Introduction to Materials Engineering: Materials Driving the Electronics Revolution

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Outline

• Microelectronics Miniaturization
• Historical Development: Electronics before Semiconductors
• The Discovery of Semiconductors and how Semiconductor Devices Work
• Historical Development: The World’s Fastest Changing Industry
• How are Semiconductor Devices Engineered
• What will the Future Bring?
Consider how Semiconductor Technology is a Part of our Lives.

→ Computers
→ Audio Systems
→ Control Systems (Cars, Washing Machines, Vacuum Cleaners …)
→ Telecommunications Systems
→ Administration, Records, Banking …
→ Defense
→ Aviation
→ Medicine/Bioengineering
What is an electronic device?

- A common definition is a “device which has a non-linear response between voltage and current”
A bit out of date: silicon wafers are now larger (300 mm) and devices are much smaller (< 1 μm² footprint)
Integrated Circuits

• It is possible to fabricate transistors (and resistors, capacitors, diodes) to be extrememly small. The minimum features sizes in state-of-the-art microelectronic circuit manufacture is < 0.05 µm.
• Billions of these small devices can be fabricated at the same time to make integrated circuits.
• These devices can then be combined to make extremely sophisticated circuits
  : Microprocessors (1+ billion devices)
  : Memory Chips (64 billion bits of memory)
• Requires Atomic-Scale understanding and engineering of materials and continuous innovation

This is the basis of the MICROELECTRONICS industry
Now at 1 billion+ transistors

Now at 22 nm

Now at 64 Gb
90nm Node 2003
65nm Node 2005
45nm Node 2007
32nm Node 2009
22nm Node 2011
16 nm node 2013
11 nm node 2015
8 nm node 2017
5 nm
7 nm
10 nm Prototype (ITJ 2002)
15 nm Prototype (IEDM2001)
20 nm Prototype (VLSI2001)
30 nm Prototype (IEDM2000)
50 nm Length (IEDM2002)

TMG roadmap until 2015

1-3 nm

www.intel.com/research/silicon/
The Microelectronics Revolution

• A few astonishing facts:
  - A Single Wafer of Silicon is Enough to Fabricate 1,000,000,000,000 + transistors!
    - *More than one hundred for each person on planet
    - *Cost to consumer < 0.000001c each
  - This is done by deep sub-micron (< 1/1000 diameter of human hair) engineering of semiconductors, metals, insulators. This requires continuous development of
    - * New Materials
    - * New Processes
    - * New Device Designs
  - Each generation of microelectronic circuit: is
    - * Smaller
    - * Faster
    - * Cheaper
    - *All at the same time!
There are tens of millions of transistors fabricated every year for every person on the planet.

The current cost for a microelectronics fabrication facility is about $4 billion, and rising. About 2000 people are employed in a single facility.

Microelectronics is now a $300+ billion industry: Depending on how exactly you measure things, it is now the world’s largest industry.
Moore’s Law

• In 1965, Gordon Moore, then Director of Research at Fairchild Semiconductor observed that:

  “The number of components on a microelectronics chip doubles every year”

• This was formulated based on observation from 1960-1965, when the number of components increased from 1 to 32. This path has been approximately followed ever since. For example, from 1990-95 the number of components on a chip increased from millions to tens of millions of components, equivalent to a doubling every 1.3 years!

  THIS MEANS WE CAN GET AN ORDER OF MAGNITUDE GREATER NUMBER OF COMPONENTS IN A CIRCUIT AT THE SAME COST EVERY FOUR YEARS
Moore’s Law: An Analogy

• If the aircraft industry had evolved at the same rate as the microelectronics industry in the last 25 years, a Boeing 777 today would cost $500, and circle the globe in 20 minutes on 5 gallons of fuel.
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• How are Semiconductor Devices Engineered
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• **1883** Thomas Edison invents vacuum tube - can't see commercial application, so loses interest.

• **1896** Hermann Hollerith, having developed electrically driven census system (1890) founds Tabulating Machine Company \(\rightarrow\) later **International Business Machines** \(\rightarrow\) IBM.

• **1897** J.J. Thompson discovers the electron!

• **1897** Karl Braun invents Cathode Ray Tube: the basic component of television (until very recently)

• **1904** John Fleming: First patent for vacuum tube

• **1907** Lee De Forest invents the triode valve (figure 12)

• **1912** Lee De Forest invents the valve amplifier (used in radios, TVs etc.)

• **1940s** First serious computers (they used vacuum tubes and/or electromechanical relays)
Schematic of Cathode Ray Tube

Schematic of Vacuum Diode

Schematic of Vacuum Triode
The Situation in the 1940's:

- Design and engineering of electronic and photonic devices had evolved into a sophisticated technology even before the semiconductor age:
  - Vacuum Tubes: Electronics (radio, TV, computers)
  - Light ↔ Electrons: Phosphors, Photoconduction, Photocells
  - Cathode Ray Tubes: Television
  - Early computers (e.g., ENIAC)

- Could the role of electronics in society have emerged using these technologies? Probably to some extent, but
  - Size (Computers the size of warehouses)
  - Power (e.g., battery radios would be very unlikely)
  - Expense (Technology available to everybody, e.g., personal computers?)
  - Reliability …
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Electrical Conduction in Solids

Electrical Conductivity Varies by 25 Orders of Magnitude - the Largest Variation of any Physical Property?

- Metals
- Semiconductors
- Insulators

E

Band Gap
Pure Silicon: covalent bonding

Silicon with trivalent impurities (e.g. boron): missing electrons = holes

Silicon with pentavalent impurities (e.g. arsenic): extra electrons

Temperature dependence of number of carriers in pure semiconductors

Atomic mechanism of doping in semiconductors
SEMICONDUCTOR
P-N JUNCTIONS

RECTIFIES of Diode Value

I ~ I_o (e^{qV_o/kT} - 1)

V

I
Transistor (here n-p-n “bipolar”) amplifies and switches

Schematic of transistor used in integrated circuits: “Metal Oxide Semiconductor Field Effect transistor” MOSFET

**SEMICONDUCTOR TRANSISTORS**
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A brief chronology of semiconductor technology.

- **1947** First transistor, made of Ge (Bell Laboratories)
- **1951** First commercial transistors (Western Electric)
- **1954** First transistor radio (Regency, $49.95)
  *Smaller, cheaper, uses less power than valve radios*
- **1954** First Si transistor - from now on replaces Ge
- **1954** First transistor computer (Bell Telephone)
- **1958/59** First integrated circuits in Si (planar fabrication)
  *(Jack Kilby, TI / Robert Noyce, Fairchild)*
- **1966** Integration reaches 1000 components / cm² in Si
- **1970** 1kb memory chip (Intel), $9 million / sales 1st year
- **1970** Intel 4004 - first microprocessor -2300 transistors, 60,000 calc. per second
- **1970** TI - first pocket calculator +/-/x/, $150, 1Kg
- **1973** 10,000 components per cm² in Silicon
- **1975** First home computer - Altair 8800, 256b
- **1976** Cray supercomputer, 100 million calcs/sec
  ↓
  ↓
  Today’s PC: n Gb RAM, n GHz, ~ $1000
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Microelectronics: An example of processes dominating properties in materials choice

Fundamental Property Defining Device Speed:
Electron Mobility = (Velocity) / (Applied Electric Field)
\[ \mu = \frac{v}{E} \]
<table>
<thead>
<tr>
<th>Material</th>
<th>( E_g ) (eV)</th>
<th>( I / D ) Gap</th>
<th>( \mu_e ) ( m^2 V^{-1} s^{-1} )</th>
<th>( \mu_h ) ( m^2 V^{-1} s^{-1} )</th>
<th>( m_e^* ) ((a) (x m_0))</th>
<th>( m_h^* ) ((b) (x m_0))</th>
<th>Sub? (diam)</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si D (c)</td>
<td>1.12</td>
<td>I</td>
<td>0.15</td>
<td>0.045</td>
<td>0.98 l 0.19 t</td>
<td>0.16 lh 0.49 hh</td>
<td>8&quot; (12&quot;)</td>
<td>Microelectronics</td>
</tr>
<tr>
<td>Ge D</td>
<td>0.66</td>
<td>I</td>
<td>0.39</td>
<td>0.19</td>
<td>1.64 l 0.08 t</td>
<td>0.28 lh 0.49 hh</td>
<td>2-3&quot;</td>
<td>Infra-red detectors</td>
</tr>
<tr>
<td>GaAs Z (c)</td>
<td>1.42</td>
<td>D</td>
<td>0.85</td>
<td>0.04</td>
<td>0.067</td>
<td>0.08 lh 0.45 hh</td>
<td>4&quot; (6&quot;)</td>
<td>Red lasers High Speed Electronics</td>
</tr>
<tr>
<td>InAs Z</td>
<td>0.36</td>
<td>D</td>
<td>3.30</td>
<td>0.046</td>
<td>0.023</td>
<td>0.40 hh</td>
<td></td>
<td>Potential for high speed devices (esp. InGaAs)</td>
</tr>
<tr>
<td>InP Z</td>
<td>1.35</td>
<td>D</td>
<td>0.46</td>
<td>0.015</td>
<td>0.073</td>
<td>0.40 hh</td>
<td>2&quot;</td>
<td>Infra-red telecommunications (lasers, detectors)</td>
</tr>
<tr>
<td>GaP Z</td>
<td>2.26</td>
<td>I</td>
<td>0.01</td>
<td>0.007</td>
<td>0.82</td>
<td>0.60 hh</td>
<td>2&quot;</td>
<td>Yellow LEDs (d)</td>
</tr>
<tr>
<td>GaN H (c)</td>
<td>3.36</td>
<td>D</td>
<td>0.038</td>
<td>0.19</td>
<td>0.60 hh</td>
<td></td>
<td></td>
<td>Blue LEDs (Lasers?)</td>
</tr>
<tr>
<td>InSb Z</td>
<td>0.17</td>
<td>D</td>
<td>8.00</td>
<td>0.125</td>
<td>0.014</td>
<td>0.40 hh</td>
<td>1-2&quot;</td>
<td>Long ( \lambda ) optics/</td>
</tr>
<tr>
<td>ZnSe Z</td>
<td>2.70</td>
<td>D</td>
<td>0.65</td>
<td>0.003</td>
<td>0.21</td>
<td>0.66 hh</td>
<td></td>
<td>Blues lasers?</td>
</tr>
<tr>
<td>SiC C/H</td>
<td>2.86</td>
<td>I</td>
<td>0.09</td>
<td>0.005</td>
<td>1.5 l 0.25 t</td>
<td>1.0 hh</td>
<td>2-4&quot;</td>
<td>High temp. electronics</td>
</tr>
</tbody>
</table>
Silicon:
Relatively Poor Electron Mobility
Relatively Good Thermal Conductivity
Relatively Good Mechanical Strength
Forms Excellent Insulating Barrier on Oxidation; SiO$_2$
Microelectronic Circuit Fabrication

START WITH SILICON WAFER
+ LITHOGRAPHY/PATTERNING
+ ETCHING
+ DOPING
+ METAL/INSULATOR DEPOSITION (interconnect, isolation)
+ PACKAGING
Lithography

0.032 μm
< 0.01 μm

(a) Coat with photoresist
(b) Expose photoresist (positive bonds broken)
(c) Remove exposed resist (Dissolves in developing solvent)
(d) Etch SiO₂ (chemical ion)
(e) Remove resist—pattern transferred to SiO₂
ETCHING

Wet vs Dry Etching:

Wet etching:
- High selectivity
- Isotropic

Dry or Plasma Etching:
- Anisotropic
- Uses less etchant (gas vs liquid)
- Sometimes poor selectivity
- Damage to substrate
Doping: Ion Implantation

Ion Implantation Energies $\sim 10$ keV - 1 MeV

Implantation Depths 10 nm - 1$\mu$m

FIGURE 8.4 Schematic of a commercial ion-implantation system, the Nova-10-160, 10 mA at 160 keV.
INSULATORS
(i) Oxidation of Silicon: SiO₂ is an excellent insulator.
   \[ \text{Si} + \text{O}_2 \rightarrow \text{SiO}_2 \]
   \[ \text{Si} + \text{H}_2\text{O} \rightarrow \text{SiO}_2 + 2\text{H}_2 \]
(ii) Chemical vapor deposition, for example:
   \[ \text{SiH}_4 + \text{O}_2 \rightarrow \text{SiO}_2 + 2\text{H}_2 \]
   Forms an oxide
   \[ 3\text{SiH}_4 + 4\text{NH}_3 \rightarrow \text{Si}_3\text{N}_4 + 12\text{H}_2 \]
   Forms a nitride

METALS
*Interconnect lines* are used to connect the devices to the outside world. They are made out of Cu (previously Al:Cu alloys)
Many vertical levels (5 – 10) of these lines are needed.
Inter-level connections or *vias* are plugs of Cu or tungsten
*Direct Device Contacts*, are made of conducting metal-silicon compounds, such as titanium disilicide
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Materials Challenges in CMOS

- Gate lengths need to decrease: higher resolution lithography
- Lower "equivalent" gate dielectric thickness (lower d or higher $\varepsilon$
- Higher mobility channel material?
- Junctions need to get shallower
Quantum Cellular Automata

+ **High Density** (Dots, Spacings ~ tens of nms)
+ **Fast:** 1 THz (Tunneling)
+ **Low Power:** Power-Delay Products < 10^{-21} J

- With currently available Al/Al_{2}O_{3} structures at ~ 100 nm dimensions, ΔE < 1 meV.
  Restricted to v. low temperature < 1 K

**State-of-the-Art**
Temperature ~ 500 mK
Power-Delay < 10^{-21} J
Number of gates ~ 3
Focused Ion Beam Templating of Quantum Dot Nanostructures (Hull Gp)

- R ~ 30 nm
- \( \sigma(R) < 10 \text{ nm} \)
- D < 10 nm
- \( \Delta L \sim 10 \text{ nm} \)
- \( \Sigma \sim 10 \text{s} \text{ nm} / 10 \text{s} \mu \text{m} \)
- \( 0 < f_s < 10^8 \text{ m}^{-1} \)
Molecular Switches and Transistors

Catenane. Open \([A^0]\), closed \([B^0]\). Application of +ve voltage brings \([A^0]\) to \([A^+]\), rearranges charge due to positive charge on two rings. Decrease in voltage returns molecule to \([B^0]\) state. Return to \([A^0]\) state by application of negative voltage. Cf Rotaxanes (Heath, UCLA; Williams, HP)
SPINTRONICS: Utilizing magnetic moment of electron rather than its charge