Nanostructures: a LEGO box for physicists

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Could you pinpoint a single breakthrough that enabled all these gadgets?
The last revolution happened ~ 60 years ago, when vacuum tubes were replaced by semiconductor devices.

Vacuum tubes show high performance but are too big.
Vacuum tubes can survive a nearby nuclear explosion
What is a vacuum tube?
What vacuum tubes are for

Diode: a valve for electrons

Triode: a switch or an amplifier
ENIAC (1946) weighed 30 tons, occupied 1800 square feet and had 17,468 vacuum tubes. It could make 5000 additions per second.

First computer bug was a real bug
Harvard Mark II computer, 1947
The first digital electronic computer was invented by Theoretical Physics Prof. John Vincent Atanasoff in 1937. It was built by Atanasoff and his graduate student Clifford Berry at Iowa State College in 1939 ($650 research grant).

- Binary numerical system
- Fully electronic
- Regenerative memory (DRAM)
1954-1963: SAGE Air Defense Project

- 23 32-bit computers
- Each contains 55,000 vacuum tubes, weighs 250 tons, and consumes 3 Megawatt
- Tracks 300 flights
- Total cost: $60 billion (double the price of Manhattan Project!)
- Performance equivalent to $8 calculator built on transistors!
Dangers of forecasting

ENIAC (1946) weighed 30 tons, occupied 1800 square feet and had 17,468 vacuum tubes. It could make 5000 additions per second.

Computers in the future may weigh no more than 1.5 tons. (Popular Mechanics, 1949)

1940's - IBM Chairman Thomas Watson predicts that "there is a world market for maybe five computers".

1950's - There are 10 computers in the U.S. in 1951. The first commercial magnetic hard-disk drive and the first microchip are introduced. Transistors are first used in radios.

1960's-70's - K. Olson, president, chairman and founder of DEC, maintains that "there is no reason why anyone would want a computer in their home." The first microprocessor, 'floppy' disks, and personal computers are all introduced. Integrated circuits are used in watches.
Semiconductor Revolution

“One should not work on semiconductors, that is a filthy mess; who knows whether they really exist.”

Wolfgang Pauli 1931

Transistor invention: 1947
John Bardeen, Walter Brattain, and William Shockley
AT&T Bell Labs

Nobel Prize in Physics 1956
“Planetary” model of atom

Ernest Rutherford, 1911

Proton mass: $1.7 \times 10^{-27}$ kg
Electron mass: $9 \times 10^{-31}$ kg

where the mass of the electron is 1/2000 the mass of the proton
and the mass of the proton equals the mass of the neutron
Catastrophe with atoms

Accelerating electron produces EM radiation (light), loses energy and spirals into the nucleus, i.e. an atom would collapse.
Niels Bohr model

The electron travels in circular orbits around the nucleus. The orbits have quantized sizes and energies. Energy is emitted from the atom when the electron jumps from one orbit to another closer to the nucleus. Shown here is the first Balmer transition, in which an electron jumps from orbit $n = 3$ to orbit $n = 2$, producing a photon of red light with an energy of 1.89 eV and a wavelength of $656 \times 10^{-9}$ m.
Wave-particle duality

WHY does an electron follow quantized orbits? The response to this question arrived from the Ph.D. thesis of Louis de Broglie in 1923. de Broglie argued that since light can display wave and particle properties, then perhaps matter can also be a particle and a wave too.

\[ \lambda = \frac{2\pi\hbar}{mv} \]

Energy and momentum of a particle are related to wavelength:

momentum \( p = mv = \hbar k = \frac{2\pi\hbar}{\lambda} \); \( \hbar \approx 10^{-34} \text{ J} \times \text{sec} \)

Energy \( E = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} \)
Only certain wavelengths will `fit' into an orbit. If the wavelength of an electron is longer or shorter, then the ends do not connect.

Why the orbits are quantized
The hydrogen atom

Electron wave functions in a potential well of a nucleus

Note discrete energy levels!
Now let’s bring many atoms together ... 10^{22} atoms per cubic centimeter!

Energy BANDS are formed!
energy

**Semiconductor or dielectric**

[Diagram showing energy levels with Conduction band and Valence band]

[Diagram showing Band gap]
The coolest thing about semiconductors: they can be doped

**Donors in silicon:**
**Phosphorus and Arsenic (group V)**

Even tiny fraction of impurities (0.00001) dramatically increases the ability to conduct current (conductivity)
Acceptors in silicon: Boron (group III)

© Bart Van Zeghbroeck, 1998
Ionization of acceptors
Energy diagram of doped semiconductors

Free electrons are supplied to the empty conduction band

Holes are left in the full valence band

Both electrons and holes can now conduct current!
P-n junction

P-type

neutral

N-type

neutral

Forward bias

Reverse bias
Field-effect transistor

Voltage on gate controls the current of electrons from source to drain.

**FET can be made very small using nanotechnology!**
Moore’s “Law” (1965): every 2 years the number of transistors on a chip is doubled

Gordon Moore, co-founder, Intel
Several billion transistors
Integrated circuits

Jack Kilby’s original IC
The Nobel Prize in Physics 2000

Zhores I. Alferov
Herbert Kroemer
Jack Kilby

"for developing semiconductor heterostructures used in high-speed- and opto-electronics"

“for his part in the invention of the integrated circuit”
Approaching the limit on the transistor size: the size of an atom
Nano-transistors

Carbon nanotube transistor

Molecular transistor

Graphene transistor
To build good computers and other electronic gadgets is only part of the story

We also want to exchange information between different places

... and to do it FAST!
• Stone Age
• Bronze Age
• Iron Age
• Ice Age

Information Age!
We have computers to generate information
But we also need sources of light, detectors, and “light wires” (waveguides) to transmit it!
P-n junction can be used to generate light!

When electron and hole recombine, they can emit a photon.
P-n junction semiconductor laser

Kroemer’s Nobel lecture

\[
\hbar \omega_{\text{light}} \approx E_{\text{gap}}
\]
Generic scheme of a laser

1) Active medium which amplifies light
2) Pumping which keeps medium active
3) Laser cavity which reflects part of the light back

http://www.worldoflasers.com/
Semiconductor diode laser

These lasers can be made very small: less than a micrometer thick and a few micrometers across.

http://britneyspears.ac/lasers.htm
2/3 of all lasers in the world are semiconductor lasers

Mostly telecommunications, optical storage, disk players, printers, ...
Digital Light Processing (DLP)

Texas Instruments 1987

800x600, 1024x768, 1280x720, and 1920x1080 (HDTV) matrices of microscopic mirrors
One mirror is only 16 microns!
Less than 1/5 of human hair width

http://www.dlp.com/includes/demo_flash.aspx
Laser mini-projectors

Need microscopic lasers of all colors: **red**, **blue**, and **green**

**Excellent** near infrared and red lasers

**Bad** blue and UV lasers

**Very bad** green lasers

mini laser projector
Band gap slavery

Only photons with energy equal to band gap energy $E_g$ are emitted.

Band gap is a property of material.

There are only a handful of materials that can be used for lasers.

$\hbar\omega_{\text{light}} \approx E_{\text{gap}}$
What happens if we shrink the active region to nanometers?
A quantum trap for electrons:

Discrete energy levels
Like in atoms!
The hydrogen atom potential and wavefunction

Note discrete energy levels!
Quantum wells

Integer number of half-waves should fit the box

Now we can control photon energy

$E_{gap1}$  $E_{gap2}$
Build your own nanostructure:

Now we can build a tiny light source for a wide range of wavelengths.
Quantum dots

Emission wavelength depends on dot size

Arakawa group 2010

Single quantum dot lasers
Problems and challenges

• How much information can we send with modern technologies?
  – About 10 Gb/s (10 billion bits per second) per single channel
  – Where is the bottleneck?

• What limits the speed of computation?
Number of transistors grows, but this does not improve the performance as much.

Reason?

We use 21-century semiconductor devices and 19-century copper wires connecting them!
Electronic circuits: 45 nm wires, 1 million transistors per mm²

Computing speed is limited by inertia of electrons
The interconnect bottleneck

- $10^9$ devices per chip
- Closely spaced metal wires slow down computation
- Huge heat generated due to electric resistance
Can electronic circuits be replaced by photonic ones?!

Using spins instead of charges would reduce heat if we learn how to move spins without carrying charge. (Sinova’s talk)

Using photons as bits of information instead of electrons would speed up the computing.

Photons travel much faster and don’t dissipate as much power.
Limitations of telecommunications

In optical communications, information is transmitted as light signal along optical fibers. Fibers have capacity of ~ 100,000 Gb/s!

However, if we want to modify, add/drop, split, or amplify signal, it needs to be first converted to electric current, and then converted back to photons

This is a slow process. Electric circuits and diode lasers have inertia!
THE DREAM: could we replace electrons with photons, and electric circuits with all-optical circuits?

Futuristic silicon chip with monolithically integrated photonic and electronic circuits

wires ➔ waveguides
How to trap light with transparent material?

Total internal reflection!

\[ \sin \theta_c = \frac{n_2}{n_1} \]

Light coming from more refractive to less refractive medium experiences total reflection – get trapped there!
Light is trapped in diamond

Water: critical angle $\sim 49^\circ$

Examples of total internal reflection
For integrated light circuits we need to use silicon chips and silicon waveguides.

\[ n_c = 1 \]
\[ n_w = 3.6 \]
\[ n_s = 1.5 \]

\( n_w > n_s, n_c \)
The problem: photon size is 100 times electron size. Waveguides are 100 times wider than electric wires!
Possible solution: photonic crystals

Note T-intersections and tight bends, as in electric wires. You cannot achieve it in usual waveguides that have to be smooth!

Still, you shrink your device by factor of 5 at most
Possible solution: plasmons?

A strip of metal guides light on its surface and shrinks its wavelength at the same time: $\lambda/n$, where $n >> 1$.

Unfortunately, metal also strongly absorbs light. This is bad for devices, but good for other things.

H. Atwater, Sci. Am. 2007
Lycurgus Cup, Roman 450 A.D.

Green in reflection, but red in transmission

Light excites plasmon oscillations in metallic nanoparticles and gets absorbed

Wavelength of plasmons, and therefore the color of light which gets absorbed or gets through, depends on a particle size and shape
Stained glass windows in Notre Dame
Cancer therapy with nanoparticles

1) Attach a drug molecule to a nanoparticle

2) Inject them into bloodstream of a patient (This is FDA-approved)

3) Particles get stuck in a cancerous tumor and release the drug

Laser-assisted therapy and drug delivery

Shine laser light on a tumor

Nanoparticles get heated and release the drug

You can also kill the tumor by heat

A proposed cancer treatment would employ plasmonic effects to destroy tumors. Doctors would inject nanoshells—100-nanometer-wide silica particles with an outer layer of gold (inset)—into the bloodstream. The nanoshells would embed themselves in a fast-growing tumor. If near-infrared laser light is pointed at the area, it would travel through the skin and induce resonant electron oscillations in the nanoshells, heating and killing tumor cells without harming the surrounding healthy tissue.

H. Atwater, Scientific American 2007
Conclusions

- We had semiconductor revolution 60 years ago. Now new revolution is needed.

- Microelectronics is approaching its fundamental limits. Revolutionary ideas are needed!
  - Single-molecule transistors?
  - New materials, new fabrication technology?

- Communication: how to increase speed?
  - Novel lasers?
  - All-optical network?
  - How to make photons smaller?

- New principles of computing??
Quantum computer

Bit

Qubit (quantum bit): state of a single electron, or atom, or photon, or molecule

- Classical computer: 0 or 1
- Quantum computer: 0 or 1 or any mixture of 0 and 1

Quantum computer can perform millions of calculations in parallel.

Especially good for searching through huge amount of data or encoding/decoding secret messages

Extremely fragile, needs low temperature