ECE·ILLINOIS

Special Topics in Semiconductor Nanotechnology

ECE 598XL

Fall 2009

ECE 598XL

- Syllabus
  - Overview: size matters
  - Formation Process
  - Characterization
  - SOA device applications and potentials
- Homework or quizzes
  - every 1-2 weeks
- Exams
  - Mid-term: Wikipedia entry - literature search report on a topic
    - (4 – 5 pages)
  - Final: proposal
    - Group project (2 – 4 students self-assembled)
    - 12 - 15 pages total
- Grades
  - 30% HW, 30% Mid-term, and 40% Final

Topics	Examples	# of lectures
1. Introduction of nanotechnology		**1**
2. Formation process of various nanotechnology building blocks		**9**
Bottom-up: Epitaxial growth (MOCVD, MBE, etc.)		
	Self-assembled quantum dots and anti-dots	1
	Patterned and templated growth	1
	VLS nanowires (highly anisotropic growth)	2
	SAE nanowires (highly anisotropic growth)	2
Top-down: lithography and etching		
Combination of bottom-up and top-down		2
Surface passivation	ALD, wet-chemical, etc.	1

3. Characterization of various nanotechnology building blocks		**4**
Structural – morphology, orientation, crystallinity, strain, compliance, and defects	SEM, TEM, AFM, STM, X-ray, EBIC	0.5
Chemical – composition and impurity	SIMS, EDS, EELS, Auger, XPS	1
Optical	PL, CL, RAMAN, NSOM, time resolved pump-probe	2
Electrical	IV, CV, conductive AFM, STM	0.5
Midterm exam		**1**
4. Nano-devices		**9**
for light emission and detection	Nanowire waveguide, LEDs and lasers	2
	Nanotube resonators	1
	Nanowire detectors	1
for energy conversion	Nanowire photovoltaic	1
	Nanowire thermoelectric devices	1
for extending IC roadmap	Nanowire and nanotube finFET etc.	1
for sensing	Resonator and transistor based etc.	1
misc.	Nanofluidics etc.	1
5. Nano-systems and manufacturing	field induced assembly, dry transfer printing etc.	**1**

Books

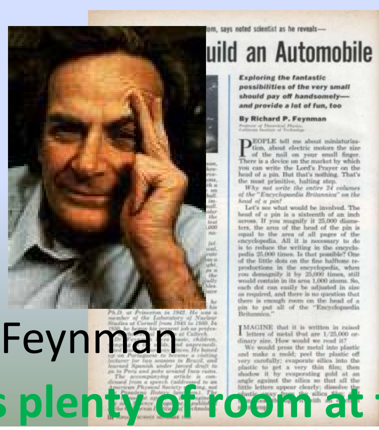
- Texts: class notes and journal papers.
- Reference books (partial list):
  - Handbook of Semiconductors and Nanodevices, by Balandin and Wang, 2006 (in reference section in Grainger)
  - Epitaxy of nanostructures, By Shchukin, Ledentsov, Bimberg, Springer, 2004
  - Semiconductor Nanostructures for Optoelectronic Applications, By Steiner, Artech House, 2004
  - Future Trends in Microelectronics, by Luryi, Xu, Zaslavsky, John Wiley & Sons, 2007

Introduction to Nanotechnology

- The definition and who owns it?
  - Chemists and Biologists: atoms (3Å), DNA (2 nm), colloidal chemistry
  - Engineers: QW laser, nano-transistors

"It is not who is right, but what is right that is of importance." T. H. Huxley

- The facts and the hype



Feynman

There is plenty of room at the bottom

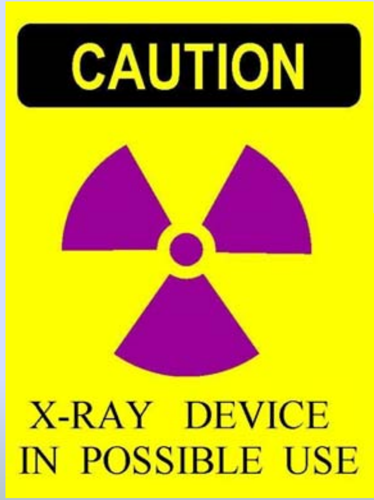
Drexler

Facts and Hype

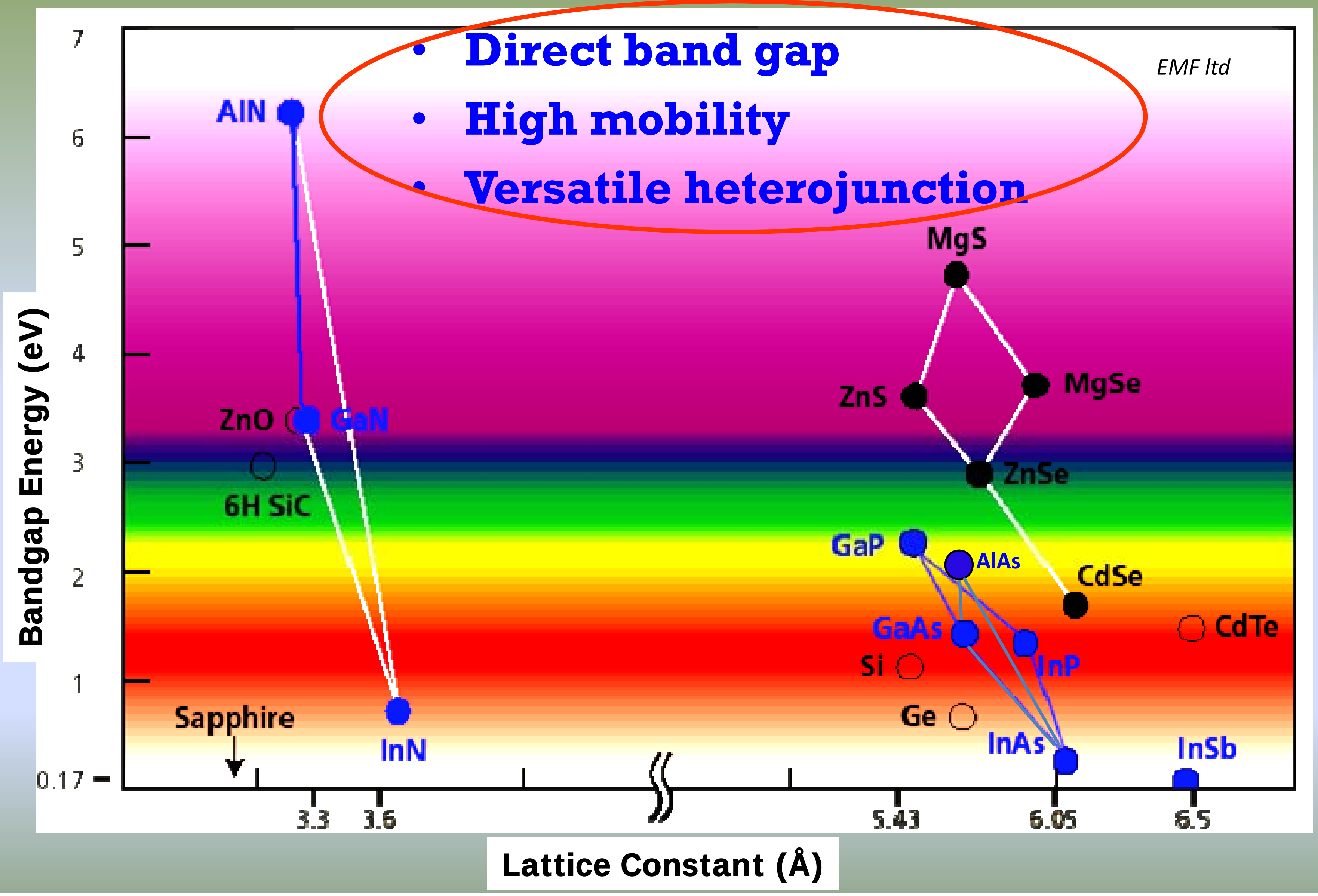
- Engineering village search –
  - Nano: 158, 499
  - Nanotechnology: 118,349
  - Nanowire: 31,205
  - Quantum Dots: 61,753
- Popular Press
- Scientific Journals targeting Nano specifically
  - Nature Nanotechnology
  - Nano Letters
  - ACS Nano
  - Nanotechnology
  - Small
  - IEEE Transactions on Nanotechnology

“Nanomaterial Safety Plan”

Nanomaterials
Might Be Present



Semiconductor bandgap



Nanotechnology Overview

SIZE MATTERS

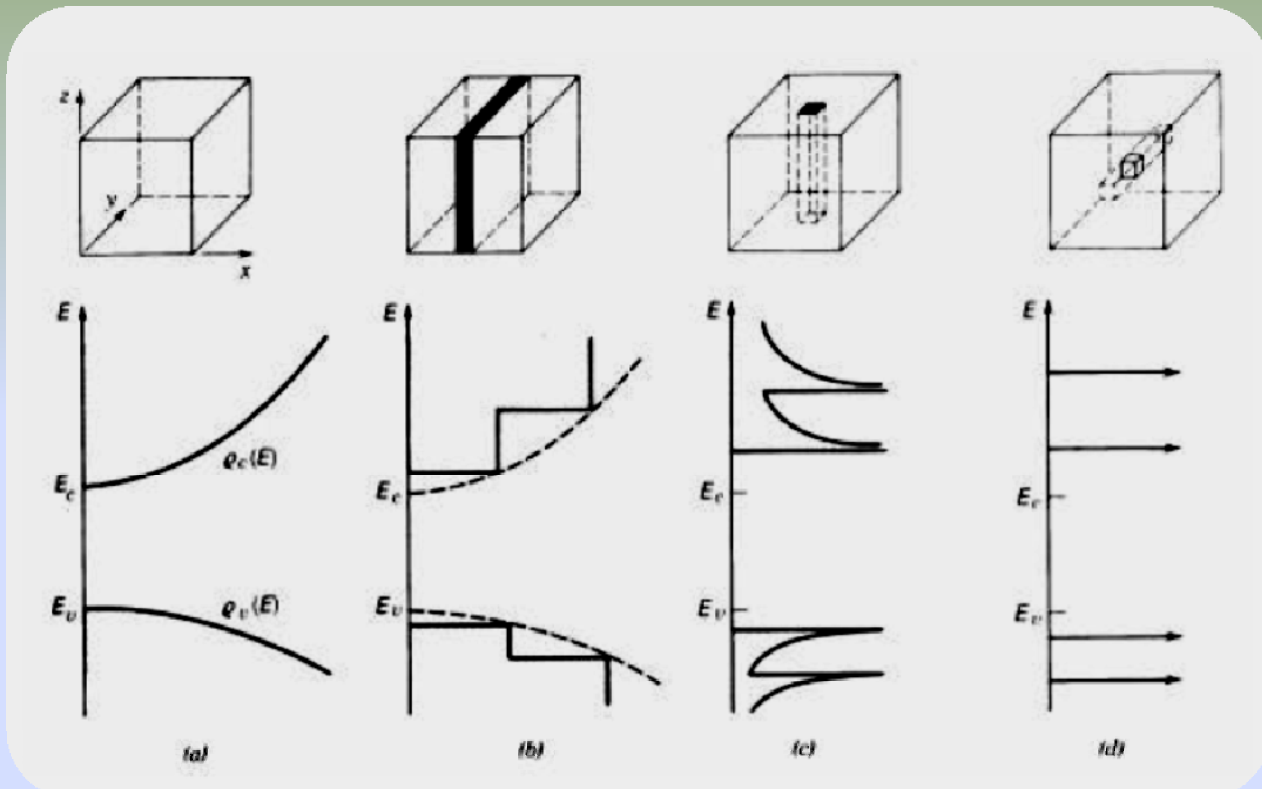
new kinds of forces and new kinds of possibilities, new kinds of effects.

When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc.

Richard Feynman, December 1959

Electronic Properties vs Size

Quantization of Density of States



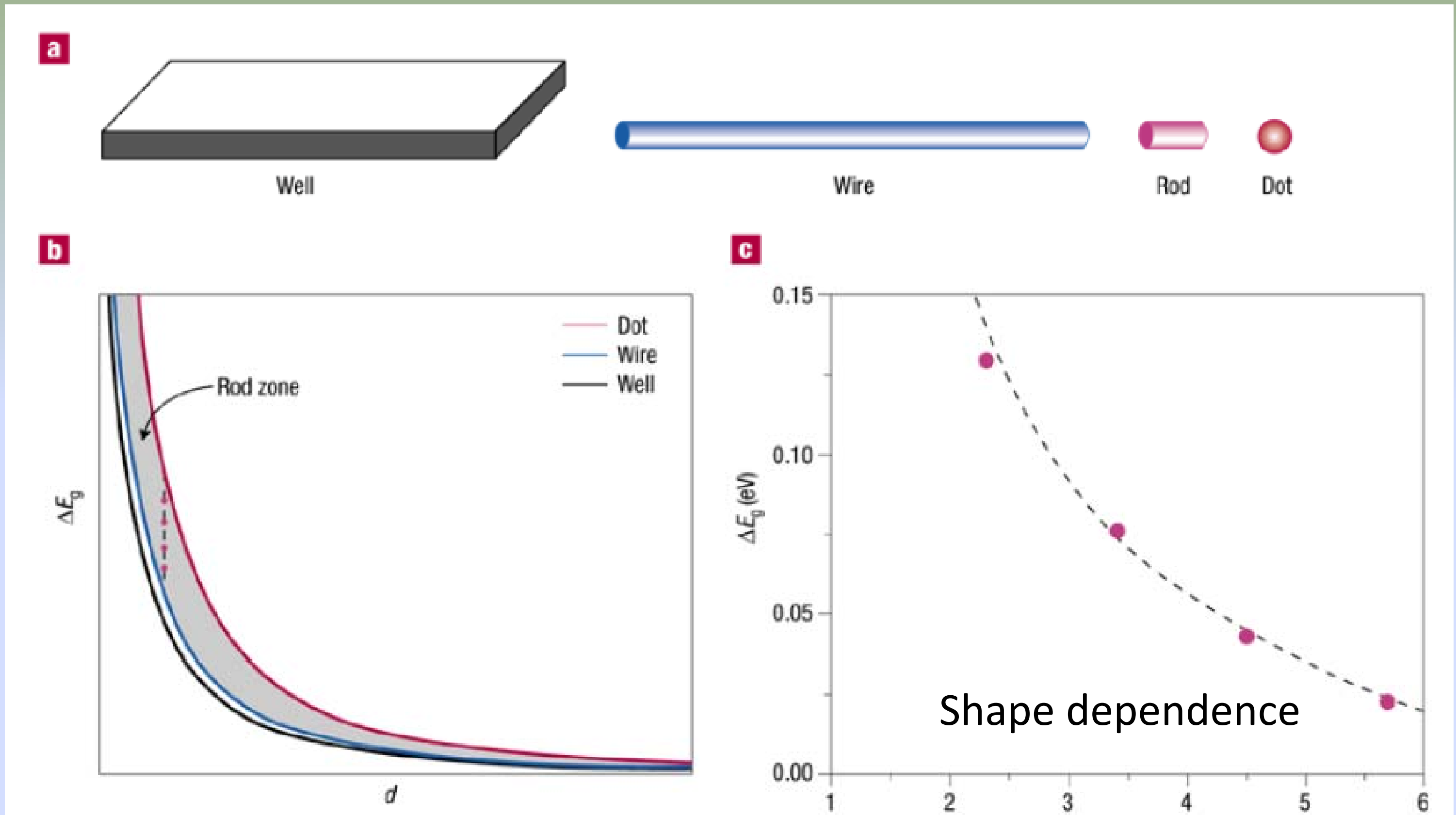
Ev and Ec split into overlapping subbands

- successively narrower as the e- motion is restricted in more dimensions

Saleh and Teich, Fundamentals of Photonics, Ch.15

Electronic Properties vs Size

Quantum confinement ΔE_g

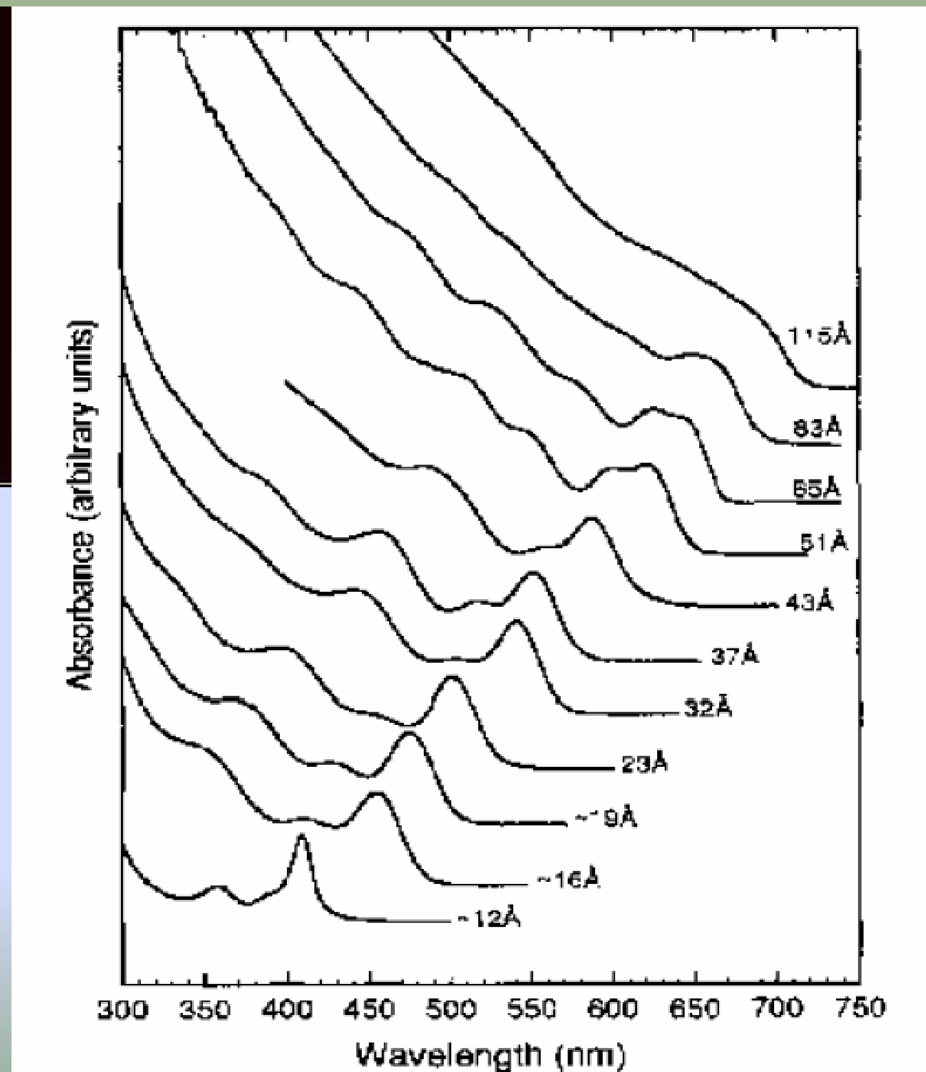


Particle-in-a-box approximation

Buhro and Colvin, Nature Materials, 2, 138 (2003)

Electronic Properties vs Size

QDs: colloidal nanocrystals



- CdSe quantum dots that are increasing in size (left to right).
- Optical absorption spectra of CdSe nanocrystals dispersed in hexane and corresponding TEM avg. size distribution (12 – 105 Å). J. Am. Chem. Soc., 115, 8706 (1993)

Electronic Properties vs Size

Quantum Well Lasers

- QW – in most commercial diode lasers
- Quantum size effect – discrete energy level – constant DOS at each step
  - Lower threshold
  - Narrow linewidth
  - Temperature stability

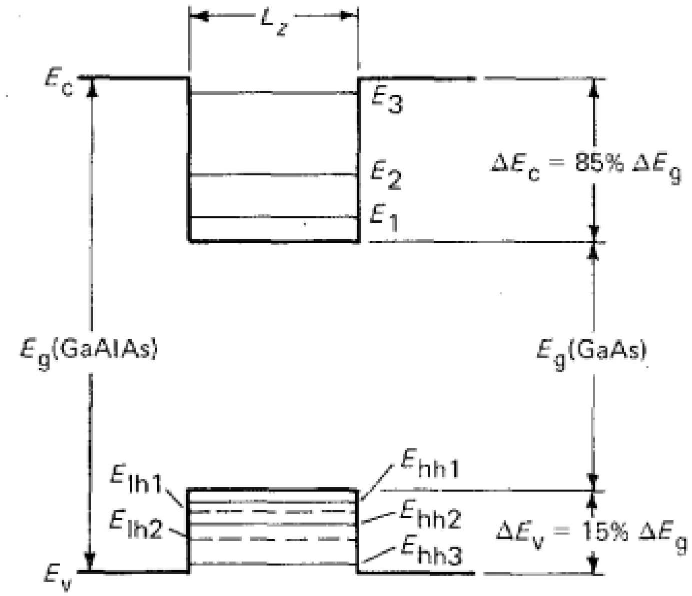
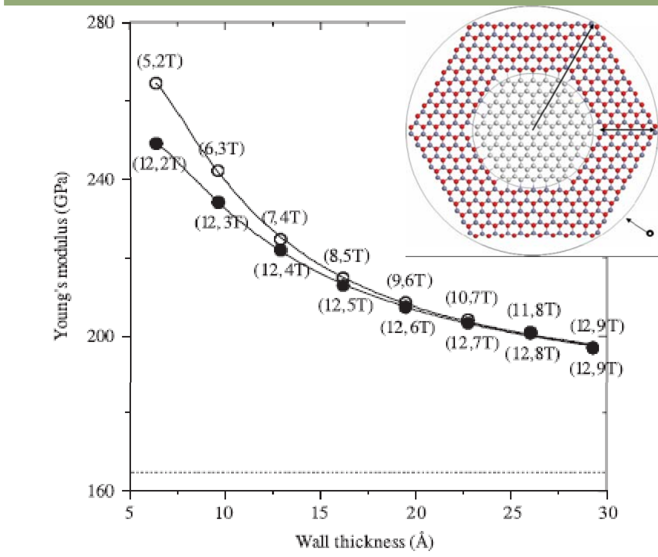


Fig. 1. Square-well potential that is characteristic of an $Al_xGa_{1-x}As$-$GaAs$-$Al_xGa_{1-x}As$ quantum-well heterostructure. For well thickness $L_z \lesssim \lambda$ (the carrier deBroglie wavelength), size quantization occurs and results in a series of discrete energy levels given by the bound state energies of a finite square well. A potential well exists in both the conduction band and the valence band giving rise to a series of bound states E_n for the electrons, E_{hhn} for heavy holes, and E_{lhn} for light holes.

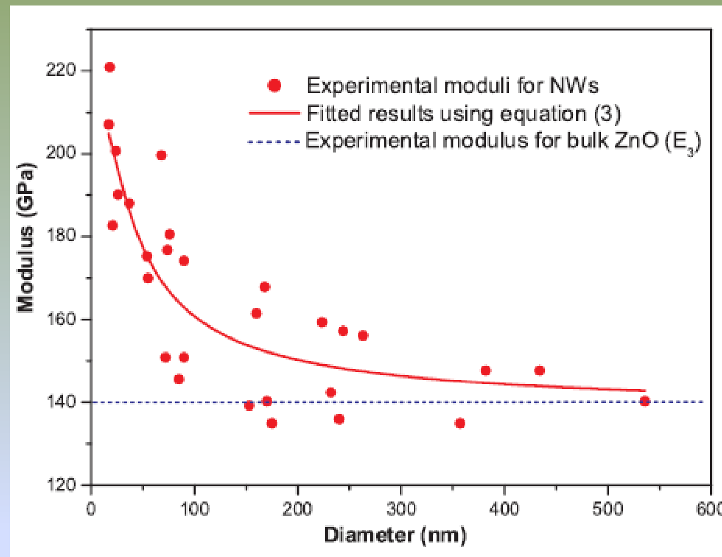
Holonyak, 1980

Mechanical Properties vs Size

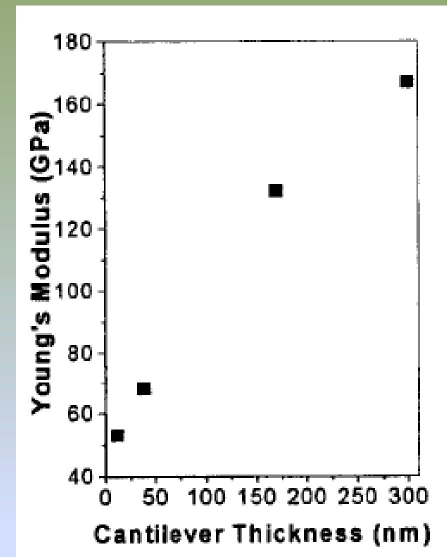
Young's Modulus Engineering



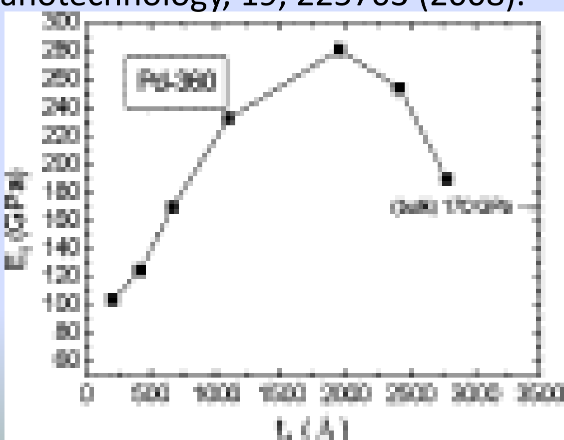
single crystal ZnO nanotube wall thickness
Nanotechnology, 19, 225703 (2008).



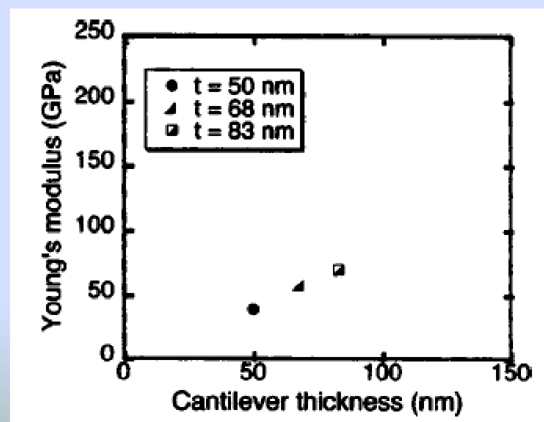
Single crystal ZnO nanowire diameter
PRL, 96, 075505 (2006).



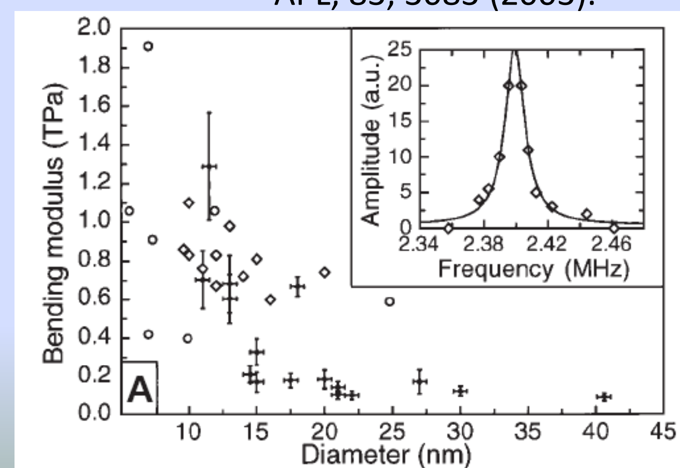
Single crystal Si thickness
APL, 83, 3083 (2003).



polycrystalline Pd film thickness
Thin Solid Films, 492, 166 (2005)

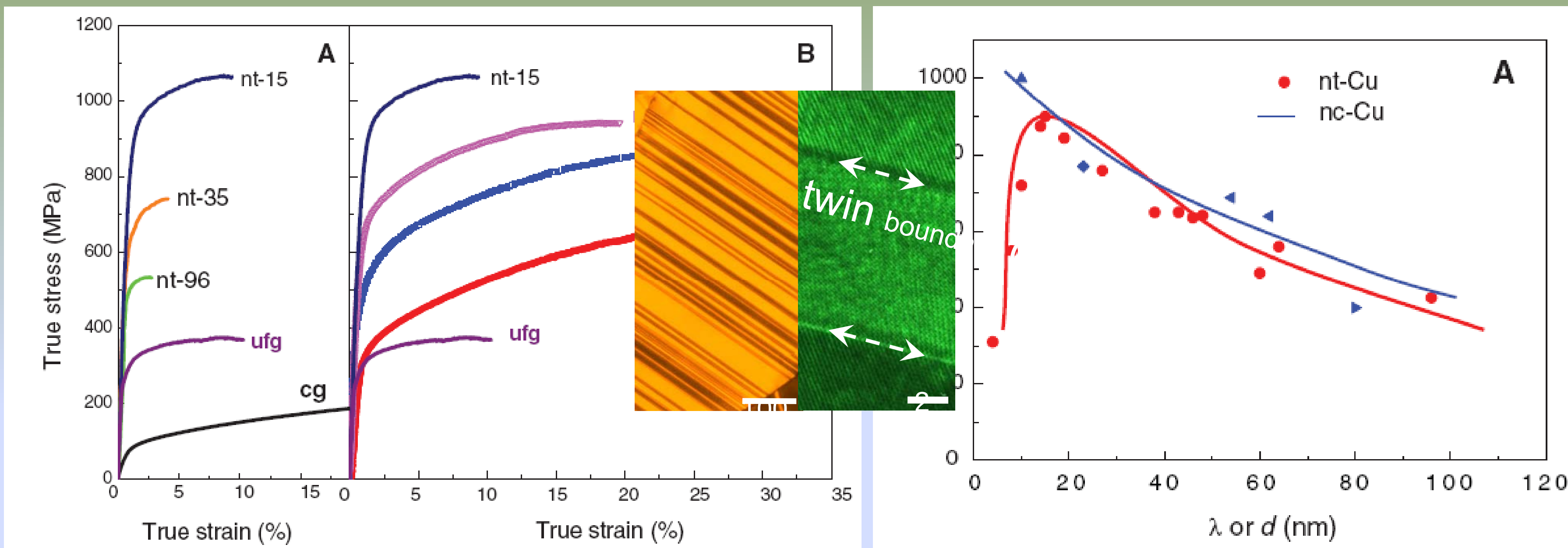


polycrystalline Cr film thickness
APL, 85, 3555 (2004)



CNT diameter
Science 283, 1511 (1999).

Effect of Twin Boundaries in Cu films



- Coherent twin boundaries are effective grain boundaries in strengthening materials
  - Strengthening Cu when high densities of nm thick twins are introduced in subum sized grains.
  - Below 15 nm twin thickness, Cu starts to soften.
- Two competing mechanism for hardening:
  - dislocation-dislocation interaction in coarse twins
  - Dislocation- twin boundary hardening in fine twins

Revealing the Maximum Strength in Nanotwinned Copper, *L Lu et al.* Science 323, 607 (2009).
Strength and ductility of nano-twinned materials L. Lu, K. Lu, et al, *Science*, 2004

Surface/interface effect on Resistivity

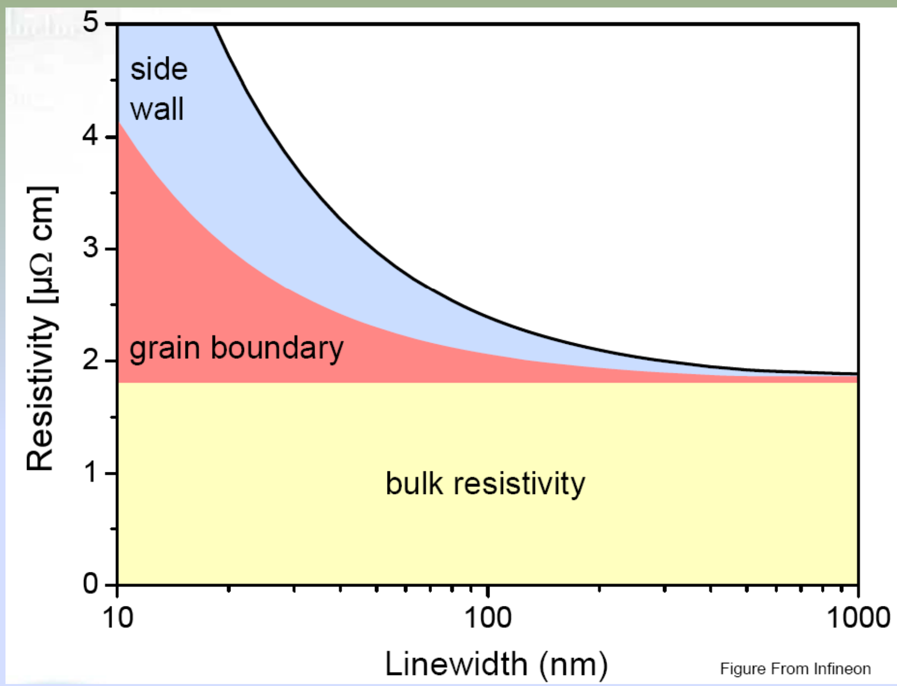
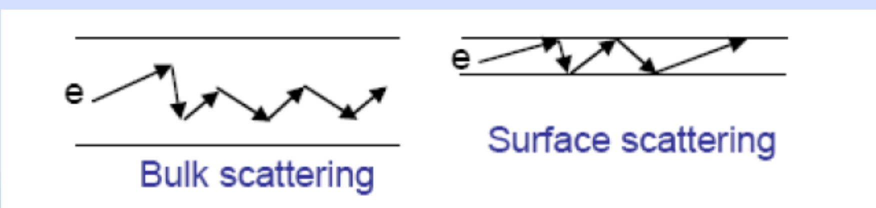
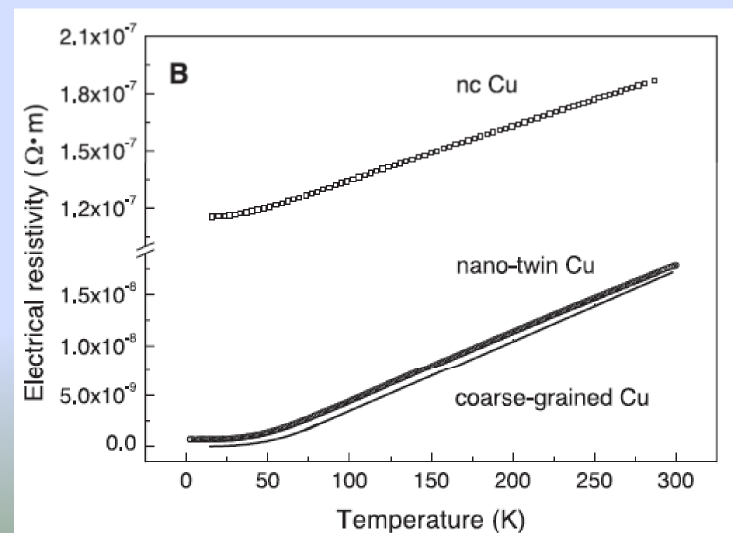


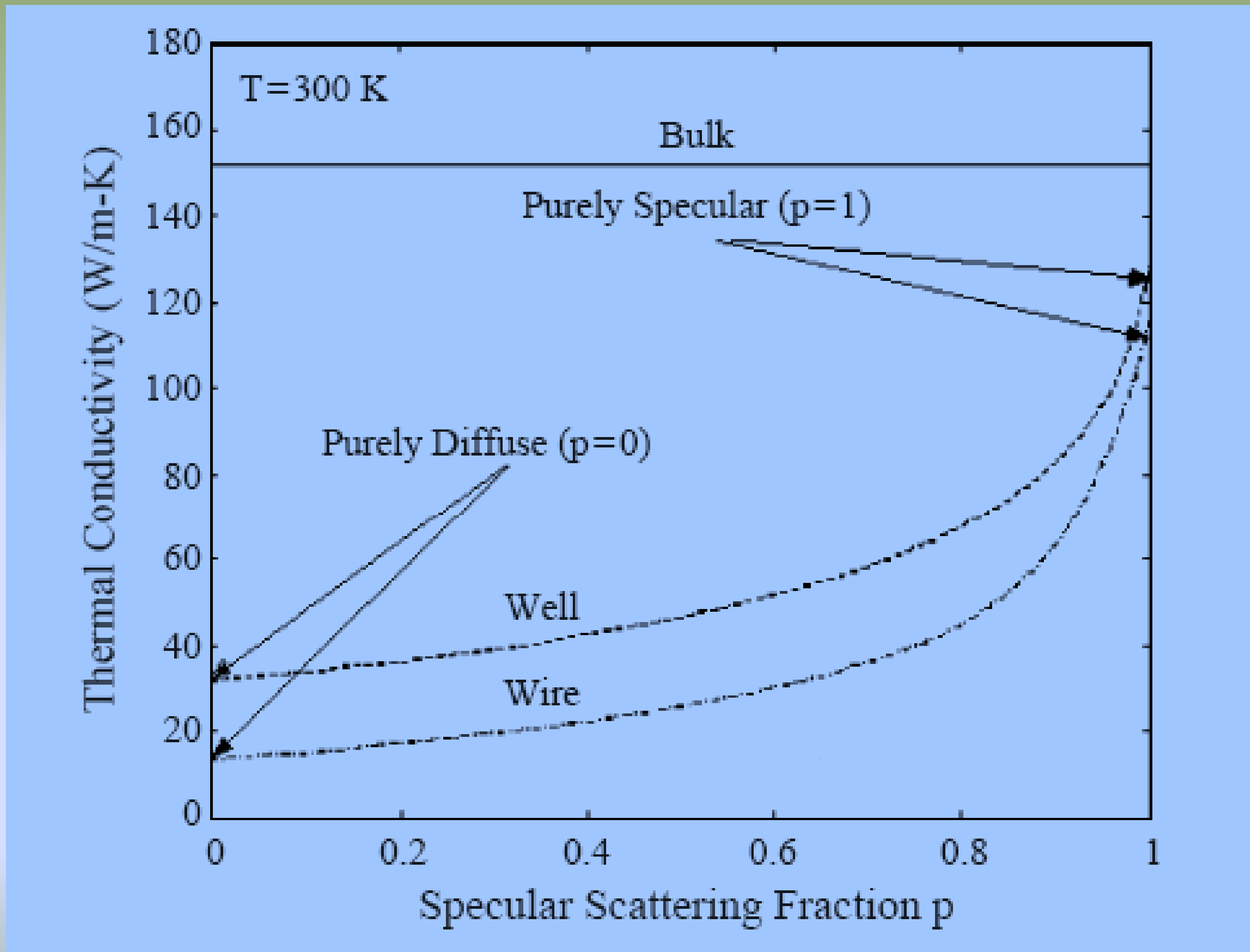
Figure From Infineon



- Carrier scattering:
  - Impurity (Coulomb) scattering (donors/acceptors): $\mu = T^{3/2}/N_i$
  - Lattice scattering (phonons):
    - GaAs $\mu_e \propto T^{-1}$; $\mu_h \propto T^{-2.1}$
    - Si: $\mu_e \propto T^{-2.4;}$ $\mu_h \propto T^{-2.2}$
    - Can be ignored at low T
  - Surface scattering: space-charge double layer; combination of μ in both layers….
    - Surface roughness
    - Impurity accumulation
    - Charge states



Thermal Conductivity vs Size



Nanophotonics: phonon engineering in nanostructures and nanodevices, Balandin, J. Nanoscience Nanotechnology, 2005

Thermal Conductivity vs Size

- Thermal conductivity decreases with size
  - Enhanced phonon scattering at boundaries - diffuse phonon scattering (when L~ MFP)
  - Phonon confinement effect – increased phonon scattering on defects/dislocations (when L<< MFP)

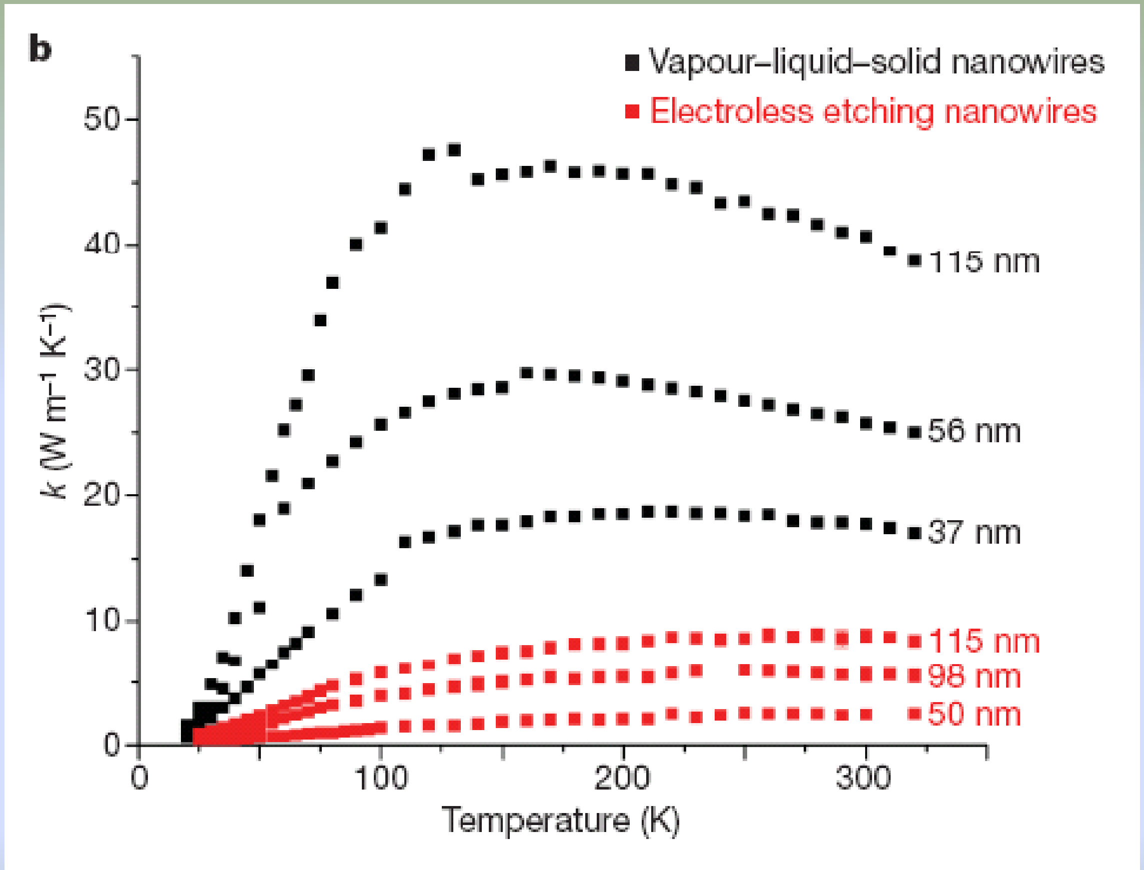
Table I. Phonon transport regimes.

Scale	Phonon dispersion	Dominant scattering processes
$L \gg$ MFP	bulk dispersion	• three-phonon Umklapp • point defects
$\lambda_0 \ll L \leq$ MFP	bulk dispersion	• three-phonon Umklapp • point defects • boundary scattering
$\lambda_0 \leq L \ll$ MFP	modified dispersion with many phonon branches populated	• three-phonon Umklapp • point defects • boundary scattering
$L < \lambda_0$	modified dispersion; only lowest phonon branches populated	• ballistic transport

Nanophotonics: phonon engineering in nanostructures and nanodevices, Balandin, J. Nanoscience and Nanotechnology, 2005

Thermal Conductivity vs Size

- decreases with roughness



AgNO3 + HF ---- Ag

Nature, 451, 163, 2008, PD Yang group

Micro and nanoelectronics vs Size

Microelectronics: Moore's Law

- Nanotechnology is essential to continue the miniaturization process and efficiency
- Path of non-Si MOSFET
  - CNT
  - Graphene
  - III-V

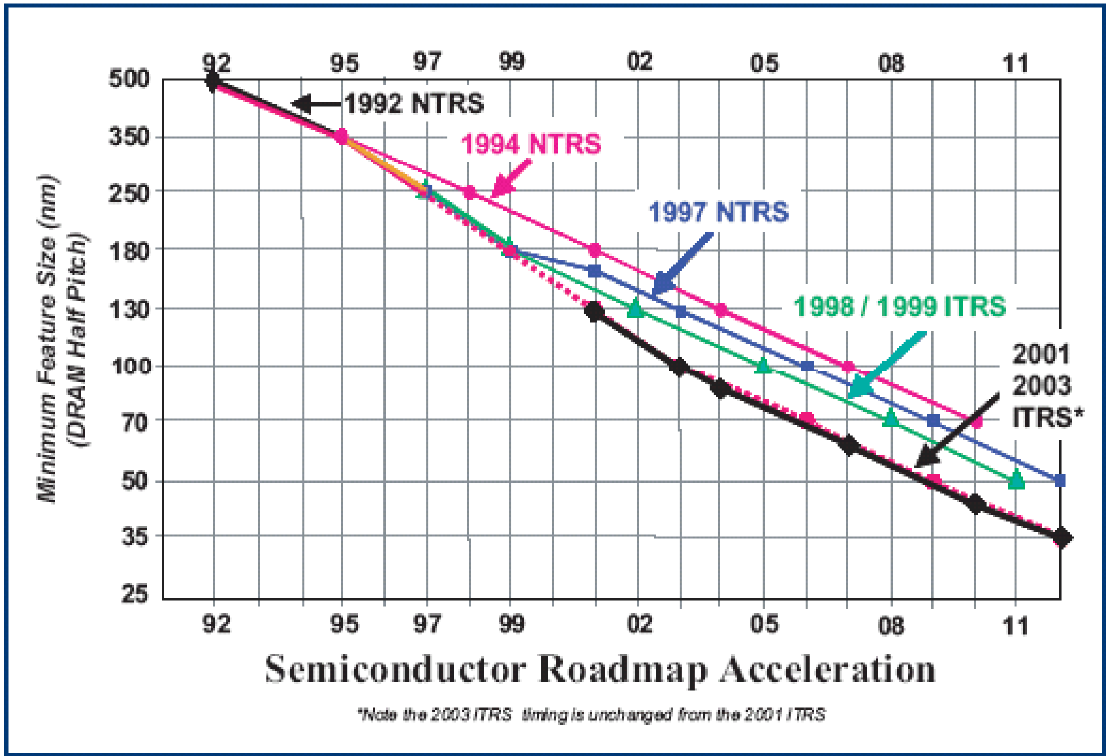


Figure 3. Historical Acceleration of Roadmap

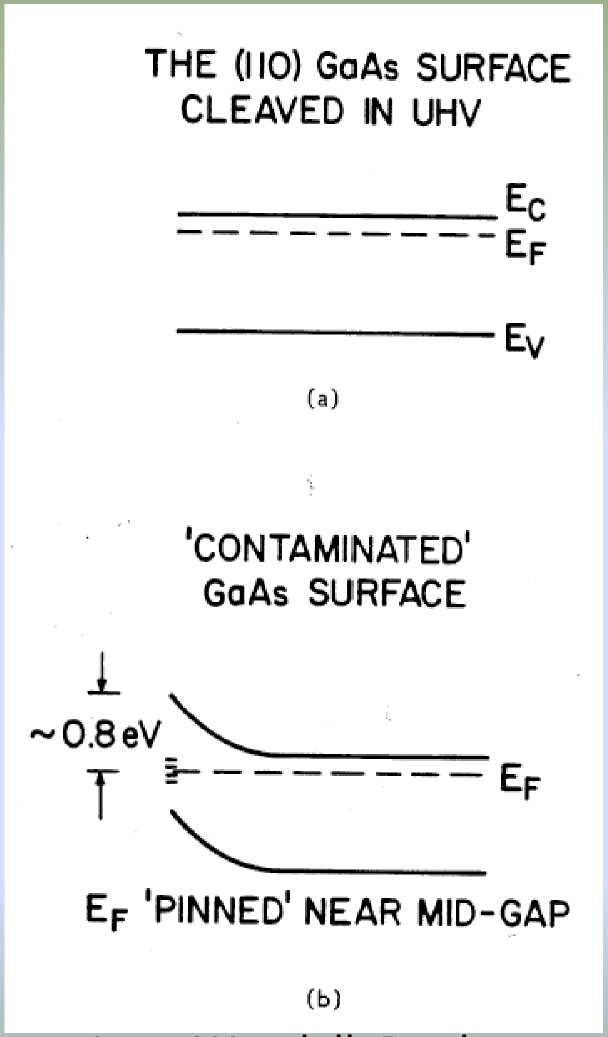
Non-Silicon MOSFET Technology

- Si-MOSFET 2008 worldwide chip sales > $250B
- All compound semiconductor devices and chips ~ $20B: mostly photonic devices and chips
- Why Si dominant?
  - Si inferior electronic and photonic materials compared to e.g. GaAs
  - Si is cheap
  - SiO_2 – electronically exquisite, in contrast, nearly all compound semiconductor native oxides are inferior
  - Reversibility of ion-induced damage in Si
  - Lack of a viable non-silicon MOSFET technology during the early R&D efforts hampered its development.
  - Stay on a revised Moore's Law path

Price/performance

Fermi Level Pinning and III-V Nanostructures

- **The surface or interface Fermi energy is nearly invariant with respect to processing technologies, and has a characteristic value which depends on the semiconductor material**



Jerry Woodall, Purdue

Nanotechnology

Building Blocks

- Quantum wells
- Quantum dots
- Nanotubes and nanowires
- Nanomembranes

Formation Mechanism

- Bottom-up
- Top-down

Advantages

- Electronic confinement
- Surface sensitivity
- Mechanical compliance

Challenges

- Size and density control
- Surface states
- Precision placement
- Integration