# EE 116: Semiconductor Devices for Energy & Electronics

Spr 2019 • Tue-Thu 10:30-11:50am • 370-370 • Prof. Eric Pop

- Two lecture/discussion meetings per week
- 10 weeks, 19 lectures
- Grade = 30% HW + 30% Midterm + 40% Final

- Midterm: week of May 7-9, in class, TBD by us
- Final: period of June 7-12, TBD by Registrar

- Web site: "Sp19-EE-116-01" on Canvas

- Office hours → Prof. Eric Pop, Wed 2-3pm, Allen-X 335
- TA Lily Xu → OH on Wed 11am-12pm, Thu 3-4pm in Allen-X 316

- Please take advantage of all instructor and TA office hours
- Please read Syllabus handout

---

## Approximate schedule by week:

1. **Introduction:** atoms, bands, electrons/holes
2. **Doping:** mass action, charge neutrality
3. **Carrier Transport:** Drift, Diffusion, Einstein relation
4. **Non-equilibrium:** continuity equation, G-R
5. **PN junction:** electrostatics, CV
6. **PN junction:** carrier transport, IV
7. **Opto-electronic devices:** LEDs, solar cells
8. **Thermoelectric energy harvesting devices**
9. **MOSFETs:** threshold voltage, square law, transconductance

## Lots of Nobel Prizes…

- 1956 Transistor (Bardeen, Brattain, Shockley)
- *1985 Quantum Hall Effect (Klitzing)*
- *1986 Scanning Tunneling Microscope (Binnig, Rohrer)*
- *1996 Buckyballs (Curl, Kroto, Smalley)*
- *1998 Density Functional Theory (Kohn)*
- 2000 Heterojunction and IC (Alferov & Kroemer, Kilby)
- *2000 Conducting polymers (Heeger)*
- *2007 Giant Magnetoresistance (Fert & Grunberg)*
- 2009 CCD and Optical Fiber (Kao, Boyle & Smith)
- *2000 Fractional QHE (Laughlin, Stormer, Tsui)*
- 2010 Graphene (Geim & Novoselov)
- 2014 Blue LED (Nakamura)

---

# EE 116 Lecture 1

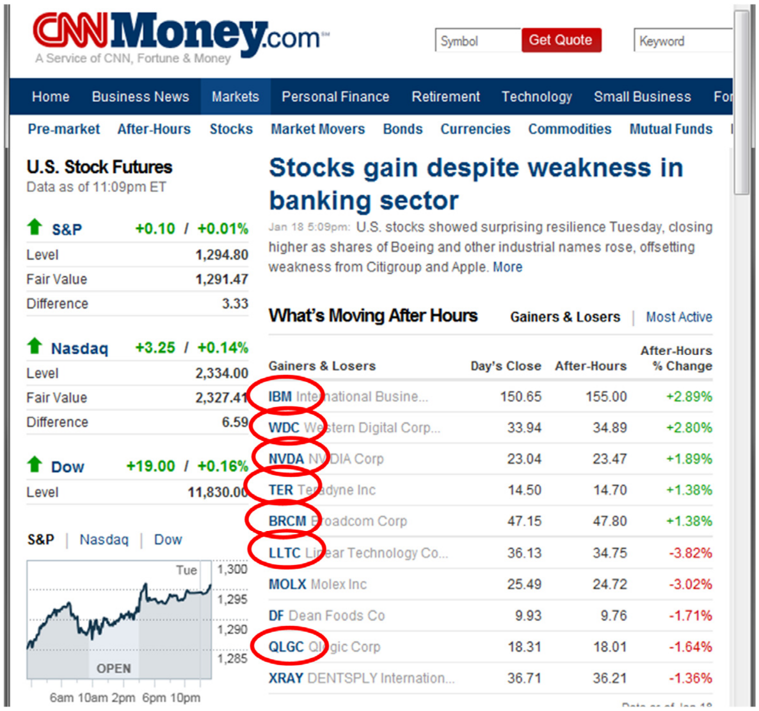
## Introduction, Some Historical Context

- Questions, questions…
  1) Why "semiconductors"?
  2) Why "devices"?
  3) Why are we here?

Google

intel

SAMSUNG



**U.S. Stock Futures**

Data as of 11:09pm ET

| S&P | +0.10 / +0.01% |
|---|---|
| Level | 1,294.80 |
| Fair Value | 1,291.47 |
| Difference | 3.33 |

| Nasdaq | +3.25 / +0.14% |
|---|---|
| Level | 2,334.00 |
| Fair Value | 2,327.41 |
| Difference | 6.59 |

| Dow | +19.00 / +0.16% |
|---|---|
| Level | 11,830.00 |

**Stocks gain despite weakness in banking sector**

Jan 18 5:09pm: U.S. stocks showed surprising resilience Tuesday, closing higher as shares of Boeing and other industrial names rose, offsetting weakness from Citigroup and Apple. More

**What's Moving After Hours** Gainers & Losers | Most Active

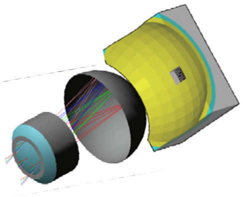
| Gainers & Losers | Day's Close | After-Hours | After-Hours % Change |
|---|---|---|---|
| IBM International Busine... | 150.65 | 155.00 | +2.89% |
| WDC Western Digital Corp... | 33.94 | 34.89 | +2.80% |
| NVDA NVIDIA Corp | 23.04 | 23.47 | +1.89% |
| TER Teradyne Inc | 14.50 | 14.70 | +1.38% |
| BRCM Broadcom Corp | 47.15 | 47.80 | +1.38% |
| LLTC Linear Technology Co... | 36.13 | 34.75 | -3.82% |
| MOLX Molex Inc | 25.49 | 24.72 | -3.02% |
| DF Dean Foods Co | 9.93 | 9.76 | -1.71% |
| QLGC QLogic Corp | 18.31 | 18.01 | -1.64% |
| XRAY DENTSPLY Internation... | 36.71 | 36.21 | -1.36% |

Light-Emitting Diodes (LED)

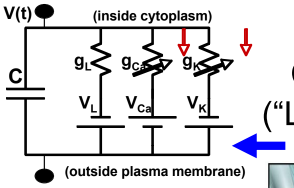
Power Devices

Photo-Voltaics
("Solar Cells")
= Diodes

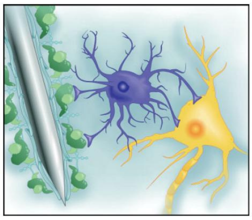
Organic Materials--
Imaging, Displays (OLED),
ultra-low power devices

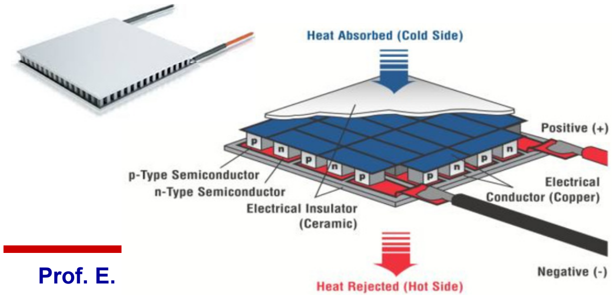


**The Physics apply broadly and there are MANY applications!**



Cell Rest Potential
("Law of the Junction")





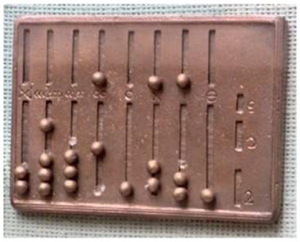
Thermoelectric
energy harvesters

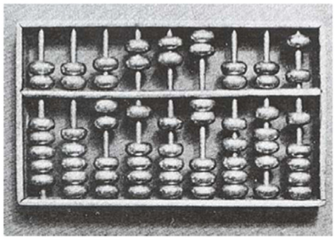
---

- What's at the heart of it all?

- What can we get out of it?

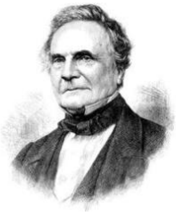
- The abacus, ancient digital memory

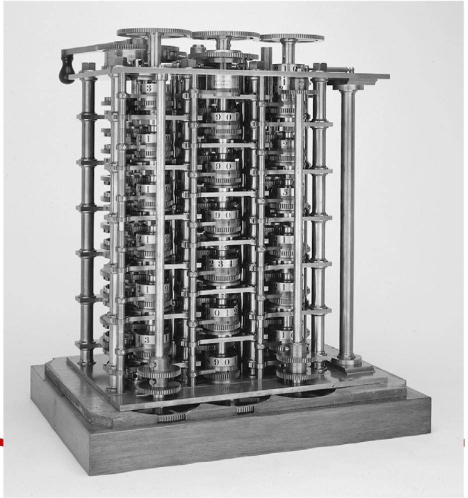

Roman Abacus (ca. 200BC)


Chinese Abacus (ca. 190AD)

  - Information represented in digital form
  - Each rod is a decimal digit (units, tens, etc.)
  - A bead is a memory device, not a logic gate

- An early mechanical computer
  - The Babbage difference engine, 1832
  - 25,000 parts


Charles Babbage
(Wikipedia)



---

- Ohm's law: V = I x R
  - Georg Ohm, 1827

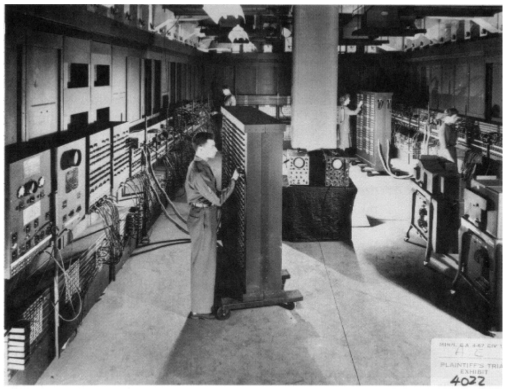
- Semiconductors are <u>not</u> metals
  - Semiconductor resistance <u>decreases</u> with temperature
  - Michael Faraday, 1834

- Discovery of the electron
  - J.J. Thomson, measured only charge/mass ratio, 1897
  - "To the electron, may it never be of any use to anybody." – J.J. Thomson's favorite toast.

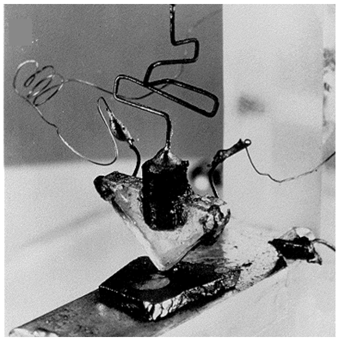
- Measuring the electron charge: $1.6 \times 10^{-19}$ C
  - Robert Millikan, oil drops, 1909

*Sources: Wikipedia, http://www.pbs.org/transistor*

- ENIAC: The first electronic computer (1946)
  - 30 tons, including ~20,000 vacuum tubes, relays
  - Punch card inputs, ~5 kHz speed
  - It failed ~every five days



- Modern age begins in 1947:
  - The first semiconductor transistor
  - AT&T Bell Labs, Dec 1947
  - J. Bardeen, W. Brattain, W. Shockley
  - Germanium base, gold foil contacts



*Sources: Wikipedia, http://www.pbs.org/transistor*

---

**John Bardeen, Walter Brattain, William Shockley at AT&T Bell Labs (1947)**

shared 1956 Nobel prize for transistor

Bardeen → to UIUC (1951-1991)

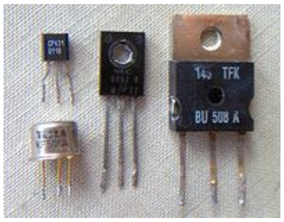
→ 2nd Nobel 1972, superconductivity

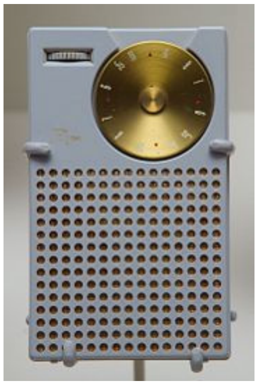
Shockley → 1956 to Shockley Semiconductor at 391 San Antonio Road (later to Stanford)

Brattain → retired 1967 to Seattle

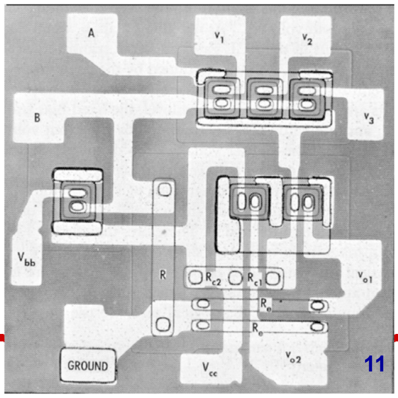
> The way I provided the name, was to think of what the device did. And at that time, it was supposed to be the dual of the vacuum tube. The vacuum tube had transconductance, so the transistor would have "transresistance." And the name should fit in with the names of other devices, such as varistor and thermistor. And… I suggested the name "transistor."
>
> – John R. Pierce AT&T Bell Labs, 1948

- First transistor radio, the Regency TR-1 (1954)
- Built with four <u>discrete</u> transistors

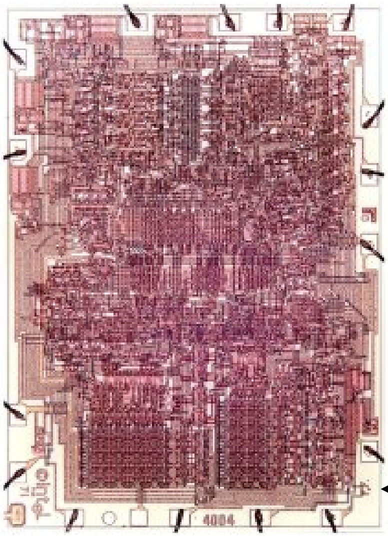




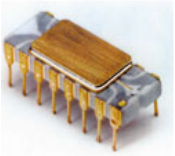
- Integrated circuits fabricate all transistors and metal interconnects on the same piece of silicon substrate
  - Jack Kilby patent TI’1959
    → Nobel prize 2000
  - Robert Noyce, 1961
    → co-founder of Fairchild, then Intel



---



- The first microprocessor, Intel 4004 (1971)
- 2250 transistors, 740 kHz operation



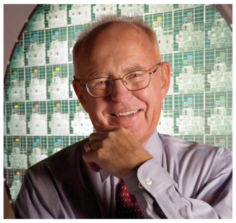
← F.F. = Federico Faggin (designer)

- Comparable computational power with ENIAC
- Built on 2” and then 3” wafers (vs. 12” today)
- 10 μm line widths (vs. 22-45 nm today), 4-bit bus width
- Used in… the Busicom Calculator:
- See [http://www.intel4004.com](http://www.intel4004.com)

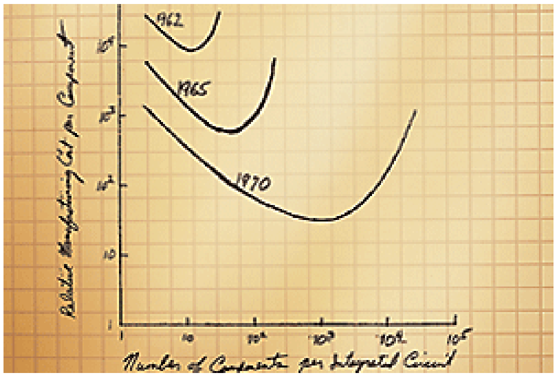
Followed by 8008 (8-bit), 8080, 8086
Then 80286, 80386, 80486 = i486 (1989, 0.8 μm lines)
Pentium, II, III, Itanium, IV, Celeron, Core 2 Duo, Atom…

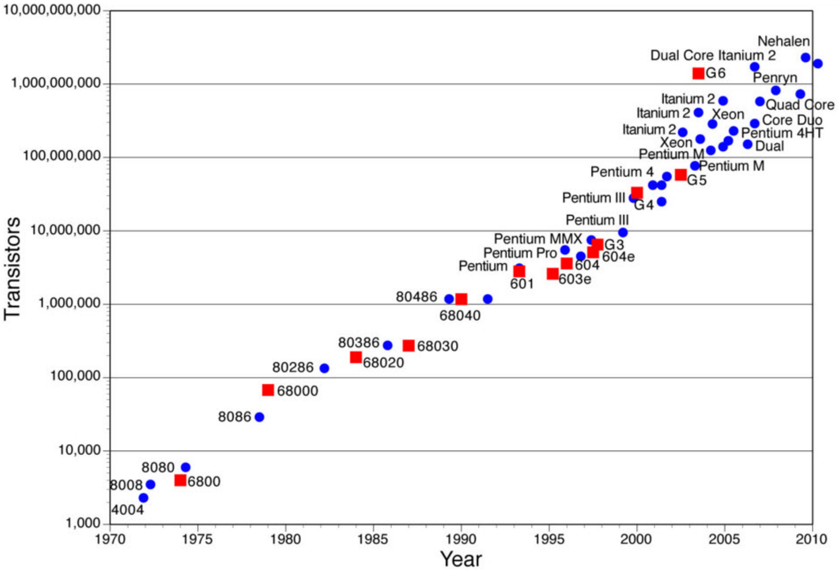
# Gordon Moore's "Law"

~ doubling circuit density every 1.5-2 years



1965

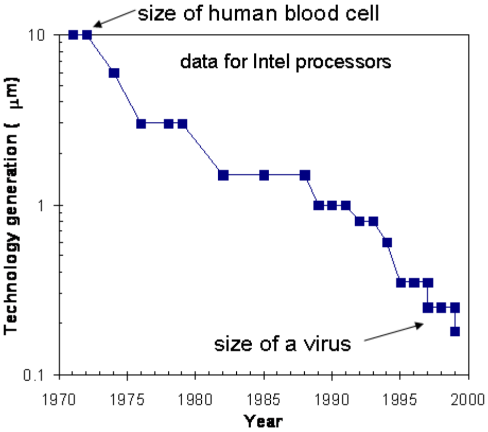


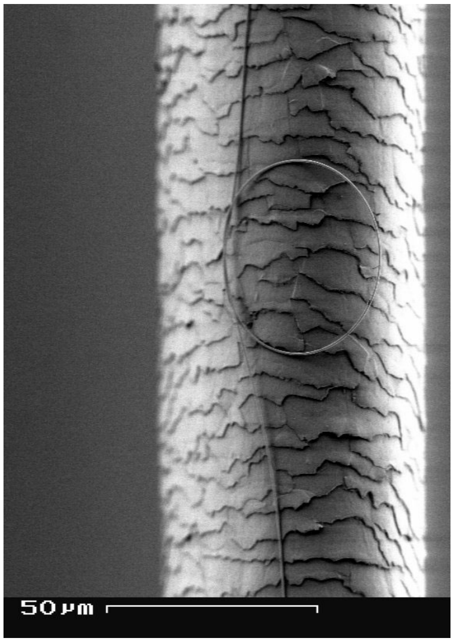


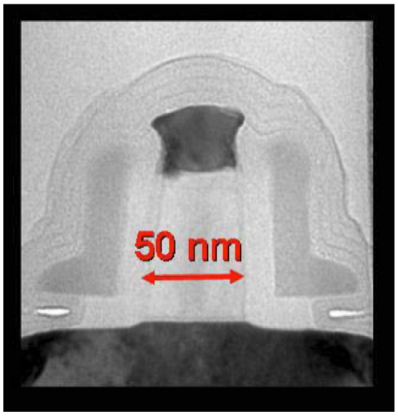
Source: http://www.intel.com

---

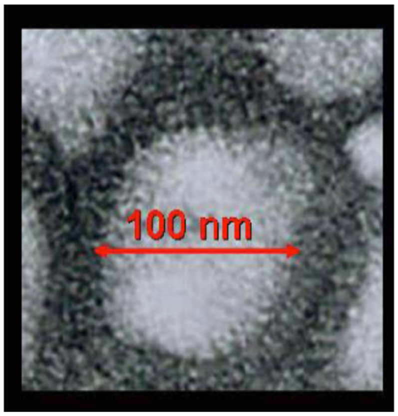
- Transistor size scaling:







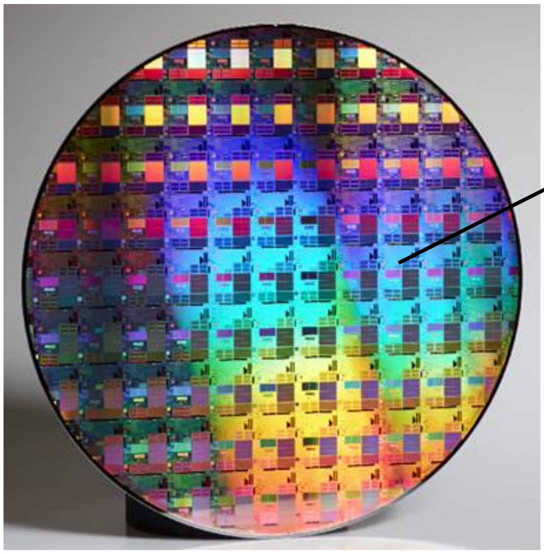
"65 nm" technology



Influenza virus

*Sources: NSF, Intel*

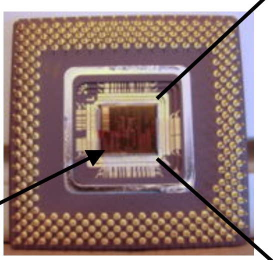
# Take the cover off a microprocessor.

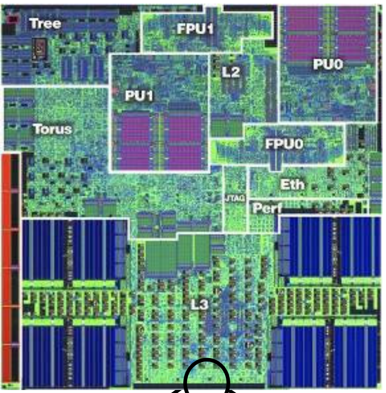


Full wafer (100s of dies)

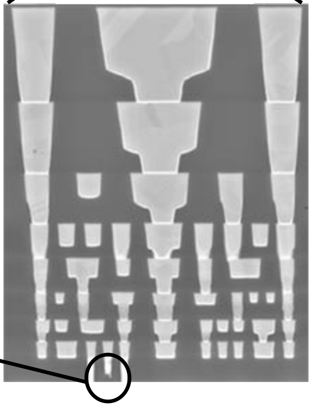
modern wafers: 200-300 mm diameter (8-12 inches)

Packaged die

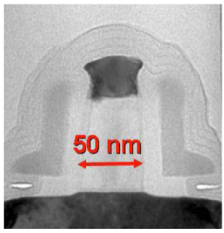




Cross-section



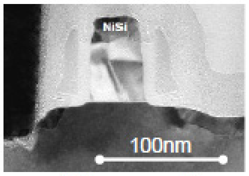
Single transistor



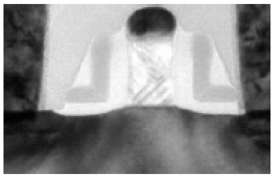
---

- 20th century transistors “carved” out of bulk 3D materials (Si) using patterning, etching
- As 3D materials shrink, they have dangling bonds and surface states → these, plus quantum mechanics limit minimum dimensions to ~10 nm
- Will 21st century transistors be made of 1D (carbon nanotube) or 2D (graphene, $MoS_2$) materials? These have ~1 nm thickness.

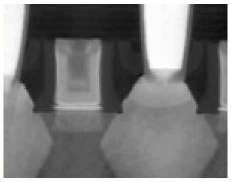
**90nm node**



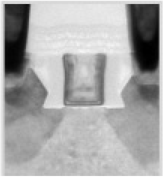
**65nm node**

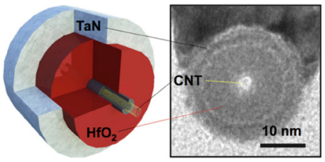


**45nm node**

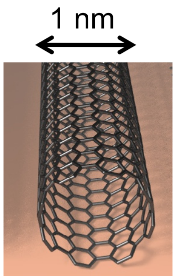


**32nm node**

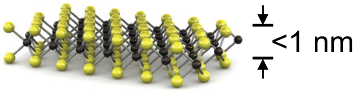




**carbon nanotubes (1D)**

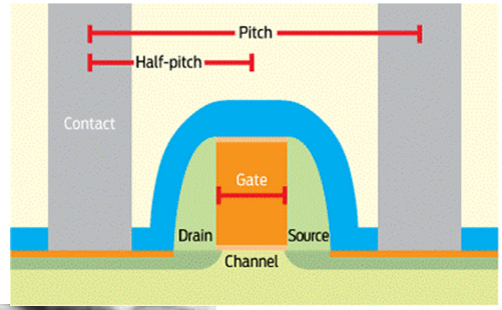


**2D materials like $MoS_2$, $WTe_2$, $ZrSe_2$**

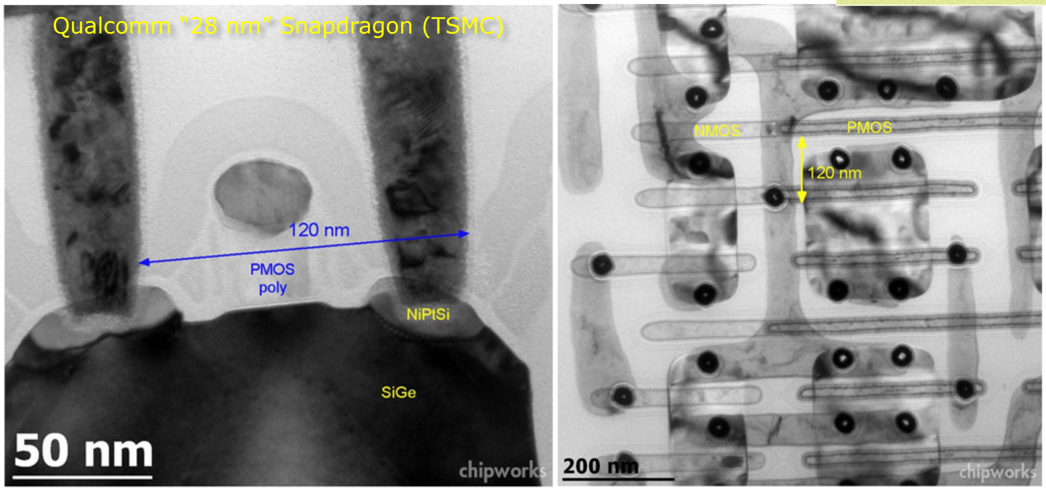


# What is a technology "node" anyway?

- Intel "22 nm" node transistors have L ≈ 35 nm, $t_{fin}$ ≈ 8 nm, **pitch ≈ 90 nm**
- Rule of thumb, pitch ≈ 3-4*$L_G$ at the moment, but…

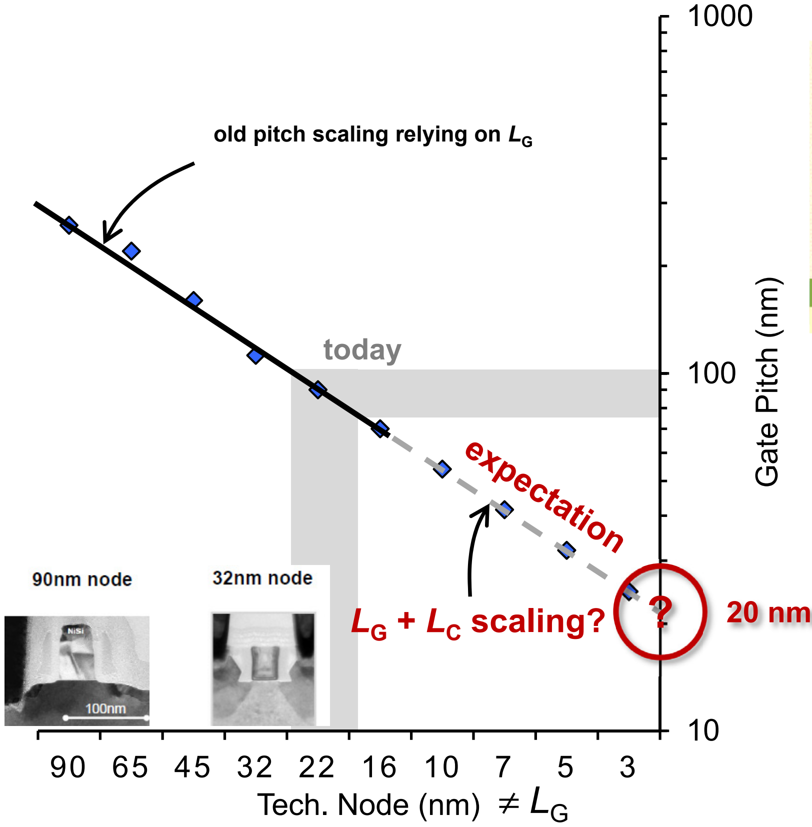


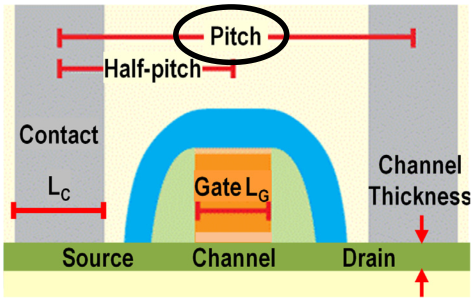
source: IEEE Spectrum



---

# Gate Length and Gate Pitch Scaling





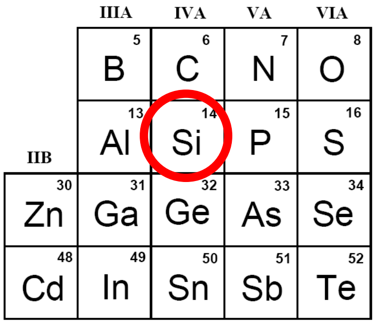
source: IEEE Spectrum

**Gate Pitch** is *key metric* of transistor scaling

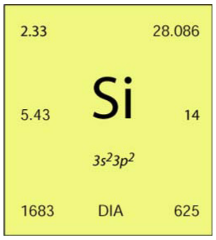
Must scale both **gate** and **contacts** ($L_G$ and $L_C$)

source: V. Moroz, Synopsis

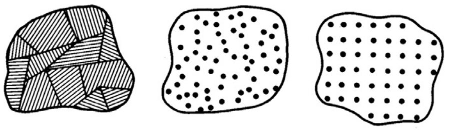
- Why semiconductors?
  - vs. conductors or insulators
  -
  - Elemental vs. compound
  -



| IIB | IIIA | IVA | VA | VIA |
|---|---|---|---|---|
| | 5 B | 6 C | 7 N | 8 O |
| | 13 Al | 14 Si | 15 P | 16 S |
| 30 Zn | 31 Ga | 32 Ge | 33 As | 34 Se |
| 48 Cd | 49 In | 50 Sn | 51 Sb | 52 Te |

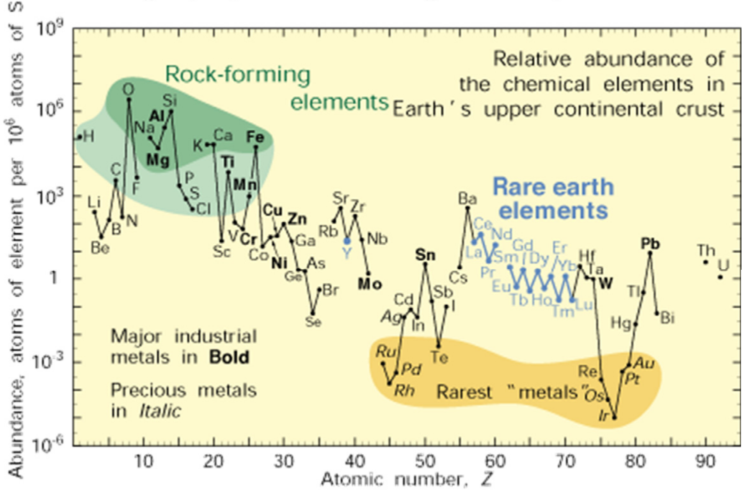


- Why (usually) crystalline?
  -
  -
  -



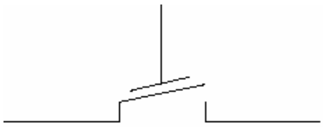
polycrystalline amorphous crystalline

- Why silicon?
  -
  -
  -

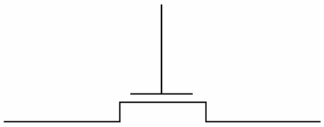


---

- Why the (CMOS) transistor?
  - Transistor = switch
  - Technology is very scalable (Moore's Law)
  - CMOS = complementary metal-oxide-semiconductor
  - Fabrication is reproducible on extremely large scales
  - Circuit engineering
  - Design abstractions

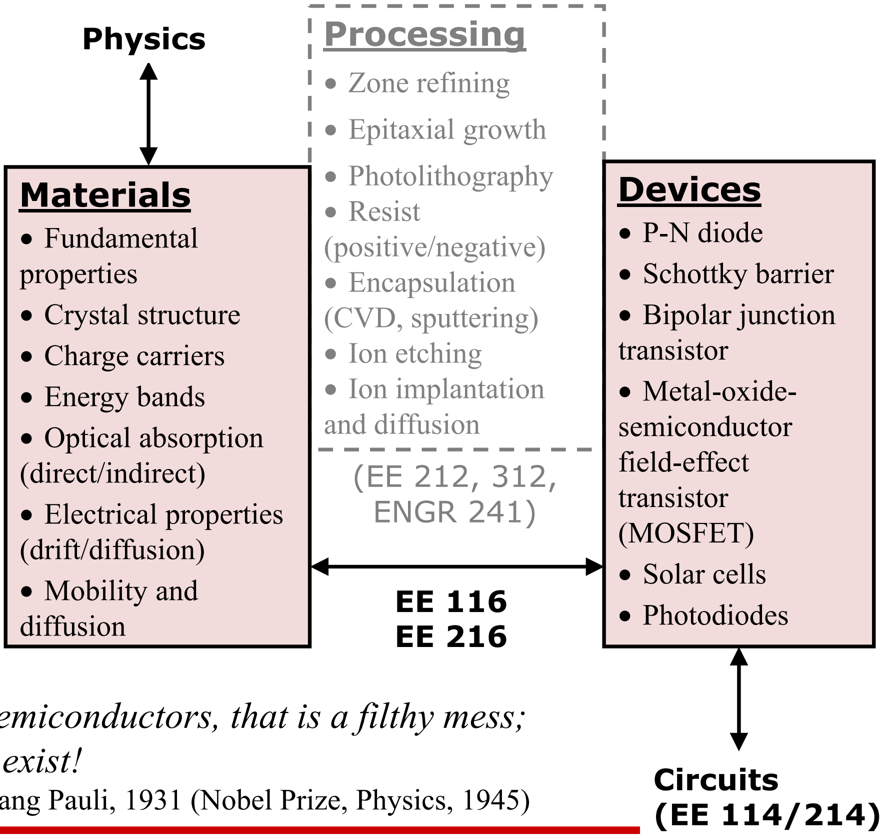


$V_G < V_T$ switch open



$V_G > V_T$ switch closed

- What do we learn in EE 116? (and later in EE 216)



**Physics**

**Materials**
- Fundamental properties
- Crystal structure
- Charge carriers
- Energy bands
- Optical absorption (direct/indirect)
- Electrical properties (drift/diffusion)
- Mobility and diffusion

**Processing**
- Zone refining
- Epitaxial growth
- Photolithography
- Resist (positive/negative)
- Encapsulation (CVD, sputtering)
- Ion etching
- Ion implantation and diffusion

(EE 212, 312, ENGR 241)

**EE 116**
**EE 216**

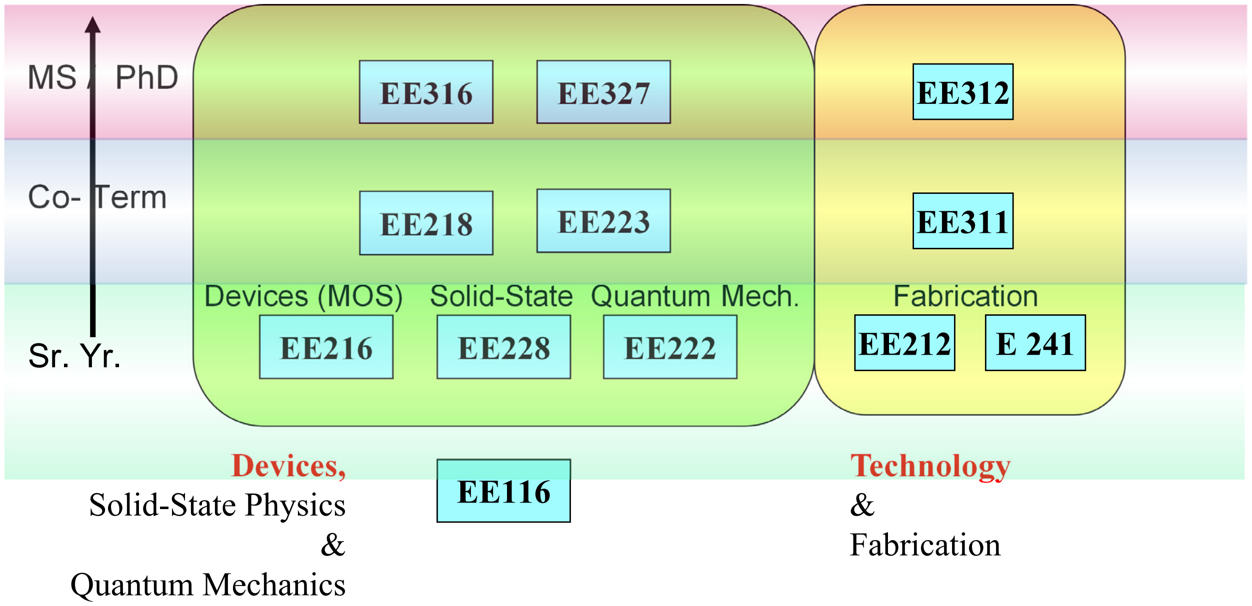
**Devices**
- P-N diode
- Schottky barrier
- Bipolar junction transistor
- Metal-oxide-semiconductor field-effect transistor (MOSFET)
- Solar cells
- Photodiodes

**Circuits (EE 114/214)**

*One shouldn’t work on semiconductors, that is a filthy mess; who knows if they really exist!*

Wolfgang Pauli, 1931 (Nobel Prize, Physics, 1945)

# Ladder of EE “device” courses



**Devices,** Solid-State Physics & Quantum Mechanics

**Technology** & Fabrication