4-point probe

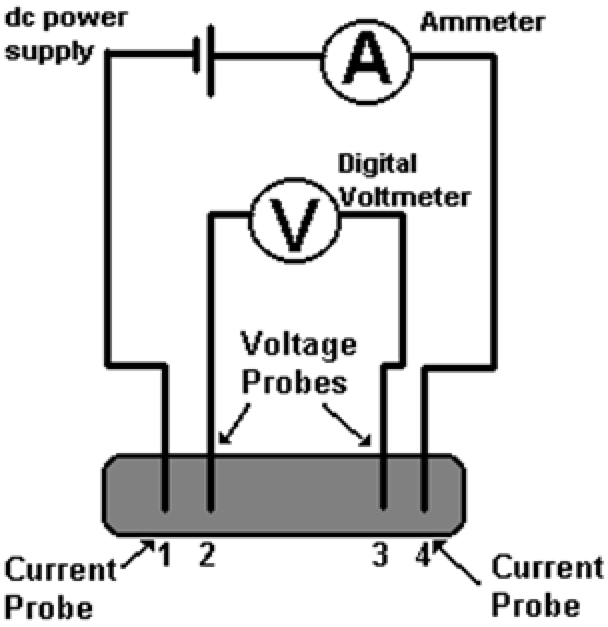
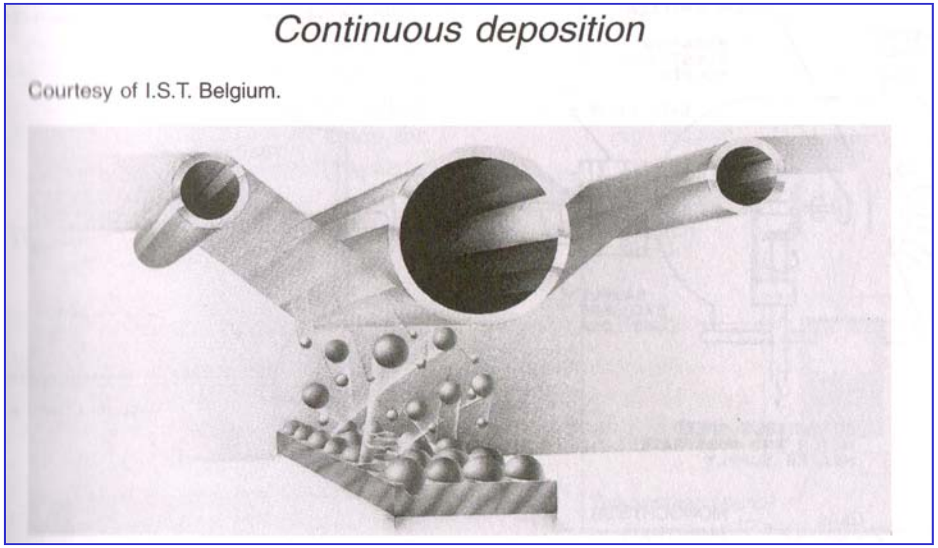


Figure 2: Schematic of Four-Point Probe

Placing Thin Films onto a Substrate Surface

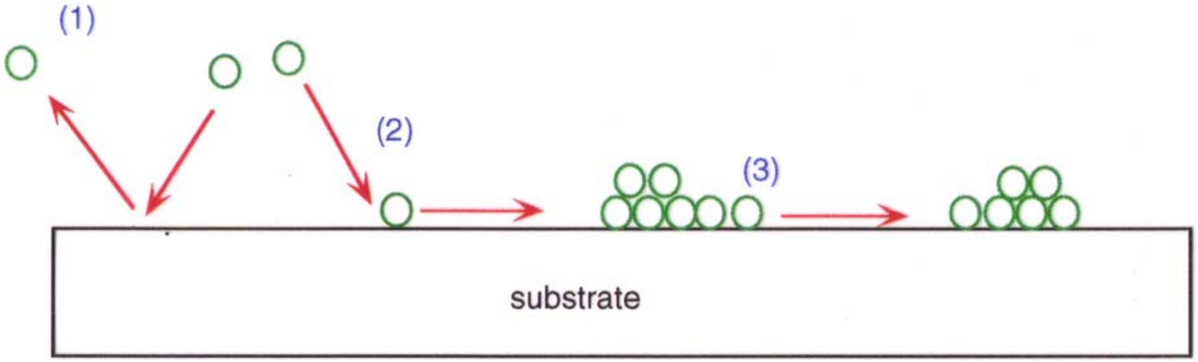


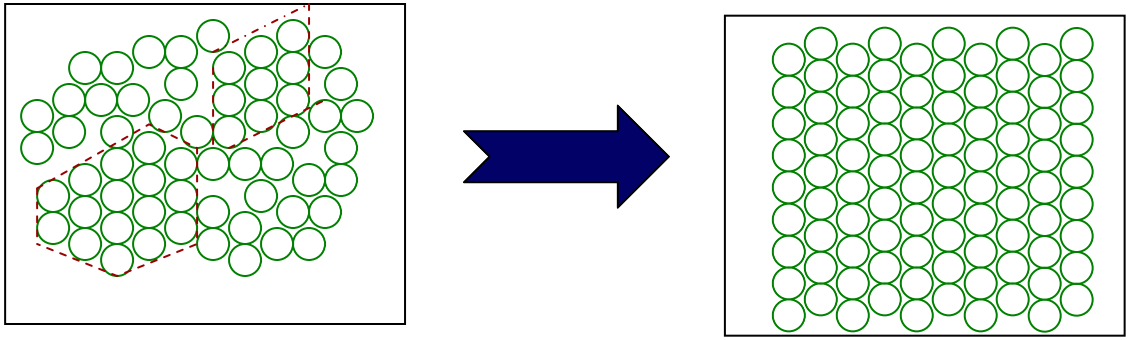
Madou, Fundamentals of Microfabrication, p. 141

The Ultimate in Physical Vapor Deposition:
Molecular Beam Epitaxy

Oxford Instruments MBE 2008

What if you could control the placement of *every* atom in the film you were forming?





- control of the atoms impinging on the substrate (wafer)
- controlled relationship between substrate and the atoms in the film (epitaxy)

Molecular Beam Epitaxy

2.6 Molecular Beam Epitaxy

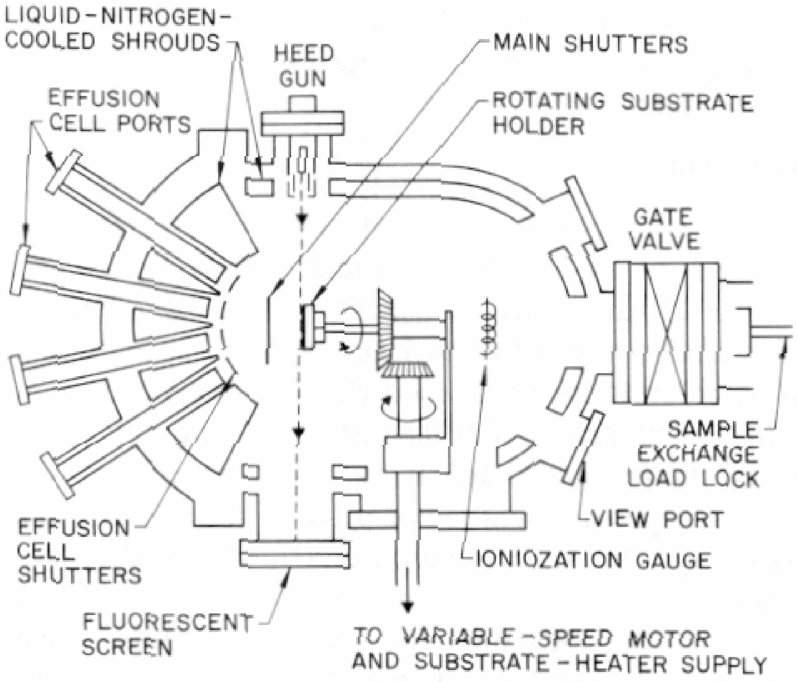


Figure 2.80 Schematic of a typical MBE system viewed from the top. The rotating sample holder has a variable speed from 0.1 to 5 rpm [338].

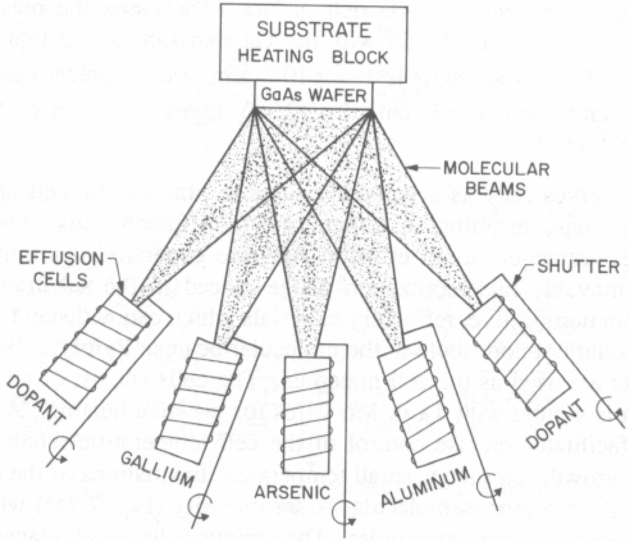


Figure 2.79 Schematic of the basic evaporation process for MBE of intentionally doped GaAs and $Al_xGa_{1-x}As$ [335].

Makes possible <u>in situ</u> diagnostics

- Ultra-high vacuum, long mean free paths
- Flux = $P_{eq}/\{2\pi kTM\}^{1/2}$

Swaminathan & Macrander
Materials Aspects of GaAs
and InP Based Structures

Watching the Growth Process Carefully: what do you need to know?

- control of the atoms impinging on the substrate (wafer)
- controlled relationship between substrate and the atoms in the film (epitaxy)

- ▪ what is the quality/cleanliness/roughness of the wafer?

  Understanding the surface: Auger spectroscopy
- ▪ how can you be sure the atoms are 'going' to the right locations?

- ▪ how can you monitor the growth rate?

  Monitoring structure and growth rate: electron diffraction

A short look at the material system….

Range of Bandgaps and Lattice Constants: Bandgap Engineering

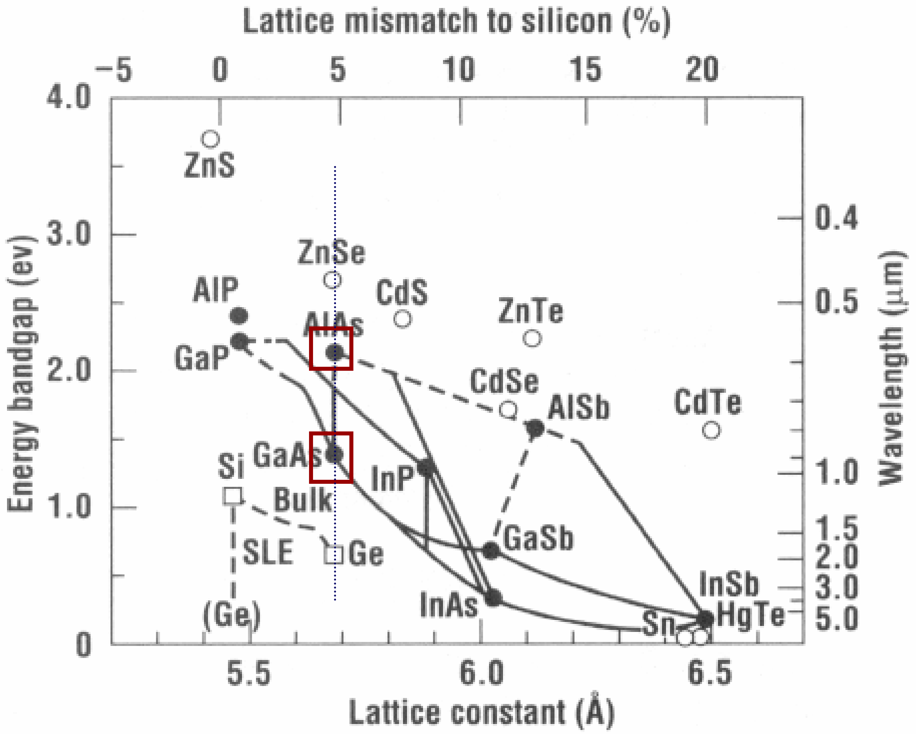


Figure 14.17 The bandgap and lattice parameter of a variety of semiconductor compounds and alloys.

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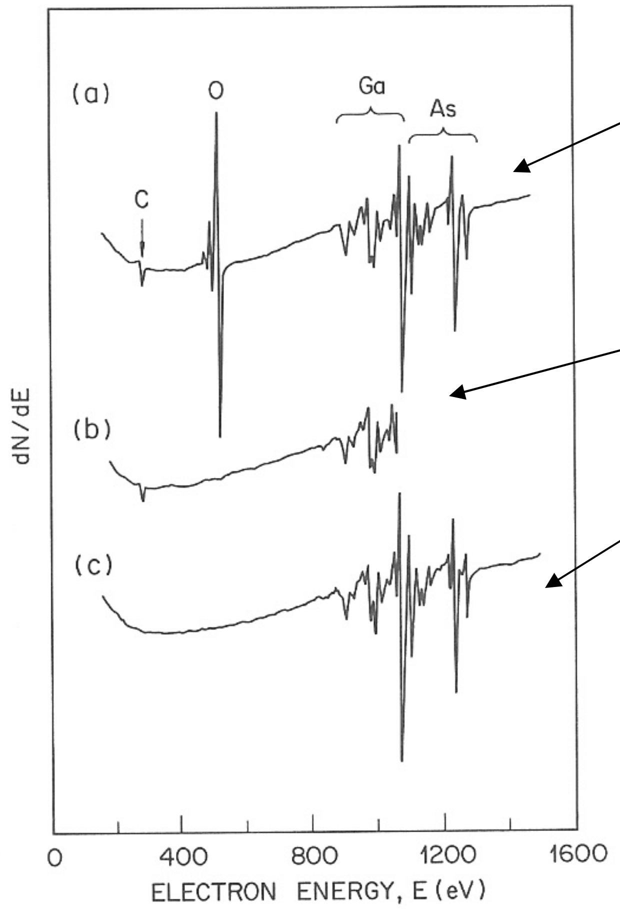
Seeing & Controlling The Surface

Auger Spectroscopy



After chemical preparation of surface

After heating substrate at 530C, 1 hour

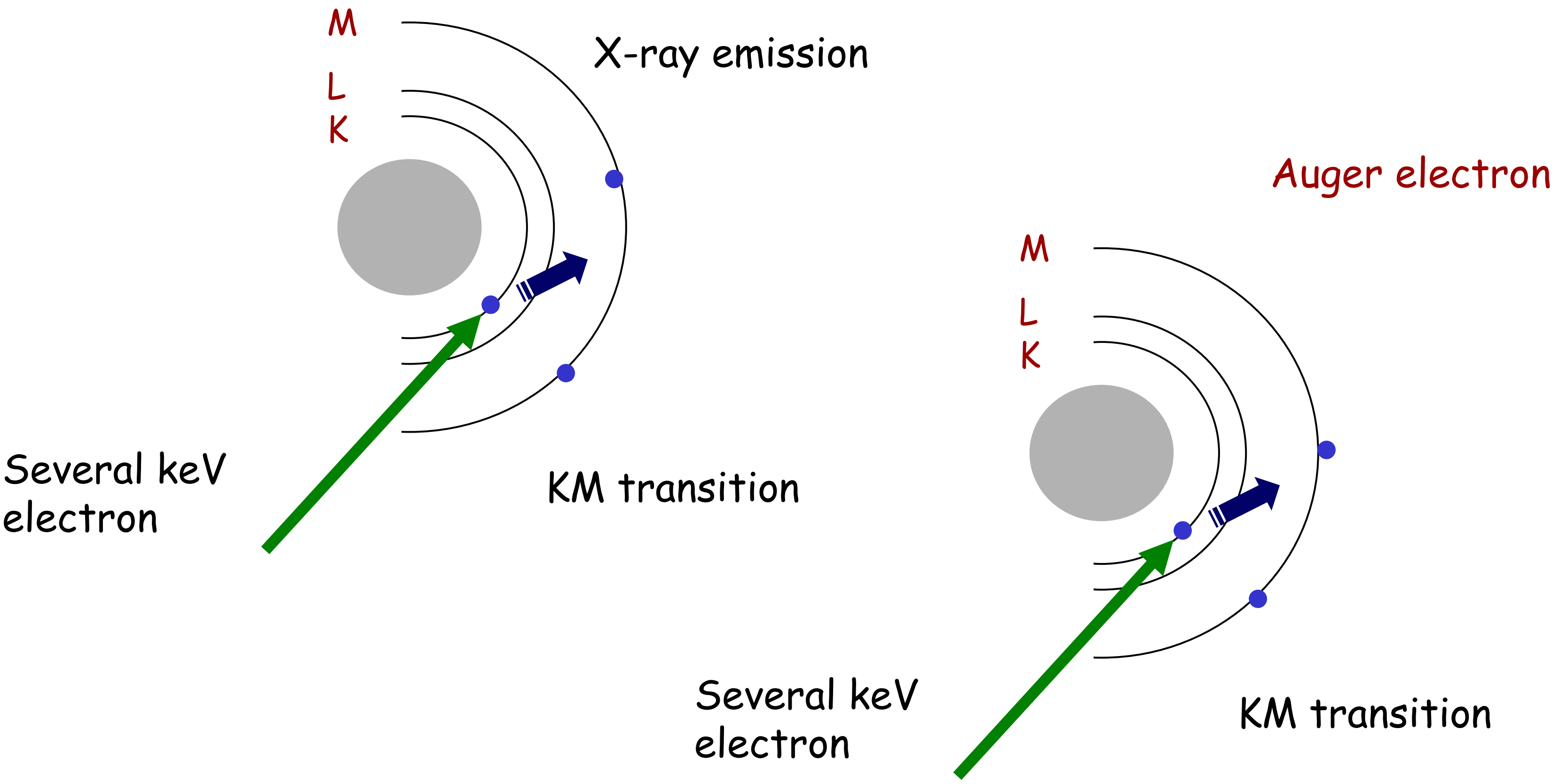
After sputtering the surface

Figure 2.81 Auger spectra taken with primary electron energy of 4 keV of the surface of (100) GaAs substrate: (a) after chemical etching (b) after heating at 530°C for 1 h and (c) after Ar^+ sputtering at 5×10^{-5} Torr for 5 min. [334].

What is the basis of Auger Spectroscopy?

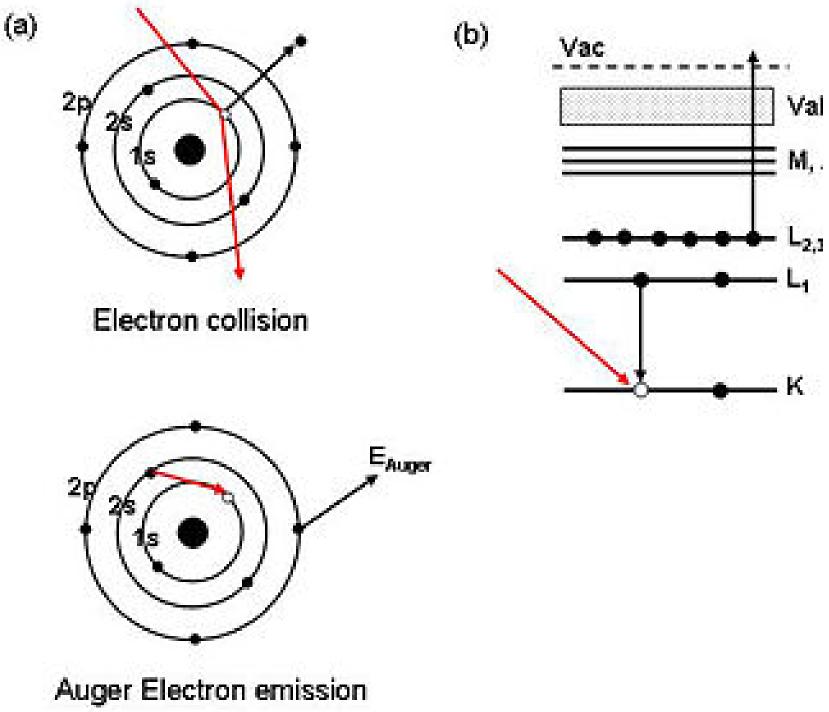
Macrander & Swaminathan

Auger electron emission



Auger electron emission

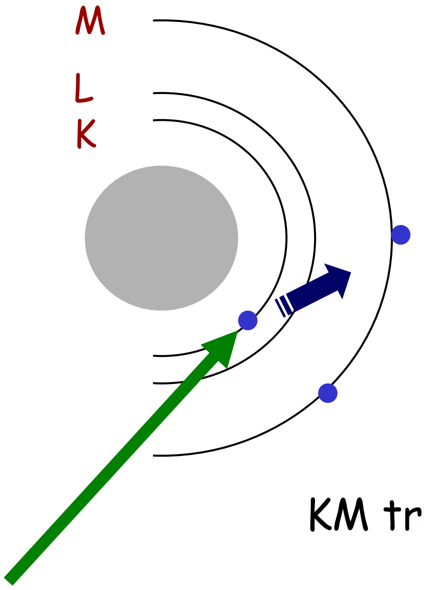
http://en.wikipedia.org/wiki/Auger_electron_spectroscopy



Electron collision

Auger Electron emission

Auger electron



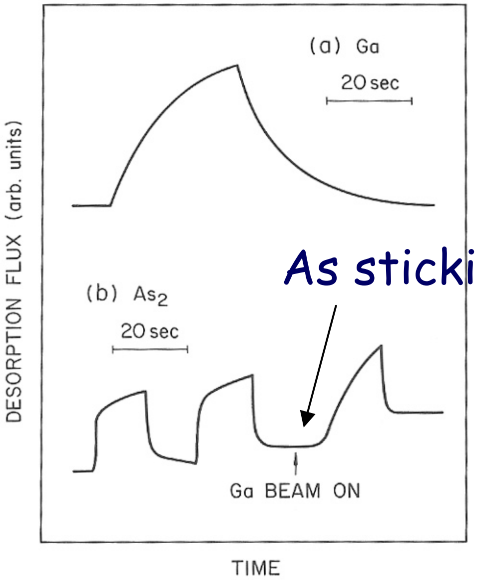
KM transition

Several keV
electron

Auger electrons have energies that are *characteristic* of the orbitals from which they originate: form a fingerprint for the material

Controlling the growth rate in GaAs MBE

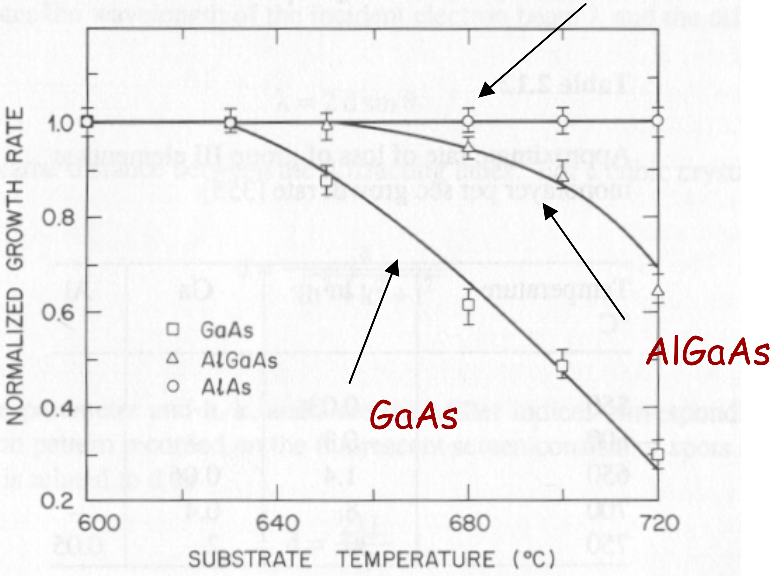
Monitor the fluxes from the wafer



As sticking follows Ga Flux

- below 750K, Ga has UNITY sticking coefficient
- (a) at 885K, Ga desorbs with 10 s surface lifetimes
- (b) at room temperature, As sticks only in the presence of Ga

Figure 2.87 Growth rates normalized to low temperature (≤620°C) values as a function of substrate temperature: (O) AlAs; (Δ) GaAs with Al (represents the Ga fraction of the growth rate); (□) GaAs without Al [348].



Desorbtion at high temperatures limits growth rate

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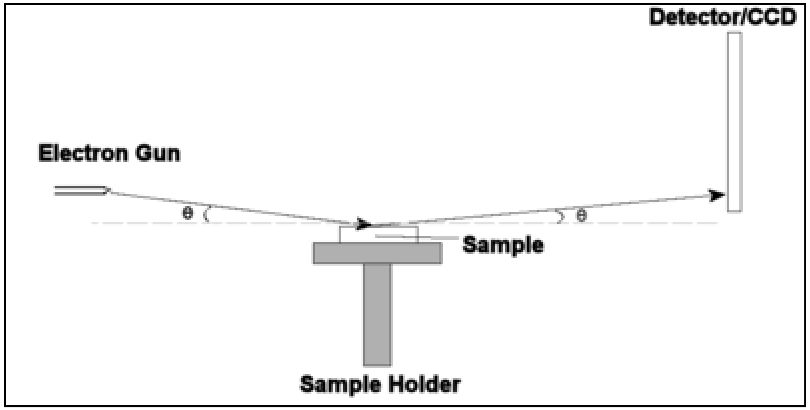
and InP Based Structures

Reflection High Energy Electron Diffraction (RHEED)



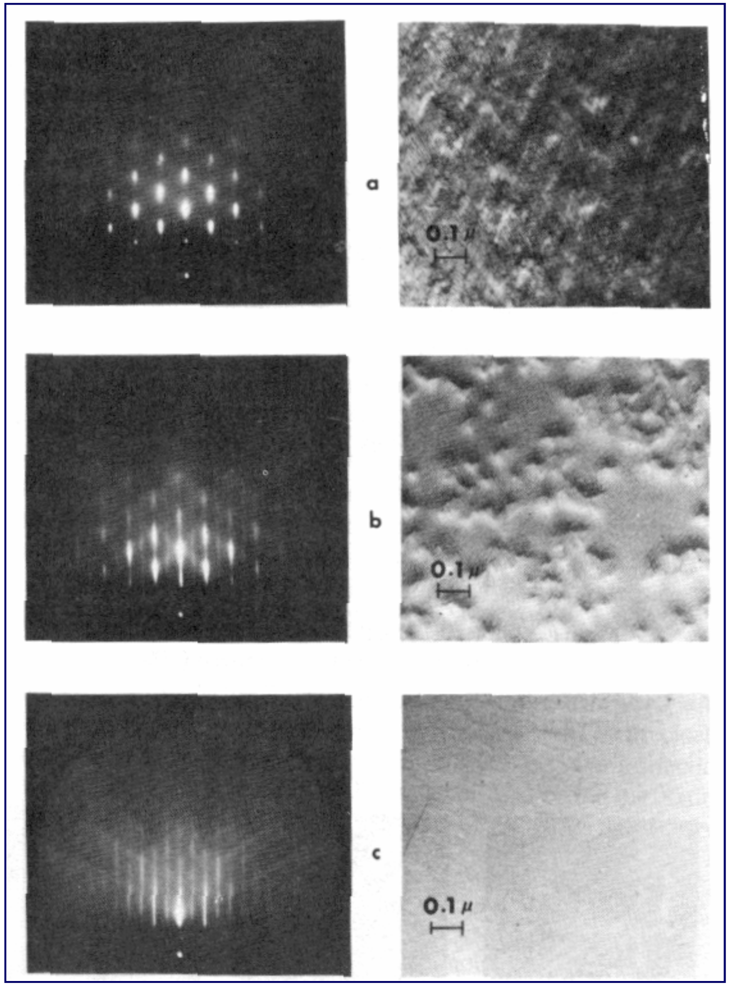
http://en.wikipedia.org/wiki/RHEED

Detailed, *in situ* measurement of the growth process

- Electron gun, 5- 40 keV, at an oblique angle to samples
- Electron energy perpendicular to sample ~ 100 eV, samples first few atomic layers
- Bragg diffraction: $\lambda = 2d \sin\theta$

  λ = wavelength of electrons ,θ = diffraction angle, d = spacing between crystal planes

Monitoring the progress of GaAs growth



40 keV beam

Br_2-methanol polished GaAs, heated to 580°C

After growth of 15 nm GaAs

After growth of 1 micron GaAs

Cho, JVST 1971

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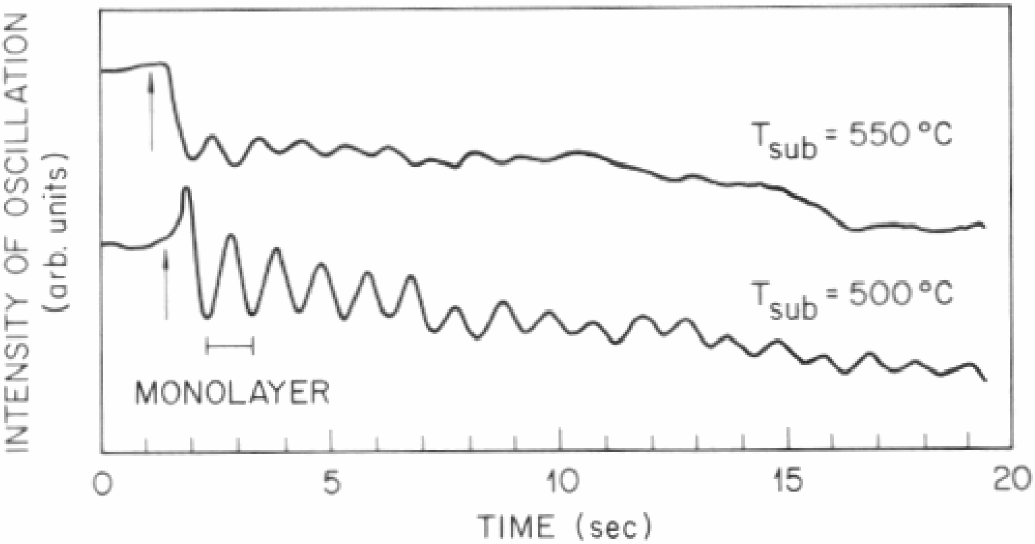
RHEED Oscillations

Figure 2.91 RHEED intensity oscillation of the specularly reflected beam during MBE growth of GaAs; the period of oscillation corresponds precisely to a monolayer, $a_o/2$ for GaAs [332].



Periodic variations in the diffracted intensity

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RHEED Oscillations Delineate Layer-by-layer growth mode

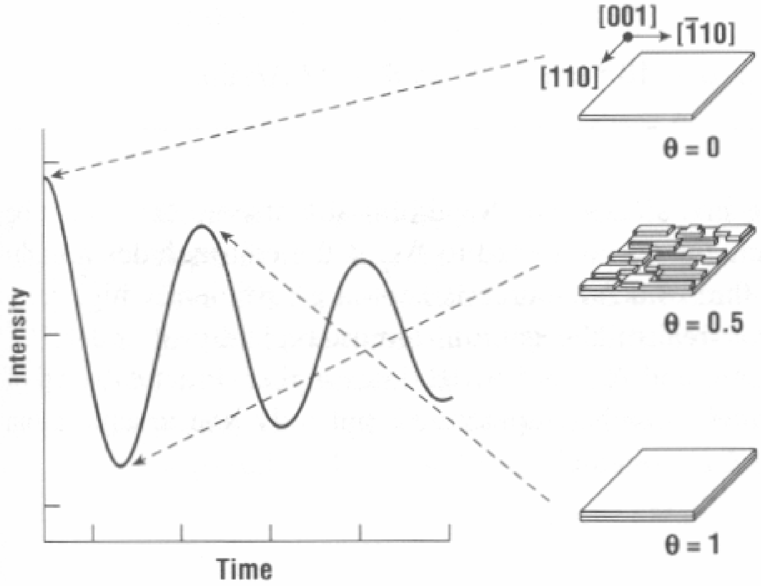


Figure 14.31 Electron diffraction oscillations during MBE growth. The peaks correspond to nearly complete layers.

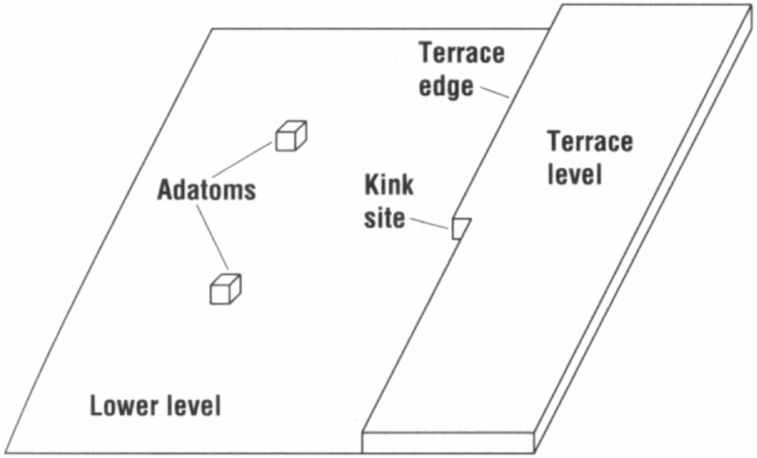
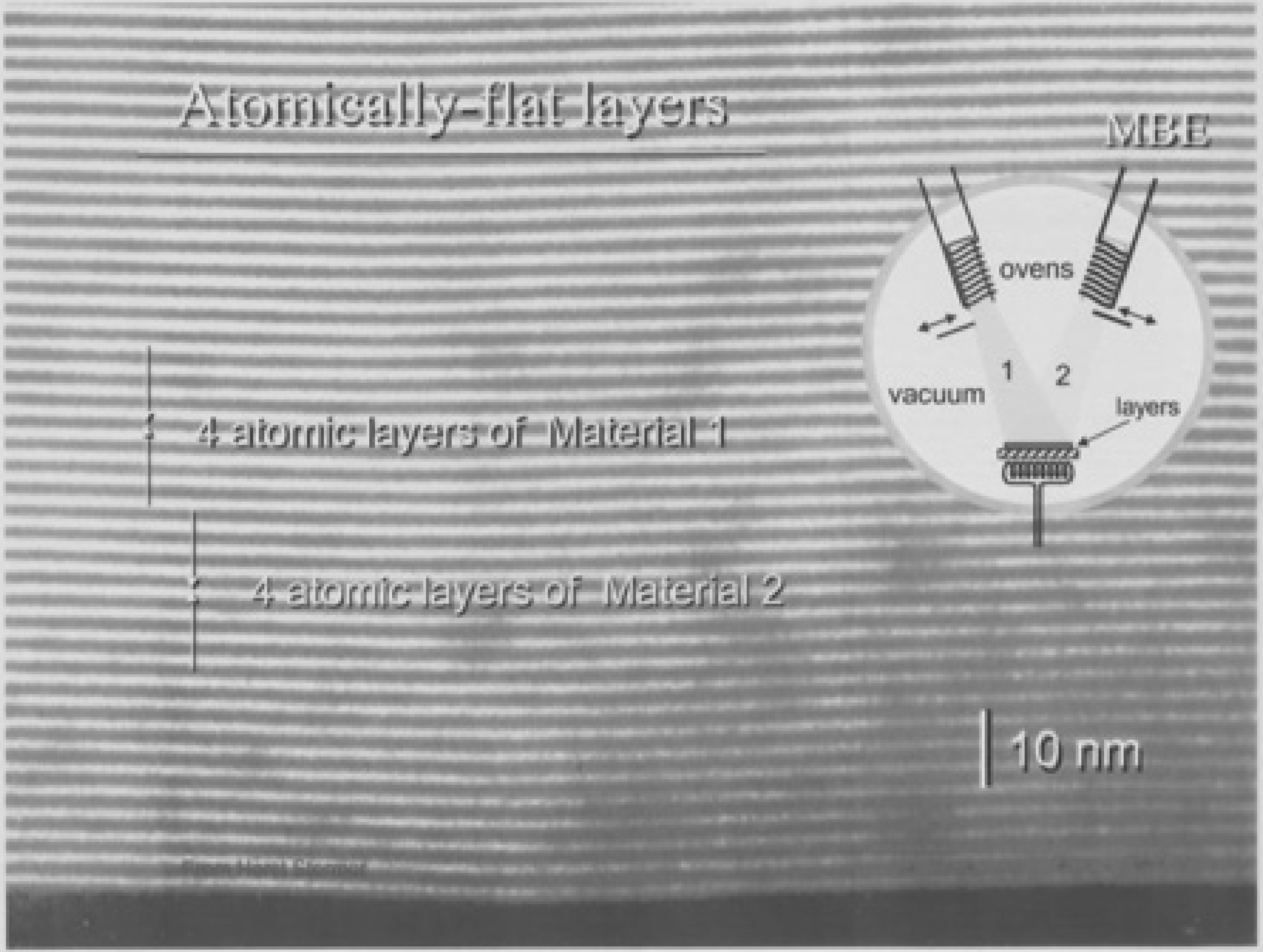


Figure 14.32 A microscopic view of a semiconductor surface during MBE growth or evaporation.

Atomically-flat layers



4 atomic layers of Material 1

4 atomic layers of Material 2

Lattice-mismatched epitaxy: an opportunity

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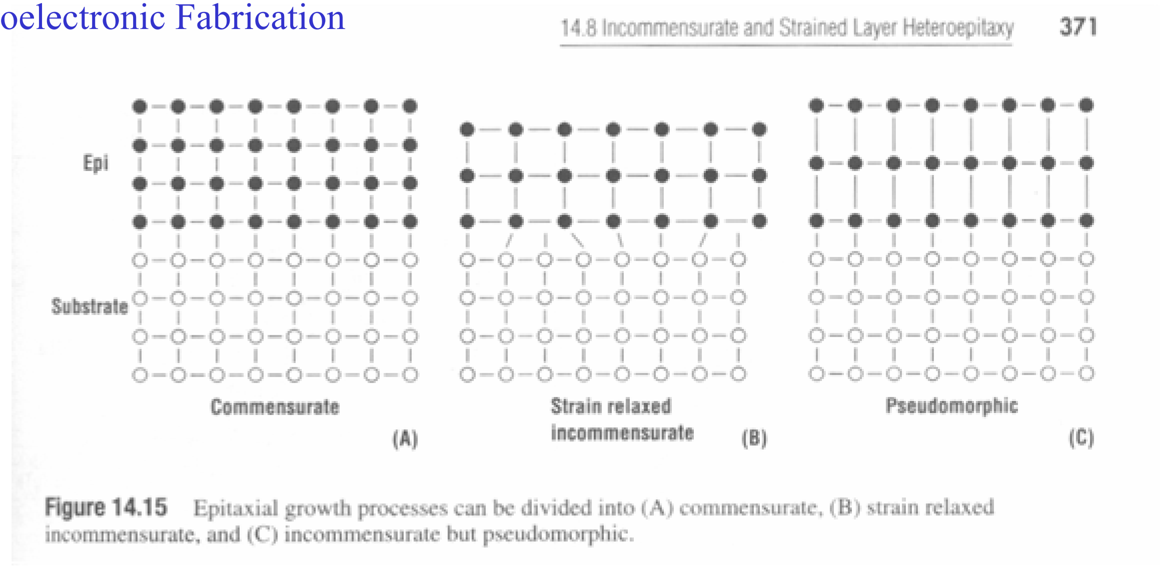

14.8 Incommensurate and Strained Layer Heteroepitaxy 371

Figure 14.15 Epitaxial growth processes can be divided into (A) commensurate, (B) strain relaxed incommensurate, and (C) incommensurate but pseudomorphic.

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Range of Bandgaps and Lattice Constants: Bandgap Engineering

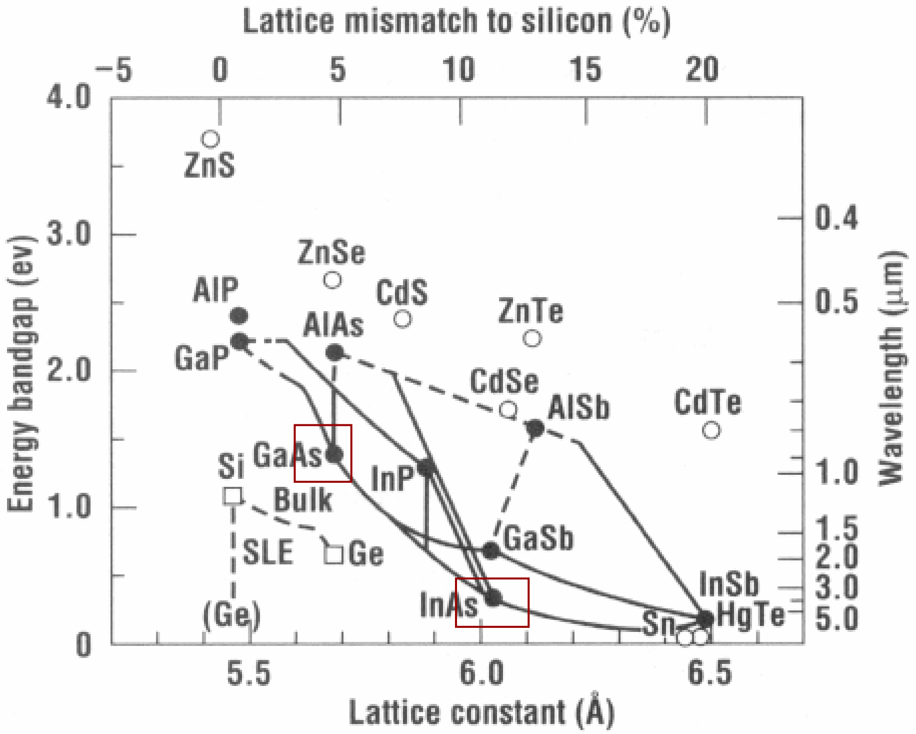

Figure 14.17 The bandgap and lattice parameter of a variety of semiconductor compounds and alloys.

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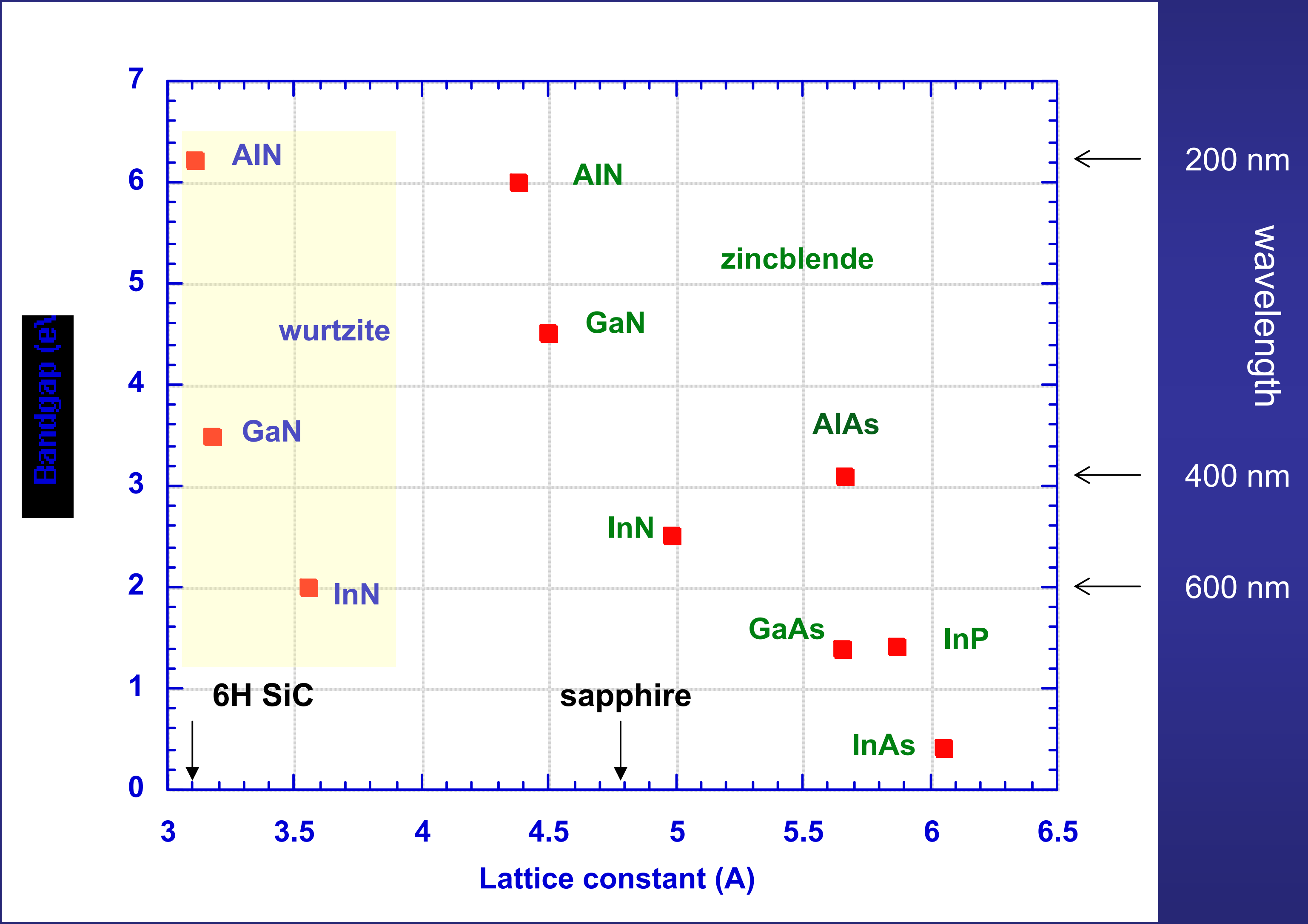
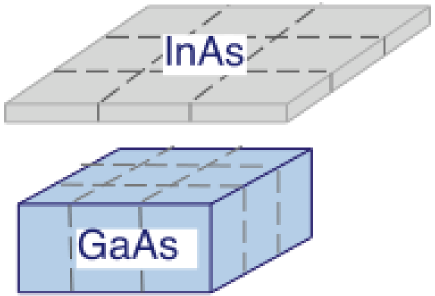
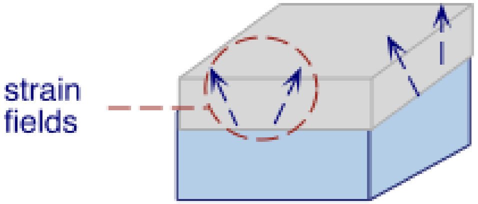
Bandgap vs. Lattice Constant



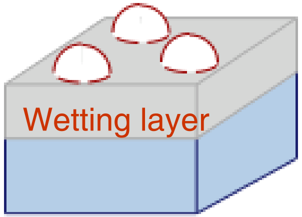
'Self-Assembled' semiconductor quantum dots



Begin with lattice-mismatched materials

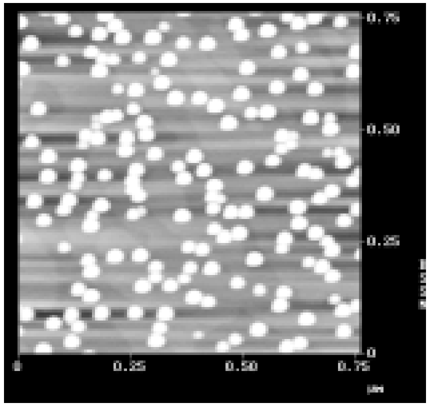


Carry out strained-layer epitaxy (Stranski-Krastonow)



Carefully form quantum dot structures

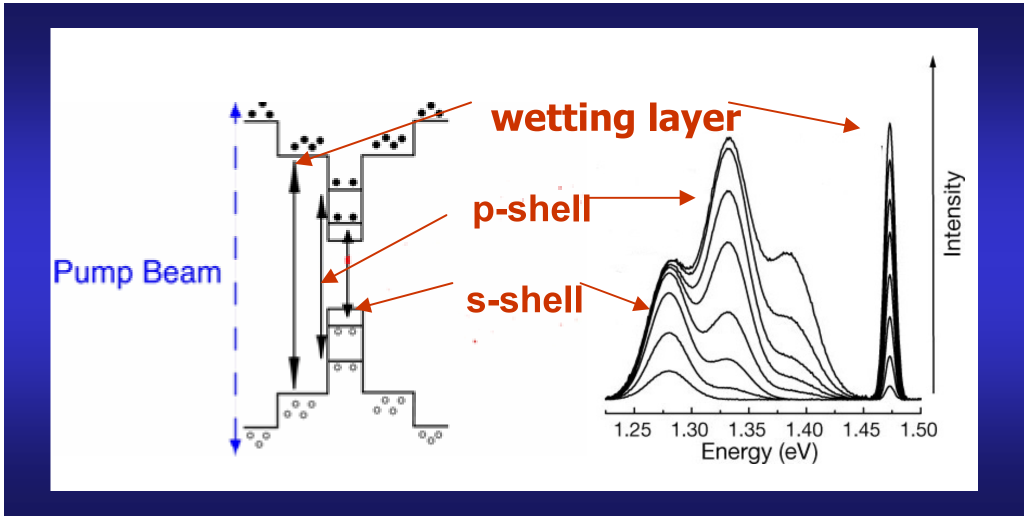
- high quality, optically efficient quantum dot arrays formed over broad areas
- 20-50 nm diameters: density and size dependent on strain, growth conditions
  ± 10% variation in size



AFM of QDs

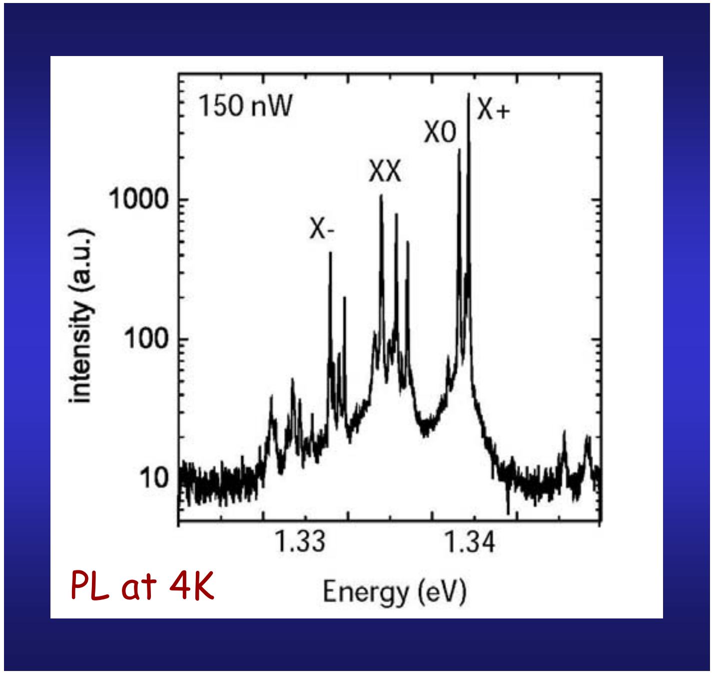
'Direct Formation of quantum-sized dots from uniform coherent islands of InGaAs on GaAs surfaces', D. Leonard, M. Krishnamurthy, C.M. Reeves, S.P. Denbaars, P.M. Petroff, Appl. Phys. Lett. **63** (23), 3203-5

‘atom-like’ optical signatures of QDs



Broad luminescence peaks reflect distribution of QD size

Narrow linewidths (~ few μeV) for single QDs
Discrete excitonic transitions observed



PL at 4K

‘high optical efficiency emitters, narrow linewidths’

Limitations to electron mobility in a metal

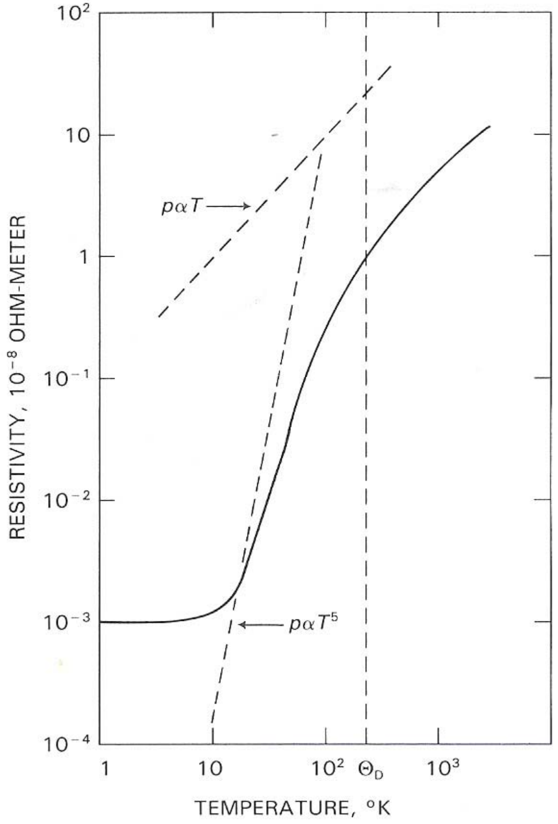


FIG. 9.2 Typical temperature dependence of electrical resistivity for silver with a Debye temperature of 226°K.

Elastic (high T) and inelastic (low T) lattice scattering
Resistivity decreases at very low temperatures

From *Electrons in Solids*
R.H. Bube

Limitations to Electron Mobility in (doped) Semiconductors

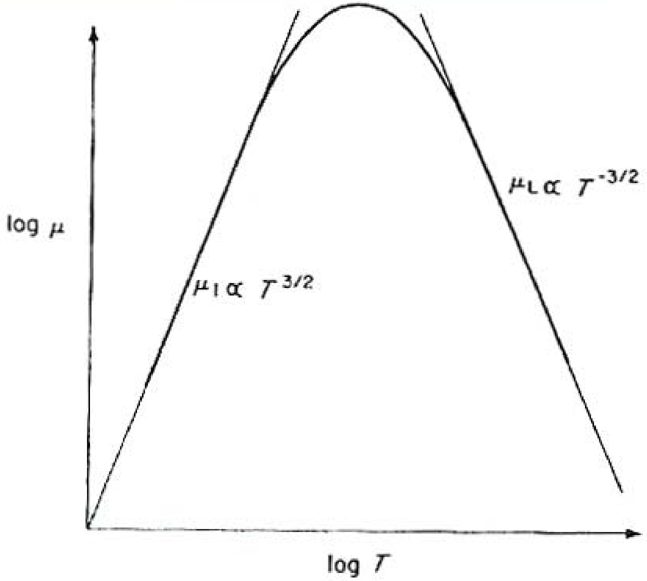
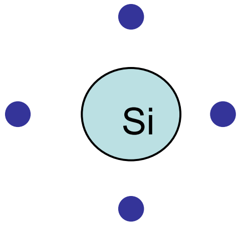


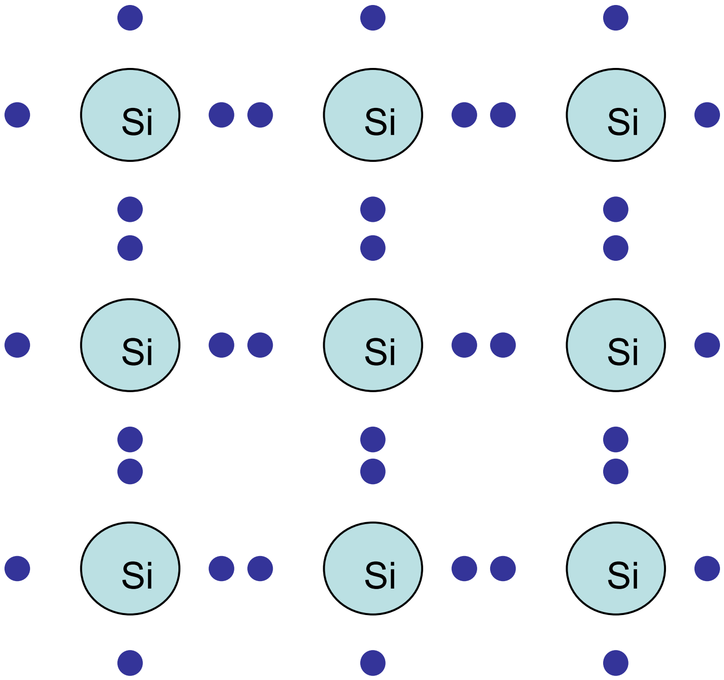
FIG. 9.5 Temperature dependence of mobility in a semiconductor with scattering by both acoustic lattice waves and by charged imperfections, resulting in a maximum mobility at a particular temperature.

Note that mobility DECREASES
(resistivity increases) at lowest T

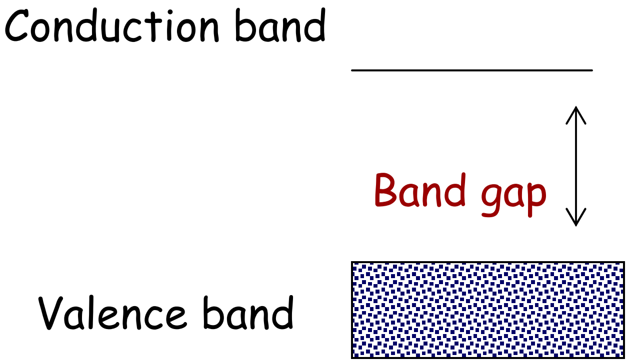
From *Electrons in Solids,* R.H. Bube

Silicon atom with 4 bonding electrons





Silicon single crystal:
2 electrons in every bond

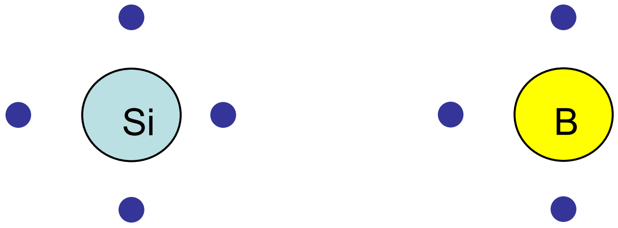


Conduction band

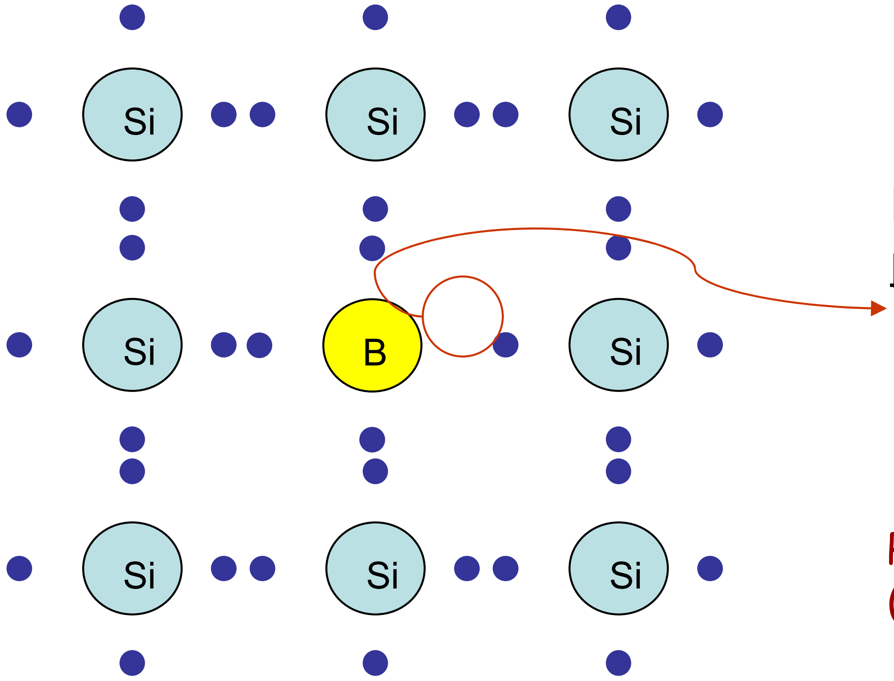
Band gap

Valence band

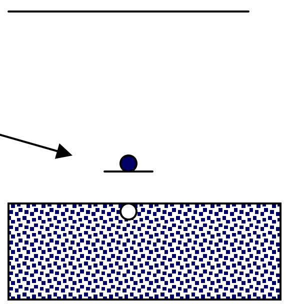
P-type Silicon



Add Boron, with 3 bonding electrons



Missing electron = hole
positively charged



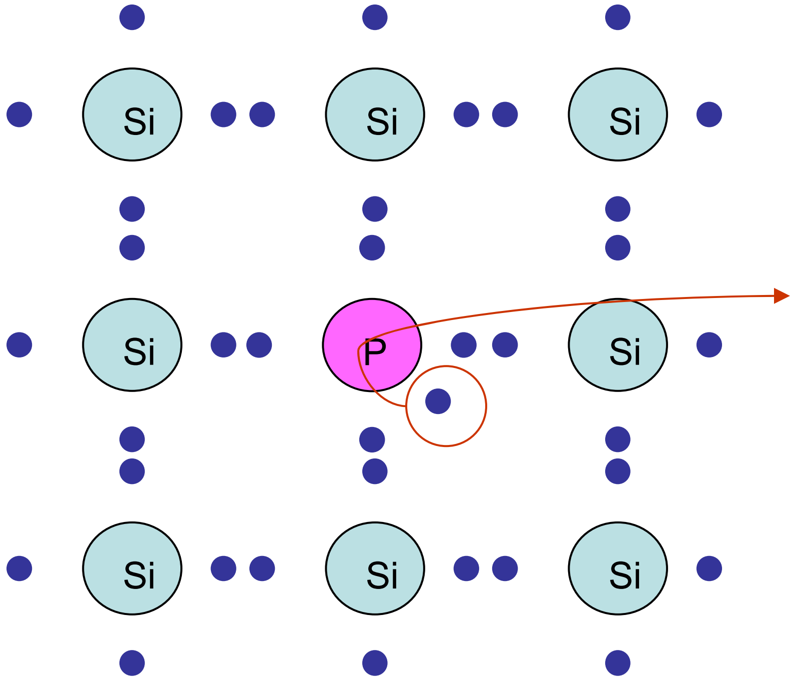
Conduction band

P-type impurity
(acceptor)

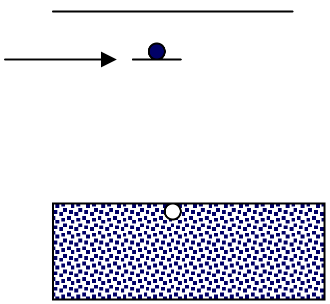
Valence band

N-type Silicon

Add Phosphorus with 5 bonding electrons



Extra electron negatively charged



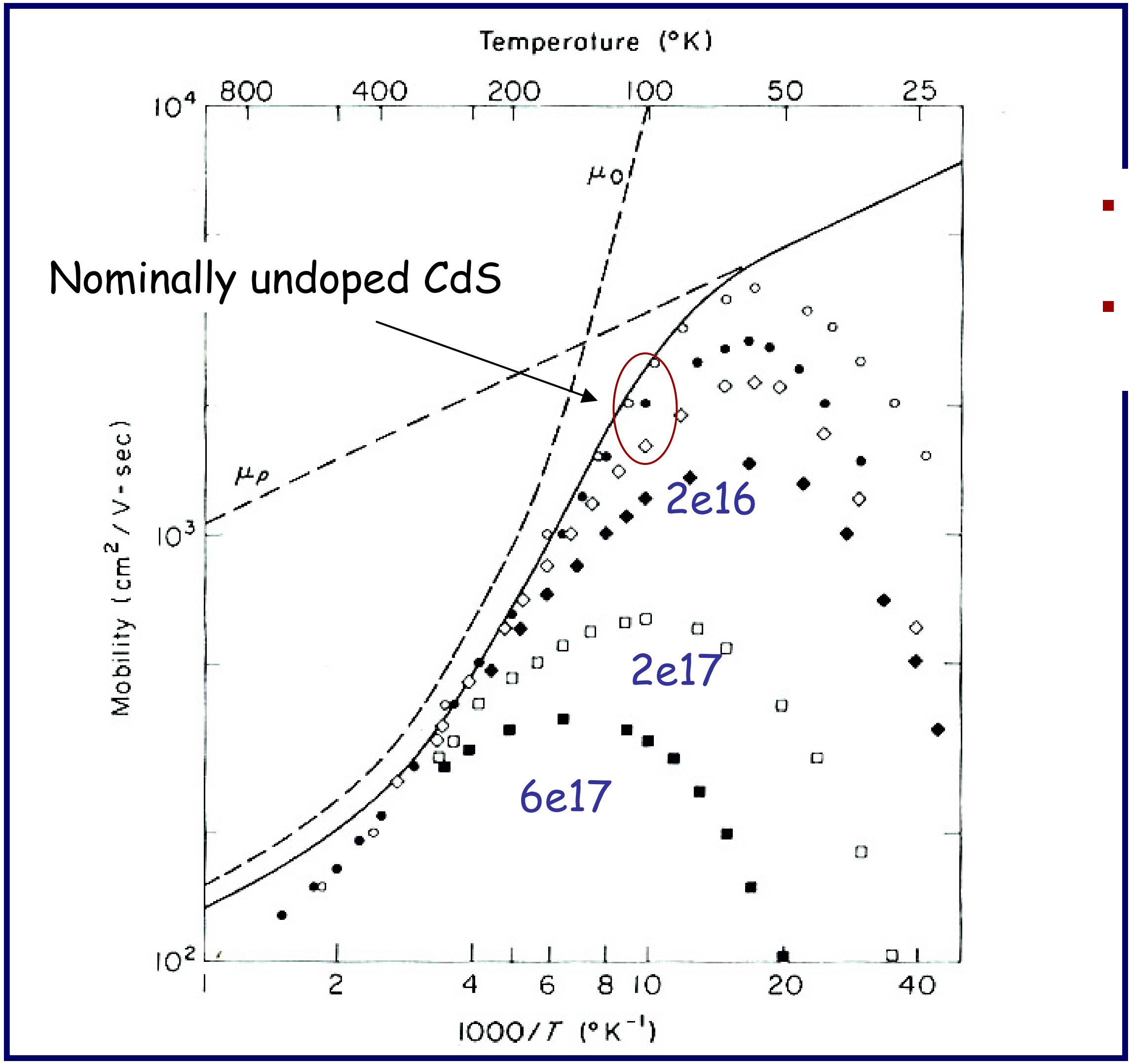
Conduction band

n-type impurity (donor)

Valence band

Dopants provide mobile carriers, but leave ionized cores

Limitations to Electron Mobility in Semiconductors



Nominally undoped CdS

2e16

2e17

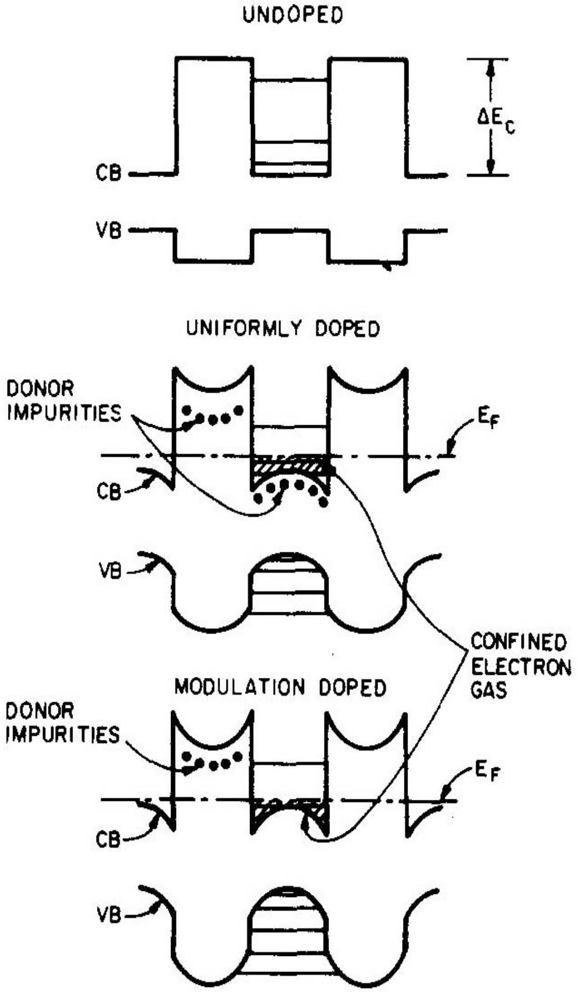
6e17

- Low mobility at low temperatures
- Dependence on dopants in the material

From *Electrons in Solids,* R.H. Bube

Piper & Halstead, Proc. Int. Conf. Semic. Physics, 1960

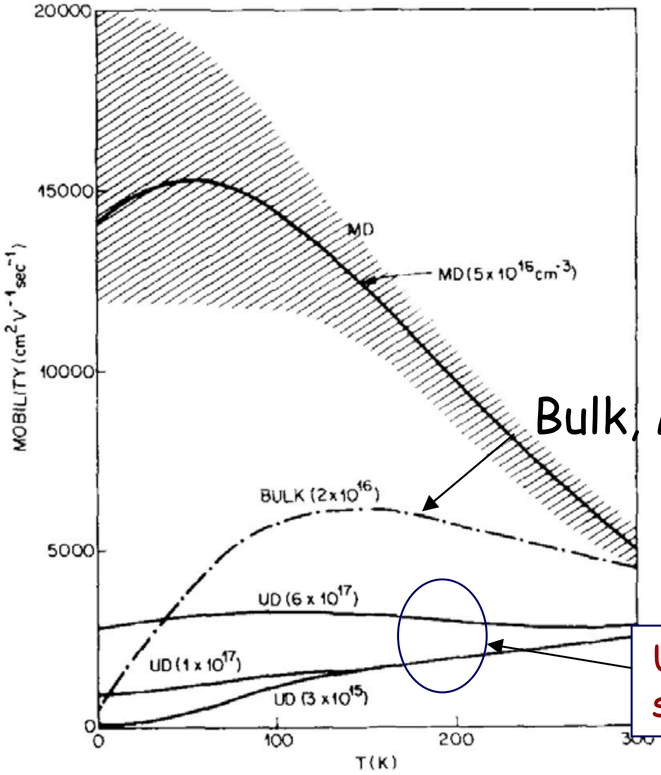
Modulation Doped Semiconductors: achieving miraculous electron mobilities



Electron mobilities in modulation-doped semiconductor heterojunction superlattices

R. Dingle, H. L. Störmer,[a] A. C. Gossard, and W. Wiegmann

Bell Laboratories, Murray Hill, New Jersey 07974
(Received 19 June 1978; accepted for publication 27 July 1978)



Bulk, MBE GaAs

Uniformly-doped superlattices

FIG. 3. Electron mobility versus temperature for bulk GaAs GaAs and several UD and MD superlattices. The crosshatched region includes most of the MD data.

Increases in electron mobility

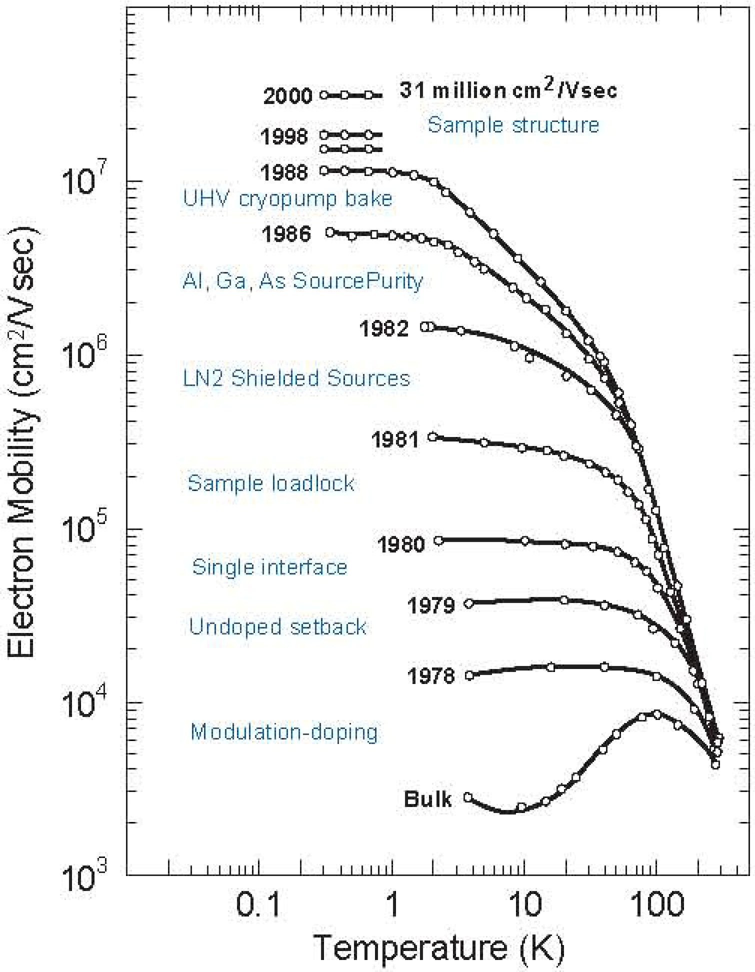


Fig. 1. History of improvements in the mobility of electrons in GaAs, annotated with the technical innovation responsible for the improvement.

Pfeiffer et al., Physica E**20**, 57 (2003)