Lecture 7 - Epitaxy Techniques and Considerations - Outline

- **Lattice-matching considerations**

  Natural lattice-matching
  1. Review of lattice-matched material systems (Lect. 1 discussion)
  2. Lattice pulling

  Forced lattice matching
  1. Pseudomorphic layers
  2. Mattews-Blakeslee limit, other models
  3. Examples - devices using pseudomorphic layers

  Mismatched epitaxy
  1. Step-grading
  2. Linear grading
  3. Examples - devices using graded heterostructures

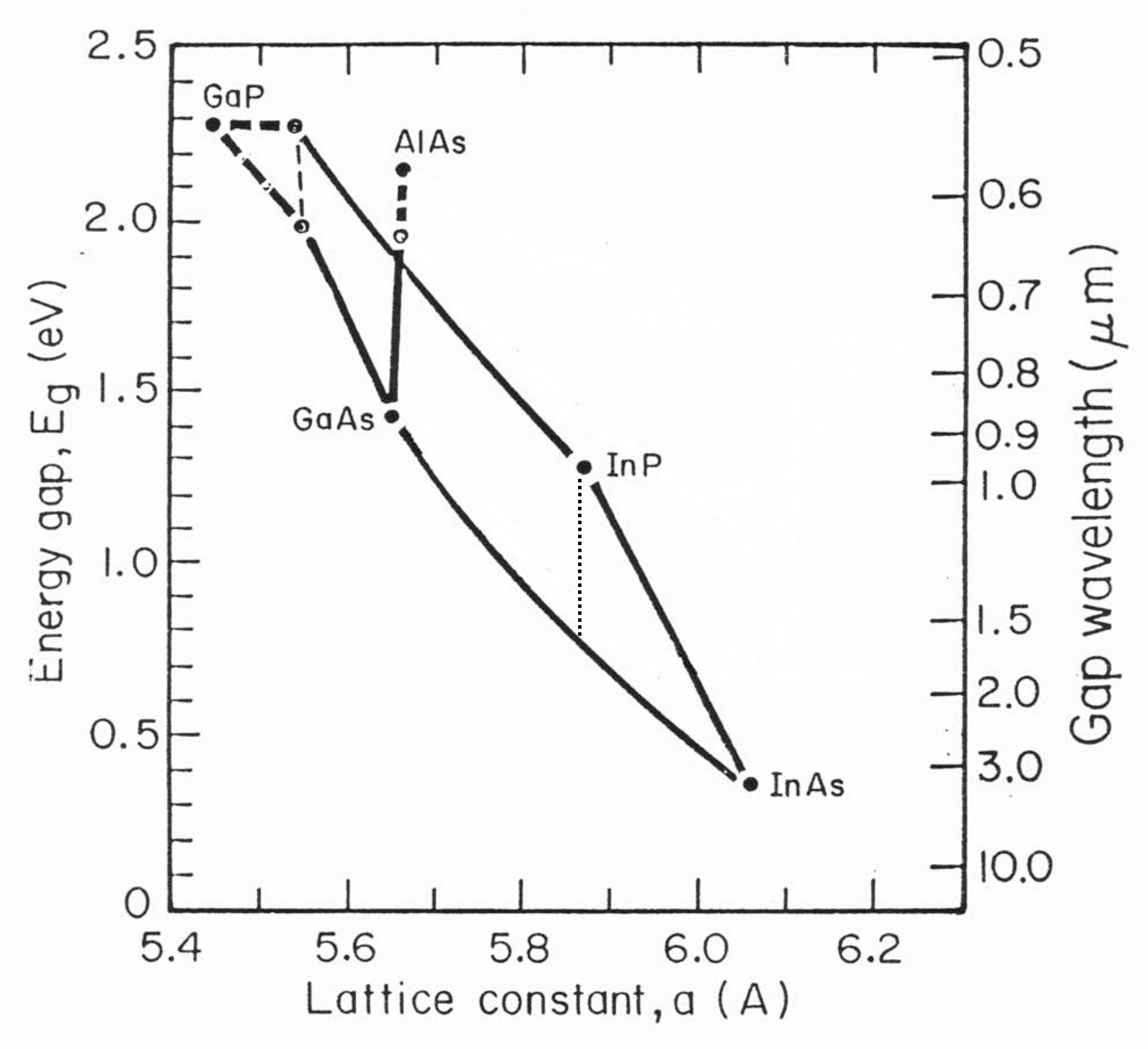
- **Epitaxy techniques - overview** (survey of commonly used techniques)

  Liquid phase epitaxy

  Gas phase epitaxy
  1. Vapor phase epitaxy; 2. Metallorganic chemical vapor deposition

  Molecular beam epitaxy
  1. Solid source; 2. Gas source; 3. Metalloganic; 4. Chemical beam

III-V systems: InGaAsP and AlGaAs



Insert 1 - Strained layers

Strained layers

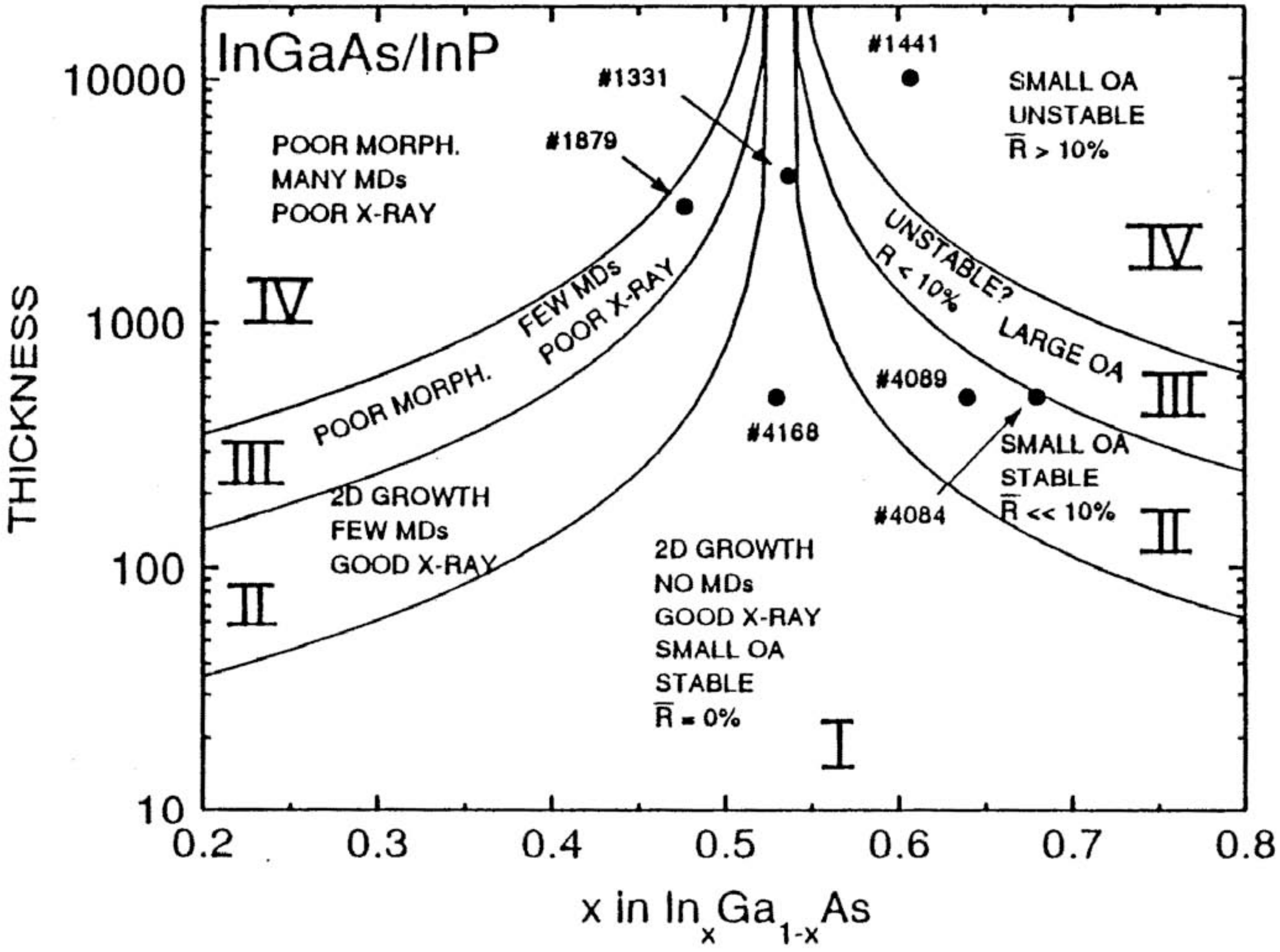
1. accommodating mismatch
2. dislocation generation
3. models
4. parameter values
5. effects of strain

Impact of strain and QW quantization on bands

15 nm wide wells
GaAs/$In_{0.06}Ga_{0.57}Al_{0.37}As$

Critical layer thicknesses - a final comment

Courtesy of Jesus Del Alamo, Professor in Electical Engineering and Jagdeep Bahl, PhD candidate; Used with Permission.

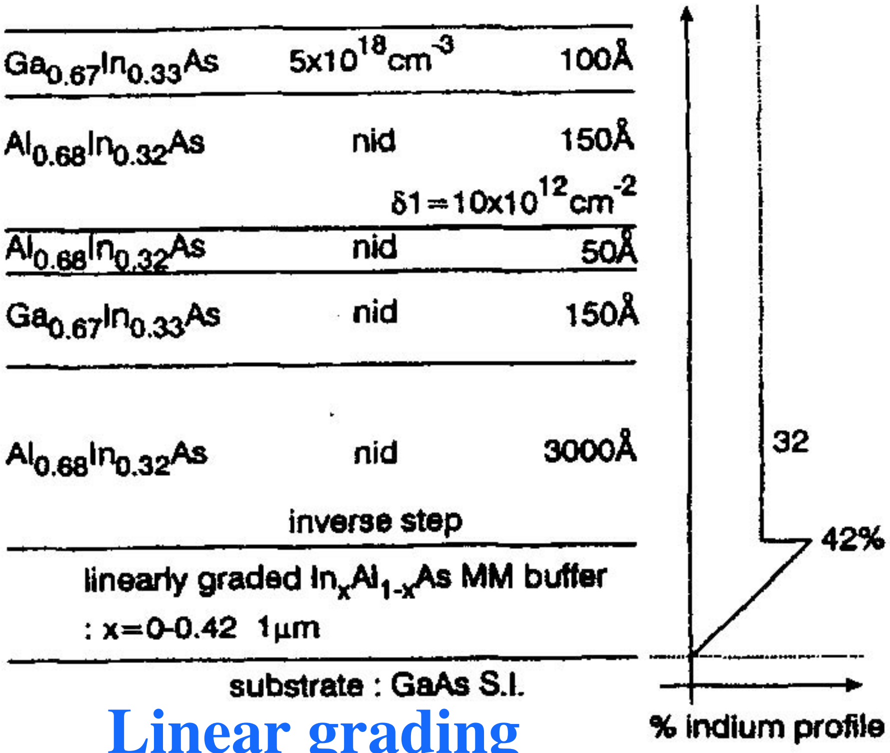


The critical thickness depends on the need -

work of Professor Jesus del Alamo and Jagdeep Bahl, MIT

Mismatched epitaxy - letting layers relax

Graded lattice constant structures



Linear grading

n^+	$In_{0.30}Ga_{0.70}As$	13 nm	$5x10^{18}$
i	$In_{0.29}Al_{0.71}As$	20 nm	
n^+	$In_{0.29}Al_{0.71}As$	30 nm	$2x10^{18}$
i	$In_{0.29}Al_{0.71}As$	4 nm	
i	$In_{0.30}Ga_{0.70}As$	40 nm	
i	$In_{0.29}Al_{0.71}As$	0.4 µm	
i	$In_{0.20}Al_{0.80}As$	0.2 µm	
i	$In_{0.10}Al_{0.90}As$	0.2 µm	
i	GaAs		

Step grading

- There is no general agreement on which approach is superior and the choice often one of convenience and/or practicality.
- Because the last layer is often not fully relaxed, it is common to grade to a certain level and then step back, as seen in the structure on the left.

Epitaxy techniques - the spectrum of options

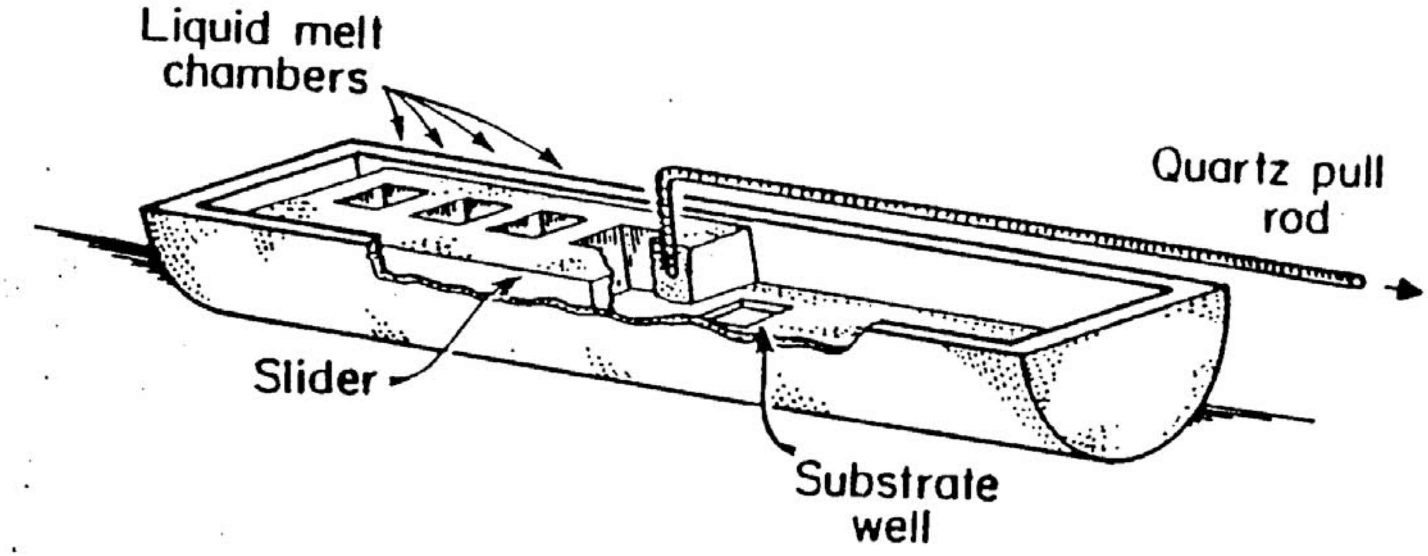
Liquid Phase Epitaxy

Vapor phase techniques (hydrodynamic flow)
- Hydride transport
- Chlorine transport
- Metallo-organic CVD

Molecular beam epitaxy (ballistic flow)
- solid source
- gas source
- chemical beam
- organo-metallic source

Liquid Phase Epitaxy - LPE

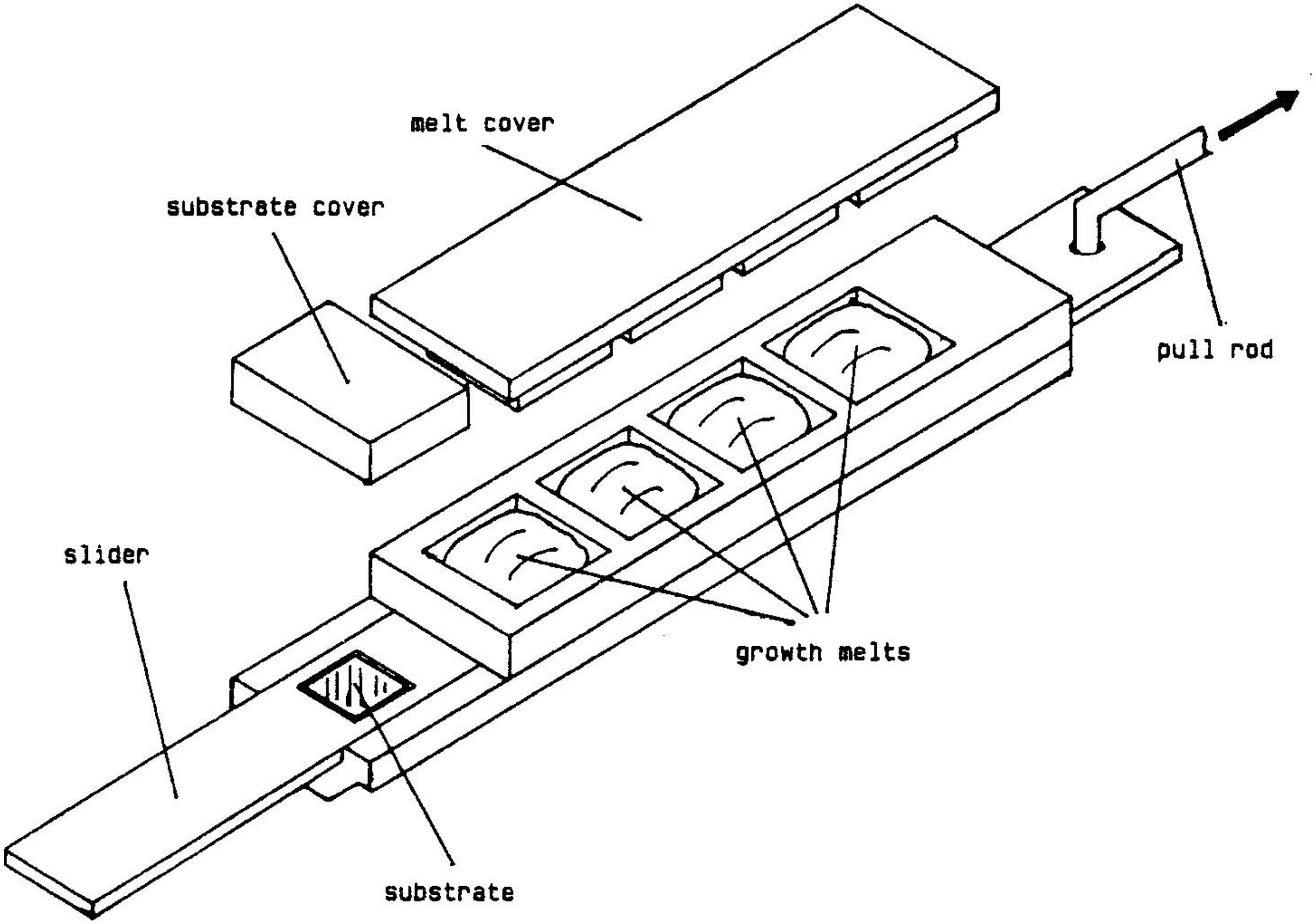
Growth from a Ga or In solution in a hydrogen ambient



Advantages:	Near-equilibrium growth, excellent crystal quality Inexpensive; Fast
Disadvantages:	Difficult to scale up for production Dimensional control poor Structure complexity limited
Current status:	Widely used for LEDs and laser diodes in well established processes. Rarely used in new installations.

Liquid Phase Epitaxy -

Explode vie

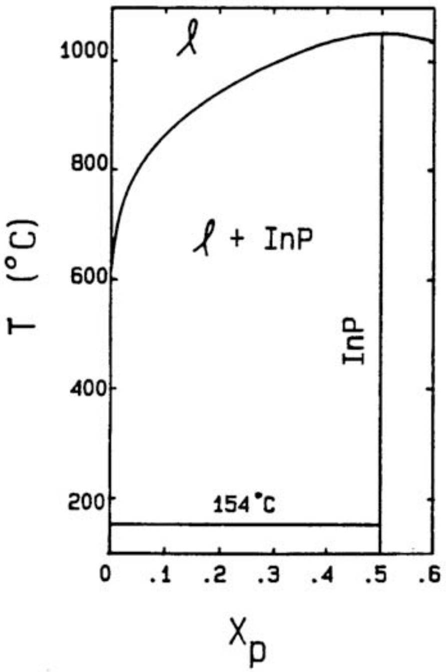


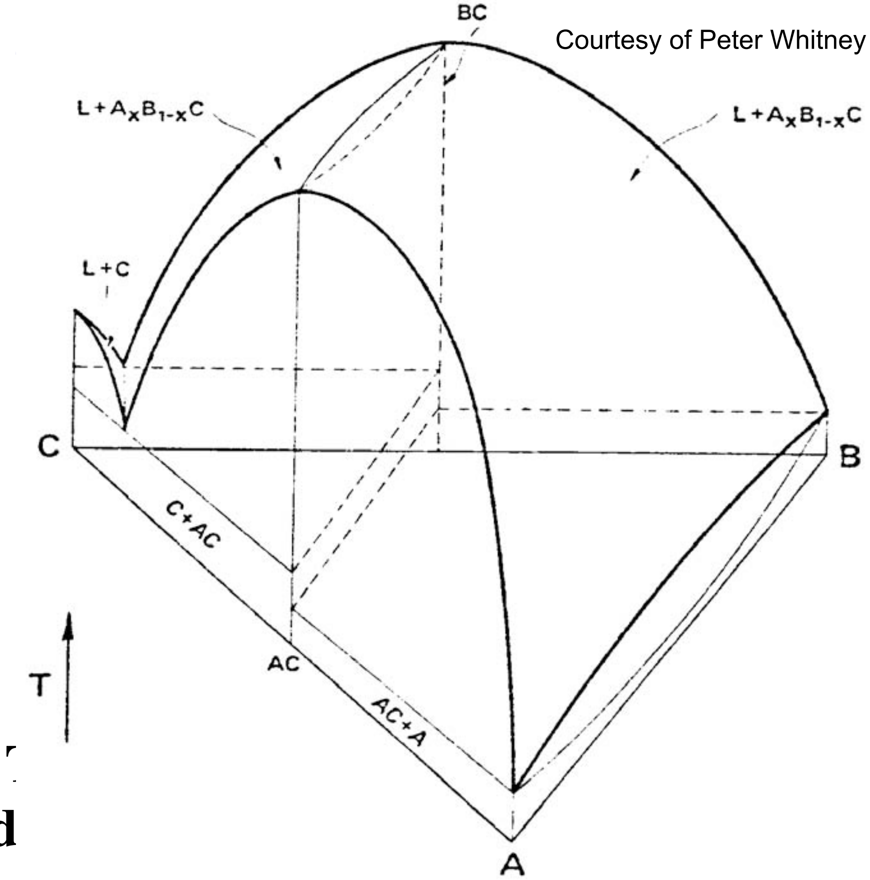
Material: Machined pyrolytic graphite

Growth ambient: Purified hydrogen at atmospheric pressure
Within a quartz tube in a resistance heated furnace

Liquid Phase Epitaxy - Melt

Courtesy of Peter Whitney PhD.





Courtesy of Peter Whitney PhD.

Binary phase diagram, In-P **d**

As T is reduced the binary (or ternary) solidifies from the melt:

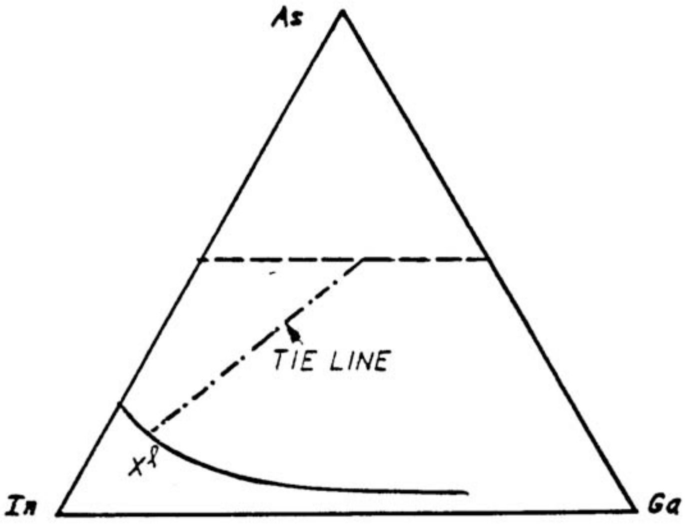
- In the case of the binary shown on the left the liquid is $In_{1-x}P_x$, and the solid is InP.
- In the case of the ternary shown on the right, the situation is more complicated. The liquid is $A_yB_zC_{1-y-z}$ and the solid is $A_xB_{1-x}C$, but the relationship between the liquid composition and x is not shown in the diagram. (cont. next foil)

Ref: P. Whitney, Ph.D. Thesis, DMSE, MIT, 1986

Images courtesy P. Whitney. Used with permission.

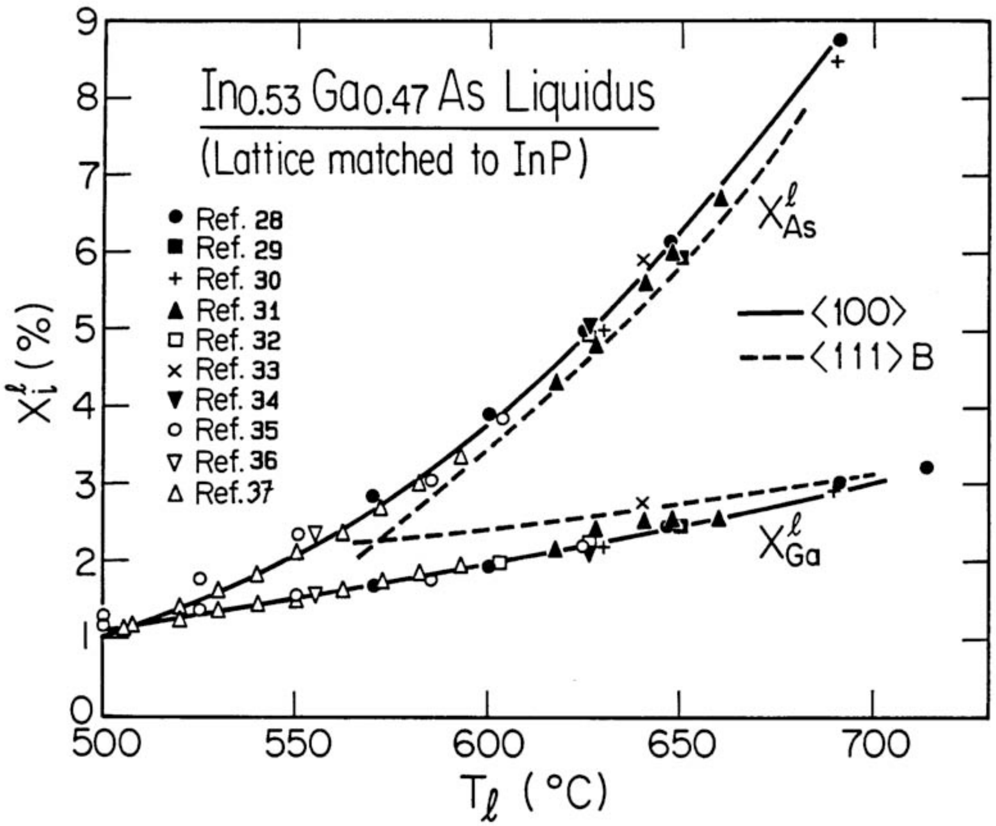
Liquid Phase Epitaxy -
Melt calculation, cont.

Courtesy of Peter Whitney PhD.



Projected isotherm and tie line for In-Ga-As system

Courtesy of Peter Whitney PhD.



Equilibrium liquidus for InGaAs lattice-matched to InP

The relationship between the ternary liquid composition and the ternary solid composition is displayed by a tie line between a projected isotherm and ternary solid line, as shown on the left,

Or by a plot of liquid composition verses temperature for a specific solid composition of interest, as shown on the right.

Ref: P. Whitney, Ph.D. Thesis, DMSE, MIT, 1986

Images courtesy P. Whitney. Used with permission.

Chlorine Transport Vapor Phase Epitaxy - VPE

$GaCl_3 + AsH_3 \text{ --> } GaAs + 3HCl$

(Image deleted)

See Enda, H., Japanese Journal of Applied Physics. 18, 2167, (1979).

Advantages: Conceptually simple

Disadvantages: Messy
Difficult to control group III supply
Uses toxic gases (AsH_3, PH_3)

Current status: Used for some GaAs epitaxy where high purity (low background doping) needed but largely superceded by MOCVD

Metallorganic Chemical Vapor Deposition - MOCVD

Group III elements transported
as a metallorganic compound
on a carrier gas: i.e.
$Ga(CH_3)_3 + AsH_3$ -->
$GaAs + 3CH_4$

<u>Advantages:</u>	All sources gaseous Precise composition and dimension control
<u>Disadvantages:</u>	Involves complex chemistry Uses toxic gases (AsH_3, PH_3)
<u>Current status:</u>	Viewed as the standard production process for many epitaxial heterostructures

Metallorganic Chemical Vapor Deposition - MOCVD

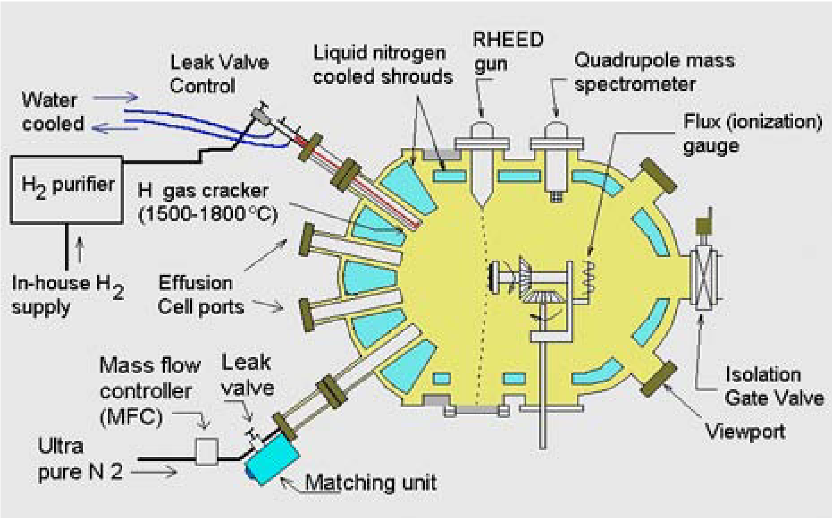
A group III precursor bubbler:

Operation:

- Bubbler held in constant-temperature bath
- Hydrogen "carrier" saturated with precursor (group III organo-metallic) at fixed T
- Precursor transported through heated lines as a "gas"
- Flow controlled by mass flow meters

Molecular Beam Epitaxy -
MBE

Slow vacuum deposition
on a heated substrate
under ultra-high vacuum
conditions; growth a
layer at a time



Courtesy of Professor Yoon Soon Fatt, NTU.

Advantages:	Extremely flexible, simple chemistry Insitu monitoring; Atomic layer control Non-equilibrium technique
Disadvantages:	No in situ cleaning or purifying reactions Expensive (to assemble and operate) Non-equilibrium technique
Current status:	A research workhorse; increasingly used heavily in production

Insert 2 - Comparison of techniques

Comparison of epitaxy techniques

1. Table of techniques
2. Timeline of techniques
3. The spectrum from VPE to MBE
4. Deviation for equilibrium
5. Further comparison of VBE and MBE

Insert 3 - MOCVD

MOCVD

1. Precursors
2. MOCVD reactor
3. Flow concerns in MOCVD reactor
4. More flow issues
5. MOCVD surface reactions
6. Optical reflection oscillations used in MOCVD