Is Silicon Age Coming to an End…?

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END OF THE WORLD 2012
16 days until December 21, 2012

- **2010- , ETHZ, Zürich (CH)**
  Senior Research Scientist

- **2007-2010, EMPA, Dübendorf (CH)**
  Research Scientist

- **2005-2007, EPFL, Lausanne (CH)**
  Scientific Collaborator

- **2002-2005, PSI, Villigen (CH)**
  Postdoctoral Scientist

- **1998-2002, TU-Delft, Delft (NL)**
  2002 PhD
  Research Assistant and PhD student

- **1996-1998, NIRDIMT, Cluj-Napoca (RO)**
  Research Assistant

- **1995-1996, EPFL, Lausanne (CH)**
  Grant from European Physical Society

- **1990-1995 "Babeş-Bolyai" Univ, Cluj-Napoca (RO)**
  1995 Engineer in Physics

  Victor Babeş – *one of the earliest bacteorologists (19th century)*

  Janos Bolyai – *one of the founders of non-euclidian geometry (19th century)*

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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PSI
PAUL SCHERRER INSTITUT

TUDelft

I.N.C.D.T.I.M.

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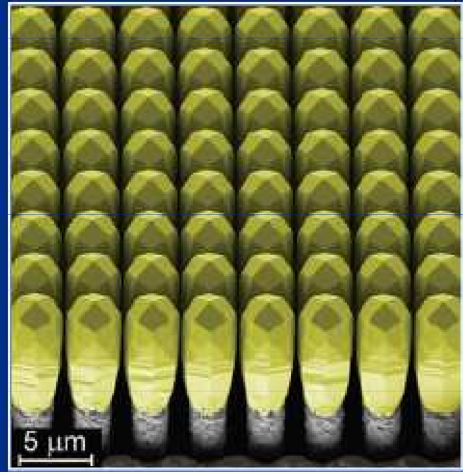
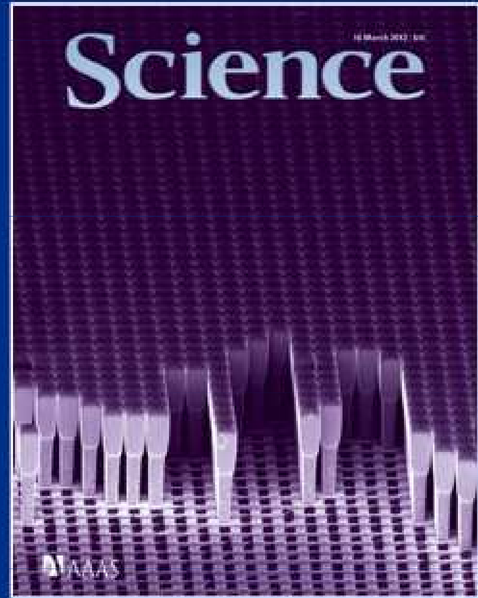
Positron Annihilation 2D-ACAR

TUDelft
Delft University of Technology

Si/Ge Heteroepitaxy





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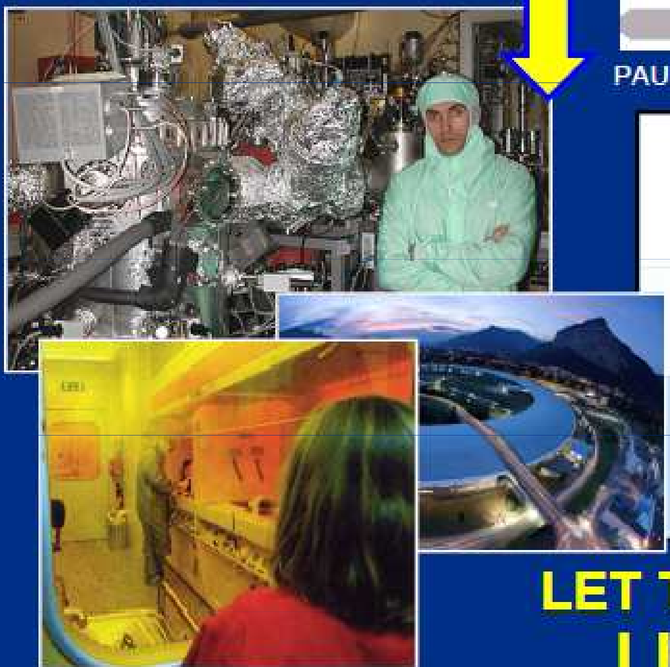
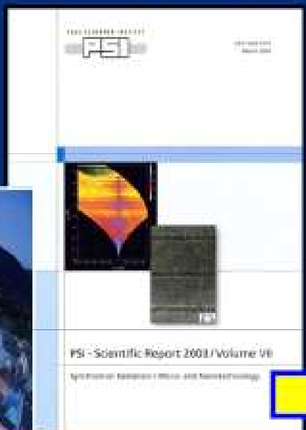
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

PSI
PAUL SCHERRER INSTITUT





LET THERE BE
LIGHT …

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COATINGS

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FÉDÉRALE DE LAUSANNE

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von
el

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Academic Ranking of World Universities in Natural Sciences and Mathematics - 2012

World Rank	Institution	Country /Region	Total Score
1	Harvard University	USA	100
2	University of California, Berkeley	USA	95.6
3	Princeton University	USA	93
4	California Institute of Technology	USA	92.8
5	Massachusetts Institute of Technology (MIT)	USA	91
6	University of Cambridge	UK	90.5
7	Stanford University	USA	90.2
8	**Swiss Federal Institute of Technology Zurich**	**Switzerland**	**74.7**
9	The University of Tokyo	Japan	73.1
10	University of California, Los Angeles	USA	72.8
11	Columbia University	USA	71.6
12	University of Colorado at Boulder	USA	71.4
12	University of Oxford	UK	71.4
14	Cornell University	USA	69

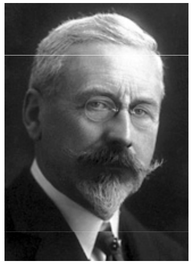
21 Nobel Prize Laureates of ETH Zürich

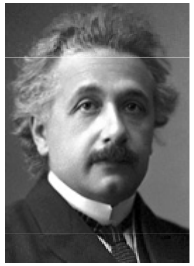
W.K. Röntgen
Physics 1901


A. Werner
Chemistry 1913


R. Willstätter
Chemistry 1915


F. Haber
Chemistry 1918


C.-E. Guillame
Physics 1918


A. Einstein
Physics 1921


P. Debye
Chemistry 1936


R. Kuhn
Chemistry 1938


L. Ruzicka
Chemistry 1938

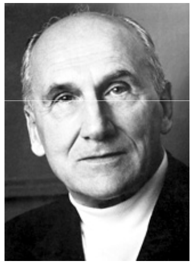

O. Stern
Physics 1943


W. Pauli
Physics 1945


T. Reichstein
Medicine 1950

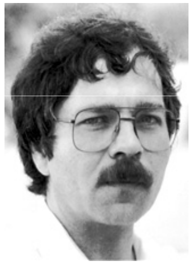

F. Bloch
Physics 1952

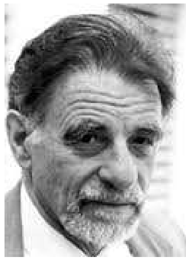

H. Staundinger
Chemistry 1953

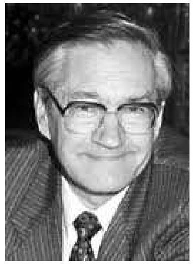

V. Prelog
Chemistry 1975


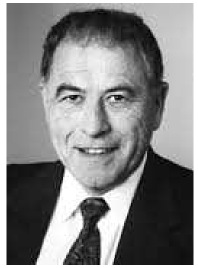
W. Arber
Medicine 1978


H. Rohrer
Physics 1986


G. Bednorz
Physics 1987


A. Müller
Physics 1987


R. Ernst
Chemistry 1991


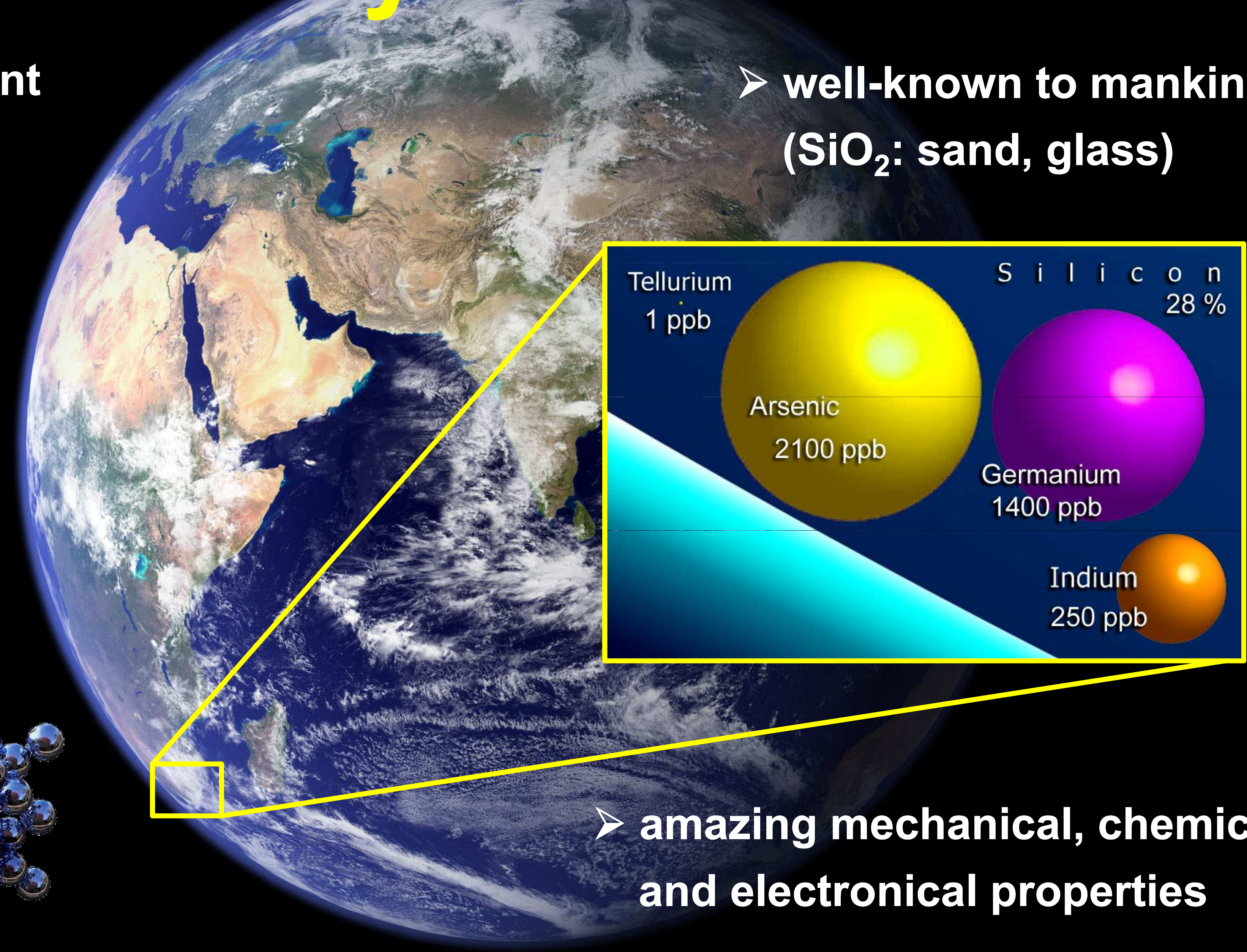
K. Wüthrich
Chemistry 2002


10 Chemistry, 9 Physics, 2 Medicine

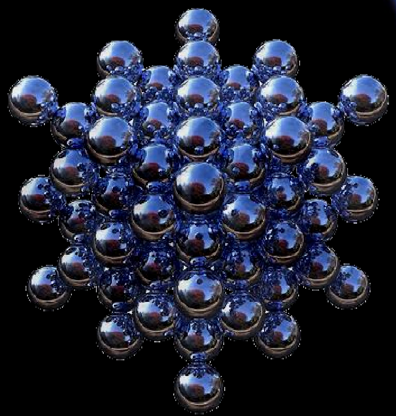
The Age of Silicon

Why Silicon?

- abundant
- cheap
- well-known to mankind (SiO_2: sand, glass)

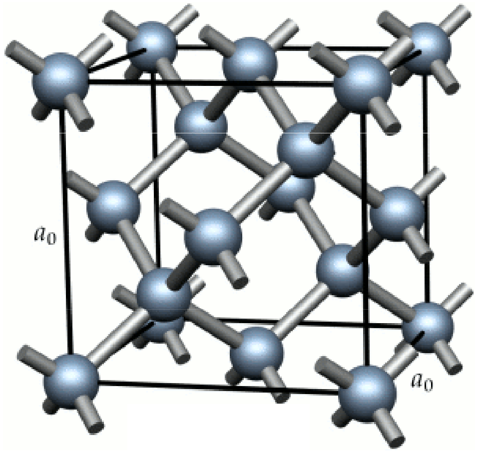


$^{28}_{14}Si$

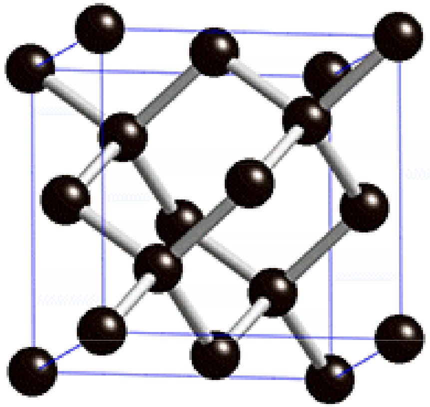


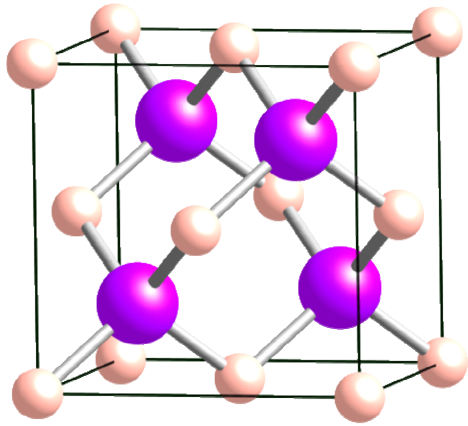
- amazing mechanical, chemical and electronical properties

Crystal Structures



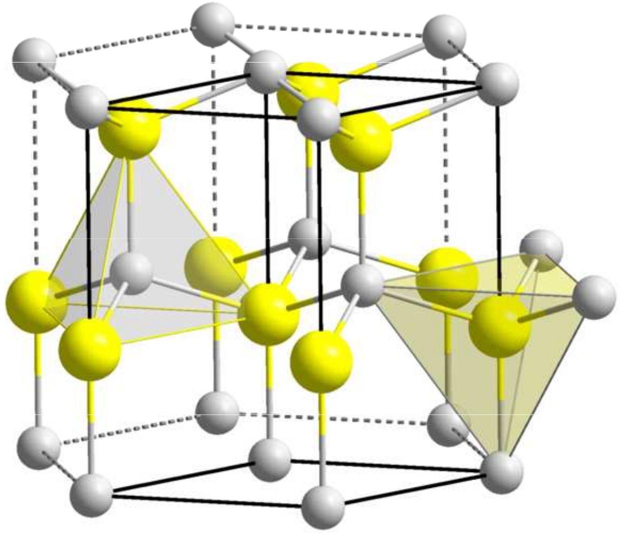
Diamond Structure
(Si, Ge)





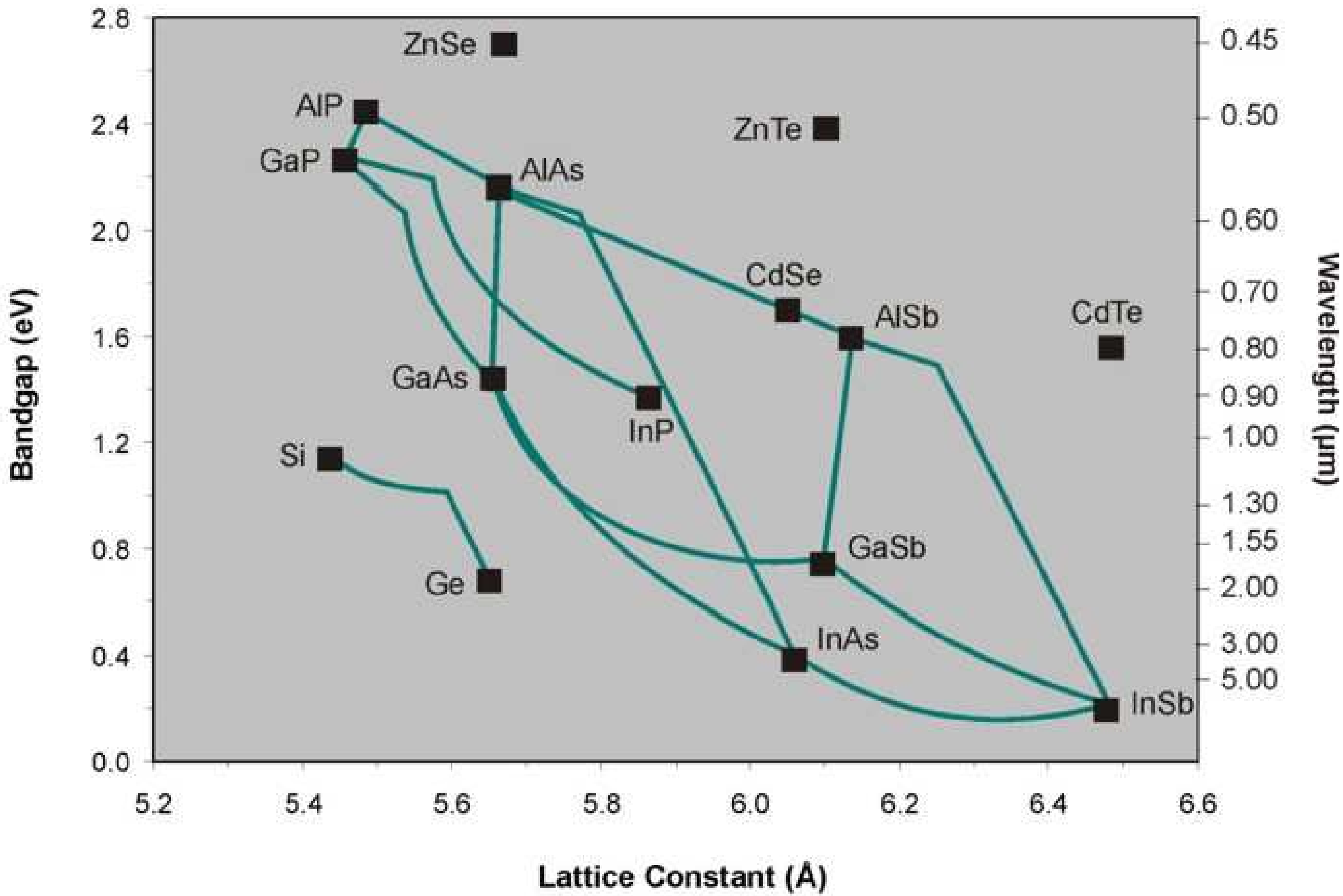
Zincblende Structure
(GaAs, InP, GaP, etc.)

I	II	III	IV	V	VI	VII
	Be	B	C	N	O	F
	Mg	Al	Si	P	S	Cl
Cu	Zn	Ga	Ge	As	Se	Br
Ag	Cd	In	Sn	Sb	Te	I
	Hg	Tl	Pb	Bi		

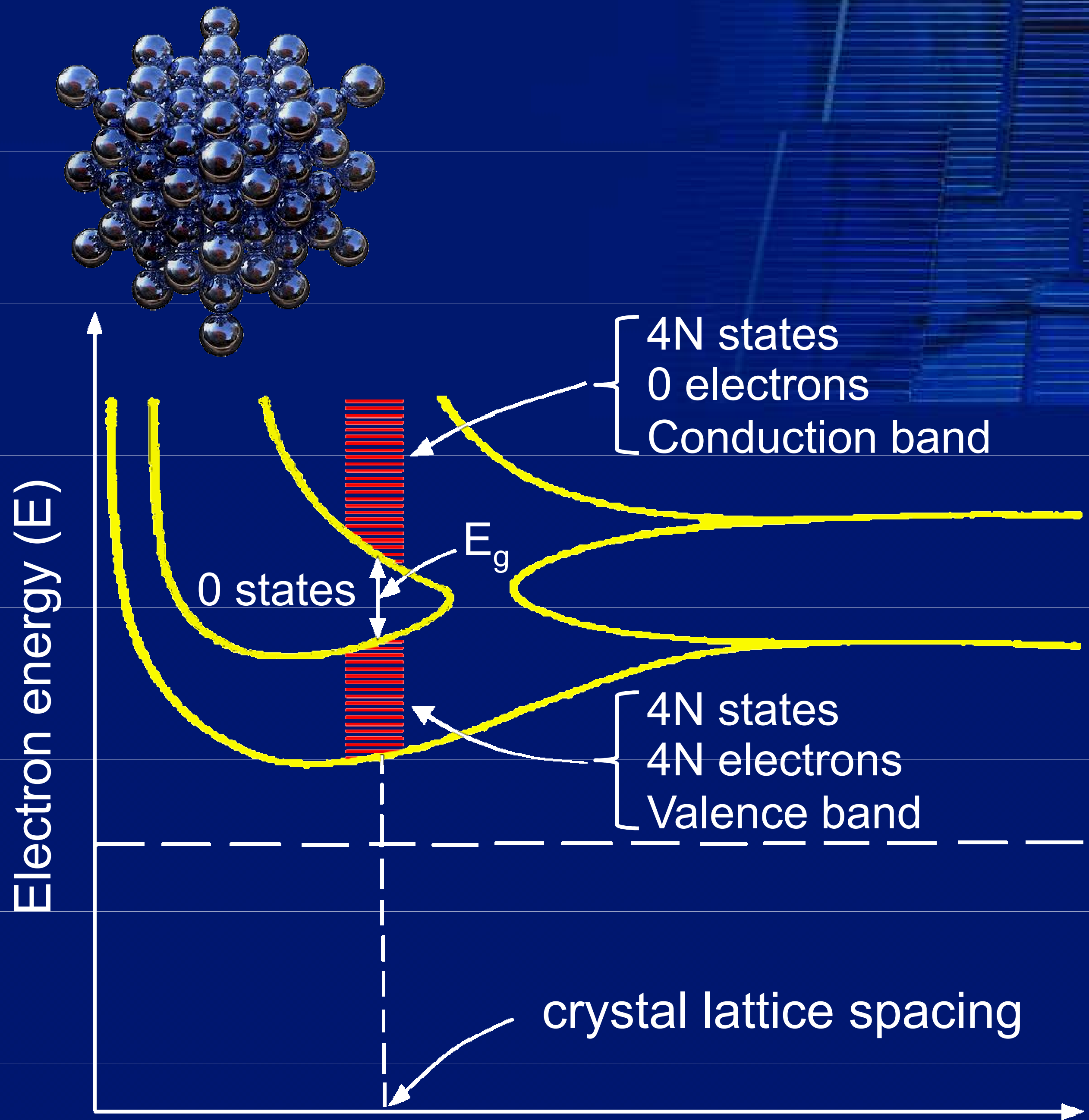


Wurtzite Structure
(GaN, AlN, CdS, BN, etc.)

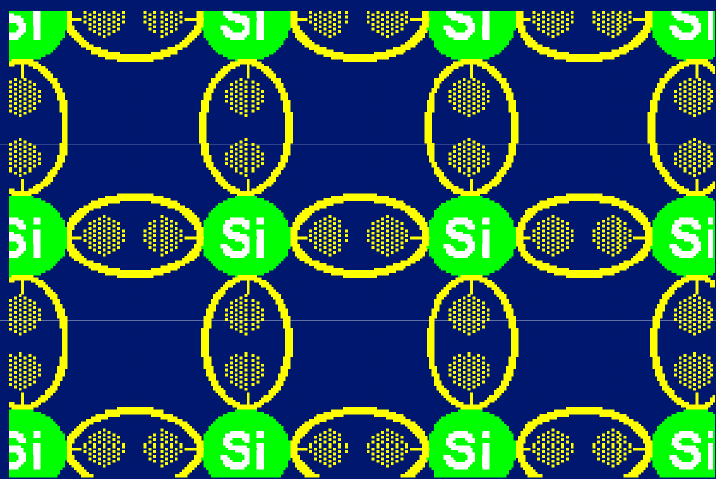
Tetrahedrally Bonded Semiconductors



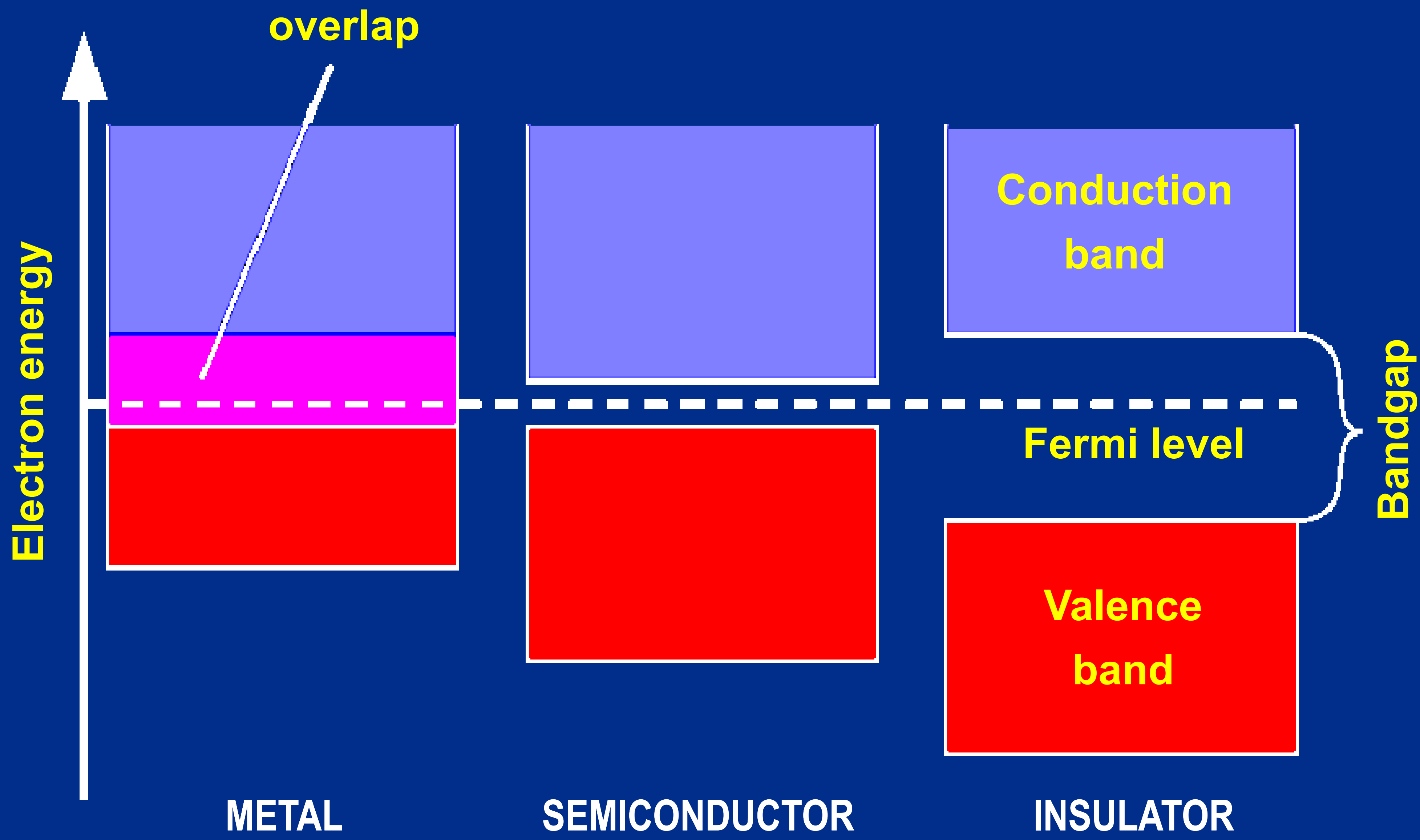
From Atomic Levels to Band Structures



Z=14: $1s^2 2s^2 2p^6 3s^2 3p^2$

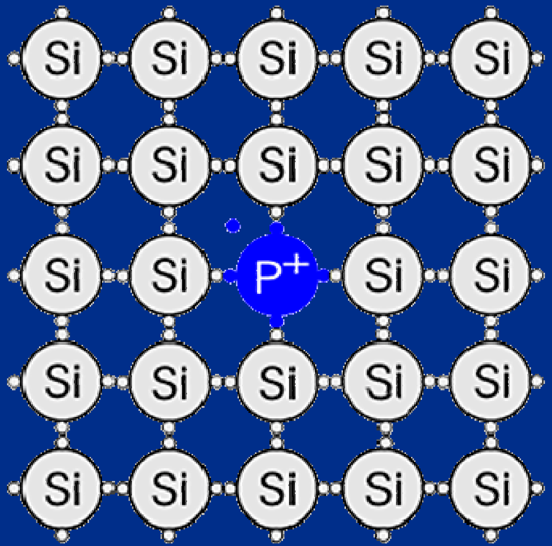


From Band Structures to Different Materials

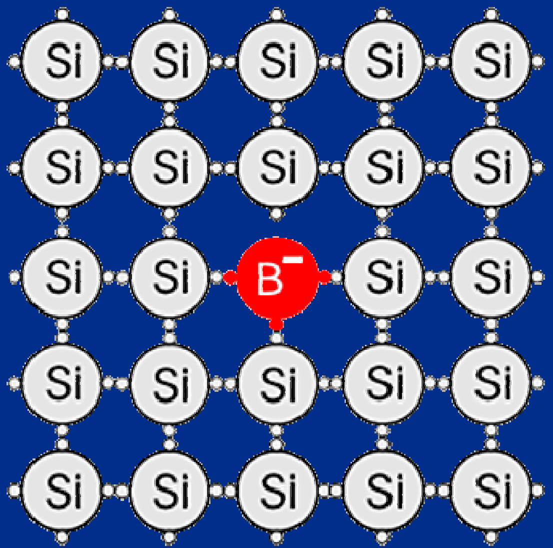


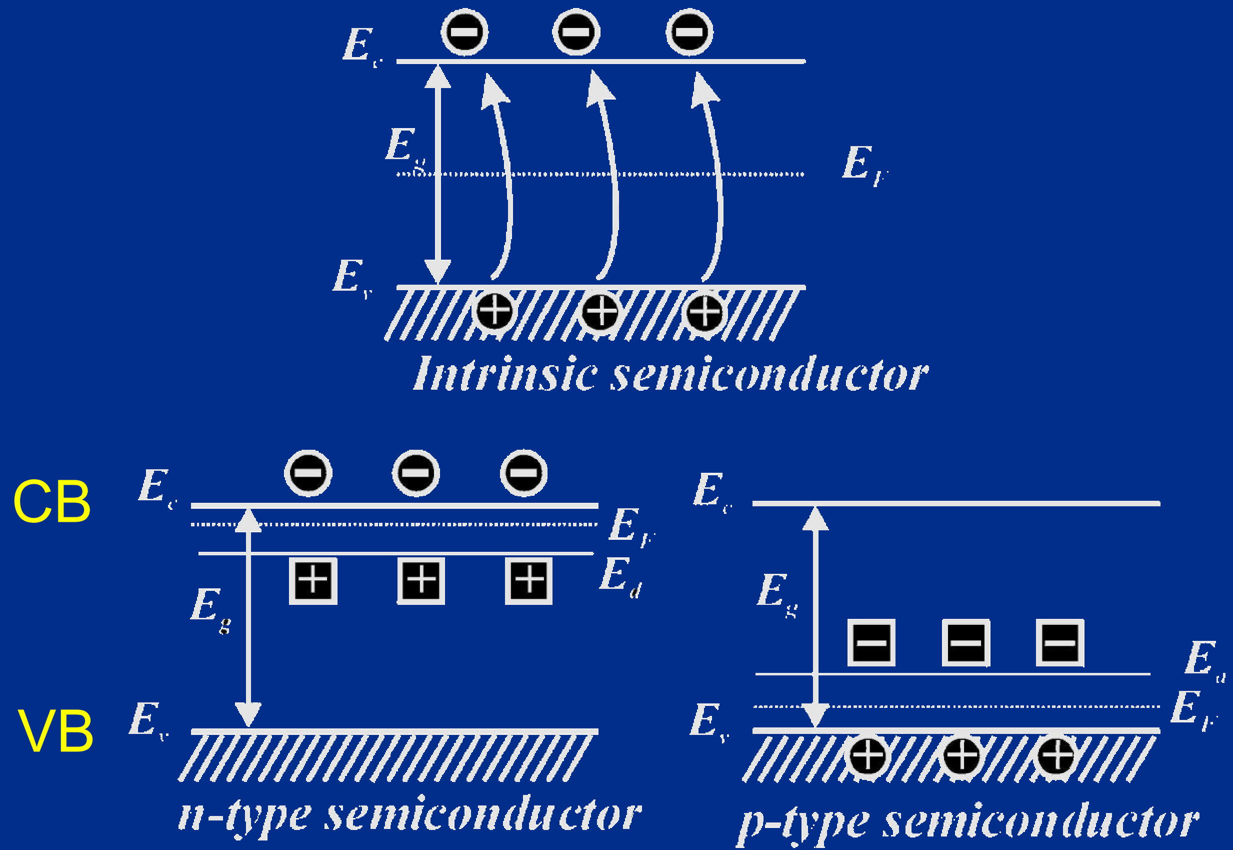
Semiconductor Doping

n-type semiconductor



p-type semiconductor





⊖ Electrons in CB (mobile)

⊕ Holes in VB (mobile)

⊞ Positive ions (immobile donors)

⊟ Negative ions (immobile acceptors)

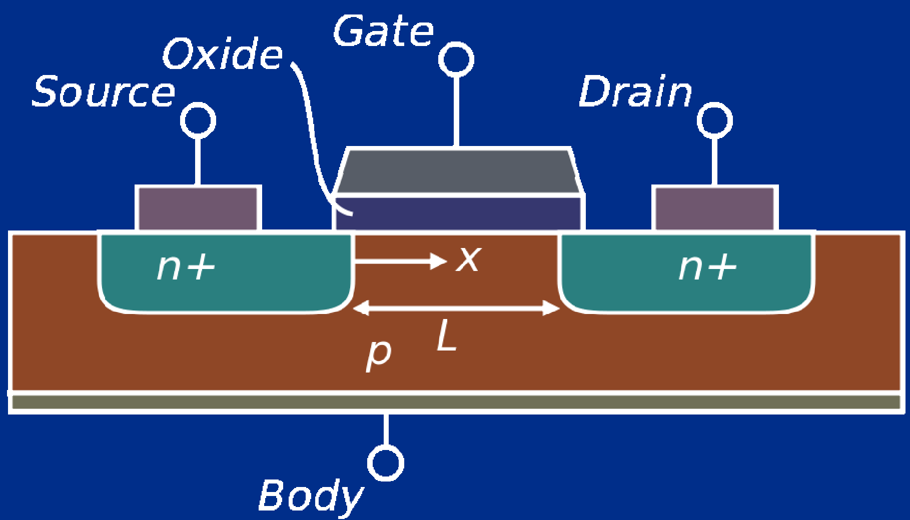
Transistor Effect

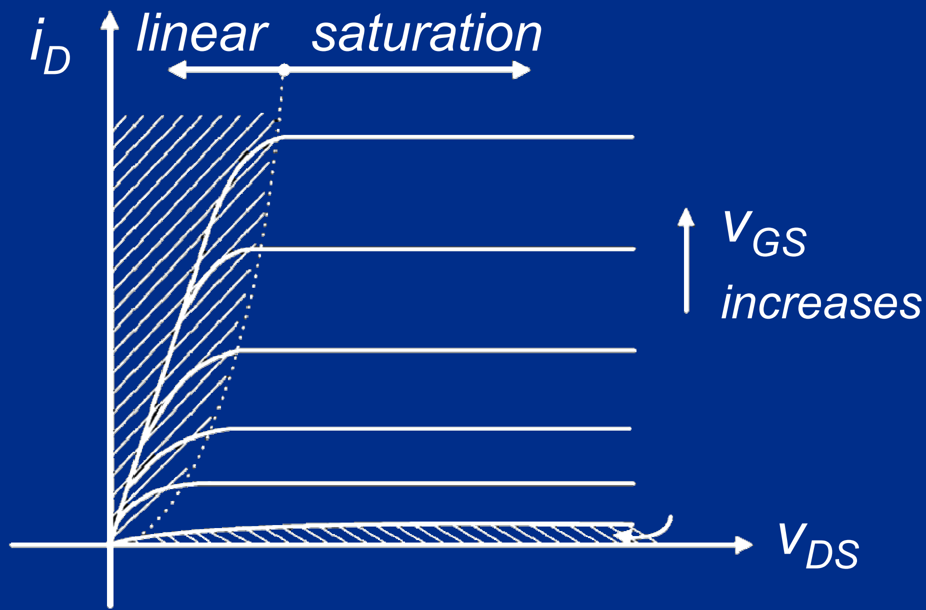
Nobel: 1956

J. Bardeen, W. Shockley, W. Brattain (1947, Bell Labs)

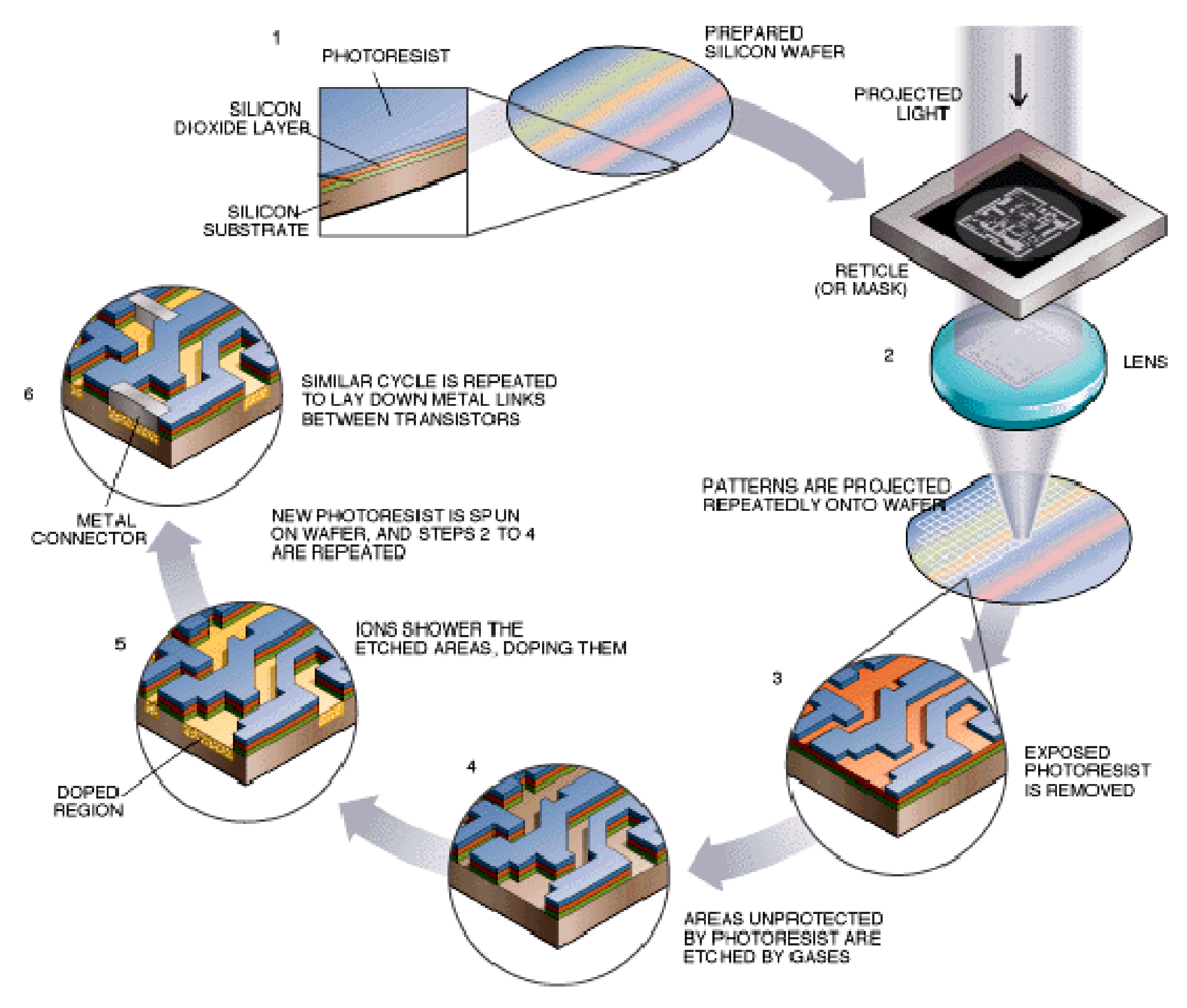
Ge Transistor

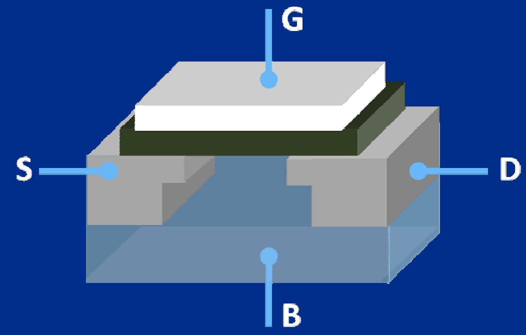
nMOSFET

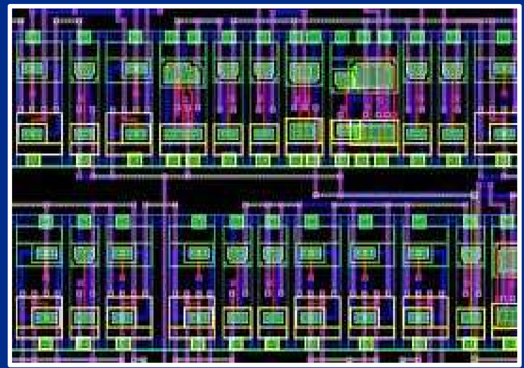


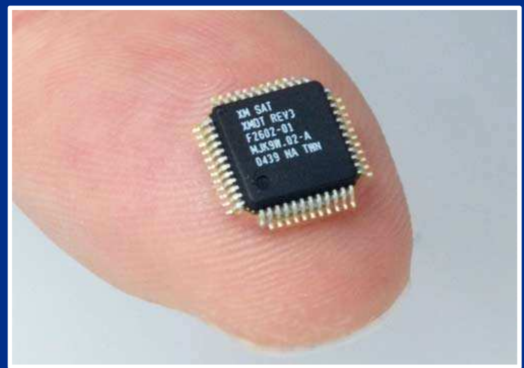


From Transistor to CMOS Devices





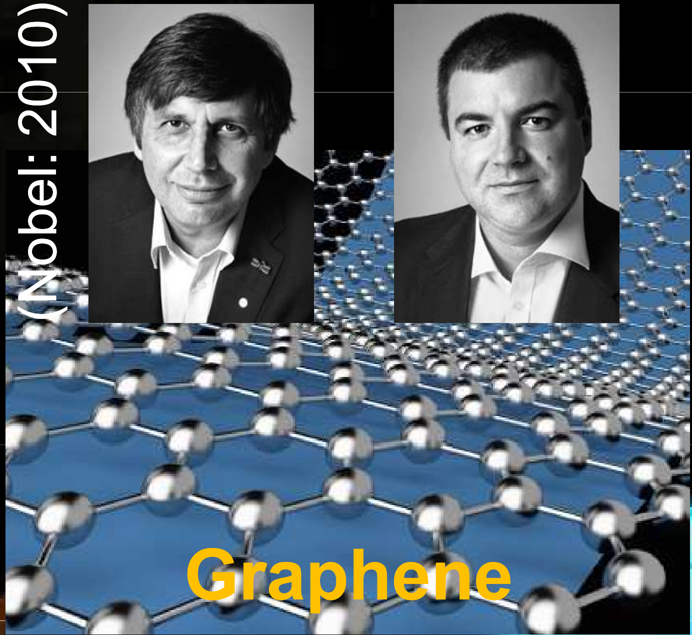




Extending Moore's Law beyond Silicon

(Nobel: 2010)

A. Geim K. Novoselov



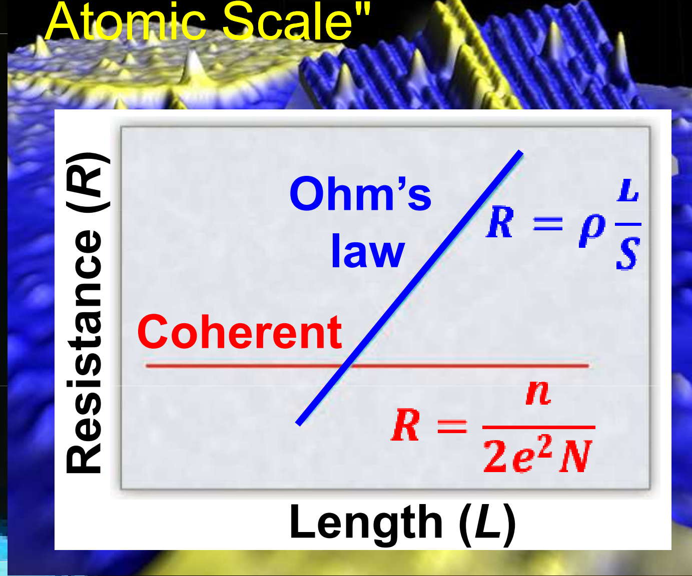
ICPS 2012 ZURICH

"Moore's law will collapse"

M. Simmons et al.

SCIENCE 335, 64 (2012)

"Ohm's law survives to the Atomic Scale"



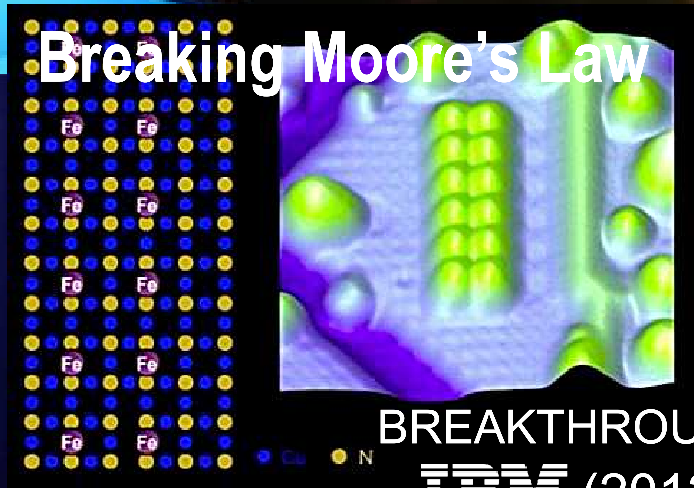
BREAKTHROUGH

(Nobel: 2007)

Nature Phys. **8**, 757 (2012)

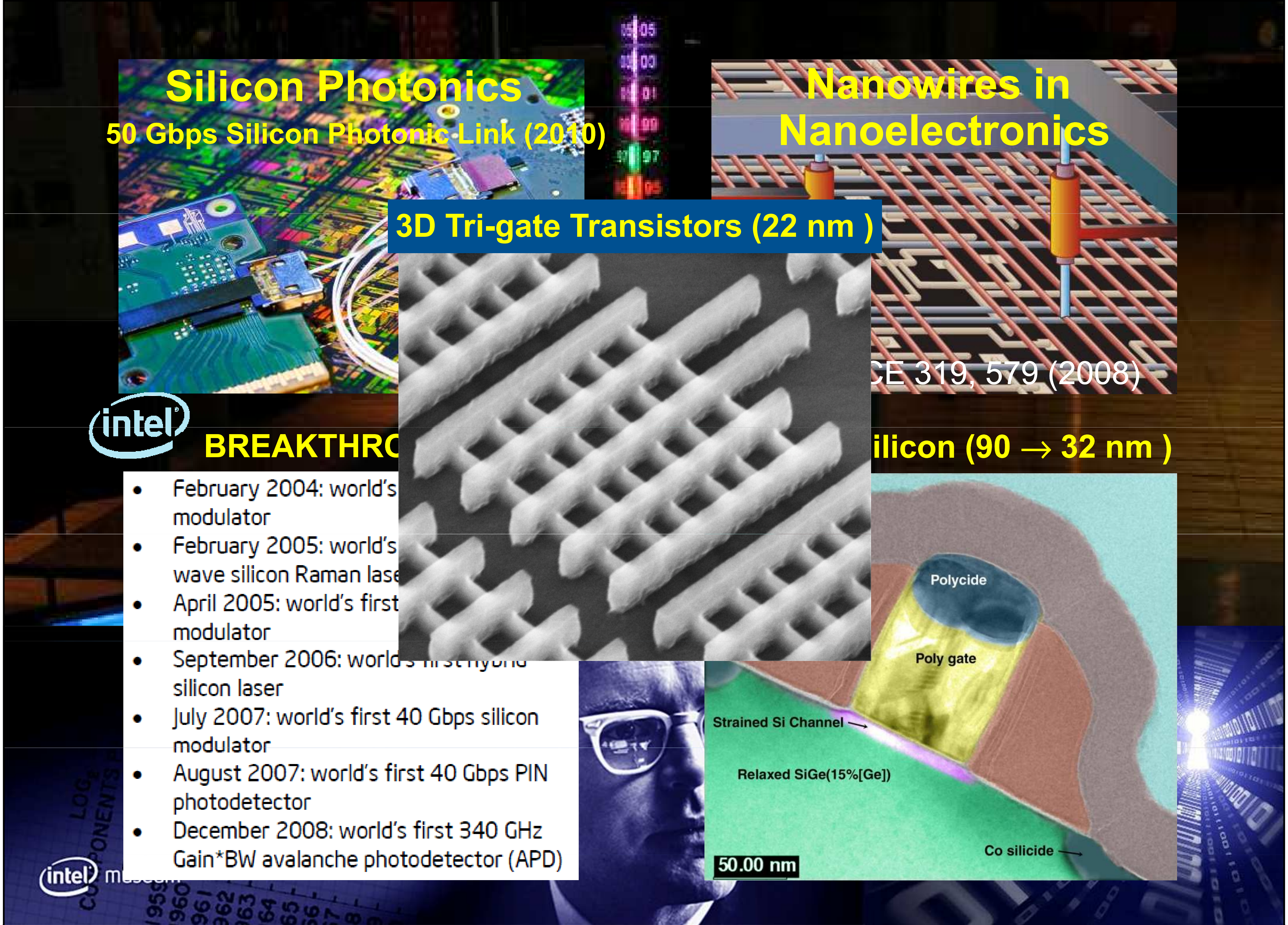
BREAKTHROUGH

IBM (2012)

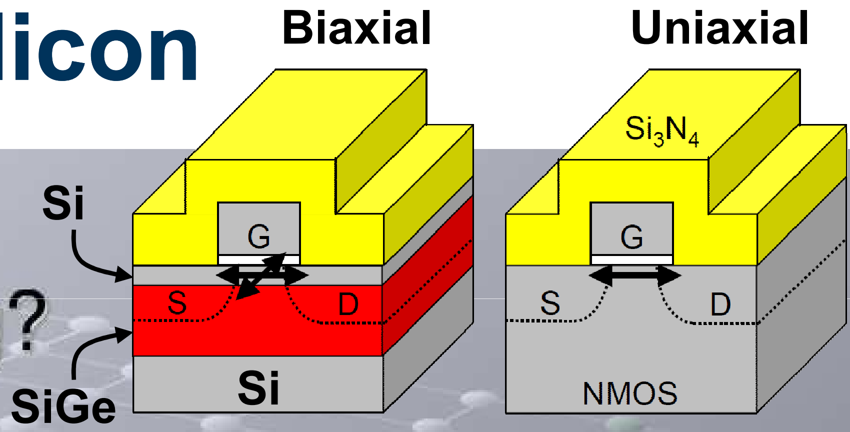


BREAKTHROUGH

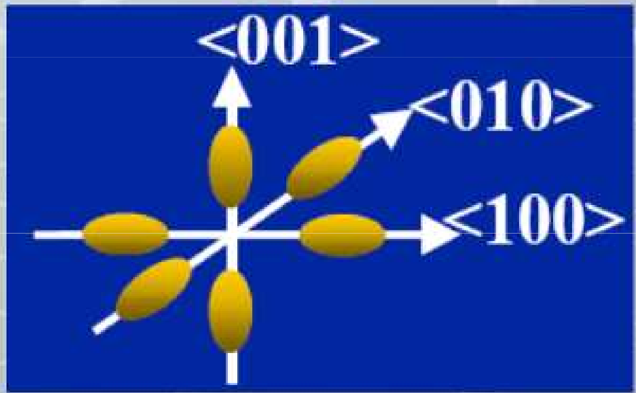
IBM (2012)

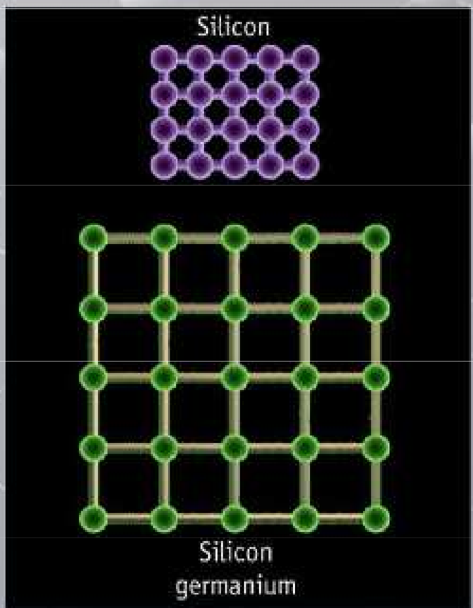

Silicon Photonics
50 Gbps Silicon Photonic Link (2010)
Nanowires in
Nanoelectronics
3D Tri-gate Transistors (22 nm)
February 2004: world's
modulator
February 2005: world's
April 2005: world's first
modulator
silicon laser
July 2007: world's first 40 Gbps silicon
modulator
August 2007: world's first 40 Gbps PIN
photodetector
December 2008: world's first 340 GHz
Gain*BW avalanche photodetector (APD)
Polycide
Poly gate
Strained Si Channel
Relaxed SiGe(15%[Ge])
Co silicide
50.00 nm

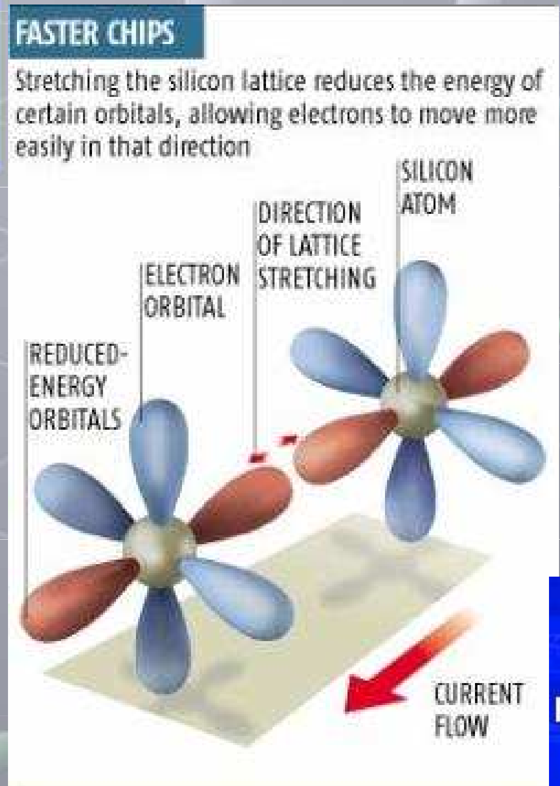
Strained Silicon

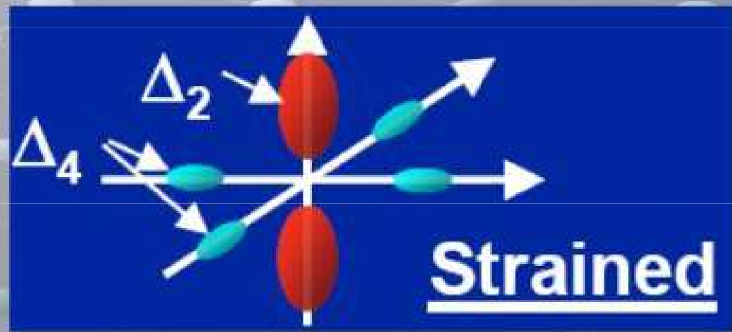


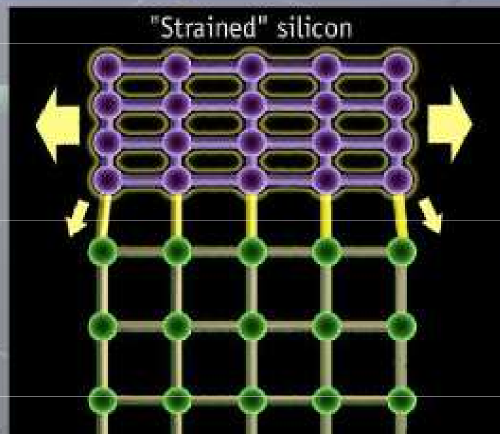
- So, what is actually happening?

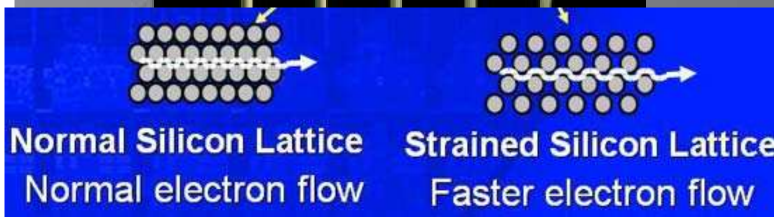




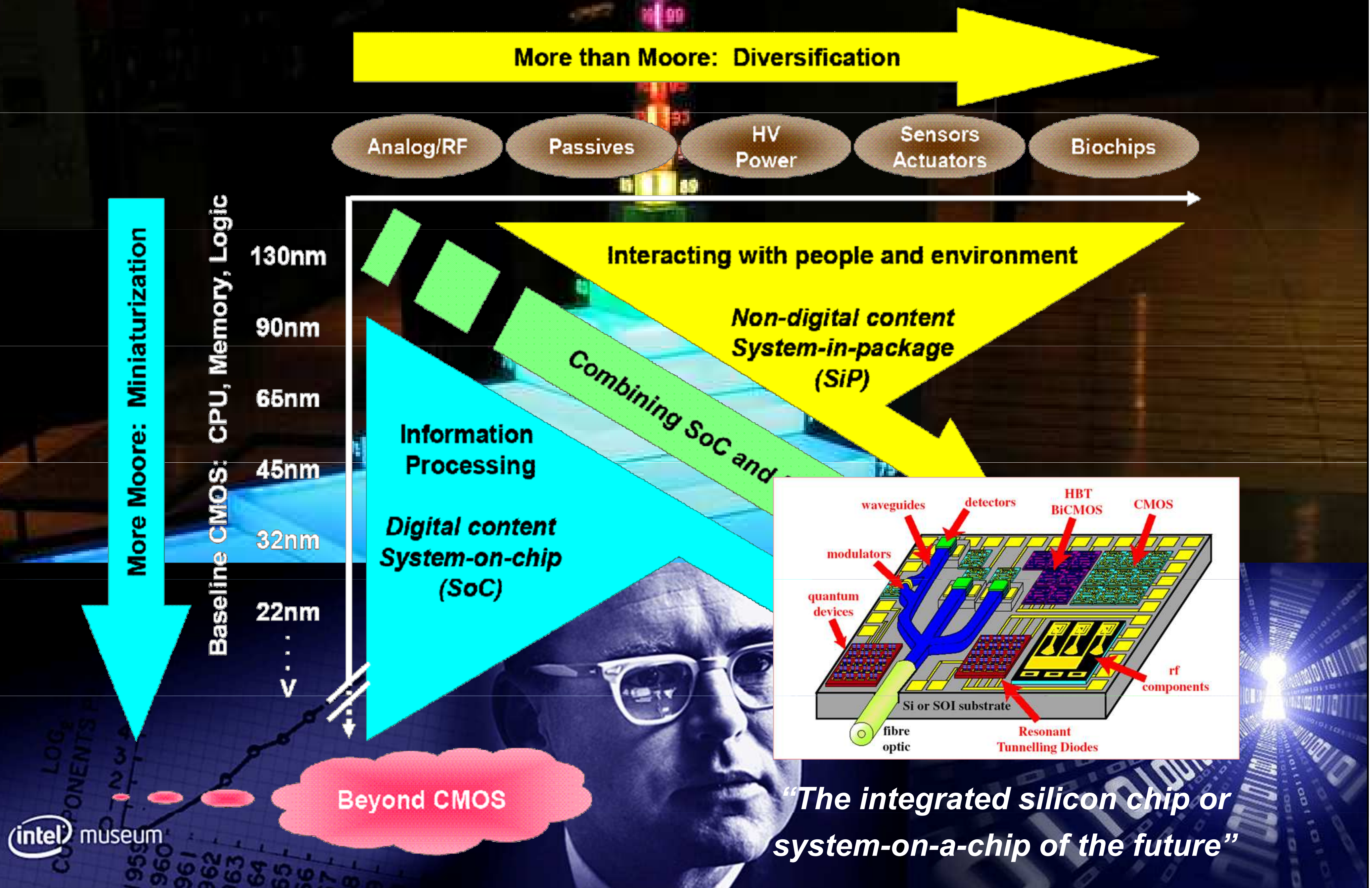




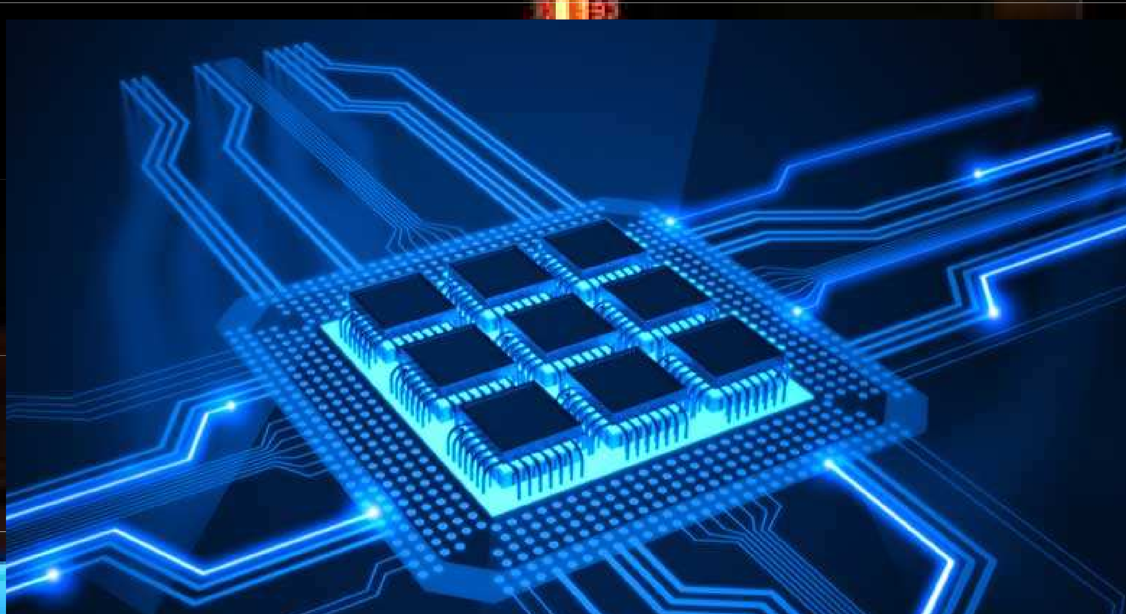




International Roadmap for Semiconductors



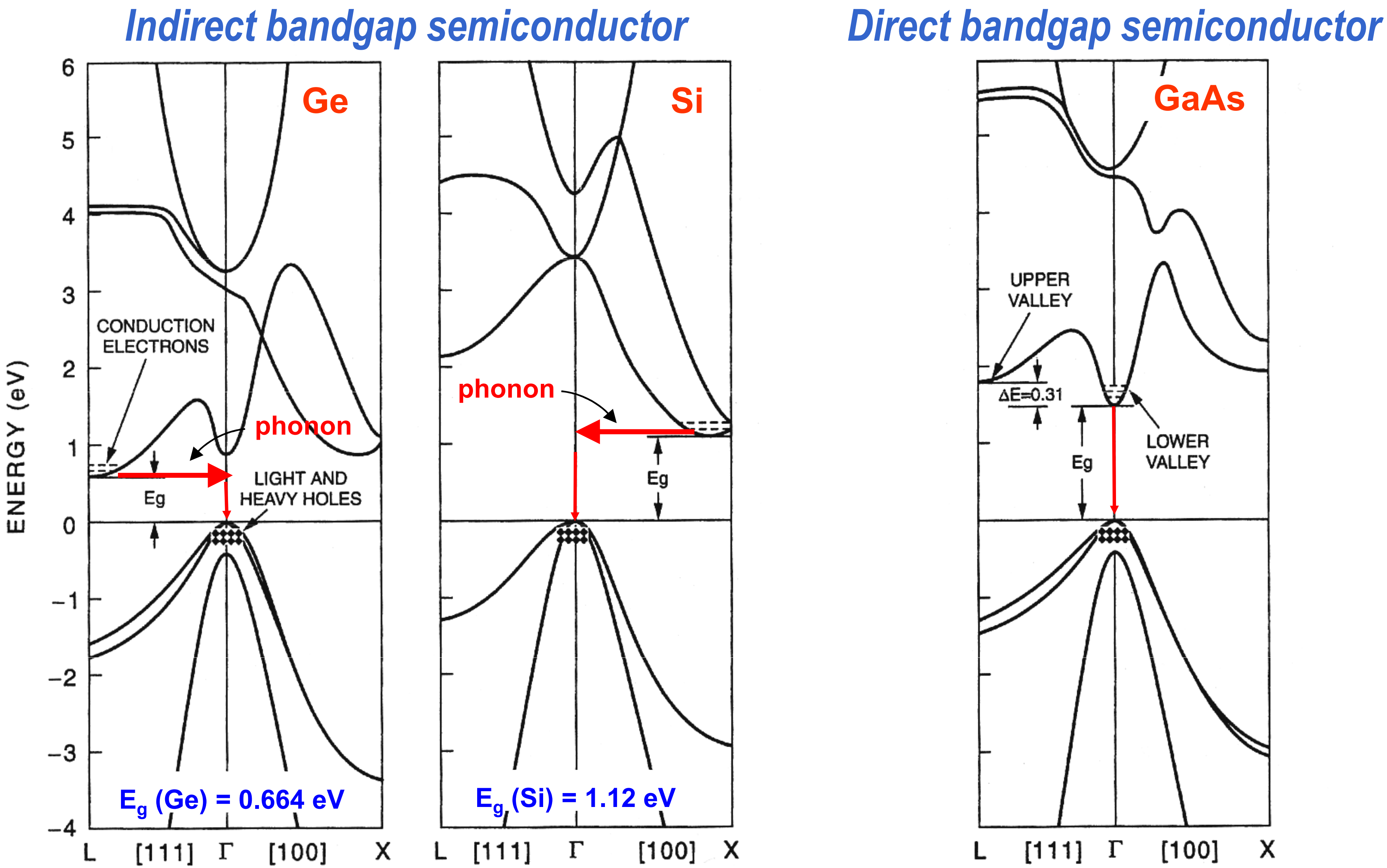
Extending Moore's Law beyond Silicon



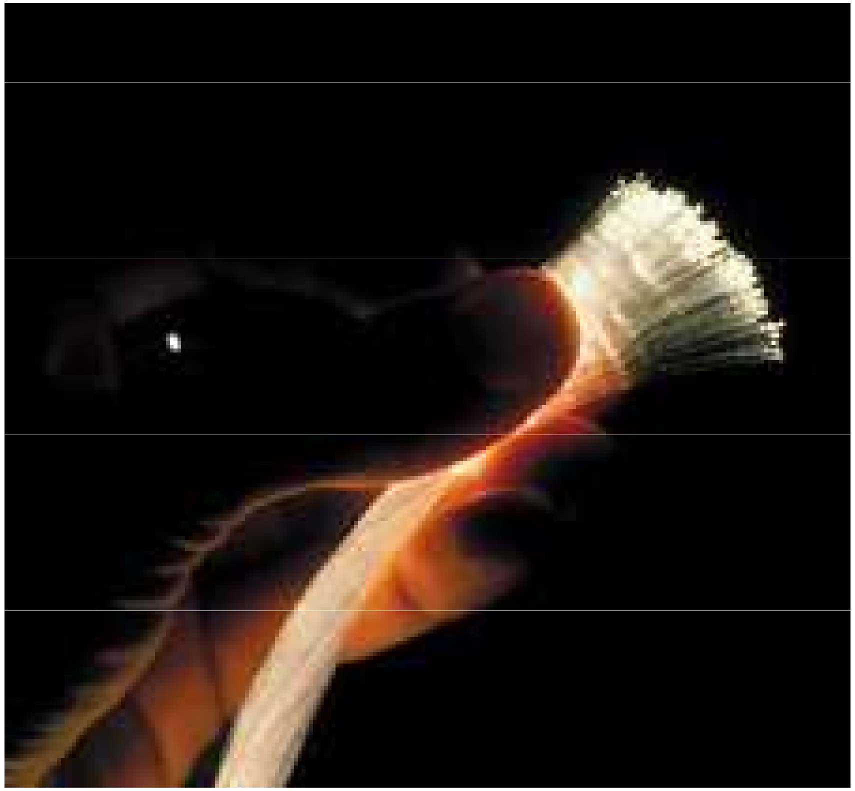
Extending Si technology to other semiconducting materials with optical and electrical properties beyond Si.

From Microelectronics to Optoelectronics

Si: Inefficient at emitting light (interband transitions involve momentum transfer, i.e., the heat-generating process for electron-hole recombination dominates)



Squeeze Light out of Silicon



Interband

- Ge-dots
- Er-doped Si
- Short period superlattices
- Porous Si
- Si nanocrystals
- Strained Si

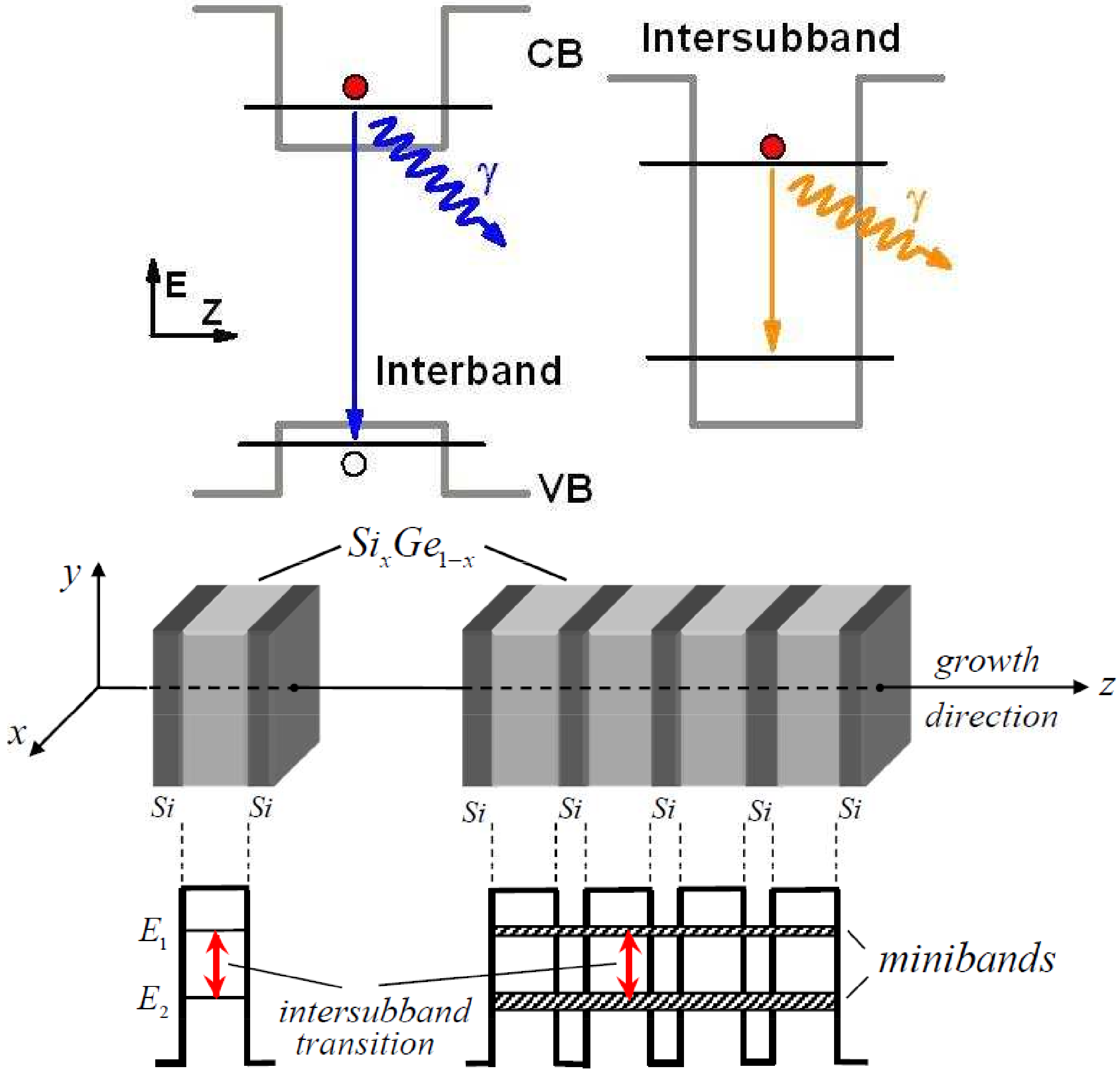
Intersubband

- Quantum Cascade Laser (QCL)

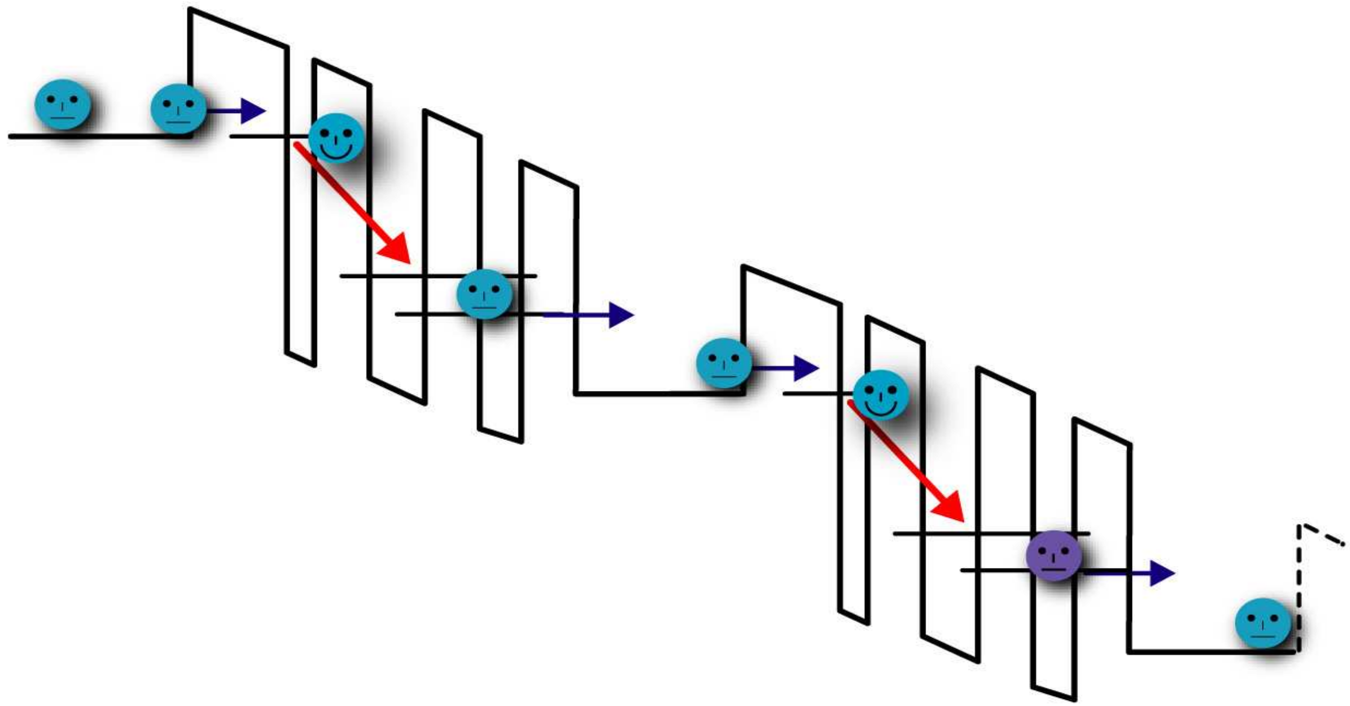
"A silicon laser would revolutionize telecommunications, electronics and computing. Squeezing light out of silicon is no easy task, but researchers are becoming more optimistic about its light-emitting abilities."

Nature **409**, 974 - 976 (2001)

Interband vs. Intersubband Transitions



Quantum Cascade Laser (QCL)



Cascade: Multiple repetition of active region

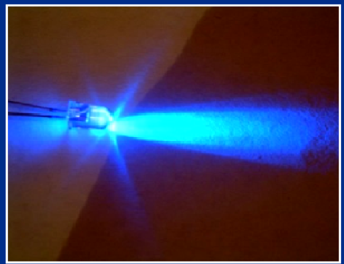
⇨ Multiple photons from one electron

Theoretical prediction: R.F. Kazarinov and R.A. Suris, *Fiz. Tekh. Poluvrodvn.* **5**, 797-800 (1971)

Design for III-V compounds (InGaAs/InAlAs: J. Faist et al., *Science* **264**, 533 (1994).

Bridging Optoelectronics and Microelectronics

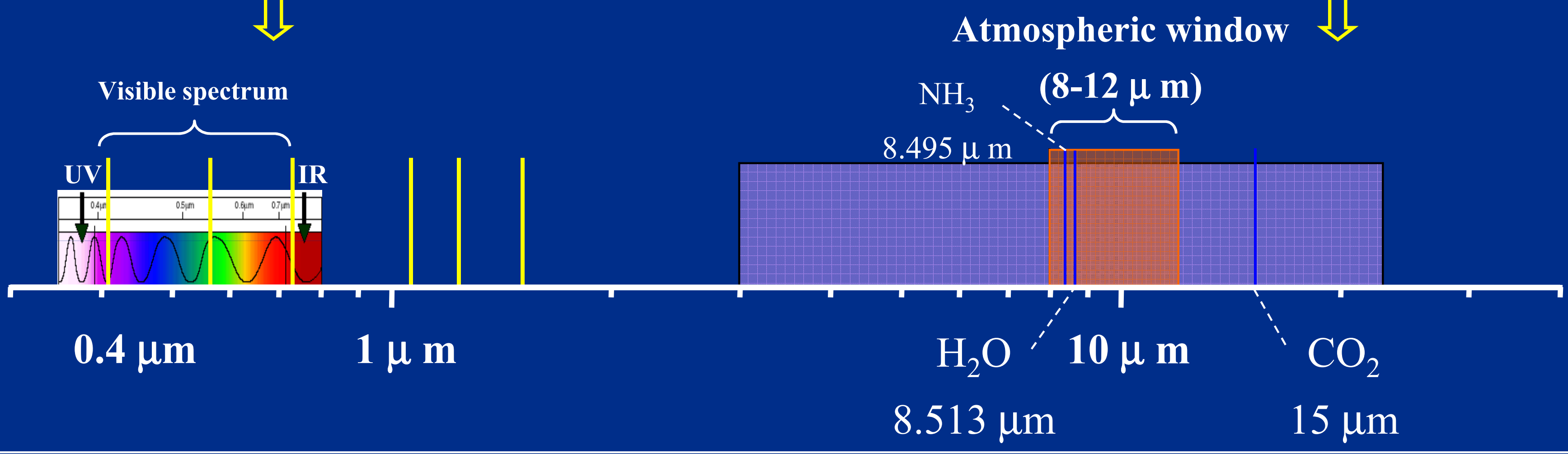
OPTO ⟺ ELECTRONICS



III-V material

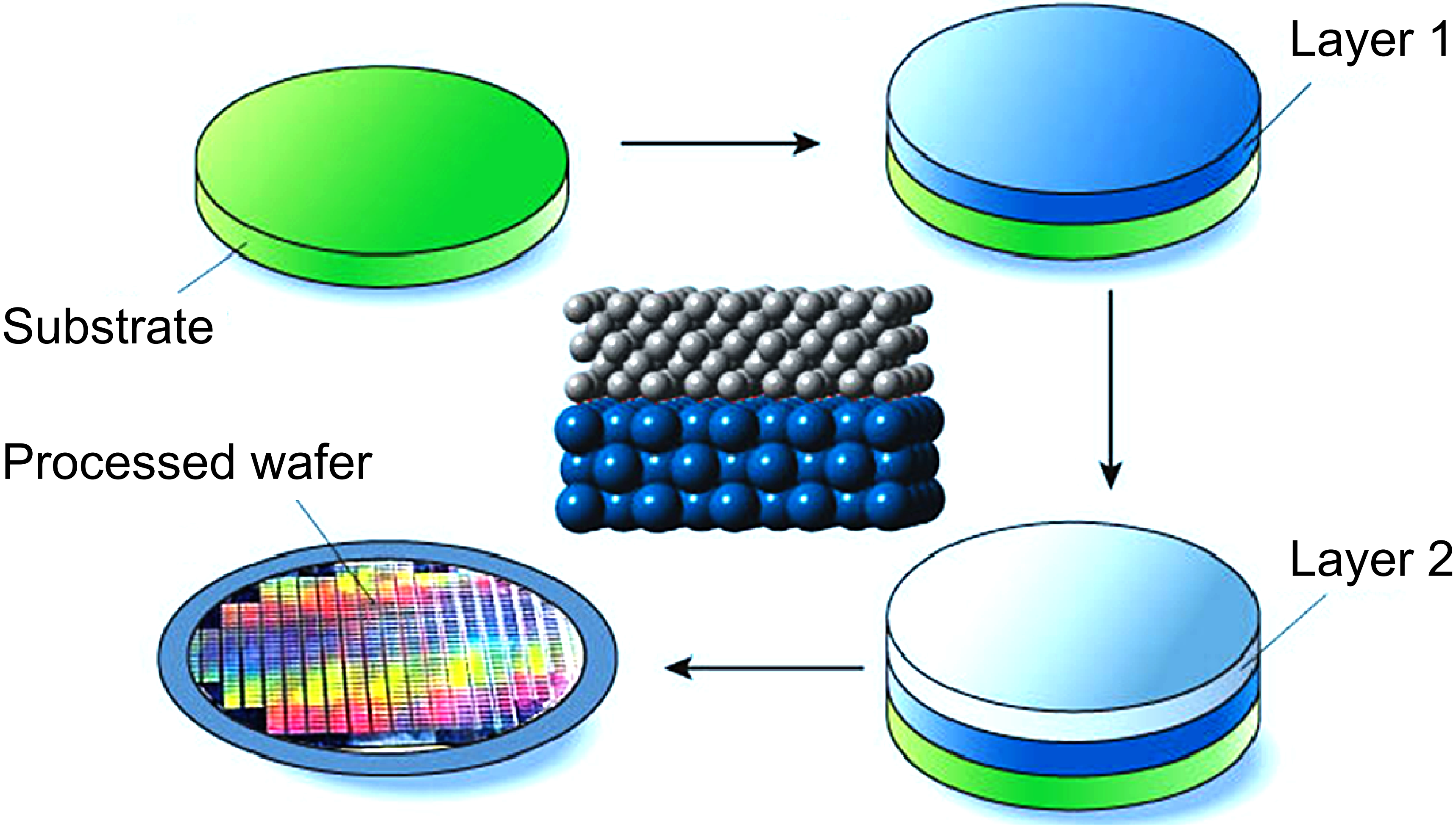
Silicon

Interband Lasers (GaN, InGaAs, GaAs/AlGaAs, etc.) ⟺ **with III-V** ⟺ **Quantum Cascade Lasers** (InGaAs/AlInAs, GaAs/AlGaAs)

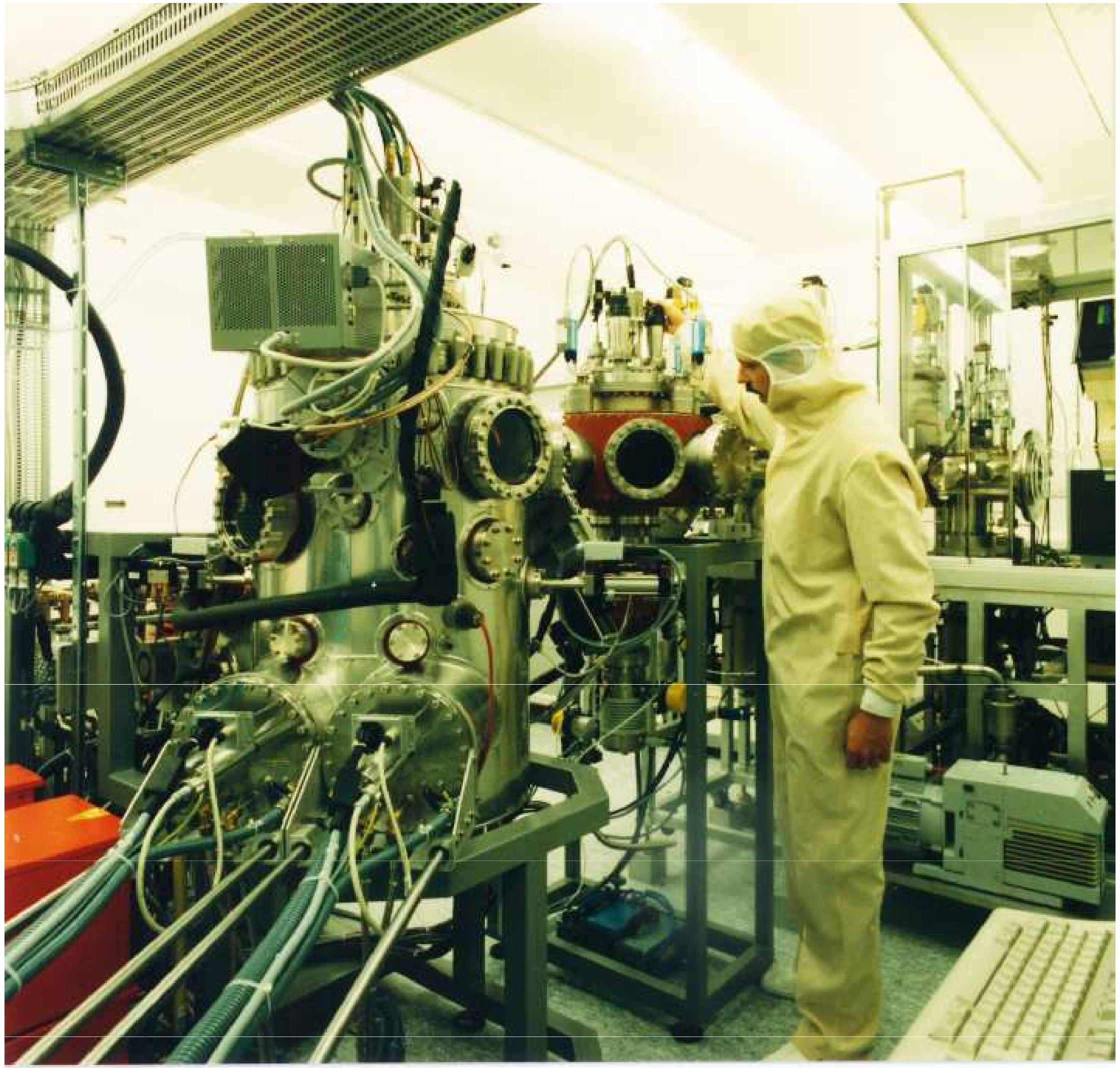


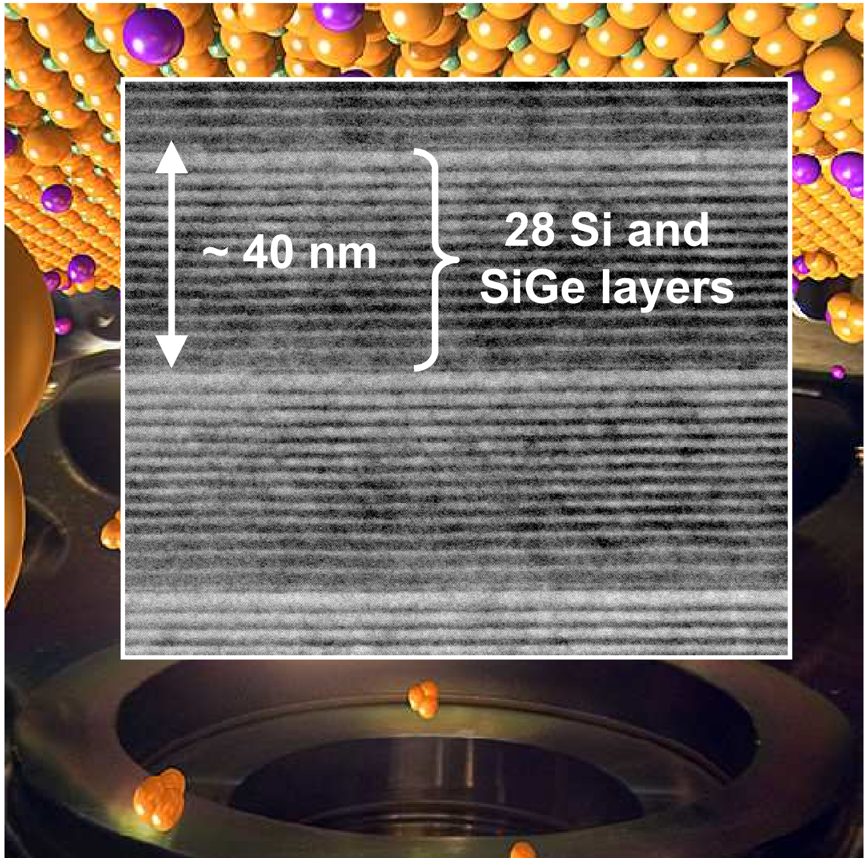
Not possible (indirect bandgap material) ⟺ **with Si** ⟺ **Possible** (nature of the bandgap irrelevant)

Monolithic Integration (Hetero-Epitaxy)



Molecular Beam Epitaxy (MBE)





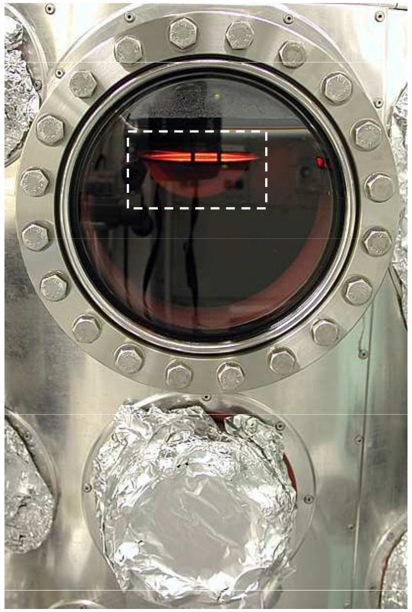
Requirements:

- Many (> 1000) few-atoms thick layers of alloy materials
- Atomic control of layer thickness
- Atomically flat layer interfaces

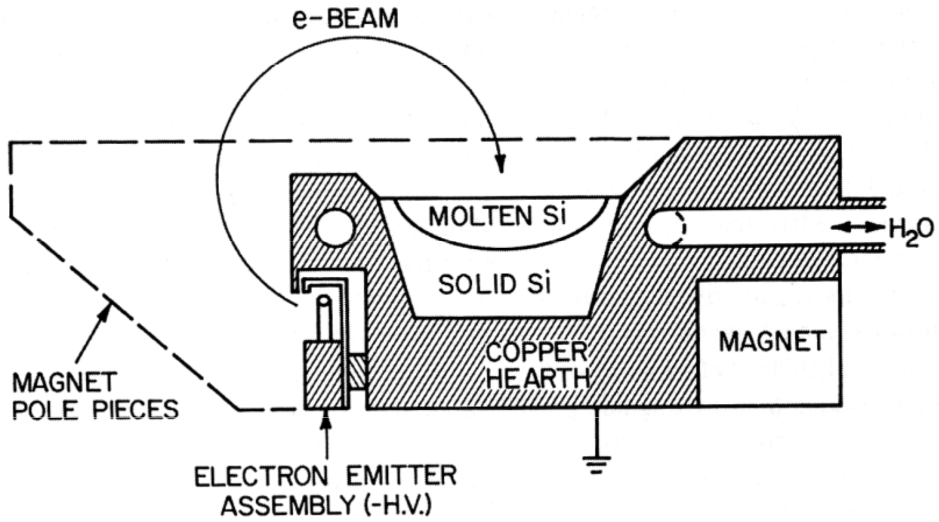
- Typical growth rates (~Å/s)

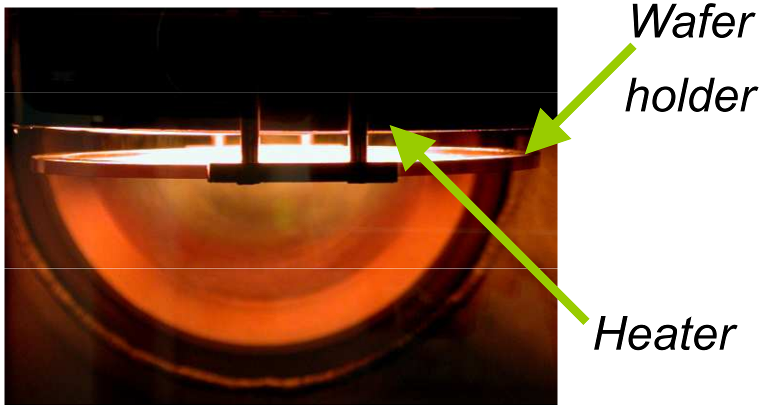
Molecular Beam Epitaxy (MBE)

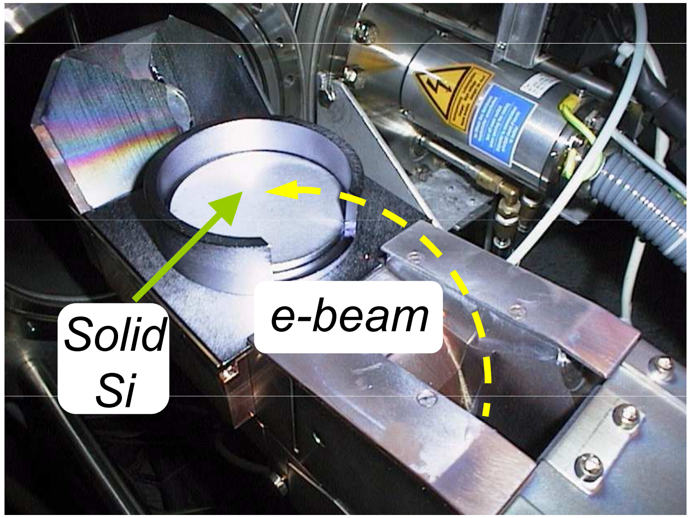
Growth chamber



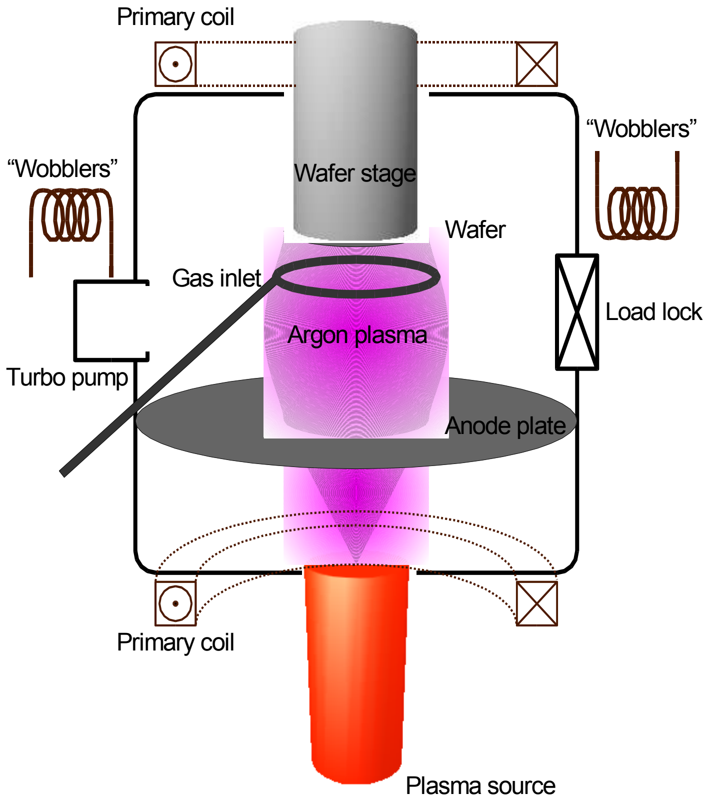
Electron beam evaporation Si and Ge sources

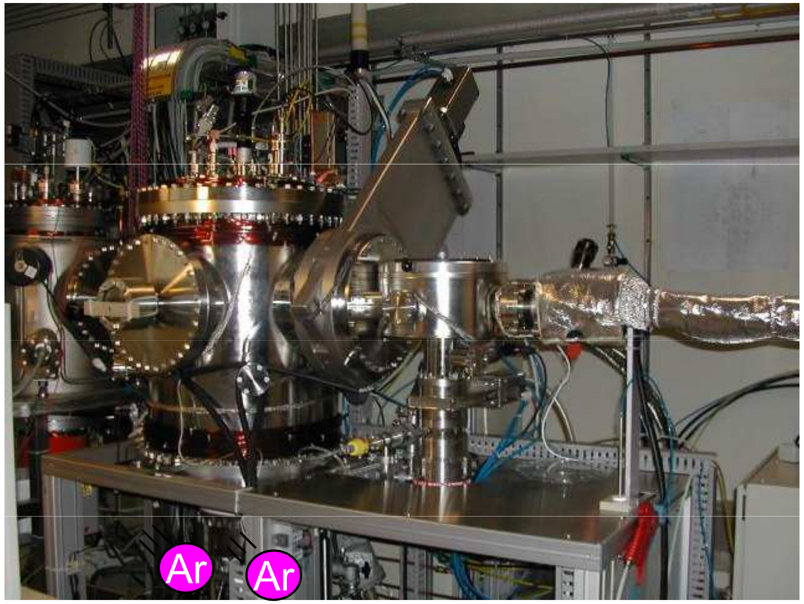


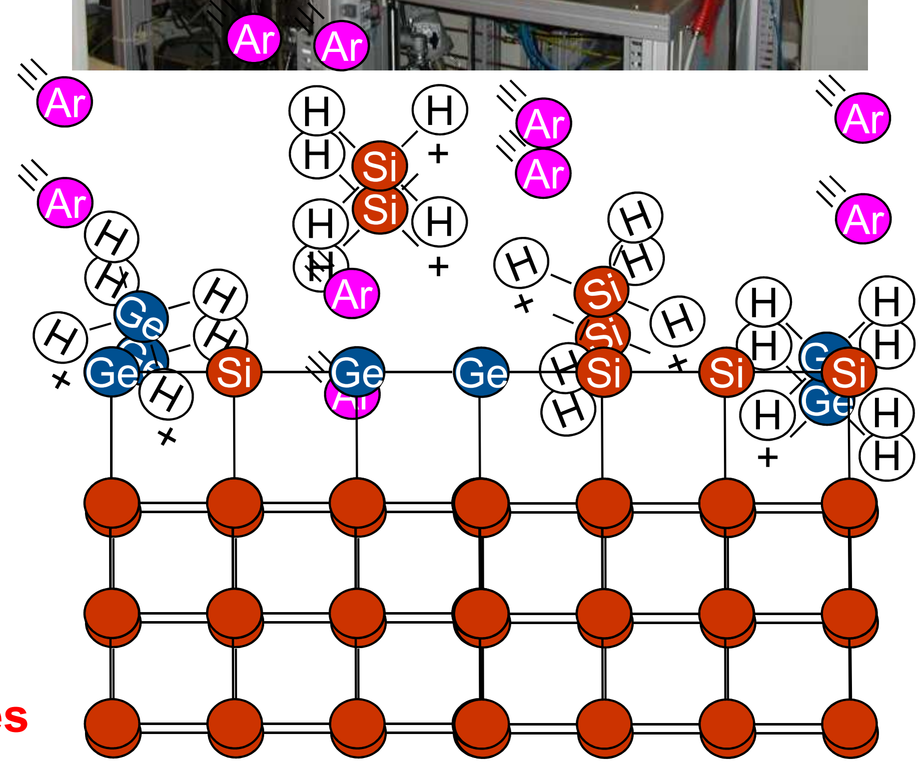




Low-Energy Plasma Enhanced Chemical Vapor Deposition







Principle of low-energy plasma-enhanced CVD:
High-current low-voltage arc discharge

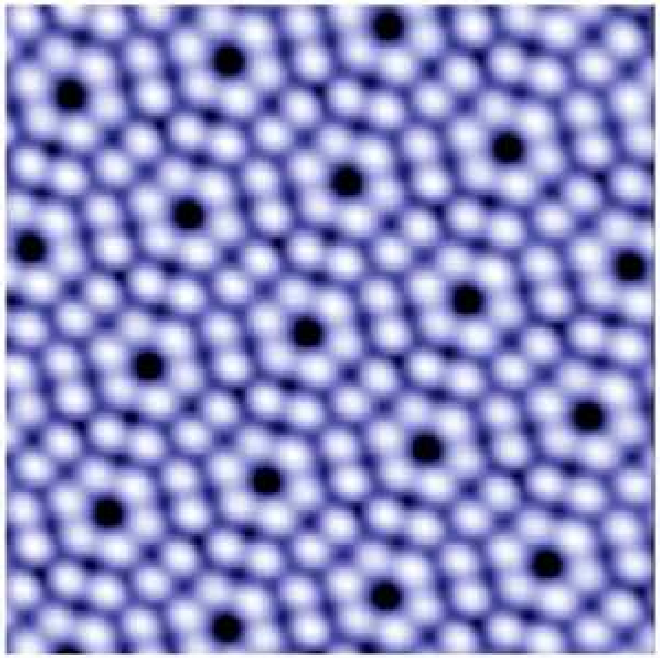
SiH_4 and GeH_4 are transformed into highly reactive radicals

Very high growth rates (0.5 µm/min) possible at low substrate temperatures

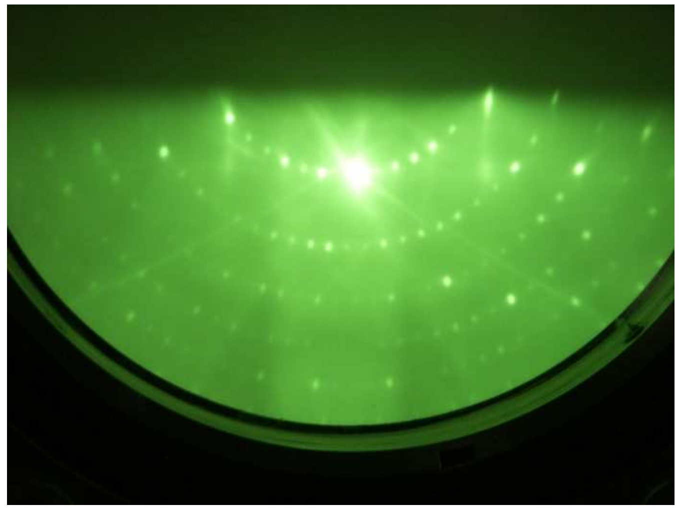
Characterization of Epitaxial Structures

- **Structural:**
  - Reflection high energy electron diffraction (RHEED)
  - Optical reflection spectroscopy
  - X-ray diffraction
  - Transmission electron microscopy
  - Secondary ion mass spectrometry (SIMS)
  - Rutherford backscattering spectrometry (RBS)
  - Scanning Tunneling Microscopy
  - Atomic Force Microscopy
- **Optical:**
  - Reflection & transmission
  - Photoluminescence
  - Raman scattering
- **Electrical:**
  - Conductivity & Hall effect

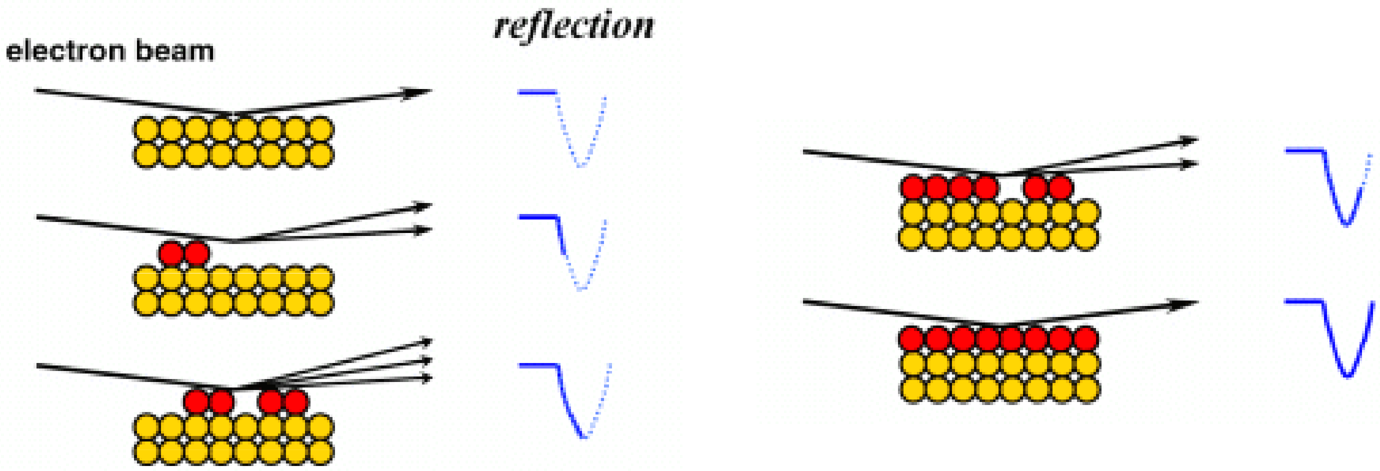
Reflective High Energy Electron Diffraction (RHEED)



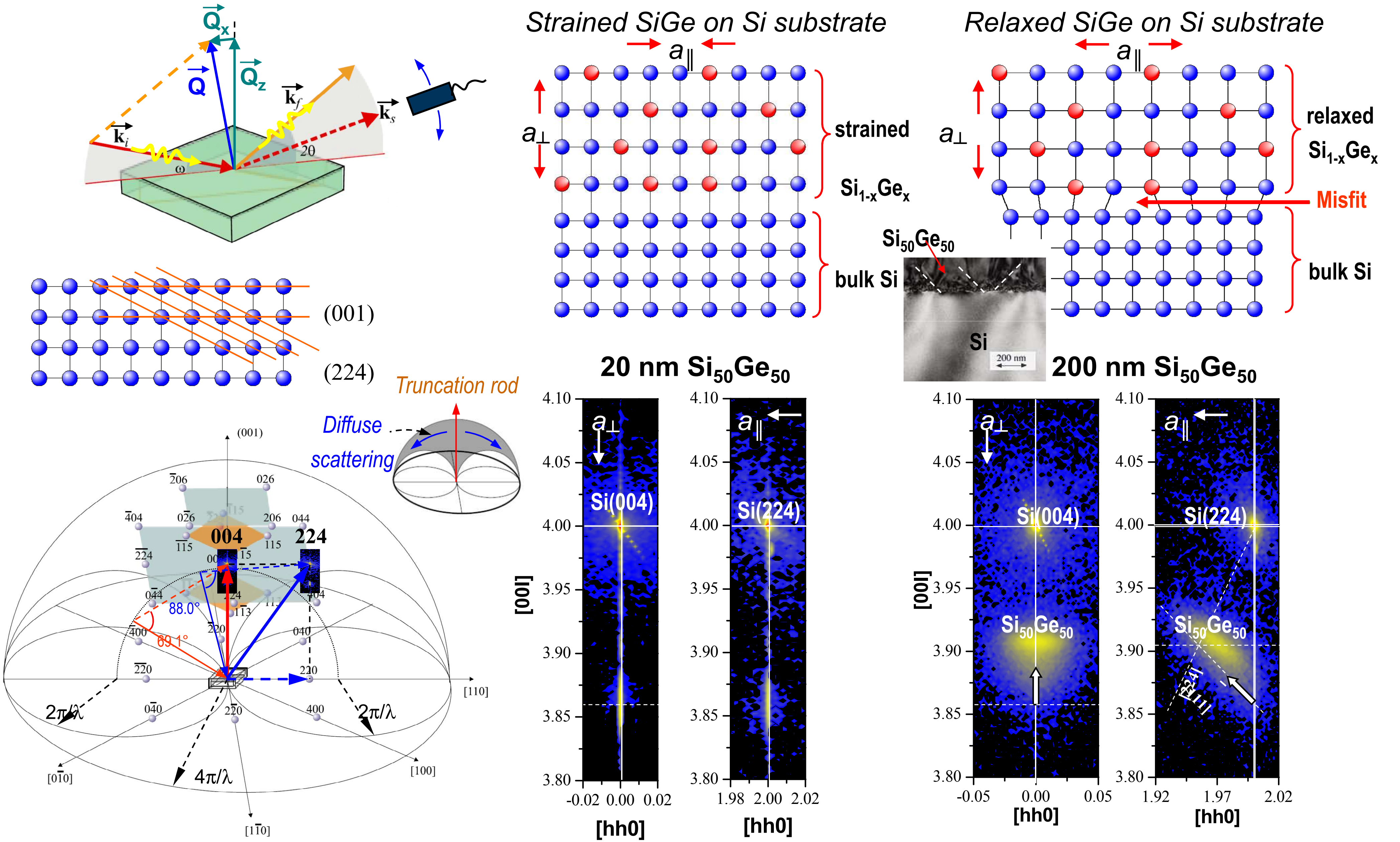
RHEED Pattern of Si(111)-7x7



Incident electron beam
along <11-2> azimuth

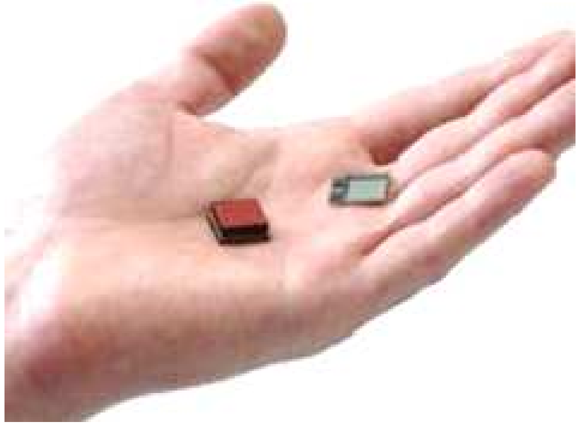


High-Resolution X-Ray Diffraction (HRXRD)



Motivation: Integrated Miniaturized X-ray Systems

nano-tera.ch



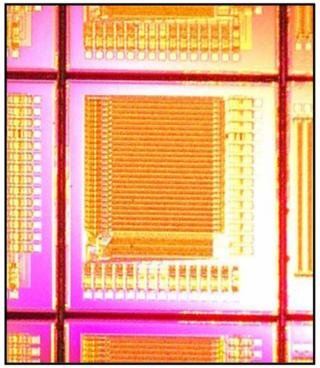
"NEXRAY"

- Next Generation X-Ray Systems
- High resolution/sensitivity
- Ge as conversion layer
- No bump-bonding (monolithic integration)

Fast, programmable X-ray sources

Ge layers for high-energy X-ray detection

Single-photon solid-state X-ray detection



Phase contrast X-ray imaging

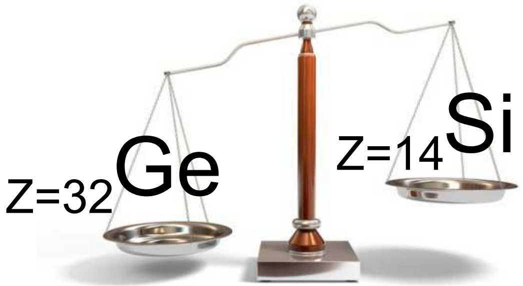
EMPA Materials Science & Technology

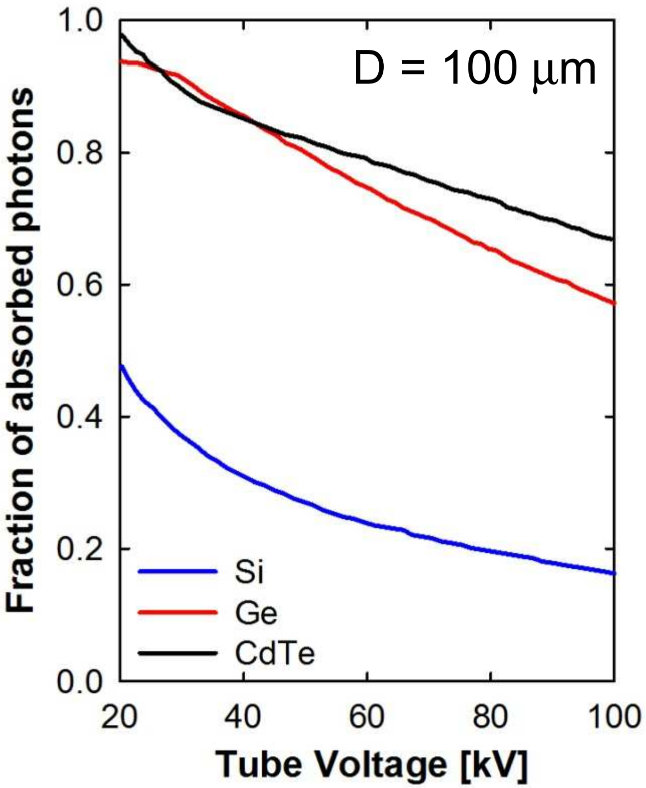
ETH Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

csem centre suisse d'électronique et de microtechnique

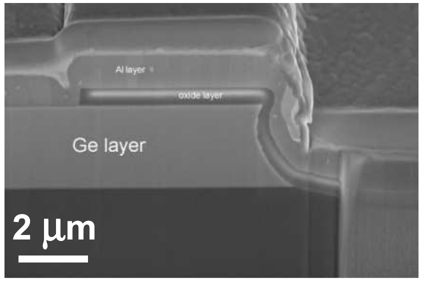
Motivation: Next Generation X-Ray Detectors

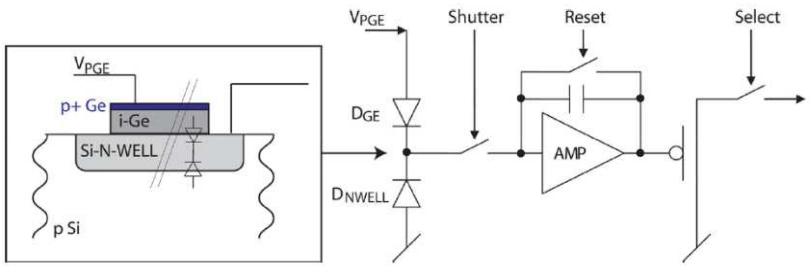
- Why Germanium?



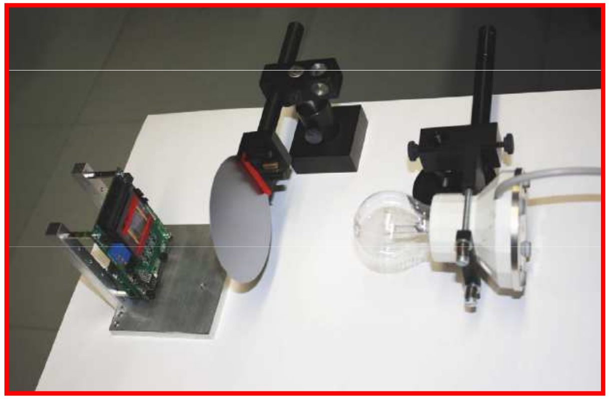


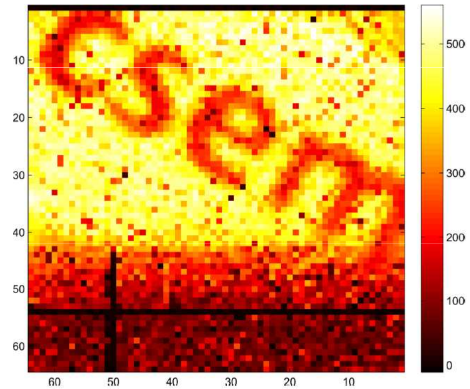
- Monolithic integration of a 3 μm Ge film with CMOS for IR radiation was demonstrated at ETHZ/CSEM





64×64 pixel IR sensor with integrated Ge photodiodes



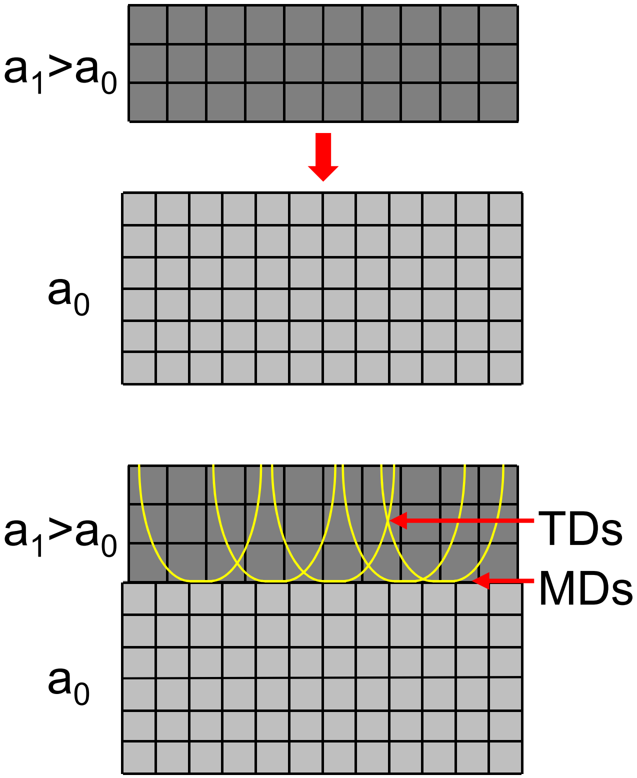


R. Kaufmann *et al*., J. Appl. Phys. **110**, 023107 (2011)

For X-rays → SUPER THICK (> 50 μm !!!) high quality (i.e. dislocations, uniformity) Ge epilayers

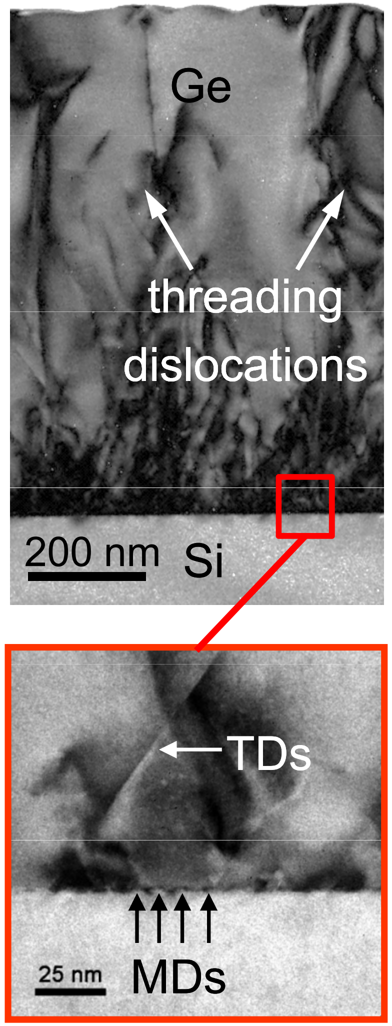
Key Problems of Hetero-Epitaxy

1. Dislocations
(lattice mismatch)

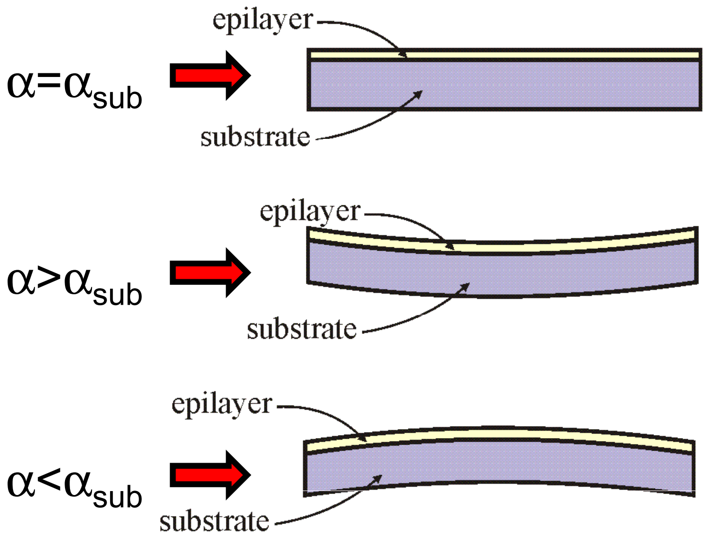


TDs – threading dislocations

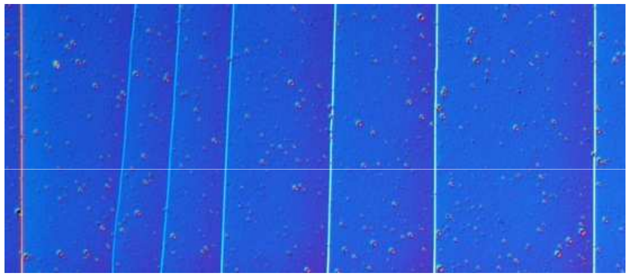
MDs – misfit dislocations



2. Wafer Bowing & Cracks
(thermal mismatch)



Nomarski top view micrograph



30 µm Ge/Si(001)

Scaling Hetero-Epitaxy from Layers to Three-Dimensional Crystals

Claudiu V. Falub *et al.*
Science **335**, 1330 (2012);
DOI: 10.1126/science.1217666

SCIENCE VOL 335 16 MARCH 2012
Published by AAAS

8 December 2011; accepted 27 January 2012

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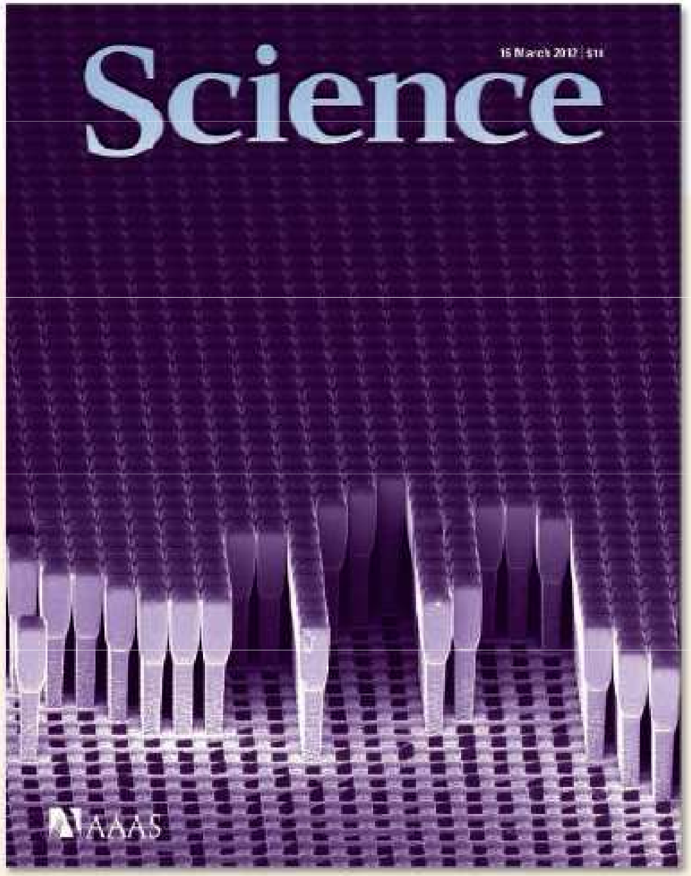

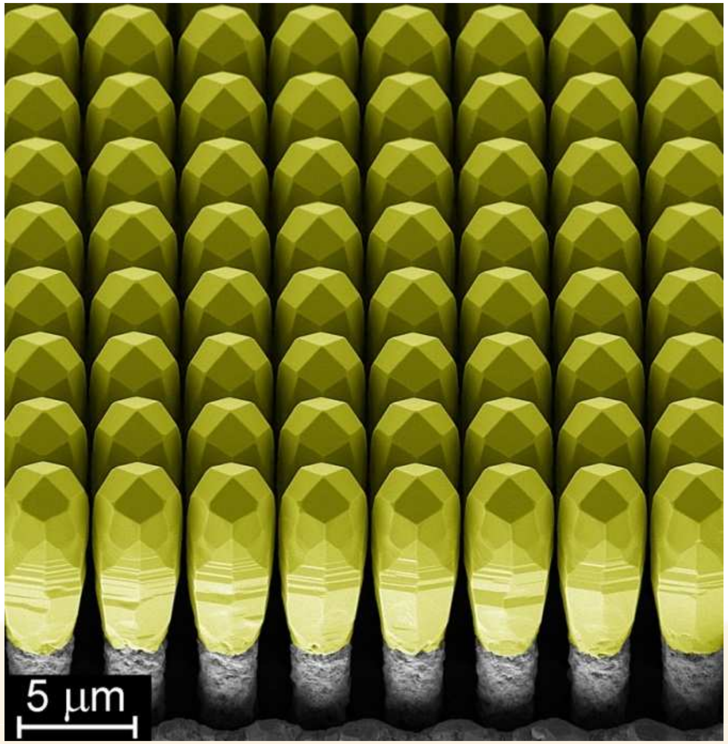

COVER

False-colored scanning electron micrograph of ~8-micrometer-tall germanium crystals, separated by finite gaps, grown onto silicon pillars. In structures like this one, wafer bowing and layer cracking are absent, allowing single-crystal integration of different materials onto a silicon substrate, which serves as a platform for many applications, such as multiple-junction solar cells, x-ray and particle detectors, or power electronic devices. See page 1330.

Image: Claudiu V. Falub, Laboratory for Solid State Physics, Swiss Federal Institute of Technology (ETH-Zürich)


To Be Continued…

Conclusions

- Silicon age has still got tremendous potential for further progress ⇒ **its end is not near, yet!**
- Moore's law may eventually no longer decide the pace of microelectronics progress.
- **"More than Moore"** will be the new driving force.

Thank you for your attention !

Khumjung, Himalaya, Nepal, November 2003