



Moore & more than Moore

Péter Fürjes

E-mail: furjes@mfa.kfki.hu





SILICON (silex)

Moore & more than Moore - 2
furjes@mfa.kfki.hu



THE ELI

H 1 Hydrogen	He 2	Li 3 Lithium	Be 4 Beryllium
Na 11 Sodium	Mg 12 Magnesium	K 19 Potassium	Ca 20 Calcium
Rb 37 Rubidium	Sr 38 Strontium	Y 39 Yttrium	Zr 40 Zirconium
Cs 55 Cesium	Ba 56 Barium	La 57 Lanthanum	Ce 58 Cerium
Fr 87 Francium	Ra 88 Radium	Ac 89 Actinium	Th 90 Thorium

Radioactive elements

Photographs show samples of the pure or nearly pure element...
Other sizes of this poster: periodictable.com
Real samples like these: element-collection.com

B 5 10.81 Boron	C 6 12.011 Carbon	N 7 14.007 Nitrogen
Al 13 26.982 Aluminum	Si 14 28.085 Silicon	P 15 30.974 Phosphorus
Ga 31 69.723 Gallium	Ge 32 72.64 Germanium	As 33 74.922 Arsenic



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



SILICON (silex)

Moore & more than Moore - 3
furjes@mfa.kfki.hu

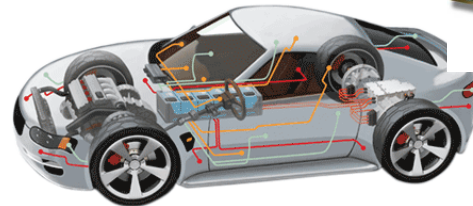
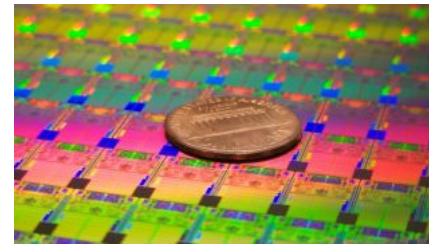
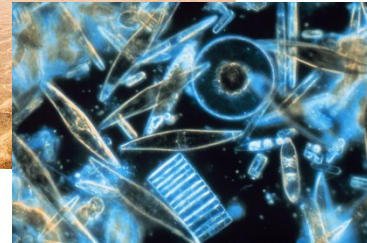


Discoverer: Jons Berzelius
1823, Sweden

Natural presence:
granite, quartz, clay, sand

2nd in incidence in the Earth

Other applications...



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



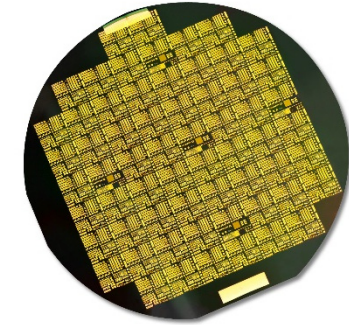
SILICON – as a chemical element

Moore & more than Moore - 4
furjes@mfa.kfki.hu



Si¹⁴
28.09

Silicon



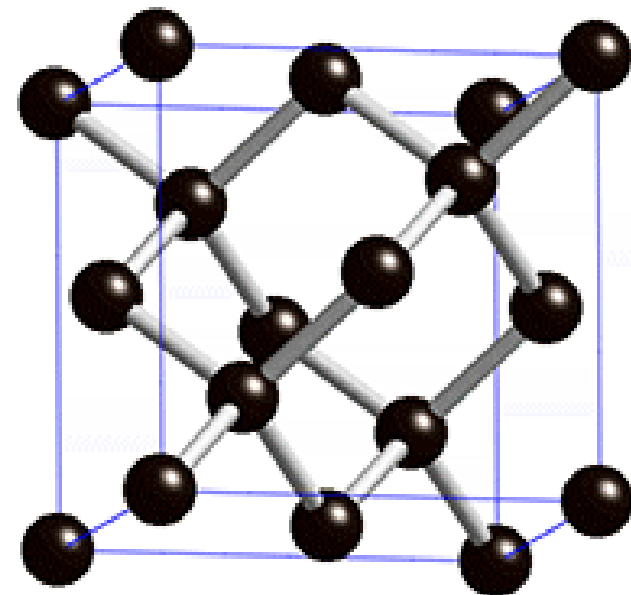
Properties: gray, metallic, extremely hard material

Atomic number: 14 (1s² 2s² 2p⁶ / 3s² 3p²)

4th group / tetravalent metalloid

Crystal: similar to diamond

Electronic property: semiconductor



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU

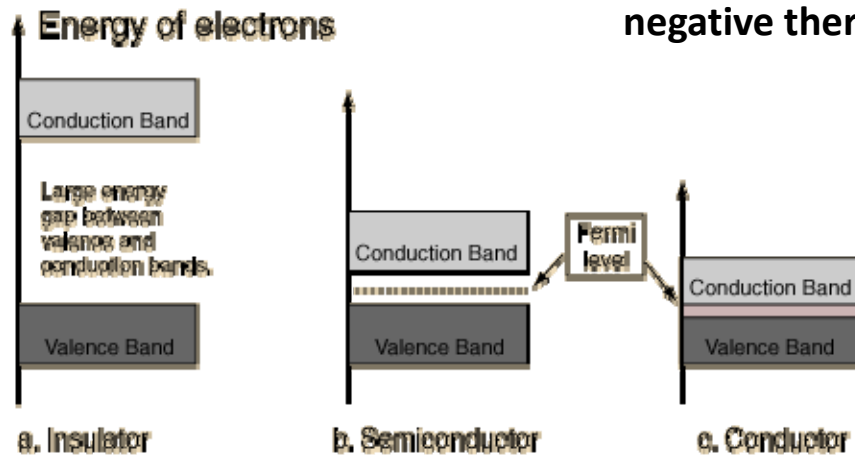


SEMICONDUCTORS

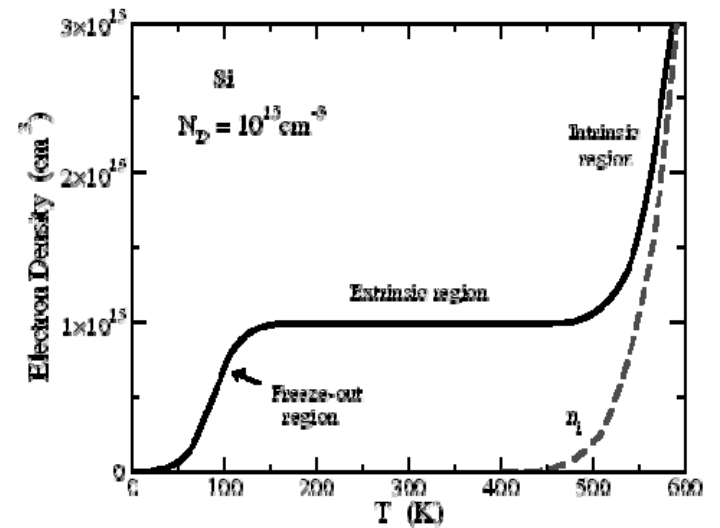
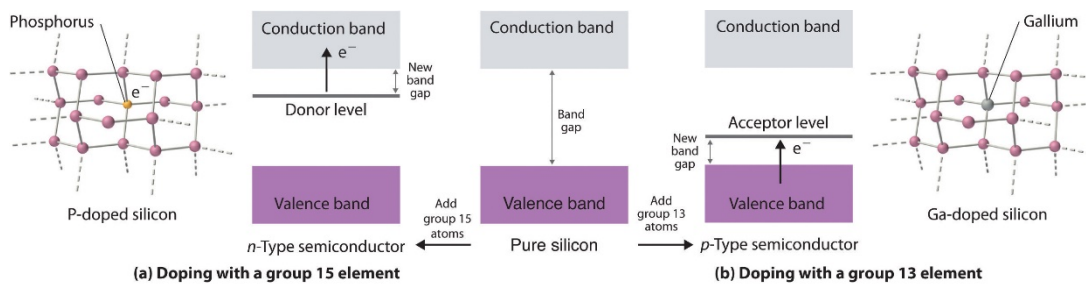
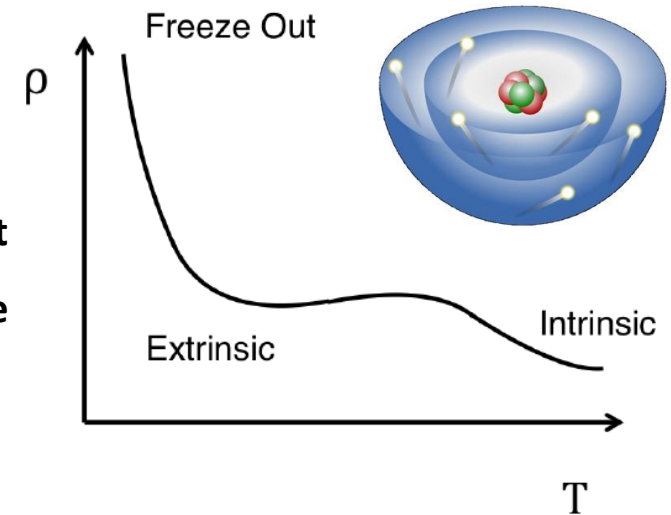
MEMS • BIOMEMS • NEMS

Resistance of semiconductors: $10^{-9} - 10^3 \text{ } \Omega\text{cm}$

How does the resistance change with the temperature?



negative thermal coefficient
of resistance



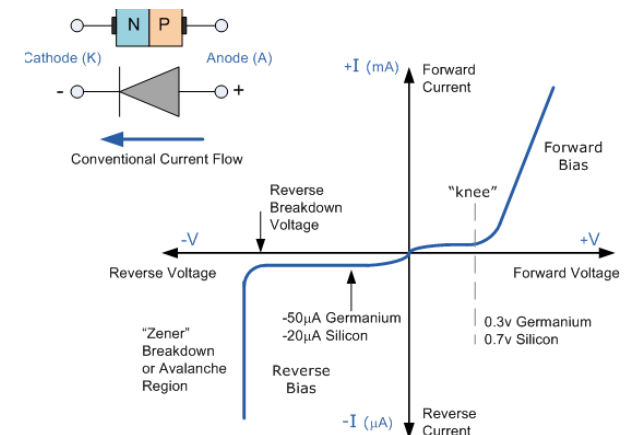
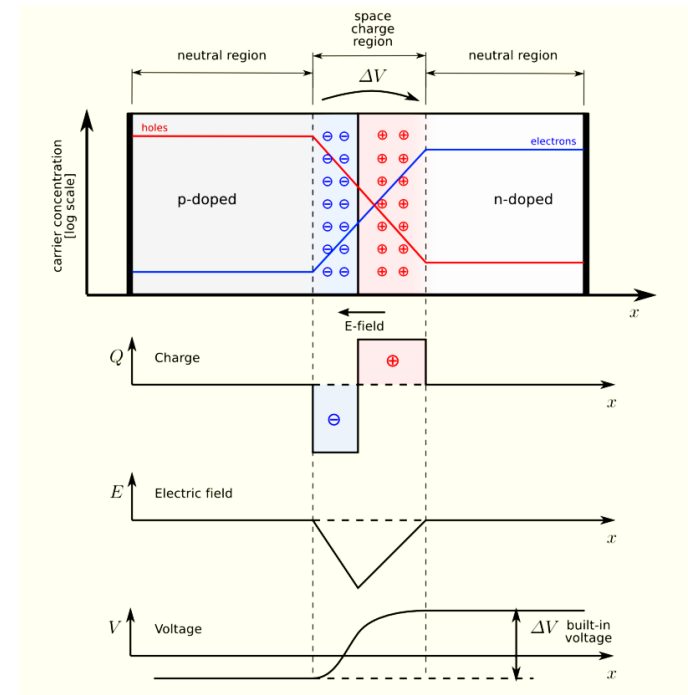
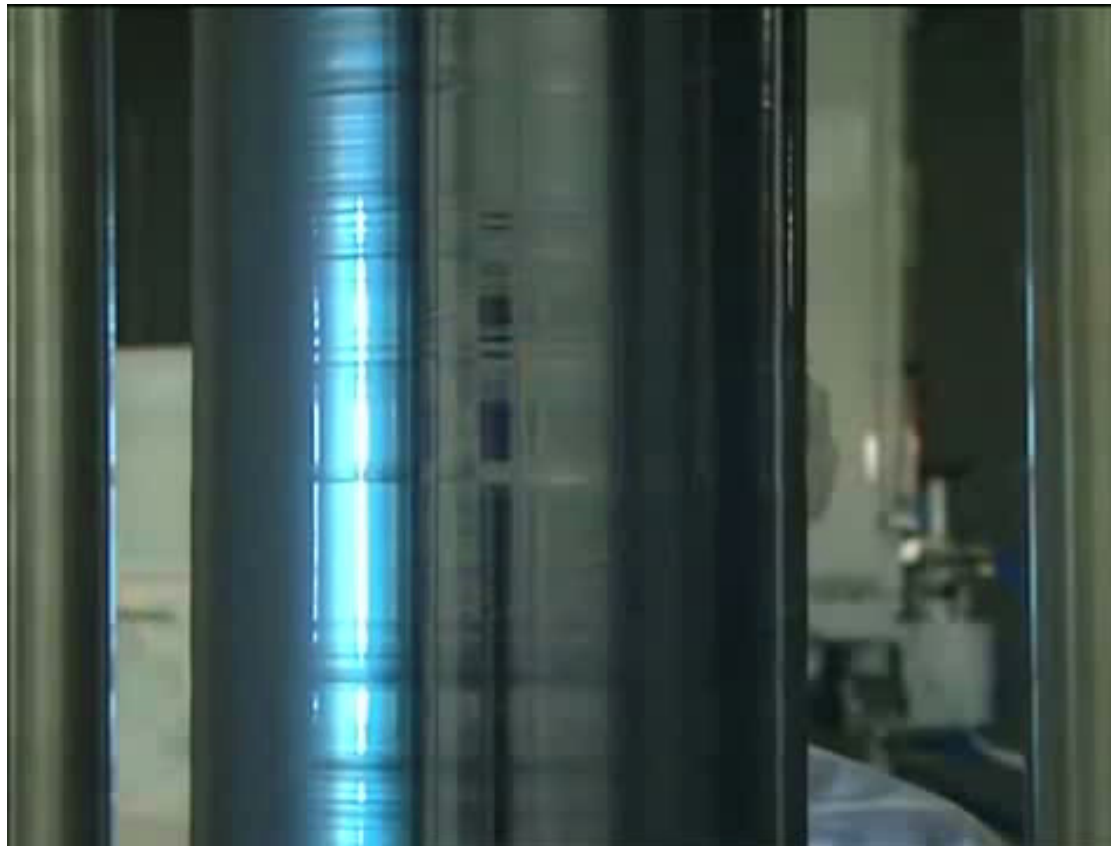


DIODE

MEMS • BIOMEMS • NEMS

Moore & more than Moore - 6
furjes@mfa.kfki.hu

**Doped semiconductors:
n-type (electron conductance)
and p-type (hole conductance)**



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



The Nobel Prize in Physics 1956



William Bradford Shockley
Prize share: 1/3



John Bardeen
Prize share: 1/3

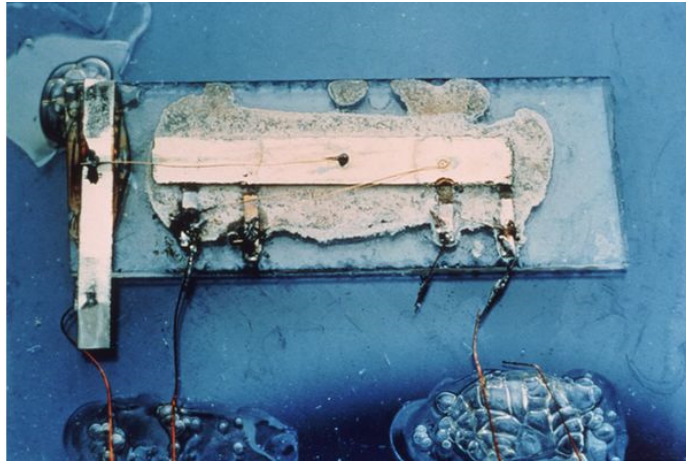


Walter Houser Brattain
Prize share: 1/3

The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain "for their researches on semiconductors and their discovery of the transistor effect".

Substitution of vacuum (electron) tube
Functions: switching / amplification / voltage stabilisation





- Transistor: solution for the problems of the vacuum (electron) tube (dissipation, reliability).
- Solution for connecting discrete devices (space saving).

The Nobel Prize in Physics 2000



Zhores I. Alferov
Prize share: 1/4



Herbert Kroemer
Prize share: 1/4



Jack S. Kilby
Prize share: 1/2

The Nobel Prize in Physics 2000 was awarded *"for basic work on information and communication technology"* with one half jointly to Zhores I. Alferov and Herbert Kroemer *"for developing semiconductor heterostructures used in high-speed- and opto-electronics"* and the other half to Jack S. Kilby *"for his part in the invention of the integrated circuit"*.

Photos: Copyright © The Nobel Foundation



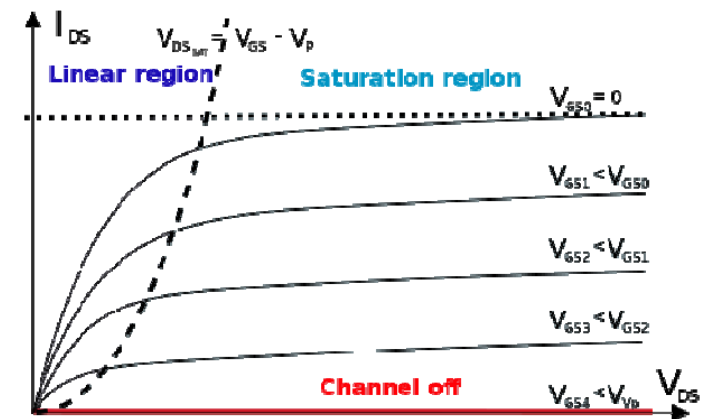
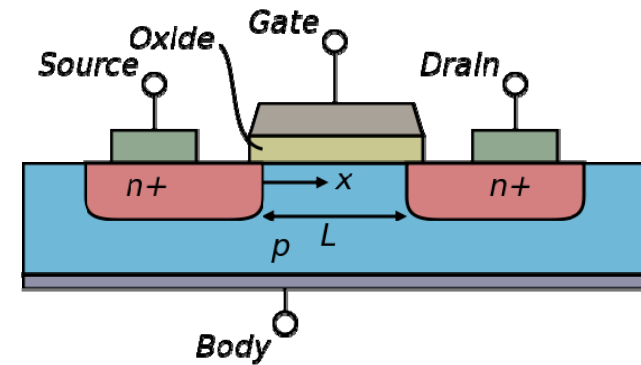
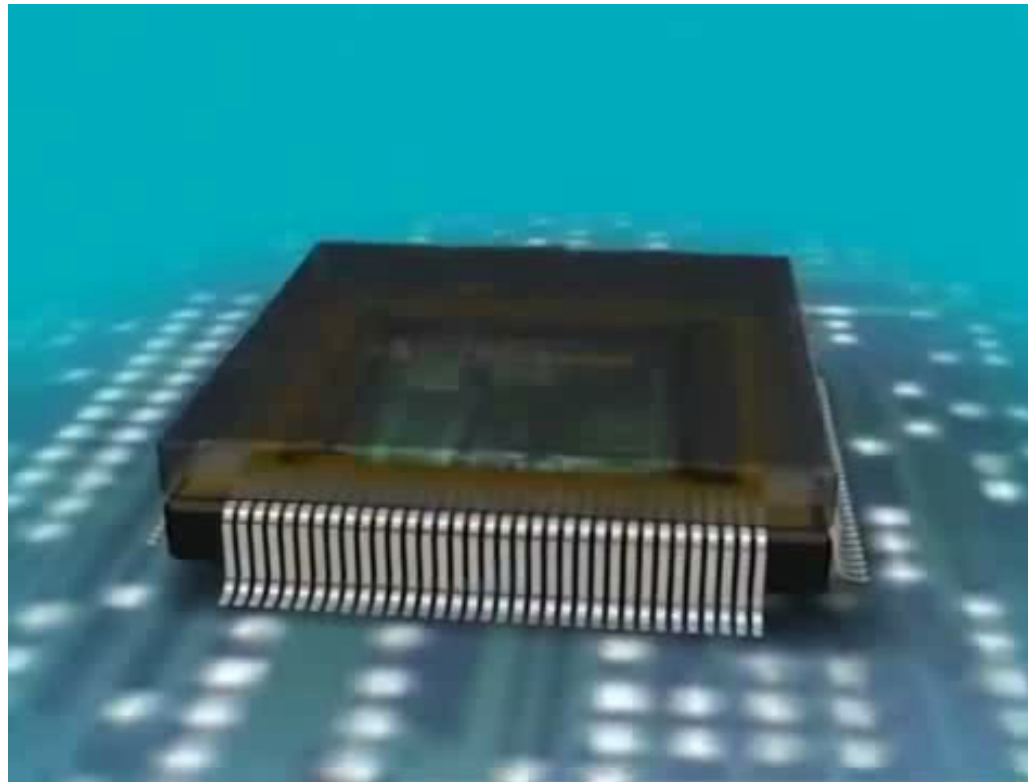


FIELD EFFECT TRANSISTOR (FET)

MEMS • BIOMEMS • NEMS

Main building block of CPU and memory

Functions: amplification (analog signals), switching



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences





COMPUTATION

Moore & more than Moore - 10
furjes@mfa.kfki.hu

MEMS • BIOMEMS • NEMS



MEMS • BIOMEMS • NEMS



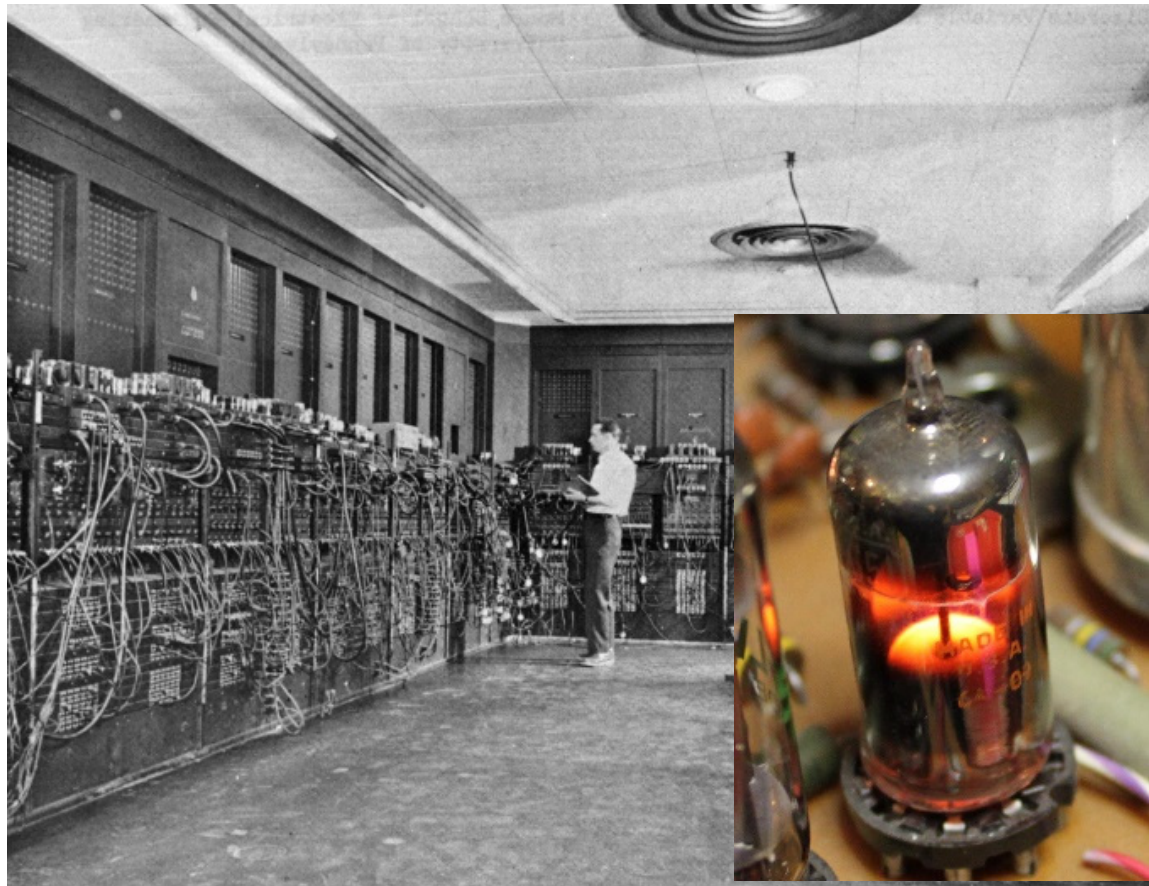
MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



Von Neumann, János (1903-1957)

ENIAC



Development of the logical architecture of the electronic computers, based on the binary system.

Basic elements: memory, program storage, command system





DEVELOPMENT of THE COMPUTATIONAL CAPACITY

Moore & more than Moore - 12
furjes@mfa.kfki.hu



1 The accelerating pace of change ...



2 ... and exponential growth in computing power ...

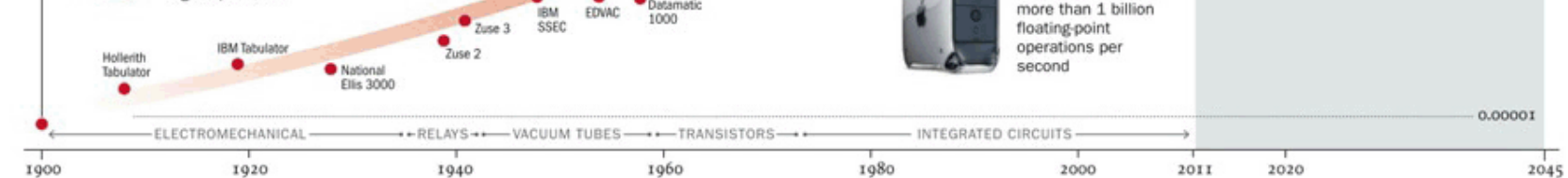
Computer technology, shown here climbing dramatically by powers of 10, is now progressing more each hour than it did in its entire first 90 years

COMPUTER RANKINGS

By calculations per second per \$1,000



Analytical engine
Never fully built, Charles Babbage's invention was designed to solve computational and logical problems



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



HOW MANY TRANSISTOR CAN BE PLACED ON A CHIP?

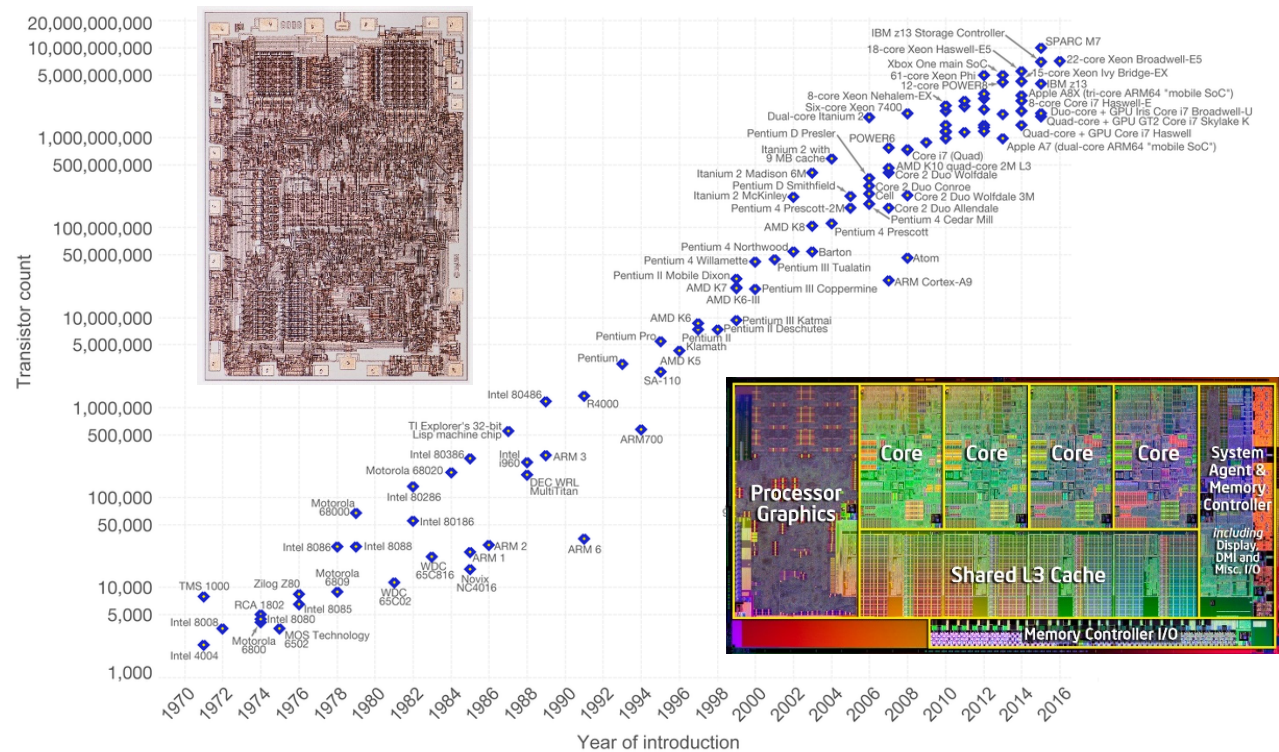


Gordon Moore (1965)

Moore's Law – The number of transistors on integrated circuit chips (1971-2016)



Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are strongly linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at [OurWorldinData.org](https://www.ourworldindata.org). There you find more visualizations and research on this topic.

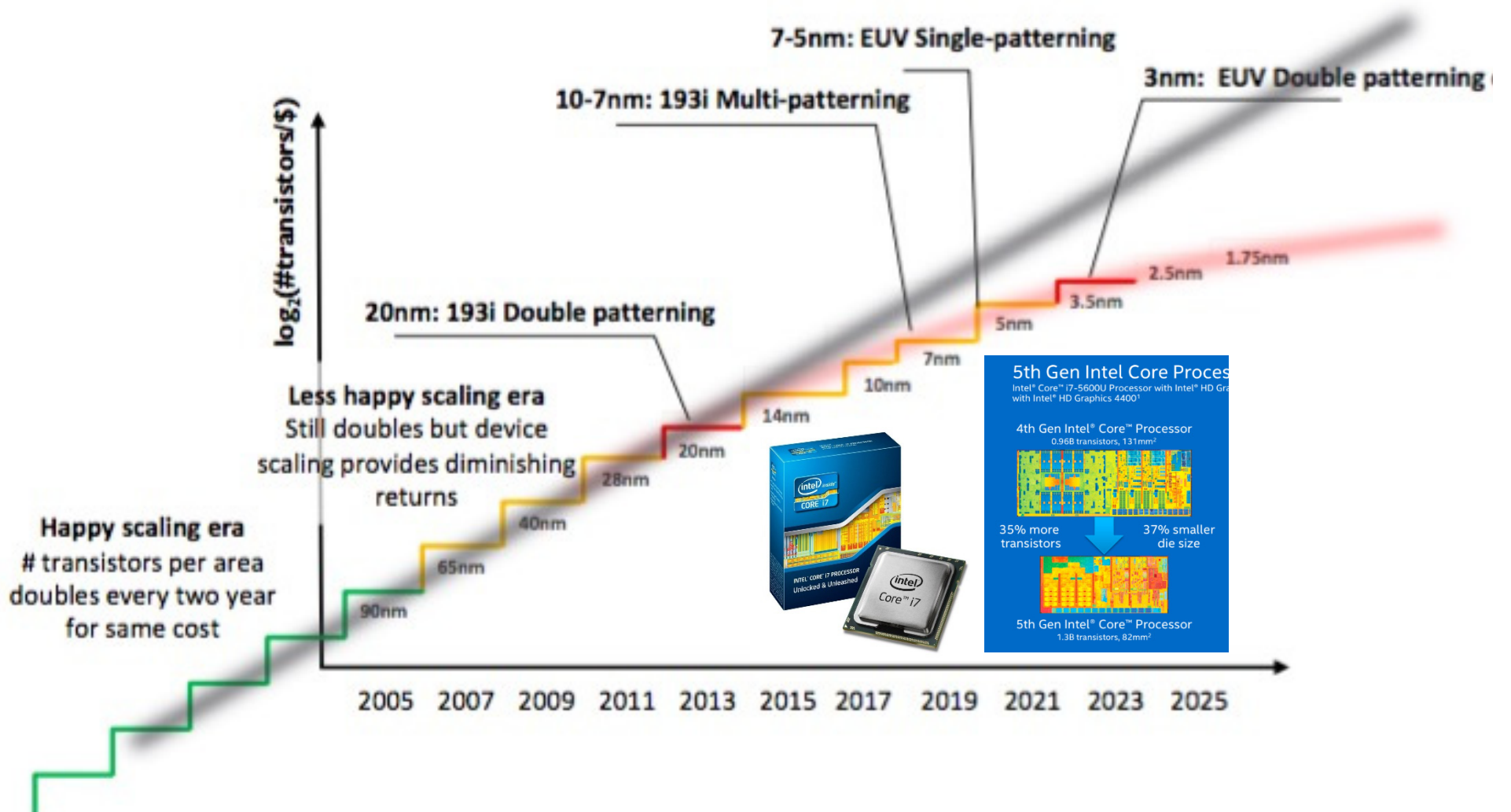
Licensed under CC-BY-SA by the author Max Roser.





TECHNOLOGY DEVELOPMENT

MEMS • BIOMEMS • NEMS



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences



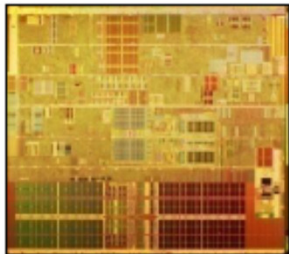
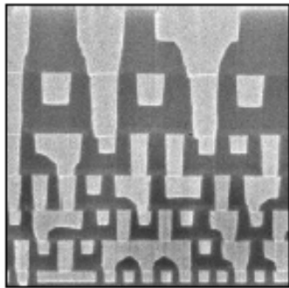
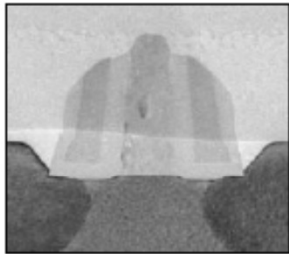


INTEL 2003 - 2011

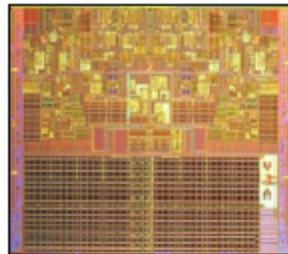
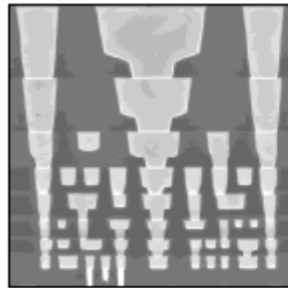
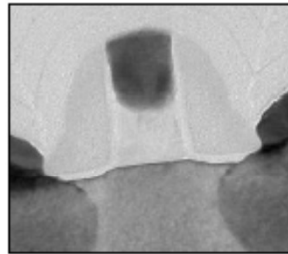
Moore & more than Moore - 15
furjes@mfa.kfki.hu



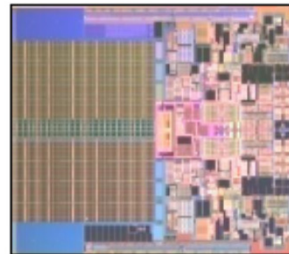
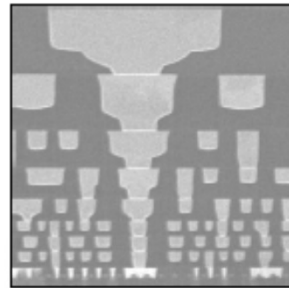
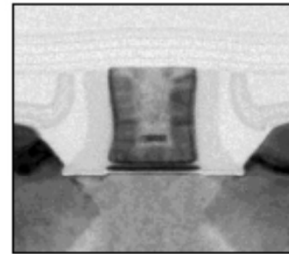
90 nm
2003



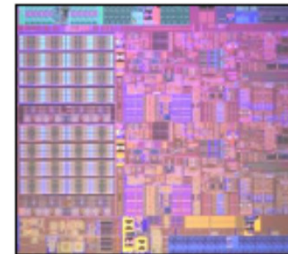
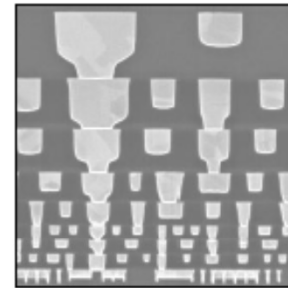
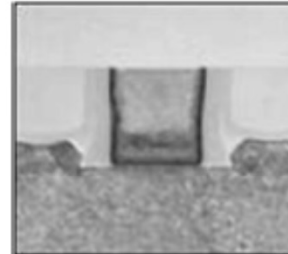
65 nm
2005



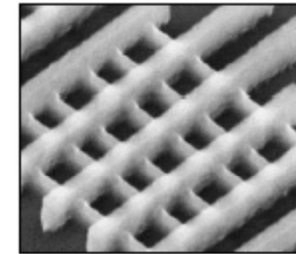
45 nm
2007



32 nm
2009



22 nm
2011



**3D TRI-GATE
transistor**



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



TECHNOLOGY: from SAND to PROCESSOR

Moore & more than Moore - 16
furjes@mfa.kfki.hu

MEMS • BIOMEMS • NEMS



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences



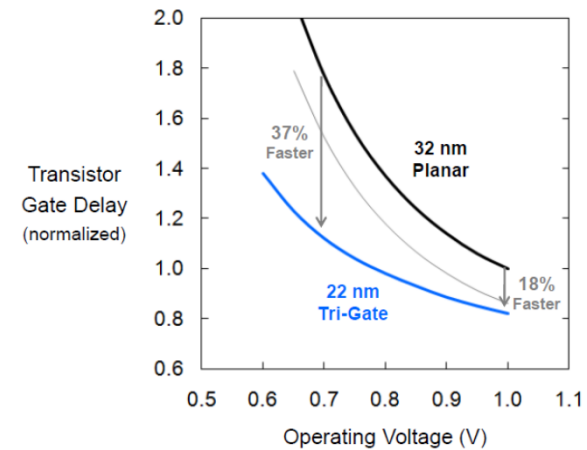
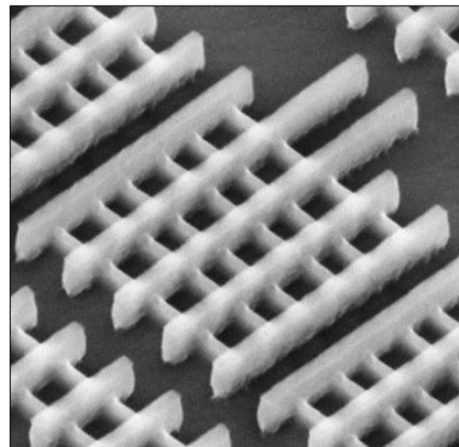
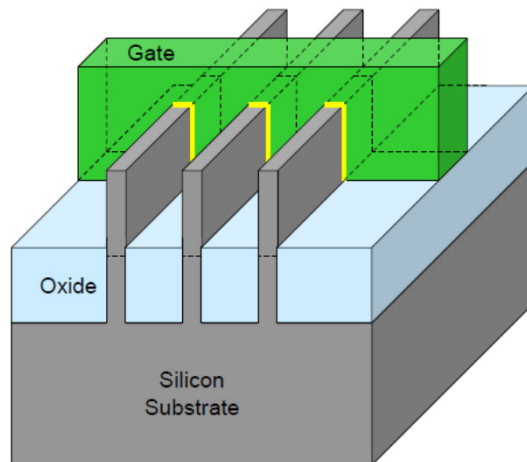
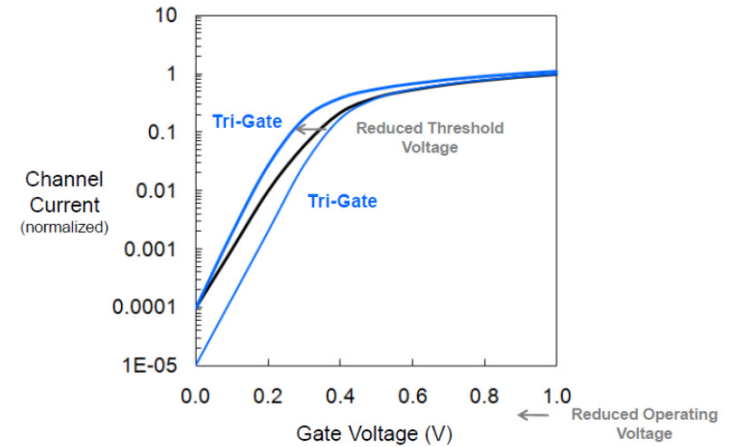
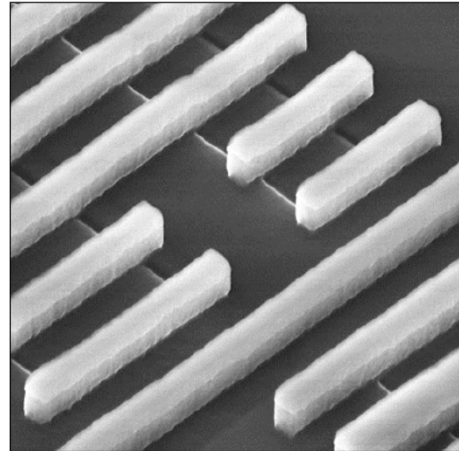
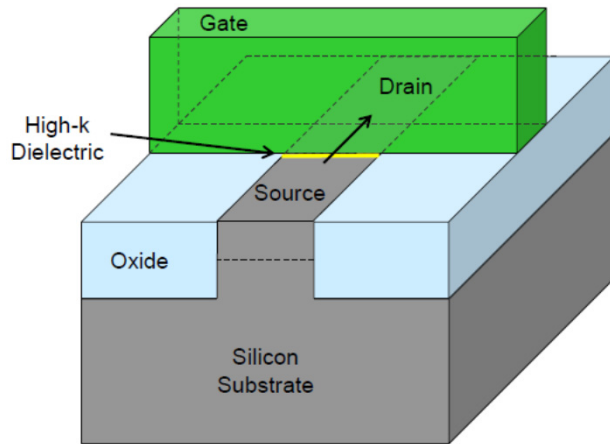
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



PLANAR vs. 3D TRANSISTOR

MEMS • BIOMEMS • NEMS



MEMS • BIOMEMS • NEMS





TECHNOLOGY: from SAND to PROCESSOR (2011)

Moore & more than Moore - 18
furjes@mfa.kfki.hu

MEMS • BIOMEMS • NEMS



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences



MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

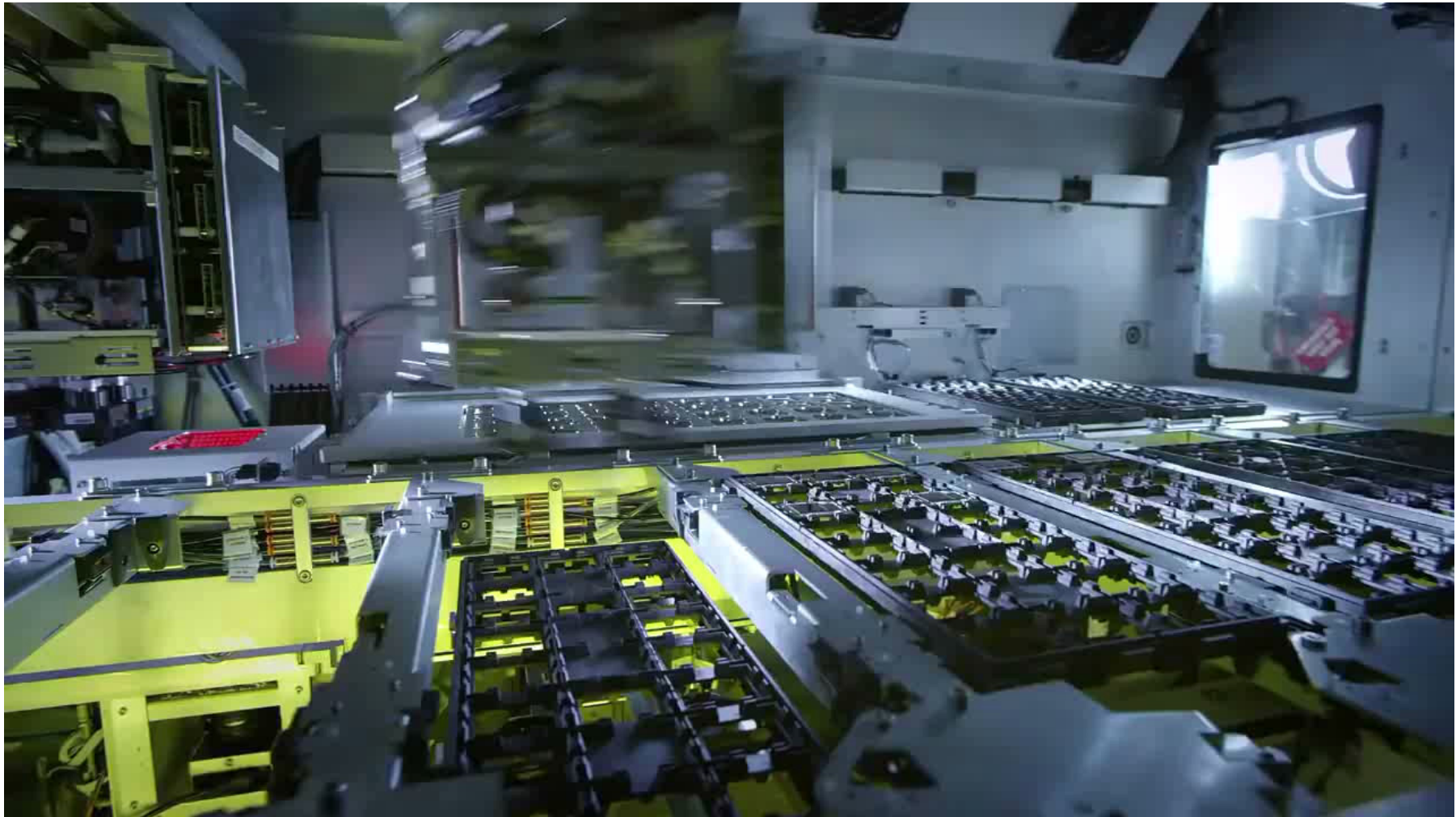
MEMS.HU
BIOMEMS.HU



INFRASTRUCTURE – MICRO / NANO – INTEL FAB

Moore & more than Moore - 19
furjes@mfa.kfki.hu

MEMS • BIOMEMS • NEMS



MEMS • BIOMEMS • NEMS



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



MORE THAN MOORE

MEMS:

Revolution of SENSORS

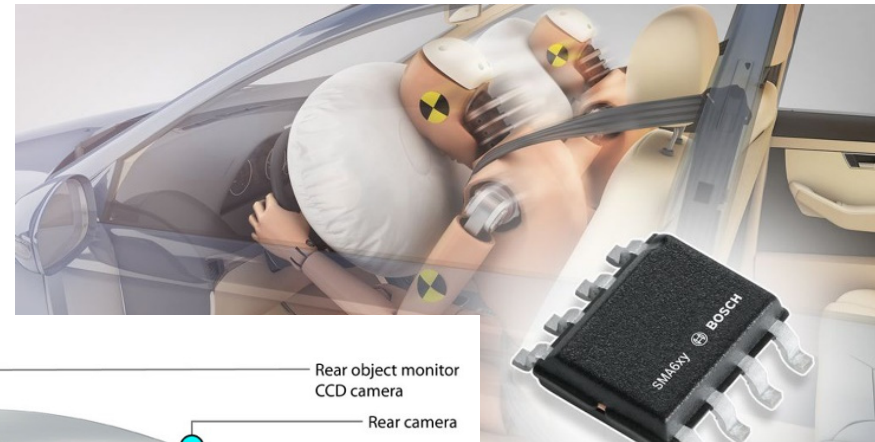




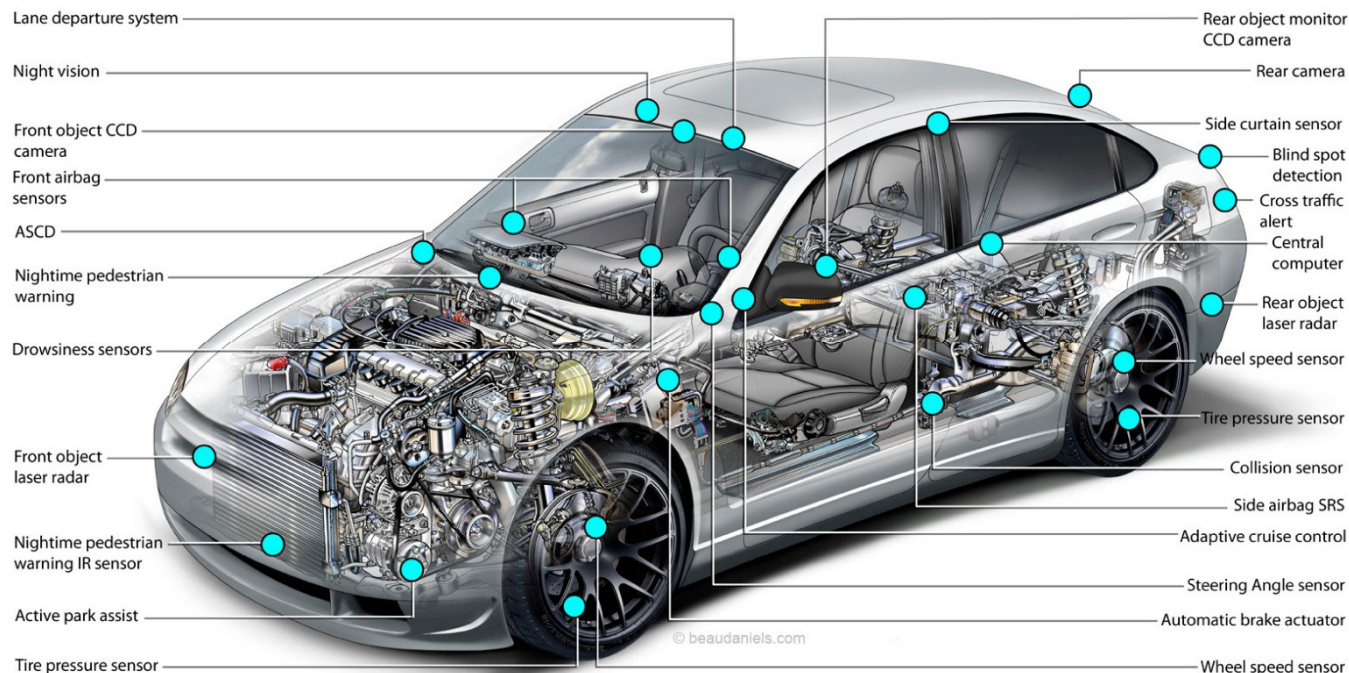
MEMS: micro-electromechanical systems

Example: automotive applications

- Engine / gear diagnostics and control
- Life- and traffic safety
- Comfort



Vehicle Sensors



© beaudaniels.com





GUESS WHO?

Moore & more than Moore - 22
furjes@mfa.kfki.hu

MEMS • BIOMEMS • NEMS

Steve Jobs

APPLE





Apple II (1977):



Lisa (1983):



Macintosh (1984):



NeXT (1989):



iMac (1998):



iPod (2001):



iPhone (2007):



iPad (2010):

MEMS • BIOMEMS • NEMS



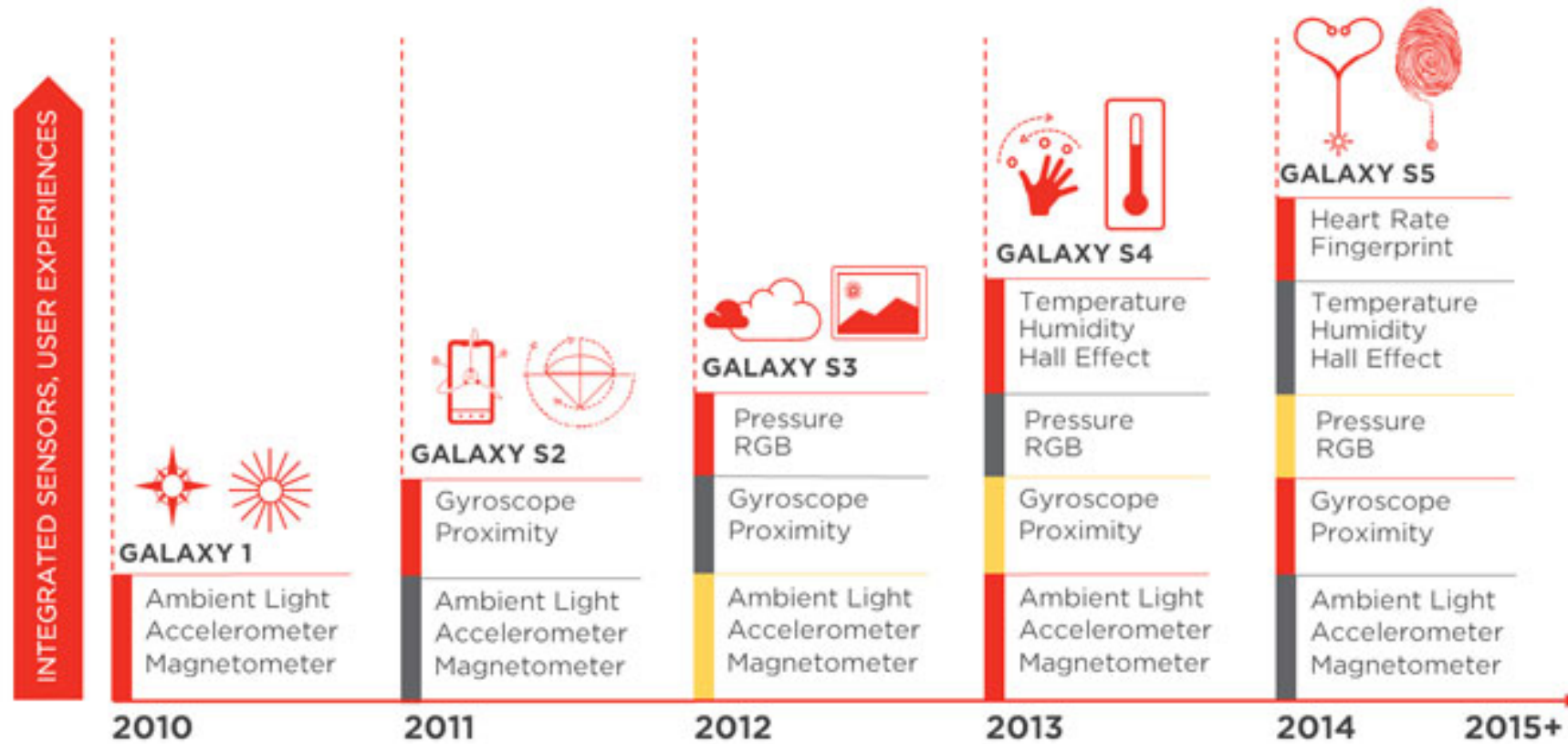
MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



MEMS • BIOMEMS • NEMS

SENSOR GROWTH IN SMARTPHONES



Sources: Driven by Apple and Samsung, Light Sensors Achieve Double-Digit Revenue Growth, IHS, June 30, 2013; MEMS: Looking back at 2014 and 5 years outlook, IHS, November 2014; Light and Proximity Sensors - A Market Ready for Explosive Growth, Tony Rizzo, Mobility TechZone, July 30, 2013; iPhone 6 Teardown, iFixit, 2014; Apple 3GiPhone Teardown Report, Portelligent, 2008; MEMS Microphone Market Tops 2 Billion Units, Mobile Dev Design, March 4, 2013

MEMS • BIOMEMS • NEMS



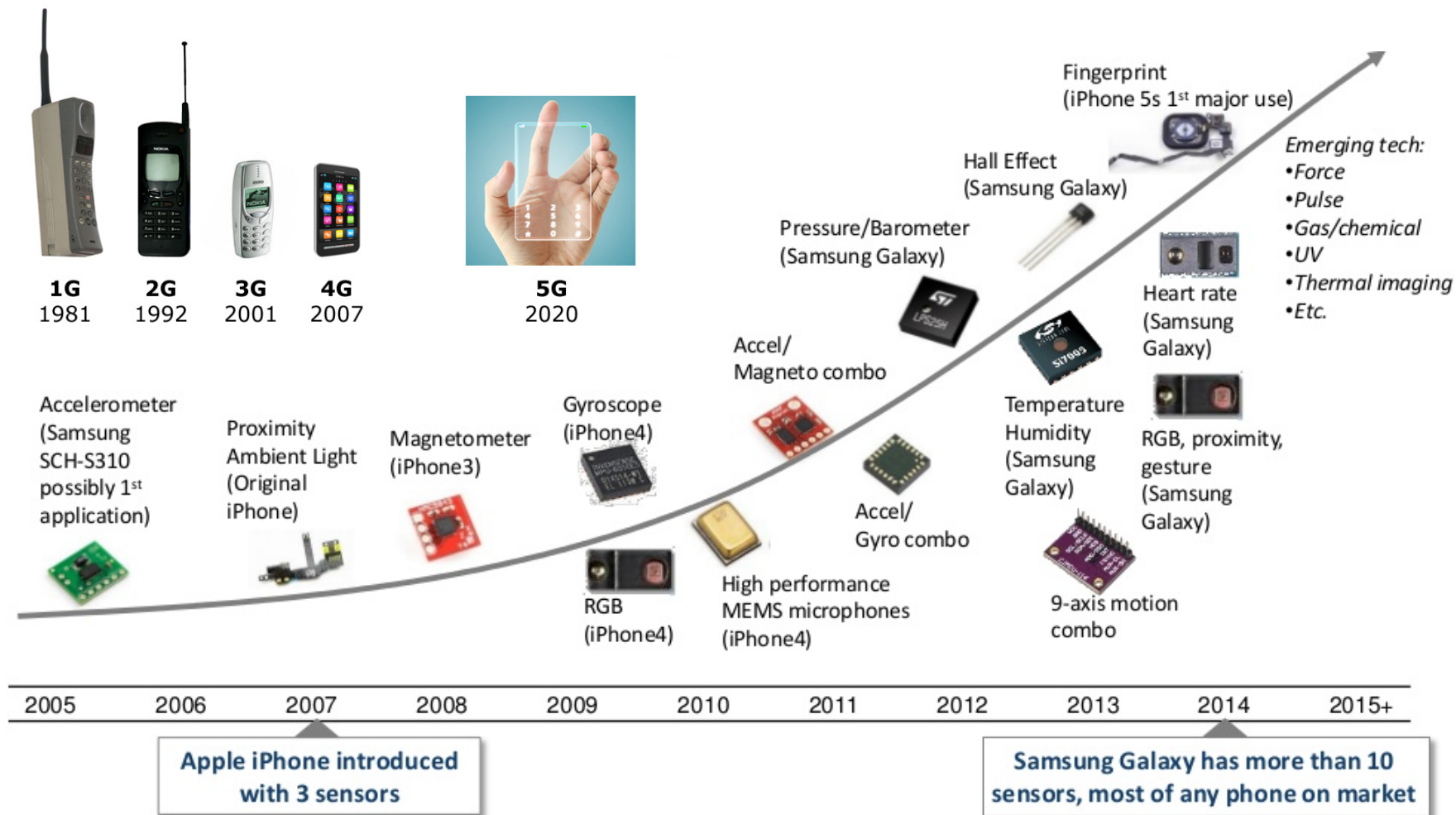
MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



SMARTPHONE'S FUTURE

MEMS • BIOMEMS • NEMS



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

MEMS • BIOMEMS • NEMS



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

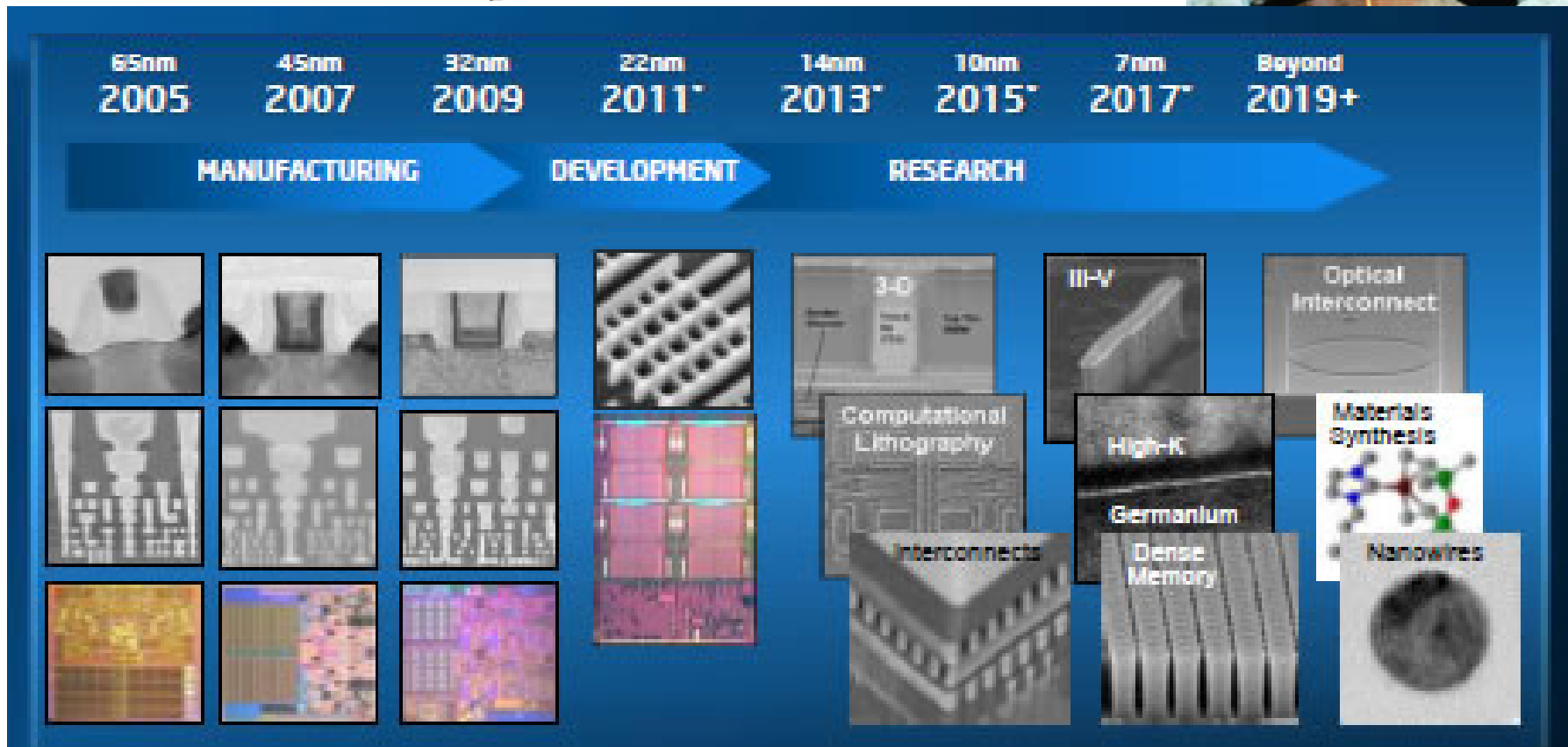
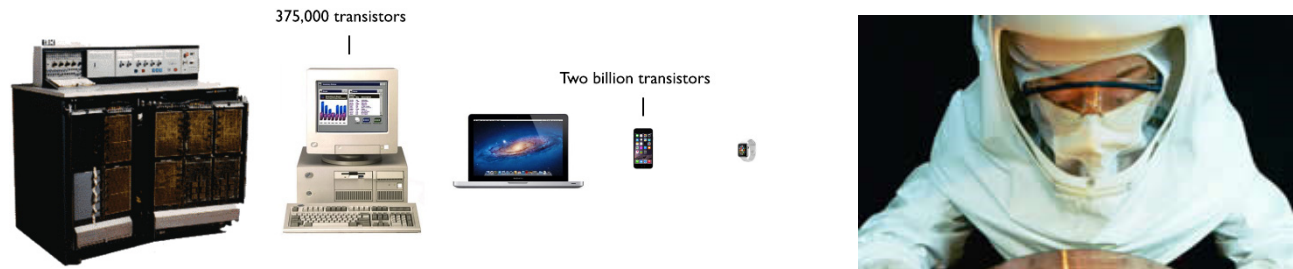
MEMS.HU
BIOMEMS.HU



BEYOND MOORE LAW ???

Moore & more than Moore - 25
furjes@mfa.kfki.hu

MEMS • BIOMEMS • NEMS



MEMS • BIOMEMS • NEMS



MEMS Lab • Institute of Technical Physics and Material Sciences • Centre for Energy Research • Hungarian Academy of Sciences
MEMS Lab • Műszaki Fizikai és Anyagtudományi Intézet • Energiatudományi Kutatóközpont • Magyar Tudományos Akadémia

MEMS.HU
BIOMEMS.HU



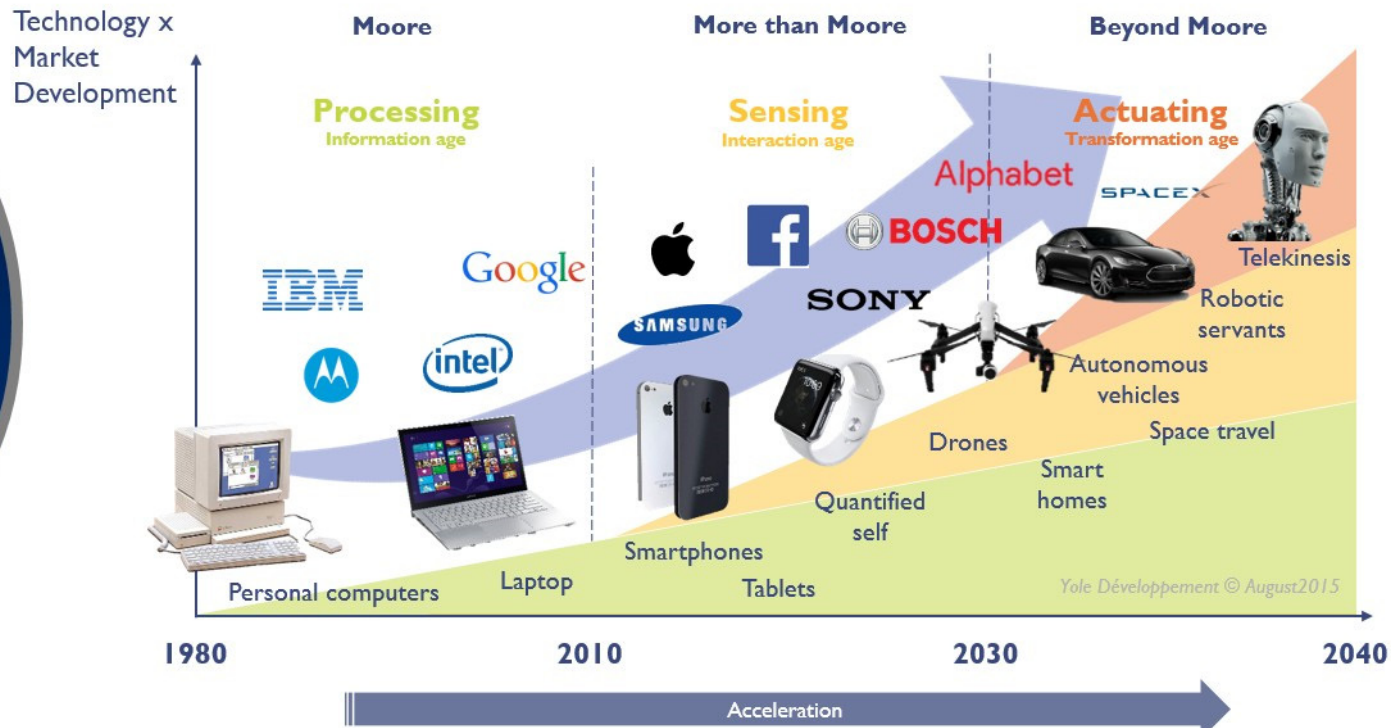
BEYOND MORE THAN MOORE ???

MEMS • BIOMEMS • NEMS

GLOBAL TECHNOLOGY ROADMAP

Moore and beyond: from information to interaction and transformation

MEMS & Sensors enable key functionalities, which are the current battleground of the industry



MEMS • BIOMEMS • NEMS

