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NANOSENSORS
Centre for Energy Research
Institute of Technical Physics and Materials Science

ADVANCED SEMICONDUCTOR DEVICES

01_Introduction

MŰEGYETEM 1782

February 12th, 2020

Scope of the course

- Introduction: Short history of semiconductor devices, More-Moore, More-than-Moore, semiconductor industry, trends, prospects, overview of the course. (J. Volk)
- CMOS technology 1 - Bulk crystal and thin film deposition techniques: Crystal growth methods, physical properties, PVD (sputtering, MBE, thermal/e-beam evaporation), CVD (MO-CVD, ALD), thermal oxidation, strain in the layers, characterization methods (surface profiler, ellipsometry, 4-probe, Hall, DLTS). (J. Volk)
- CMOS technology 2 - Patterning: Photo-, EUV-, X-ray, e-beam lithography, etching (wet, dry, reactive ion) annealing, rapid thermal annealing, wire bonding, wafer bonding, 2D/3D micromachining. (J. Volk)
- Advanced Si devices 1: MOS capacitor, accumulation/depletion/inversion, threshold voltage, defects (interface and fix charges), C-V measurement, CCD, MOS-FET. (J. Volk)
- Advanced Si devices 2: Scaling of MOS, high-k dielectrics, Zener tunneling, leakage issue, hot carrier effects, Strained MOS (Si, Ge, SiGe), UTB-SOI, FIN FET, tri-gate, NW transistor, prospects (ITRS). (J. Volk)
- Advanced Si devices 3: Memory devices (SRAM, DRAM, flash), 2D semiconductor devices, power devices, Si solar cell. (J. Volk)
- Compound semiconductors - Physics and technology: Deposition techniques, band engineering, heterojunctions (type I, II, III), band bending, p-n heterojunction, lattice mismatch, polar semiconductors, 2DEG at heterointerfaces. (J. Volk)

Scope of the course

- Compound semiconductor devices: Quantum well, LED (Blue, IR), laser diode, GaAS HEMT, GaN H-FET, MESFET, high frequency noise. (J. Volk)
- Polymeric semiconductors: materials, polymer solar cell, OLED, pressure sensors, printed electronics, perovskite solar cells. (J. Volk)
- Sensors and actuators: MEMS, physical, chemical, biological sensors, actuators, tactile sensors, robotic applications, biointerfaces, artificial nose, skin. (J. Volk)
- Novel device platforms 1 - Spintronic devices: Giant magnetoresistance, spin valves, MRAMs, spin transfer torque, STT RAM. (Gy. Mihály)
- Novel device platforms 2 - Resistive switching memories: Concept of memristors, resistors with memory, electrochemical metallization cells, valence change memories, phase change memories. (A. Halbritter)
- Novel computing architectures - Brain inspired computing, analog memories with tunable plasticity, in memory computing, resistive switching crossbar devices as artificial neural networks, spiking neural networks. (A. Halbritter)

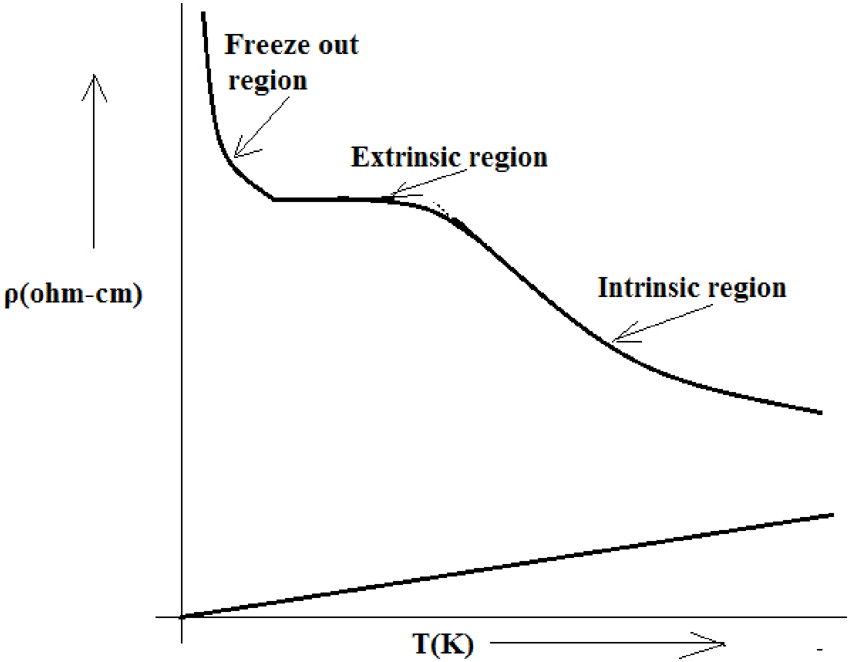
Σ12 lectures + 1 backup (Feb 12, 19, 26, March 4, 11, 18, 25, Apr 1, 8, 29, May 6, 13, 20)

Exam

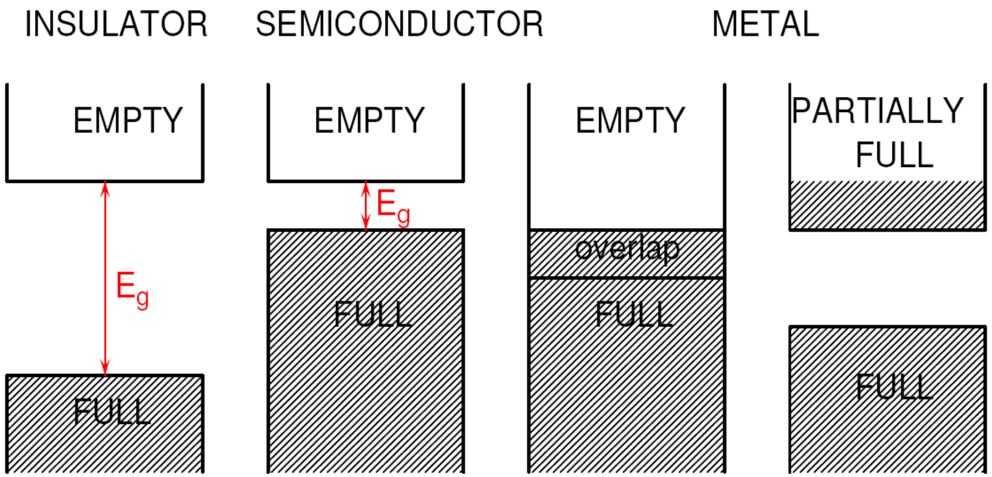
- Oral exam in the exam period.
- Printed out lecture notes can be used.
- Emphasis is put on the level of understanding.

Semiconductors

- Electrical conductivity value: between metal and insulators
- Resistance falls as its temperature rises (metals are the opposite)
- Conductivity can be changed by impurities (Called doping if it is done intentionally. For Si:10^{-4}-10^{4} Ωcm is common.)
- Medium energy forbidden band between conduction and valence band (band gap ~0.2-5eV)



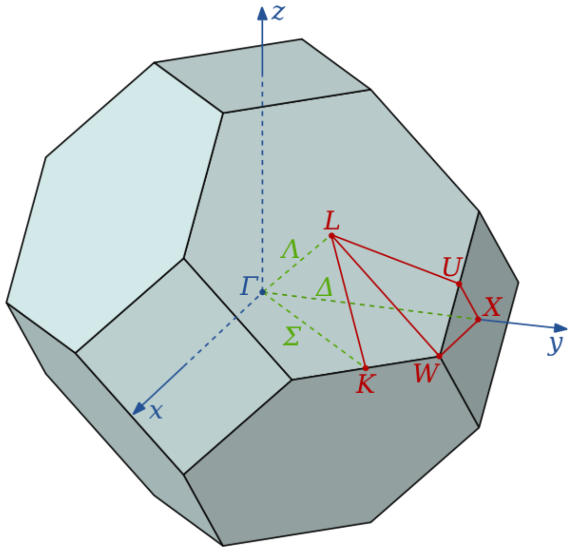
Band diagrams of solids



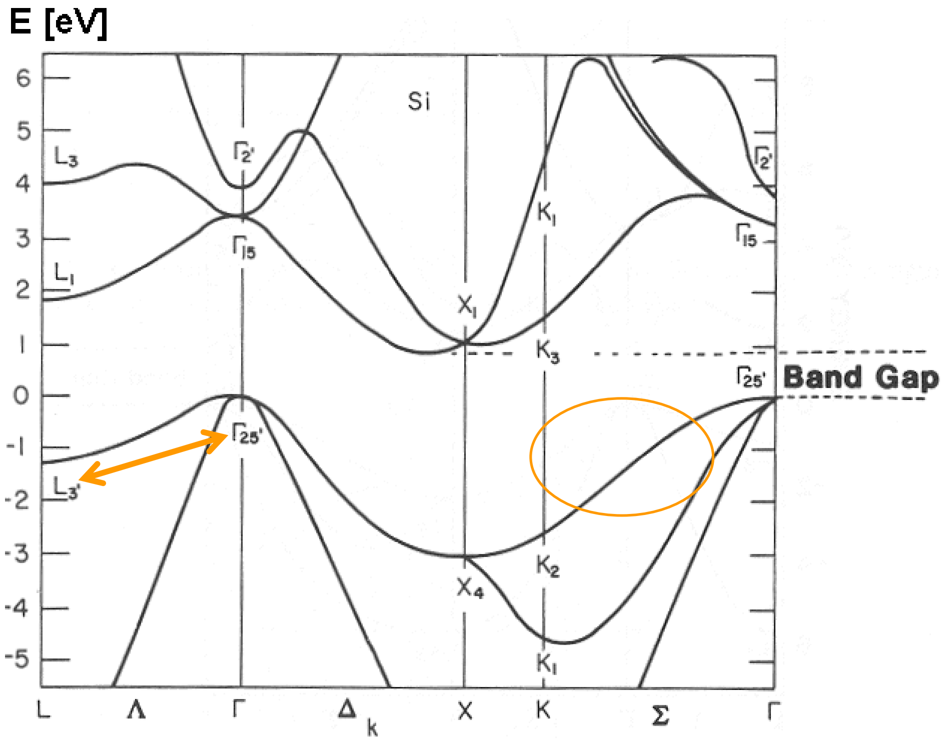
Semiconductors

Solution of the Schrödinger's equation on a crystal by Bloch's theorem

$$\psi_{n\mathbf{k}}(\mathbf{r}) = e^{i\mathbf{k}\cdot\mathbf{r}} u_{n\mathbf{k}}(\mathbf{r})$$



First Brilluin zone of a fcc crystal



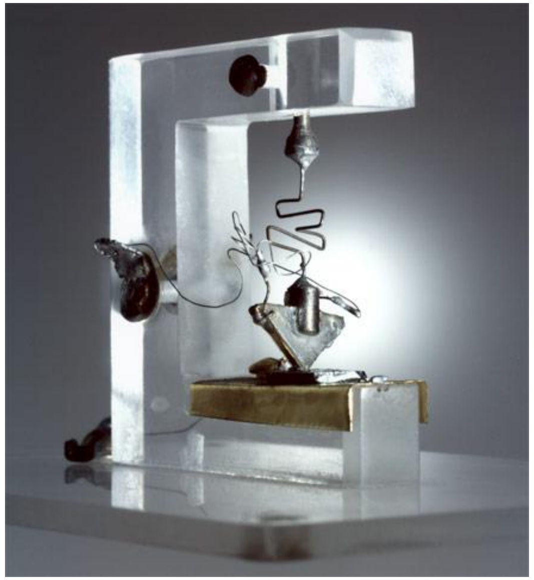
Band structure of Si

For the basic understanding of semiconductor devices it is often enough to consider the band edges (band diagram picture with effective masses).

Short hystory of the semiconductor devices

Discrete device

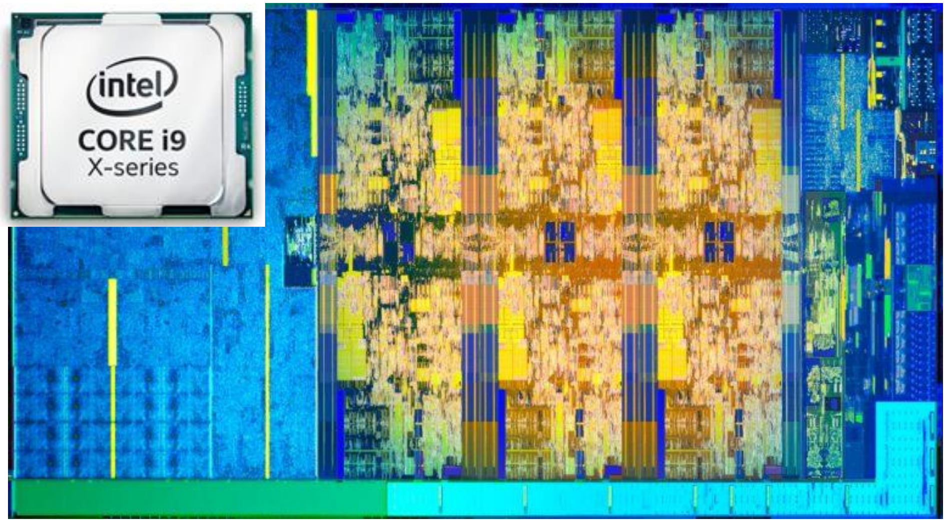
Point contact **Trans**fer res**istor** (1947)
J. Bardeen, W. Brattain, W. Shockley
(Nobel price in 1956)



70 years

Ultra-large-scale integration (ULSI)

10 billion transistors fabricated by
14-nm technology



None of the fields developed as dynamically in the last 70 years as semiconductor industry!

Top car in 1937 vs middle-class car 10 years ago

Mercedes Benz 320 (1937)

- shown in Indiana Jones movie (Raiders of the Lost Ark)
- 3,200 ccm engine
- 77 HP
- 130 km/h

Mazda 5 (2007)

- (my car)
- 1,800 ccm engine
- 110 HP
- 180 km/h

70 years

1,4-2,5 x

Significant (+40-150%) but not so drastic enhancement in performance.

Top computer in 1969 vs today's middle-class smartphone

Apollo Guidance Computer (1969)

- on board each Apollo Command Module (CM) and Apollo Lunar Module (LM)
- 2048 words of memory ~ 4kB RAM
- 78kB ROM

Huawei P20 Lite (2019)

- my smart phone
- 4GB RAM
- 64GB ROM

50 years

X ~1M times

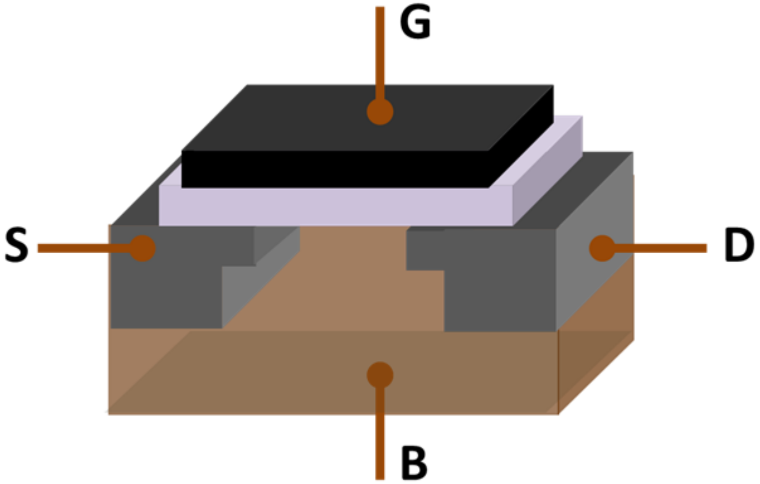
Enormous (1 million times) enhancement within 50 years!

Metal-Oxide* Field Effect Transistor (MOSFET)

- Atalla was investigating the surface passivation of Si; later he used thermal oxidation (Bell Labs)
- Atalla proposed to use MOS for FET, significantly reduced number of traps in the channel (compared to previous transistors e.g. Ge) due to the high-quality oxide
- MOSEFT was invented and demonstrated by Mohamed Atalla and Dawon Kahng in 1959
- Became the basic component of central processing unit (CPU) and memory


Mohamed Atalla


Dawon Kahng



*oxide is referred to SiO2 in semiconductor technology

Integrated circuit (IC)

- Set of electronic circuits on one small flat piece (or "chip") of semiconductor material (normally Si)
- Cheaper, faster, and less expensive than discrete transistors
- Dominated by MOSFETs
- First functional (hybrid) IC was demonstrated by **Jack Kilby** (Texas Instrument in 1958 (1/2 Nobel Price in Physics 2000). However, it used external wires making the mass production troublesome
- Half year later **Robert Noyce** at Fairchild Semiconductor invented the first true monolithic IC (all components on a single chip) using Cu contact lines and planar process → suitable for mass production, ie. real technological breakthrough!

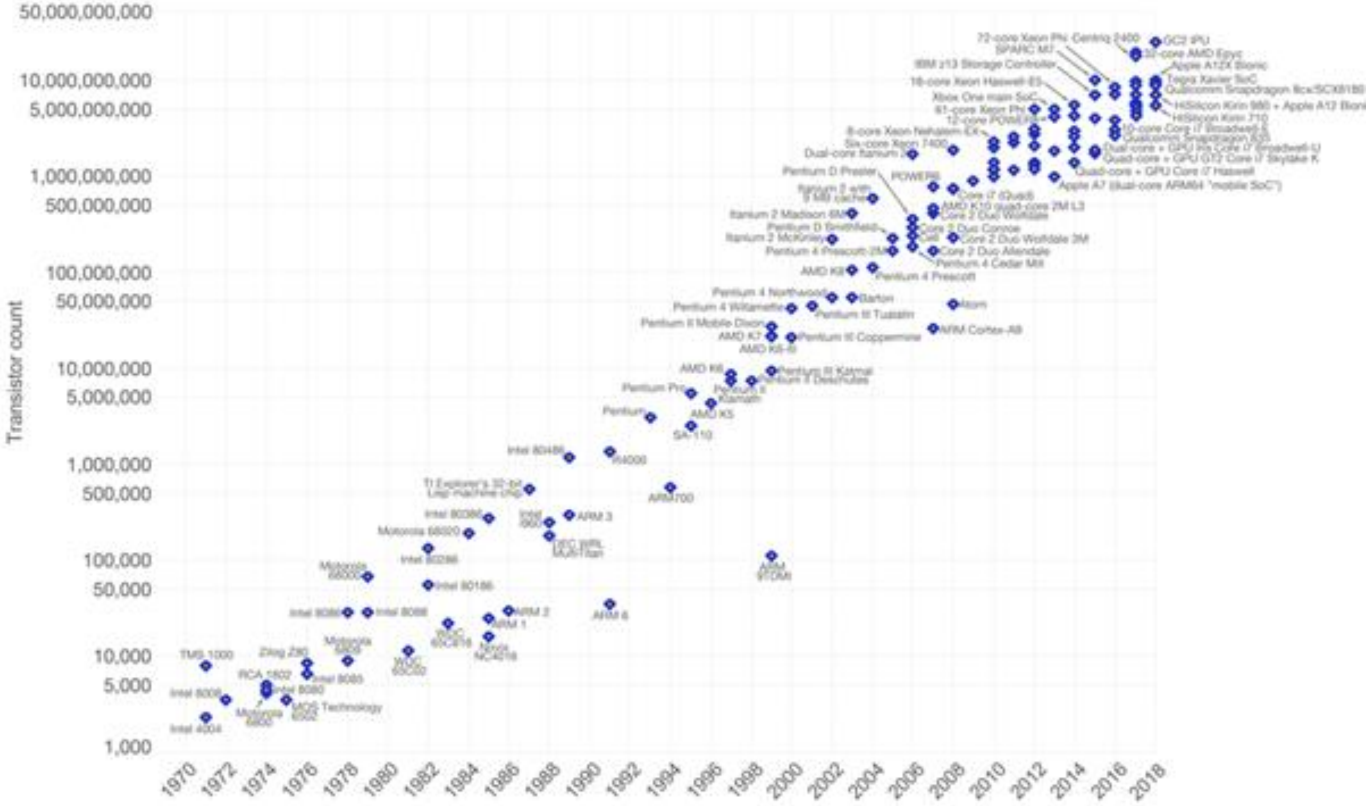

Jack Kilby


Robert Noyce

Robert Noyce (the Mayor of Silicon Valley) , American physicist, co-founder of Fairchild Semiconductor in 1957 and Intel Corporation in 1968,

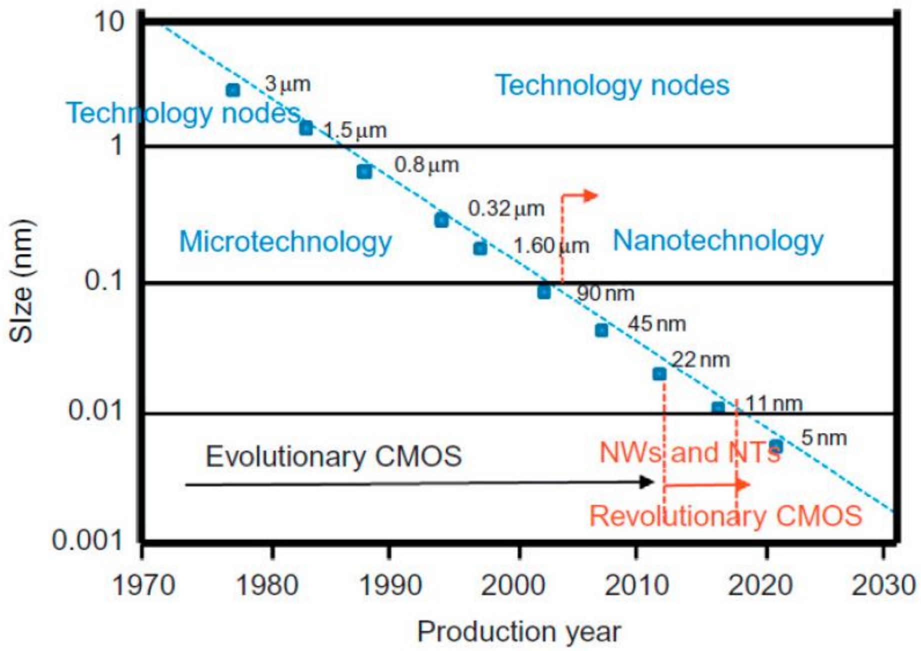
The Man Behind the Microchip: Robert Noyce and the Invention of Silicon Valley

More Moore: trends in CMOS technology

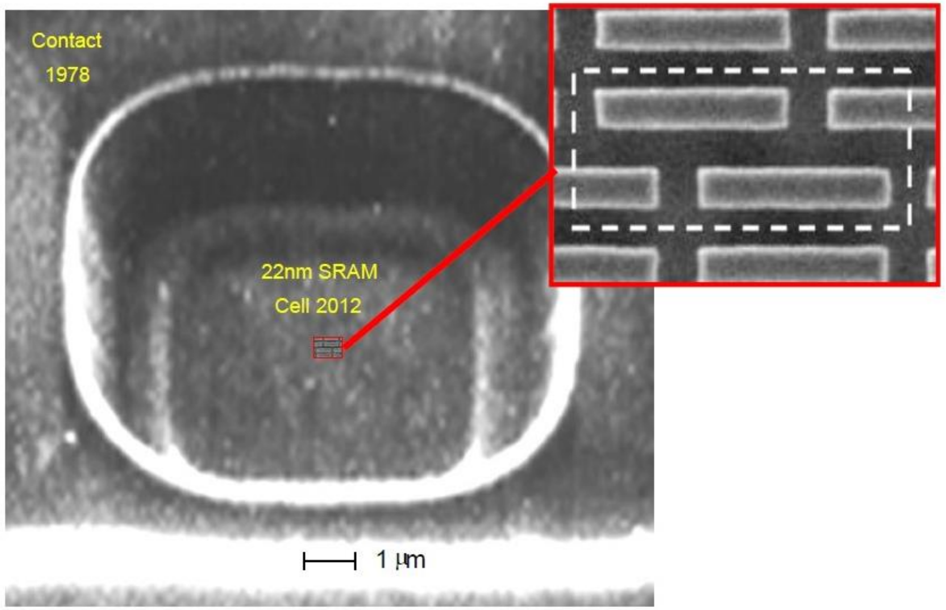


- Gordon Moore: The number of transistors in a dense integrated circuit doubles about every two years
- The progress followed/follows the Moore’s empirical law for several decades
- Closely related to the scaling of MOSFET
- Most forecasters, including Gordon Moore expect Moore's law will end by around 2025

More Moore: MOSFET downscaling



Miniaturization of transistor gate length at different technology nodes and production years

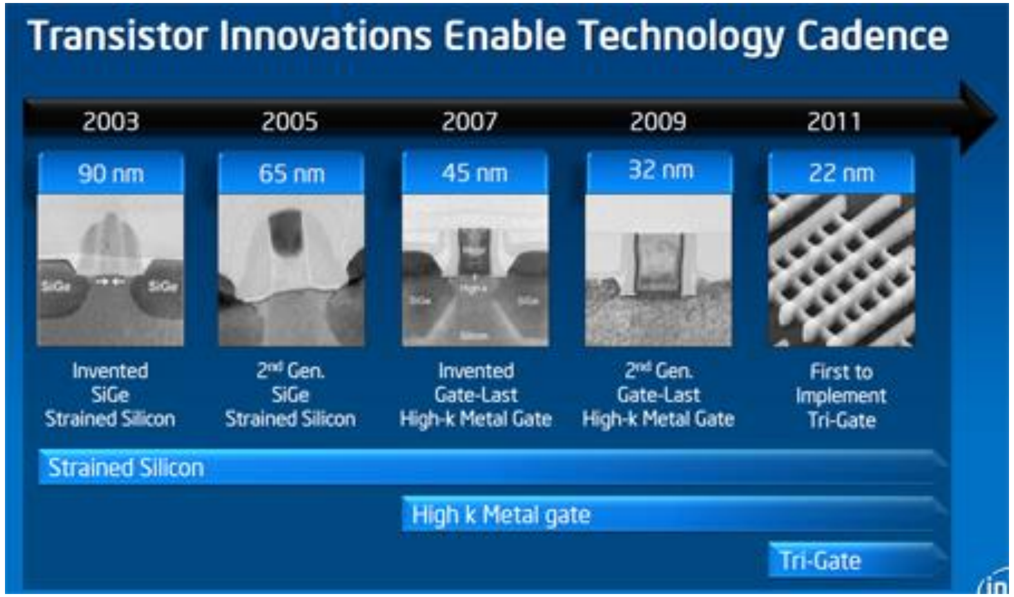


2012 22-nm static random-access memory (SRAM) is dwarfed by a 1978 SRAM contact

- Progress is predicted by the International Technology Roadmap for Semiconductors (ITRS) which a set of documents produced by a group of semiconductor industry experts.

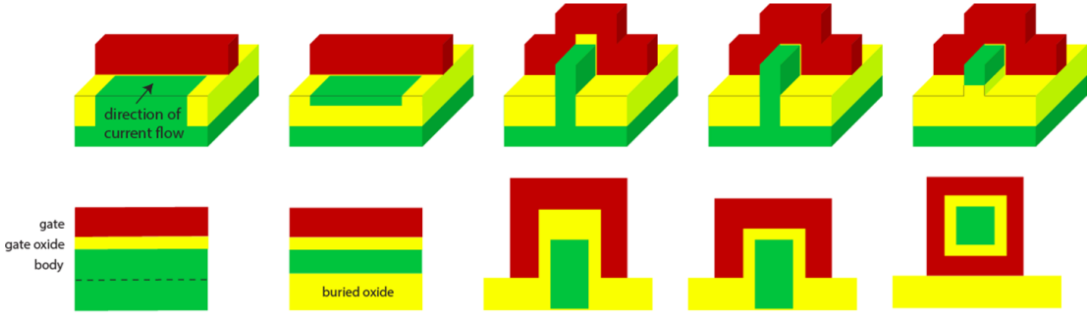
More Moore: MOSFET downscaling

- Several innovations were needed to follow the More's law

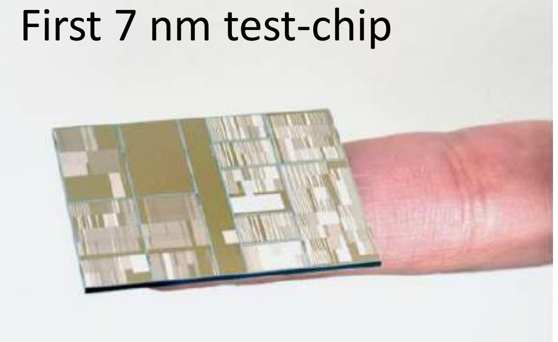


Company	Logo	Technology name
Intel		10nm, 10nm+, 10nm++
Samsung		10nm, 8nm, 7nm, 6nm, 5nm, 4nm
TSMC		10nm, 7nm, 5nm
GlobalFoudries		7nm
IBM		7nm, 5nm

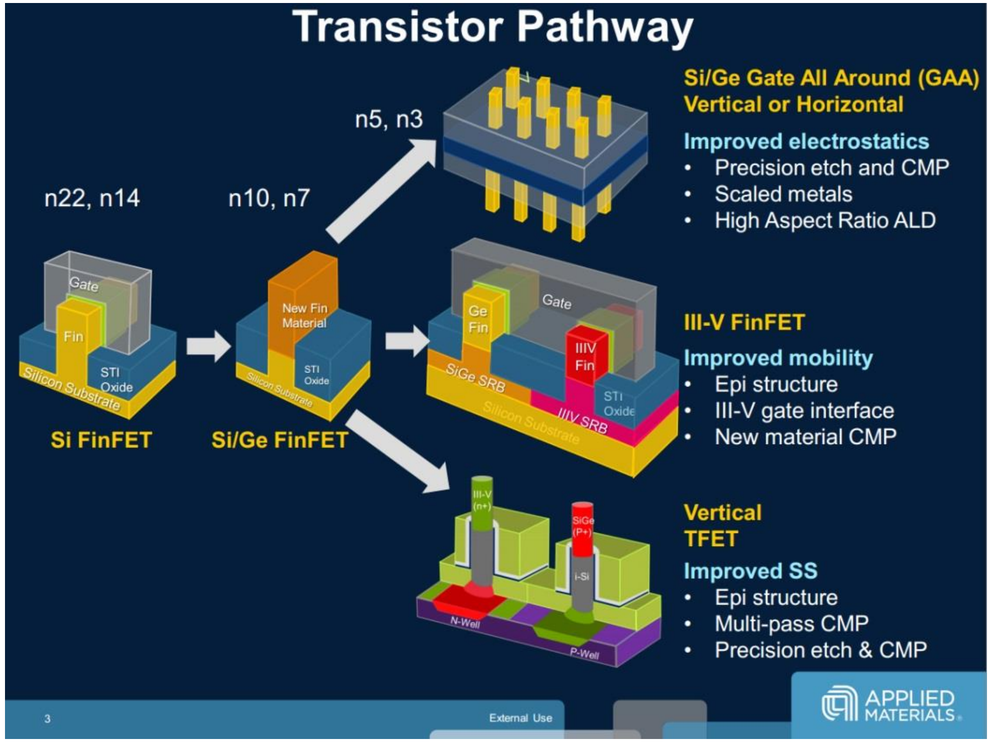
Table 2: 5 major players in the 10/7/5-nm chip manufacturing

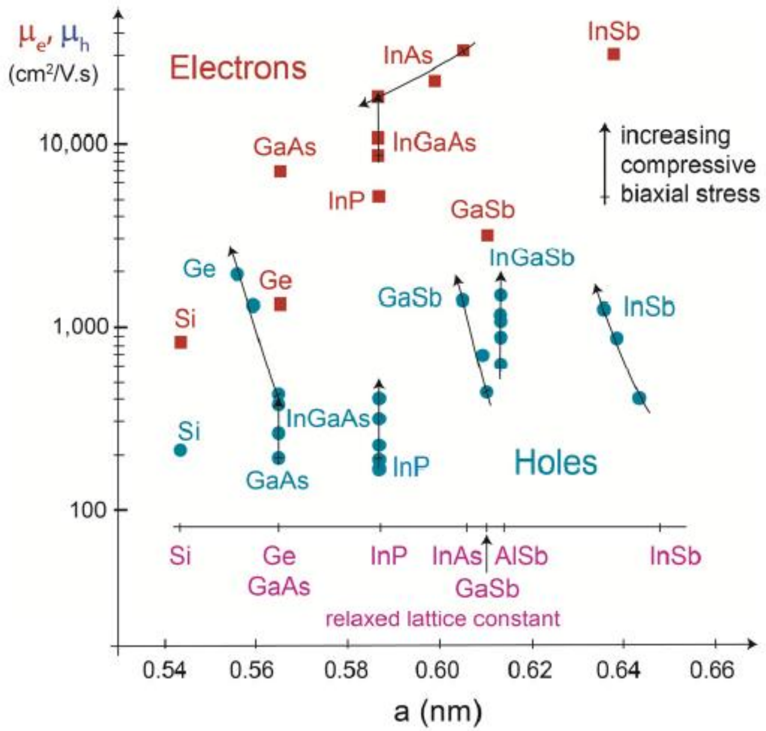


Planar bulk MOSFET | Extremely-Thin-Body MOSFET | FinFET | Tri-gate MOSFET | Gate-All-Around Nanowire MOSFET



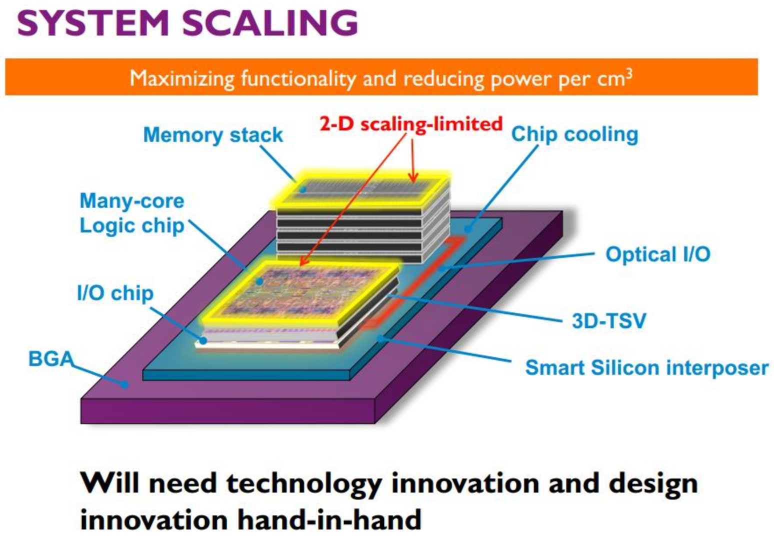
MOSFET scaling: what's next?





- New device architectures: horizontal and vertical nanowires (NW) for gate-all-around (GAA) transistors
- New channel materials beyond Si: Ge-Si or Ge for p-MOS, III-V (InGaAs) for n-MOS (no novel 2D material or CNT on the horizon, yet)

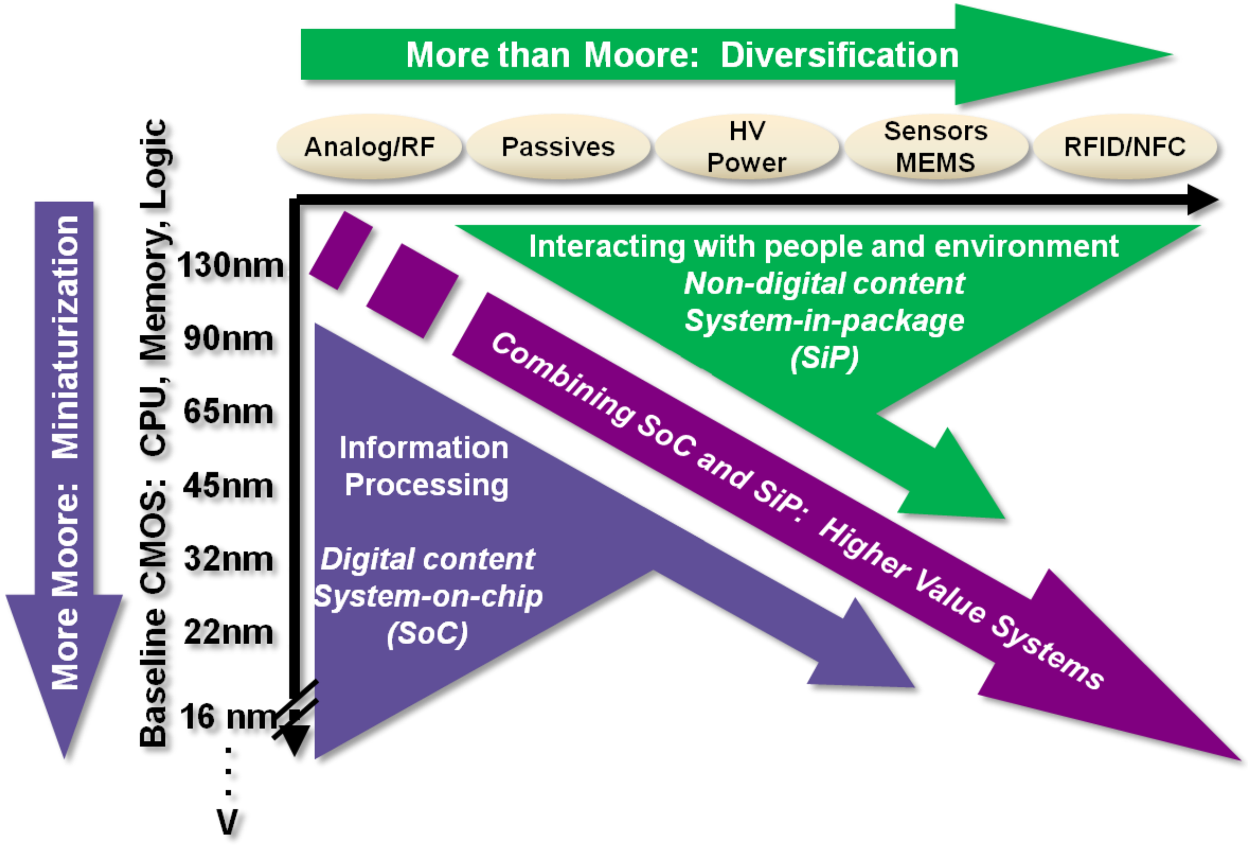
MOSFET scaling: economical aspects



- 3D integration and chip cooling rather than size reduction
- Economical concerns: 450 mm wafer, EUV lithography etc.? Cost per chip does not decrease further.

ASML's EUV lithography machine may eventually look like

More Moore vs. More than Moore

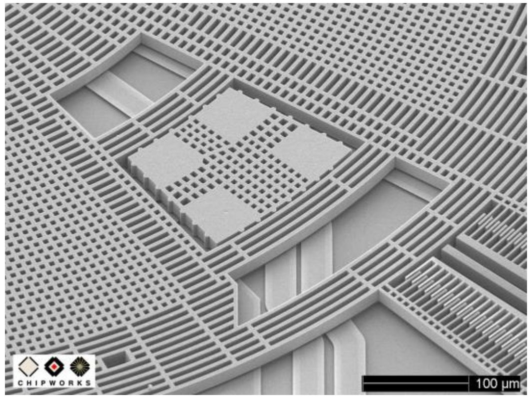


More-than-Moore with new functions

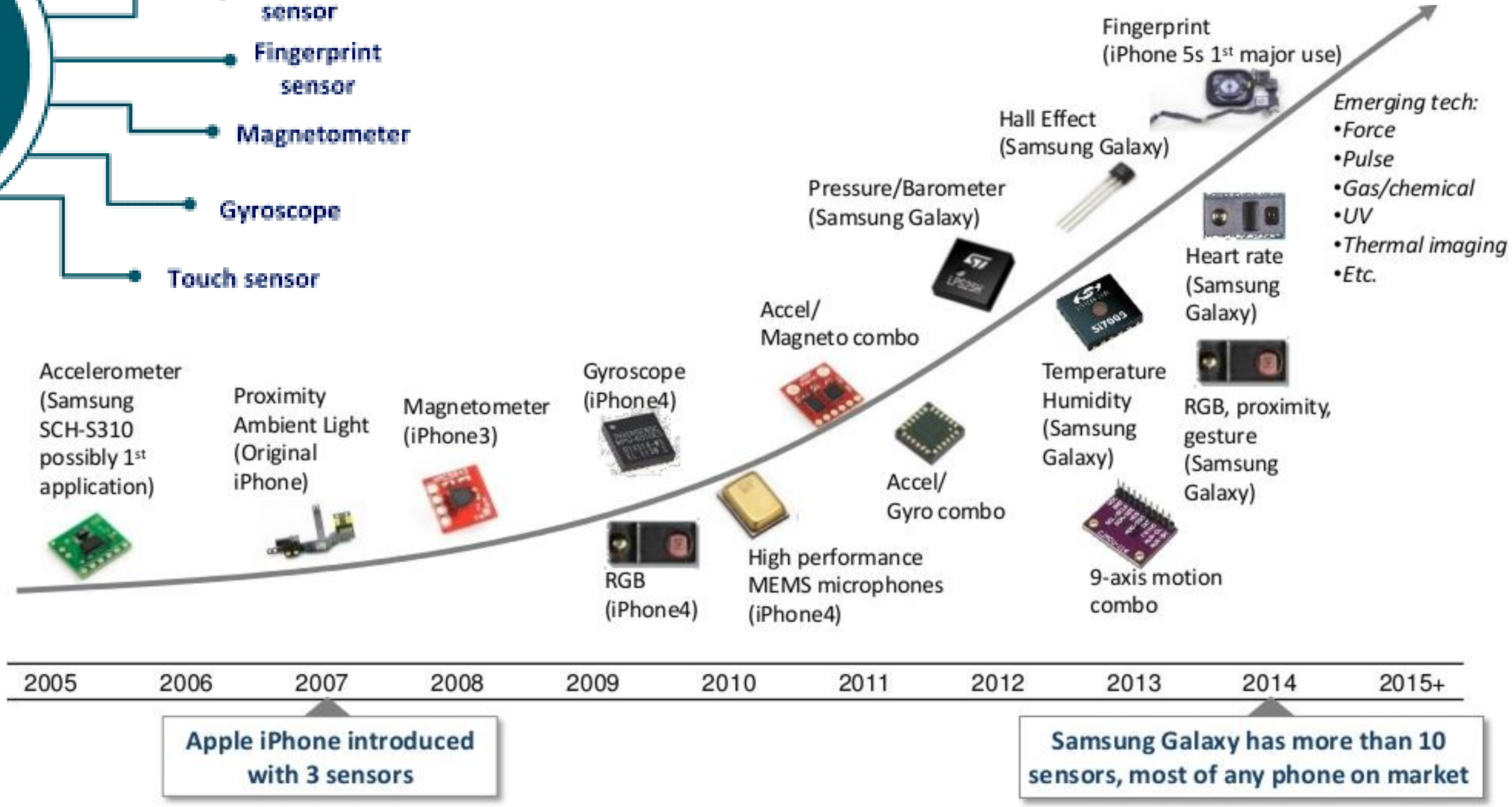
- System-on-chip
- Micro-/Nano-Electromechanical Systems (MEMS/NEMS): sensors and actuators
- Cheap, printed and flexible electronics, semiconductor polymer
- Internet of (every) things (IoT), autonomous sensor networks powered by energy harvesters

More than Moore: the revolution of the sensors

Smartphone applications



MEMS gyroscope



Sources: This little motion sensor went to the market..., Sonja Thompson, IT News Digest, March 22, 2007; Willie D. Jones, IEEE Spectrum, A Compass in Every Smartphone, January 29, 2010; Consumers boost MEMS combo sensors, Electronic Product Design and Test, March 19, 2014; Samsung Turns up the Pressure on Competition with Pressure Sensor in Galaxy S4, IHS, March 20, 2013; Behind the sixth sense of smartphones: the Snapdragon processor sensor engine, Qualcomm, April 24, 2014; MEMS for Cell Phones & Tablets, Yole Developpement, May 2012; Fairchild, Emergence of a $Trillion MEMS Sensor Market, SensorCon, 2012; MEMS Microphone Market Tops 2 Billion Units, Mobile Dev Design, March 4, 2013

More than Moore and beyond Moore