Principles of Micro- and Nanofabrication for Electronic and Photonic Devices

Film Deposition
Part I: Epitaxy 外延生长

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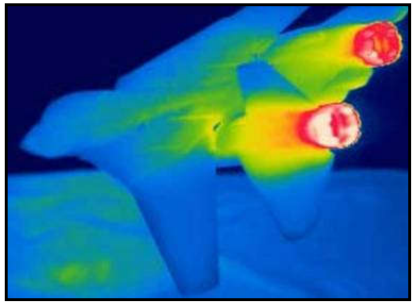
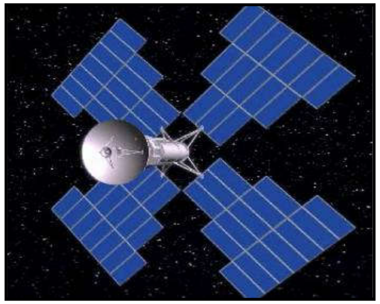
Optoelectronic Devices

LEDs

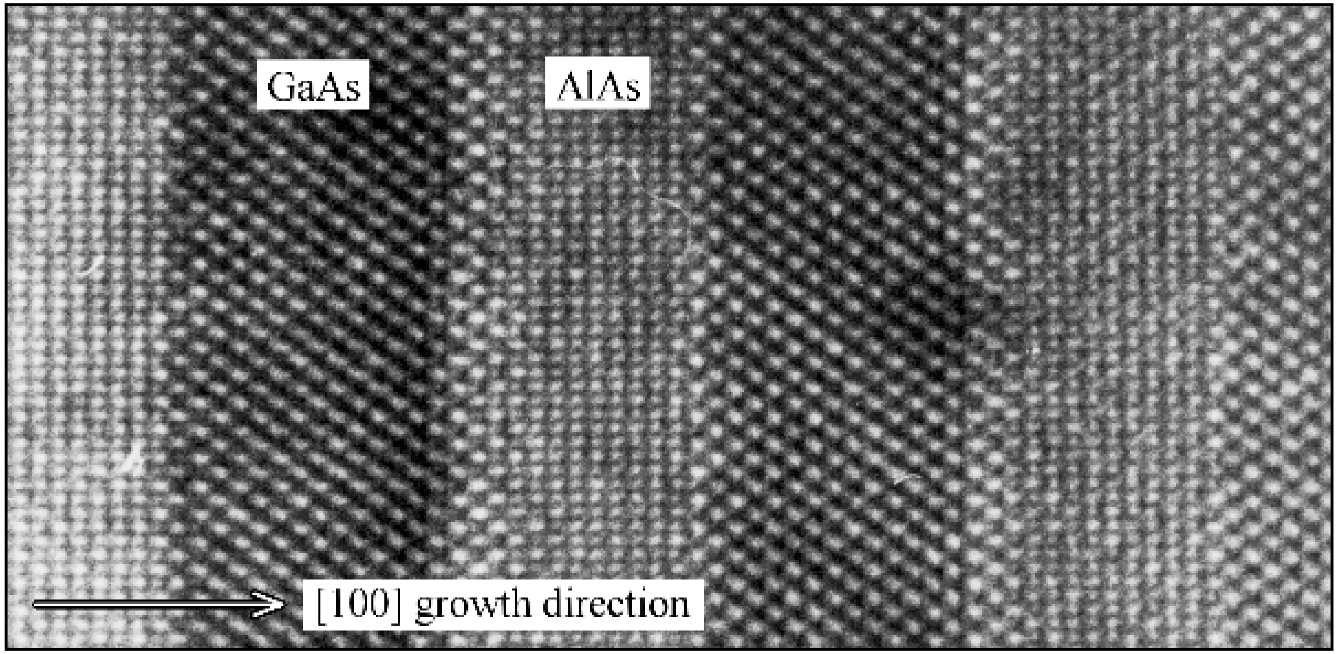
lasers



IR imaging

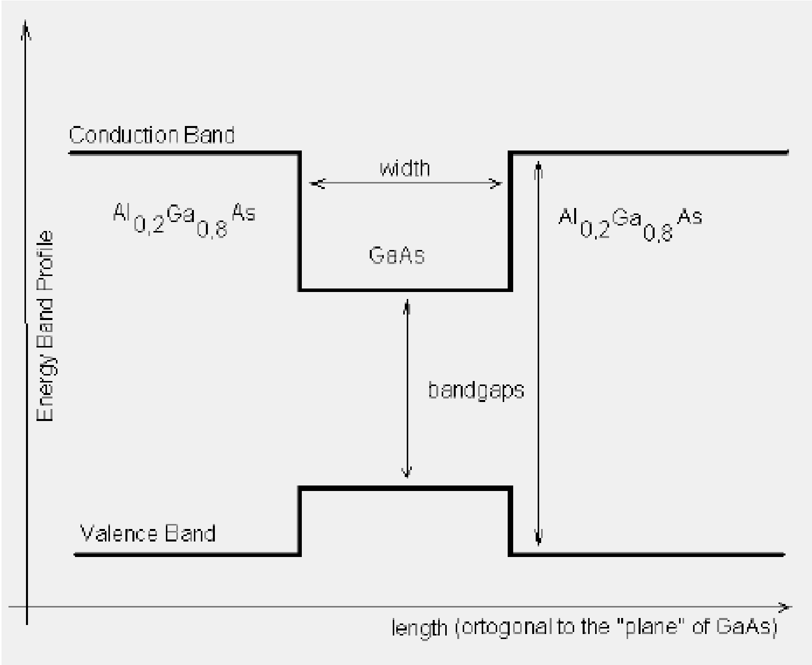


solar cells

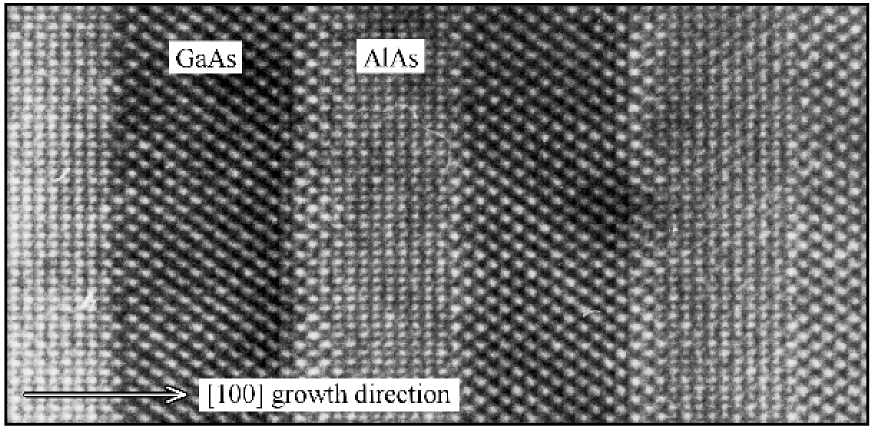


grow single crystal films on single crystal substrates

Semiconductor Heterostructures



GaAs/AlGaAs heterostructure: bandgap engineering

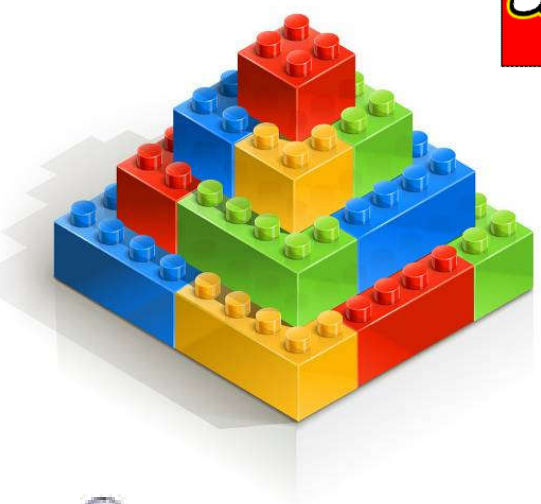


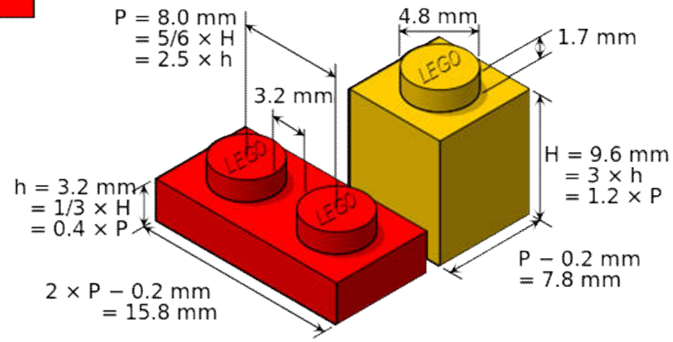
Z. I. Alferov

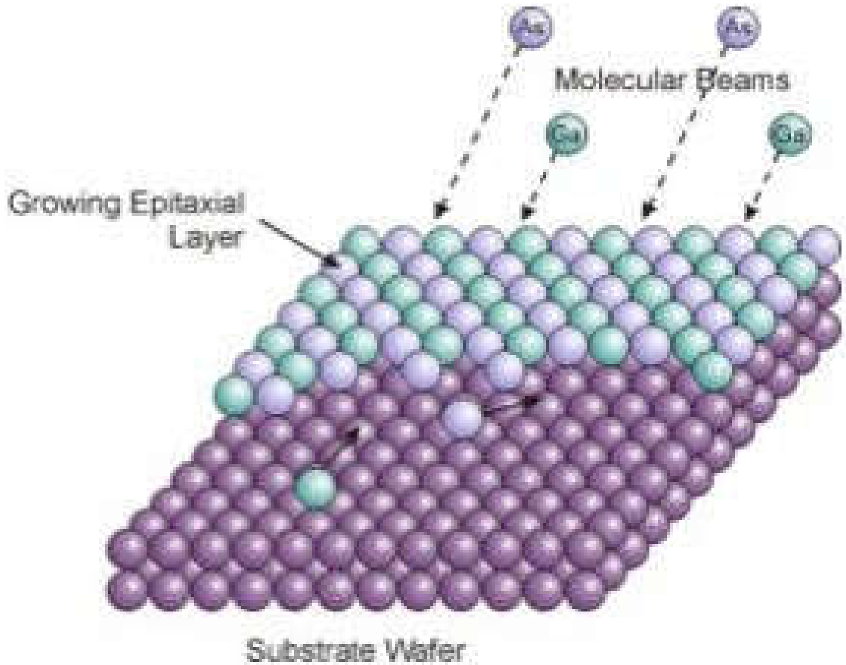
H. Kroemer

2000 Nobel Prize in Physics

Epitaxy (外延)







epi-

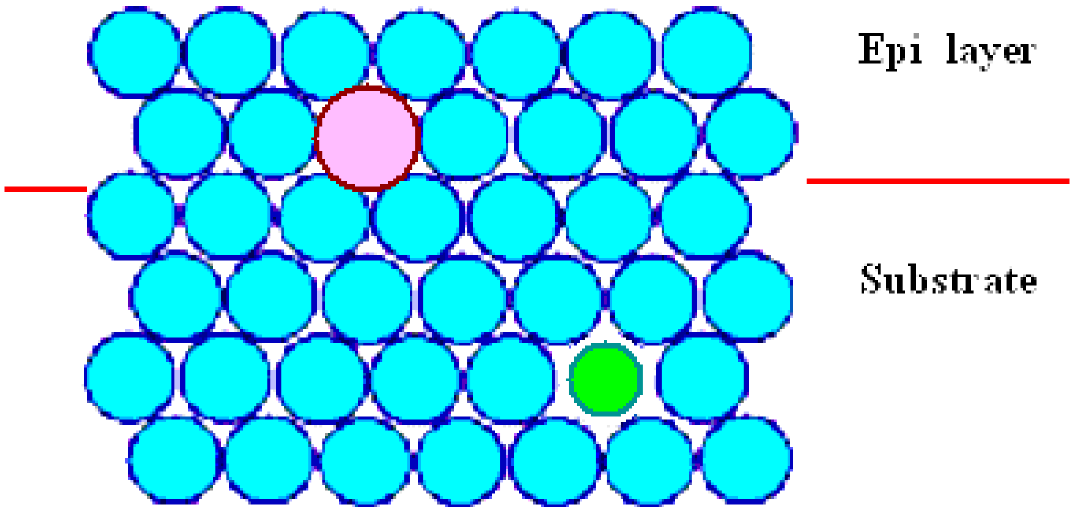
surface, 表面

-taxy

arrange, 排列

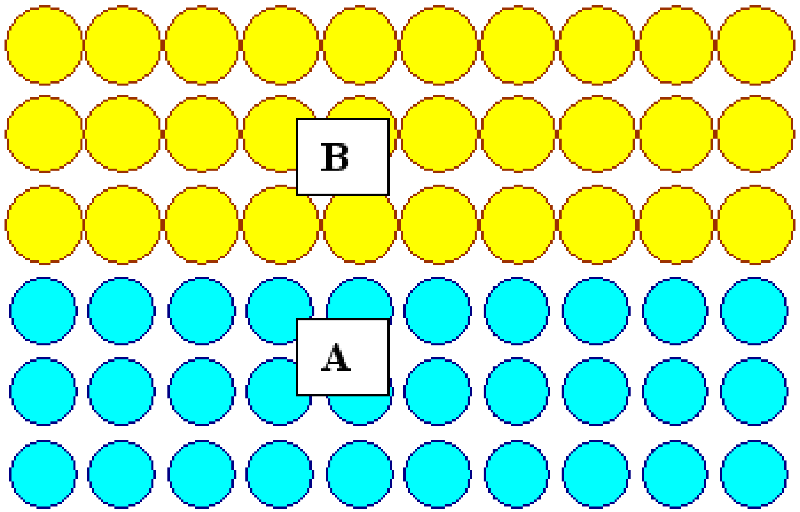
Epitaxial Growth

Homoepitaxy



(doped) Si on Si,
GaAs on GaAs,
...

Heteroepitaxy



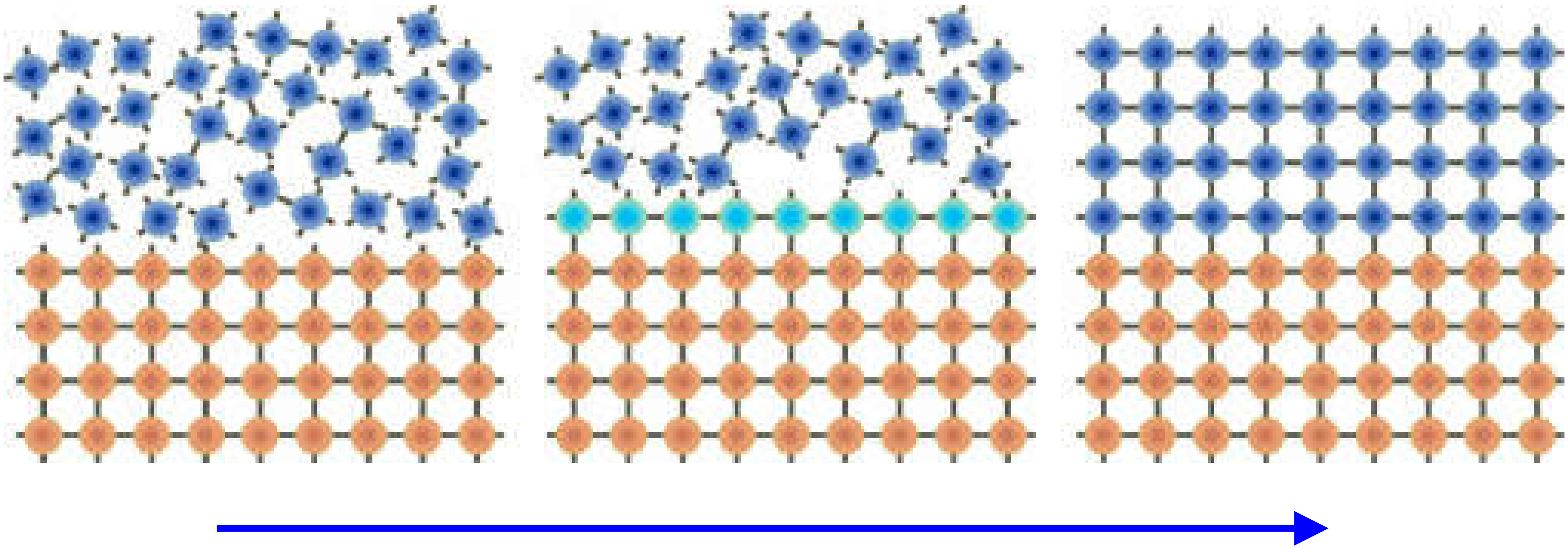
AlAs on GaAs
Ge on Si,
...

Methods

- Solid Phase Epitaxy (SPE)
  - amorphous Si -> crystalline Si
- Liquid Phase Epitaxy (LPE)
  - $2Ga\ (l) + 2AsCl_3\ (l) = 2GaAs\ (s) + 3Cl_2\ (g)$
- Chemical Vapor Deposition (CVD)
  - $Ga(CH_3)_3\ (g) + AsH_3\ (g) = GaAs\ (s) + 3CH_4\ (g)$
- Molecular Beam Epitaxy (MBE)
  - $2Ga\ (g) + As_2\ (g) = 2GaAs\ (s)$

Methods

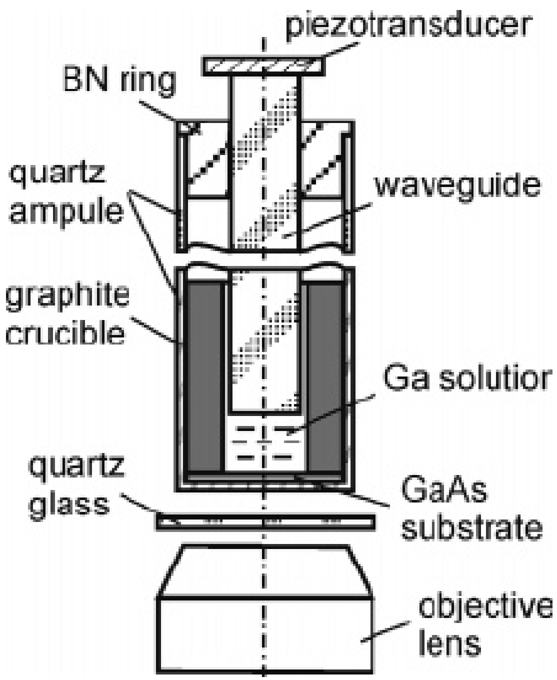
- **Solid Phase Epitaxy (SPE)**
  - amorphous Si -> crystalline Si

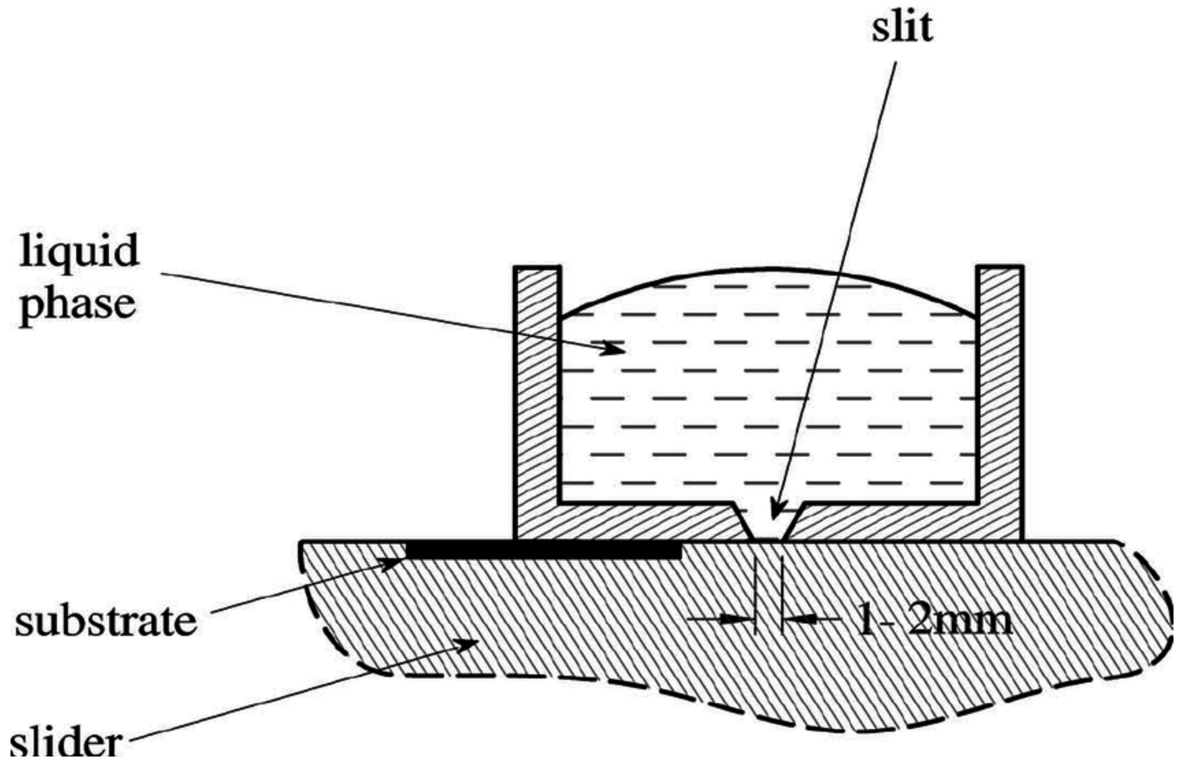


annealing at high temperature

Methods

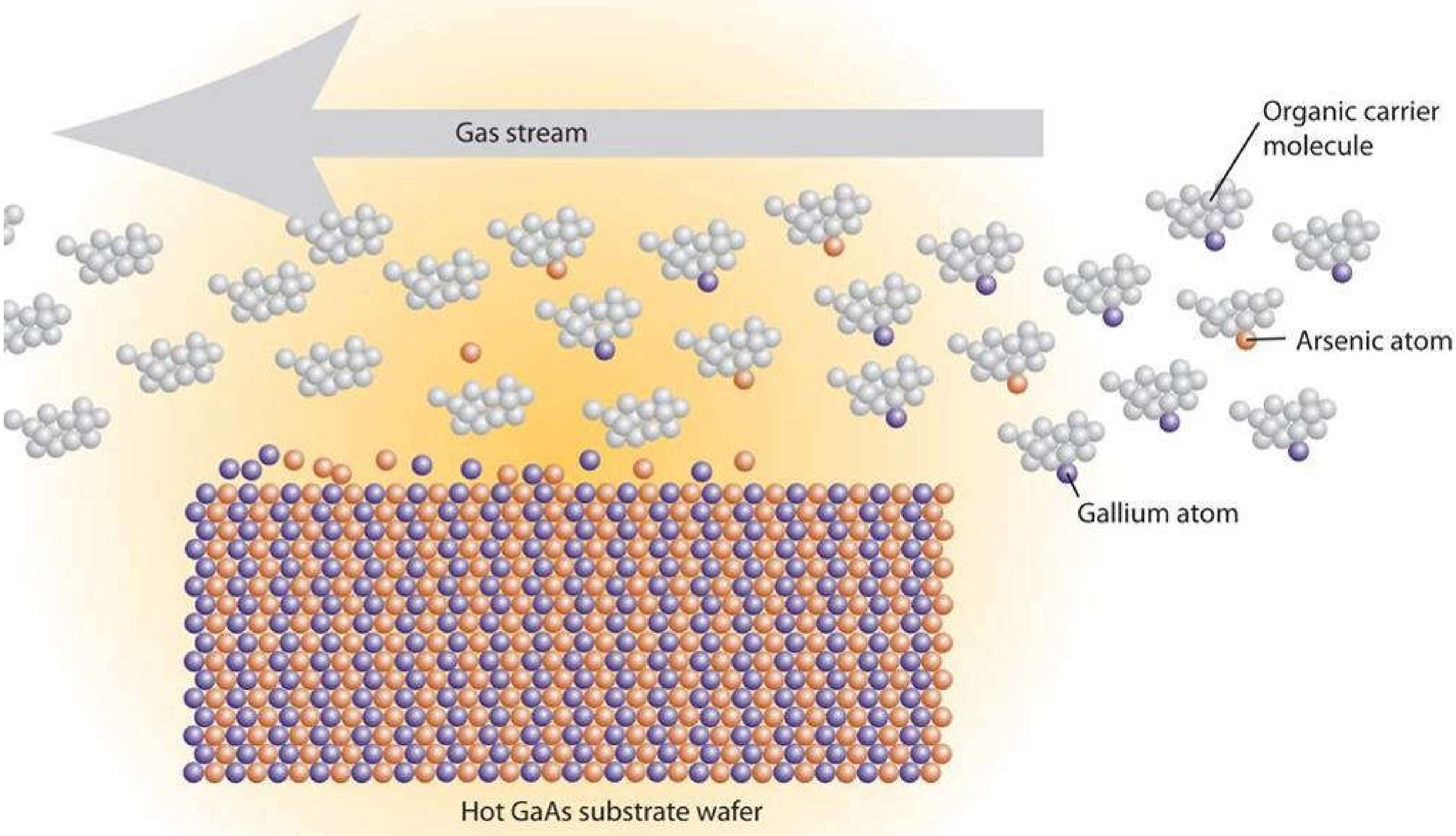
- **Liquid Phase Epitaxy (LPE)**
  - **$2Ga\ (l) + 2AsCl_3\ (l) = 2GaAs\ (s) + 3Cl_2\ (g)$**





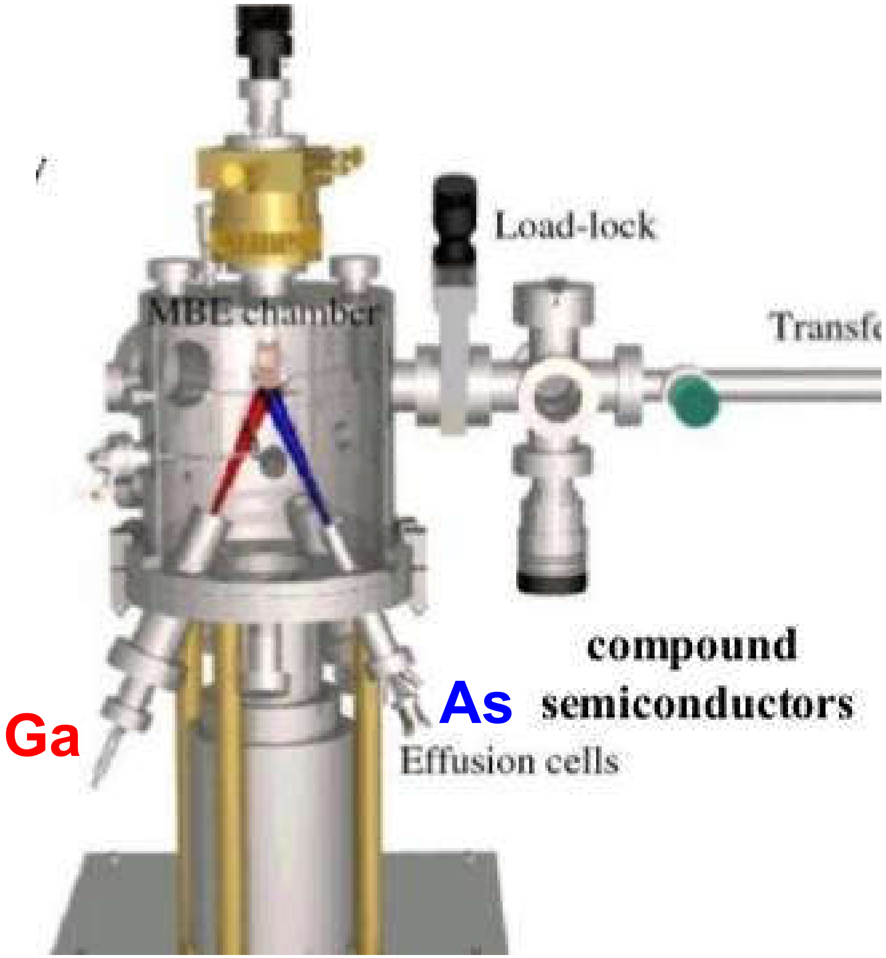
Methods

- **Chemical Vapor Deposition (CVD)**
  - $Ga(CH_3)_3\ (g) + AsH_3\ (g) = GaAs\ (s) + 3CH_4\ (g)$

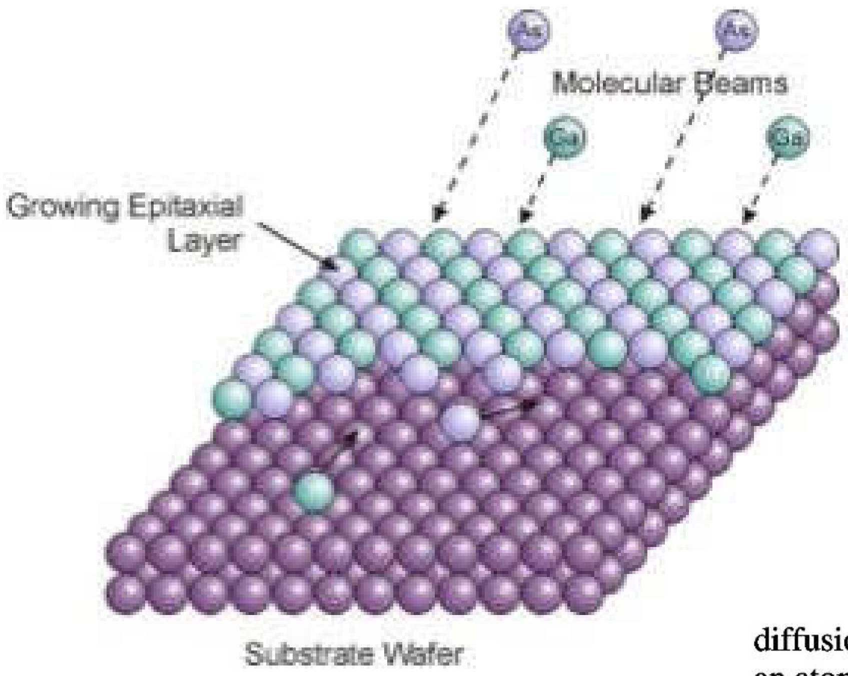


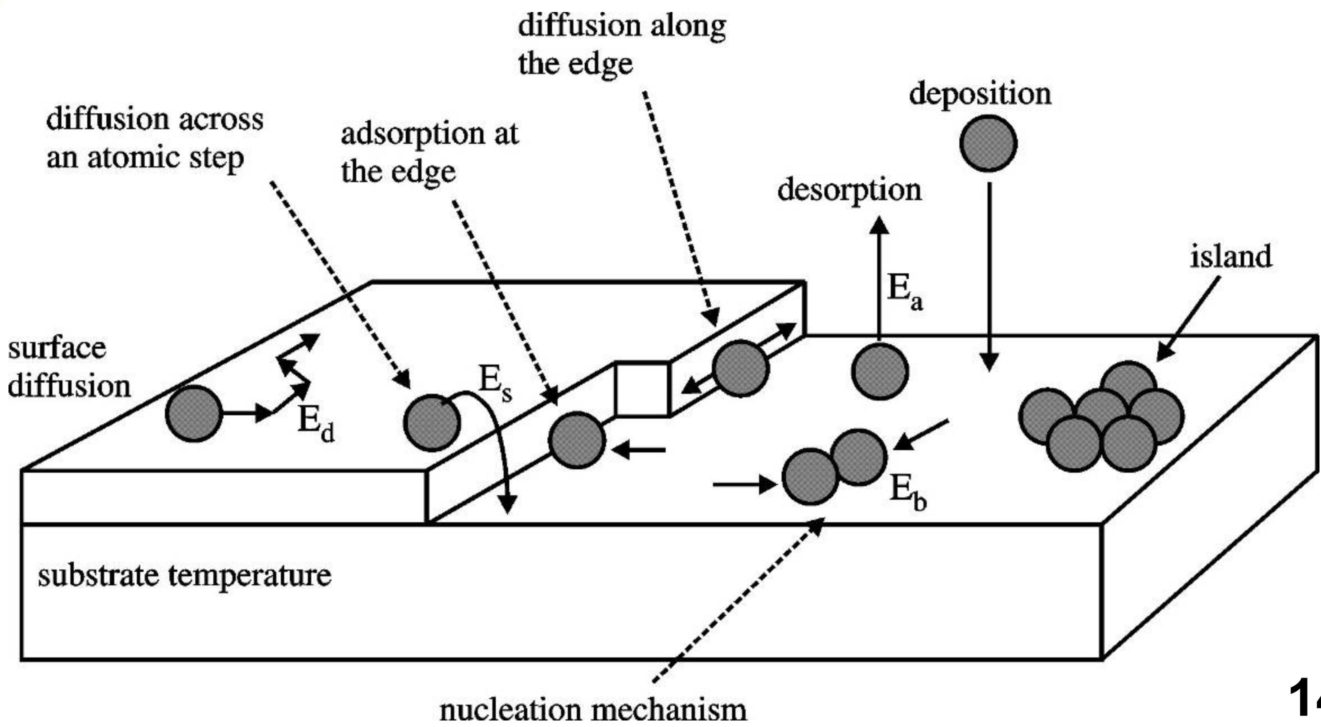
Methods

- **Molecular Beam Epitaxy (MBE)**
  - **$2Ga (g) + As_2 (g) = 2GaAs (s)$**

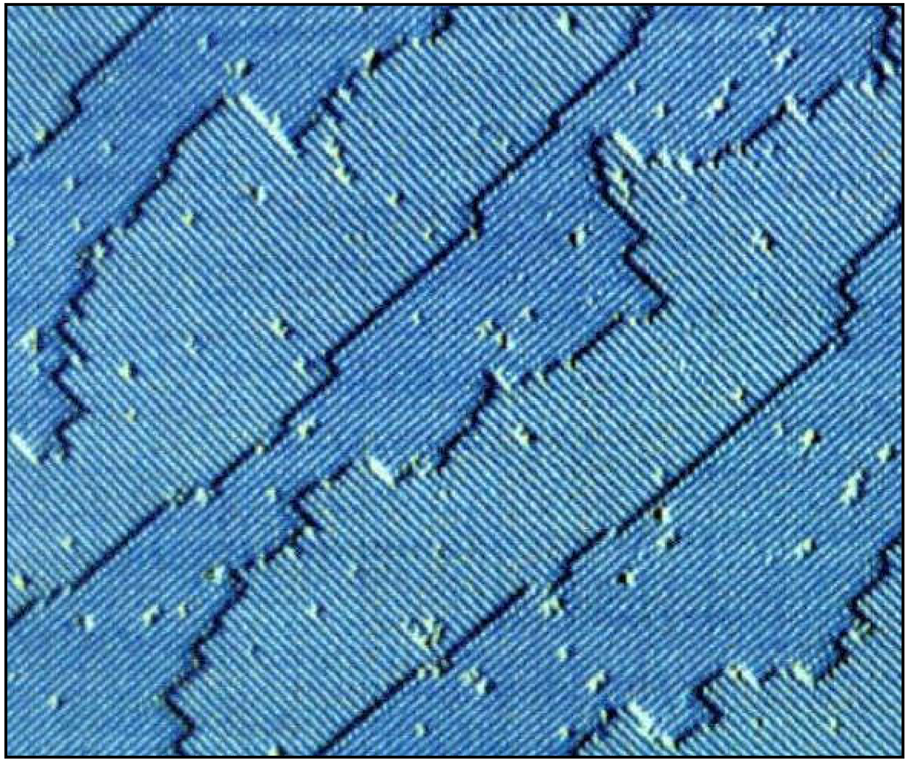


Deposition at Surfaces





Deposition at Surfaces

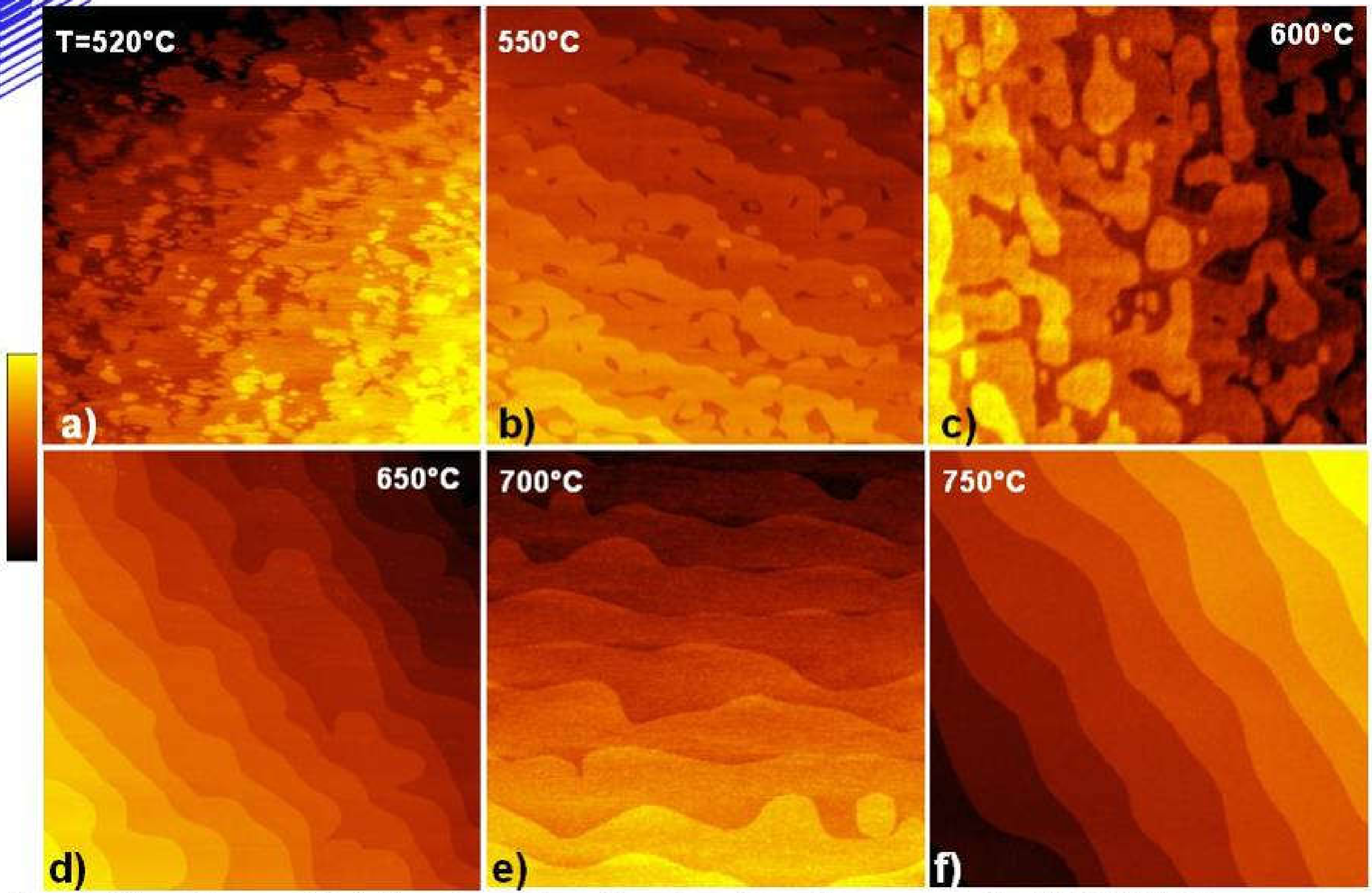


Si (100) surface

terrace (梯田)

Deposition at Surfaces

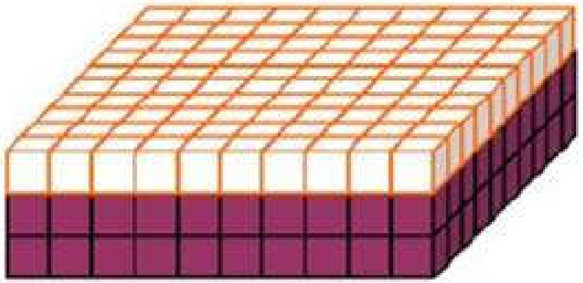
GaAs growth



Transition from 2D island nucleation to step flow growth (MOCVD).
5X5μm² post-growth AFM scans, heigth scale 2-5nm

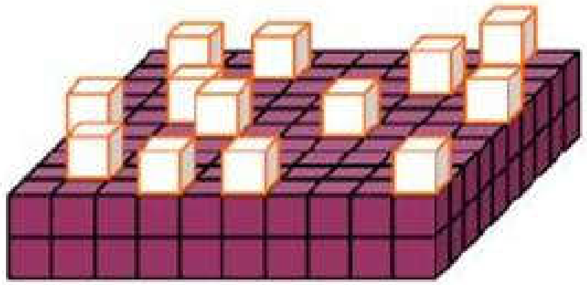
Growth Mechanisms

competition between surface and interface energies



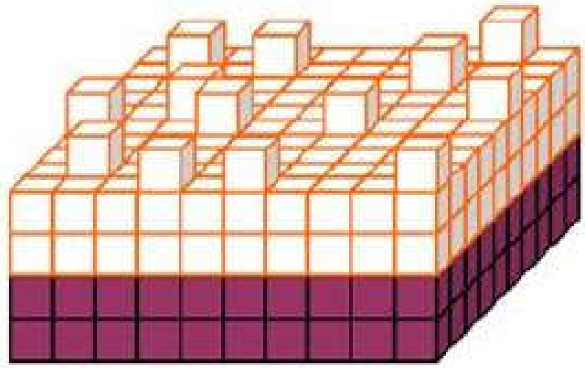
Frank-van der Merwe mode
(2 dimensional growth mode)

interface energy ↓



Volmer-Weber mode
(Island growth mode)

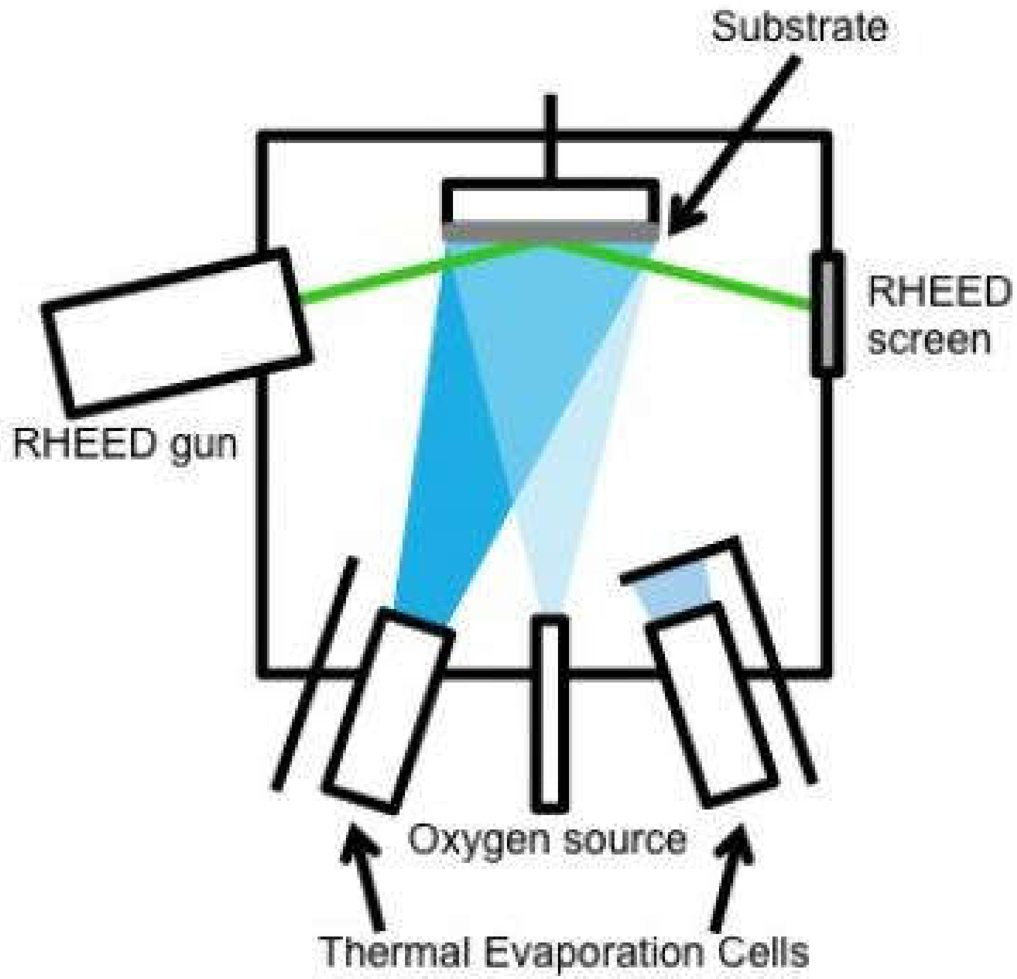
interface energy ↑



Stranski-Krastanov mode
(Layer & island growth mode)

interface energy ↓ ↑

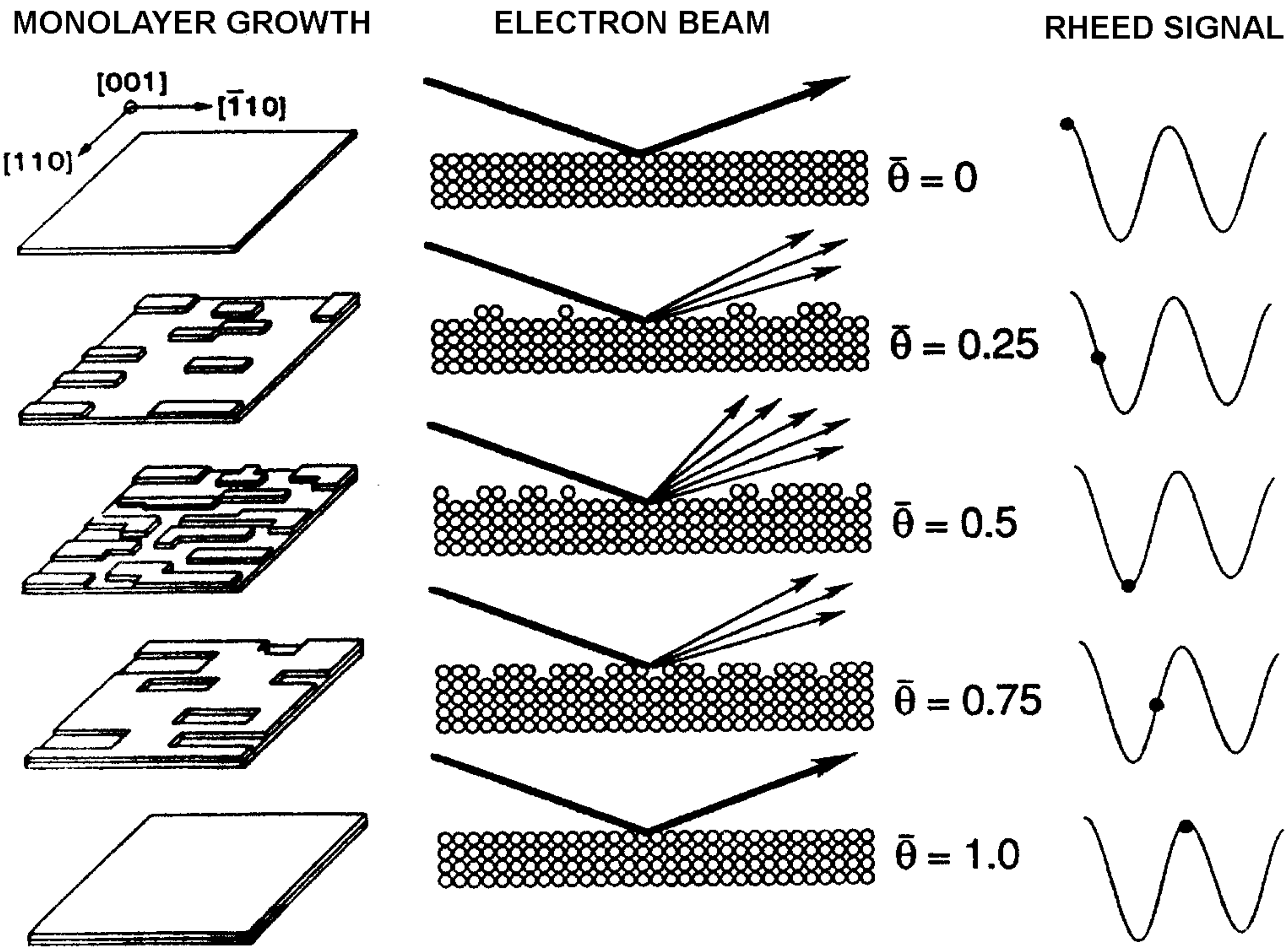
Online Surface Monitoring



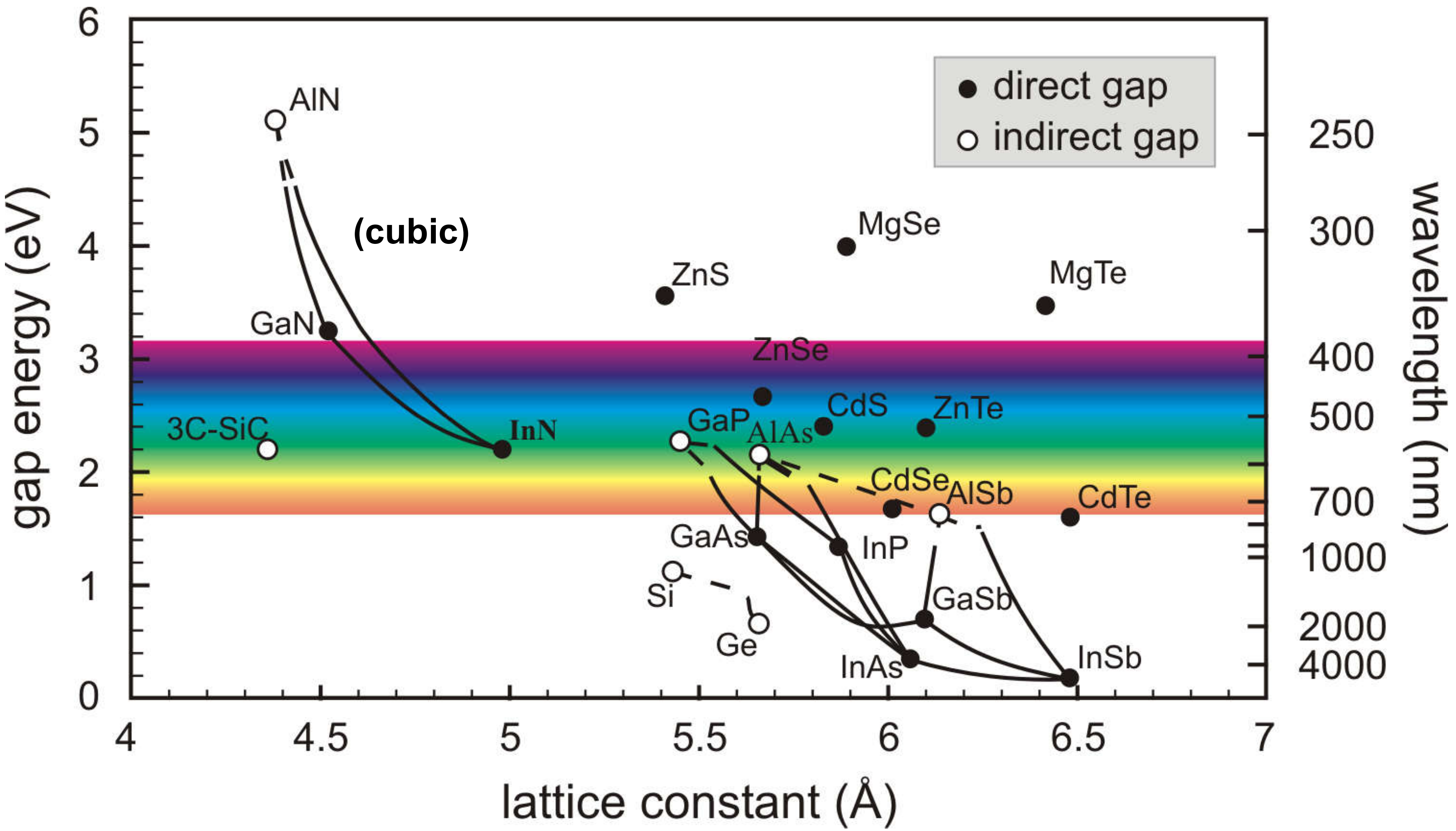
MBE system

Reflection high-energy electron diffraction (RHEED)

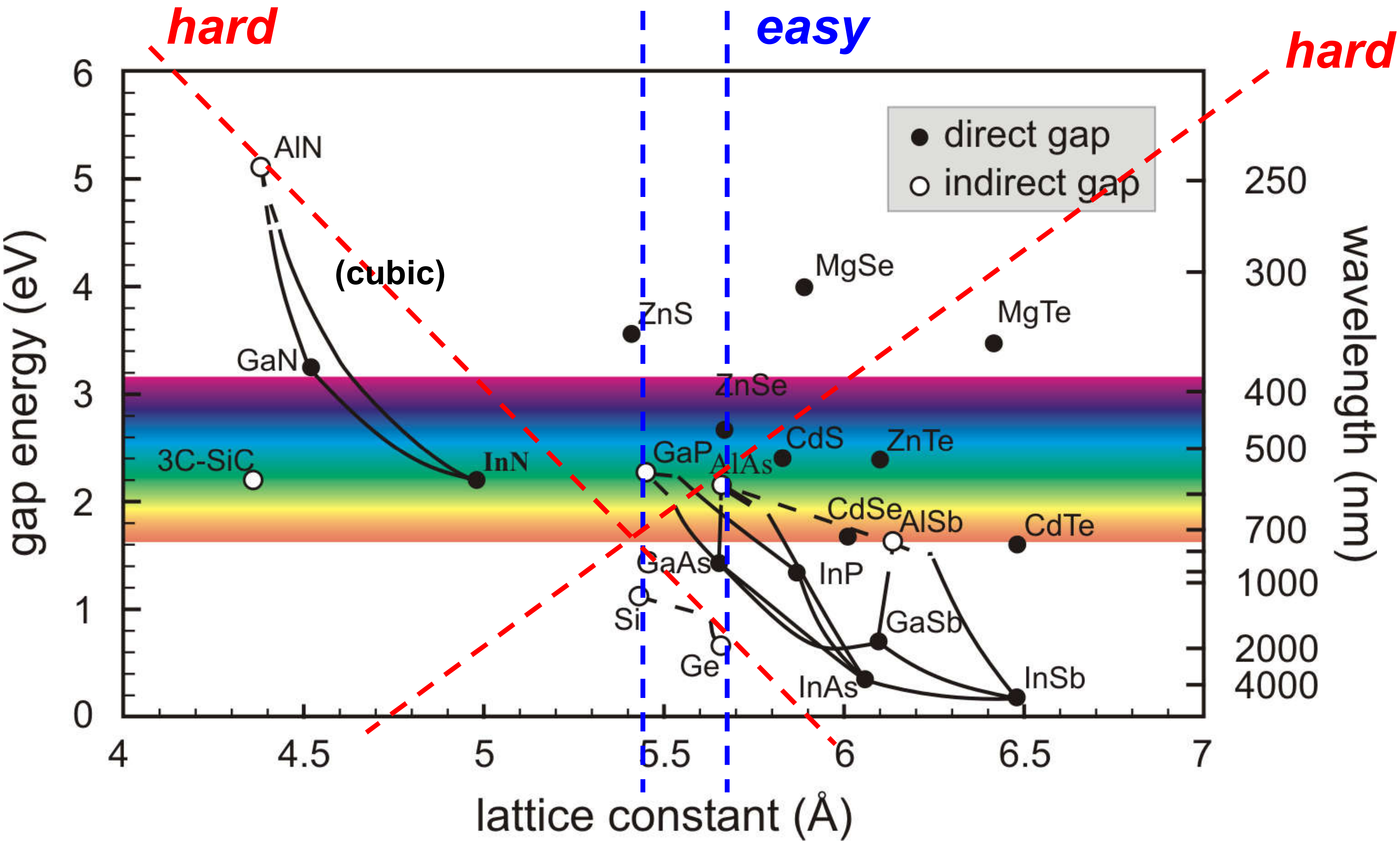
Online Surface Monitoring



Lattice Constants vs. Bandgap



Lattice Constants vs. Bandgap



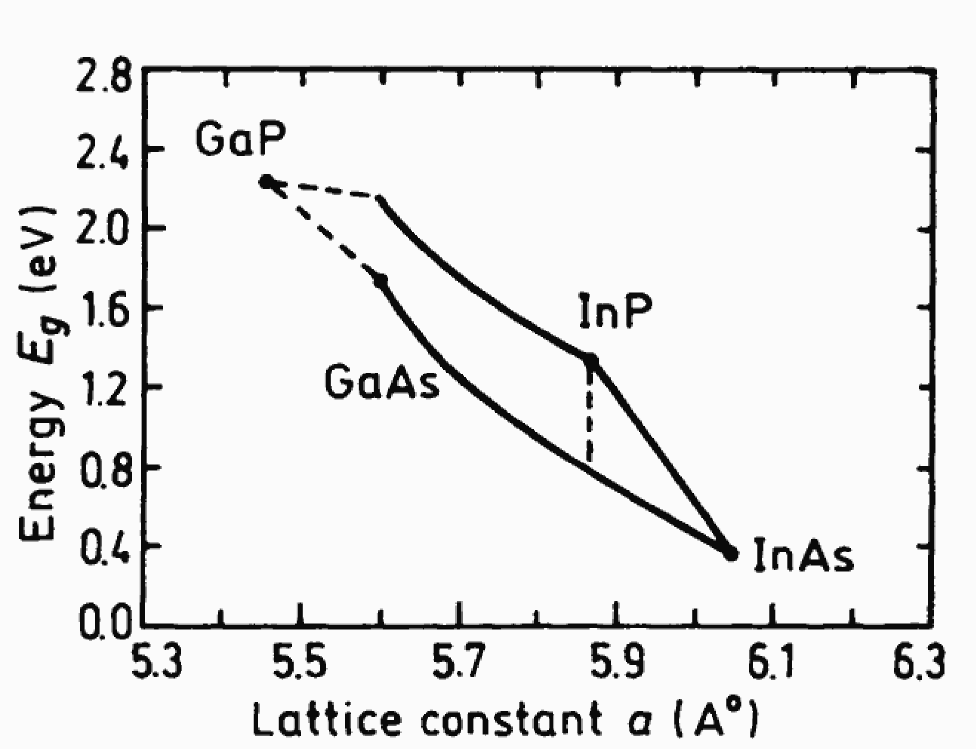
Lattice Constants vs. Bandgap

Vegard's law: assume linear mixing

For A_xB_{1-x}

$$a = x \cdot a_A + (1-x) \cdot a_B$$

$$E_g = x \cdot E_{gA} + (1-x) \cdot E_{gB}$$



Q: $In_xGa_{1-x}As$ on InP?

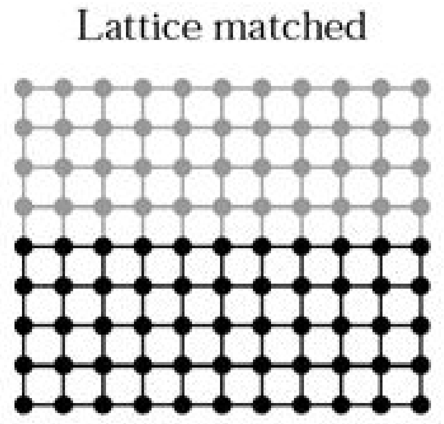
Q: How to design a 1.55 μm laser?

Lattice Matched/Mismatched Growth

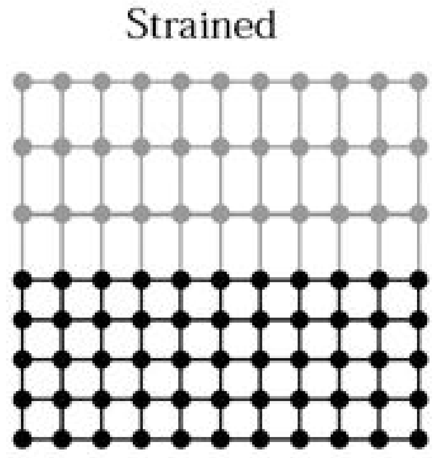
'metamorphic' growth

thin film

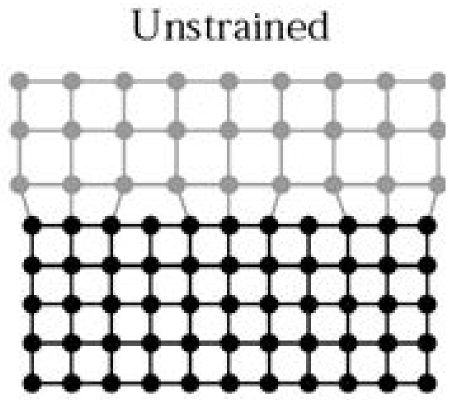
thick film



substrate



substrate

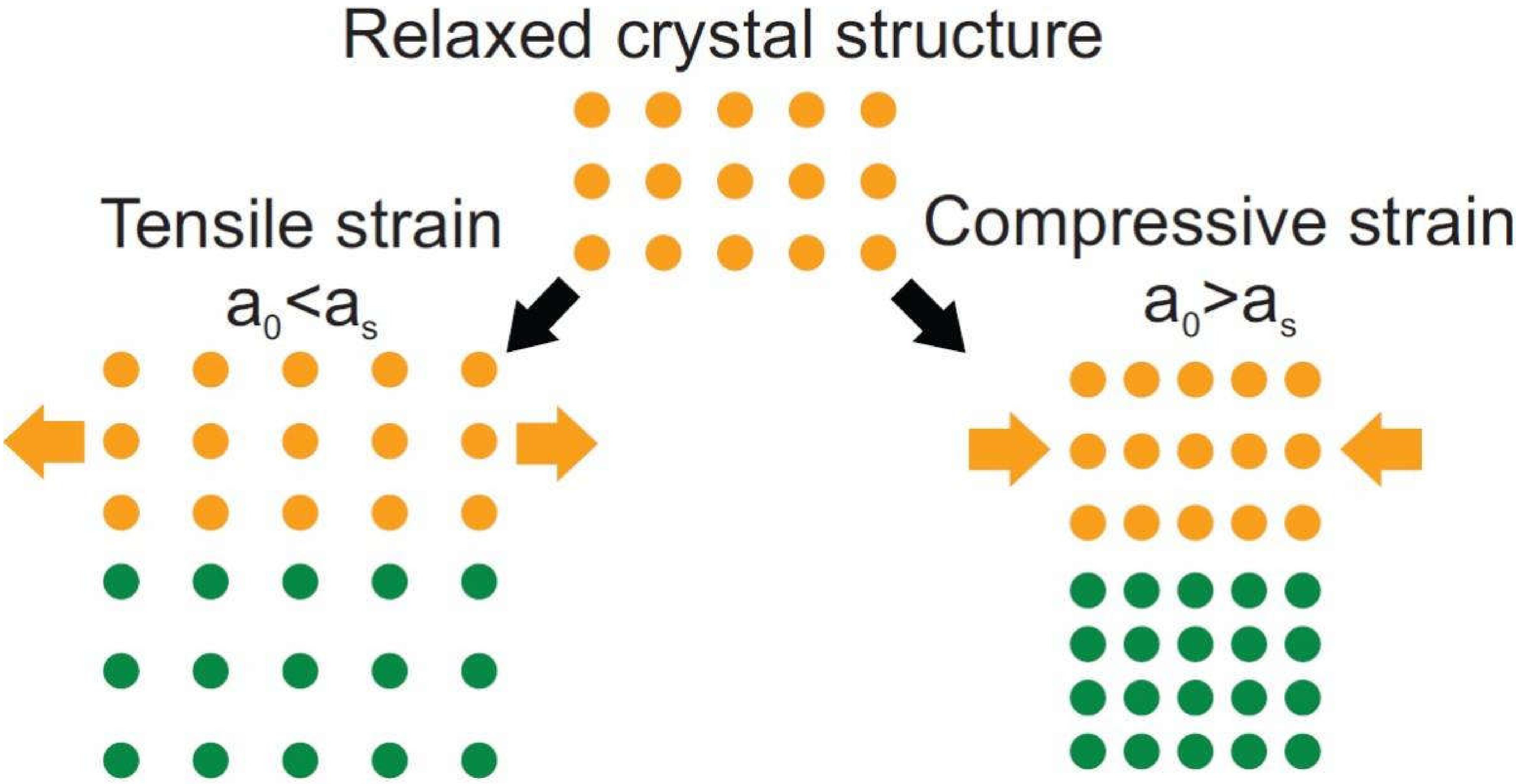


substrate

Si on Si
GaAs on GaAs
AlAs on GaAs
GaAs on Ge
...

GaAs on Si, Ge on Si, GaN on Si, ...

Strain in the Film



Growth Energy

strain energy

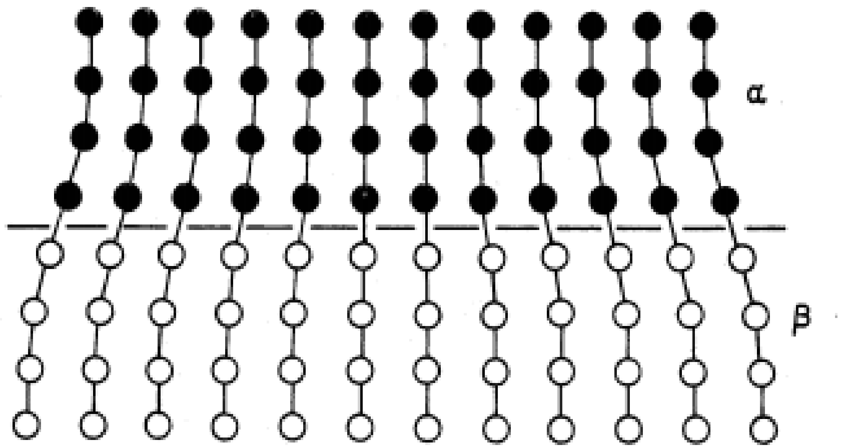


Fig. 3.34 A coherent interface with slight mismatch leads to coherency strains in the adjoining lattices.

$$E_\varepsilon = \frac{\varepsilon^2 Y}{1-\nu} d$$

$$E_\varepsilon \propto d$$

misfit dislocation energy

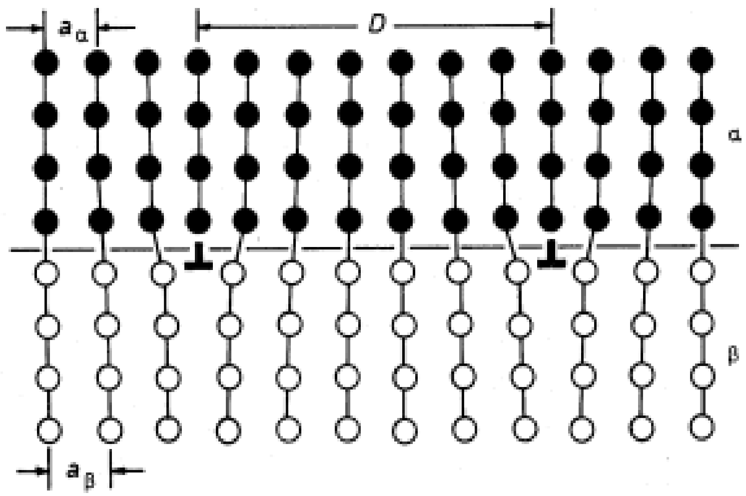
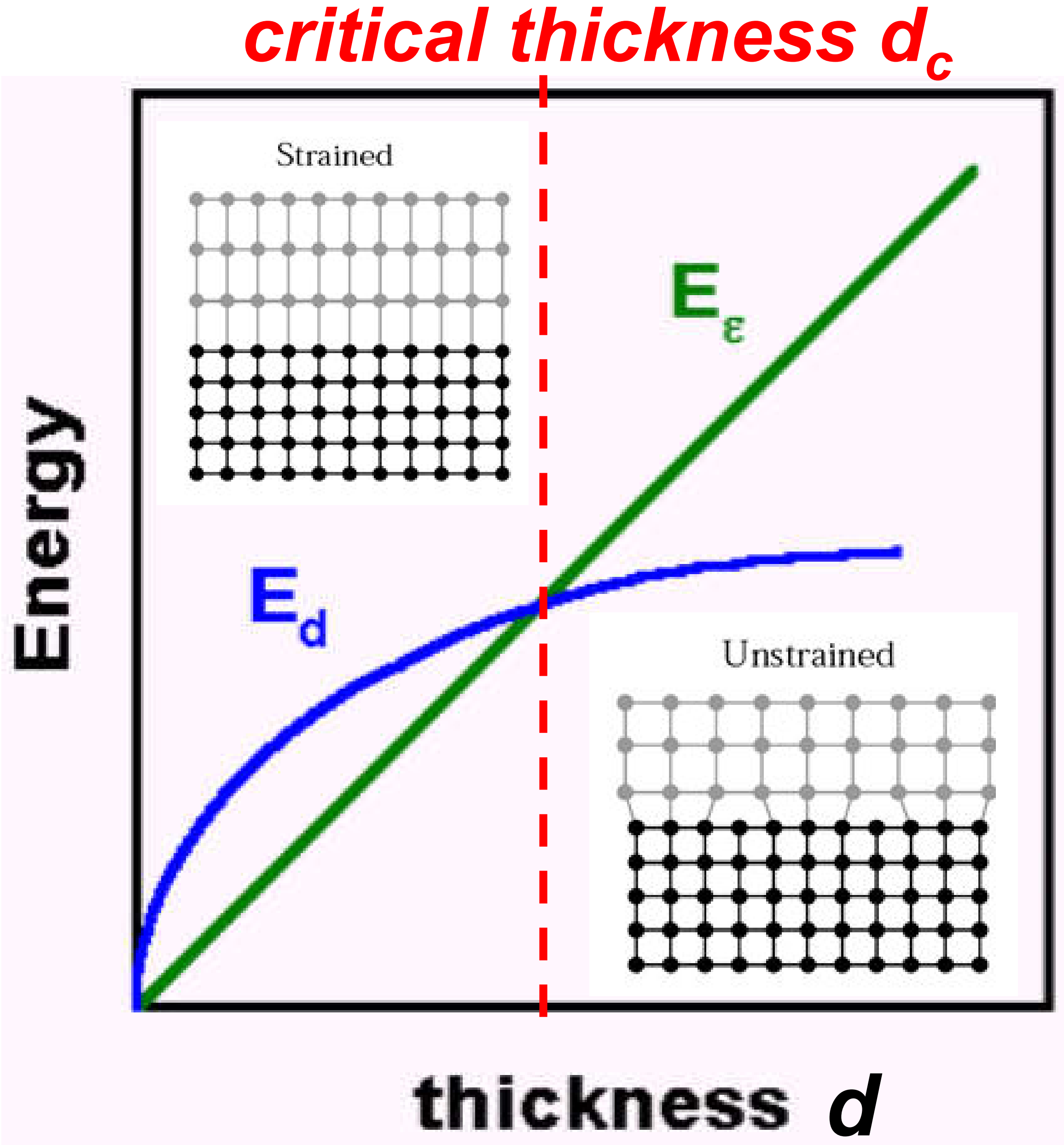


Fig. 3.35 A semicoherent interface. The misfit parallel to the interface is accommodated by a series of edge dislocations.

$$E_d = \frac{\mu b^2}{2\pi(1-\nu)S} \ln\left(\frac{\beta d}{b}\right)$$

$$E_d \propto \ln(d)$$

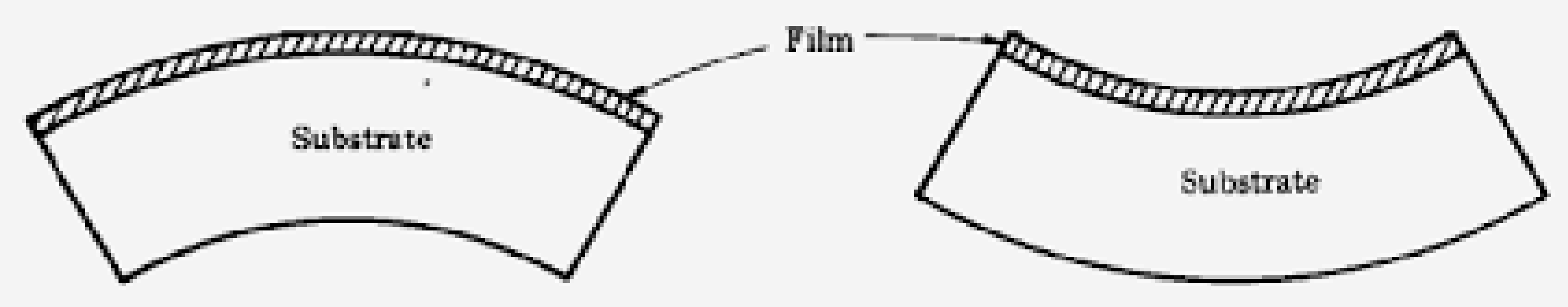
Growth Energy



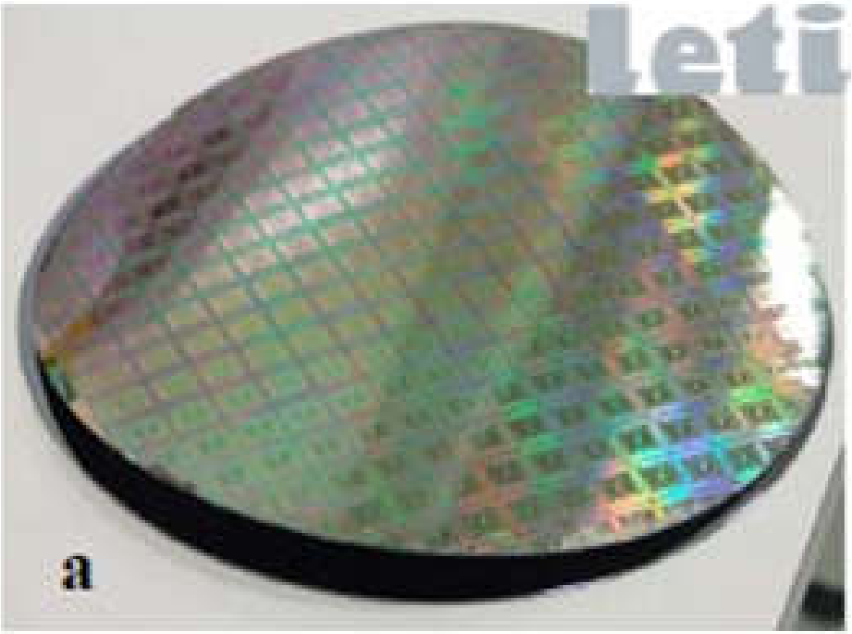
$$E_\varepsilon \propto d$$

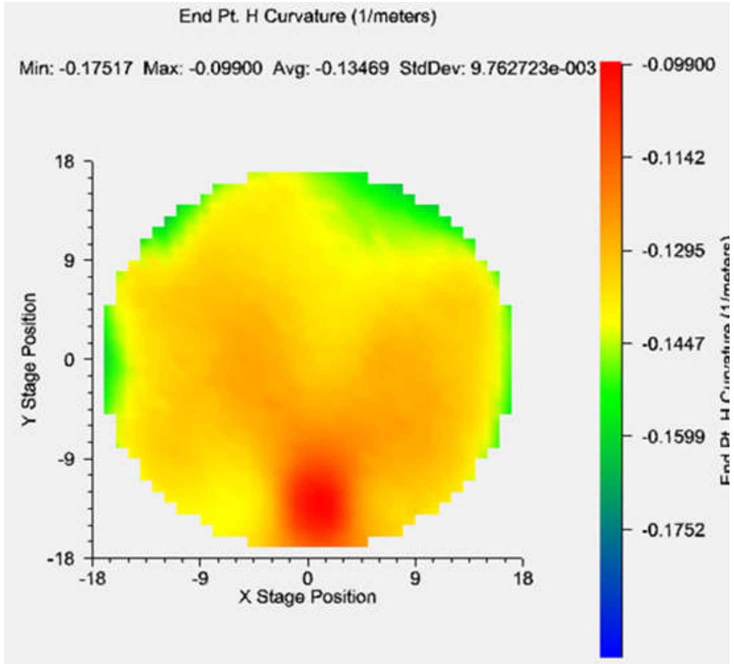
$$E_d \propto \ln(d)$$

Wafer 'Bowing' by Stress



compressive **tensile**

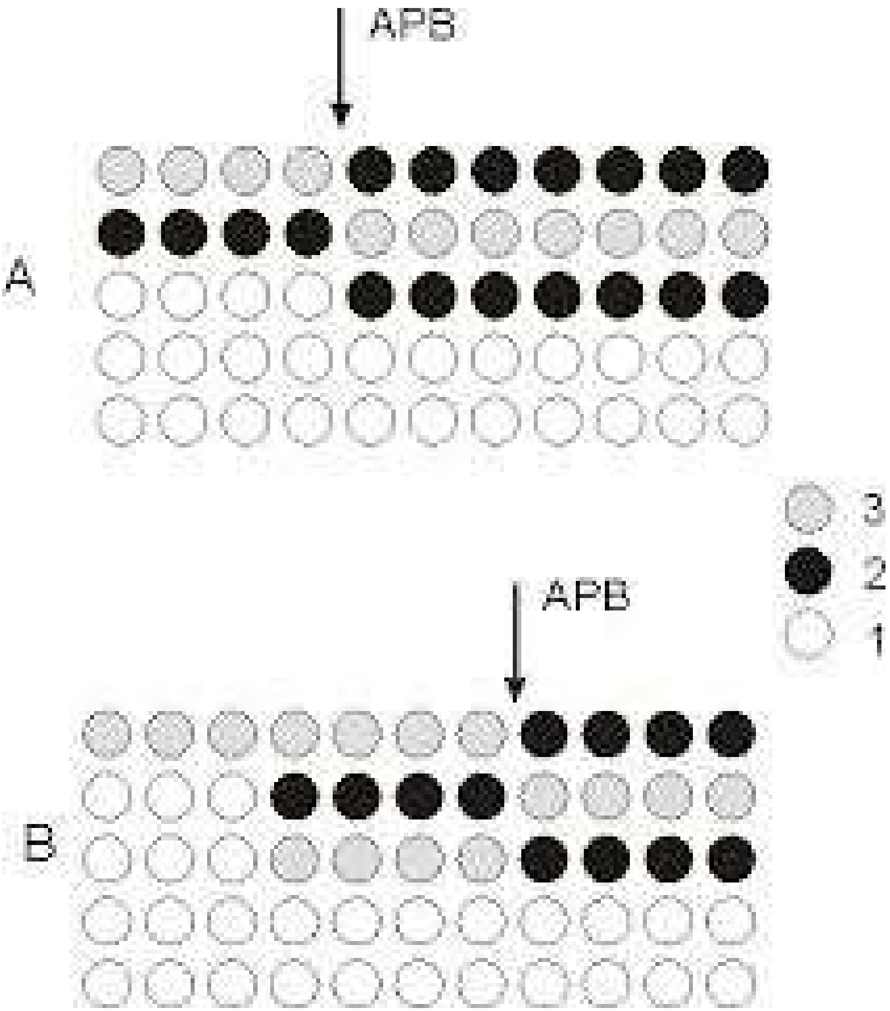




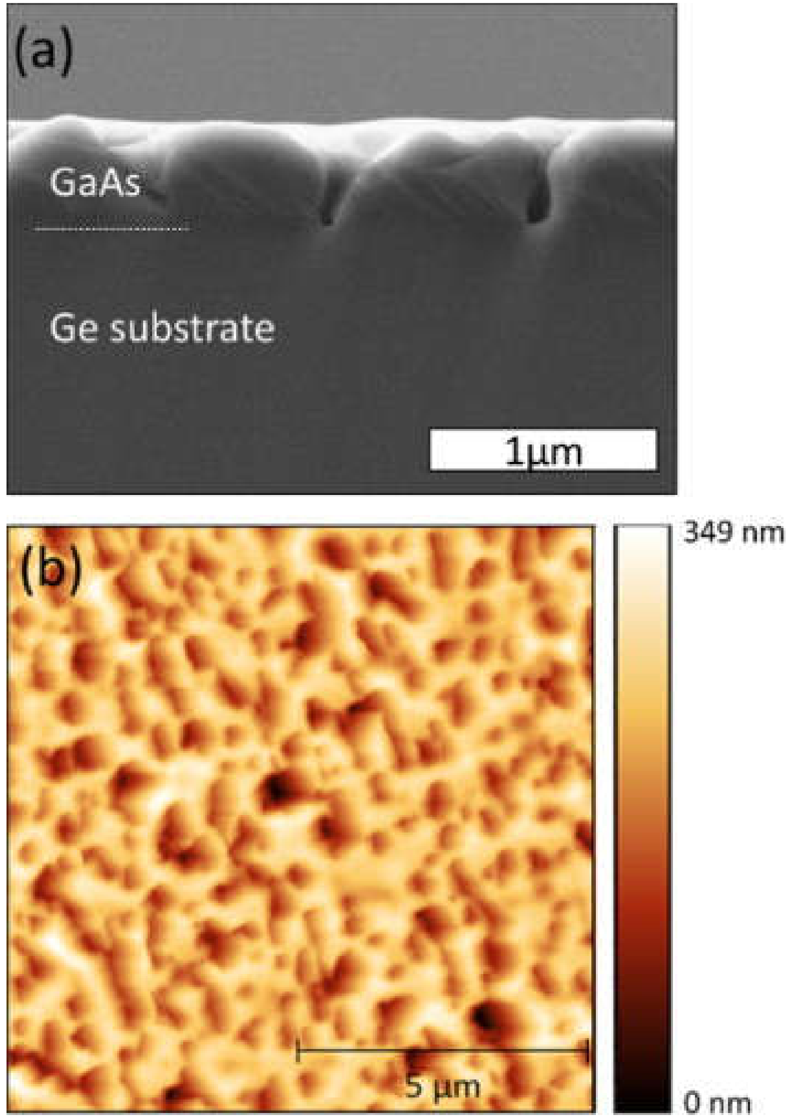
stress measured by curvature

Anti-Phase Boundary (APB)

GaAs is lattice matched to Ge, but ...



Ga
As
Ge

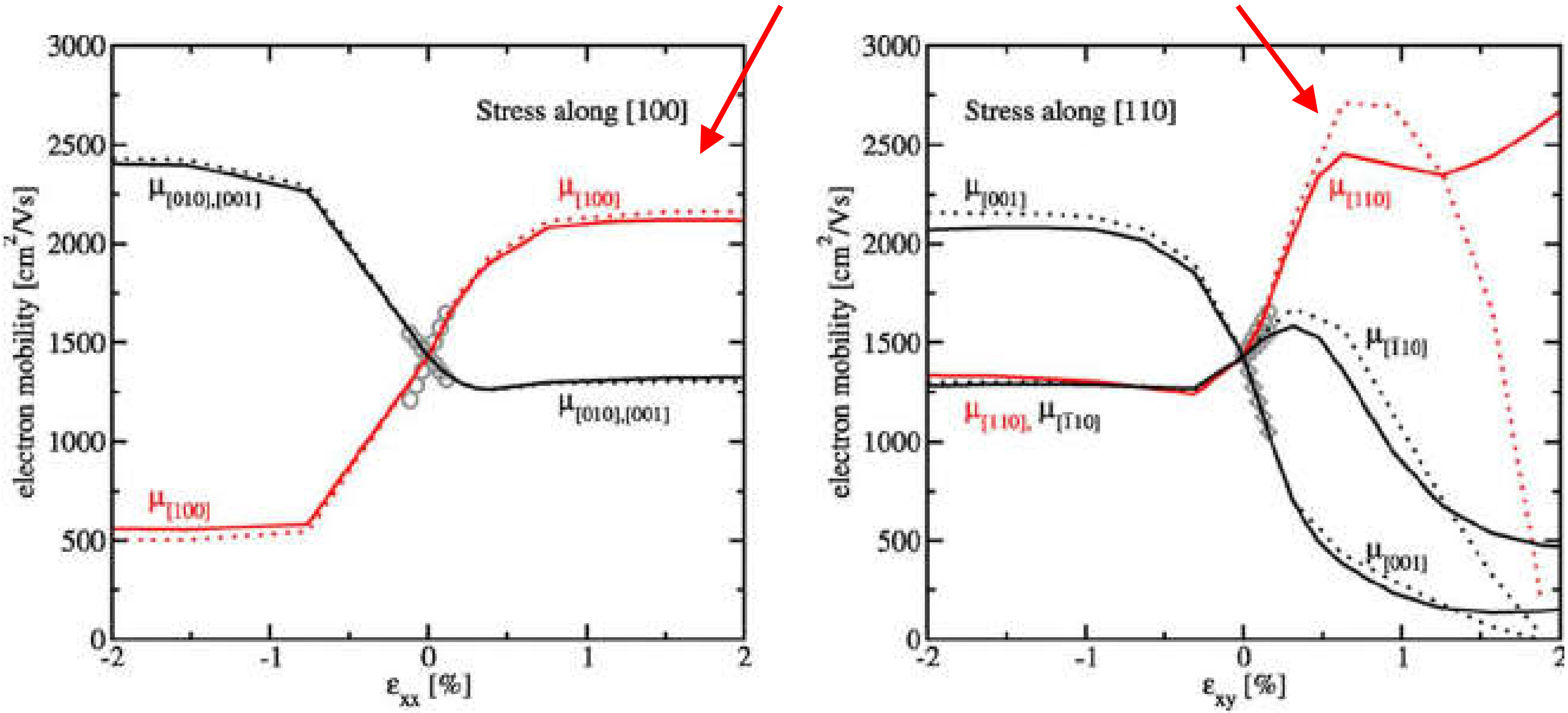


Applications

- Strained Si for CMOS
- Quantum Wells
- III-V Quantum Dots
- Colloidal Quantum Dots
- Superlattice
- Selective Area Growth
- GaN Growth
- Nanowires
- 2D Materials Growth
- Multijunction Solar Cells
- Epitaxial Liftoff

Strained Silicon

tensile strain increases electron mobility



compressive strain increases hole mobility

Strained Silicon

NMOS: uniaxial tensile stress from stressed SiN film

PMOS: uniaxial compressive stress from sel. SiGe in S/D

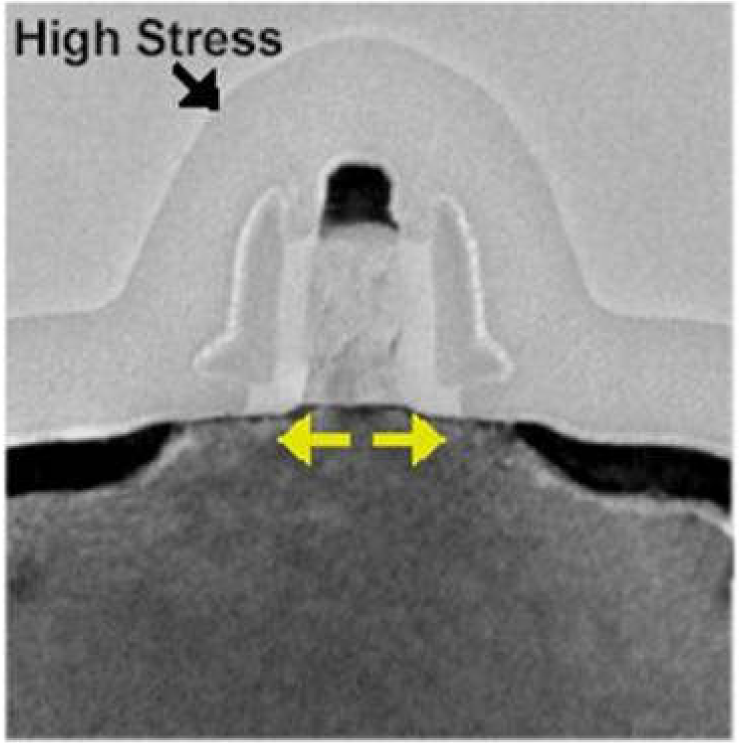


Fig. 3 TEM of NMOS transistor showing high tensile stress nitride overlayer.

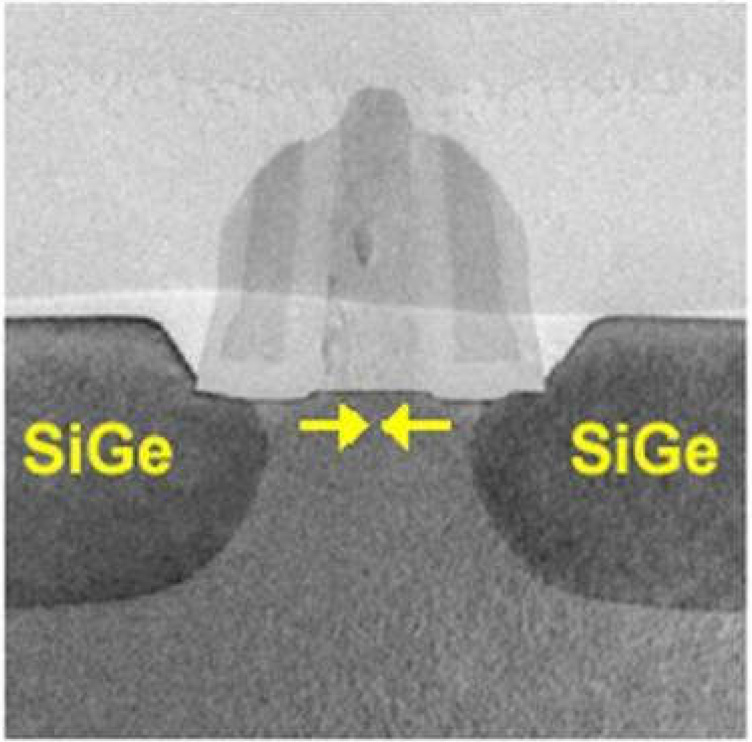


Fig. 4 TEM of PMOS showing SiGe heteroepitaxial S/D inducing uniaxial strain.

From K. Mistry et al., "Delaying Forever: Uniaxial Strained Silicon Transistors in a 90nm CMOS Technology," *2004 VLSI Technology Symposium*, pp. 50-51.

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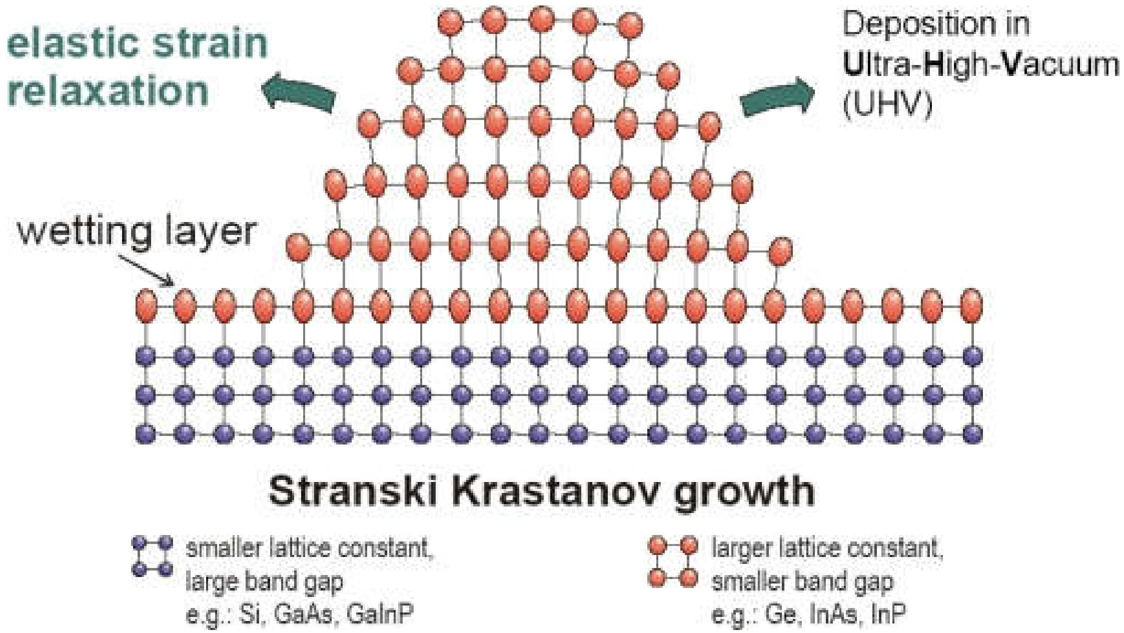
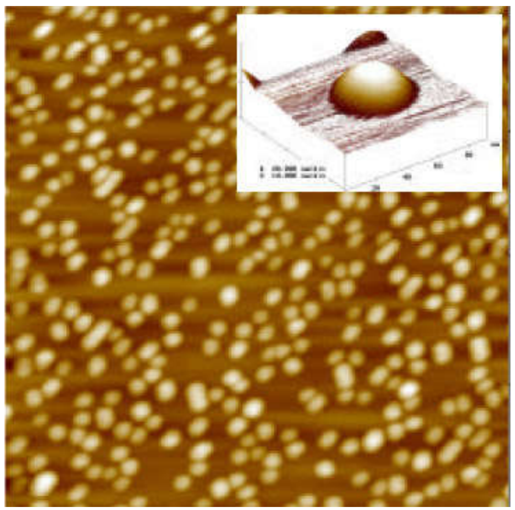
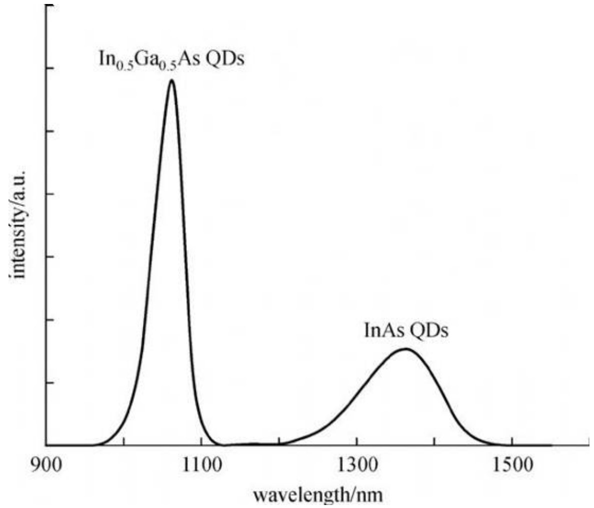
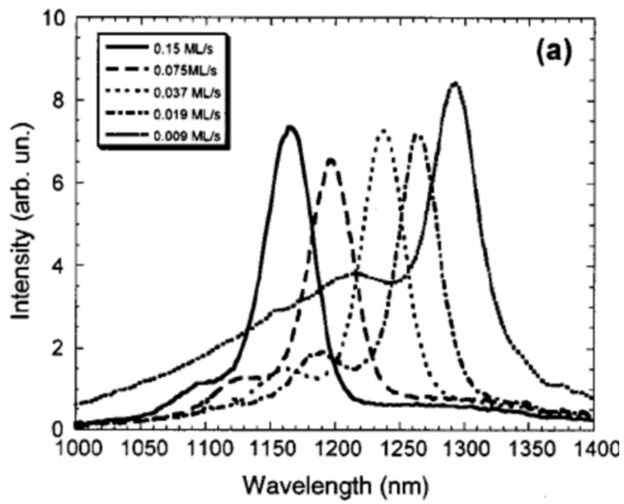
III-V Quantum Dots

InGaAs is not lattice matched to GaAs



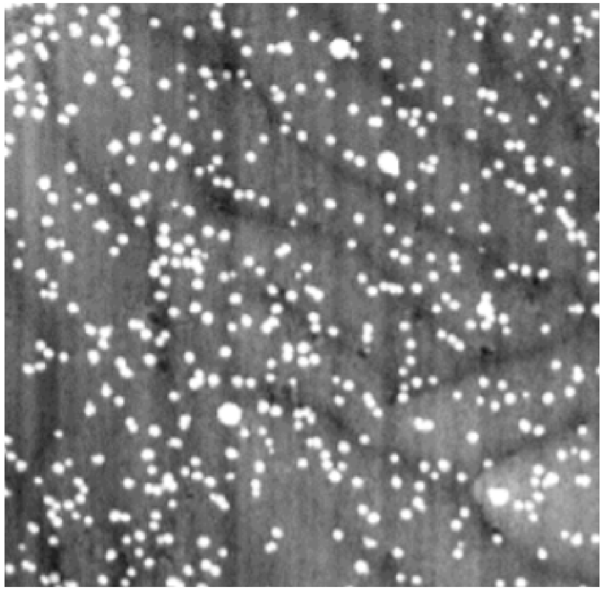


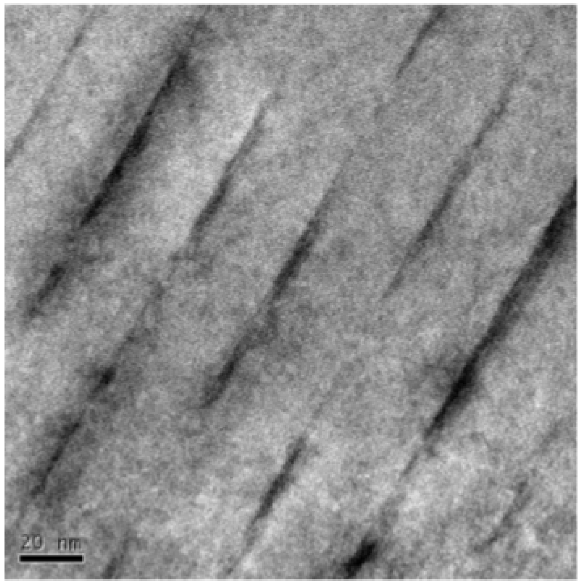




Quantum Dot based lasers

III-V Quantum Dots





InGaN quantum dot LEDs

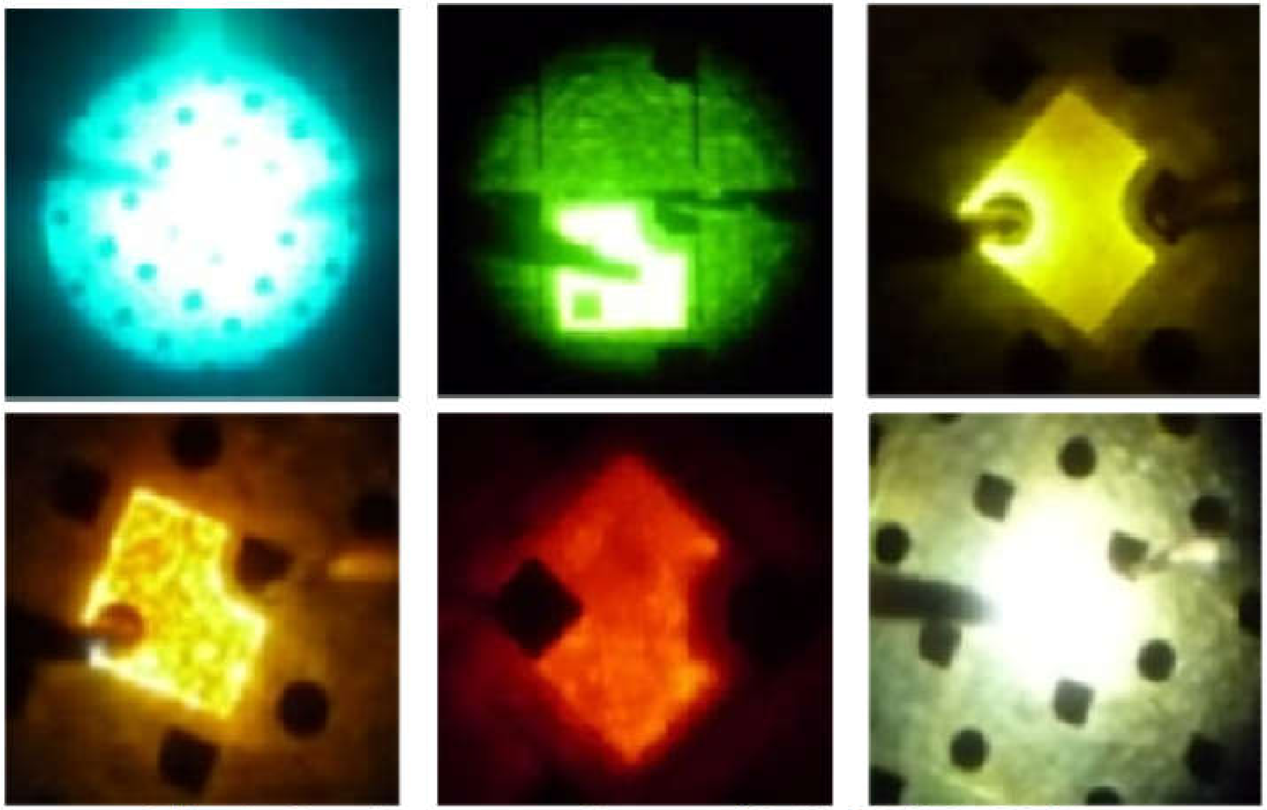
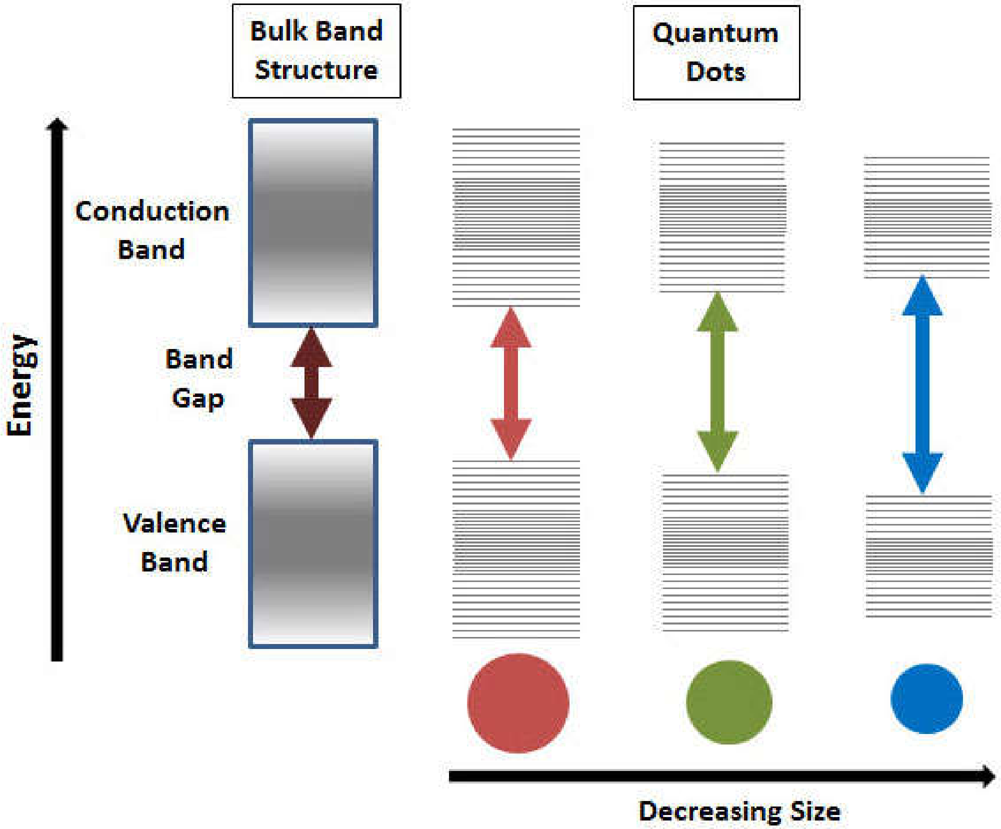
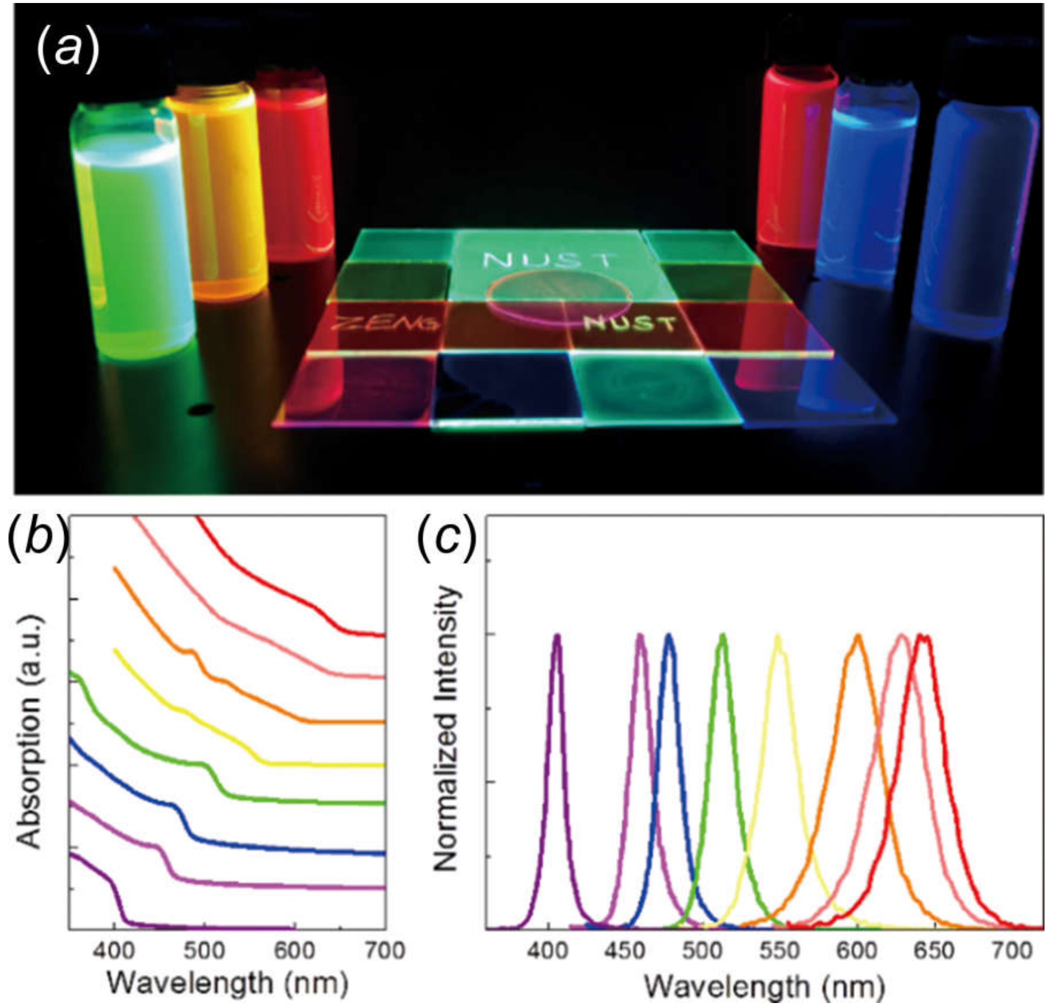


Fig. 2. Luminescence photos of InGaN QDs LEDs.

L. Wang, *et al.*,. *Front. Optoelectron.* **7,** 293 (2014)

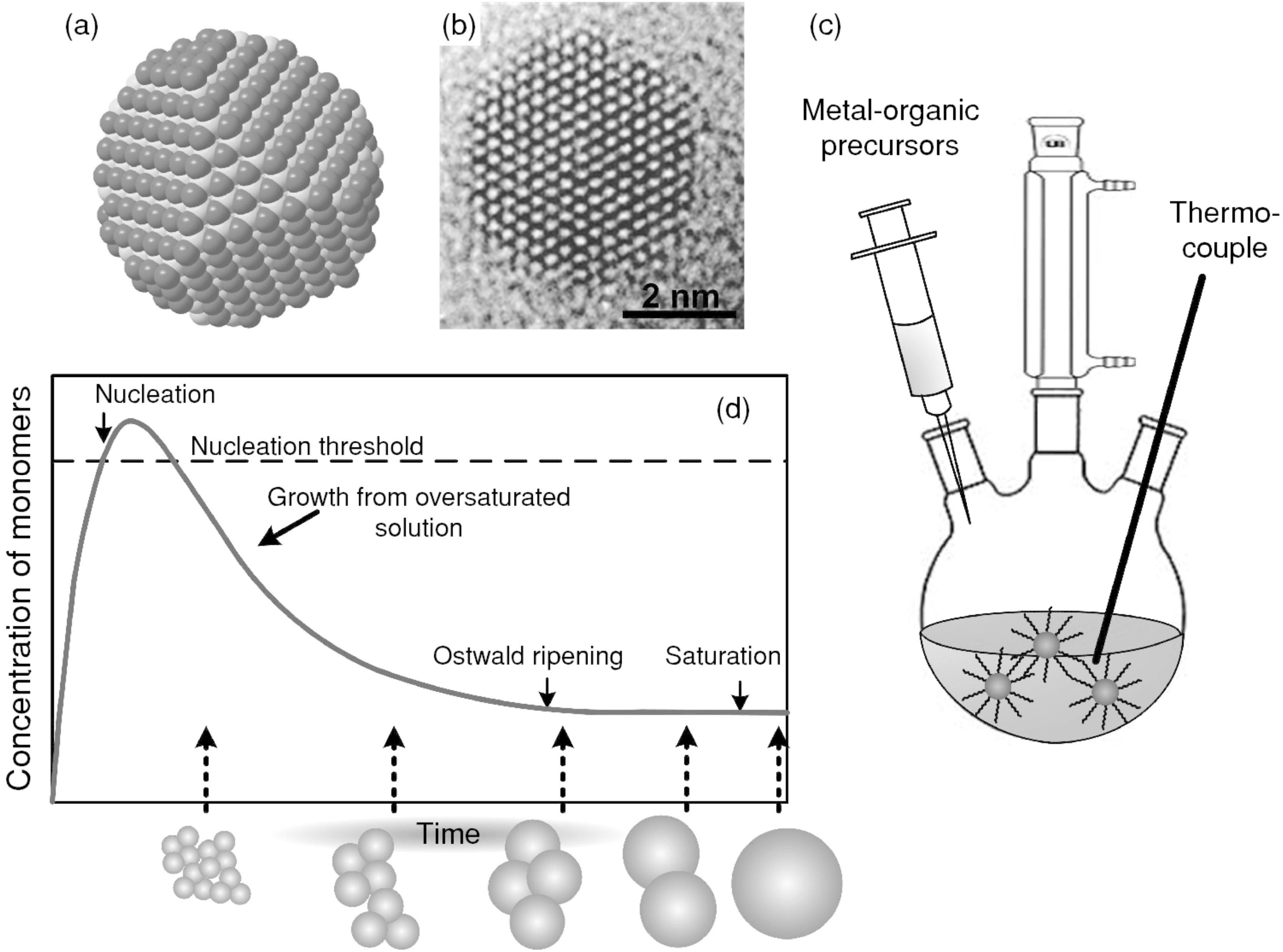
Colloidal Quantum Dots



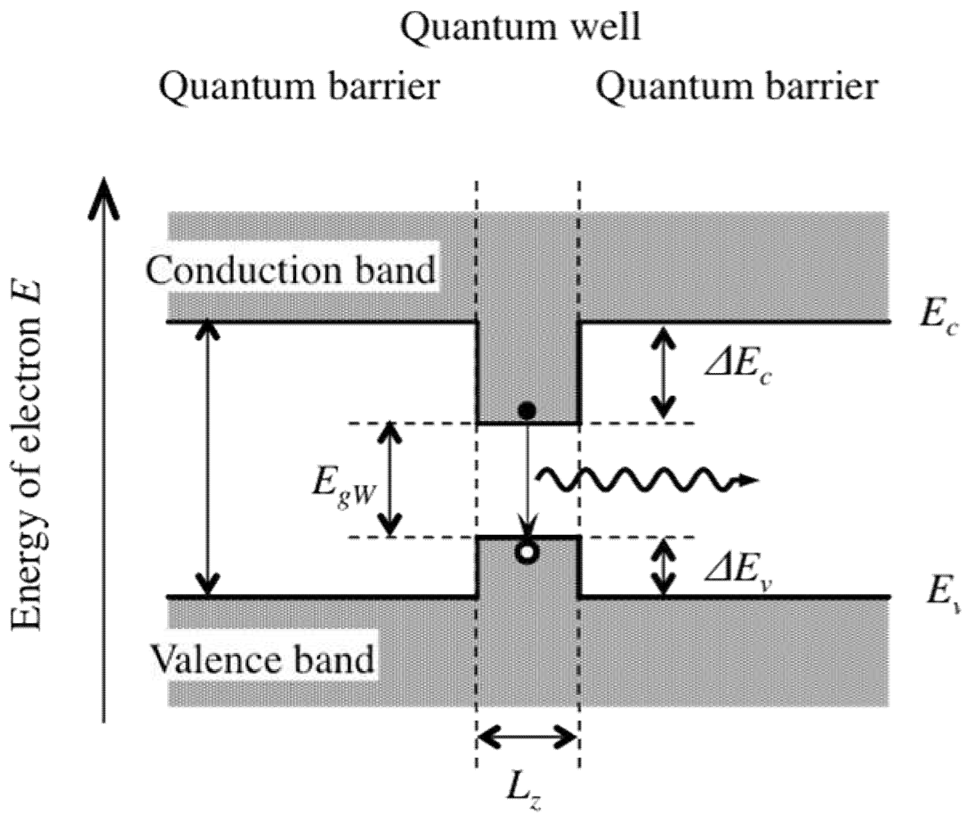


C. B. Murray, *et al.*,. *Annu. Rev. Mater. Sci.* **30,** 545 (2000)

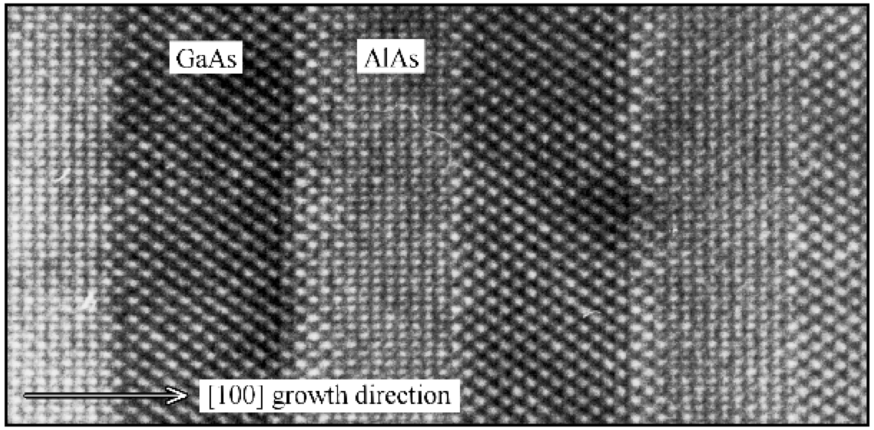
Colloidal Quantum Dots

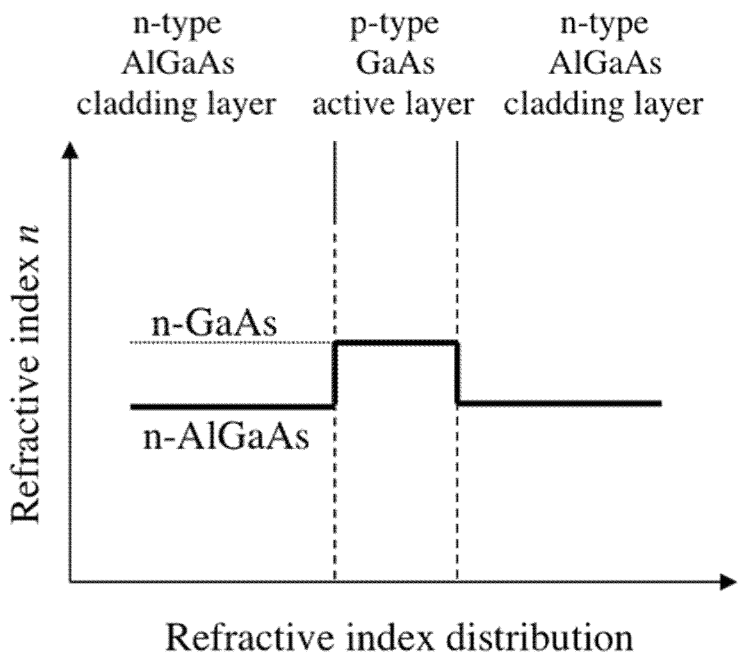


Quantum Wells



AlGaAs / GaAs quantum wells

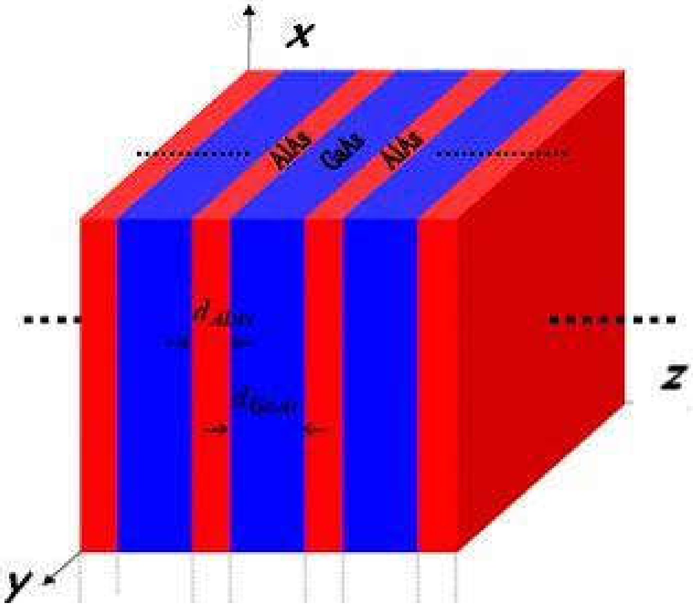


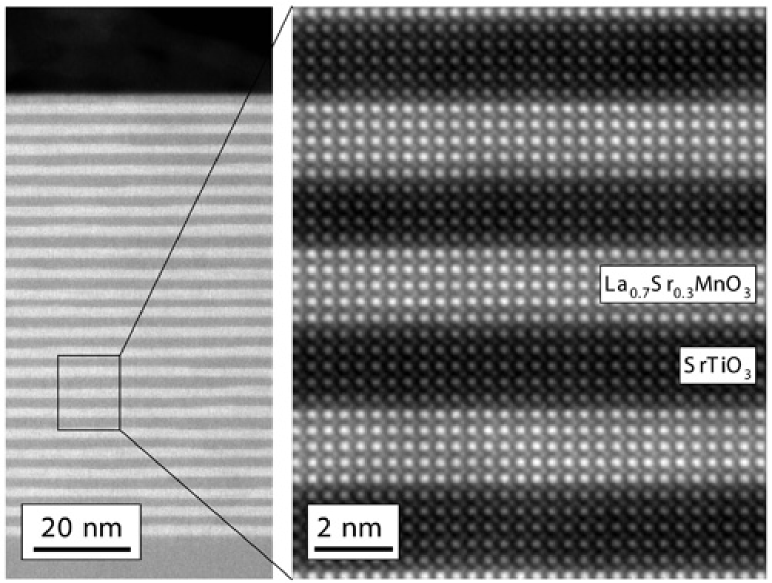


1. electronic confinement
2. optical confinement

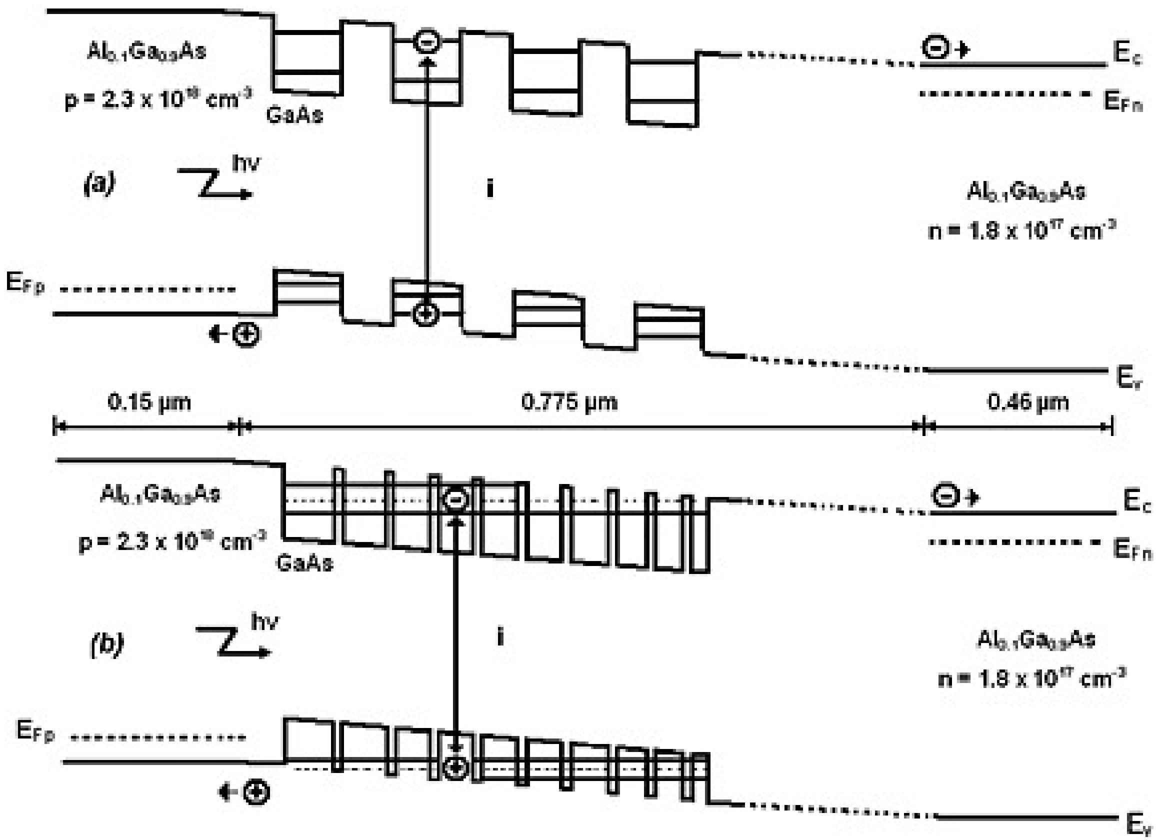
2000 Nobel Prize in Physics

Superlattice 超晶格





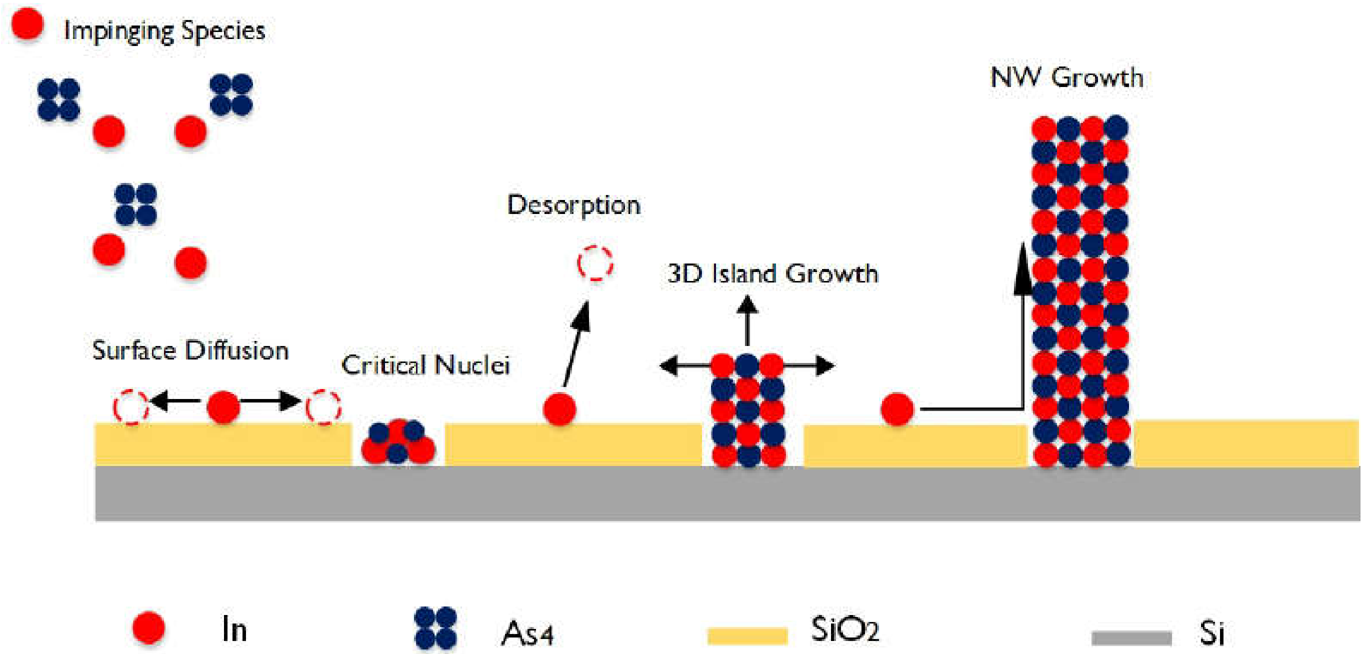
conventional quantum wells

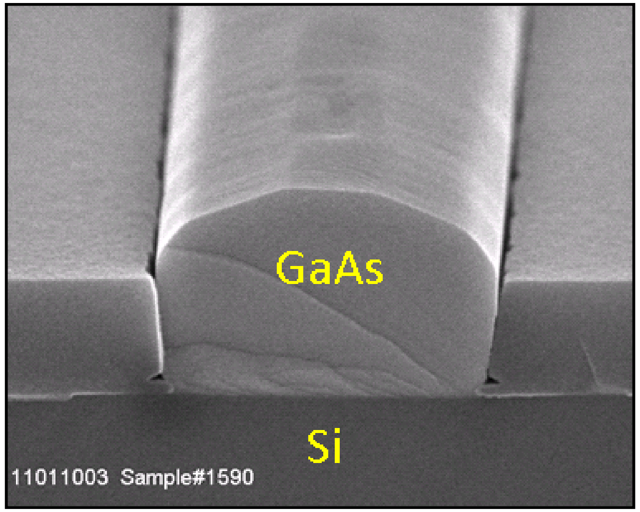


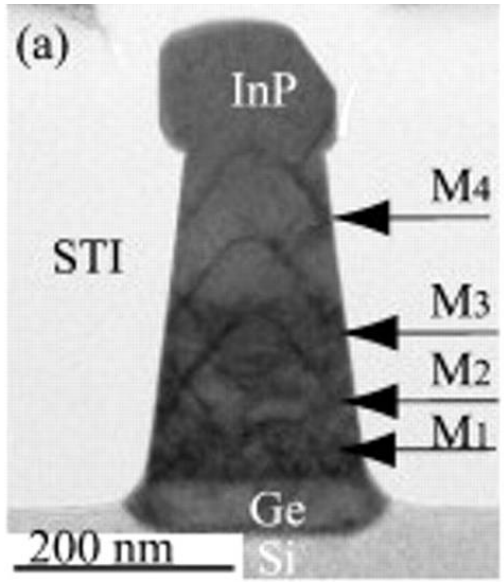
superlattice

Selective Area Growth

At high T, Ge, III-Vs grow on Si, but not on SiO_2

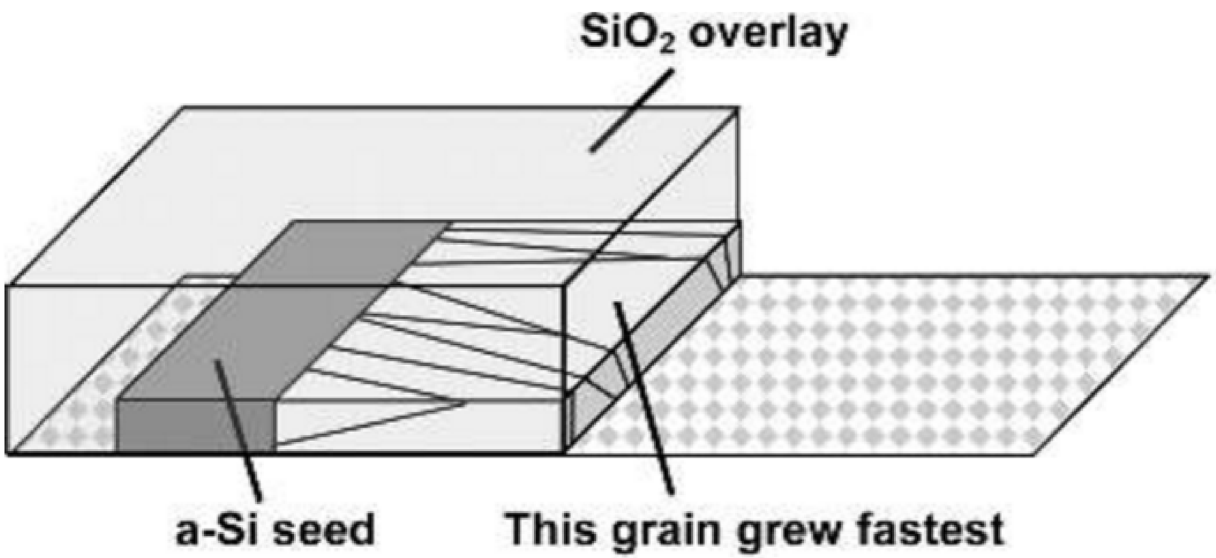


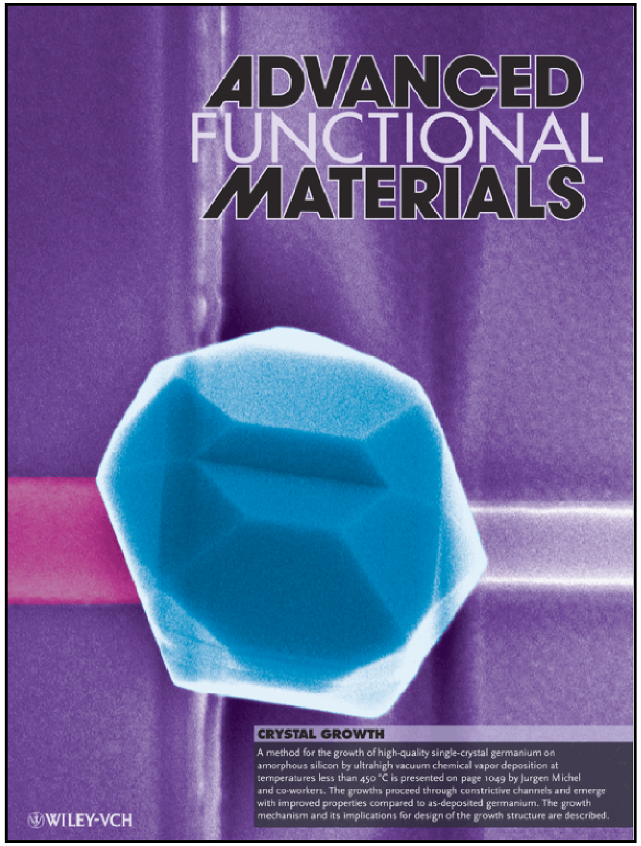




Selective Area Growth

Grow Ge single crystals on amorphous substrate





UHVCVD

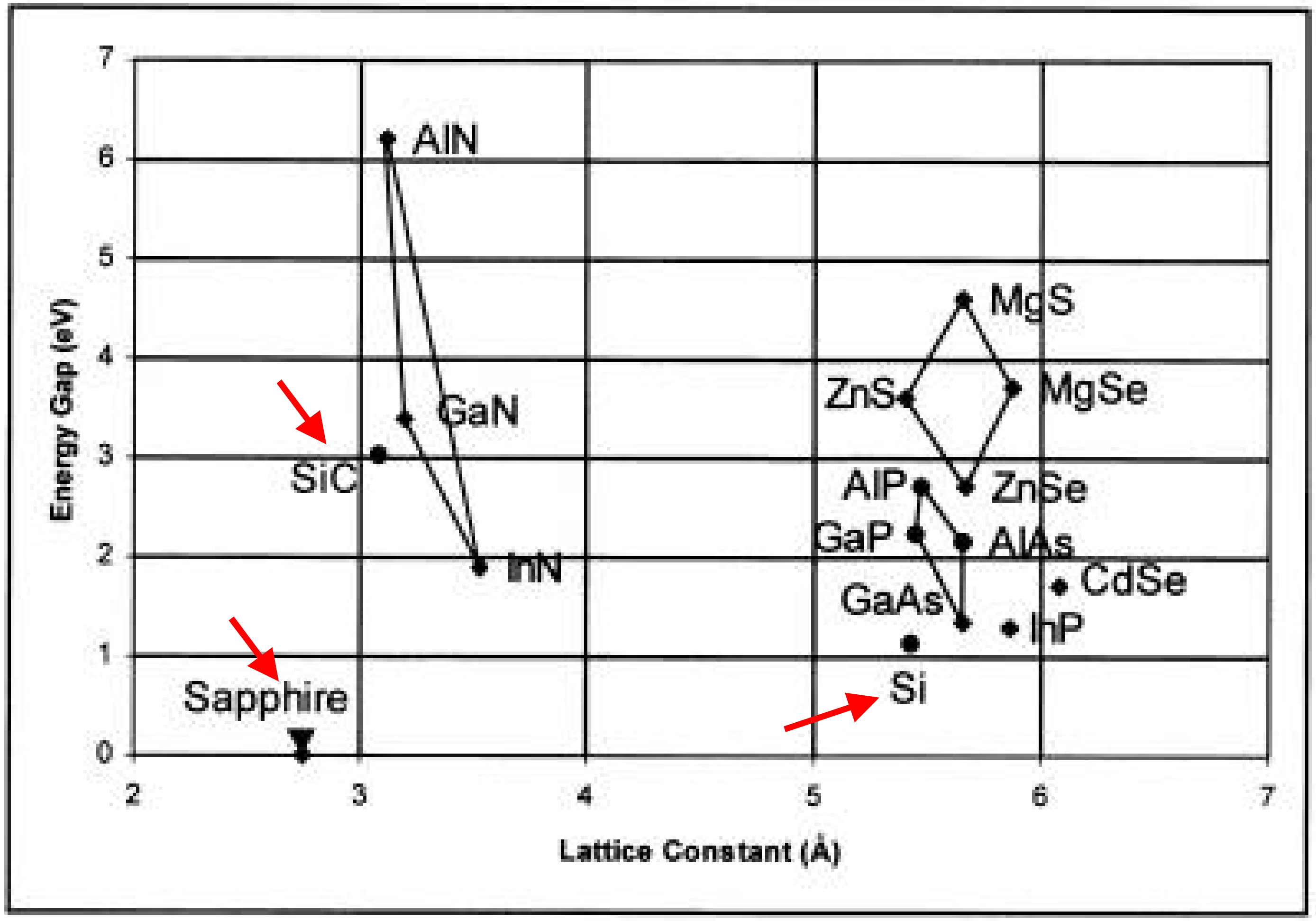
GeH_4 (g) = Ge (s) + $2H_2$ (g)

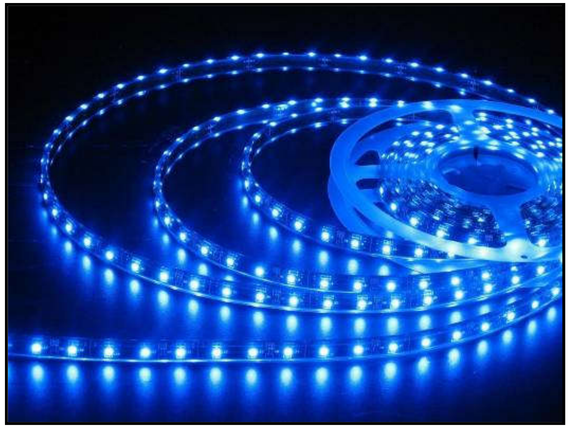
selective, only on Si, not SiO_2

GeO is not stable

K. McComber, *et al.*, *Adv. Func. Mater.* **22,** 1049 (2012)

GaN Growth





InGaN blue LEDs

substrate price

GaN	$$$$
SiC	$$$
sapphire	$$
silicon	$

Gallium Nitride (GaN) LED

- **GaN LED on sapphire**
  - 日本，Nichia
  - 2014 Nobel Prize in Physics

I. Akasaki

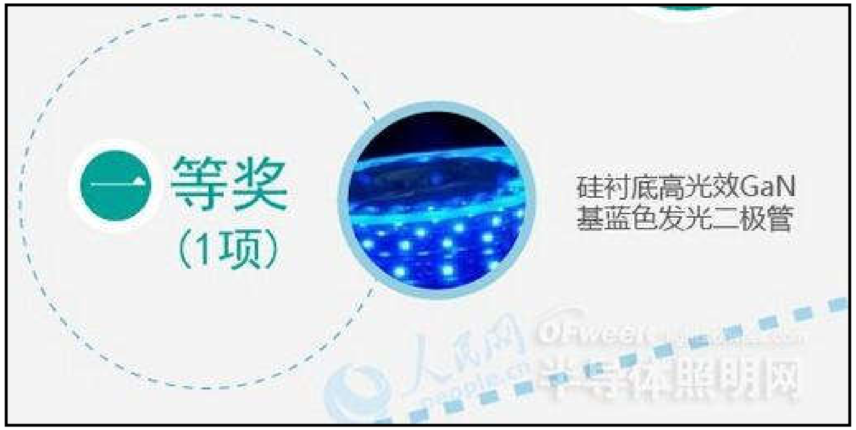
H. Amano

S. Nakamura

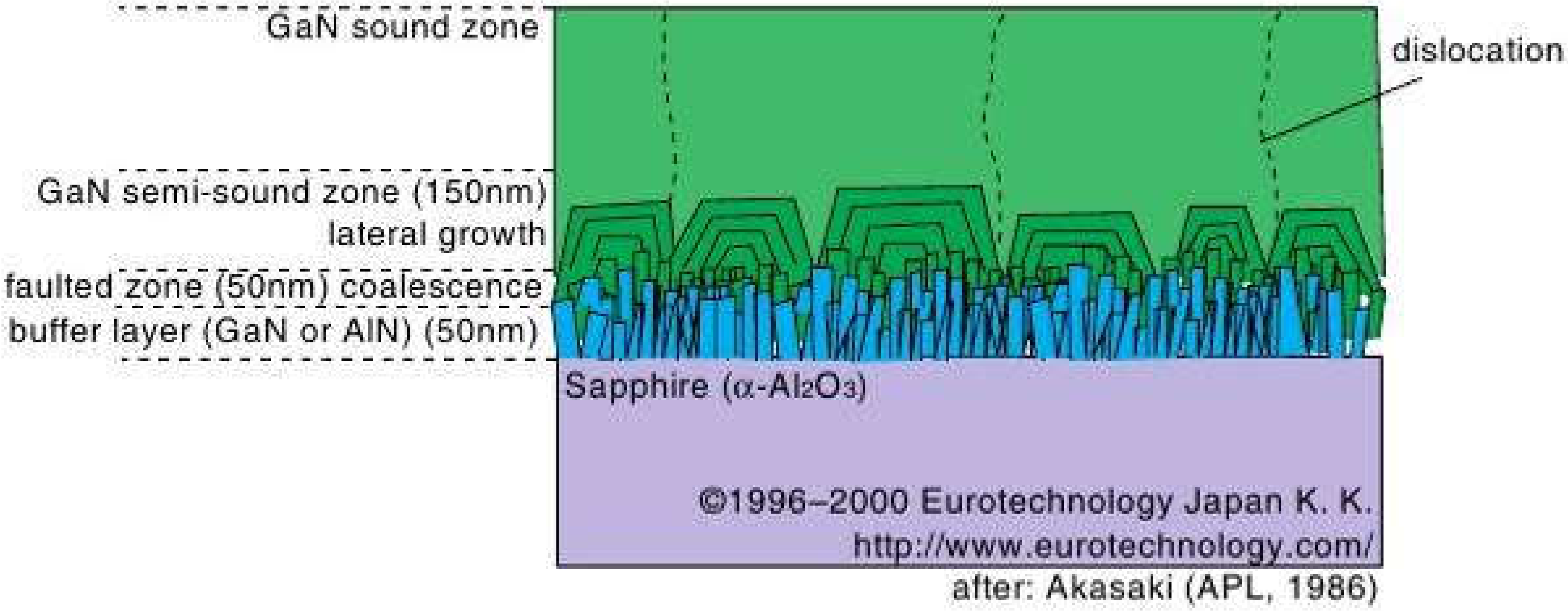
- **GaN LED on silicon carbide (SiC)**
  - USA, Cree

CREE ™

- **GaN LED on silicon**
  - 中国，南昌大学
  - 2015年中国技术发明一等奖



GaN Growth on Sapphire



I. Akasaki

H. Amano

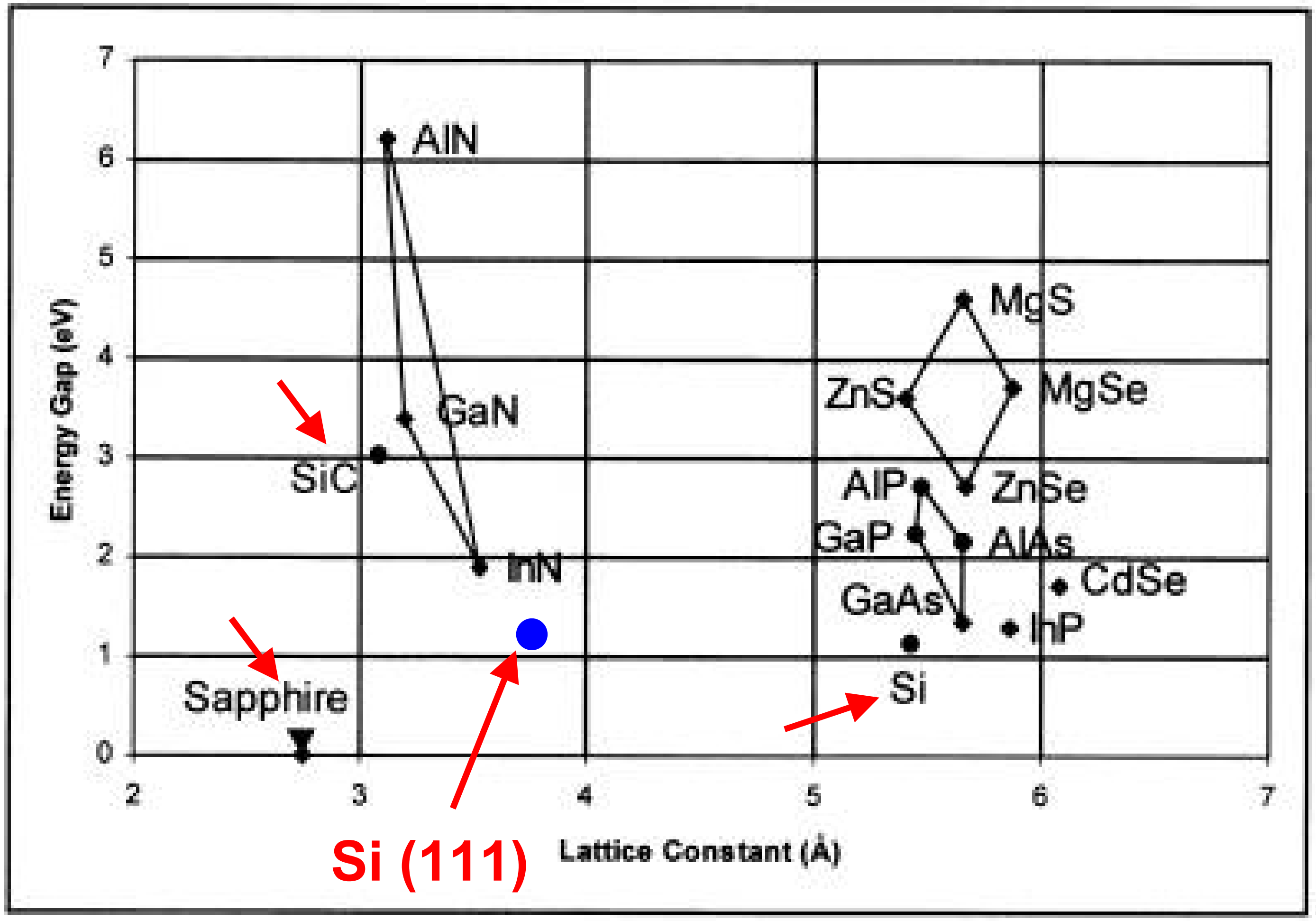
S. Nakamura

2014 Nobel Prize in Physics

H. Amano, *et al.*,. *Appl. Phys. Lett.* **48,** 353 (1986)
H. Amano, *et al.*, *Jpn. J. Appl. Phys.* **28,** L2112 (1989)
S. Nakamura, *et al.*, *Appl. Phys. Lett.* **64,** 1687 (1994)

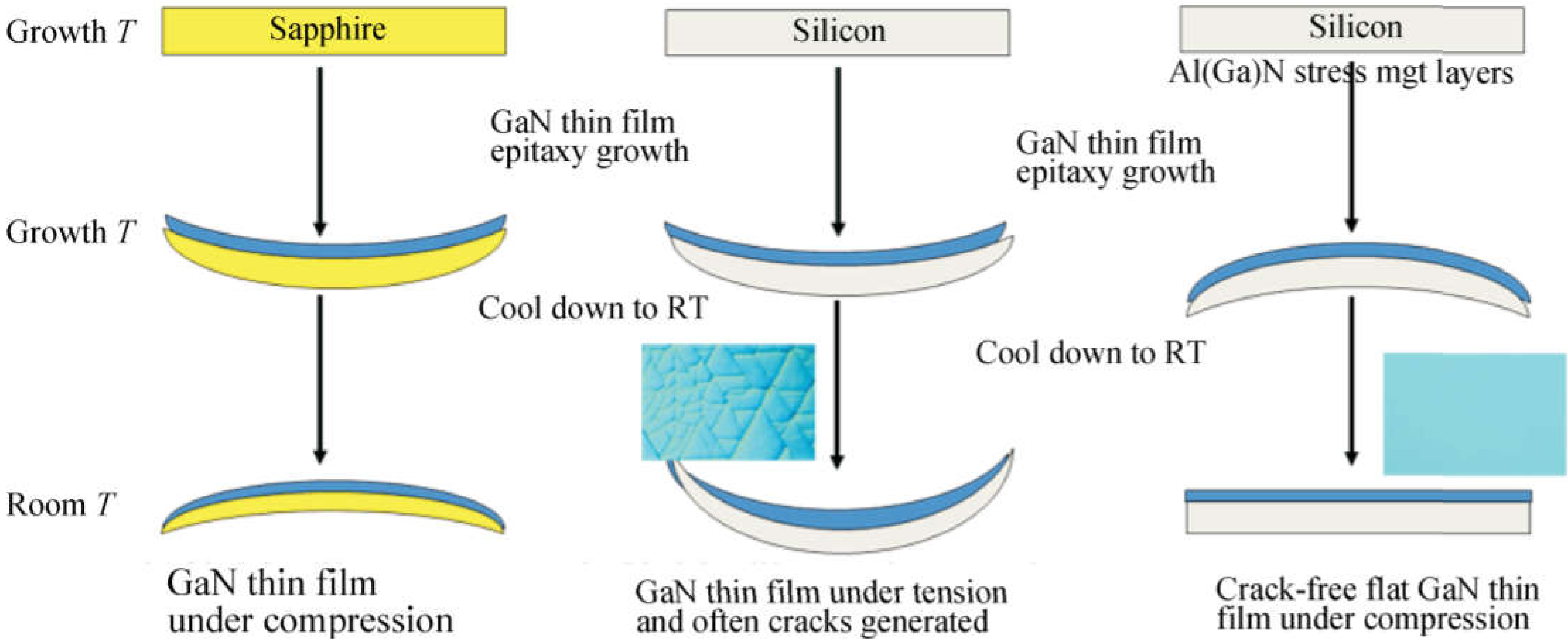
1. **growth with AlN buffer**
2. **GaN p-type doping**
3. **GaN blue LED!**

GaN Growth on Silicon

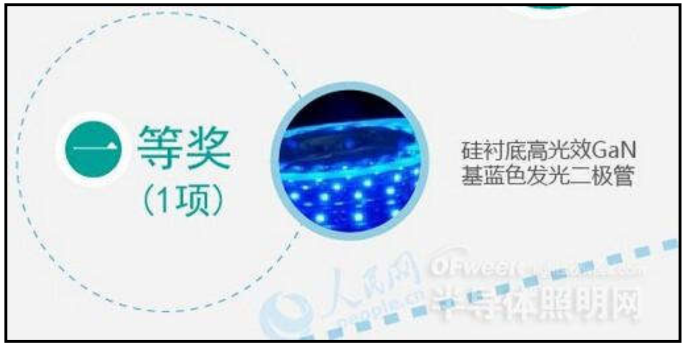


GaN Growth on Silicon

CTE(×10⁻⁶/K):7.5(sapphire)>5.6(GaN)>2.6(Si)



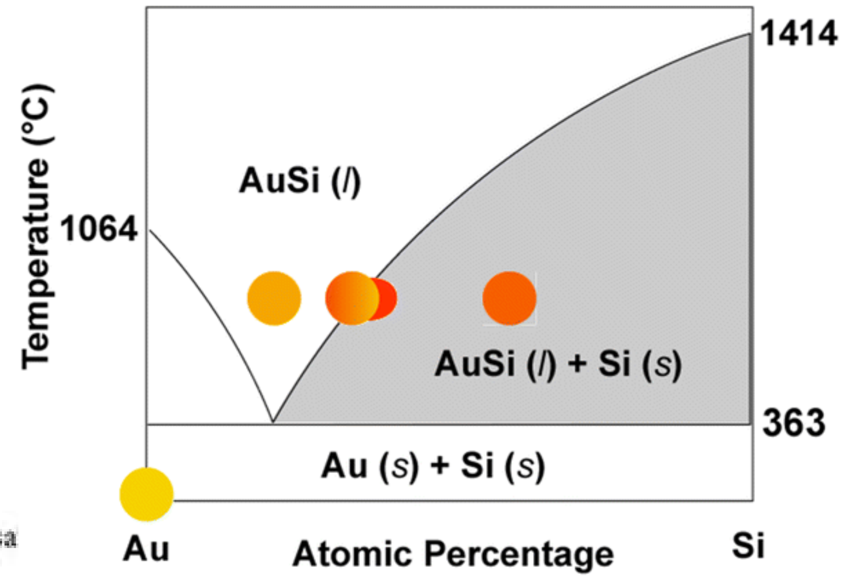
Q. Sun, *et al.*,. *J. Semicon.* **37,** 044006 (2016)

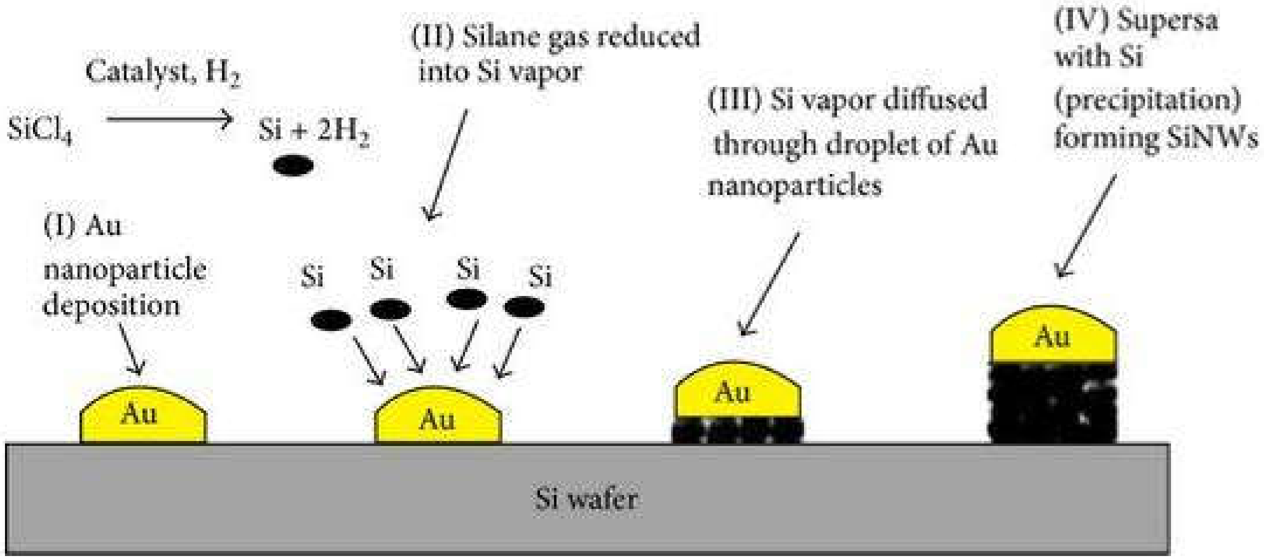


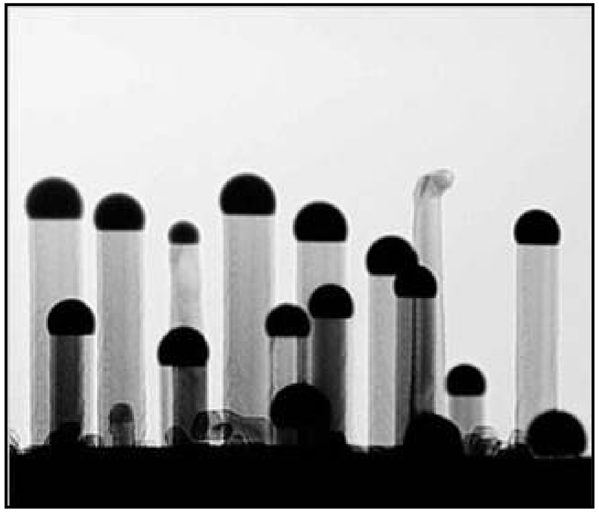
2015年中国技术发明一等奖

Si Nanowire Growth

VLS: *Vapor-Liquid-Solid*

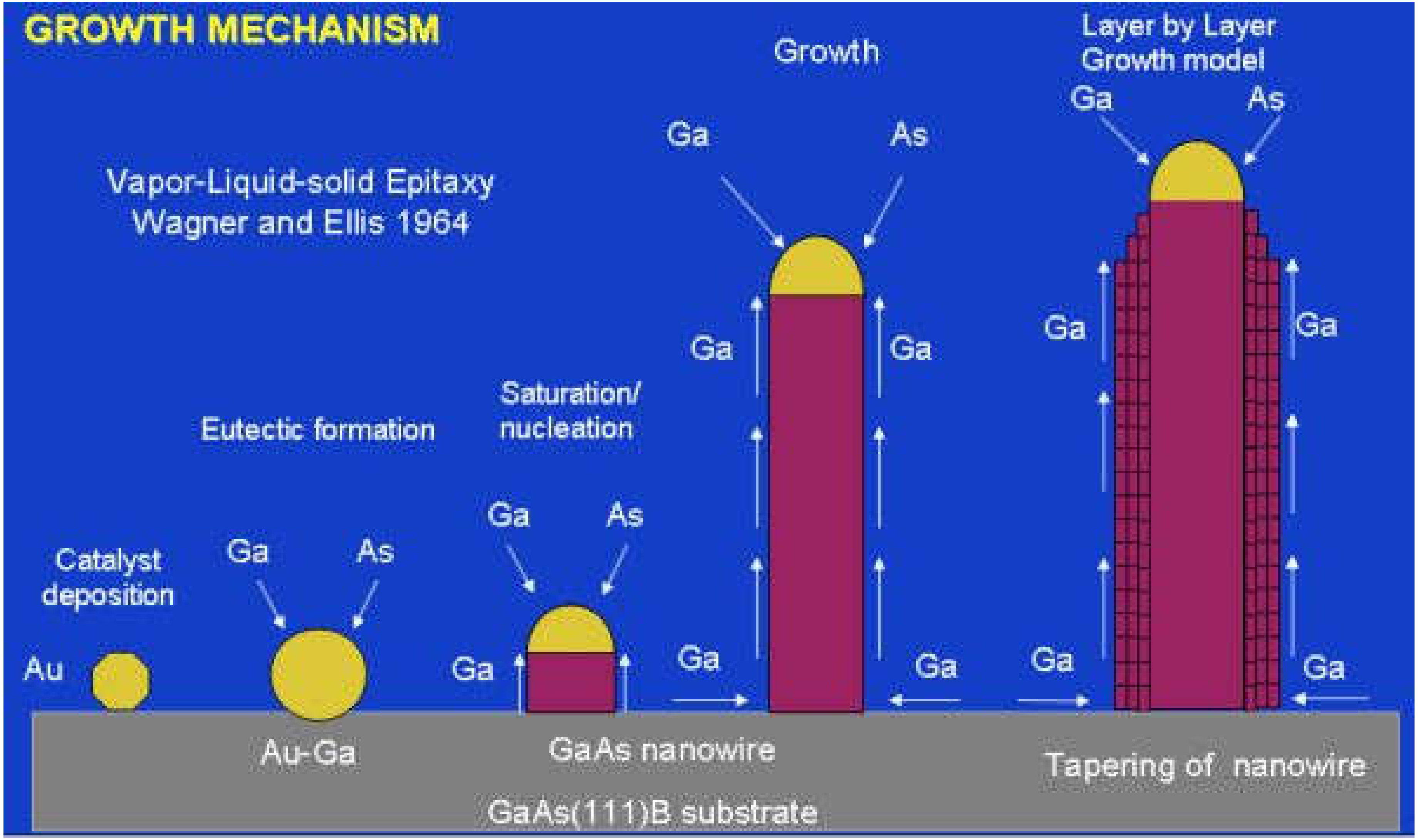






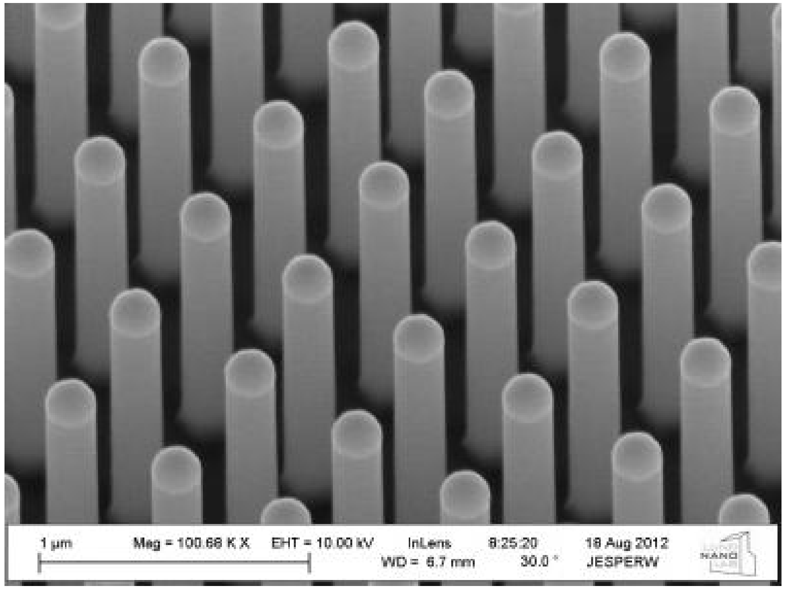
Au-Si eutectic alloy

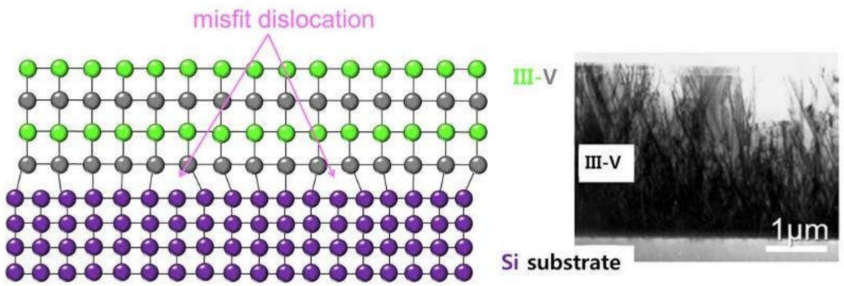
III-V Nanowire Growth



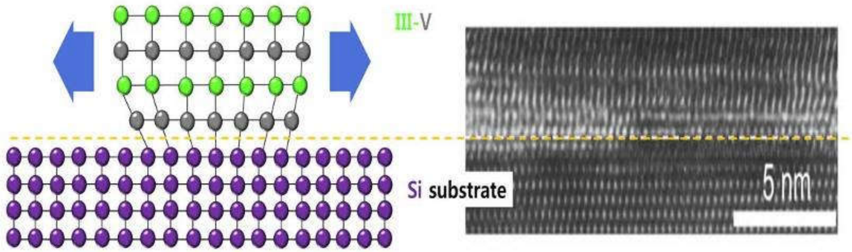
metal catalysts reduce growth temperature

III-V Nanowire Growth



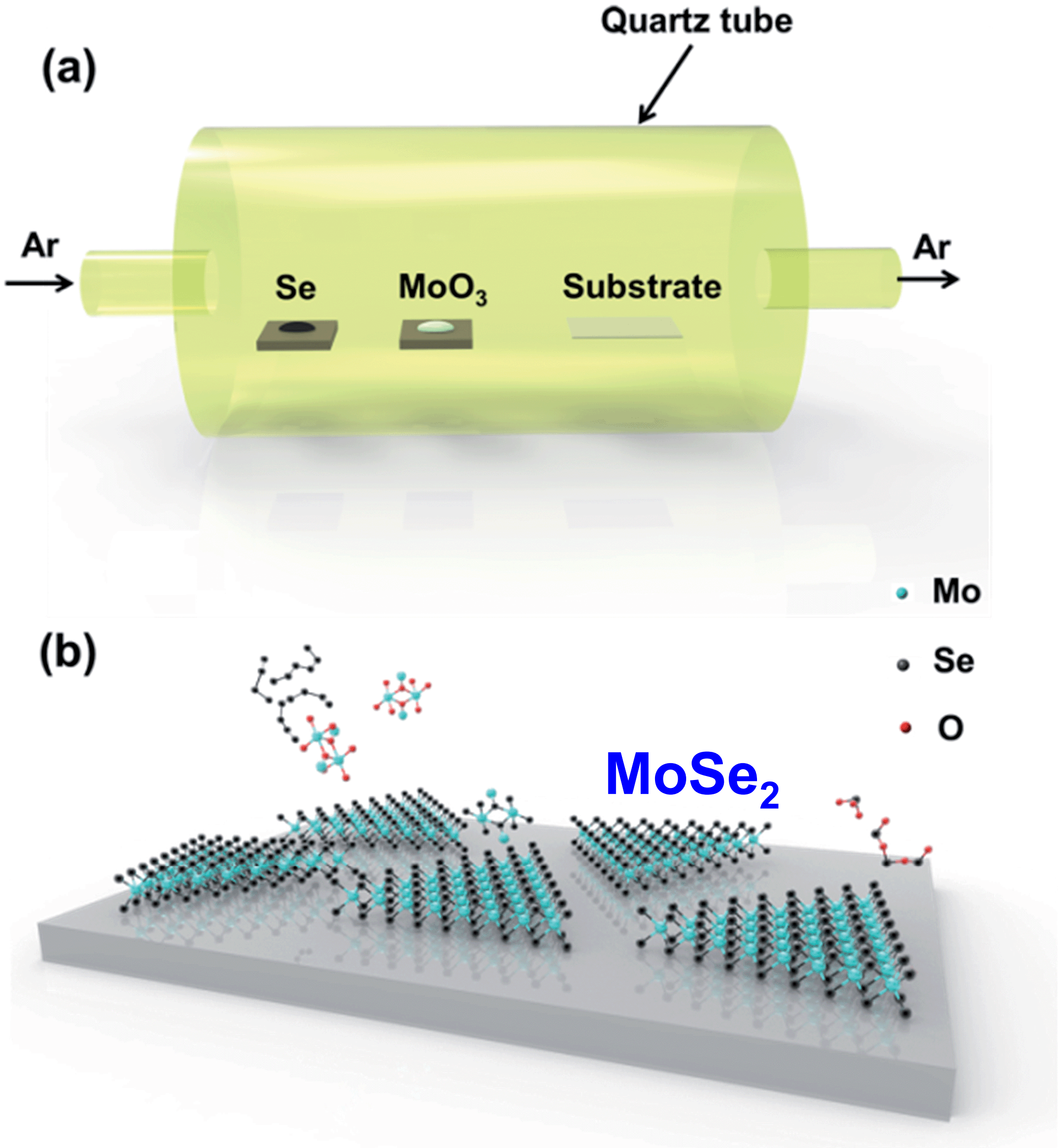


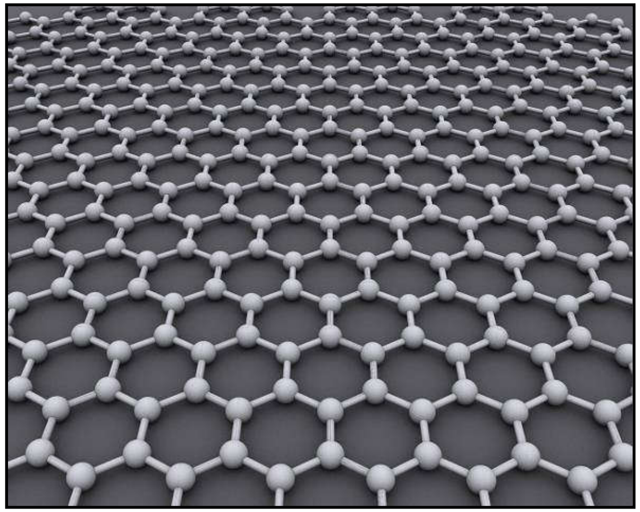
- **Direct growth of III-V film on Si:** Creation of massive threading dislocation due to the large lattice mismatch strain between III-V and Si

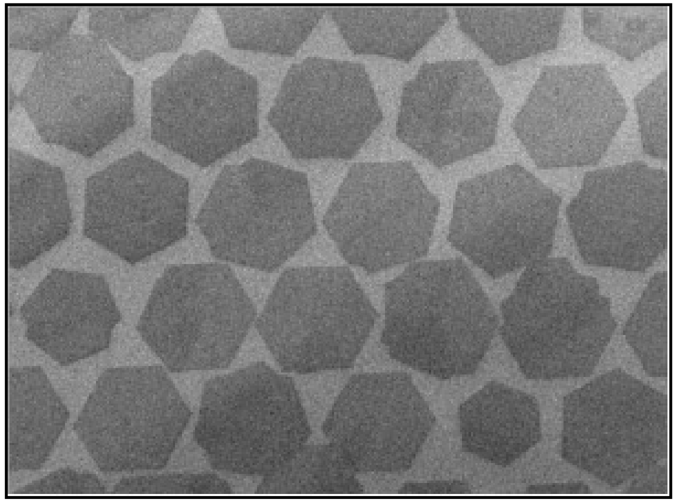


- **Direct growth of III-V film on Si:** Defect-free III-V can be grown on Si because lattice mismatch strain can relieved via the nanowire sidewall

2D Materials Growth



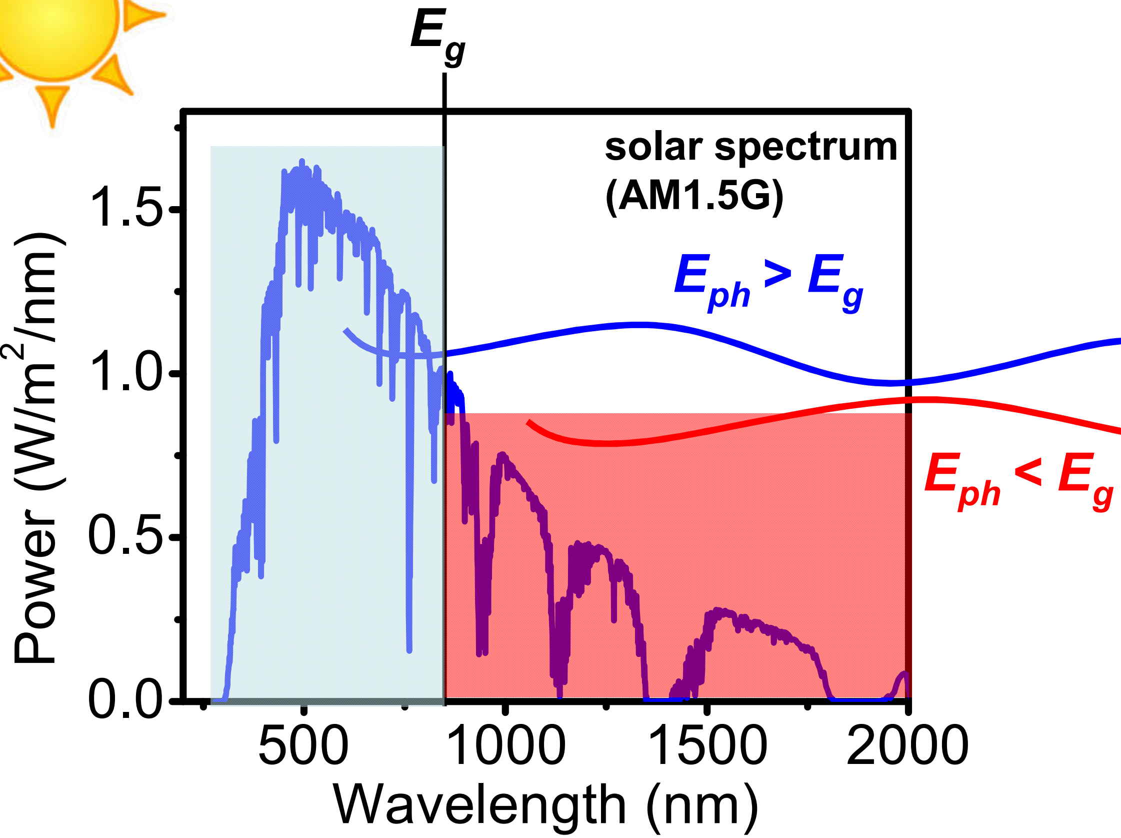




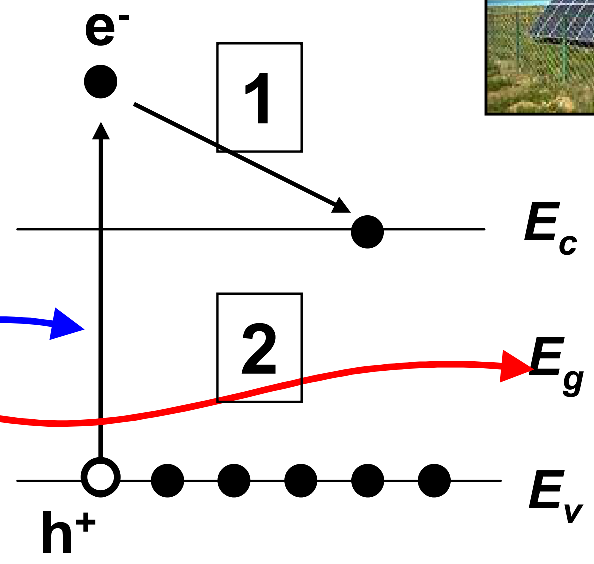
grain boundaries exist

lattice match is not restrict for monolayers

Solar Cells



ASTM G173-03



Energy Loss:

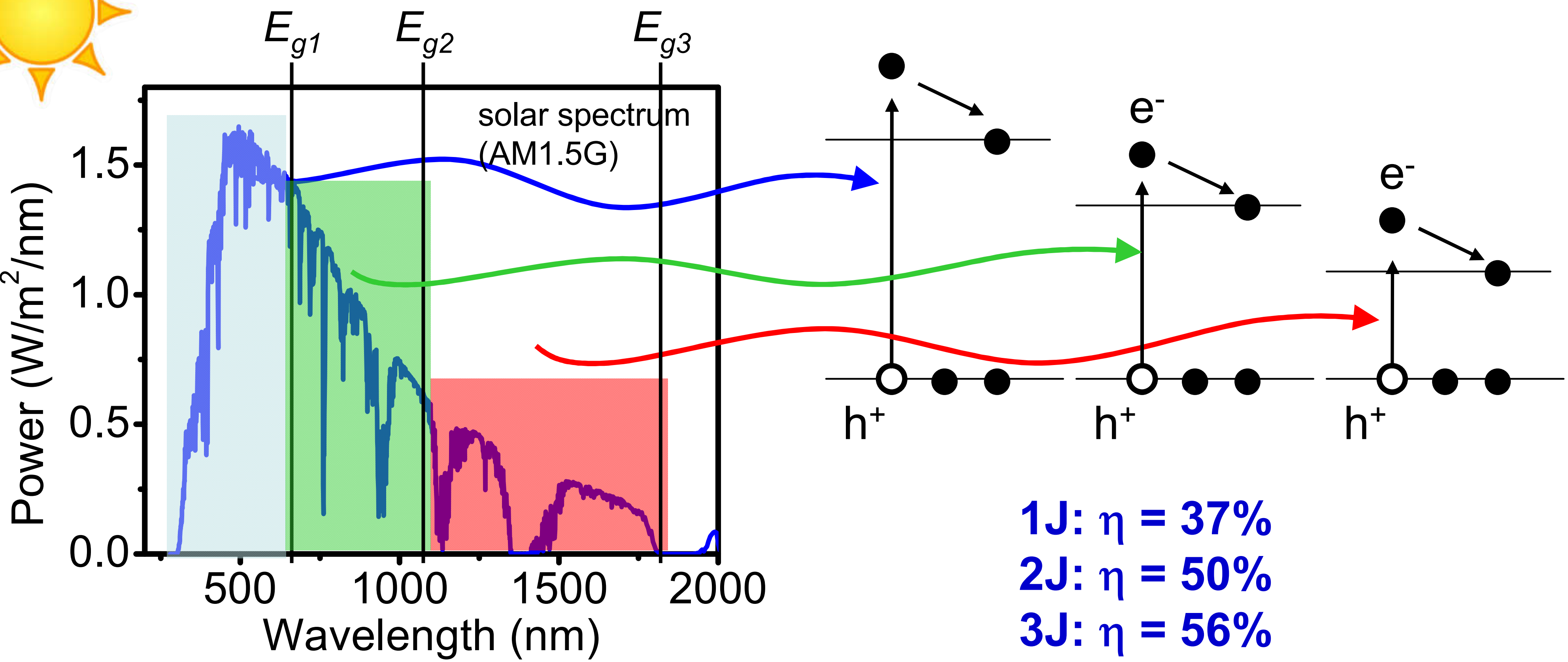
1. Thermalization

2. Sub-bandgap pass

A single junction cell cannot get >37% efficiency

W. Shockley and H. A. Queisser, *J. Appl. Phys.* **32**, 510 (1961)
C. H. Henry, *J. Appl. Phys.* **51**, 4494 (1980)

Multijunction Solar Cells



ASTM G173-03

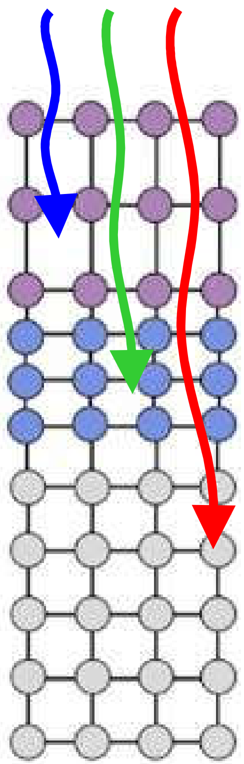
1J: η = 37%
2J: η = 50%
3J: η = 56%
infinite J: η = 72%

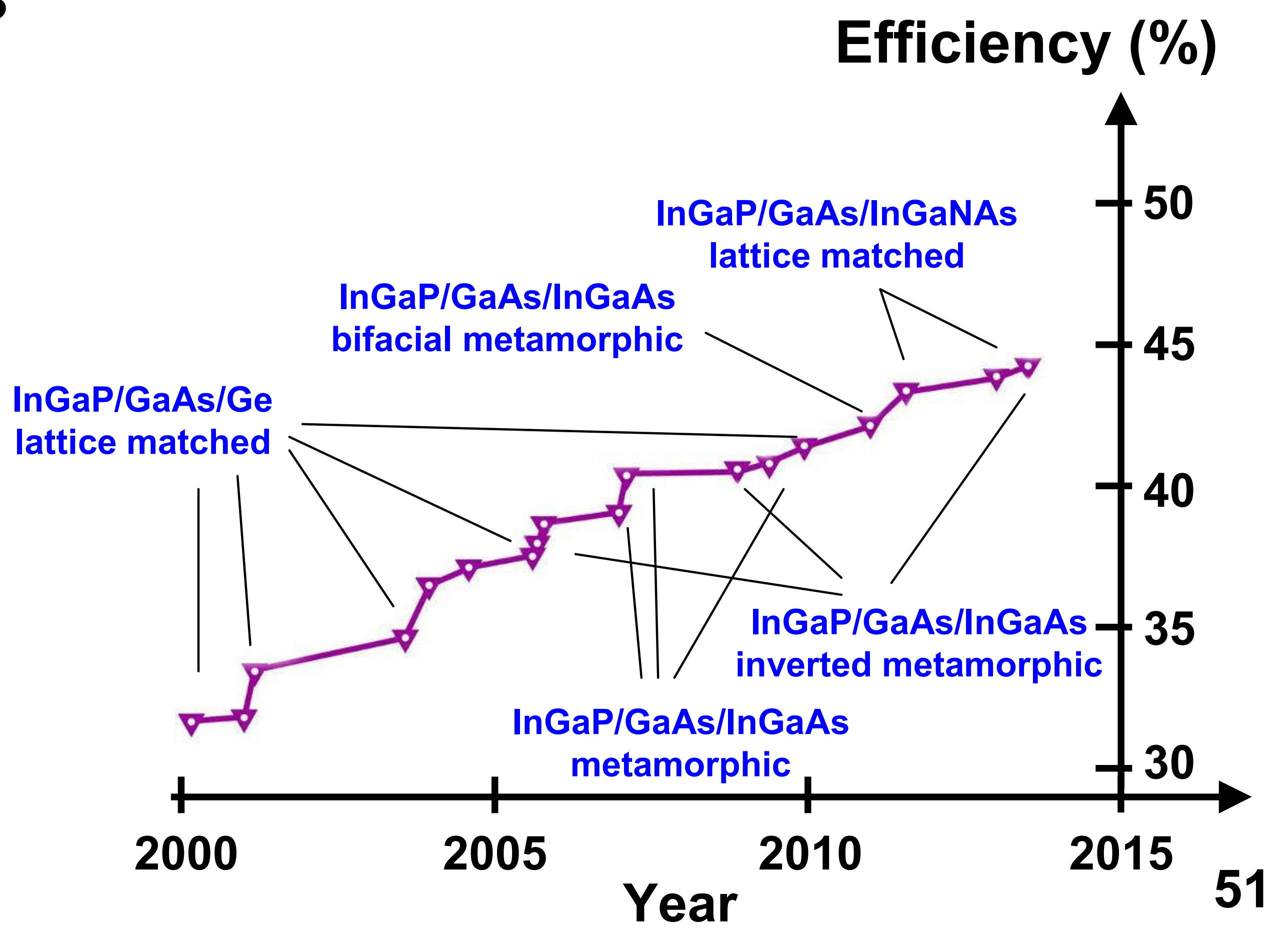
Use the entire solar spectrum

W. Shockley and H. A. Queisser, *J. Appl. Phys.* **32**, 510 (1961)
C. H. Henry, *J. Appl. Phys.* **51**, 4494 (1980)

Multijunction Solar Cells

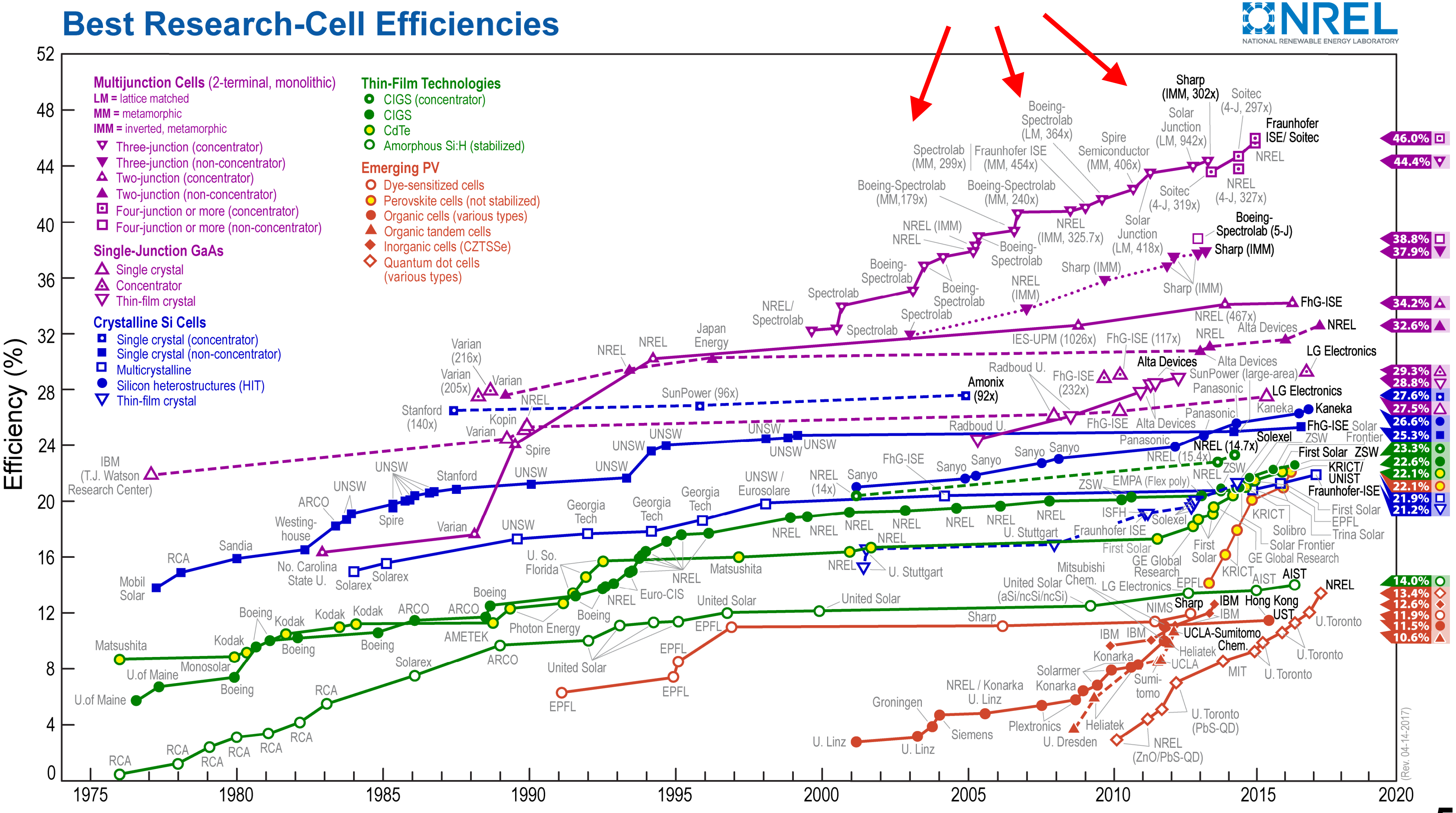
- Lattice matched epi-growth (MOCVD or MBE)
- Current matching
- Suitable bandgaps



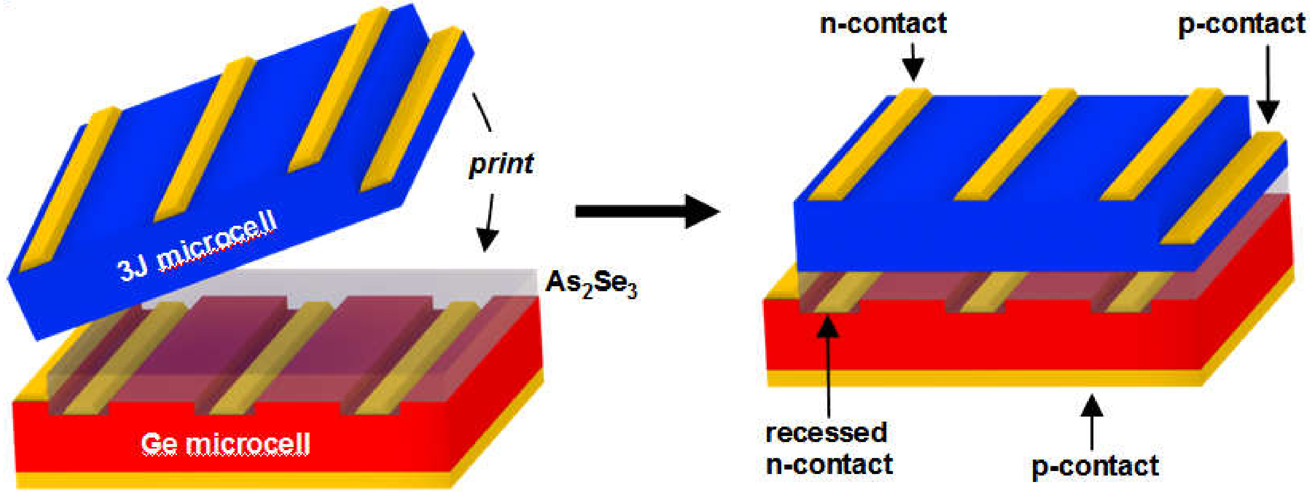


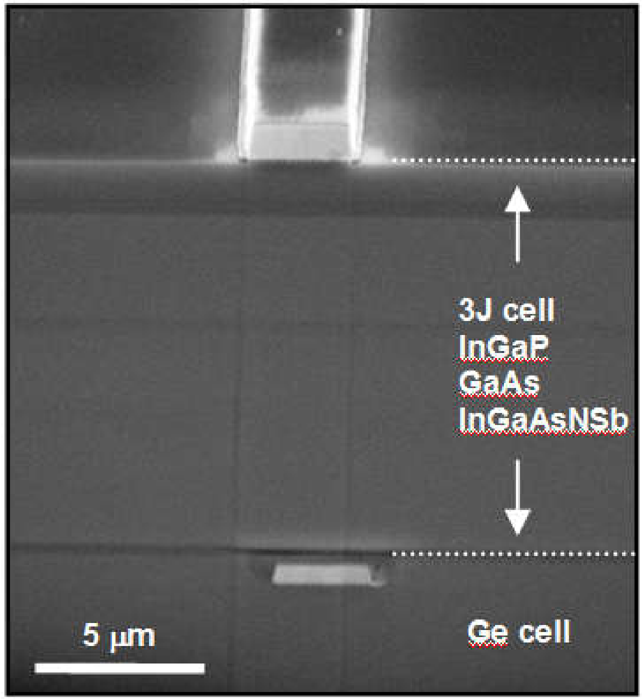
Multijunction Solar Cells

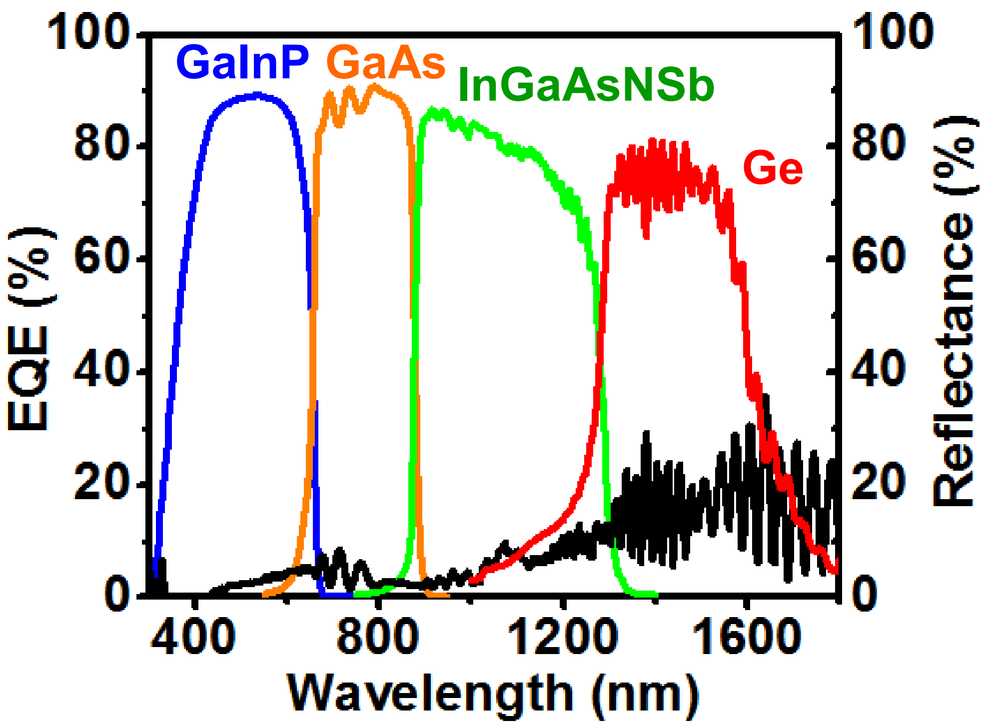
most efficient solar cells



Stacked MJ Solar Cells







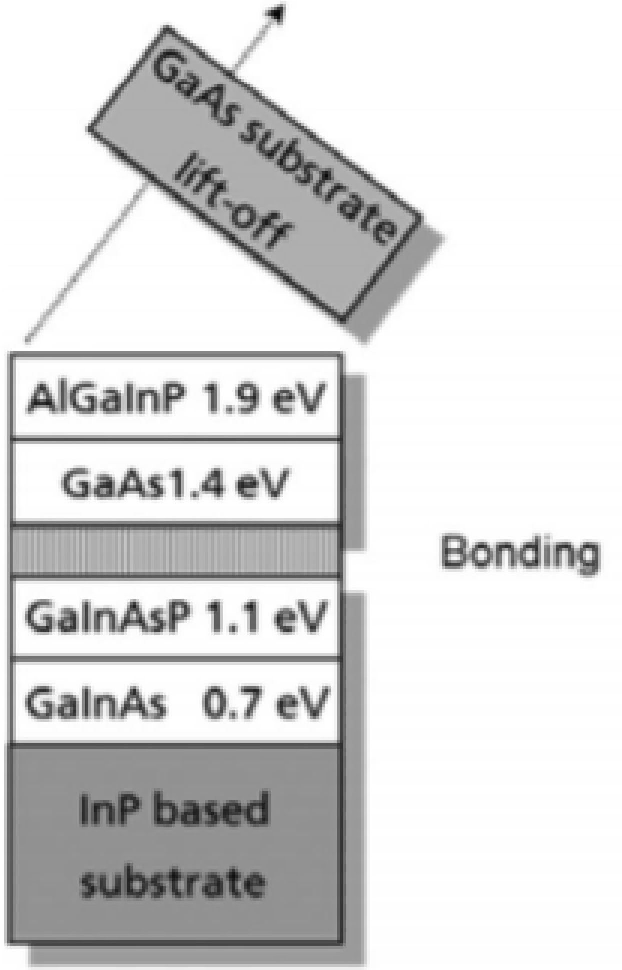
stacked GaInP/GaAs/InGaAsNSb // Ge solar cells

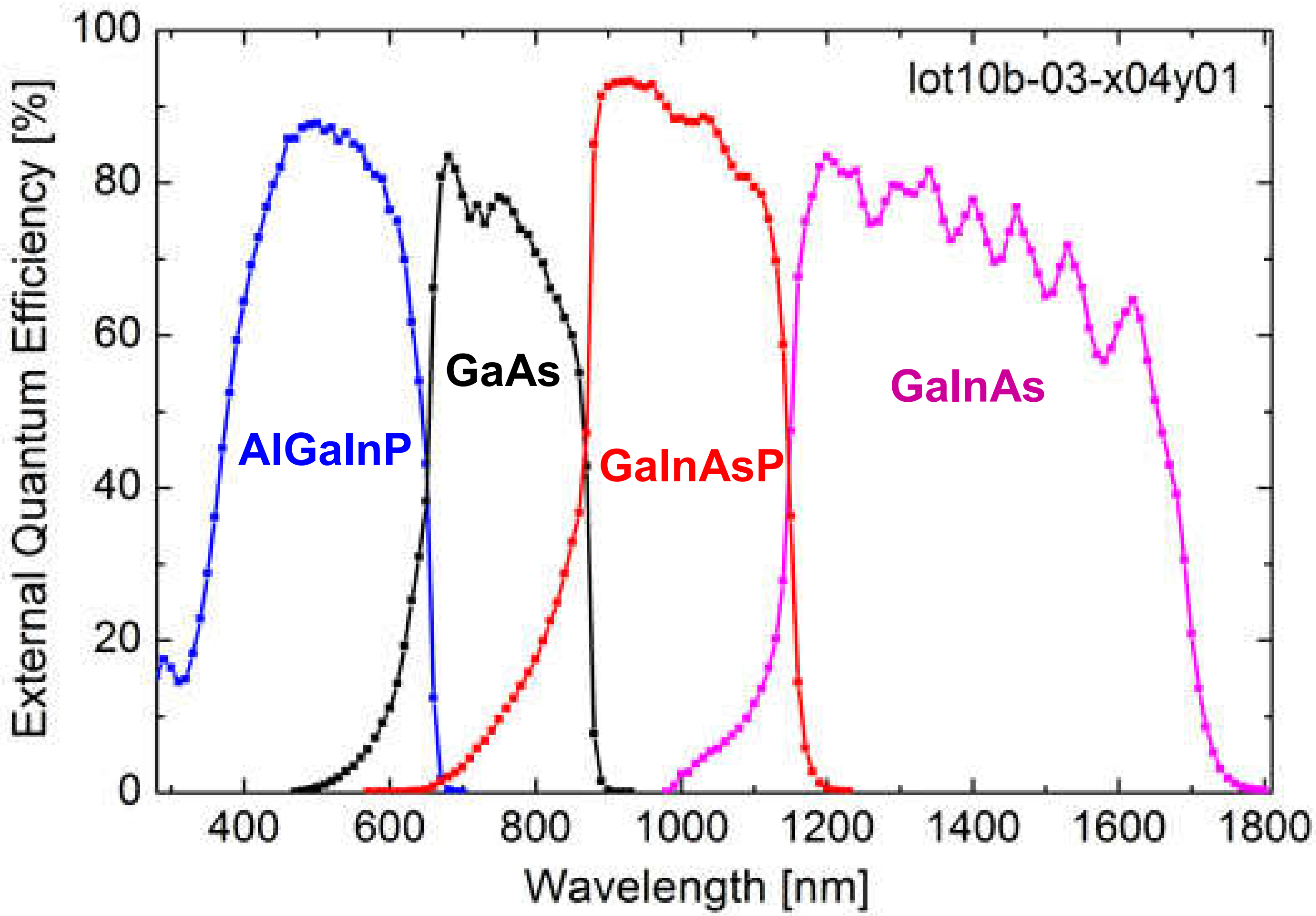
Efficiency: 44%

X. Sheng, *et al.*, *Nature Mater.* **13**, 593 (2014)

Stacked MJ Solar Cells

bonded AlGaInP/GaAs // GaInAsP/GaInAs solar cells



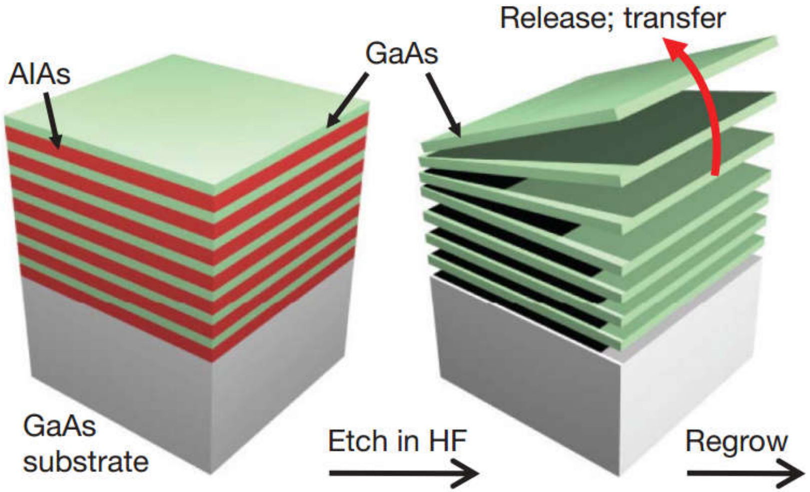


World record efficiency: 46%

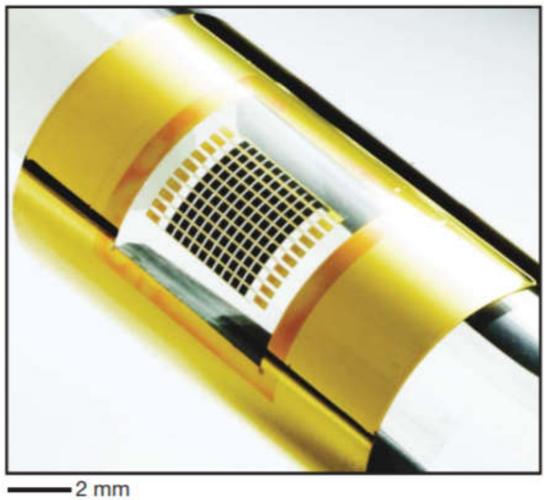
F. Dimroth, *et al.*, *IEEE J. Photovolt.* **6**, 343 (2016)

Epitaxy Liftoff

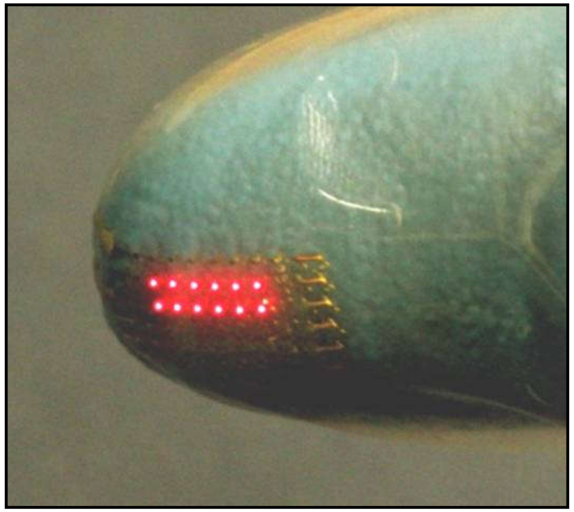
- GaAs and AlAs
  - lattice matched growth
  - AlAs is selectively etched by HF



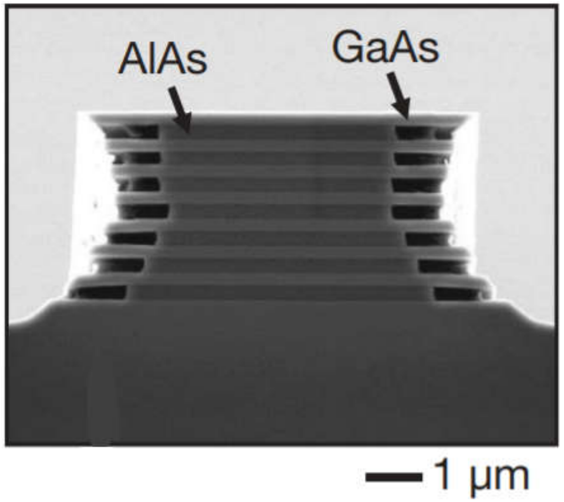
- flexible III-V devices



solar cells



LED

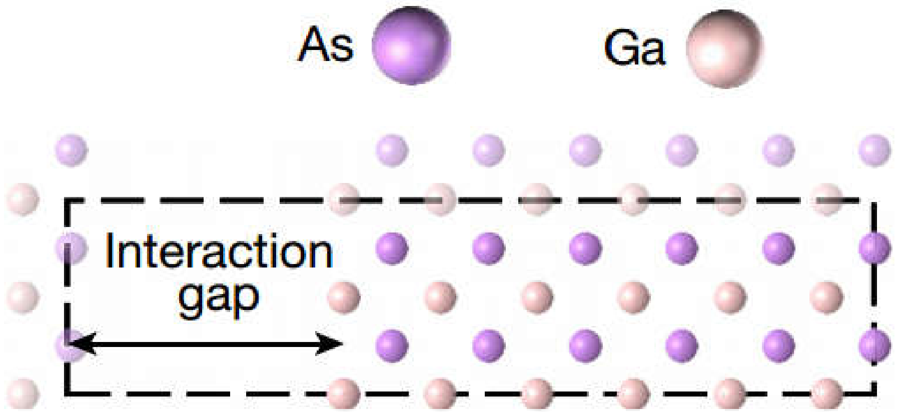


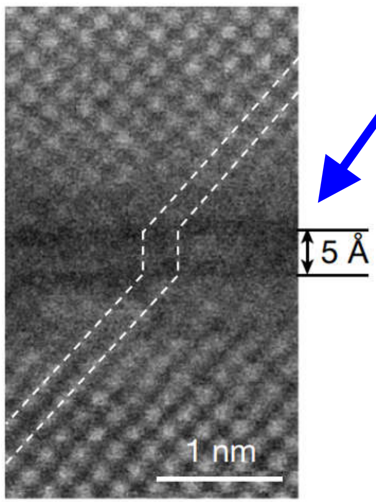
S. I. Park, *et al.*, *Science* **325,** 977 (2009)
J. Yoon, *et al.*, *Nature* **465,** 329 (2010)

'Remote' Epitaxy

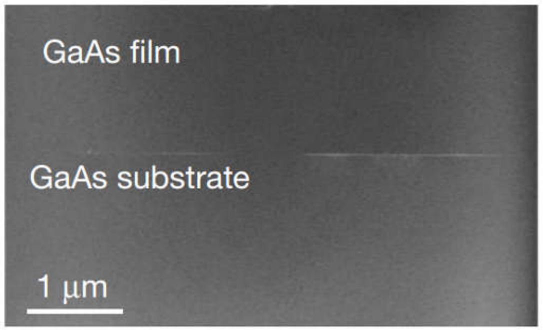
Remote epitaxy through graphene enables two-dimensional material-based layer transfer

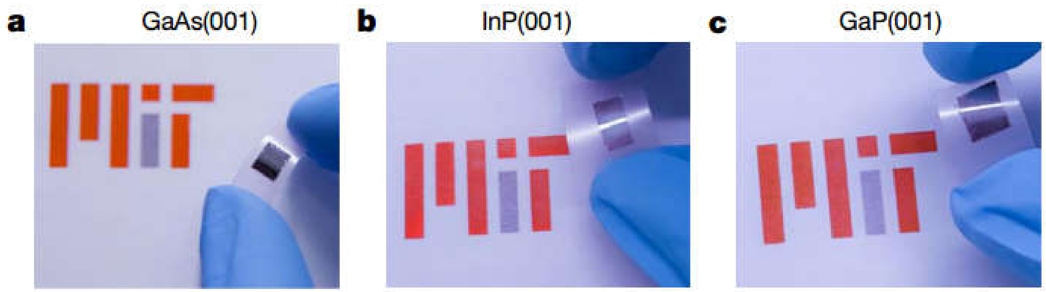
Yunjo Kim[1]*, Samuel S. Cruz[1]*, Kyusang Lee[1]*, Babatunde O. Alawode[1], Chanyeol Choi[1], Yi Song[2], Jared M. Johnson[3], Christopher Heidelberger[4], Wei Kong[1], Shinhyun Choi[1], Kuan Qiao[1], Ibraheem Almansouri[1,5], Eugene A. Fitzgerald[4], Jing Kong[2,6], Alexie M. Kolpak[1], Jinwoo Hwang[3] & Jeehwan Kim[1,4,6]





graphene interlayer





Y. Kim, *et al.*, *Nature* **544,** 340 (2017)