Nanoelectronics: Besides and Beyond Moore

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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:

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1920s</td>
<td>semiconductor components ([photo]diodes)</td>
</tr>
<tr>
<td>1925</td>
<td>idea of the field effect transistor (FET)</td>
</tr>
<tr>
<td>1947</td>
<td>first working transistor</td>
</tr>
<tr>
<td>1959</td>
<td>the integrated circuit (IC)</td>
</tr>
<tr>
<td>1960</td>
<td>the first metal-oxide-silicon (MOS) transistor</td>
</tr>
<tr>
<td>1970</td>
<td>solid state memories; the microprocessor</td>
</tr>
<tr>
<td>1980</td>
<td>the PC</td>
</tr>
<tr>
<td>1990s</td>
<td>ubiquitous internet and cellular phones</td>
</tr>
</tbody>
</table>
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
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
Electronic “work horses”

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

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 BJT's
Jan. 28, 1930.

J. E. LILIEFELD

1,745,175

METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926
Transistor revolution
Integrated circuits - ICs

all components of a circuit on a piece of semiconductor
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

![ITRS Roadmap](image)

### Key Techologies and Timeline:

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<tbody>
<tr>
<td>DRAM 1/2 Pitch</td>
<td>65nm</td>
<td>45nm</td>
<td>32nm</td>
<td>22nm</td>
<td>16nm</td>
</tr>
<tr>
<td>193 nm immersion with water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>193 nm immersion with other fluids, EUV, ML2</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>EUV</td>
<td></td>
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</tr>
<tr>
<td>193 nm immersion with other fluids and lens material, Innovative: 193 nm immersion with water, Imprint, ML2</td>
<td></td>
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<tr>
<td>EUV</td>
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<tr>
<td>Innovative 193 nm immersion, Imprint, ML2, Innovative technology</td>
<td></td>
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<tr>
<td>Innovative technology</td>
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<tr>
<td>Innovative EUV, imprint, ML2</td>
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</table>

### Legend:
- **Research Required**
- **Development Underway**
- **Qualification/Pre-Production**
- **Continuous Improvement**

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Winter School on Nanoelectronics and Nanophotonics
Bilkent University – Ankara, Turkey Jan. 20th–25th

NanoElectronics
Moore’s law cannot continue forever...
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

- Nanoparticle
- Vertical QD
- Nanowire

1 nm 10 nm 100 nm 1μm
2-dimensional electron gas

Semiconductor heterostructure

GaAs
n-AlGaAs
AlGaAs
GaAs

2DEG

100 nm

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, ...)

How to define nanostructures out of a 2DEG?

1. Resist e-beam after development evaporation gate structure after lift-off
lateral quantum dots

- High-mobility 2DEG ($\sim 10^6$ cm$^2$/Vs)
- Density $\sim 10^{15}$ m$^{-2}$ $\Rightarrow \lambda_F \sim 30$ nm
- Resolution gate structure $\sim 20$ nm
- Dot size $\sim 100$ nm
- Comparable to electron wavelength $\Rightarrow$ discrete energy spectrum
vertical quantum dots

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

n-GaAs drain
AlGaAs barrier
InGaAs well
AlGaAs barrier
n-GaAs source

0.4 to 0.6μm

Other geometries possible
constant interaction model

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

\[ \mu_{\text{dot}}(N) \equiv U(N) - U(N-1) = \]

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

\[ E_C = \frac{e^2}{C} \]

charging energy:

\[ E_C = \frac{e^2}{C} \]

\[ C \propto R, \quad R \text{ (radius) } 100 \text{ nm} \]

\[ \Rightarrow E_C \sim \text{few meV} \]

\[ -|e|\varphi_N = (N - \frac{1}{2})E_C - \frac{E_C}{|e|} C_g V_g \] electrostatic potential

\[ \mu_{ch}(N) = E_N \] chemical potential
Coulomb blockade

\[ \Delta \mu_{\text{dot}} = \mu_{\text{dot}}(N+1) - \mu_{\text{dot}}(N) = U(N+1) - 2U(N) + U(N-1) = E_C + \Delta E \]

addition energy
single-electron tunneling

Linear response

Non-linear transport

\[ \Gamma_L \Gamma_R \]

\[ \mu(N) \]

\[ \mu_D \]

\[ V_g \]

\[ V_{g'} \]

\[ \Delta E \]

\[ E_{add} \]

\[ dI/dV_s \]

\[ V_{sd} \]

\[ N-1 \]

\[ N \]

\[ N+1 \]

\[ V_g \]

\[ \mu(N) \]

\[ \mu_D \]

\[ \mu(N+1) \]

\[ \mu_S \]

\[ \Delta \]
2D harmonic potential: Fock-Darwin states

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

\[
\tilde{\omega}^2 \equiv \omega_0^2 + 1/4 \omega_c^2 \quad \omega_c = eB/m^* \quad \text{(cyclotron frequency)}
\]
Shell filling

- Voltage range: -1.5 to -0.8 V
- Current peaks at specific electron numbers:
  - N=0
  - N=2
  - N=6
  - N=12

- Addition energy (meV):
  - e^2/C
  - e^2/C + ΔE

- Electron configurations:
  - e^2/C
  - e^2/C + ΔE
  - e^2/C
  - e^2/C
  - e^2/C + ΔE
  - e^2/C
1869
Mendeleev arranges 63 known elements in a periodic table

"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

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ta</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Et</td>
<td>4</td>
<td>Au</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Sa</td>
<td>8</td>
<td>To</td>
<td>9</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>14</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>17</td>
<td>Fr</td>
<td>18</td>
<td>El</td>
<td>19</td>
</tr>
<tr>
<td>20</td>
<td>Da</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Ta: Tantalum
- Au: Gold
- Ho: Holmium
- Wi: Wismium
- Fr: Francium
- El: Eridium
- Da: Dassium
- Ha: Hadium
- Ko: Koelum
- Cr: Coryum
- Ja: Jatinum
- Oo: Ootium

Artificial Atoms
**Coupled quantum dots**

**vertical, laterally coupled quantum dots**

**lateral, coupled quantum dots**

![Vertical Coupled Quantum Dots](image1)

![Lateral Coupled Quantum Dots](image2)
Coupled quantum dots

dots in series: transport at triple points only !!

charge cycle I:
\((N,M) \rightarrow (N+1,M) \rightarrow (N,M+1) \rightarrow (N,M) \rightarrow \ldots\)

charge cycle II:
\((N+1,M+1) \rightarrow (N+1,M) \rightarrow (N,M+1) \rightarrow (N+1,M+1) \rightarrow \ldots\)

"Temperature filter"

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

"Temperature filter"

Elastic tunneling

\[ \Gamma_L \quad t \quad \Gamma_R \]

Width \( \approx \frac{h}{\text{lifetime}} \approx h \)

Graph showing current vs. source-drain voltage with peaks indicating elastic and inelastic current.

GS - GS elastic current

FWHM = 4 \( \mu \text{eV} \)

3.5 x 100 mK = 35 \( \mu \text{eV} \)

\[ \Rightarrow \text{FWHM is an order of magnitude smaller than thermal energy} \]
Why organic electronics???

*organic materials*
- light and flexible
- easy to process $\rightarrow$ 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 $\rightarrow$ cost, efficiency, power dissipation
- self-assembly and recognition (switches & sensors)
- molecular synthesis allows great flexibility
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

OLED

solar cells

electronic paper
\( \mu \) is the constant of proportionality between the drift velocity \( v \) of the charge carriers and the electric field \( E \) that induces this drift velocity:

\[
v = \mu E
\]

<table>
<thead>
<tr>
<th>material</th>
<th>mobility [cm(^2)/(Vs)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si (crystalline)</td>
<td>1350 (e)</td>
</tr>
<tr>
<td>InAs (bulk)</td>
<td>30,000 (e)</td>
</tr>
<tr>
<td>GaAs (quantum well)</td>
<td>up to (<del>10,000,000) (e) at low ( T ) (</del> 1K)</td>
</tr>
<tr>
<td>CNT</td>
<td>100,000 (e)</td>
</tr>
<tr>
<td>Cu</td>
<td>42 (e)</td>
</tr>
<tr>
<td>pentacene (crystalline)</td>
<td>30 (h)</td>
</tr>
<tr>
<td>pentacene (thin film)</td>
<td>(~1) (h)</td>
</tr>
</tbody>
</table>
When band transport occurs?

In general, an energy $\Delta E$ 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

<table>
<thead>
<tr>
<th>Conduction Mechanism</th>
<th>Characteristic Behavior</th>
<th>Temperature Dependence</th>
<th>Voltage Dependence</th>
</tr>
</thead>
<tbody>
<tr>
<td>direct tunneling</td>
<td>$J \propto V \exp \left( -\frac{2d}{\hbar} \sqrt{2mF} \right)$</td>
<td>none</td>
<td>$J \propto V$</td>
</tr>
<tr>
<td>Fowler-Nordheim tunneling</td>
<td>$J \propto V^2 \exp \left( -\frac{4d}{3q\hbar V} \sqrt{2mF^{3/2}} \right)$</td>
<td>none</td>
<td>$\ln(J/V^2) \propto 1/V$</td>
</tr>
<tr>
<td>thermionic emission</td>
<td>$J \propto T^2 \exp \left( -\frac{\Phi - q \sqrt{qV/4\pi\varepsilon}}{kT} \right)$</td>
<td>$\ln(J/T^2) \propto 1/T$</td>
<td>$\ln(J) \propto V^{1/2}$</td>
</tr>
<tr>
<td>hopping conduction</td>
<td>$J \propto V \exp \left( -\frac{\Phi}{kT} \right)$</td>
<td>$\ln(J/V) \propto 1/T$</td>
<td>$J \propto V$</td>
</tr>
</tbody>
</table>
Organic Thin-Film Transistors (OTFTs)

- **Organic semiconductors: OTFT**
  - Doping is difficult due to low purity
  - Conducting channel by accumulation
  - Predominantly hole transport (p-type)

- **Inorganic semiconductors: MOSFET**
  - 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*
## Organic Thin-Film Transistors (OTFTs)

### Organic Semiconductors

<table>
<thead>
<tr>
<th>Category</th>
<th>Examples</th>
<th>Typical Mobility (cm²V⁻¹s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polymers</td>
<td>Polyacetylene</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Poly(3-alkylthiophene) (P3AT)</td>
<td></td>
</tr>
<tr>
<td>Small Molecules</td>
<td>Pentacene</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Oligothiophenes</td>
<td></td>
</tr>
<tr>
<td>Single-Crystals</td>
<td>Pentacene</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Rubrene</td>
<td></td>
</tr>
</tbody>
</table>
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:

$$\sigma = 10^5 \text{ Sm}^{-1}$$

(teflon: $10^{-16} \text{ Sm}^{-1}$; copper: $10^8 \text{ Sm}^{-1}$)
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 cm²/Vs, up to 20 at RT)
- Stable in air
- Growth parameters known

review:
Organic single-crystals

A

Al₂O₃

Co

SiO₂

Si

B
Organic single-crystals

In collaboration with Anna Molinari, Alberto Morpurgo (TU Delft)
Organic single-crystals
Organic single-crystals
Organic single-crystals

Co/Al₂O₃/rubrene
RT, L = 300 μm
µ = 1 cm²/(Vs)

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,  
single 1,8-octanethiol molecules inserted in octanethiol monolayer

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

octanethiol: 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

divanadium molecule as spin impurity


Tunneling through alkanedithiol SAMs

C8 dithiol, 10 micron circular pads, probe station room temperature
Tunneling through alkanedithiol SAMs

C8 dithiol, probe station room temperature

10 μm circles (80 μm²)

20 μm x 20 μm (400 μm²)

scaled curves
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

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

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"

Albert Fert

1/2 of the prize

France

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

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.

www.mesaplus.utwente.nl/nanoelectronics
I would like to thank the following people for kindly supplying material:

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