New devices and materials for 21st century electronics

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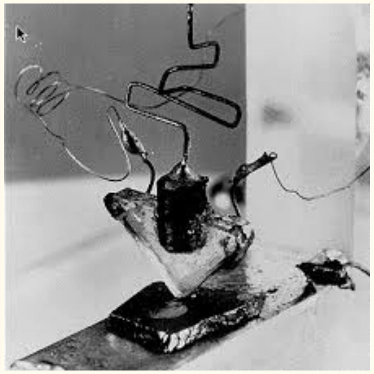
History of semiconductor technology

1947

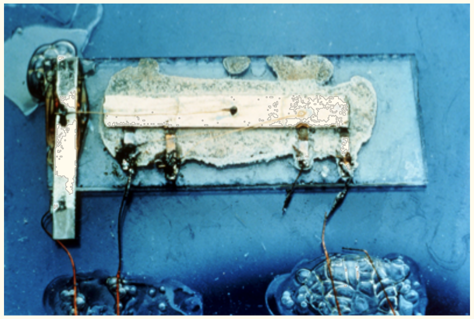


Point contact transistor

1951

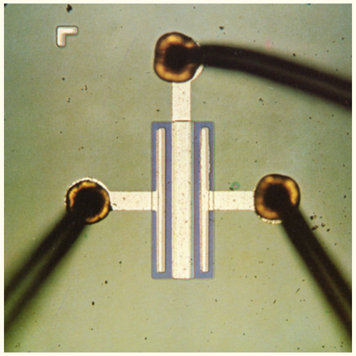
Commercial junction transistors

1958



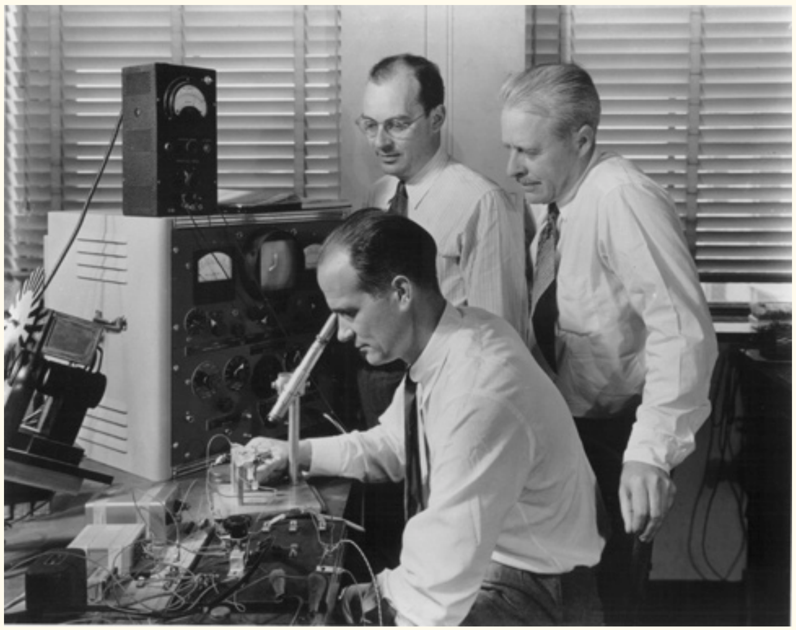
Kilby's original germanium multi-chip "solid-circuit" oscillator

1960



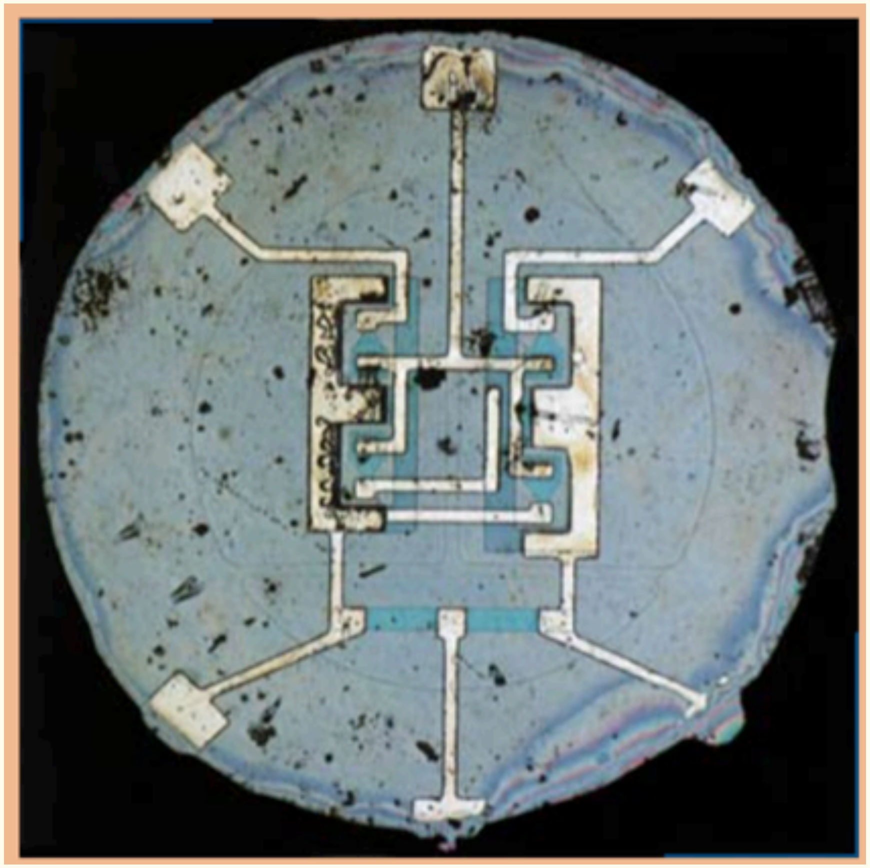
Fairchild p-type MOS switching transistor

Inventors of the first transistor



Inventors of the first transistor
circa Dec. 23, 1947
Courtesy: AT&T archives

Early Integrated Circuit



An early prototype integrated circuit fabricated at Fairchild using the planar processing technique.
This "flip-flop" circuit uses 4 transistors.

Price ?

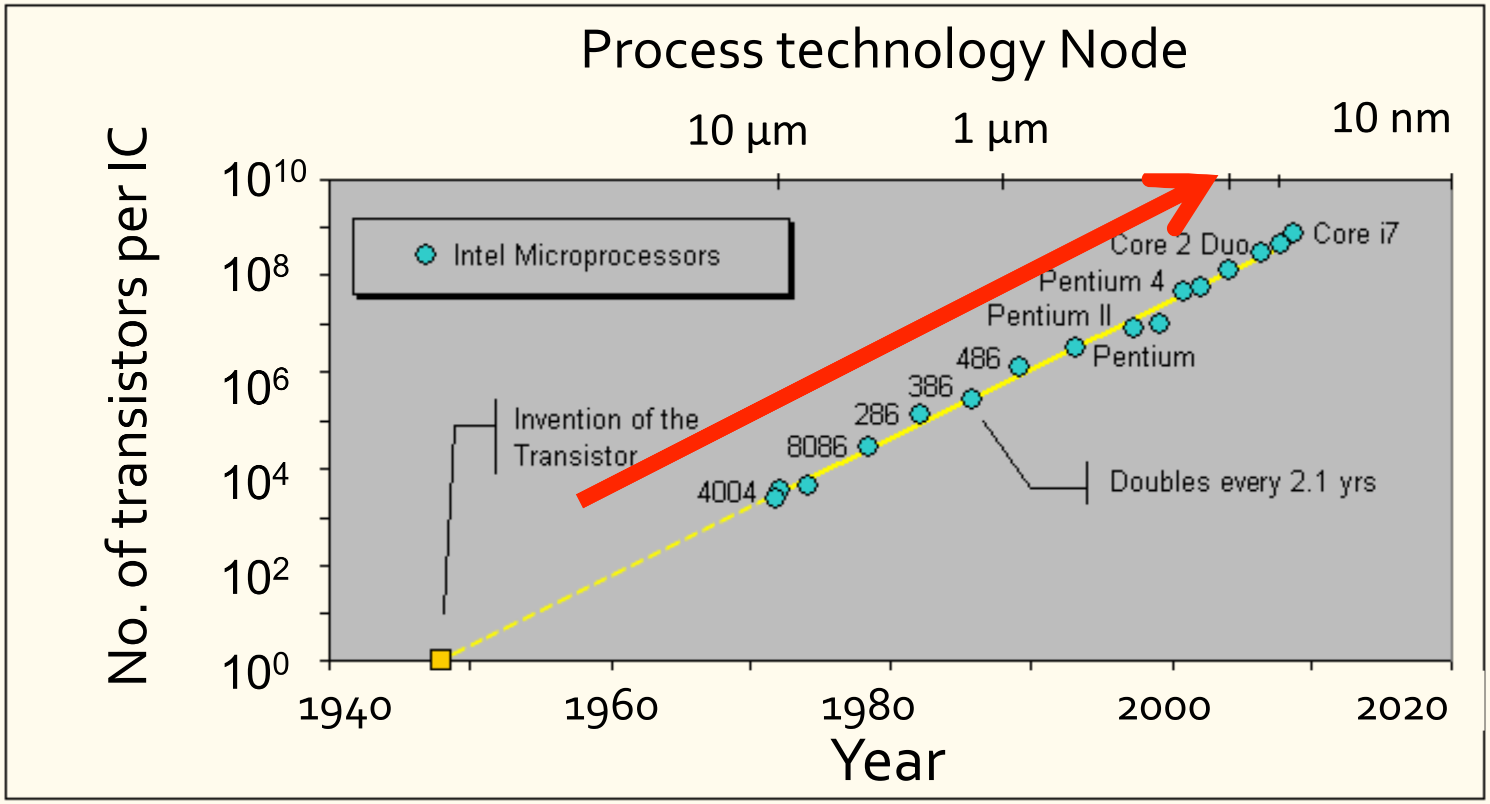
Michael Riordan, From Bell Labs to Silicon Valley: A saga of Semiconductor Technology Transfer, The Electrochemical Society, Interface, 2007

From sand to circuits
Transistors

Current transistors for most digital ICs are made from **silicon.**

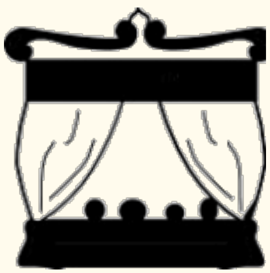
However, first transistor was made from **germanium. WHY?**

Technology trends: Moore's law



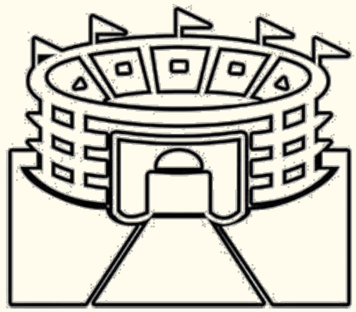
If transistors were people …

Music hall



2300

Large stadium

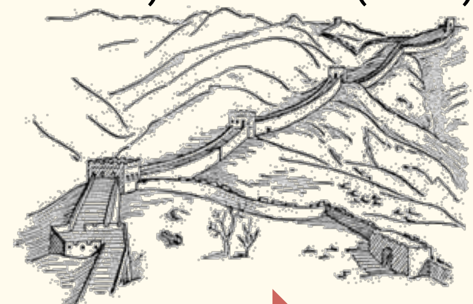


134,000

Tokyo

32M

China (few years back) & India (now)



1.3B

1970 **1980** **1990** **2000** **2010**

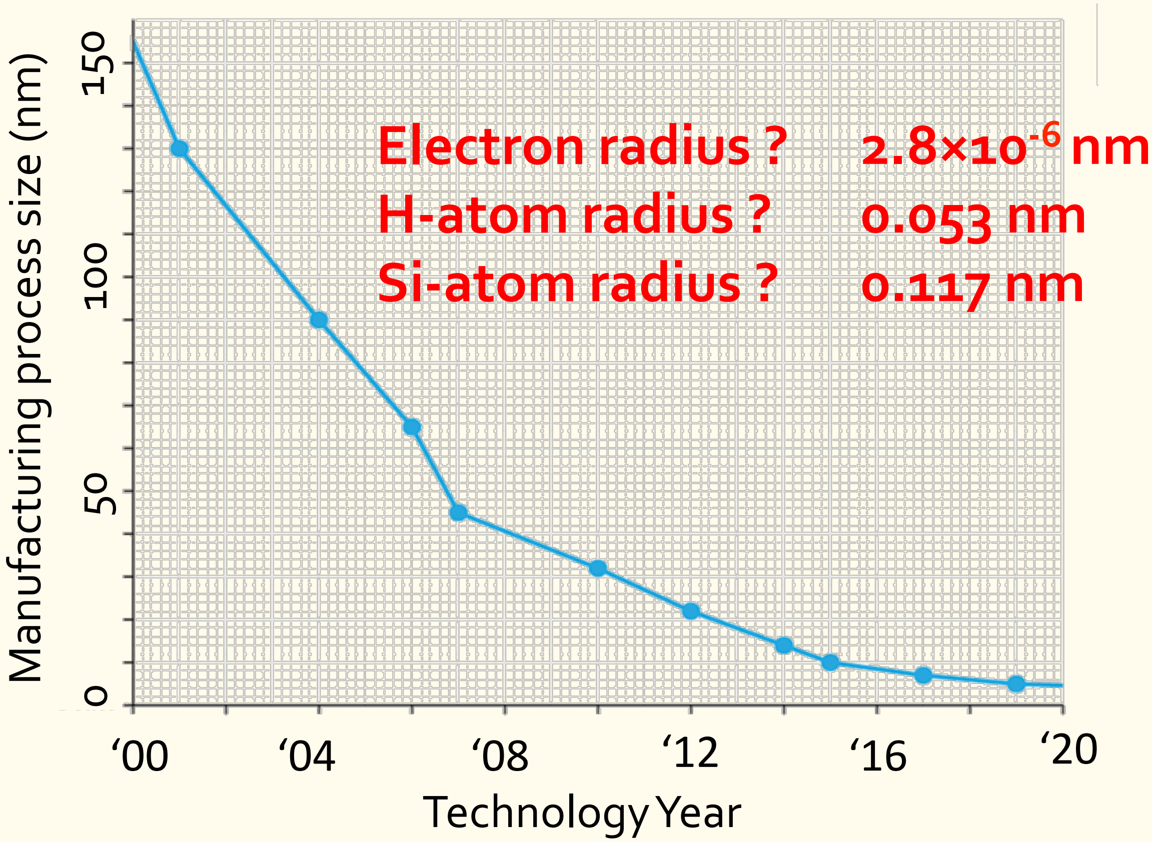
Intel 4004

Intel 286

Pentium 3

Core i7

Technology trends in 21st century



Technology trends in 21st century

New transistors

Field-effect transistors
Tunnel transistors

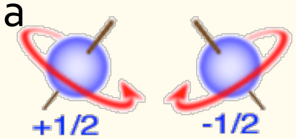
Differentiated products

- Health care
- Energy efficiency
- Consumer entertainment

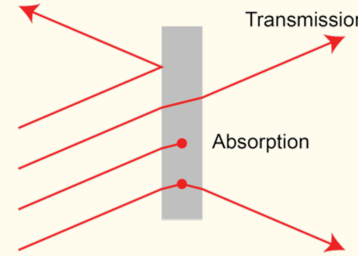
New materials

3D, 2D, 1D

New physical phenomena



Electron spin
light-matter interaction …



System integration

Three-D system on chip
Wireless communication

Technology trends in 21st century

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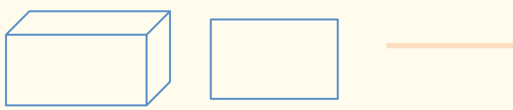
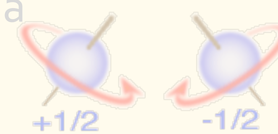
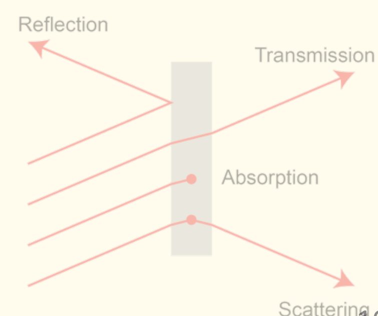


New physical phenomena

Electron spin
light-matter interaction …

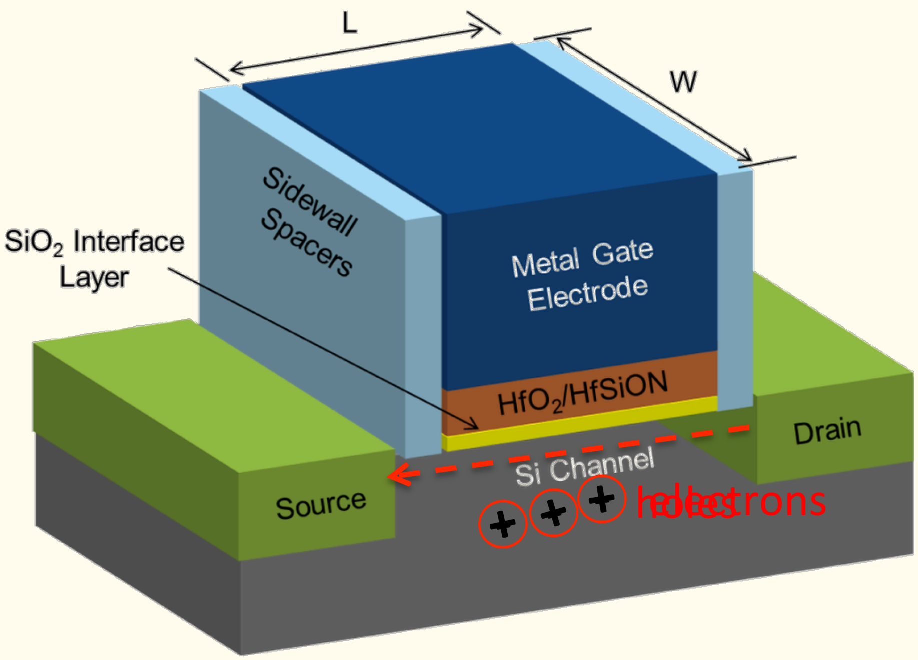




System integration

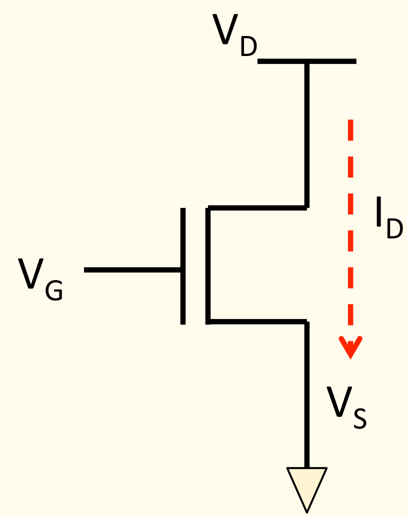
Three-D system on chip
Wireless communication

Basic planar transistor



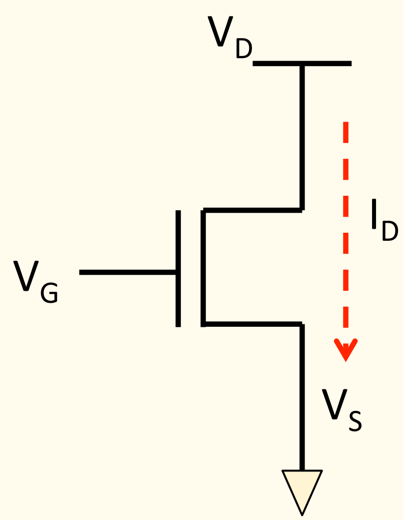
Current between drain and source is carried by either <u>electrons (n-type) or holes (p-type)</u>.

A transistor is essentially a voltage controlled resistor.

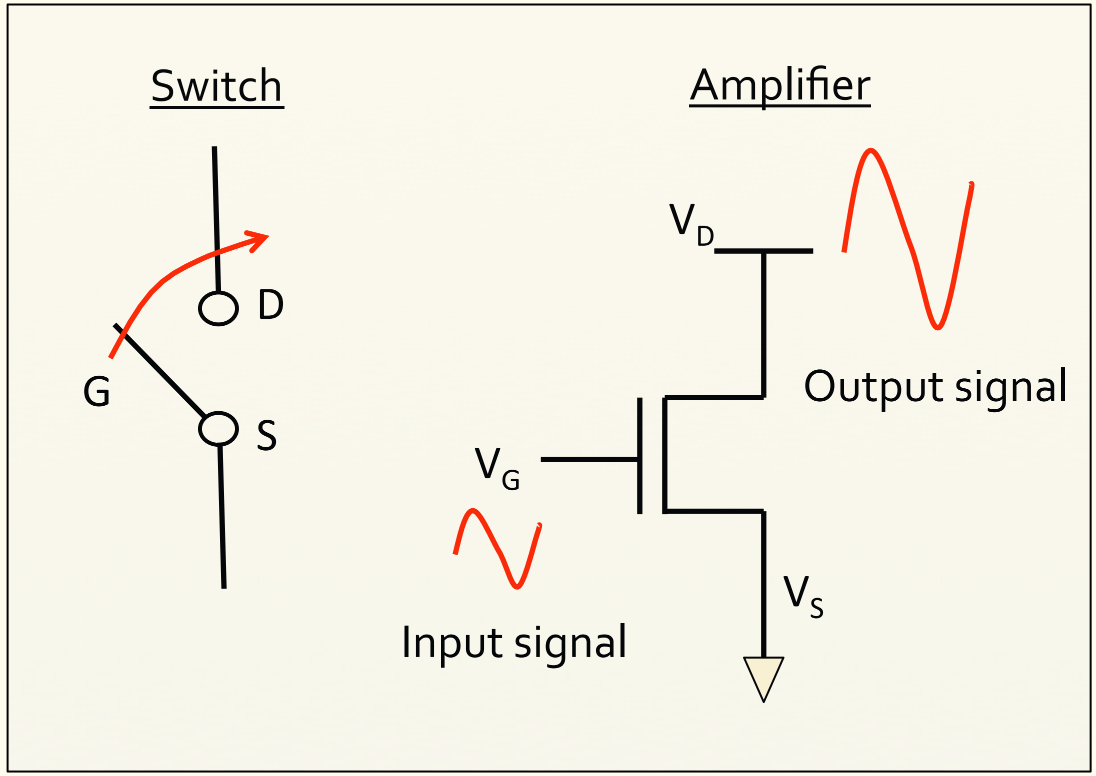


$$\boxed{I_D = f(V_D, V_G, V_S)}$$

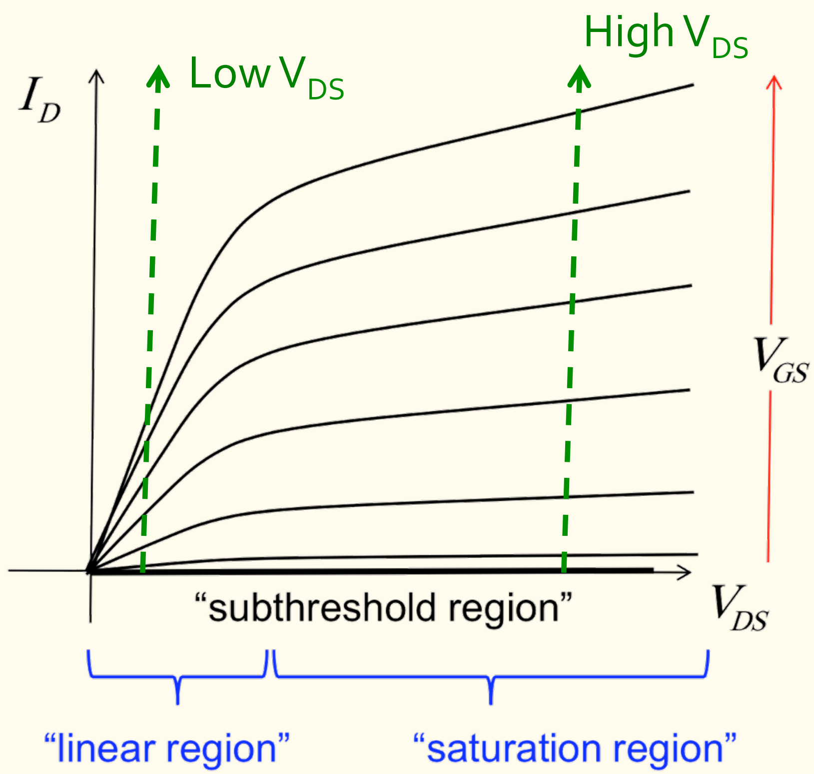
Transistor functionality



$$I_D = f(V_D, V_G, V_S)$$

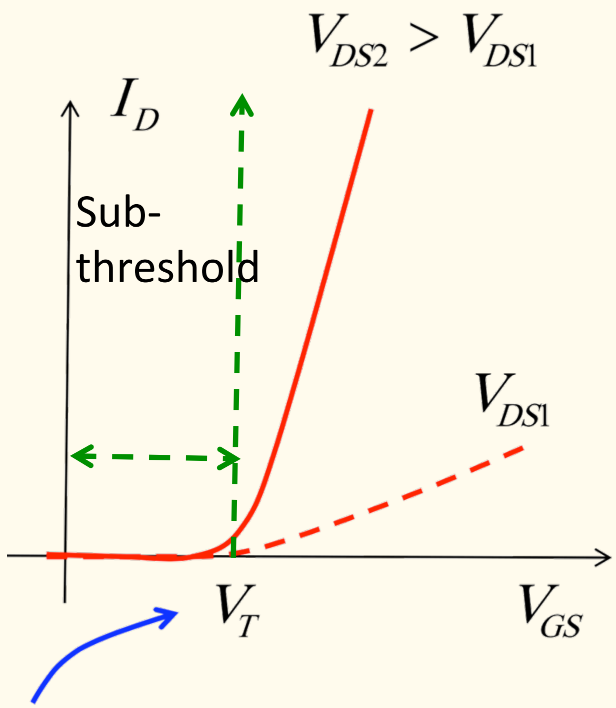


Transistor functionality: output characteristics



- ✓ For low-V_{DS}, transistor behaves as a linear resistor
- ✓ For high-V_{DS}, transistor current is saturated with V_{DS} (current source)

Transistor functionality: <u>transfer characteristics</u>



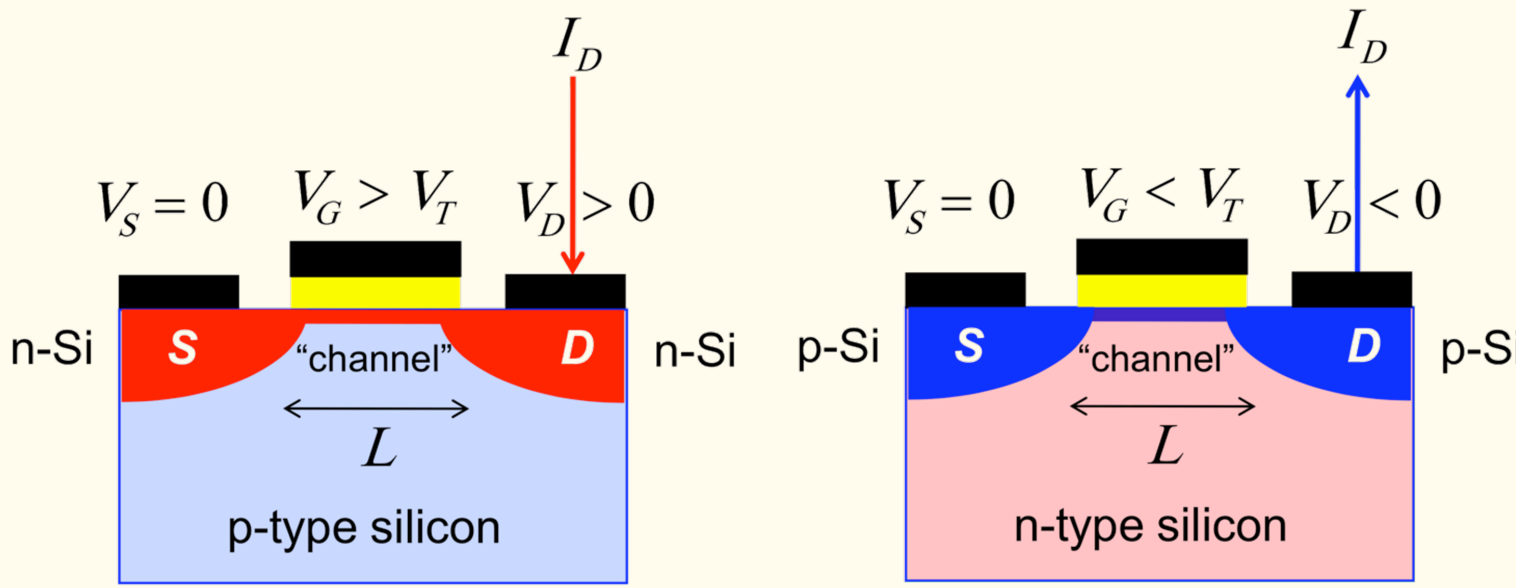
"threshold voltage"

✓ For $V_{GS} > V_T$, we ideally want I_D to be zero for all V_{DS} values.

In reality, I_D is NON-ZERO for $V_{GS} < V_T$ and is also affected by V_{DS}.

This behavior becomes worse as the device length is scaled → short-channel effects

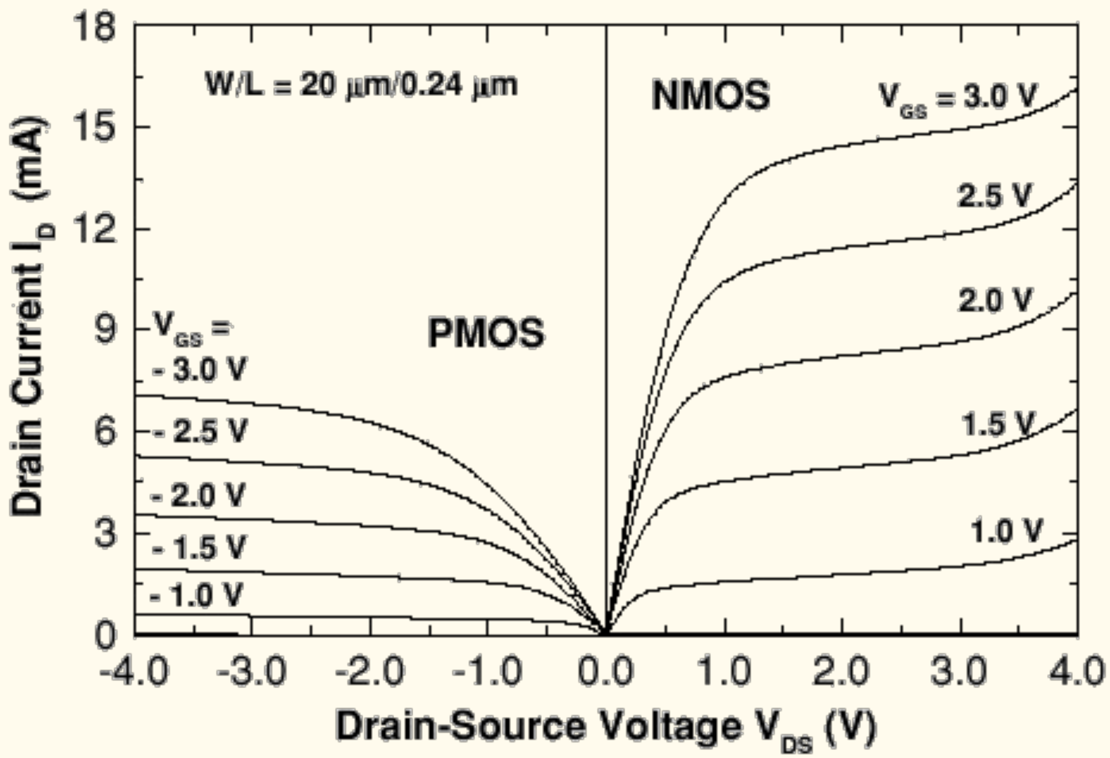
Transistor functionality: <u>complementary devices</u>



Side view

Side view

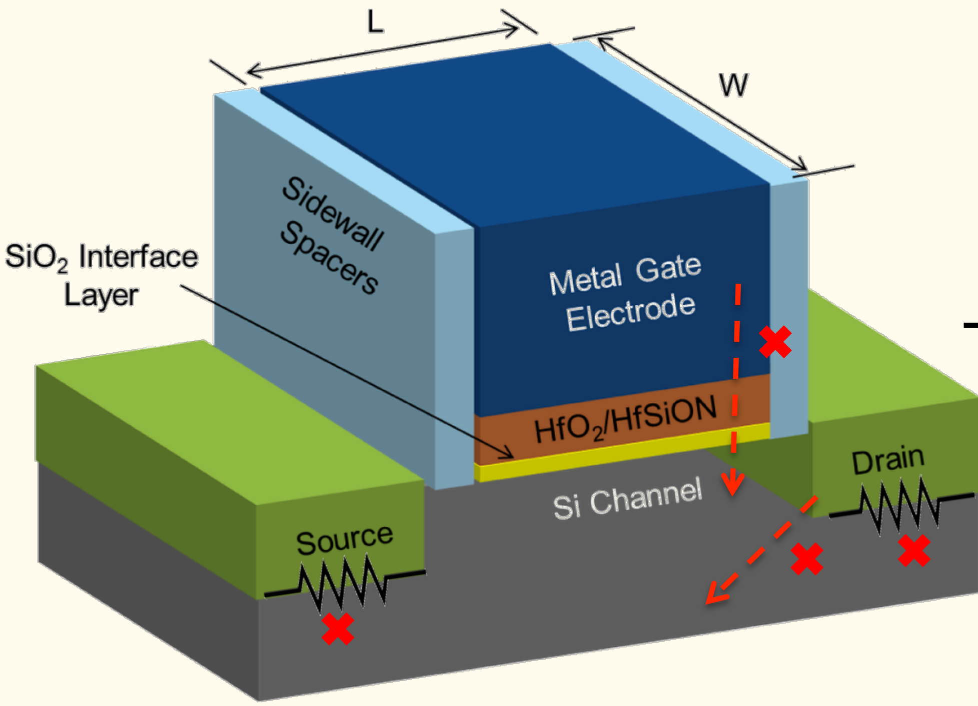
Transistor functionality: <u>complementary devices</u>



(*a*)

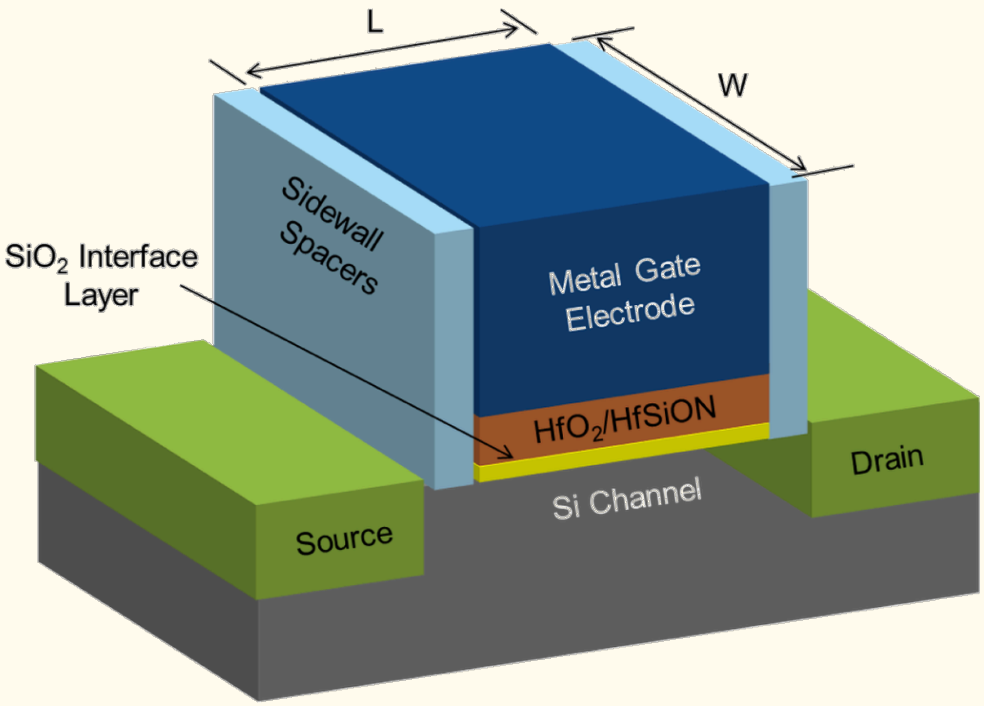
- ✓ For p-type devices, polarity of voltages is reversed compared to n-type
- ✓ More importantly, current of p-type device is lower than that of n-type device.

Goals of transistor design



1. Maximize saturation current
2. No current through the gate and body
3. Reduce current when switch is open
4. Reduce parasitic resistance

Basic planar transistor



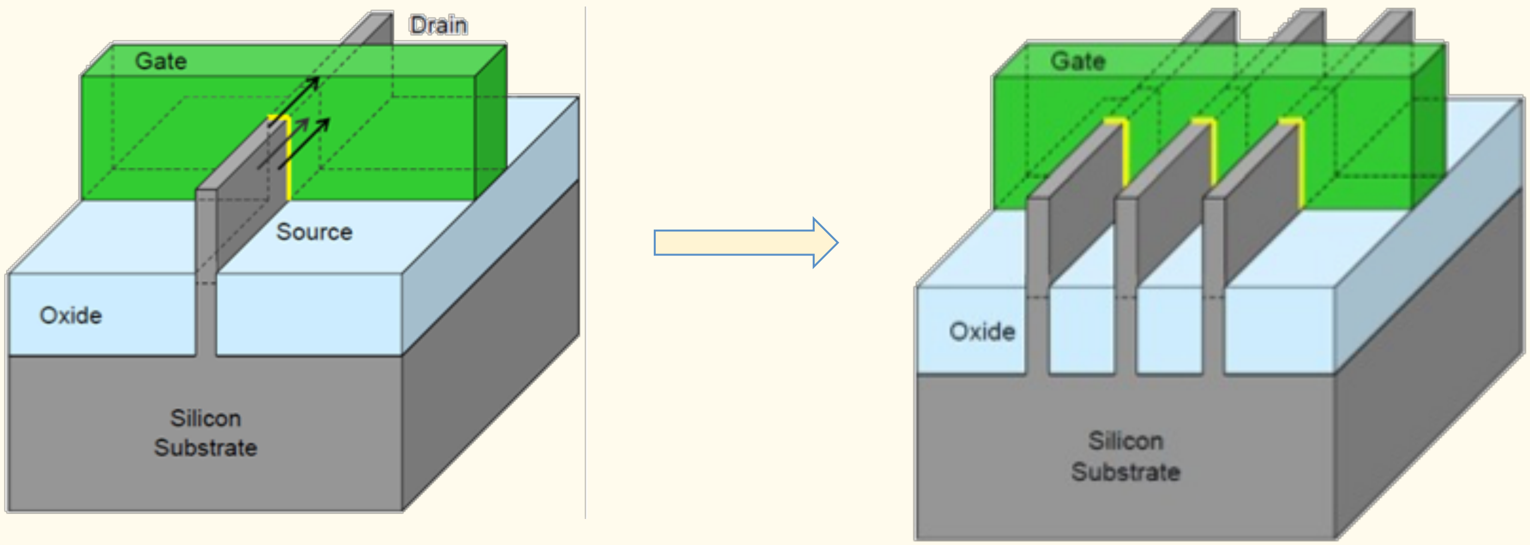
Scaling device length increases saturation current → faster device ☺

But
leakage increases ☹
Power consumption increases ☹
Short-channel effects increase ☹

New transistor ideas ??

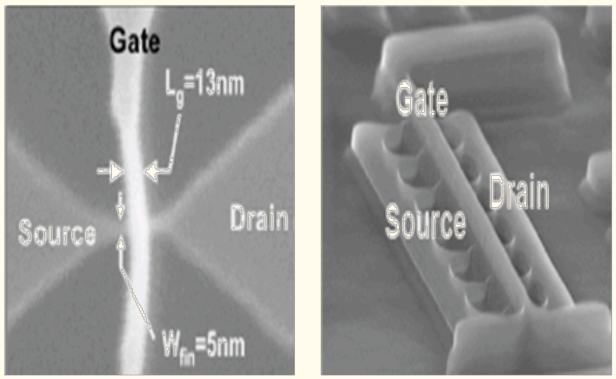
Multi-gate transistors- 1/2

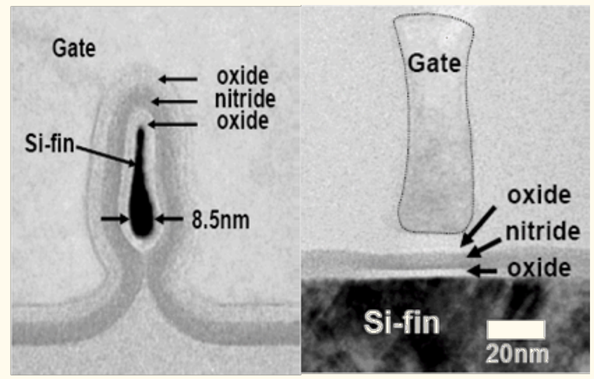
<u>FinFET → improved electrostatics → improved short-channel effects</u>



- ✓ Intel ivy-bridge
- ✓ Intel atom
- ✓ Global foundries, TSMC, AMD, IBM

Multi-gate transistors- 2/2
Scanning Electron Microscope images

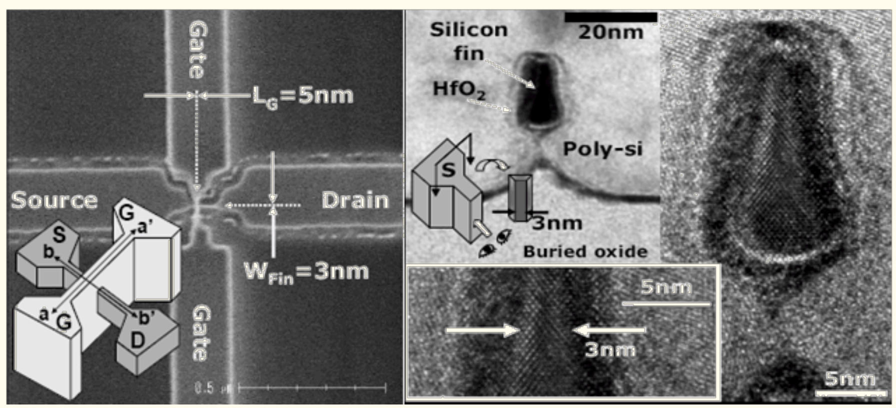




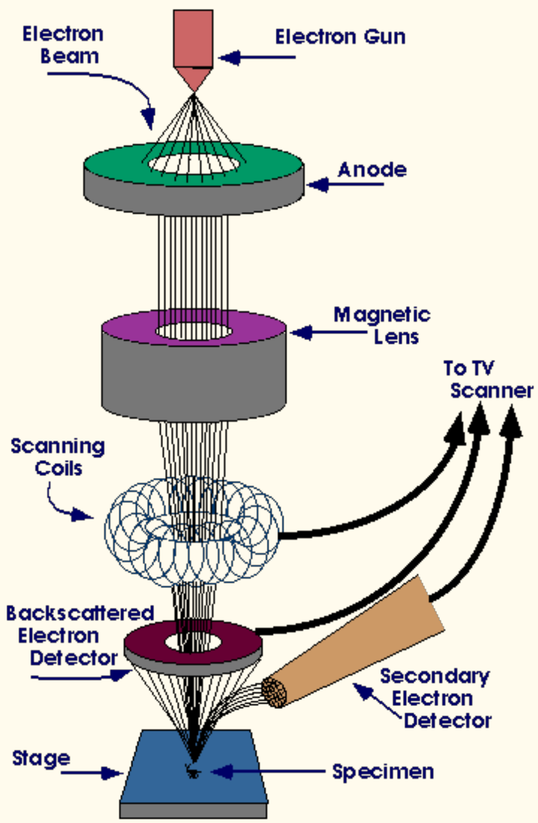
Tri-gate FinFET
(Infineon)

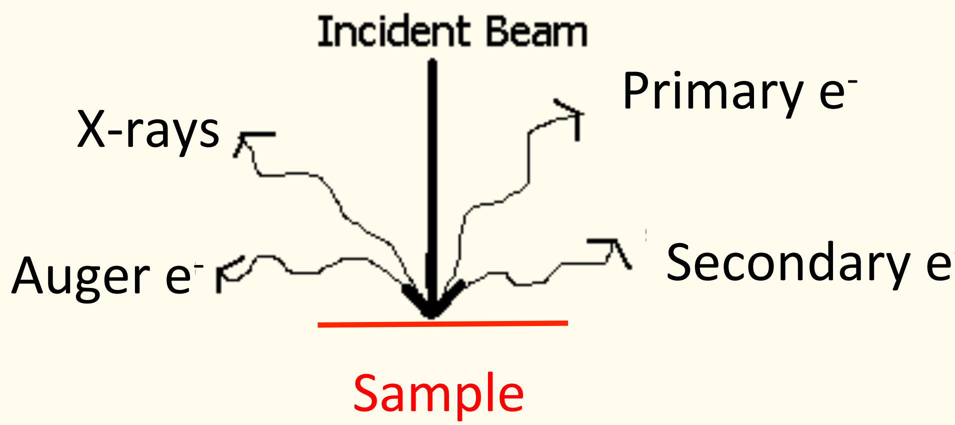
Dual gate FinFET
(Berkeley)

Gate All Around
FinFET
(KAIST)



Scanning electron microscope



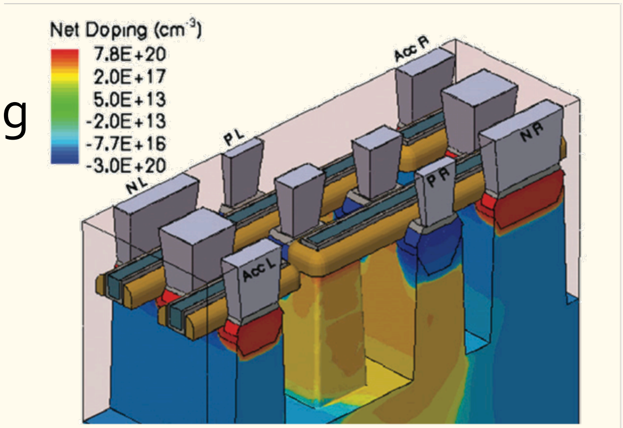


- Vacuum
- Sputter coat non conductive samples with a conductive film

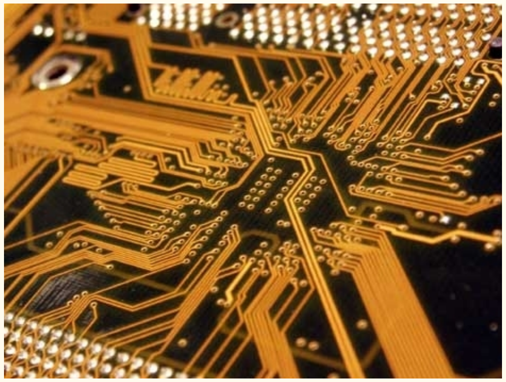
https://www.purdue.edu/ehps/rem/rs/sem.htm

Hot research topics

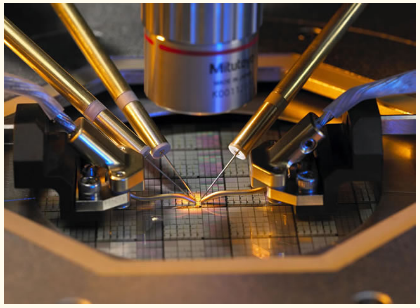
Physical modeling



Circuit design



Device fabrication



On wafer test and measurement

Technology trends in 21st century

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Field-effect transistors
Tunnel transistors

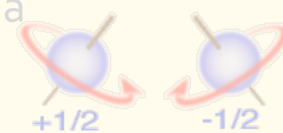
Differentiated products
- Health care
- Energy efficiency
- Consumer entertainment

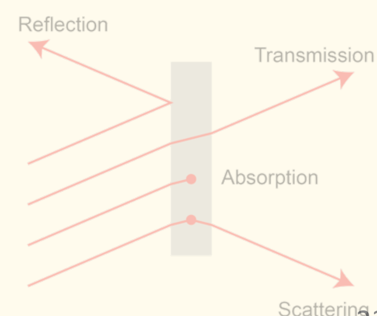
New materials

3D, 2D, 1D

New physical phenomena

Electron spin
light-matter interaction …





System integration

Three-D system on chip
Wireless communication

New materials

Digital electronics is dominated by silicon

- ✓ Availability of both n-type and p-type (CMOS)
- ✓ Mature technology
- ✓ Return on investment for foundries

However, future requirements (high performance, low power, more functionality) would require exploring alternate materials.

Materials beyond silicon

3D materials

- Germanium
- **Silicon-Germanium**
- III-V materials (GaAs, InGaAs, GaN, InGaN, AlN)

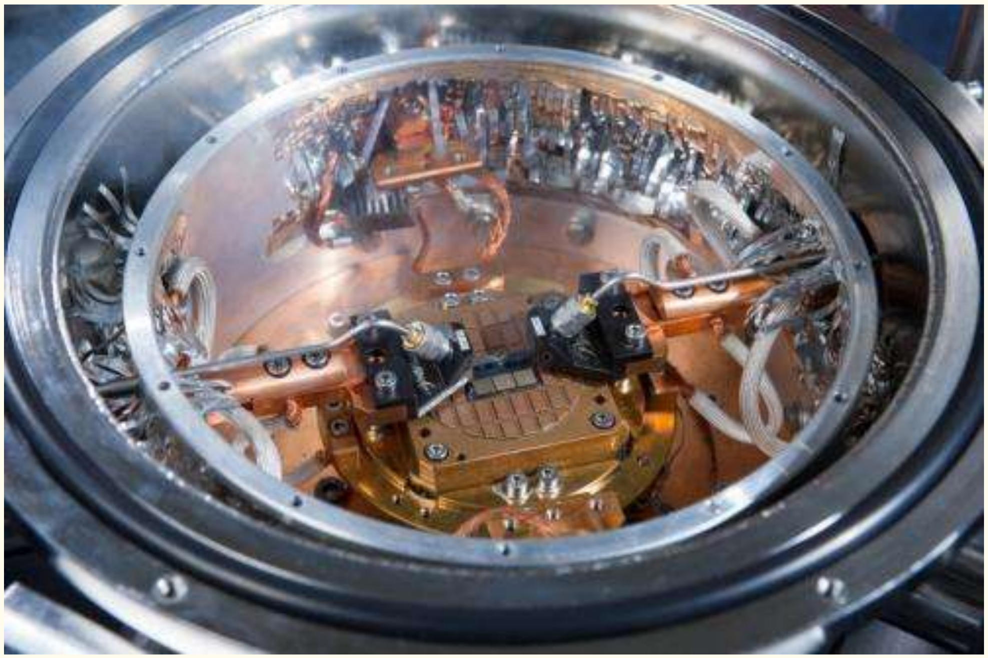
2D materials

- **Graphene**
- Transition metal dichalcogenides (MoS_2, WSe_2)

1D materials

- Carbon nanotubes

Silicon-Germanium

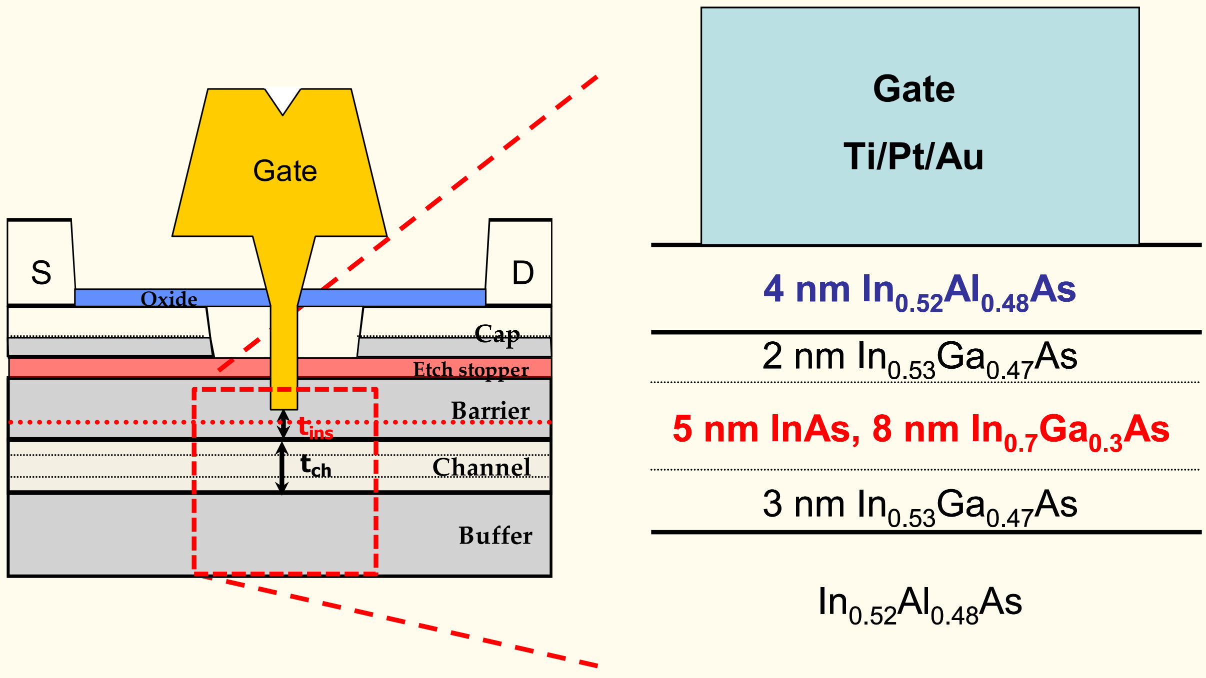


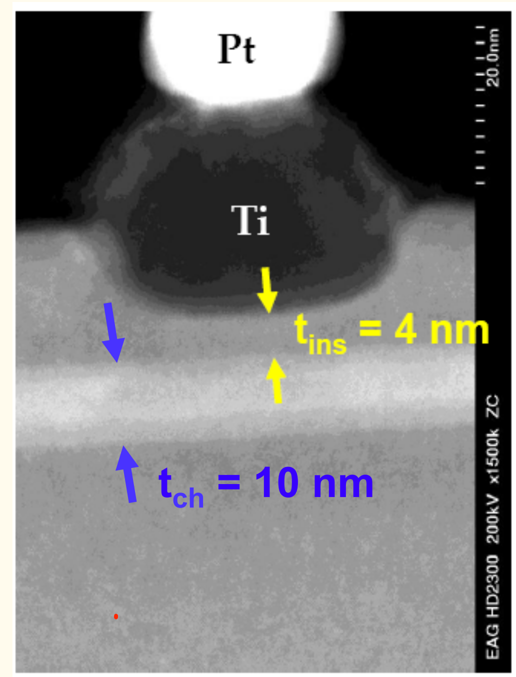
High-speed silicon-germanium chips and measurements probes inside a cryogenic probe station

From: Prof. John Cressler's lab at the Georgia Institute of Technology.

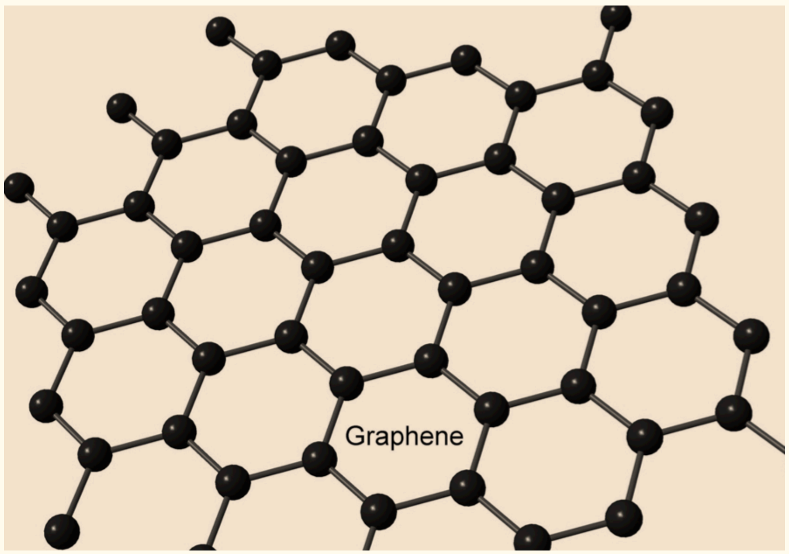
Transistors operate at 800 GHz at cryogenic temp; 400 GHz at 300 K.

III-V materials



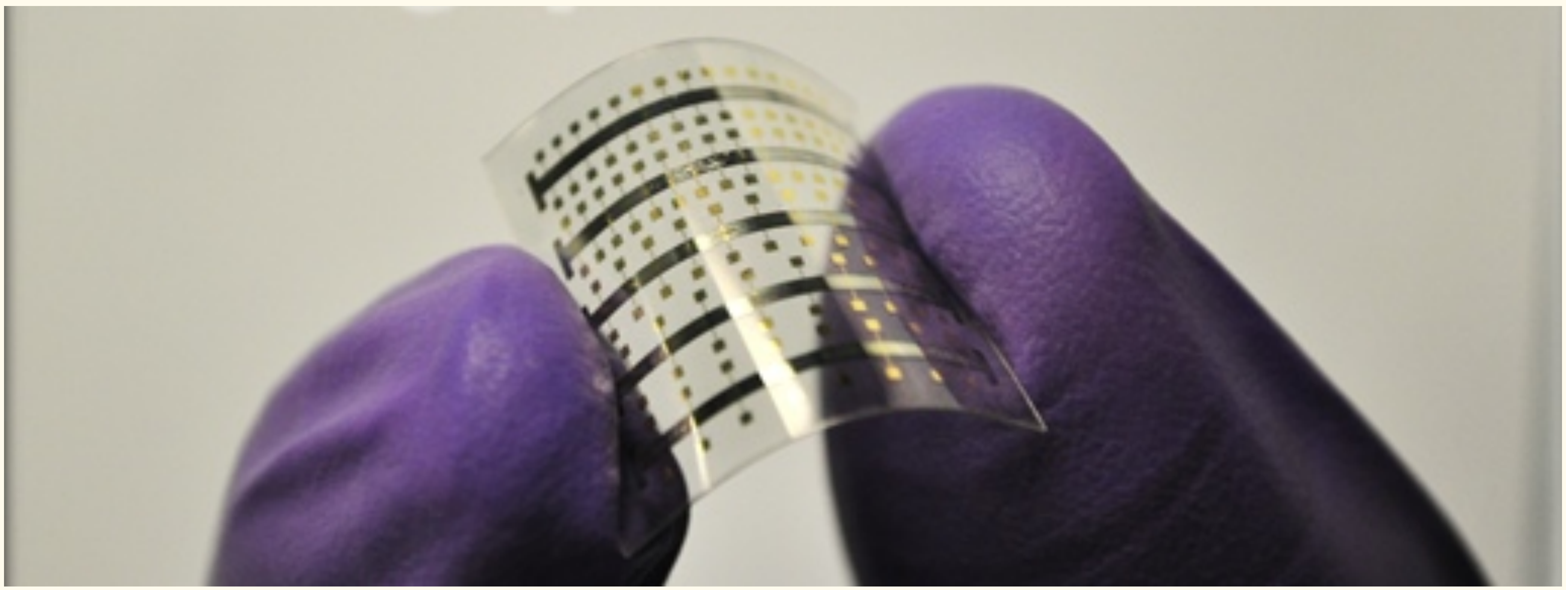


Graphene



- ✓ Graphene is a 2D sheet of carbon atoms arranged in a honeycomb lattice.
- ✓ Pristine 2D graphene has extremely high carrier mobility ~ 120,000 cm^2/Vs.
- ✓ Graphene has opened up an entire realm of 2D materials.

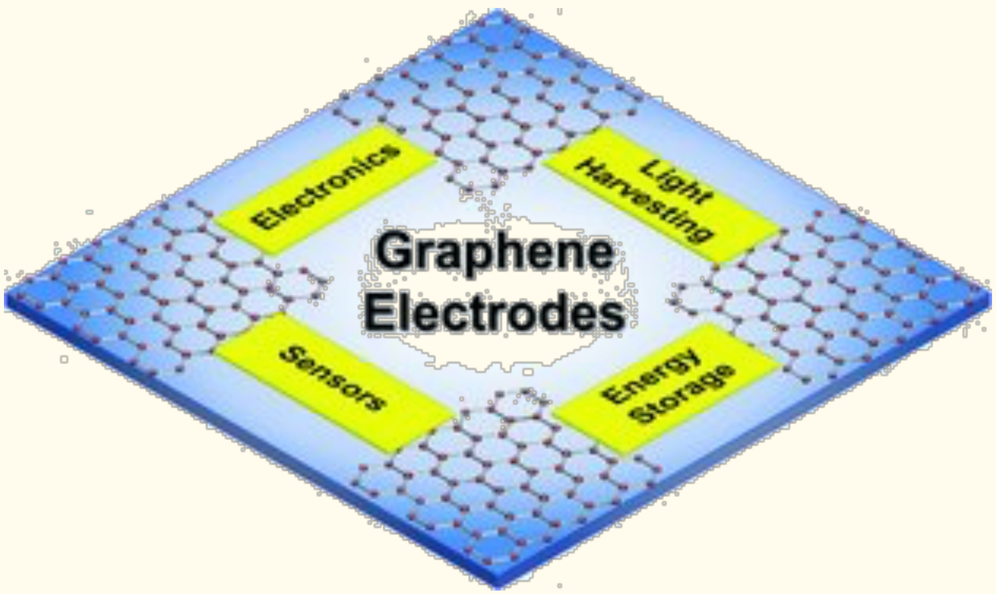
Flexible low power graphene transistors

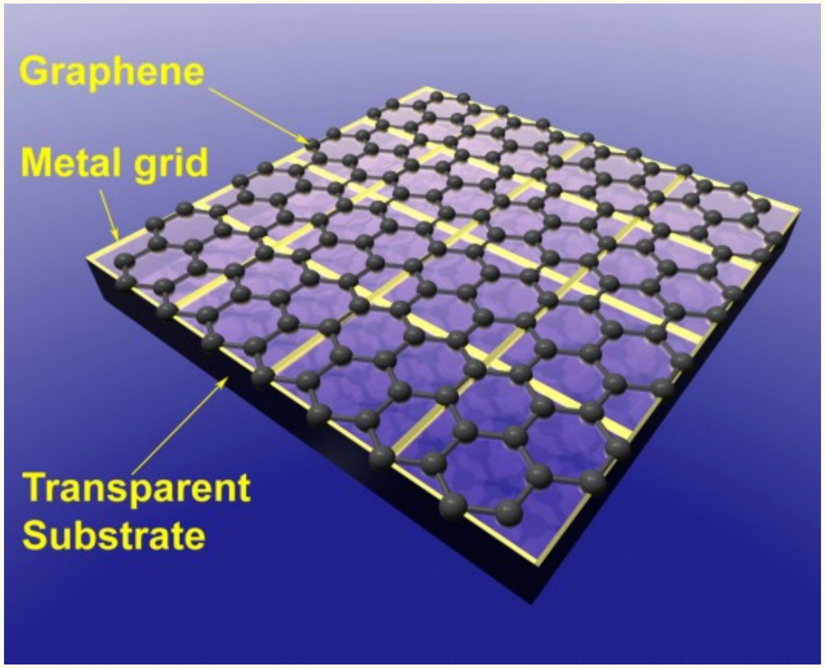


A set of 35 graphene transistors on PET substrate.

Fabricated at Imperial College, London, 2012.

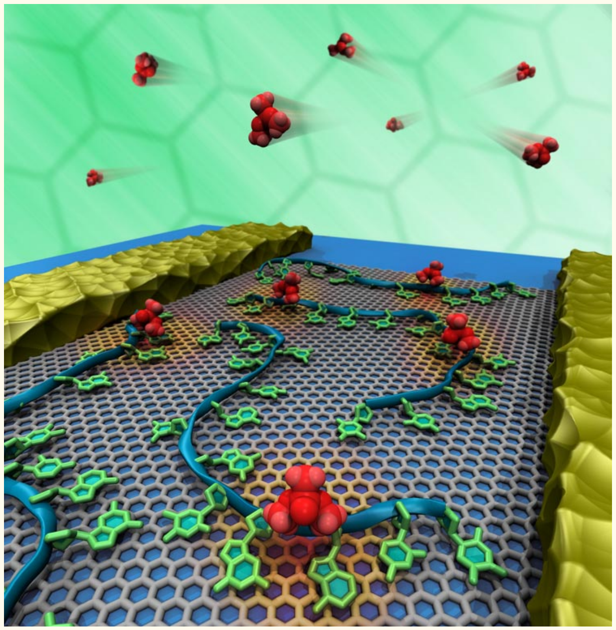
Graphene electrodes





http://www.gizmag.com/transparent-flexible-graphene-based-electrodes/19397/

Graphene sensor



DNA decorated graphene sensor
Physics world, 2010

- ✓ Resistance of graphene changes when DNA/graphene reacts with a chemical.
- ✓ Change in resistance ~ 50%.
- ✓ Fast measurement < 10 seconds.
- ✓ Useful to detect chemical weapons/toxic compounds.

http://physicsworld.com/cws/article/news/2010/aug/31/dna-helps-turn-graphene-into-a-chemical-sensor