Transitioning beyond classical CMOS
Chronicle of a (R)evolution foretold

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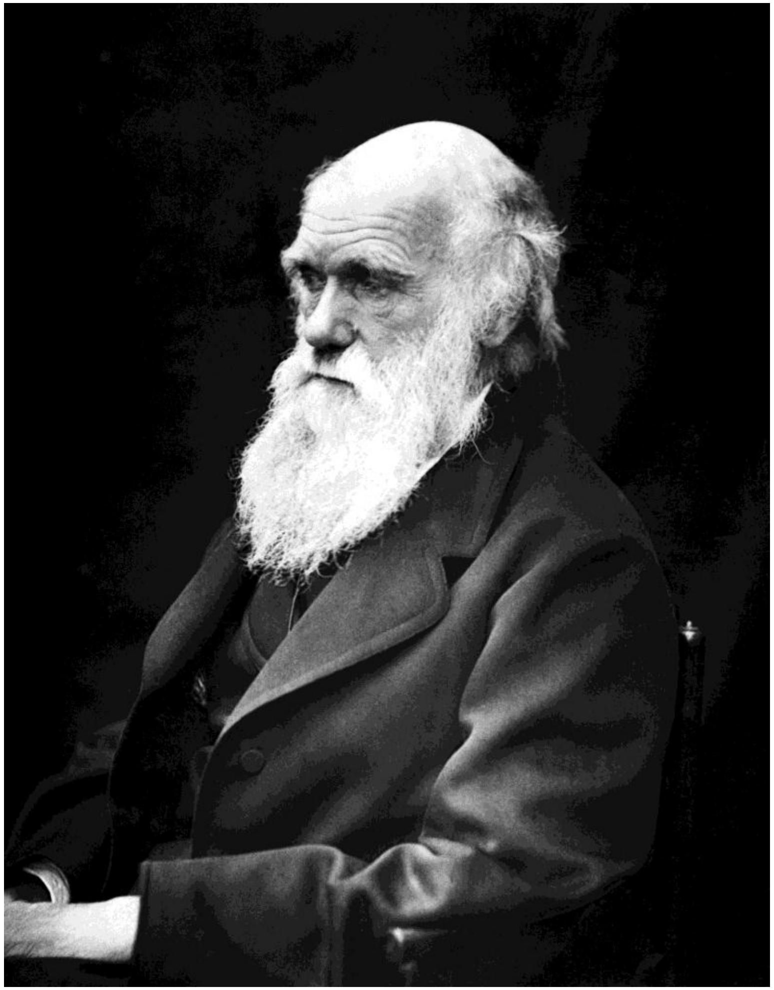
Evolution ...

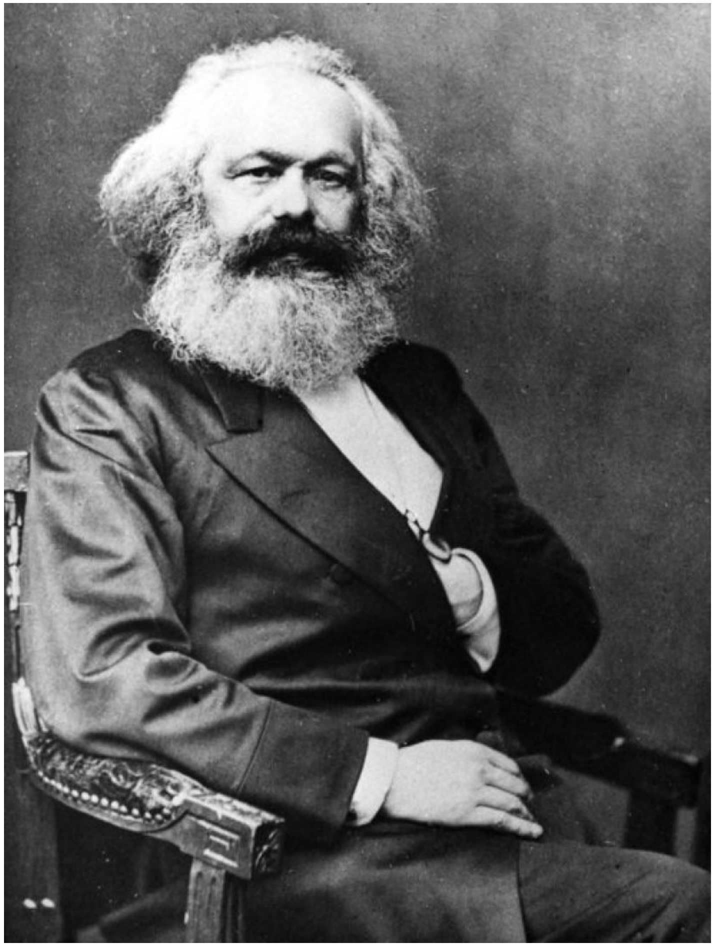
“It is not the strongest of the species that survive nor the most intelligent but the one most responsive to change.”



Charles Robert Darwin
1809 - 1882

On the origin of species (1859)

Or revolution ...



Karl Heinrich Marx
1818 - 1883

“When people speak of ideas that revolutionize society, they do but express the fact that within the old society, the elements of a new one have been created."

Manifesto of the Communist Party (1848)

Questions to be addressed ...

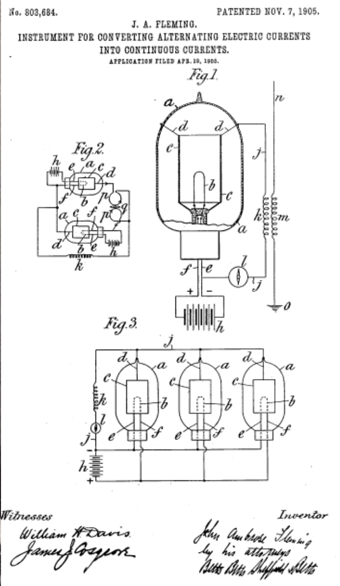
Will the transition be evolutionary or revolutionary ?

- What will the driving forces be ?
- How can simulation lead the way ?
- Could the transition be ‘disruptive’ ?
- Who will be the leaders, winners and losers ?

In order to answer these questions we will engage in some time travel....

History of electronics

Classical physics



No. 803,684. PATENTED NOV. 7, 1905.

J. A. FLEMING.

INSTRUMENT FOR CONVERTING ALTERNATING ELECTRIC CURRENTS INTO CONTINUOUS CURRENTS.

APPLICATION FILED APR. 19, 1905.

Witnesses

William H Davis

Inventor

John Ambrose Fleming
by his attorneys

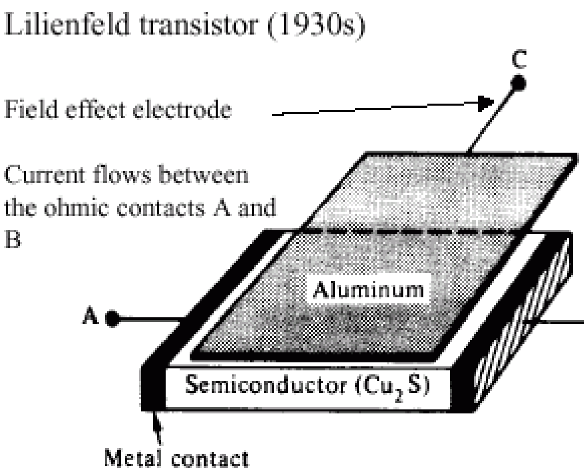
November 16, 1904: Sir John Ambrose Fleming invents and patents the vacuum tube

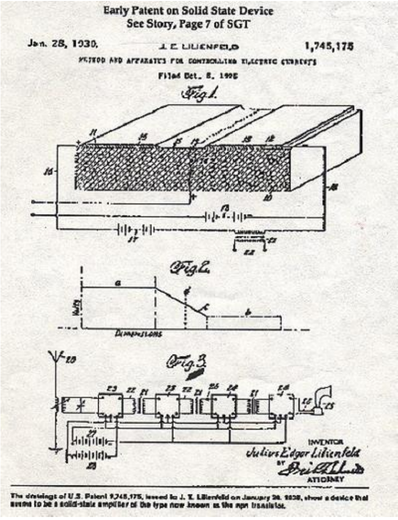
(the US Supreme Court later invalidated his US Patent claiming prior art).

1904

Year 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080

History of electronics





Early Patent on Solid State Device
See Story, Page 7 of SGT

Jan. 28, 1930. J. E. LILIENFELD 1,745,175

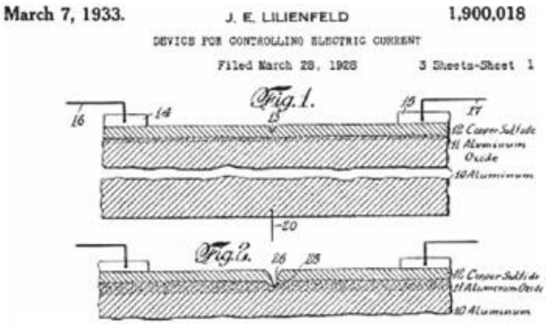
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926

The drawings of U.S. Patent 1,745,175, issued to J. E. Lilienfeld on January 28, 1930, show a device that seems to be a solid-state amplifier of the type now known as the npn transistor.

Classical physics

Solid state physics



March 7, 1933. J. E. LILIENFELD 1,900,018

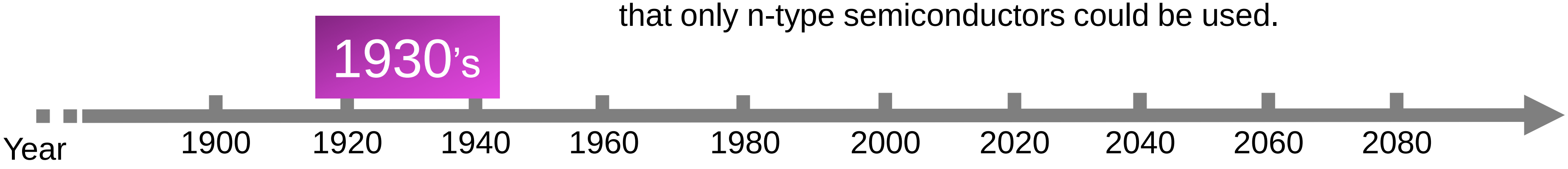
DEVICE FOR CONTROLLING ELECTRIC CURRENT

Filed March 28, 1928 3 Sheets-Sheet 1

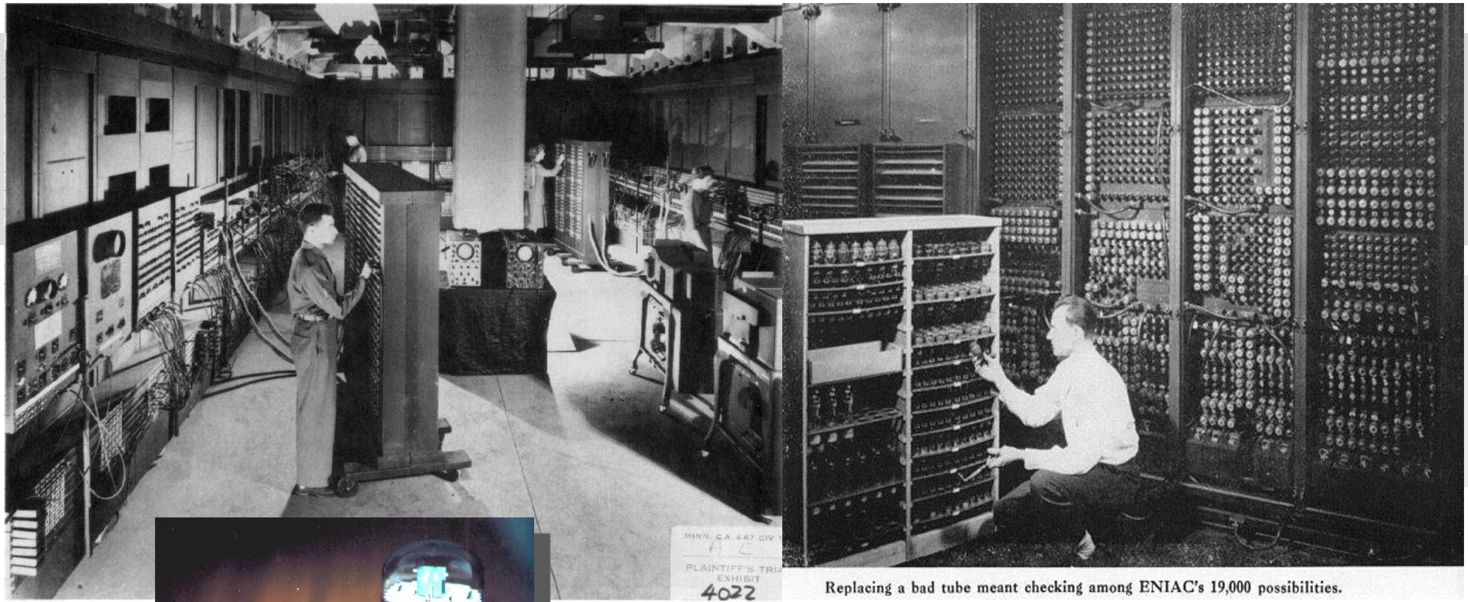
Lilienfeld FET transistor

Lilienfeld could not build FET because of excessive surface states at the interface between the oxide and the semiconductor. Charges were so numerous that current flowed with zero bias.

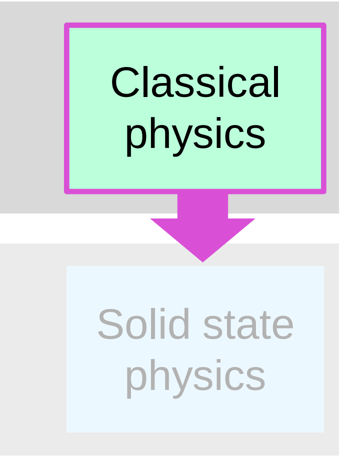
It was only possible to turn OFF the device by driving the carriers deep (now called a “depletion mode” FET). Charges were such that only n-type semiconductors could be used.



History of electronics



Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.


Classical physics

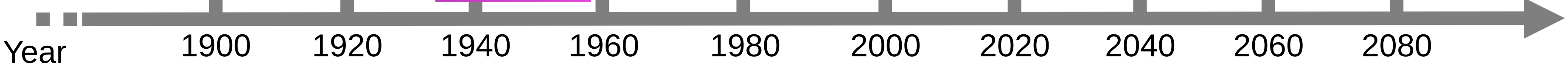
Solid state physics

ENIAC: the first electronic computer

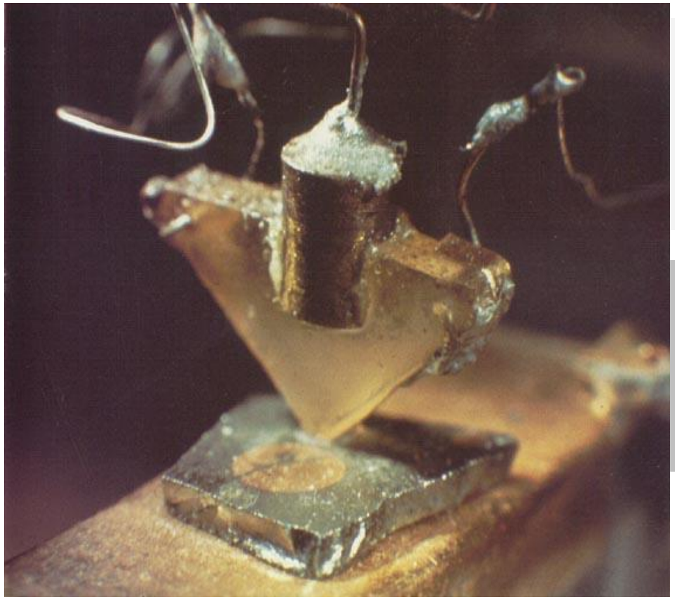
Built by John W. Mauchly (computer architecture) and J. Presper Eckert (circuit engineering), Moore School of Electrical Engineering, University of Pennsylvania. Formed Eckert & Mauchly Computer Co. and built the 2nd computer, “Univac”.

Went bankrupt in 1950.

1946



History of electronics



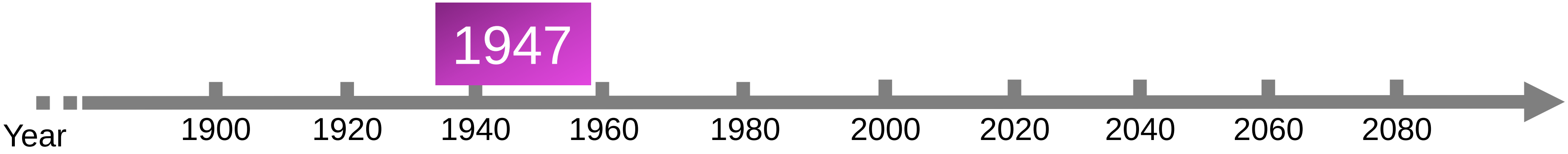
Classical physics

Solid state physics

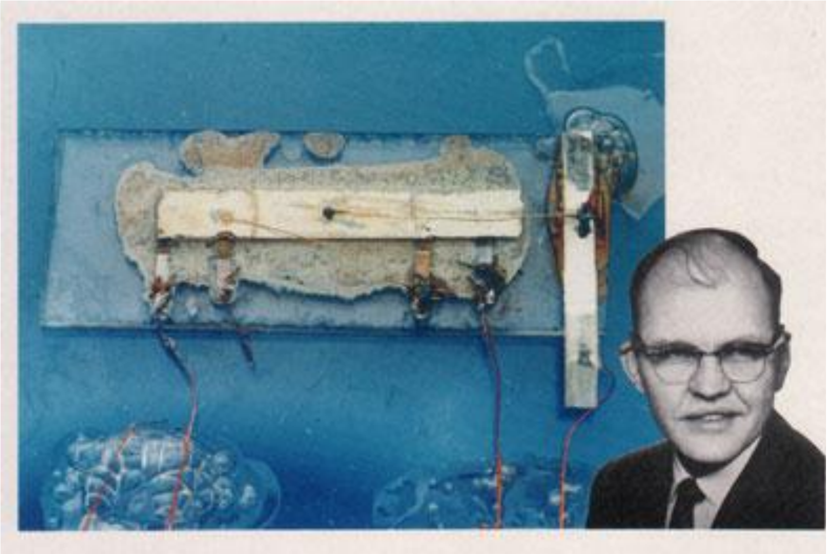
The first transistor was invented at Bell Laboratories on December 16, 1947

by William Shockley, John Bardeen and Walter Brattain.

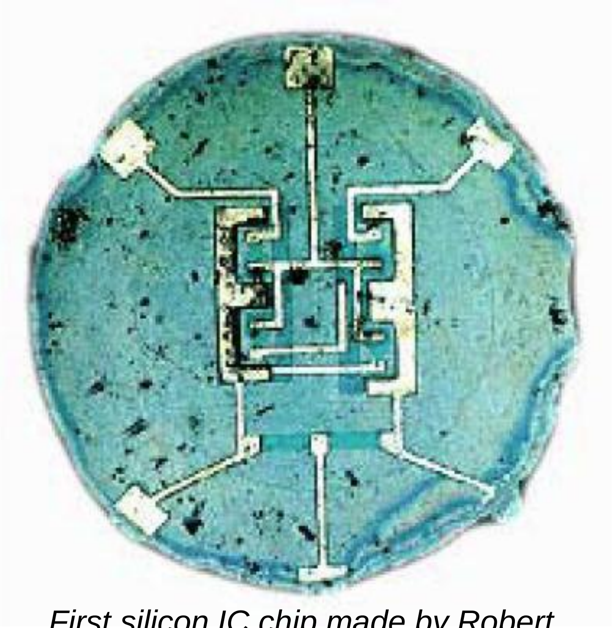
The word "transistor" comes from its ability to regulate and switch current (TRANSfer resISTOR).



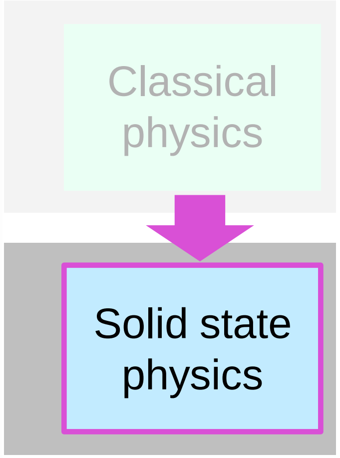
History of electronics



Jack Kilby and first Germanium IC



First silicon IC chip made by Robert Noyce of Fairchild in 1961

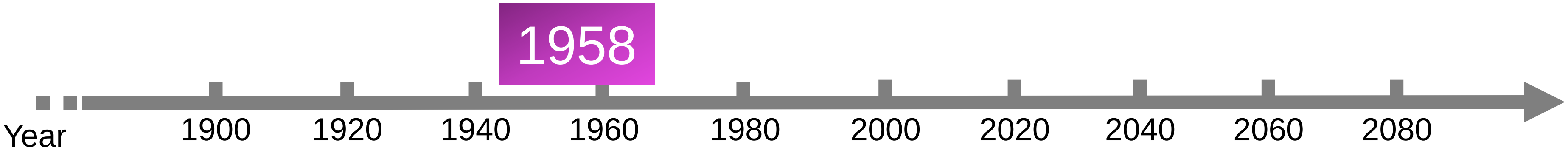


Classical physics

Solid state physics

Invention of the integrated circuit

In 1958 and 1959, Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Camera, came up with a solution to the problem of large numbers of components, and the integrated circuit was developed.

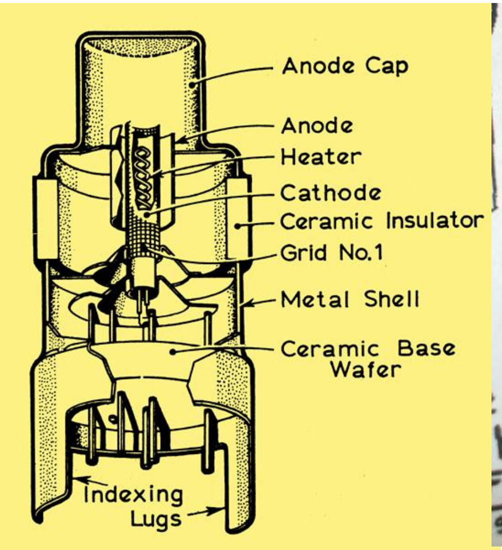


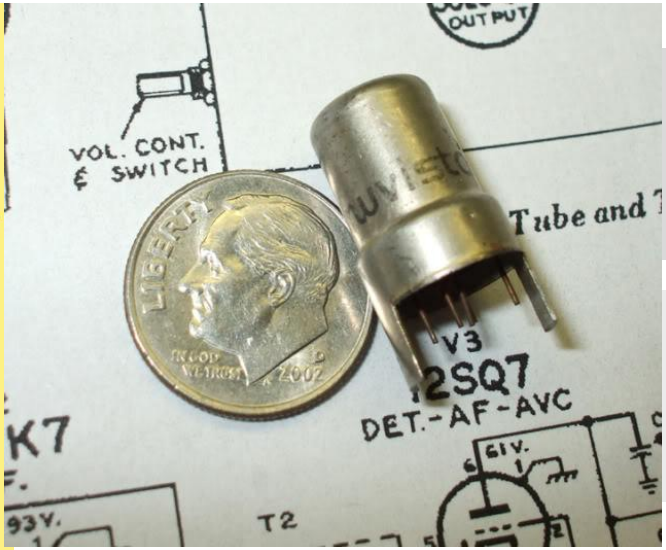
1958

Year

1900 1920 1940 1960 1980 2000 2020 2040 2060 2080

History of electronics





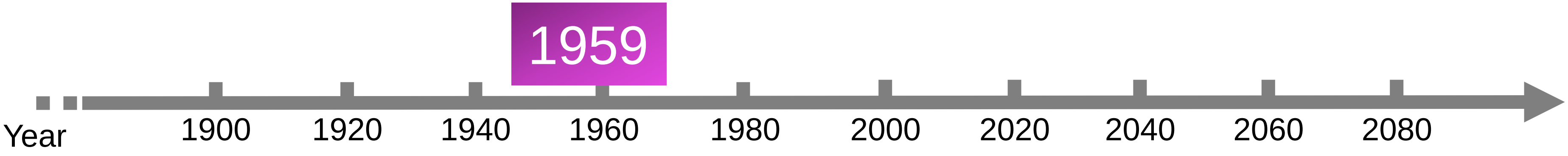
Classical physics

Solid state physics

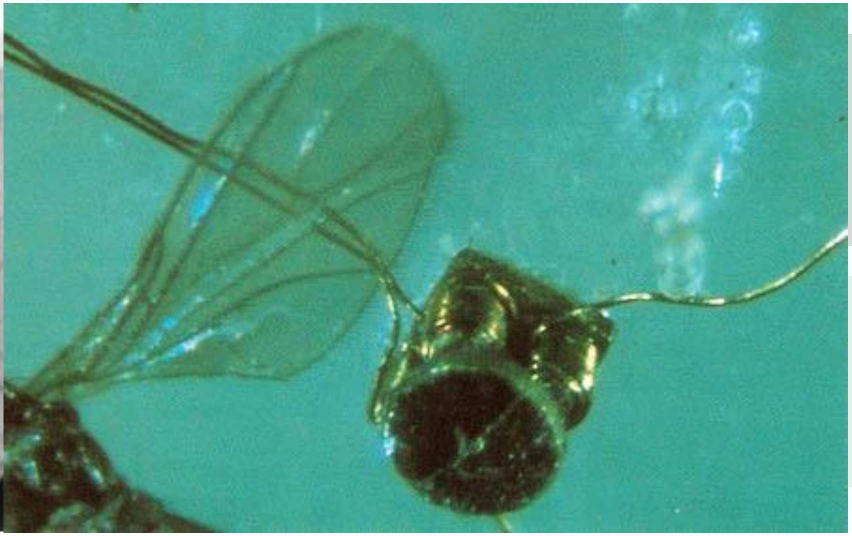
Nuvistors

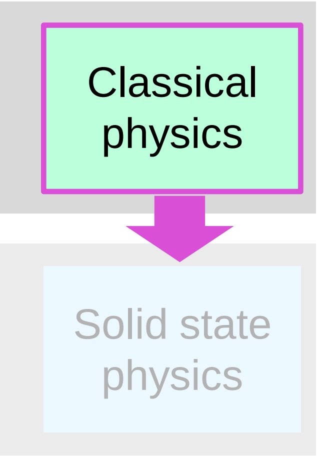
RCA's (1959) introduction of the Nuvistor vacuum tube, heralded one of the attempts of tube manufacturers to hold onto a major portion of the small–signal amplification market.

The Nuvistor is a thimble-sized vacuum tube (enclosed in miniature metal rather than glass) that promised high-reliability, low-noise, and low-power operation.



History of electronics



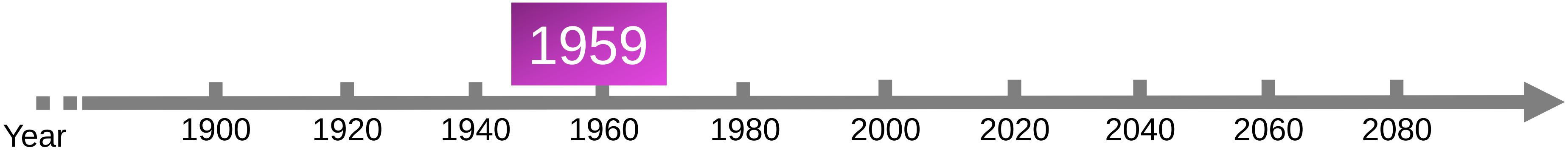


Classical physics

Solid state physics

First nano award

In 1959, when Richard Feynman suggested the possibility of building structures one atom or molecule at a time, the idea seemed fantastic. Feynman offered a $1,000 prize to the first person who could make a working electric motor that would fit inside a cube that measured 1/64 of an inch on each side. He guessed it would be a long time before he had to pay up. But just two and a half months later, William McLellan, a physicist at the University of California Institute of Science and Technology, claimed the prize. Working on his lunch breaks with a microscope, toothpick, and watchmaker's lathe, McLellan assembled a motor that met Feynman's requirements.



1959

Year 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080

History of electronics

IBM-PC Model 5100 (1975)

IBM-PC Model 5150 (1981)

Classical physics

Solid state physics

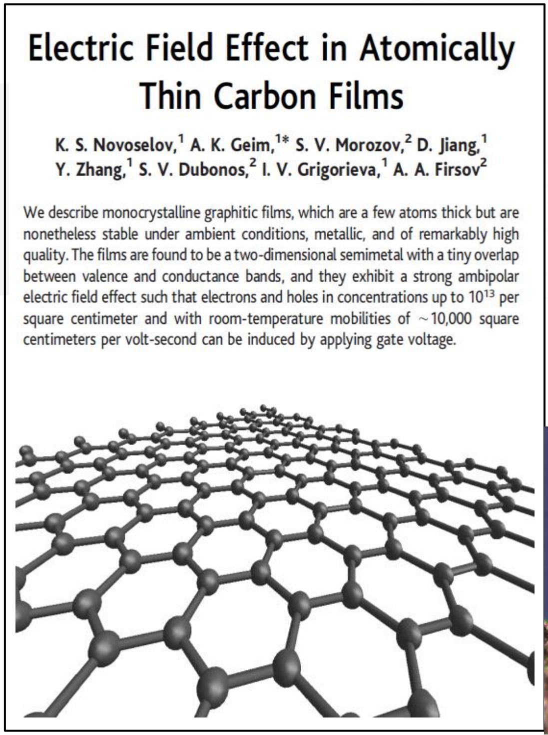
Release of the first IBM PC in 1975

The Model 5100 used a proprietary IBM processor called the PALM (for Put All Logic in Microcode). The 5100 shipped with 16K to 64K of memory, used a tape drive for program storage, and depending on configuration the machine sold for $8,975 to $19,975.

1975

Year 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080

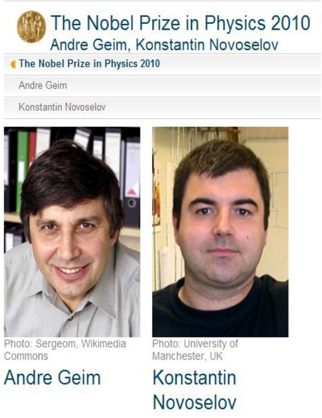
History of electronics



Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1*] S. V. Morozov,[2] D. Jiang,[1]
Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect such that electrons and holes in concentrations up to 10^{13} per square centimeter and with room-temperature mobilities of ~10,000 square centimeters per volt-second can be induced by applying gate voltage.

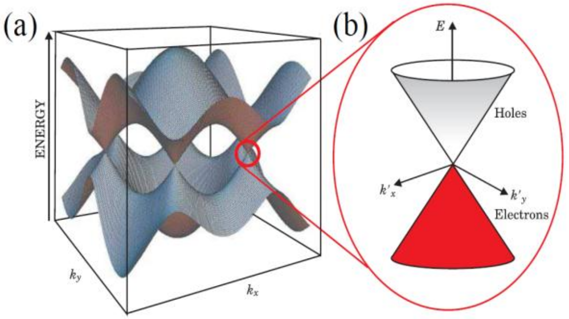


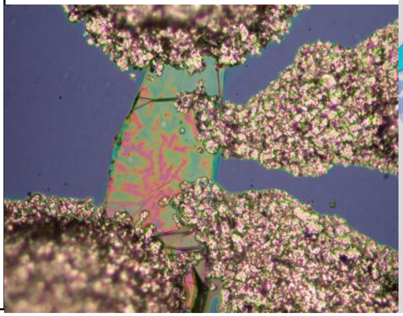
The Nobel Prize in Physics 2010
Andre Geim, Konstantin Novoselov

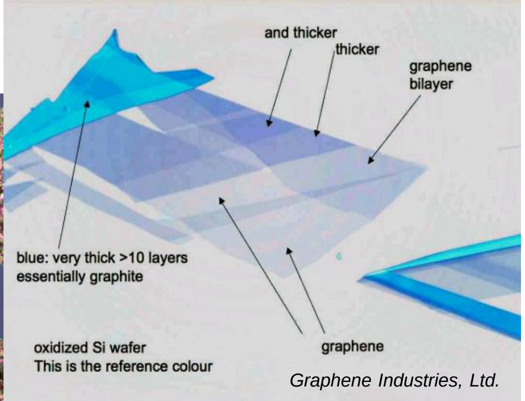
The Nobel Prize in Physics 2010
Andre Geim
Konstantin Novoselov

Photo: Sergeom, Wikimedia Commons
Andre Geim

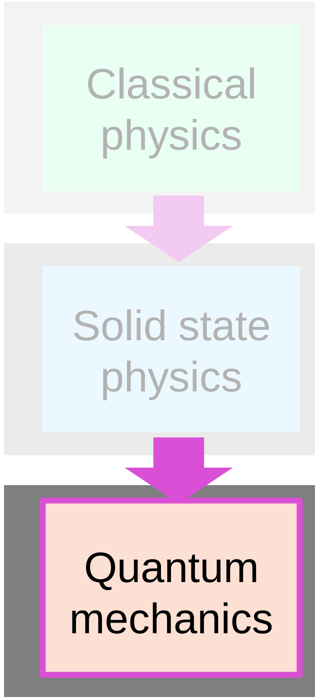
Photo: University of Manchester, UK
Konstantin Novoselov







Graphene Industries, Ltd.



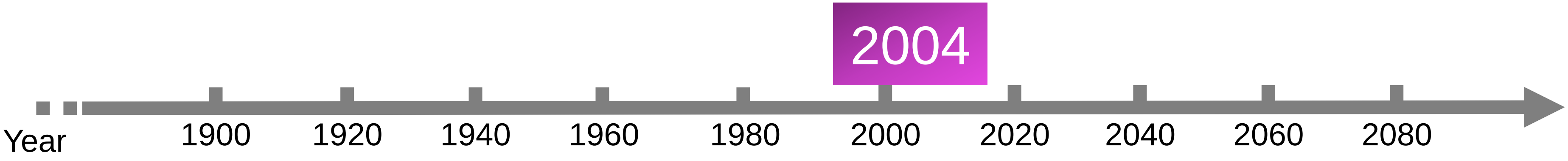
Classical physics

Solid state physics

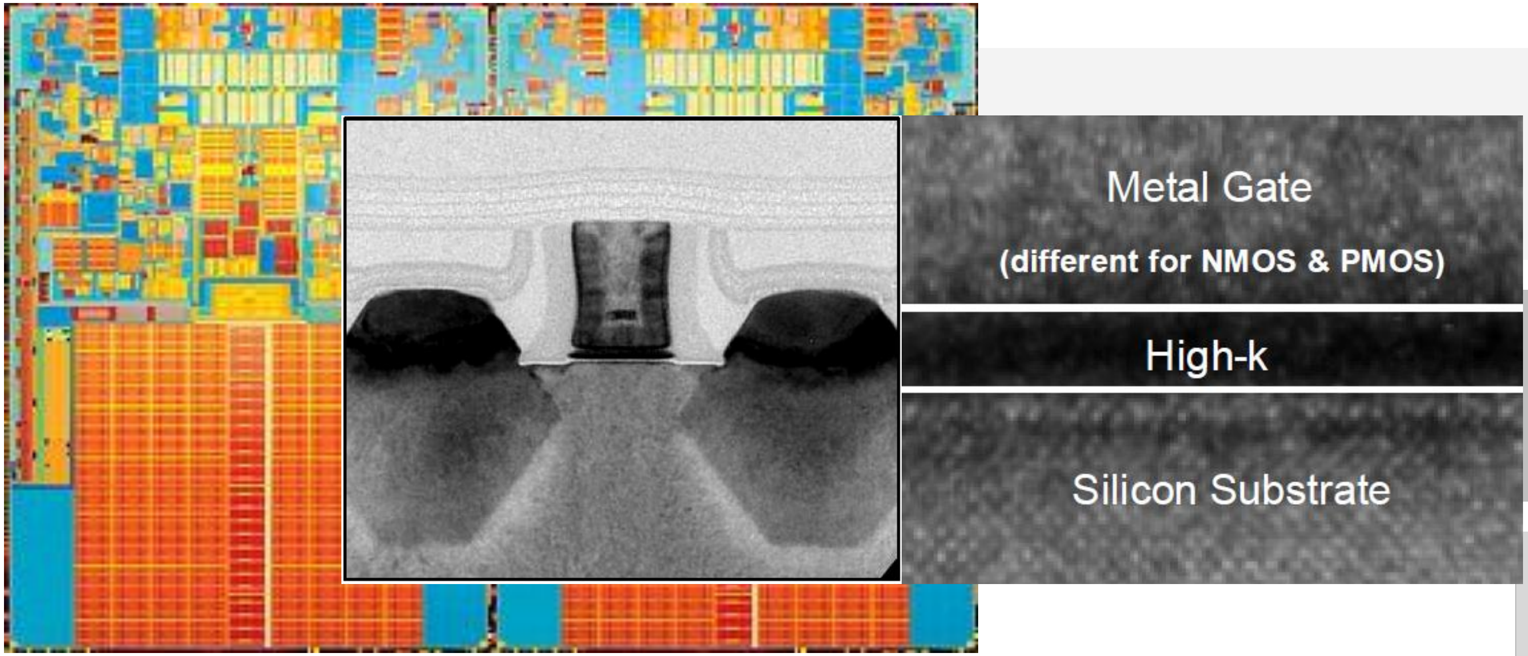
Quantum mechanics

“Discovery” of graphene.....

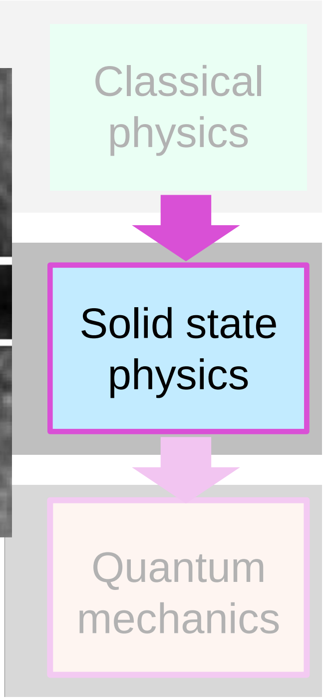
The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov “for groundbreaking experiments regarding the two-dimensional material graphene”



History of electronics



Core 2 Quad processor, ~8x10^8 transistors



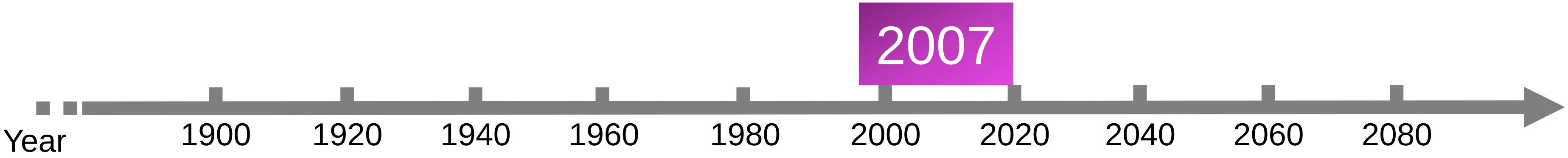
Classical physics

Solid state physics

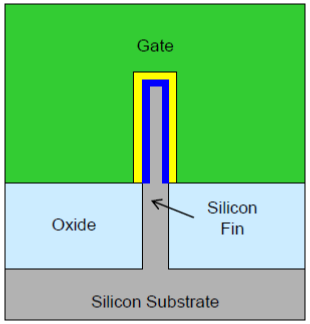
Quantum mechanics

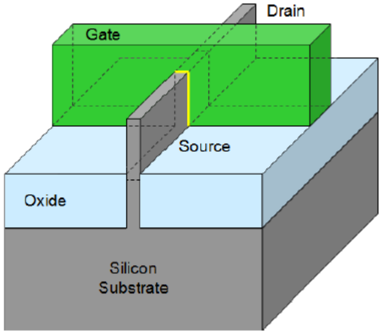
Introduction of high-k/metal gates by INTEL

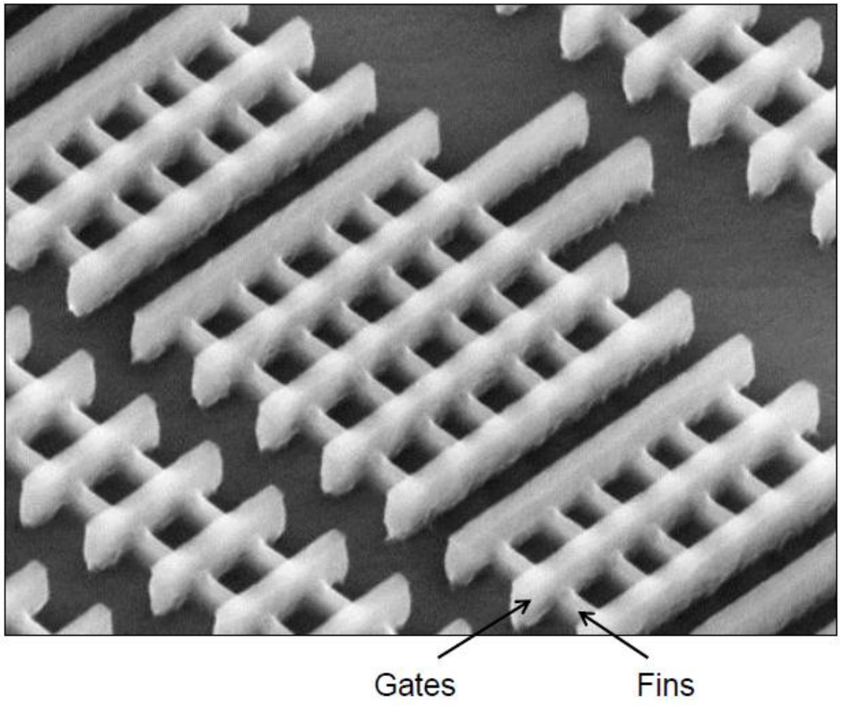
Intel processors (45 nm technology node) integrate high-*k*/metal gates stacks, allowing improved performances and reduced power consumption.



State-of-the art







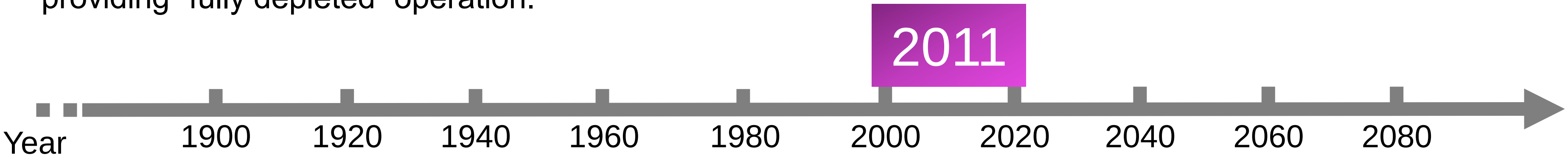
Classical physics

Solid state physics

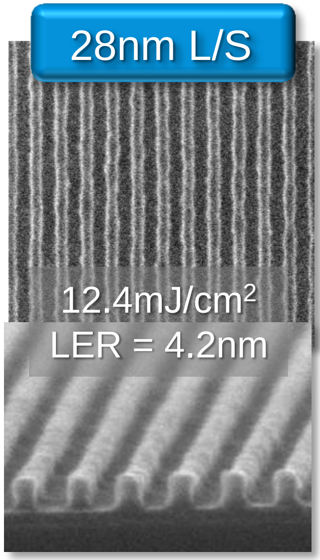
Quantum mechanics

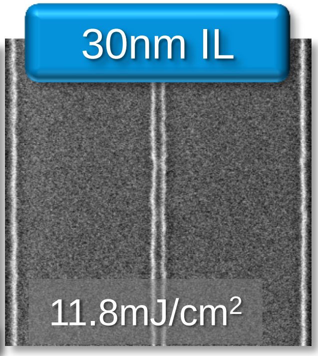
INTEL introduces FinFETs in the 22 nm technology

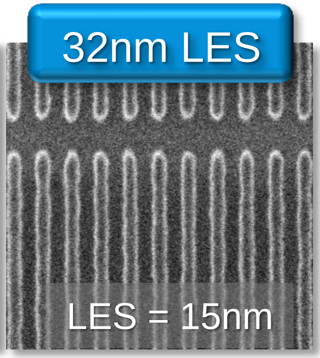
3-D Tri-Gate transistors form conducting channels on three sides of a vertical fin structure, providing “fully depleted” operation.

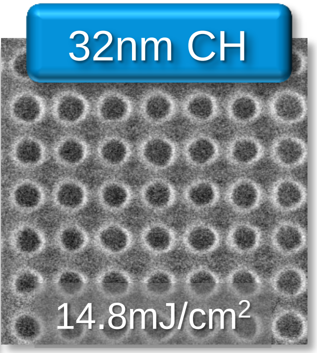


State-of-the art: EUV litho performance

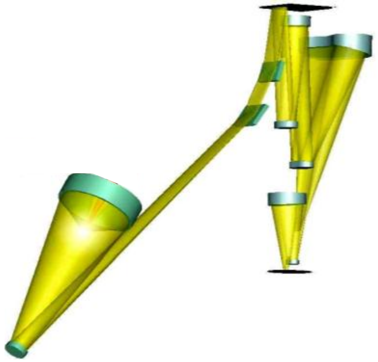


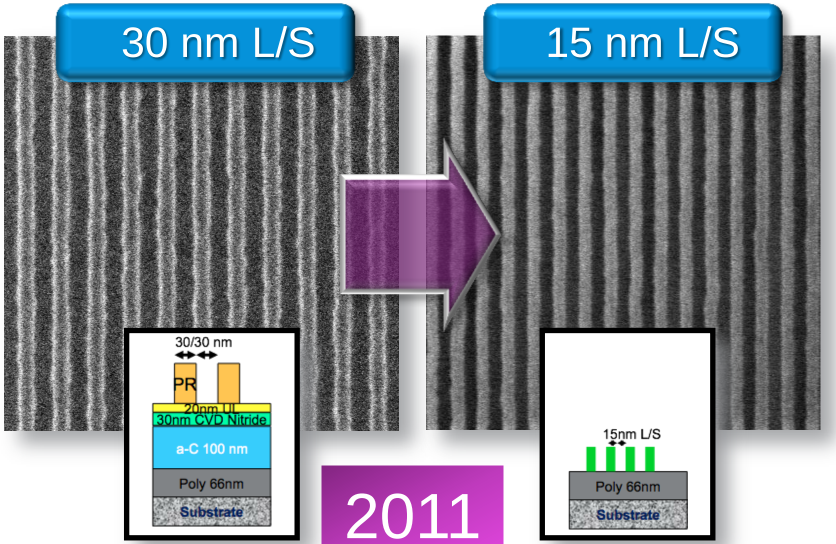






Local CDU: 1.2nm

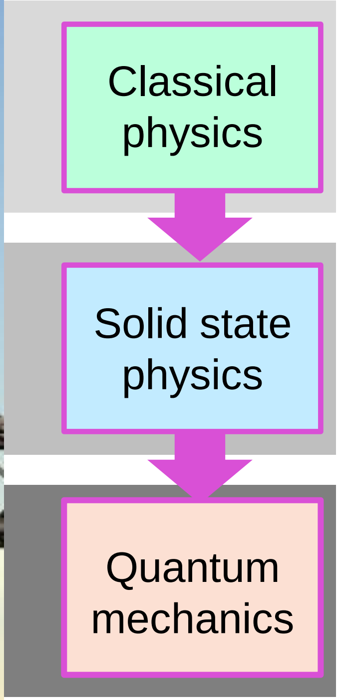




2011

EUV extendability: self-aligned double patterning

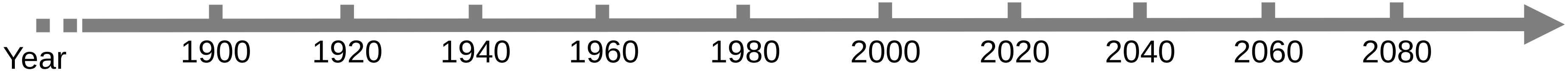
Year 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080



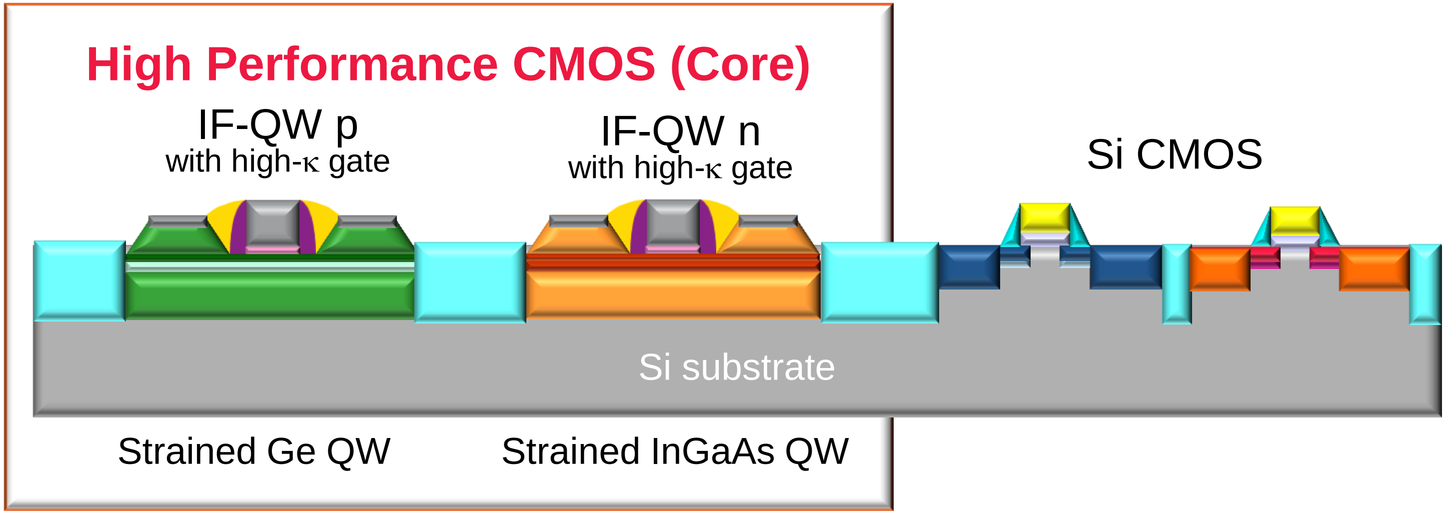
Classical physics

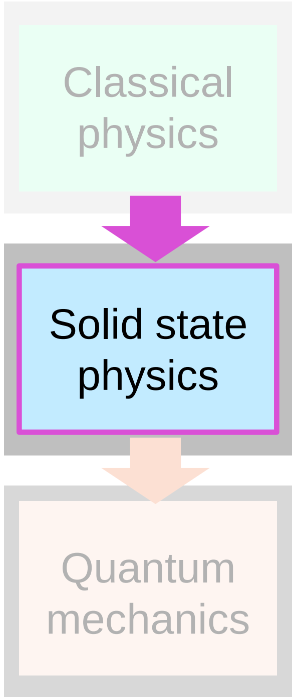
Solid state physics

Quantum mechanics



A look into the future.....



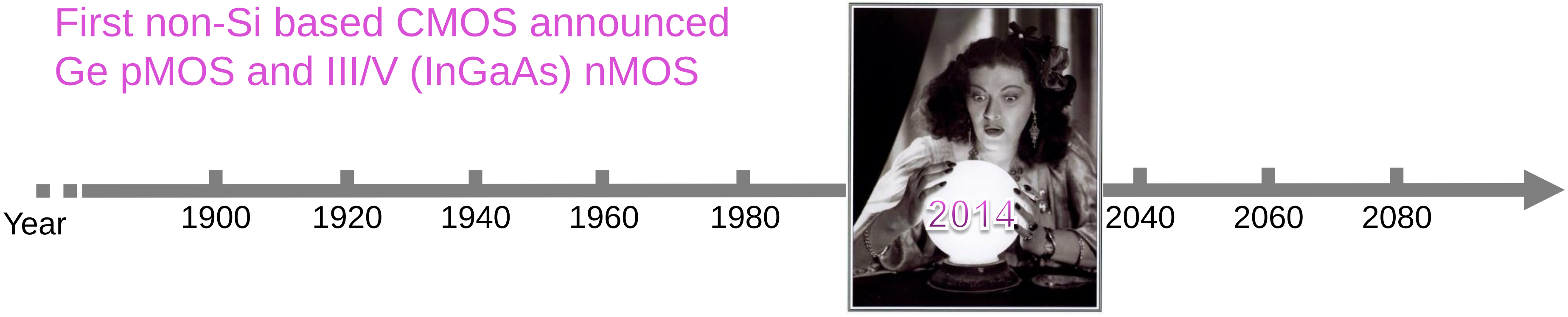

Classical physics

Solid state physics

Quantum mechanics

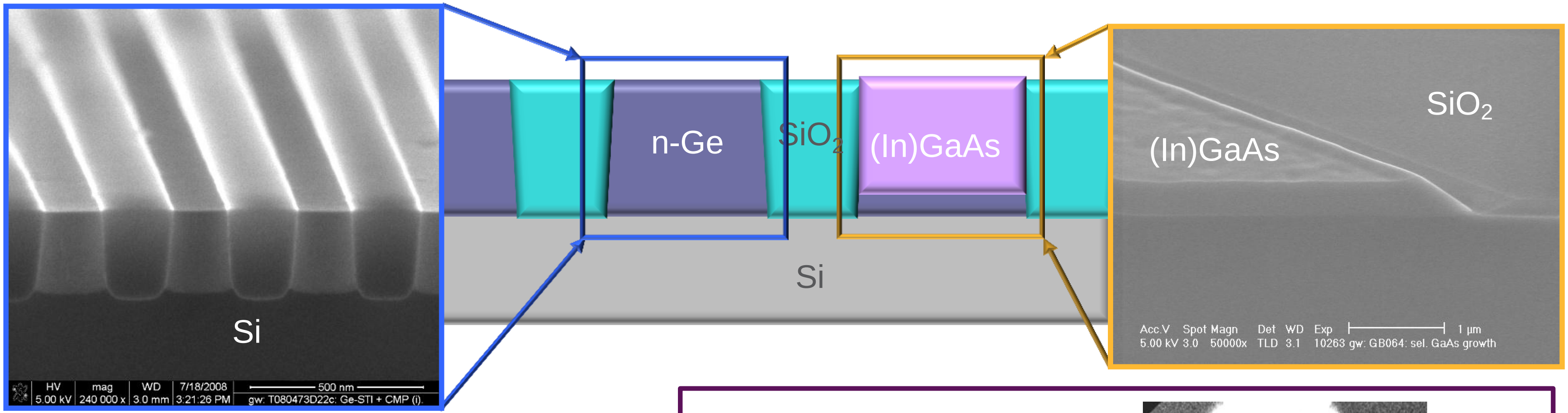
1. **Selective growth** of Ge and/or III/V in STI trenches
2. **High-κ gate stack** for low EOT
3. **IF-QW device** with self-aligned **doped raised S/D** for contacts
4. Further **strain engineering** for mobility boost

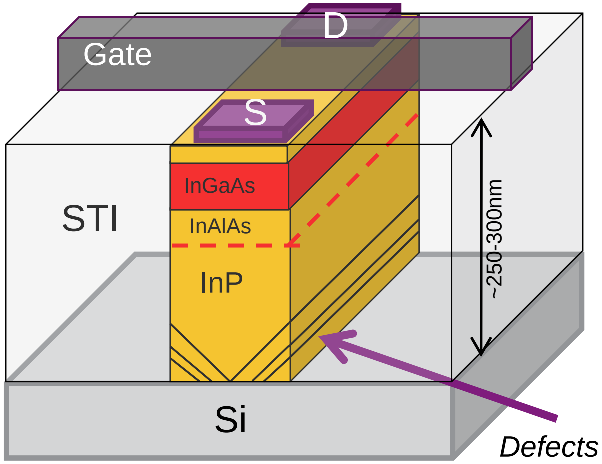
First non-Si based CMOS announced
Ge pMOS and III/V (InGaAs) nMOS



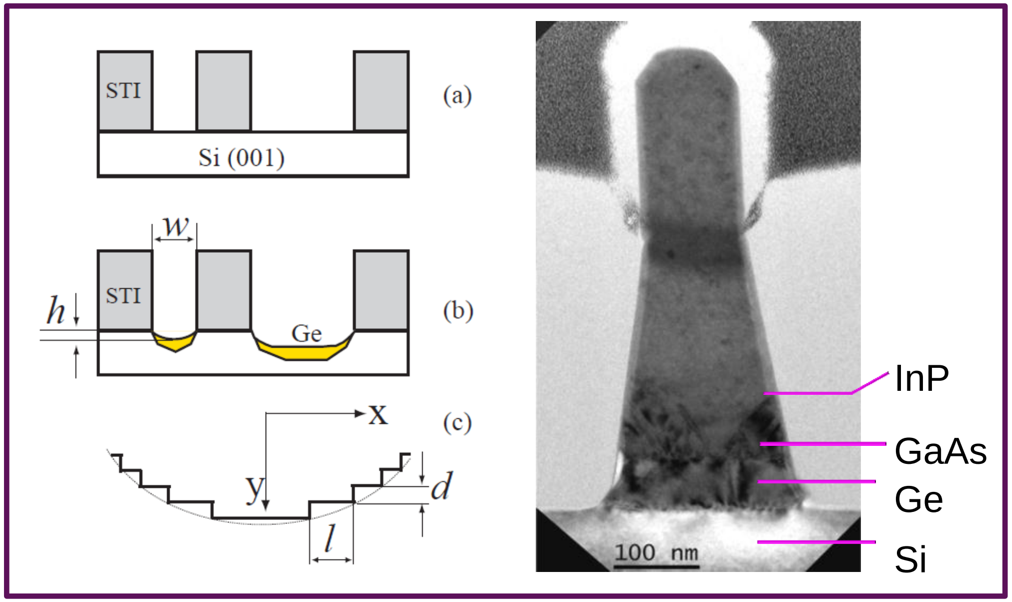
Ge and III/V selective growth on Si wafers

- Local selective growth after STI allows integration of Ge and III/V materials on Si wafers, also for FinFETs.





Defects trapped at trench edges



Ge and III/V CMOS by wafer bonding

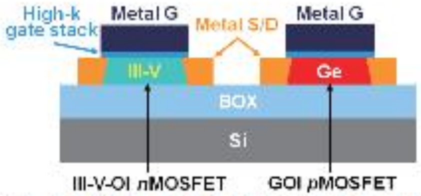


Fig. 1 Ultimate COMS transistors with III-V *n*MOSFETs and Ge *p*MOSFETs on Si substrates with BOX layer.

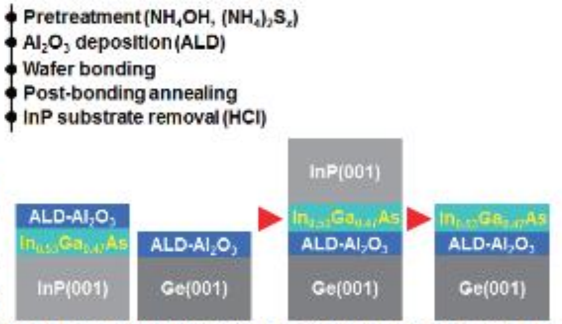

- Pretreatment (NH$_4$OH, (NH$_4$)$_2$S$_x$)
- Al$_2$O$_3$ deposition (ALD)
- Wafer bonding
- Post-bonding annealing
- InP substrate removal (HCl)

Fig. 2 Process flow for fabricating InGaAs-on-Ge wafers using the ALD-Al$_2$O$_3$ DWB technique.

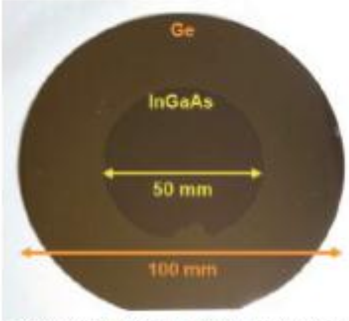


Fig. 3 Photograph of an InGaAs-on-Ge wafer. A 2-inch InGaAs layer integrated on a 4-inch Ge wafer with an Al$_2$O$_3$ BOX layer.

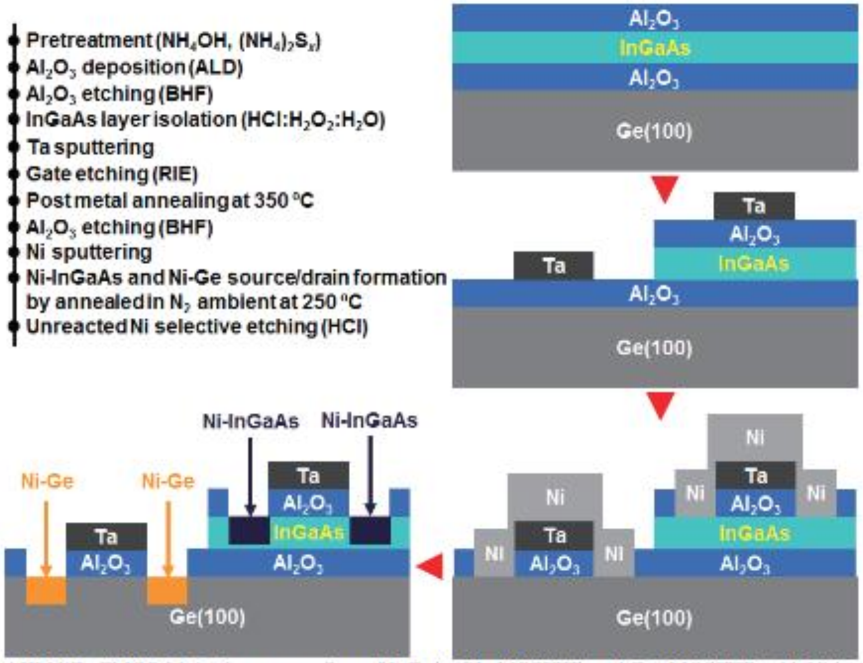

- Pretreatment (NH$_4$OH, (NH$_4$)$_2$S$_x$)
- Al$_2$O$_3$ deposition (ALD)
- Al$_2$O$_3$ etching (BHF)
- InGaAs layer isolation (HCl:H$_2$O$_2$:H$_2$O)
- Ta sputtering
- Gate etching (RIE)
- Post metal annealing at 350 °C
- Al$_2$O$_3$ etching (BHF)
- Ni sputtering
- Ni-InGaAs and Ni-Ge source/drain formation by annealed in N$_2$ ambient at 250 °C
- Unreacted Ni selective etching (HCl)

Fig. 4 III-V/Ge CMOS fabrication process flow of InGaAs-OI *n*MOSFETs and Ge *p*MOSFETs with Ni-based metal S/D on an InGaAs-on-Ge wafer.

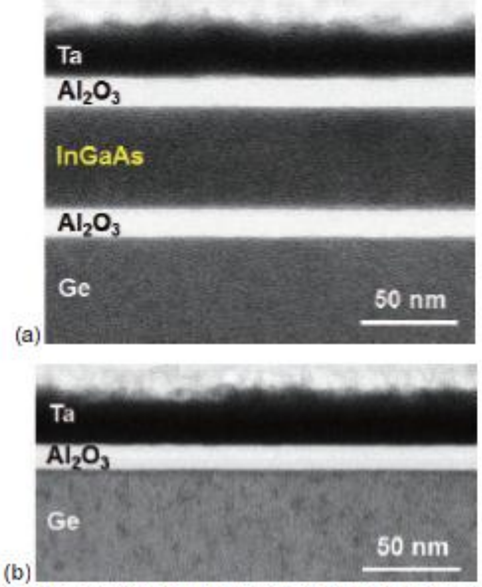
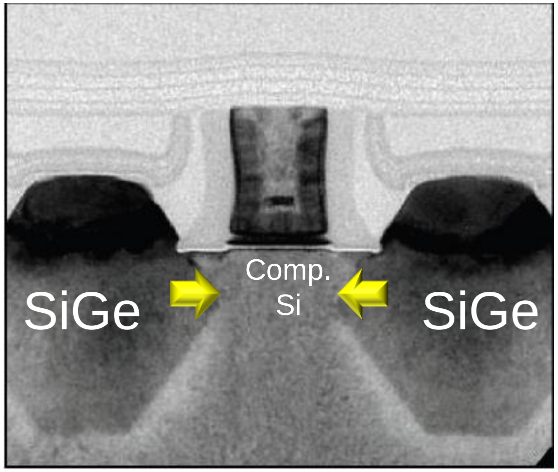


Fig. 5 Cross-sectional TEM image of the MOS interfaces of (a) 50-nm-thick InGaAs-OI *n*MOSFET and (b) of Ge *p*MOSFET with Ta/Al$_2$O$_3$ metal-gate/high-k gate-stack.

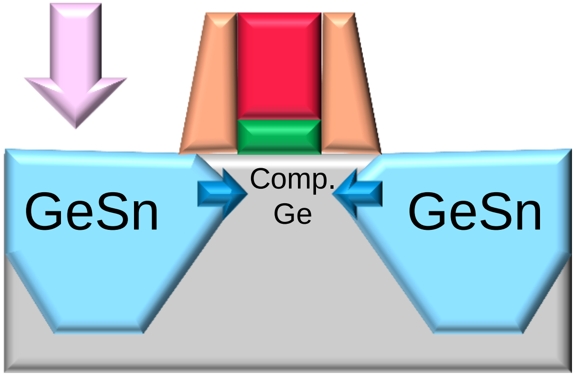
M. Yokoyama et al, VLSI 2011

Introducing strain in Ge devices

Compressively strained Ge is mandatory to outperform sSi pMOSFETS
Transfer sSi technologies to compressively strained Ge channels using GeSn

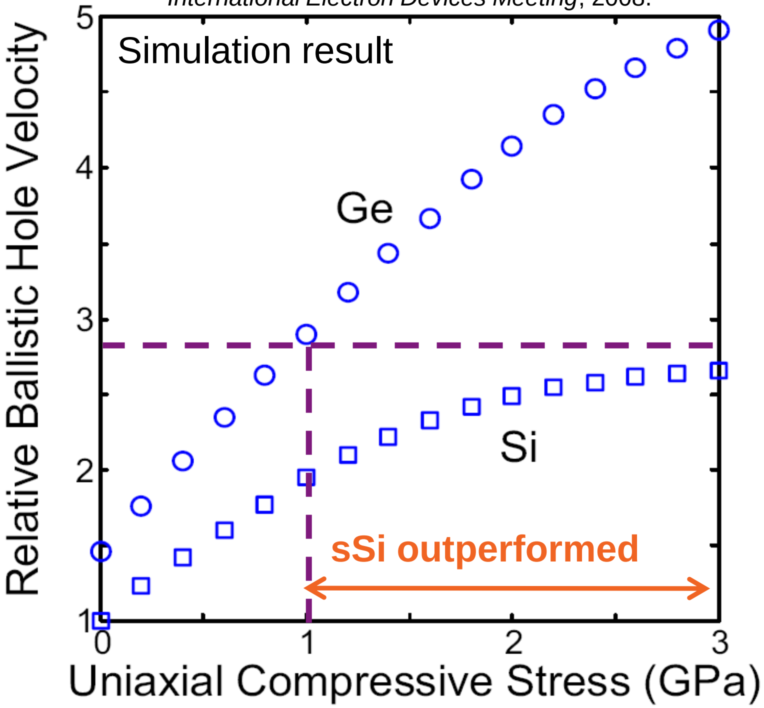


45nm compressive Si pMOSFET from INTEL



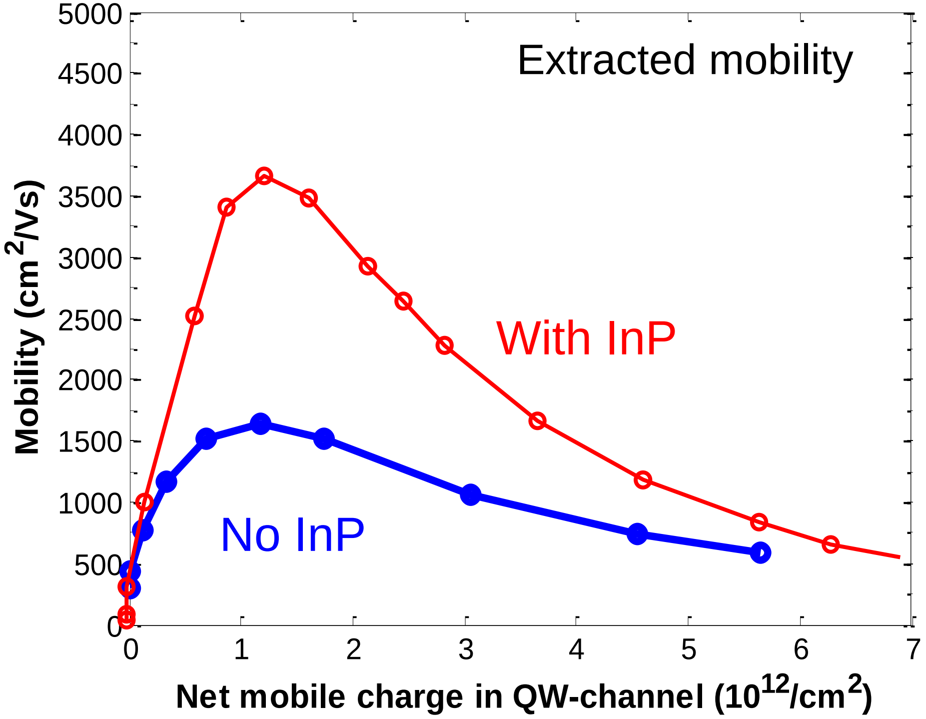
New compressively strained Ge MOSFET architecture

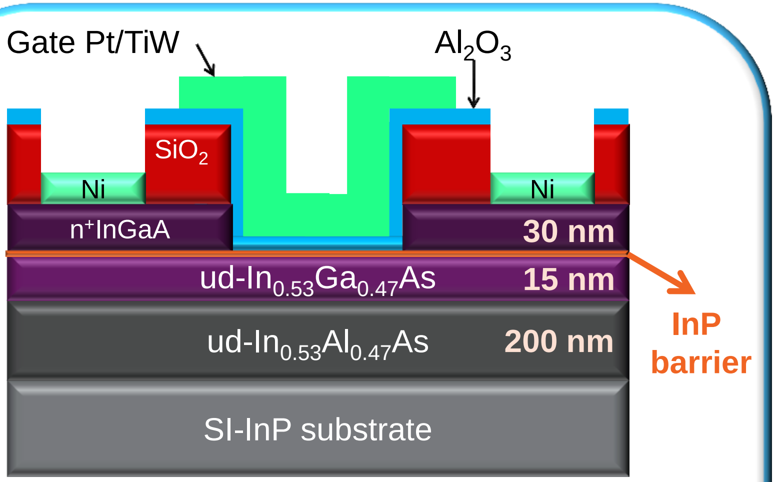
D.A. Antoniadis and A. Khakifirooz, “MOSFET performance scaling: limitations and future options”, *International Electron Devices Meeting*, 2008.



1GPa is requested in Ge channels to outperform sSi hole mobilities

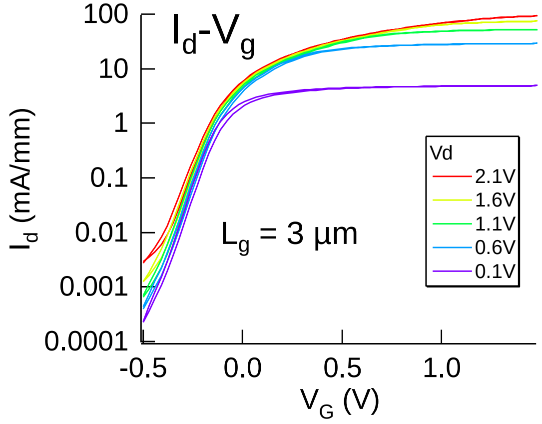
Implant Free Quantum Well (IFQW) device





- L_g = 3-20 µm, EOT = 4.5 nm
- With and without 4 nm InP barrier.
- In-situ epitaxial n^+-$In_{0.53}Ga_{0.47}As$ S/D
- Gate stack: $(NH_4)_2S$ + 10 nm ALD Al_2O_3

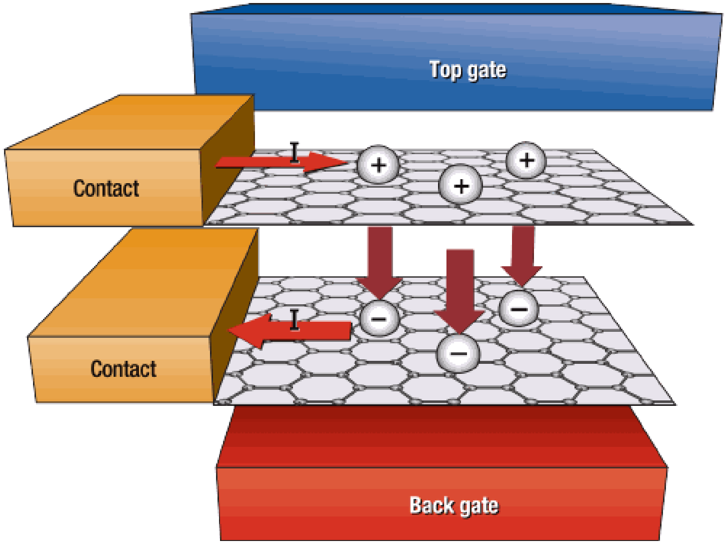
- Good I_{on}/I_{off} ratio of ~10^5
- Sub-threshold slope ~ 100 mV/dec
- Low hysteresis (if not biased into deep depletion)
- Extrinsic currents limited by R_s of 15 Ω.mm
  - due to 20 µm spacing between S/D metal and gate

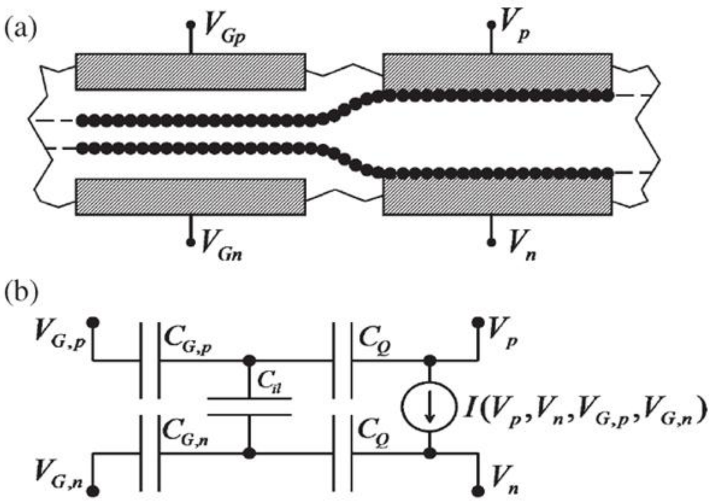


A look into the future.....

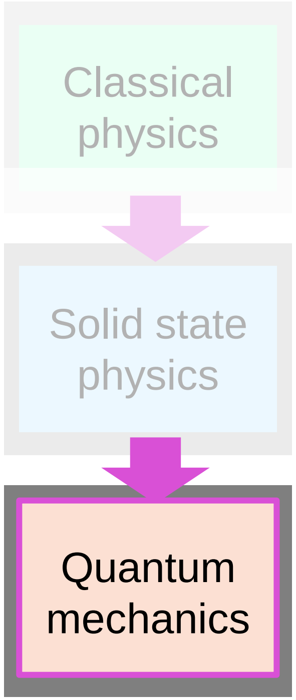
Theory predicts that the ground state of a suitable graphene bilayer may be an above-room-temperature Bose-Einstein condensate corresponding to a coherent superposition of excitons.

A logic device based on such a superfluid condensate of excitons is the bilayer pseudospin FET (BiSFET), which controls the presence or absence of the condensate via applied gate voltages.





S.K. Banerjee et al, IEEE ELECTRON DEVICE LETTERS, VOL. 30, NO. 2, 158, FEBRUARY 2009

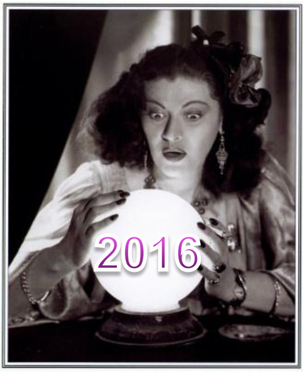

Classical physics

Solid state physics

Quantum mechanics

First demonstration of new devices based on 2D materials (i.e. graphene)

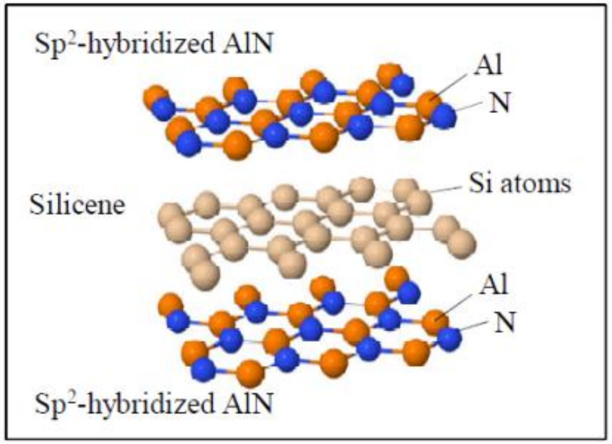
Year 1900 1920 1940 1960 1980

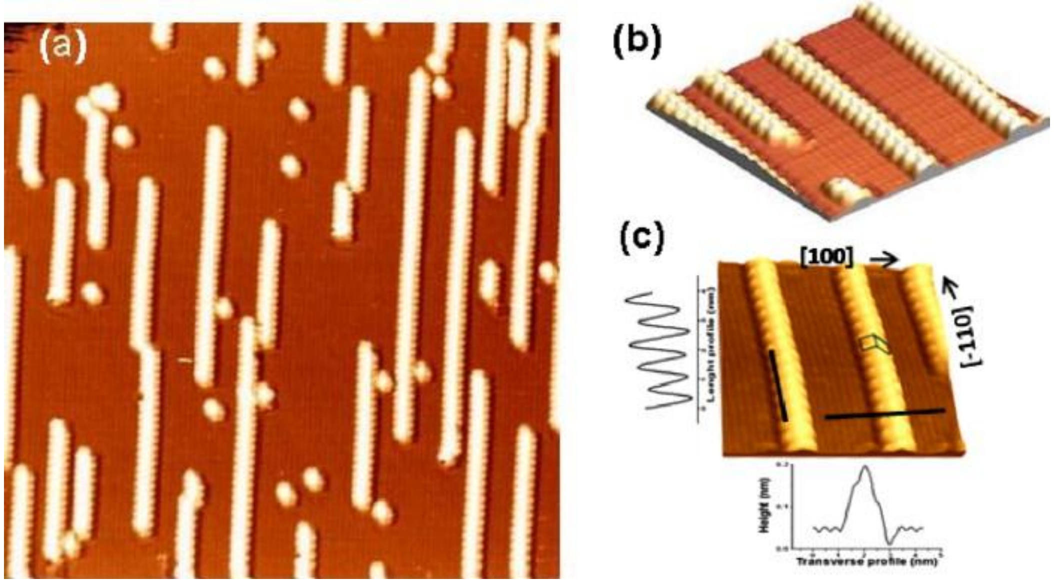


2040 2060 2080

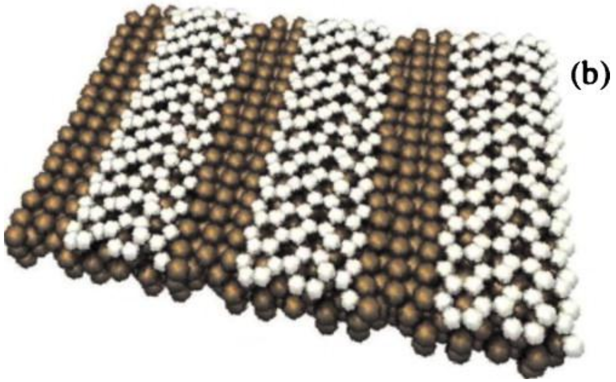
Other 2-D materials: Silicene

- ▶ Silicene is the Si equivalent of graphene.
- ▶ Promising results have been obtained on silicene nanoribbon fabrication on Ag surfaces.
- ▶ Can also be made on AlN





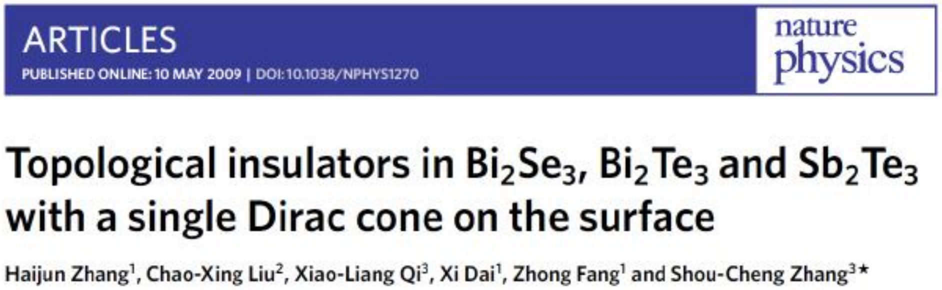
STM images of straight, parallel 1D silicon nanostructures grown on a Ag(110) surface. (a) Large view (42×42 nm2, filled states); (b) 3D view (12×12 nm2, filled states); and (c) detailed view (6.22×6.22 nm2, filled states).



Filled-states STM image, 11×10 nm2 (V = −3.3 V, I = 1.90 nA) of the dense array of SiNRs forming a 1D grating with a pitch of ∼ 2 nm (a); ball model of the corresponding calculated atomic structure (b).

P. De Padova et al, Appl. Phys. Lett. 96, 261905 (2010), B. Aufray et al, Appl. Phys. Lett. 96, 183102 (2010)

3D Topological insulators



ARTICLES

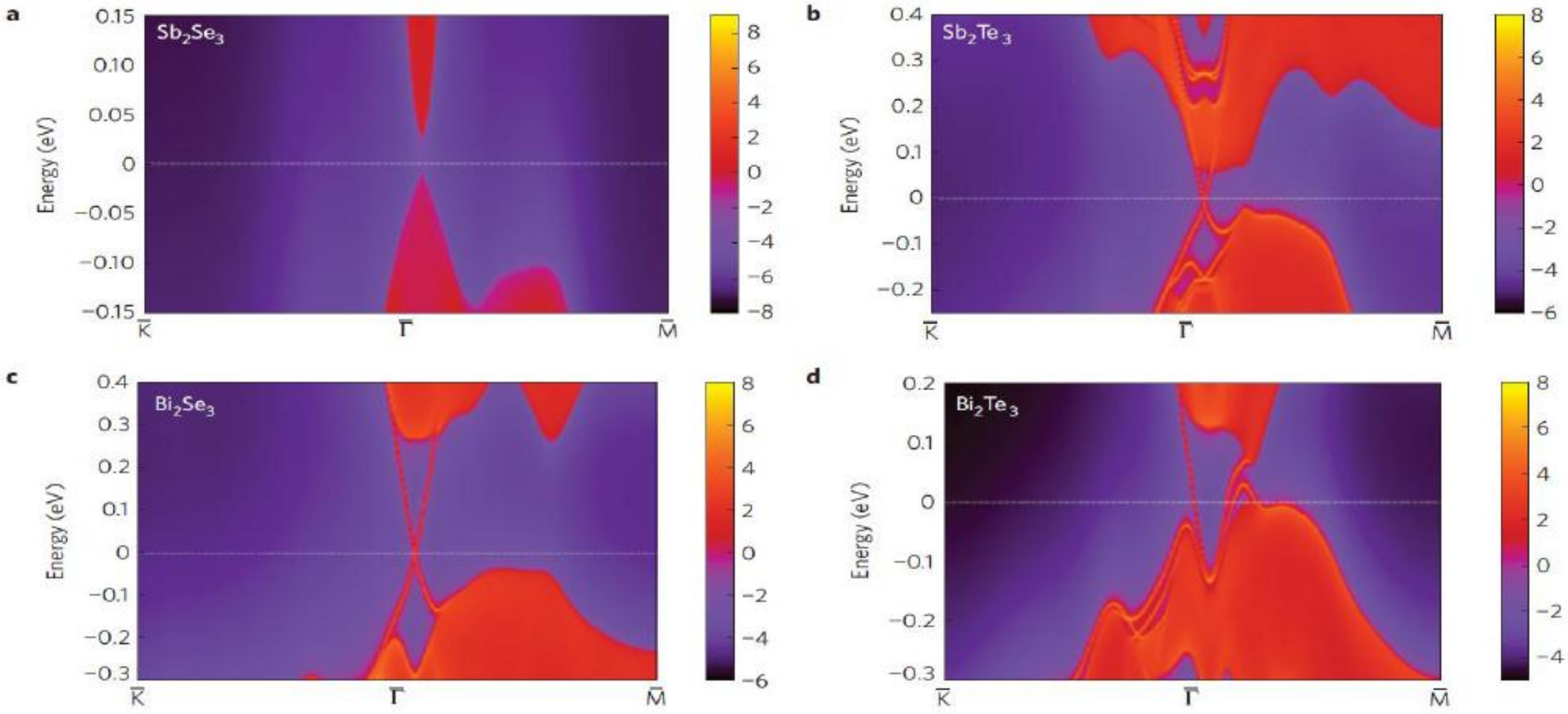
PUBLISHED ONLINE: 10 MAY 2009 | DOI:10.1038/NPHYS1270

nature physics

Topological insulators in Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface

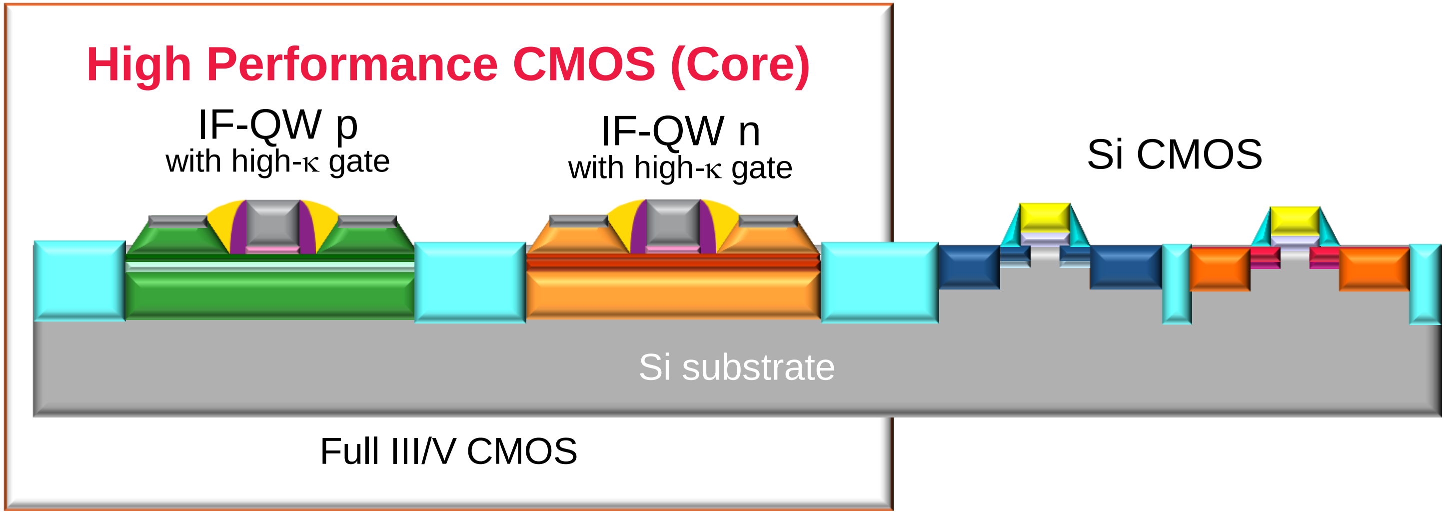
Haijun Zhang[1], Chao-Xing Liu[2], Xiao-Liang Qi[3], Xi Dai[1], Zhong Fang[1] and Shou-Cheng Zhang[3]*

Energy and momentum dependence of the LDOS



Sb_2Se_3 has no surface state

A look into the future.....



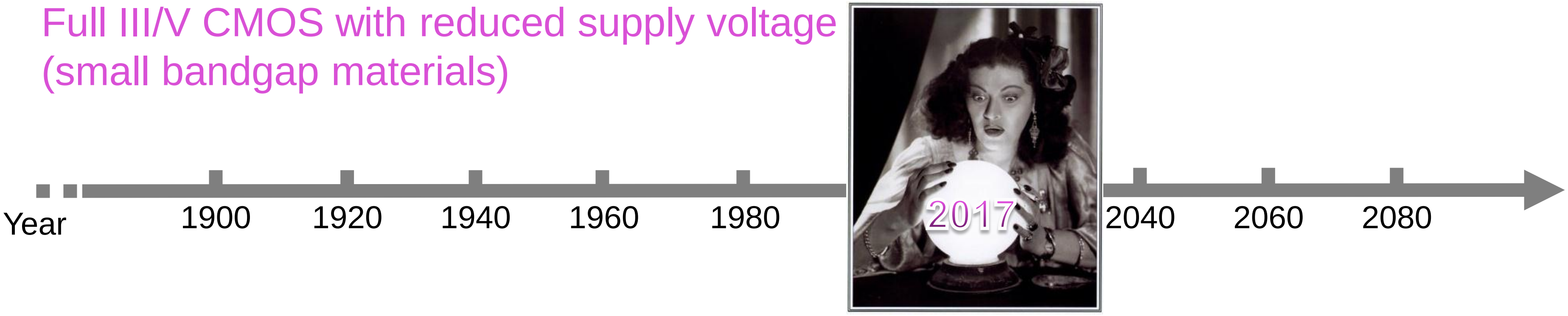
Classical physics

Solid state physics

Quantum mechanics

1. **Selective growth** of III/V in STI trenches
2. **High hole mobility materials** for pMOS
3. **IF-QW device**
4. Further **strain engineering** for mobility boost

Full III/V CMOS with reduced supply voltage (small bandgap materials)



III/V pFET

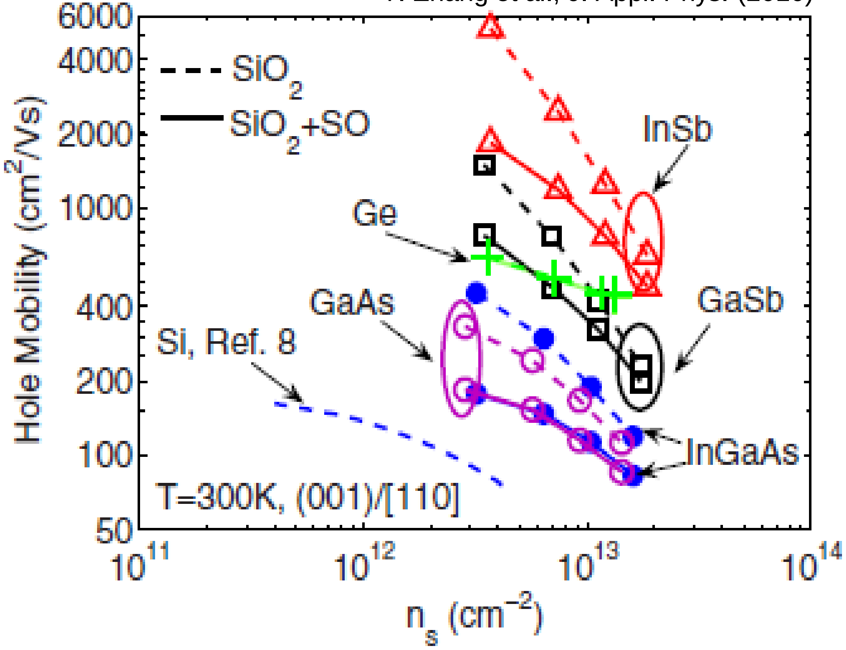
High hole mobility for III-Sb p-channel

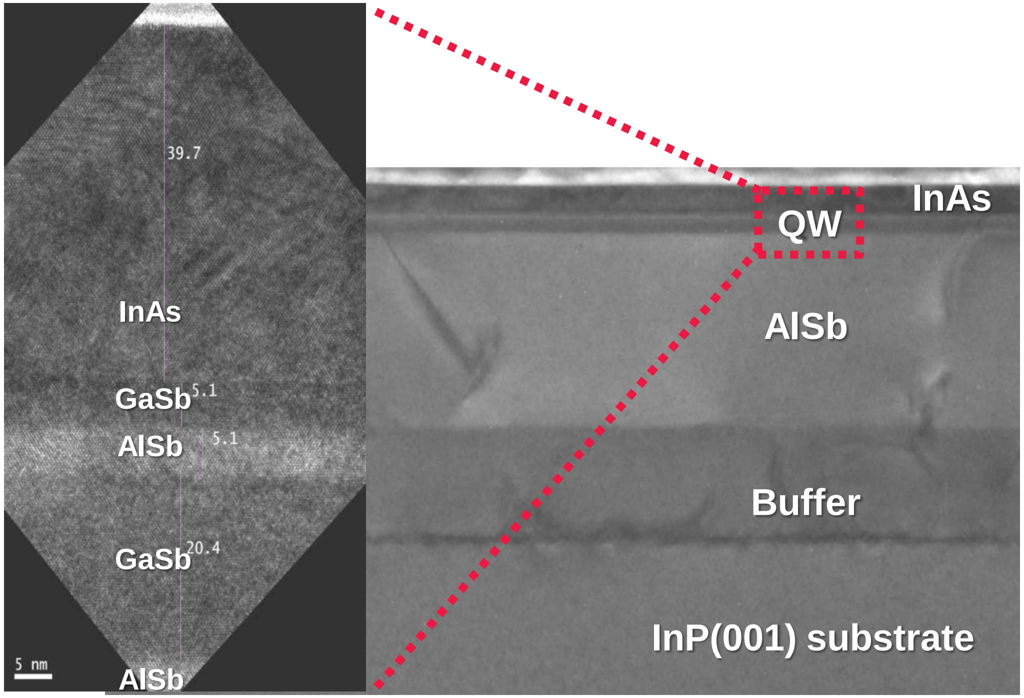
InSb followed by GaSb has the largest hole mobility compared to Ge, InGaAs and GaAs

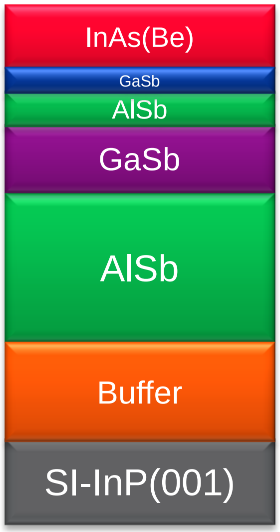
Optimized structural stack quality

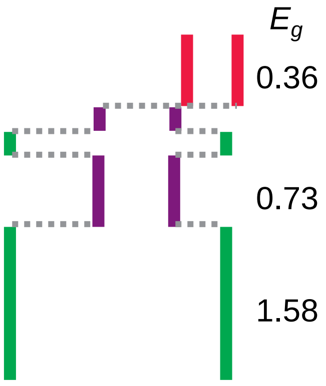
The **AlSb interfacial layer** plays a key role in the growth of high quality QW stack

Y. Zhang et al., J. Appl. Phys. (2010)



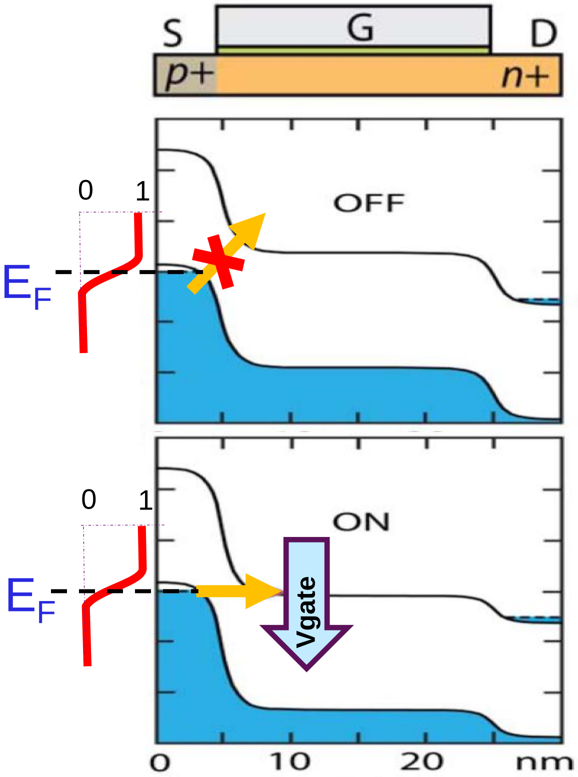


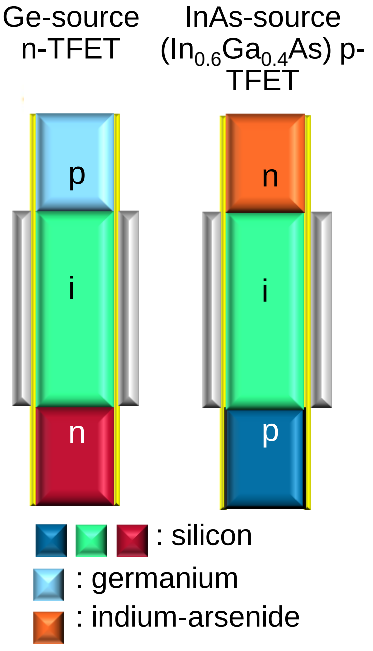


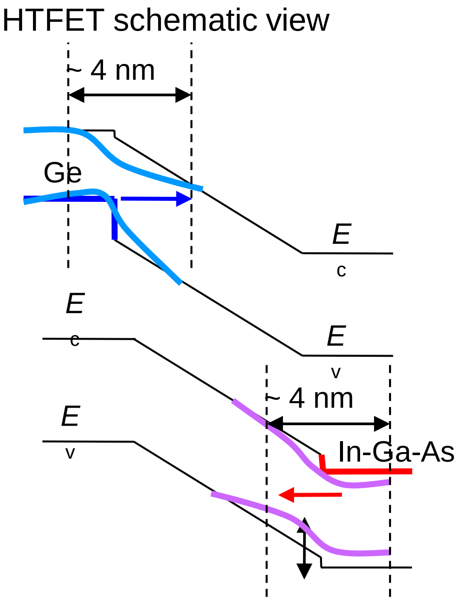


Band alignment of GaSb – AlSb – InAs

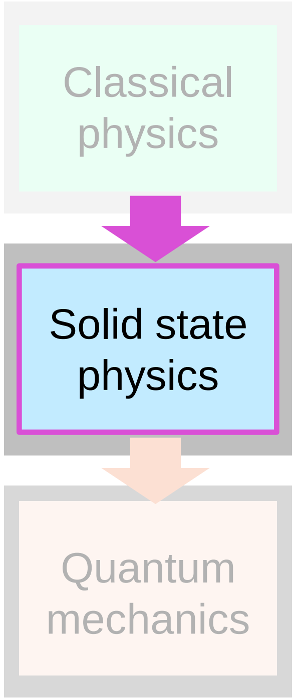
A look into the future.....







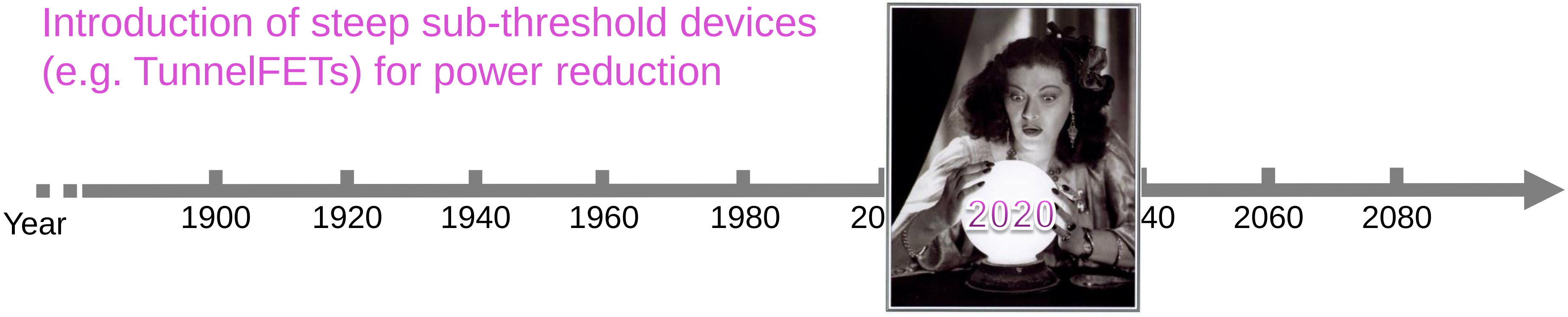
Heterojunction TFET boosts the ON current by increasing the source tunneling efficiency by using low bandgap material in the source


Classical physics

Solid state physics

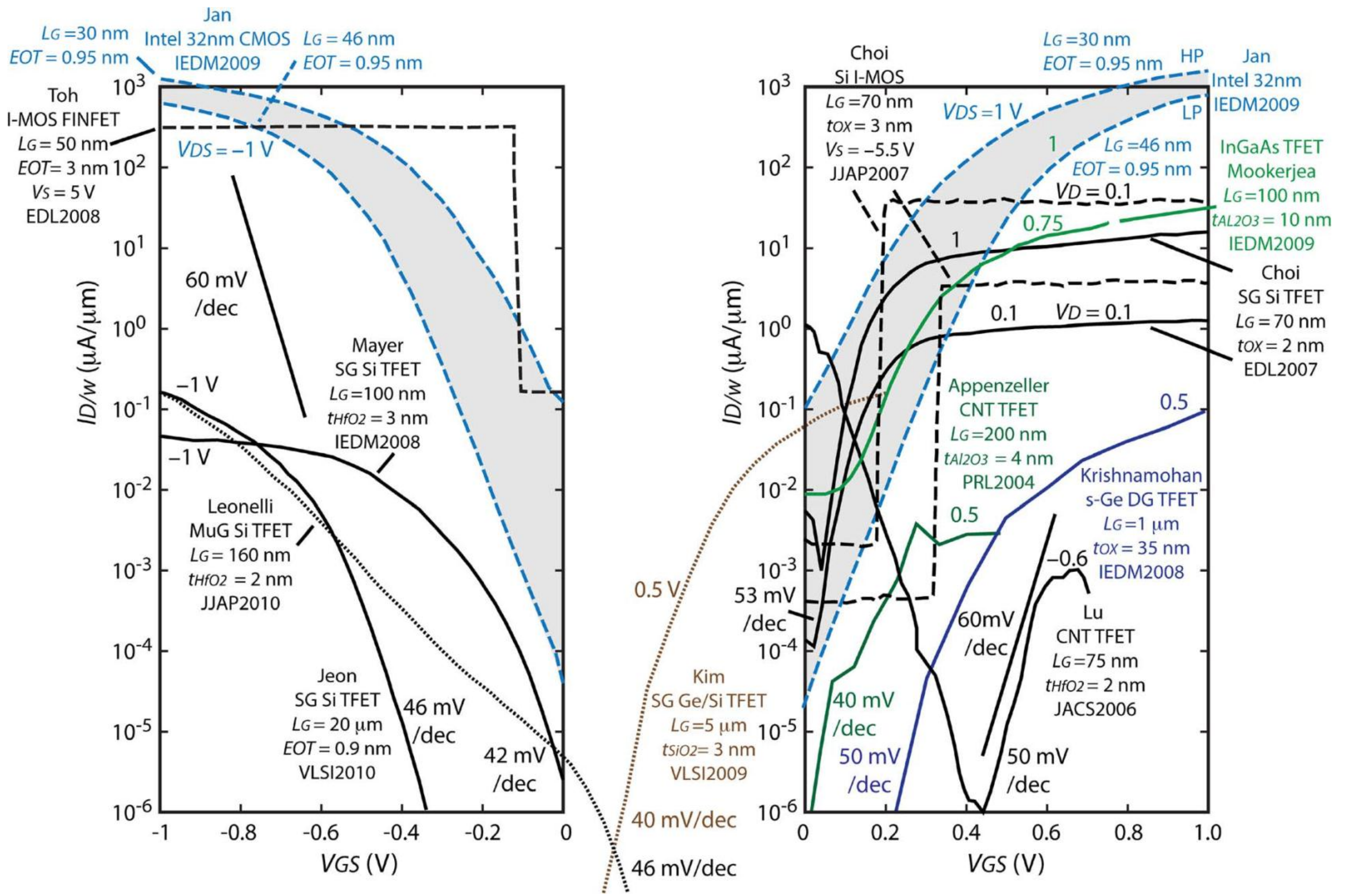
Quantum mechanics

Introduction of steep sub-threshold devices (e.g. TunnelFETs) for power reduction



TunnelFET challenge: ON-current

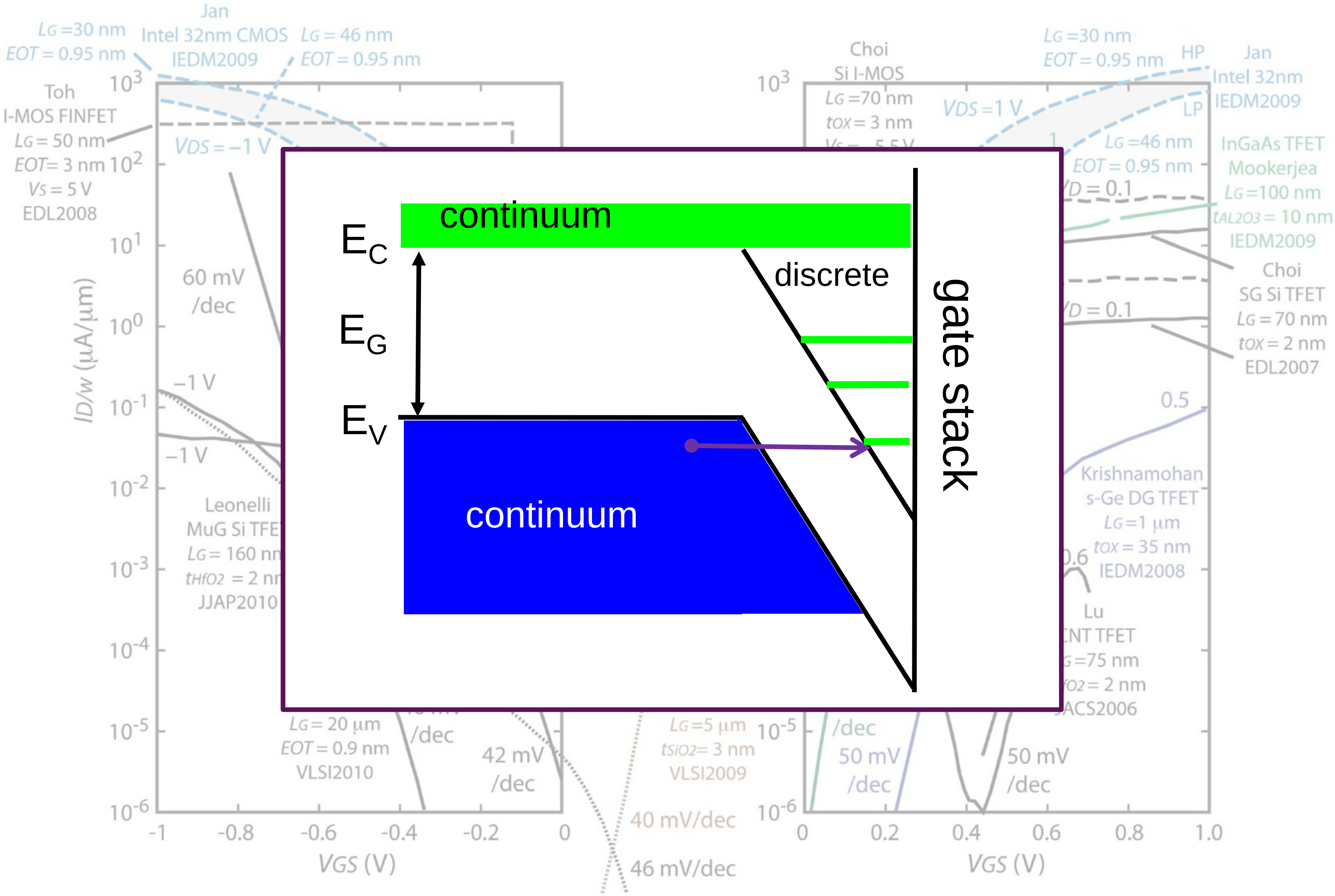
- ... with SS < 60 mV/dec but with (too) low ON current



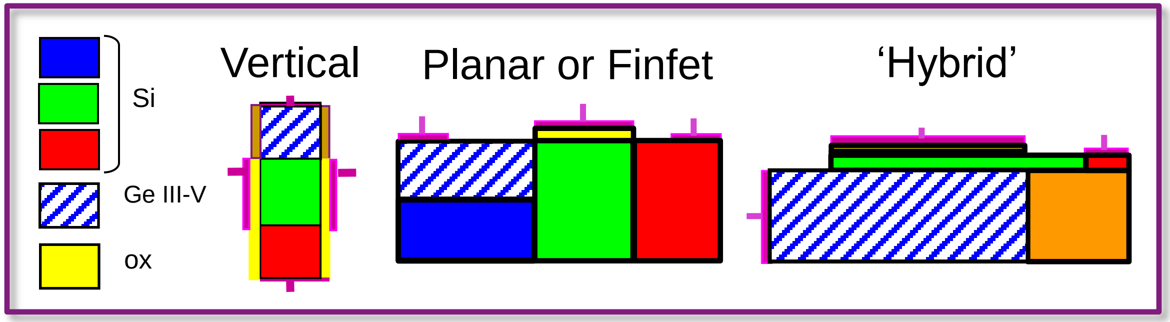
Alan C. Seabaugh and Qin Zhang, Proceedings of the IEEE, Vol. 98, No. 12, p. 2095, 2010

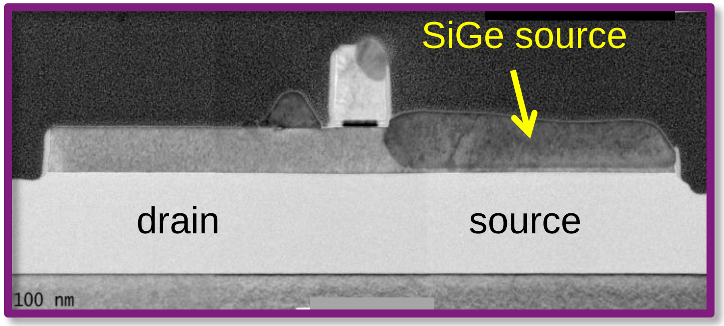
TunnelFET challenge: ON-current

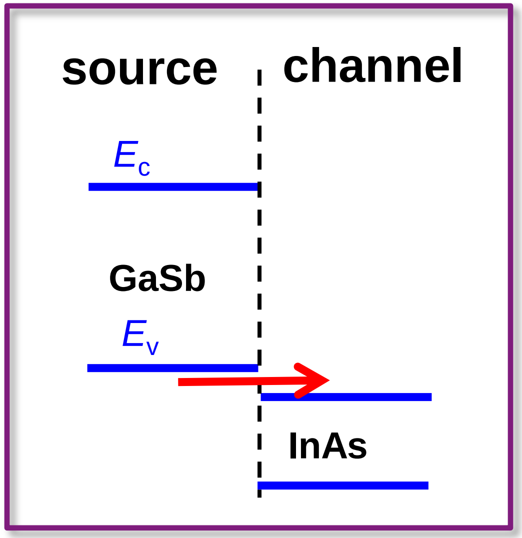
- ... with SS < 60 mV/dec but with (too) low ON current

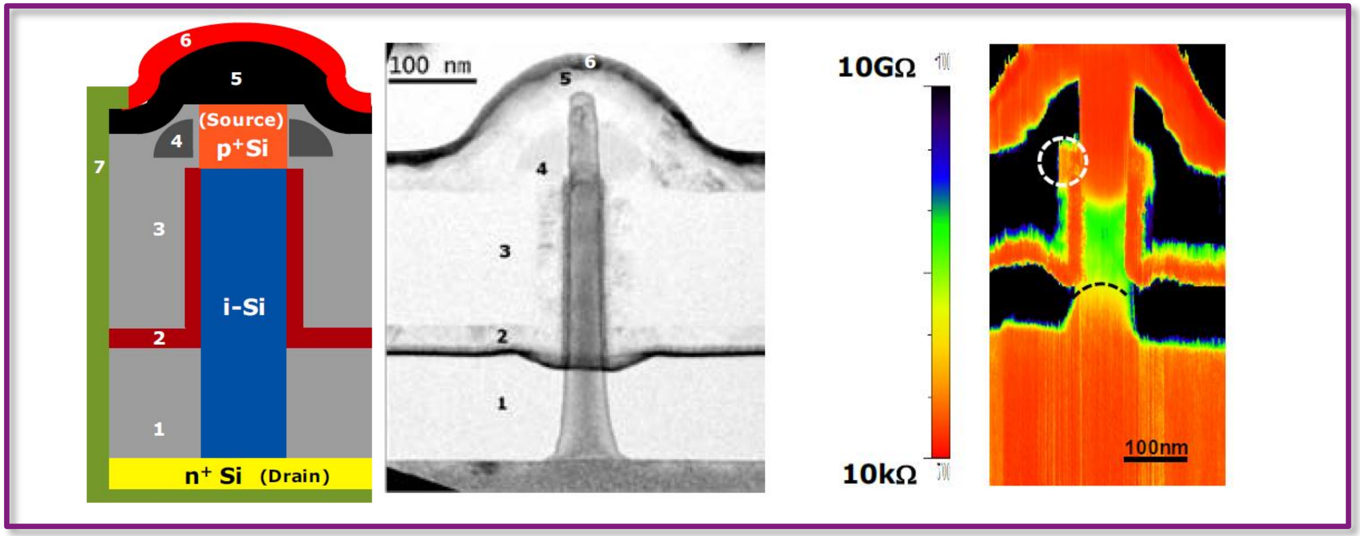


TunnelFET implementation









- Extensive modeling effort to calibrate tunneling efficiency (using P-i-N diodes)
- Exploration of new device concepts with improved field control
- Integration of demonstrators (vertical & horizontal) in progress

The pinch-off nanowire MOSFET

A junctionless device

- Negative gate voltage will push the majority carriers (electrons) to the middle of the wire. For sufficient negative gate voltage the channel is pinched off.
- No source and drain needed

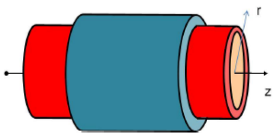
junctionless nPOFET

no strain, [001] channel

R = 5 nm, L = 16 nm

V_{DS} = 1 mV

V_{GS} = 0 V



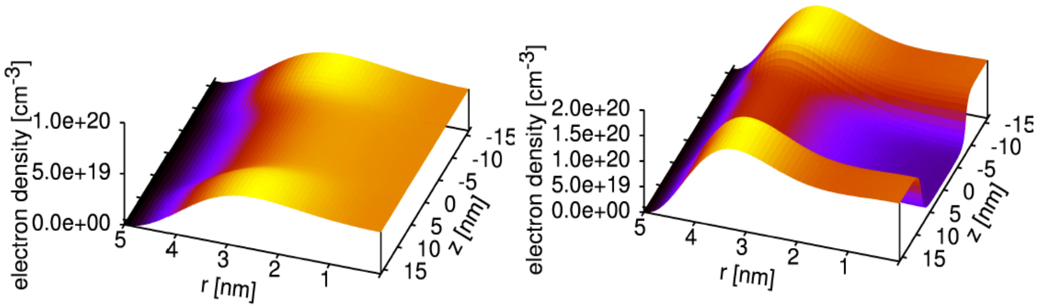
junction nMOSFET

no strain, [001] channel

R = 5 nm, L = 16 nm

V_{DS} = 1 mV

V_{GS} = 1 V



Bulk (volume) transport vs interface transport

Difference in charge density leads to difference in transport type

NMOSFET ON

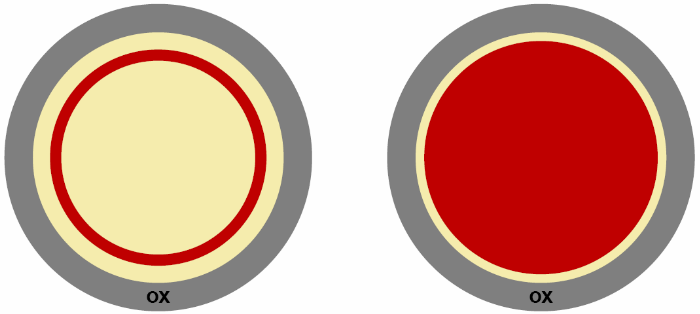
$V_G >> V_T > 0$

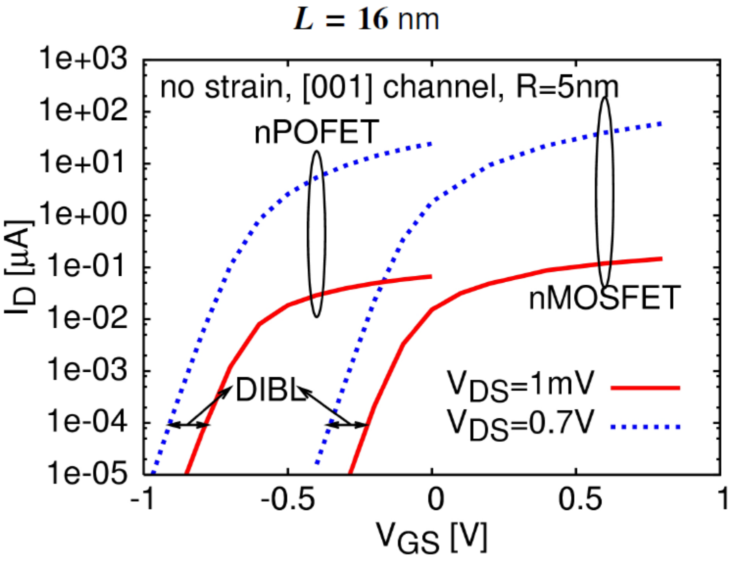
Electron density profile

pinch-off MOSFET ON

$V_G = 0 > V_T$

Electron density profile





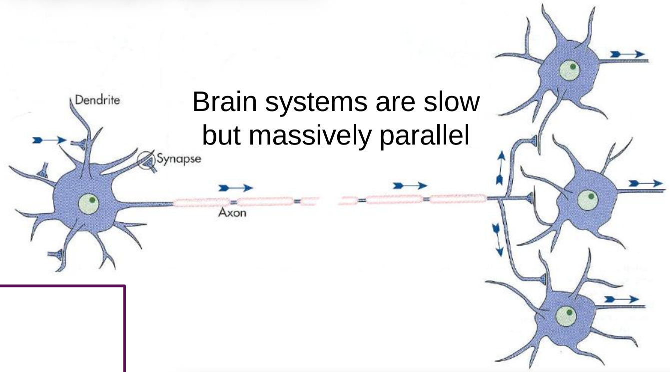
DIBL (nPOFET) ≈ DIBL (nMOSFET) ≈ 177 mV/V

SS (nPOFET) ≈ SS (nMOSFET) ≈ 60 mV/dec

A look into the future.....

Brain neuron

The master of low power ...



Brain systems are slow
but massively parallel

Organic systems

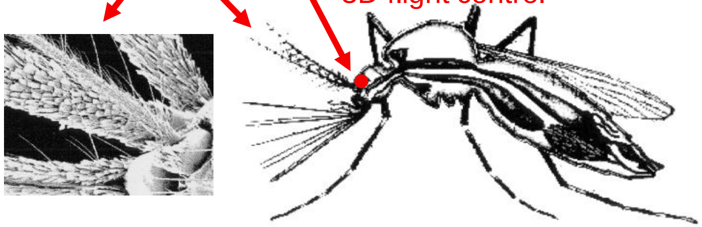
Ultra small volume
Small number of neuron cells
Extremely low power

Real time image processing
(Artificial) Intelligence
3D flight control

Brain

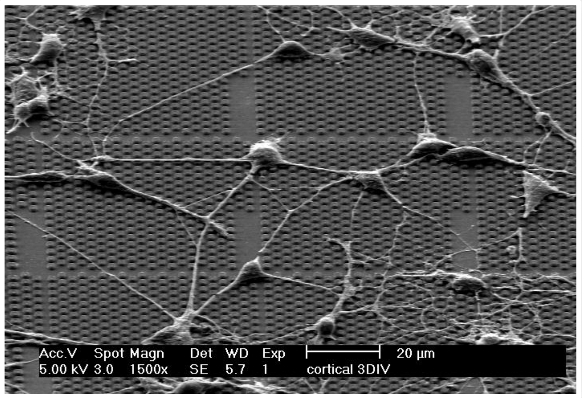
Sensor

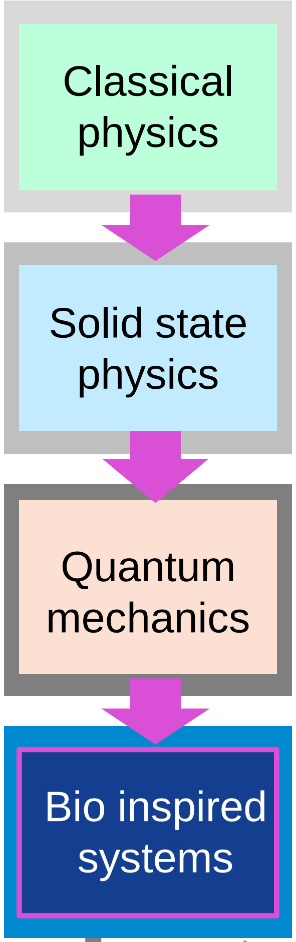
Infrared
Humidity
CO_2



Mosquito

Source: Prof. Iwai





Classical physics

Solid state physics

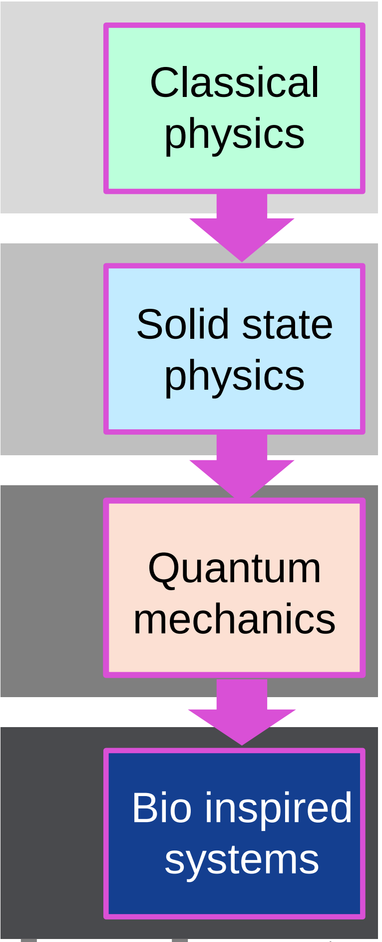
Quantum mechanics

Bio inspired systems

Introduction of bio-inspired systems

(bottom-up approach, self-assembling and self learning)

Year 1900 1920 1940 1960 1980 200 2025 2060 2080



Classical physics

Solid state physics

Quantum mechanics

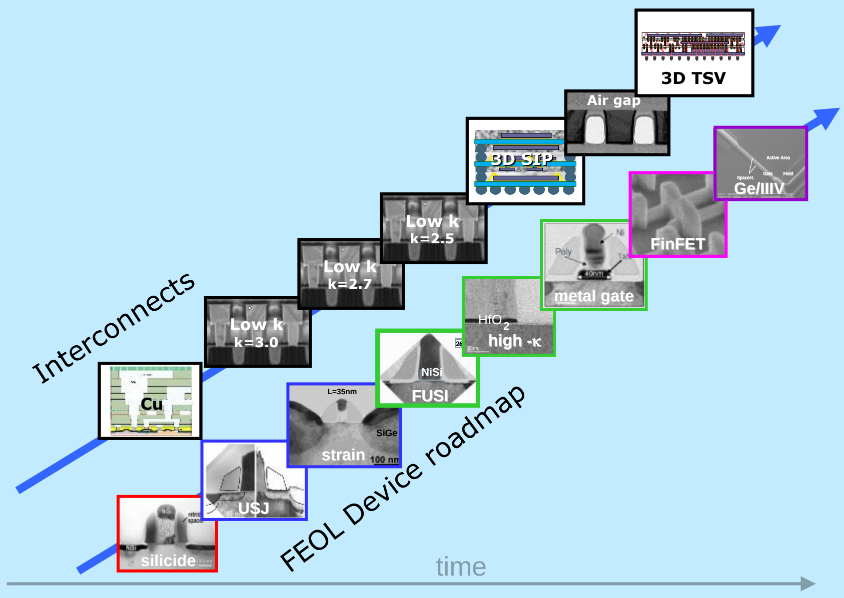
Bio inspired systems

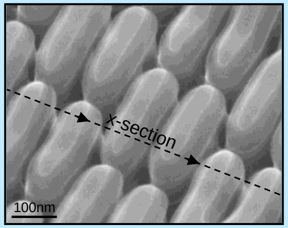
Year 1900 1920 1940 1960 1980 2000 2020 2040 2060 2080

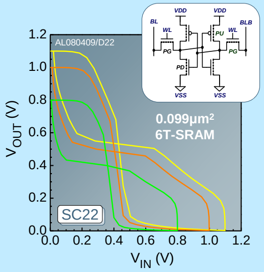
“More Moore” vs “More-than-Moore”

CMOS

CMOS Scaling

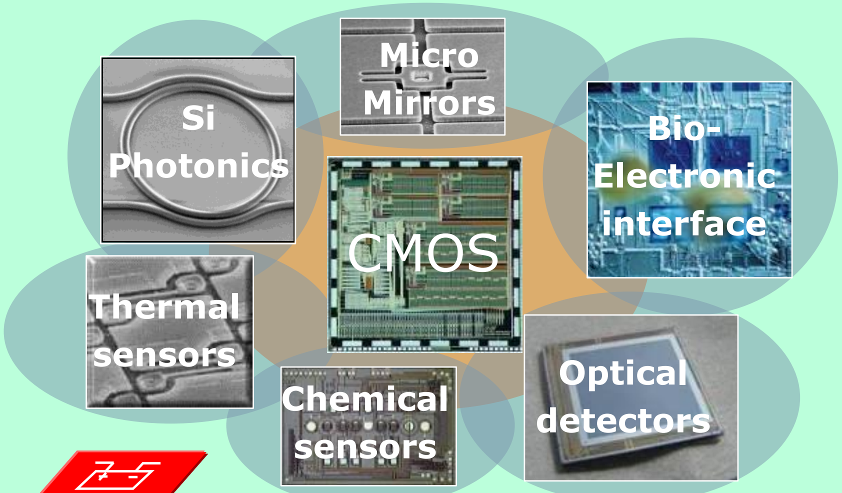


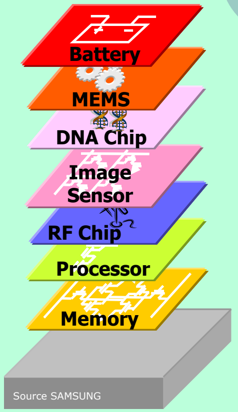




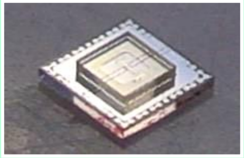
CMORE

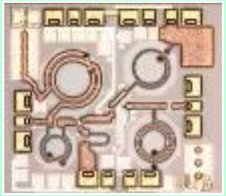
Multi-functional SOC/SIP

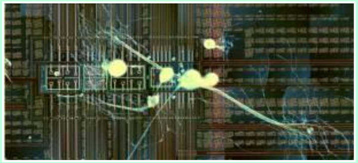




Source SAMSUNG



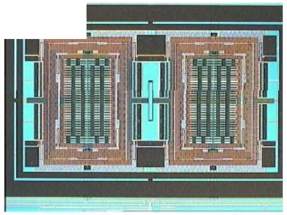


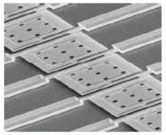


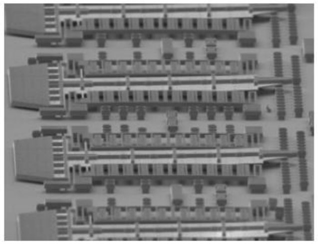
SiGe MEMS technology

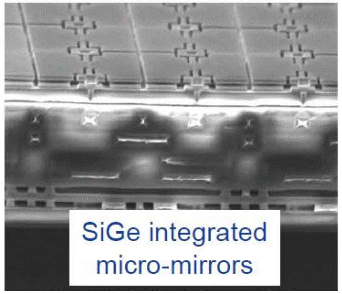
For tight integration with driver IC

Different above CMOS MEMS approaches		
	Al	**Poly-SiGe**
Post CMOS integration	yes	yes
Fracture strength [GPa]	0.2	> 2
Mechanical Q	low	> 10.000
Reliability	creep: hinge memory effect	No creep

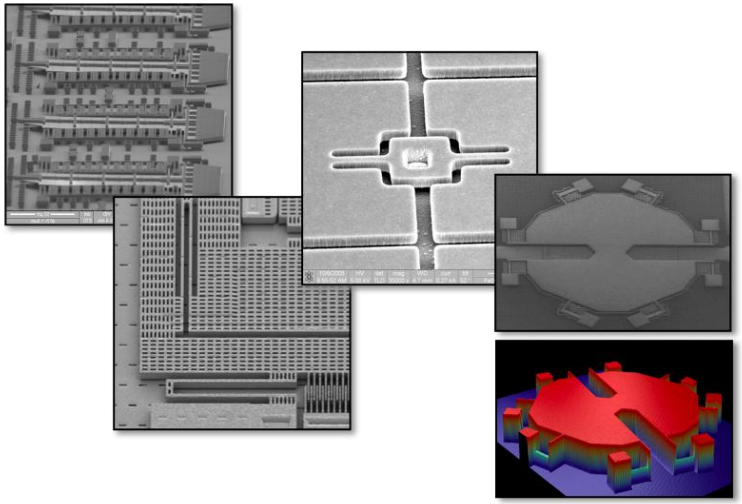

CMOS integrated SiGe gyroscope


Bolometer: poly-SiGe


SiGe cantilever array


SiGe integrated micro-mirrors

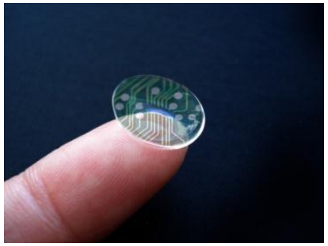

0-level packaged switches: glass caps



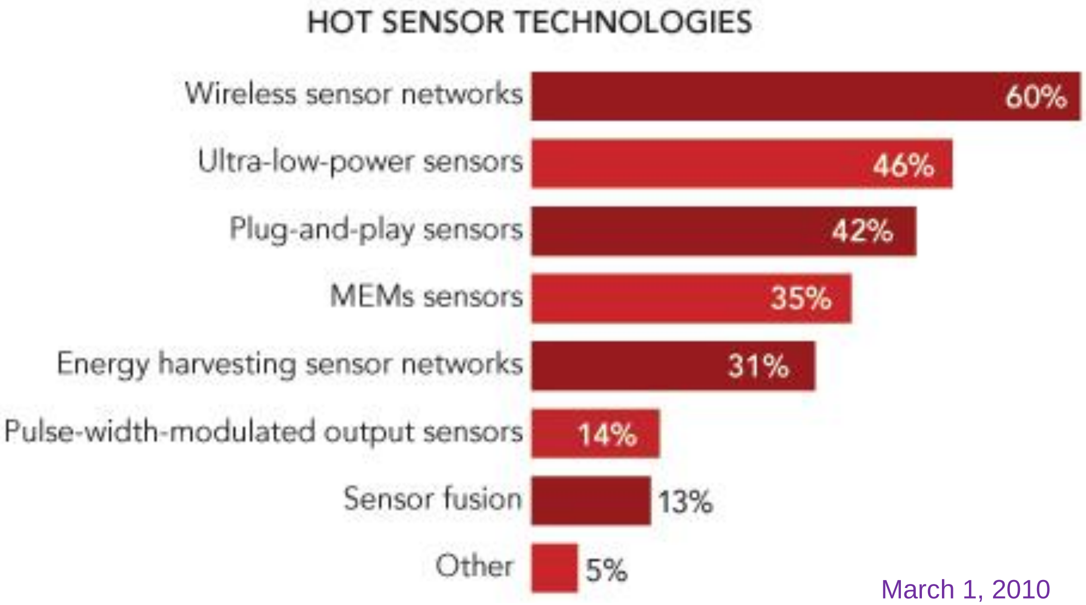
Poly-SiGe:

- better mechanical properties than Al: higher strength and Q factor
- better reliability properties than Al: less creep and fatigue

Sensors everywhere



The 2010 Trend Watch Sensor Survey Results



March 1, 2010

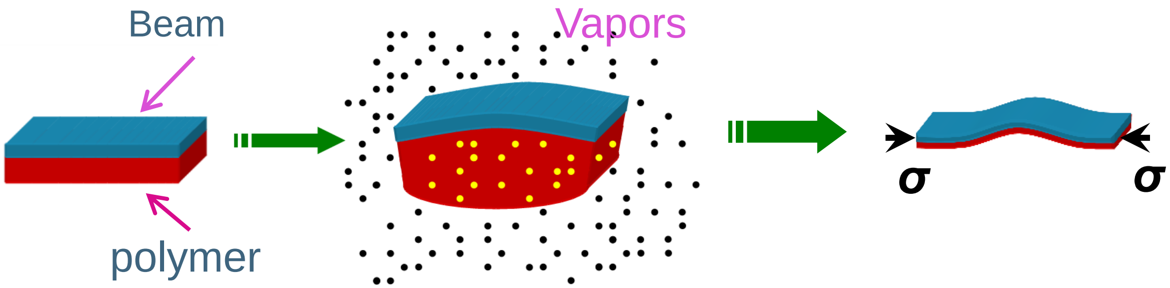
McKinsey: "Get Ready For Sensor-Driven Business Models" (March 3, 2010)

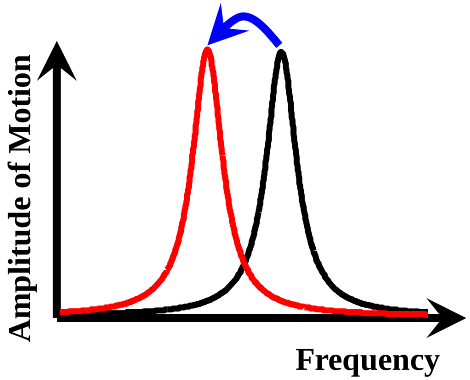
Underlying the Internet of Things are technologies such as RFID, sensors and smart-phones

e-nose: sensing in complex environments

e-nose: array of non-specific, cross-reactive sensors combined with an information processing system

$$\frac{\Delta f_n}{f_n} = \frac{1}{2}\left(-\frac{\Delta m}{m} + \frac{\Delta k}{k} + \frac{\alpha_n \Delta\sigma}{1+\alpha_n \sigma}\right)$$





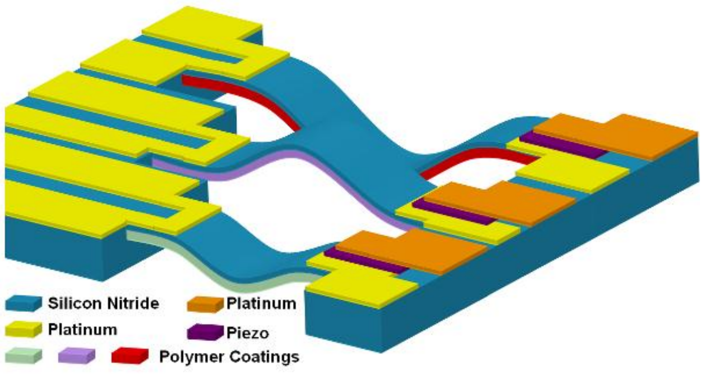
Adsorption → Extra mass

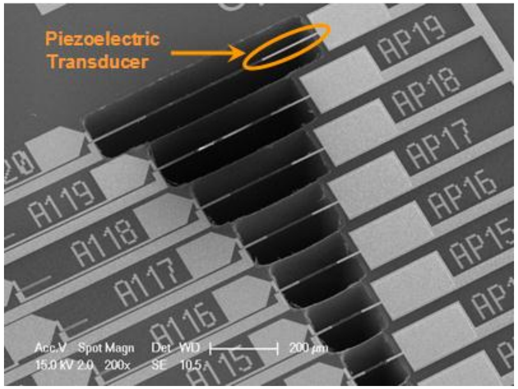
Swelling → Stress

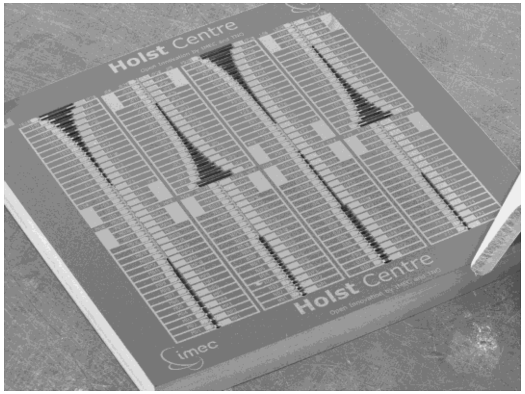
→ Lower Frequency

e-Nose: from vision to reality:

2.6 10^{-3} frequency shift / %EtOH, Power = 0.00017 mW







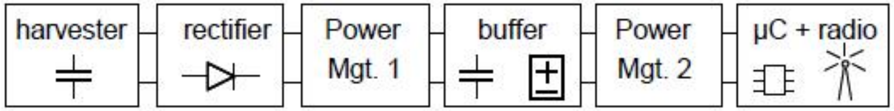
Die = 8.8 mm x 8.8 mm, 160 resonators

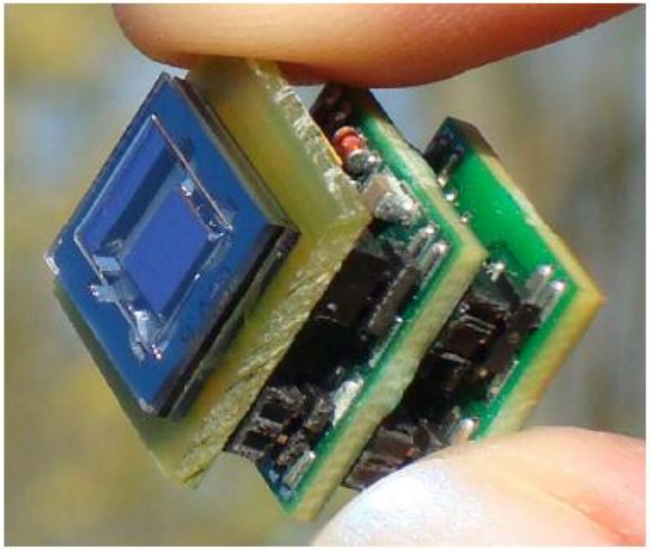
Body area network examples
Personal healthcare & lifestyle solutions

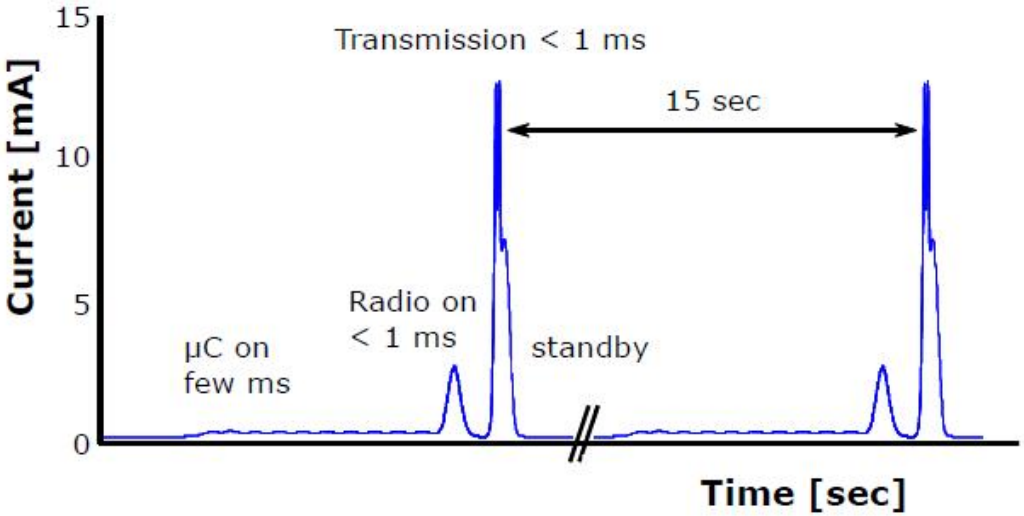
Necklaces/patches Watch-type Headsets Base Stations

Autonomous wireless sensor node

Harvester : 17 μW, 3.0 – 8.5 V
Rectifier : η = 60%
Power Mgt. : 2.2 – 4.2 V
Start-up time : < 1 minute capacitor charging
Transmission : 15 seconds + charging

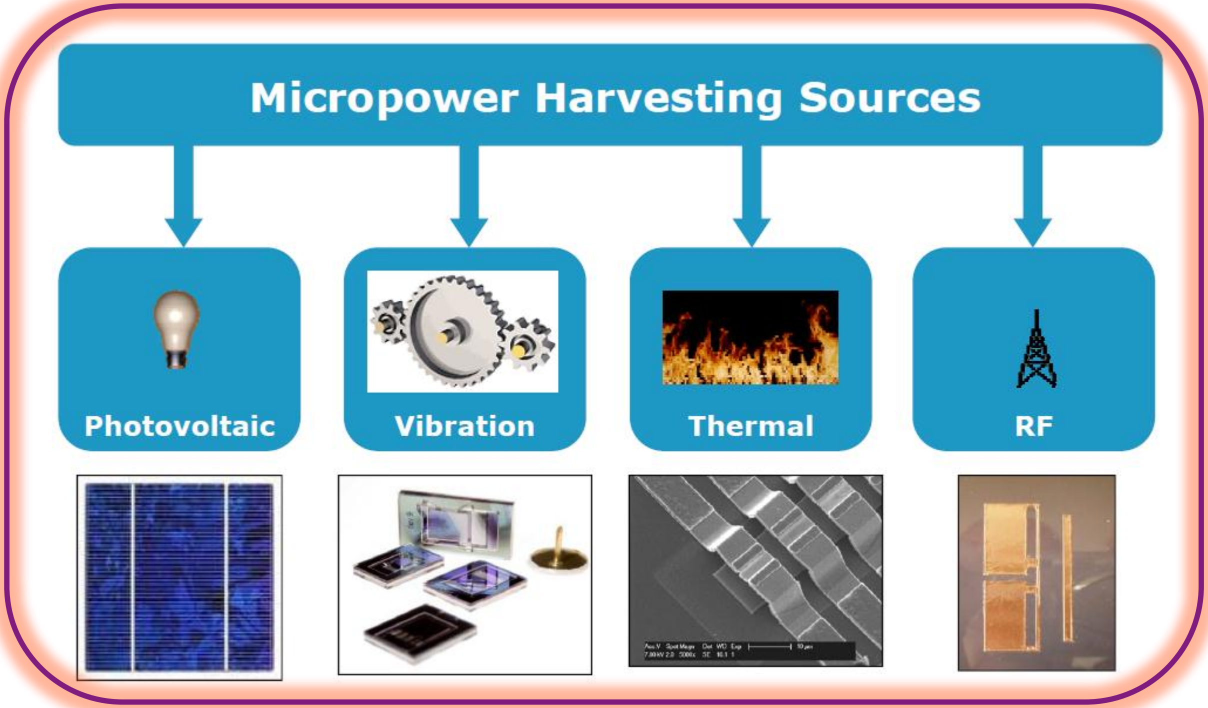






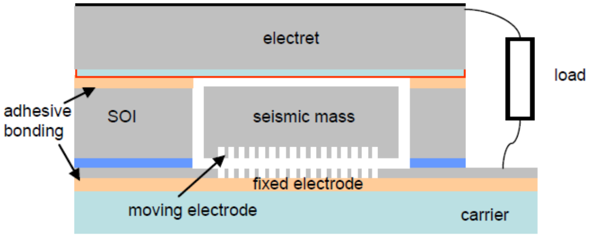
autonomy by 10 μW power consumption

Energy harvesting

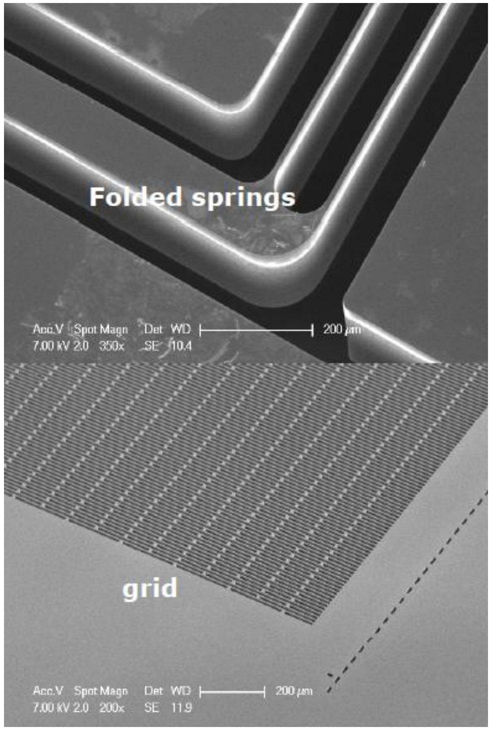


Micropower Harvesting Sources

- **Photovoltaic**
- **Vibration**
- **Thermal**
- **RF**



Electrostatic energy harvester



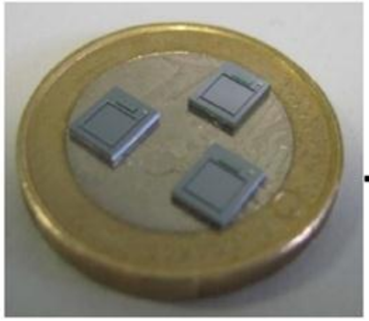
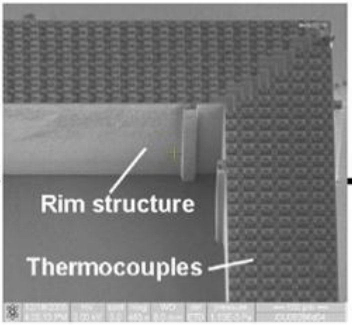
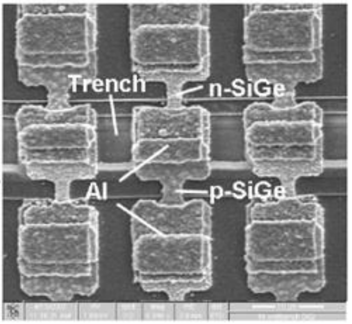


Photo of thermopile chips

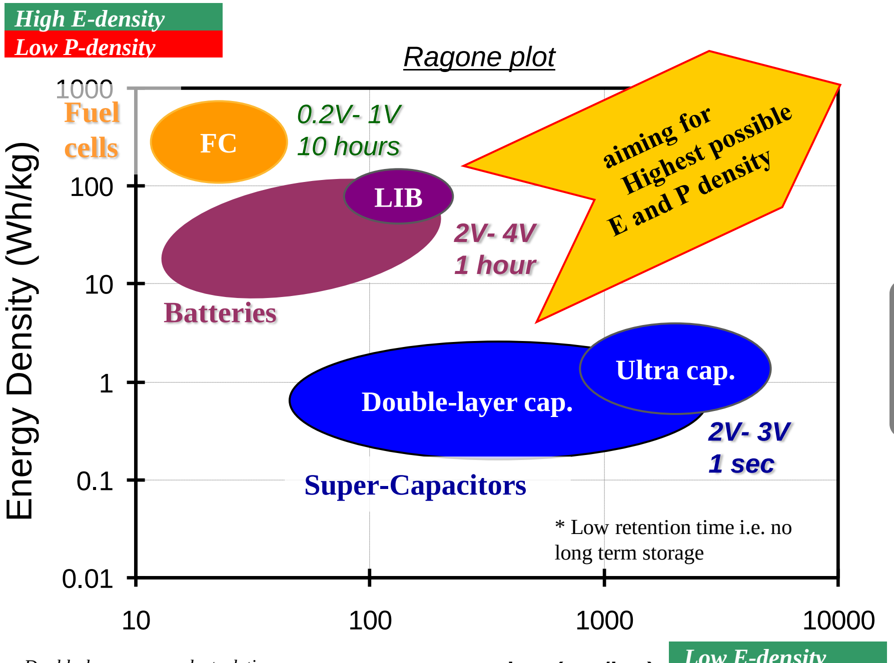


Zoom-in on a corner



Zoom-in on thermocouples

Energy storage



Double-layer caps= electrolytic
Ultra-capacitors = solid-state

Power Density (W/kg)

Low E-density
High P-density

Thin film	Battery packs	
Miniature	**Portable**	**Mobile**
<~1g	~10-100g	~1kg-100kg
<~0.1cm³	1-10cm³	0.1-1m³
10uAh-1mAh	10mAh-1Ah	10Ah-100Ah
disposable & autonomous systems	*portable electronics*	*automotive transportation*

~1 cm²; 1mAh

Emerging Technologies

Li-ion battery pack:
8cells
14.4V, 73Wh
(5A.h)

Tesla-Roadster (340km)

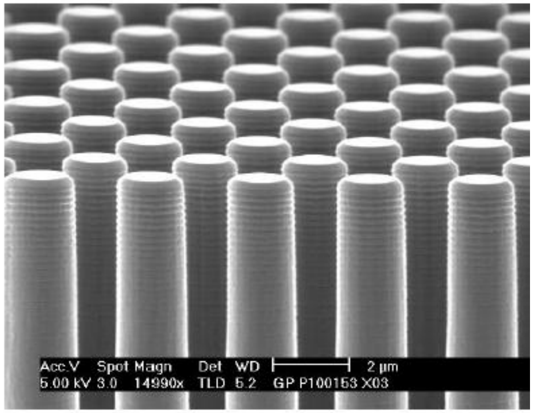
Li-ion battery pack:
450kg (200kW)
375V, 56kWh (eq. 8L gaz)
6800 cells (18mmx65mm)

Storage for micro systems:

- All Solid-State devices (integrated systems)
- Microelectronic fabrication techniques

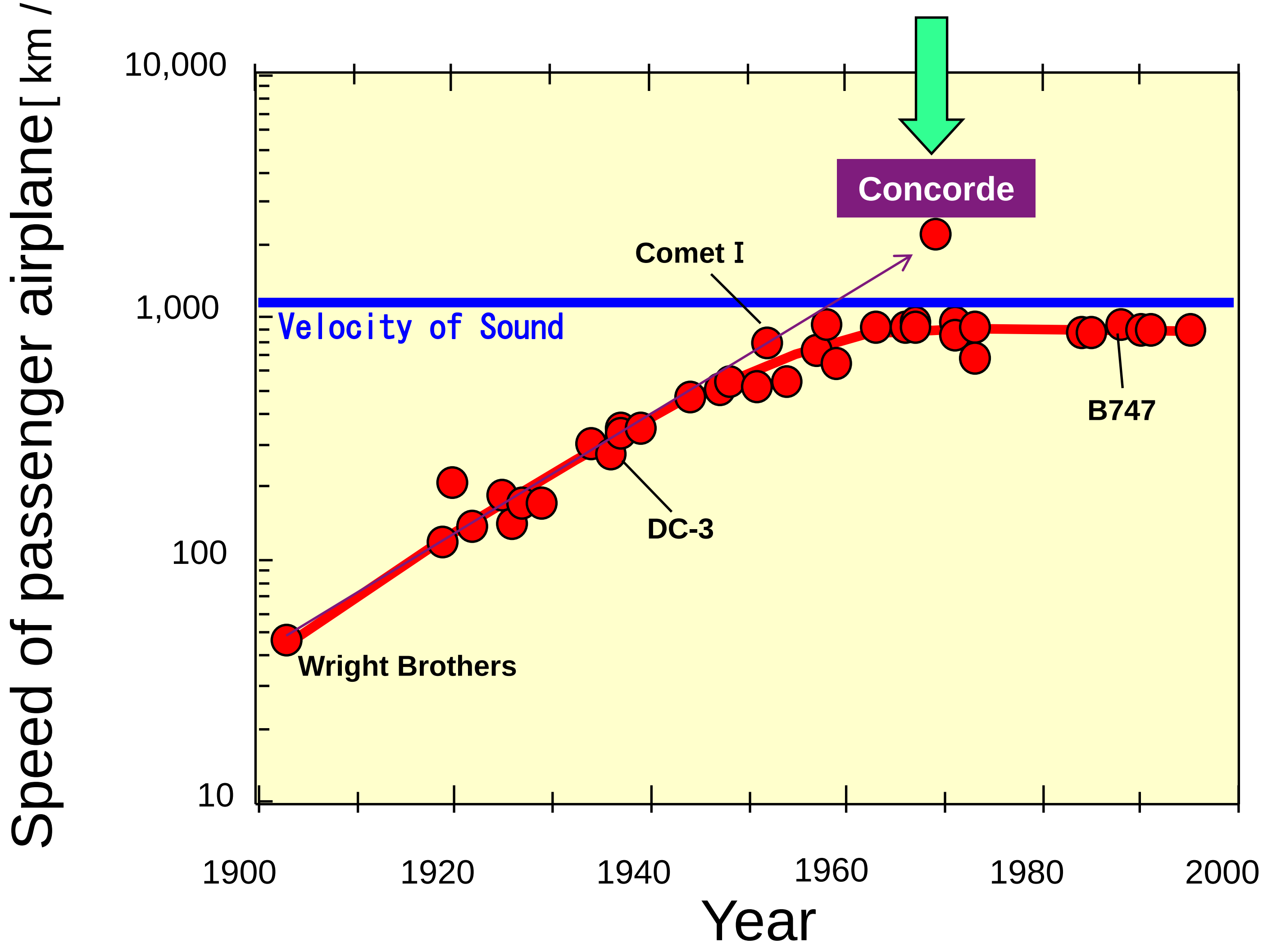
Size determines total capacity:

- High energy density even more important for small form systems



Where’s the elephant in the room ?

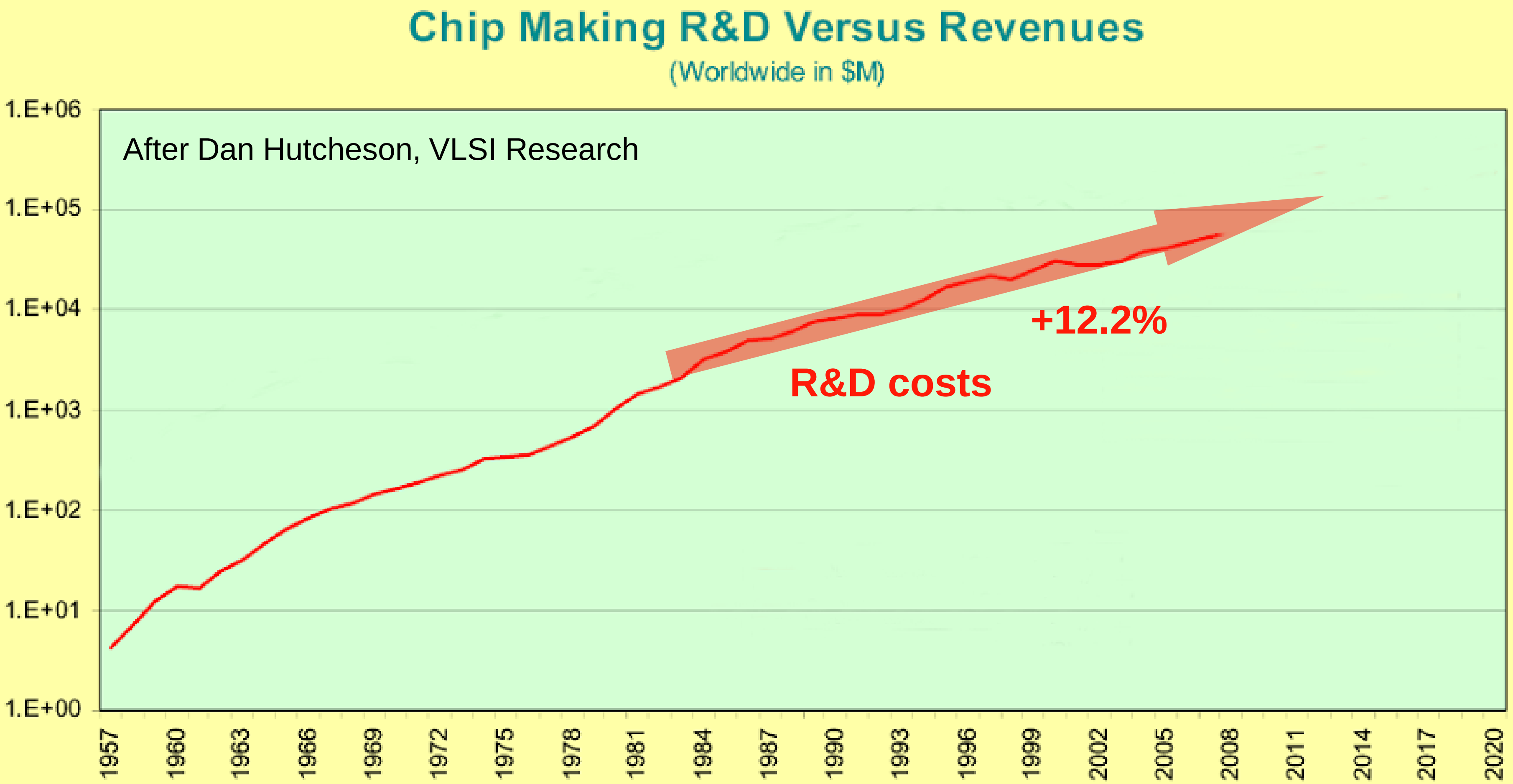
The importance of economics....



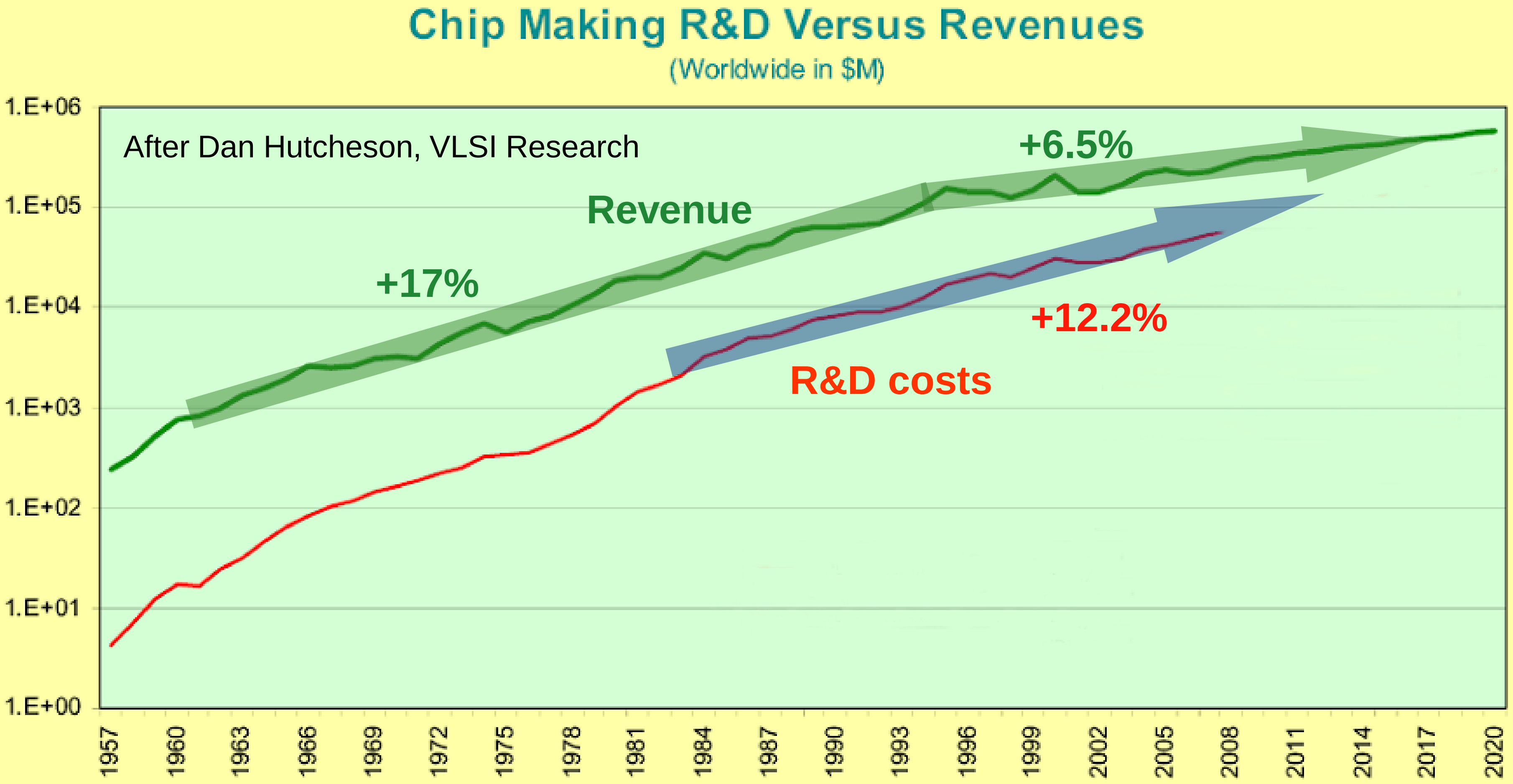
Progress of Passenger Airplane Speed

Source: Prof. Iwai

Cost of semiconductor research is increasing dramatically....



...while growth rate of semiconductor revenues is reduced



Joint multi-disciplinary R&D

… THE KEY TO INNOVATION

Conclusions

Will the transition be evolutionary or revolutionary ?

Continuous progress occurs, but once in a while small revolutions happen
(but often their importance is only recognized much later...)

Eugène Delacroix
Liberty leading the people (1830)

Will the transition be evolutionary or revolutionary ?

Continuous progress occurs, but once in a while small revolutions happen
(but often their importance is only recognized much later...)

- What will the driving forces be ?

  Value to customers (i.e. "More than Moore")
  Economics (boundary condition)

- How can simulation lead the way ?

  Theory starts to run ahead of experimental evidence
  In the world of quantum mechanics simulation is of key importance

- Could the transition be 'disruptive' ?

  Why not? (e.g. bio inspired systems...)

Who will be the winners and losers?

The winners will be the companies that see the revolution coming, quickly adapt to change and successfully team up in joint multi-disciplinary R&D to continuously innovate.

The losers will be everybody else....

ASPIRE
INVENT
ACHIEVE