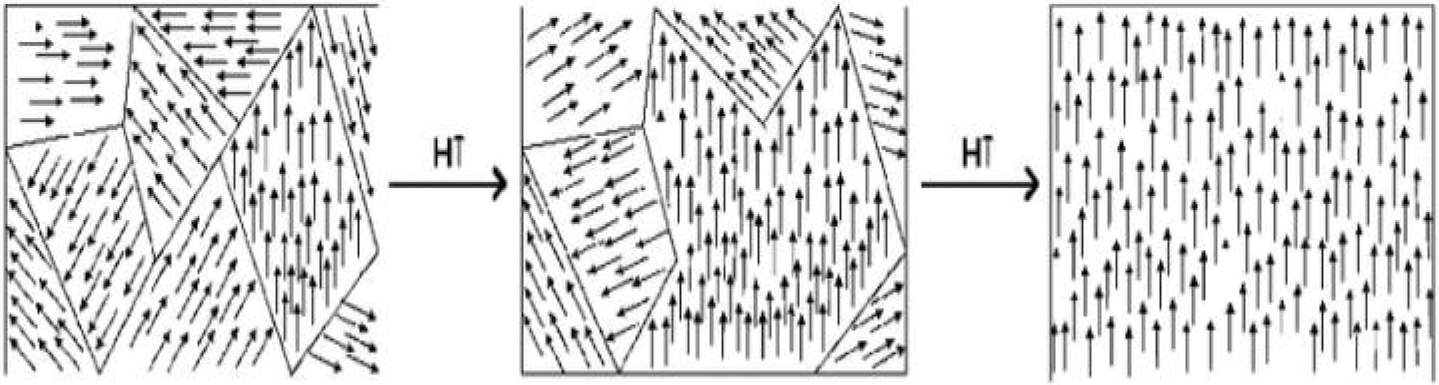
Mr: Remanence

H_{CM}: Coercive force

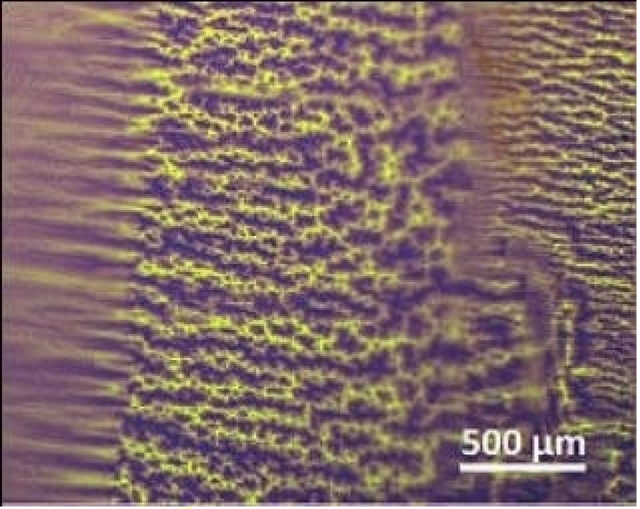


Hystersis loop of the magnetite nanoparticles with superparamagnetism

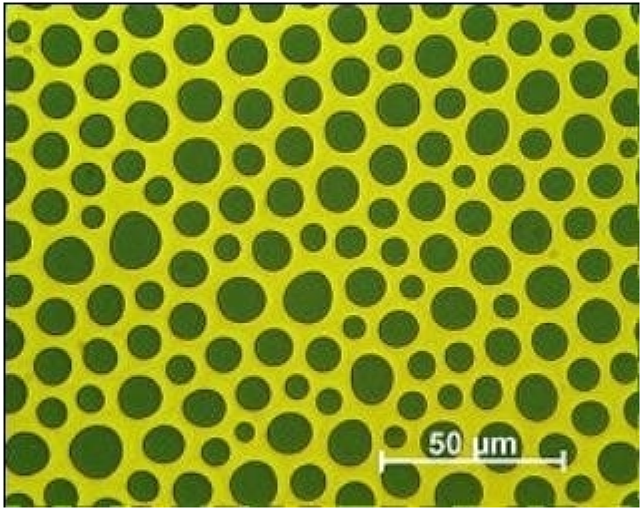
Magnetic **domain** decribes a region within a magnetic material which has uniform magnetization. This means that the individua magnetic moments of the atoms are aligned with one another and they point in the same direction. The regions separating magnetic domains are called domain walls, where the magnetisation rotates coherently from the direction in one domain to that in the next domain.



Rotation of orientation and increase in size of magnetic domains due to an externally applied field

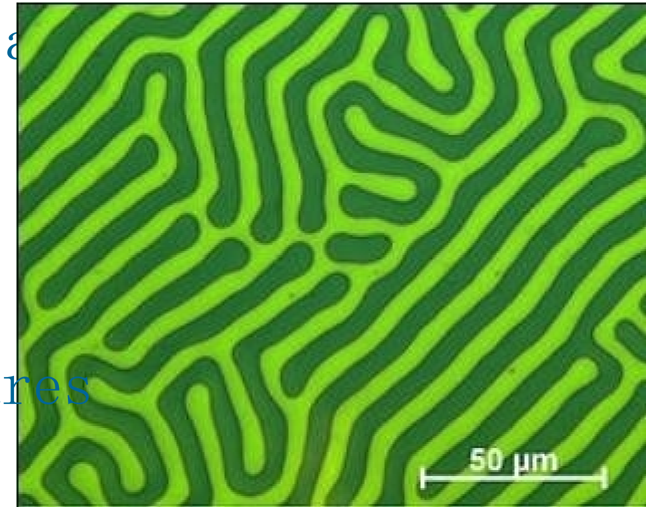


Domain structure of a shape-memory alloy



Domain structure of a examplary magnetic bubble domain

Domain structure of a examplary meander domain



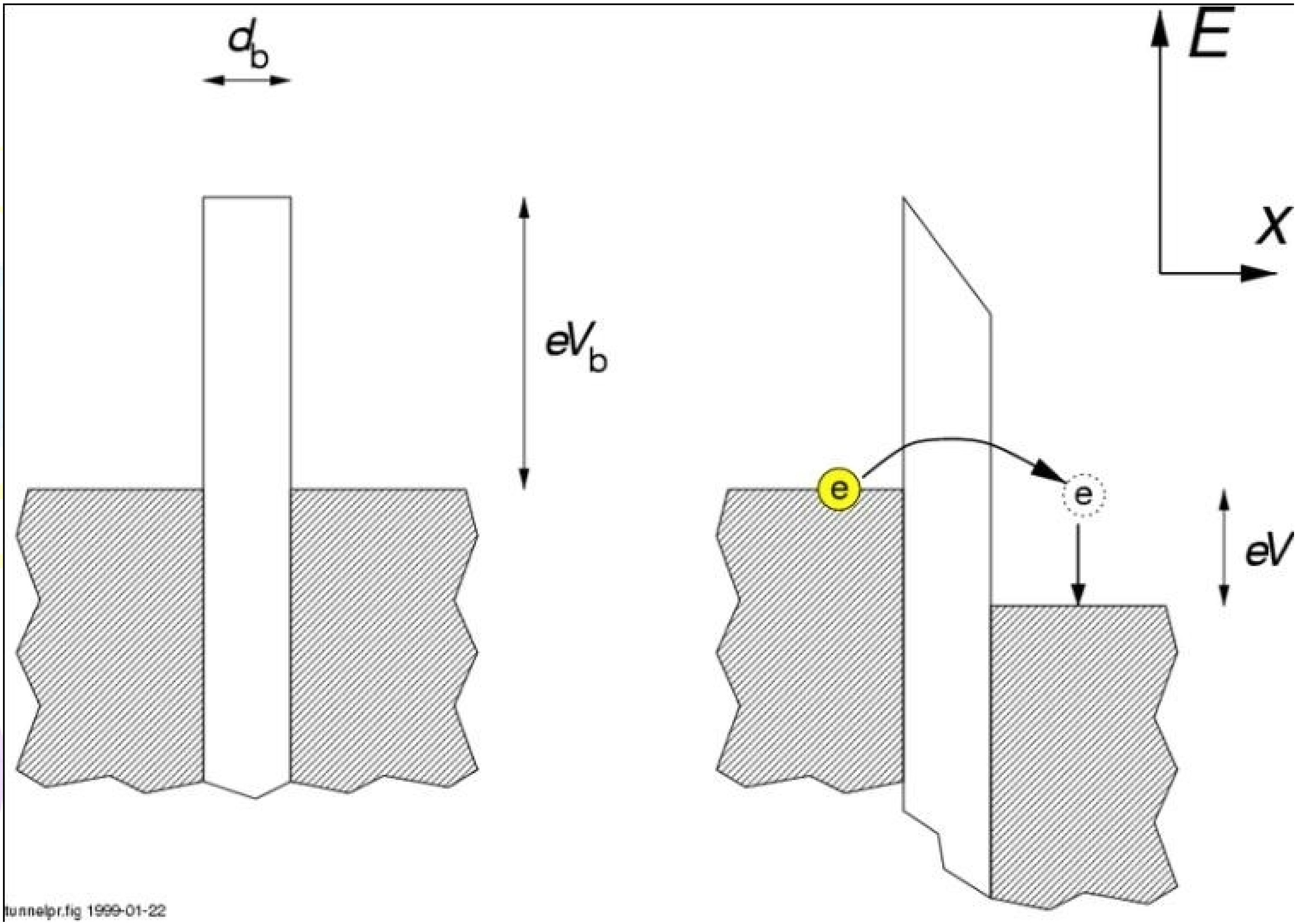
Magnetooptical images of domain structures

When heated above a certain temperature, a pie
of ferromagnetic material undergoes a phase
transition, and the uniform magnetization wit
a domain spontaneously disappears: each atom
has its own direction of magnetic moment,
independent from its neighbouring atoms (typi
of the paramagnetic state).

Curie temperature: the transformation
temperature (critical temperature) of ferrom
and paramagnetic substance

- 3.4 Electronic properties
  - Tunneling current
    - Based on the quantum tunneling effect, the current can be obtained with certain expression
  - Ballistic transport
  - Coulomb blockade
    - in which tunneling is completely forbidden at certain voltages due to the electron charge eff

- 有一个足够小的岛，一个电子进到这个岛里时，如果原来这个岛里有一个电子，新来的这个电子就会受到排斥，因为岛很小，两个电子靠得很近，相互排斥很强，排斥能使系统能量升高，就会阻止第二个电子的到来，称作库伦阻塞；只能当外加电压使系统释放出这个电子后，第二个电子才能再来，这就构成了计算机的基本单元一个“比特（0和1）”。这个效应可用来制作单电子的晶体管和单电子存储器，人们认为，它们是构筑纳米电子学的基础。 —— 王占国



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