Strain Balancing

By: Omkar Jani

Overview:

- **Introduction to Strain**
- **Heteroepitaxy and Lattice Mismatch**
- **Concept of Critical Thickness**
- **Multi-layer Strain Balancing**
- **Examples and Applications**

What is Strain?

- <u>Physical Definition</u> = $\dfrac{\text{Change in Dimension}}{\text{Original Dimension}}$

- **<u>Definition</u>: Measure of the extent to which a body is deformed when subjected to stress.**

- **<u>Examples</u>: Linear Strain, Bulk Strain, Shear Strain.**

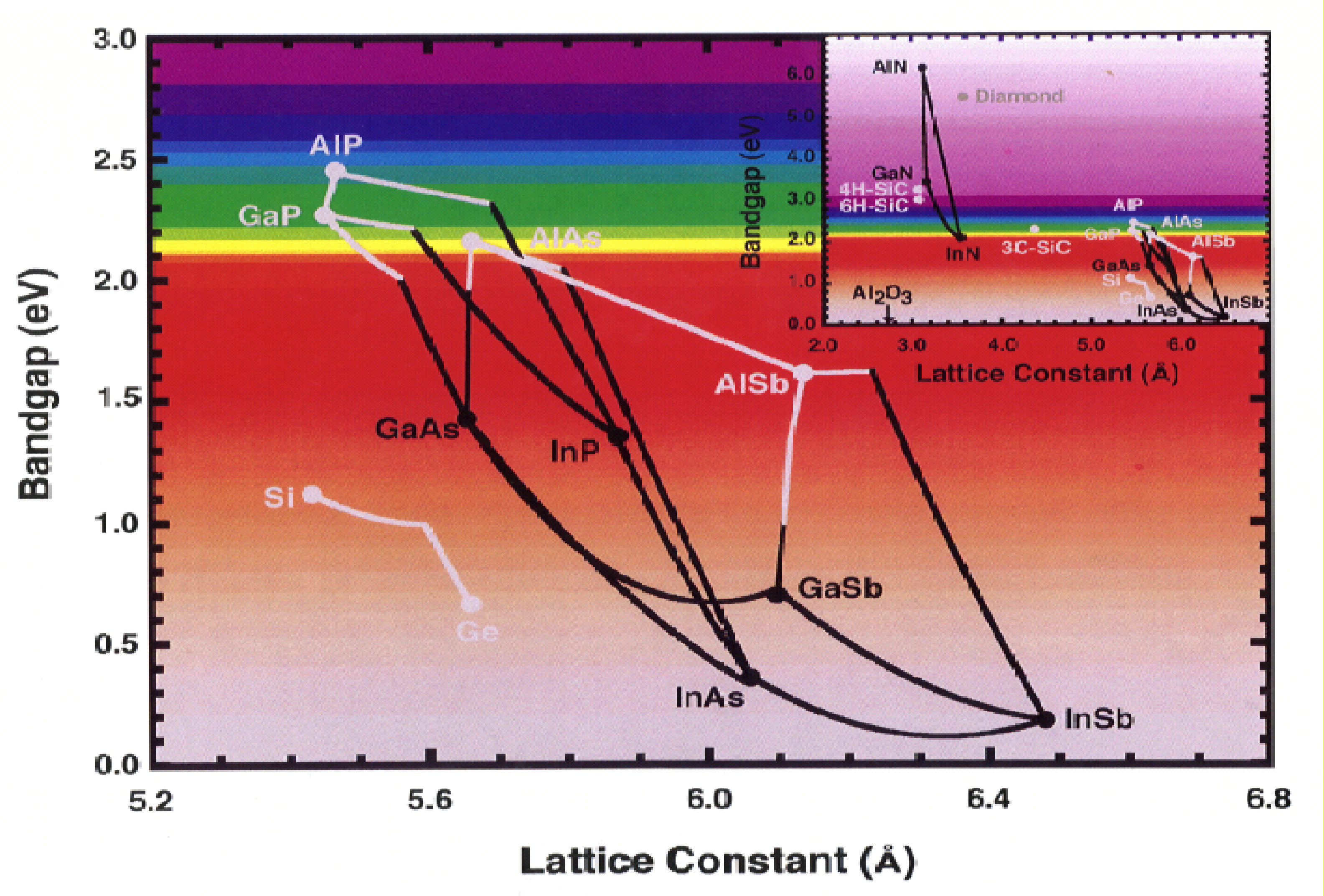
Why Strain Balancing?

- <u>Heteroepitaxy</u>: Growth of epitaxial layer of one layer on top of a different substrate

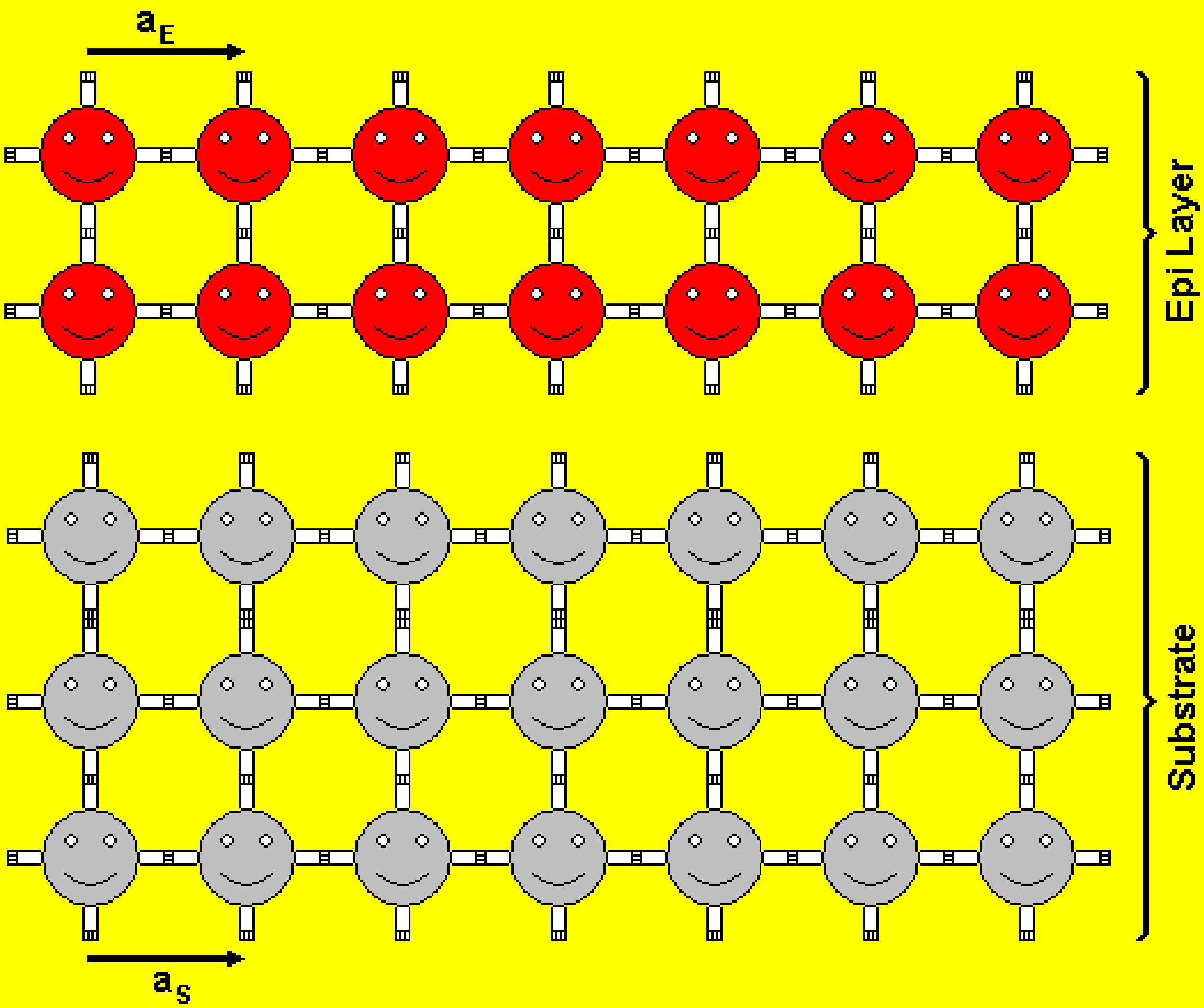
- Note that different materials have different Lattice Constants

- <u>3 Cases in Heteroepitaxial Growth</u>:
  a. Commensurate (Lattice Matched case)
  b. Pseudomorphic (Strained case)
  c. Incommensurate Strain Relaxed

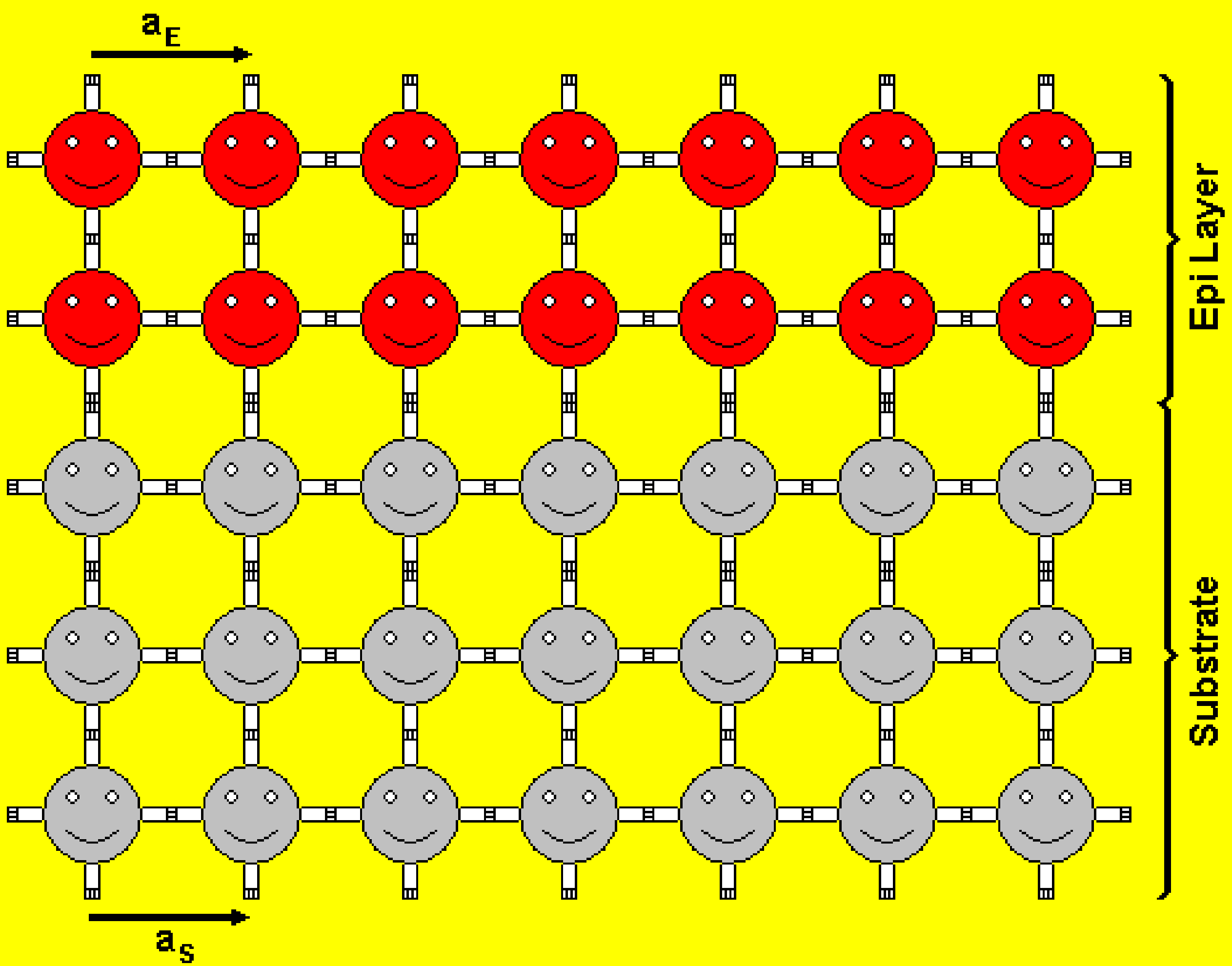
Bandgap Vs. Lattice Constant



a. Commensurate Structure



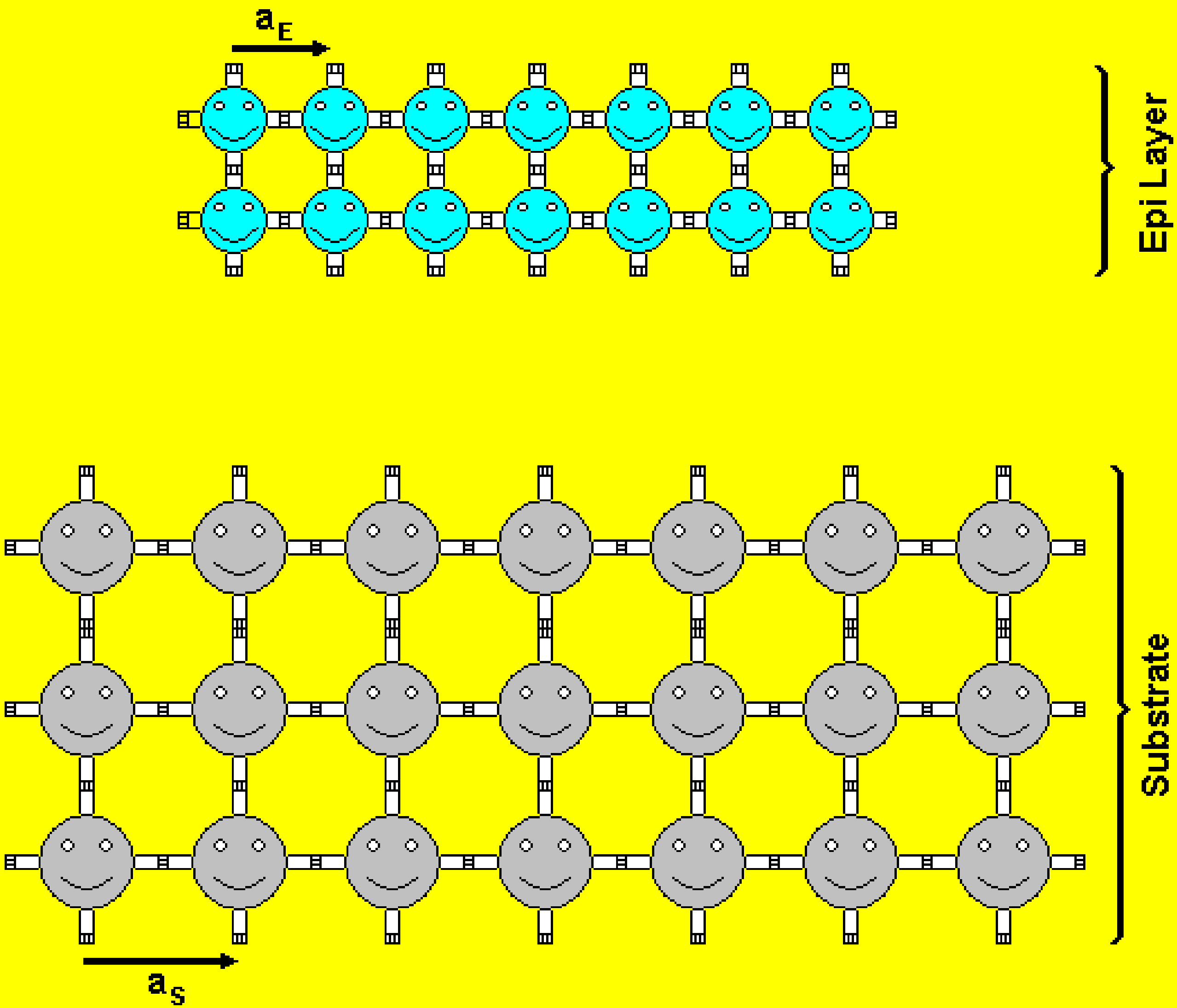
a. Commensurate Structure



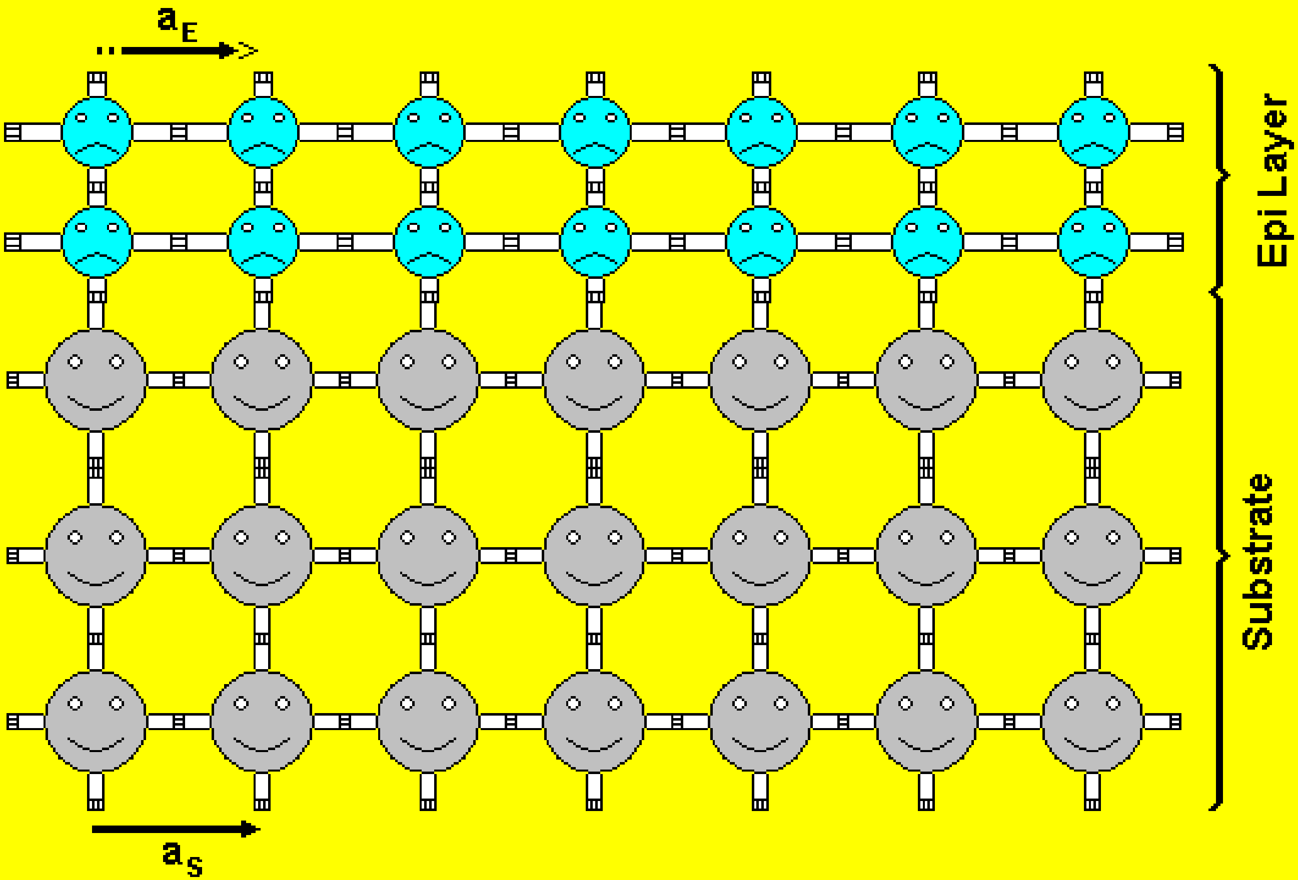
Observation:

- If the lattice constants of two materials are same, then they are known as ‘Lattice Matched’ materials
- There is a regular transition in atomic arrangement from one material to another
- No defects occur at their interface

b. Pseudomorphic Structure



b. Pseudomorphic Structure



Observation:

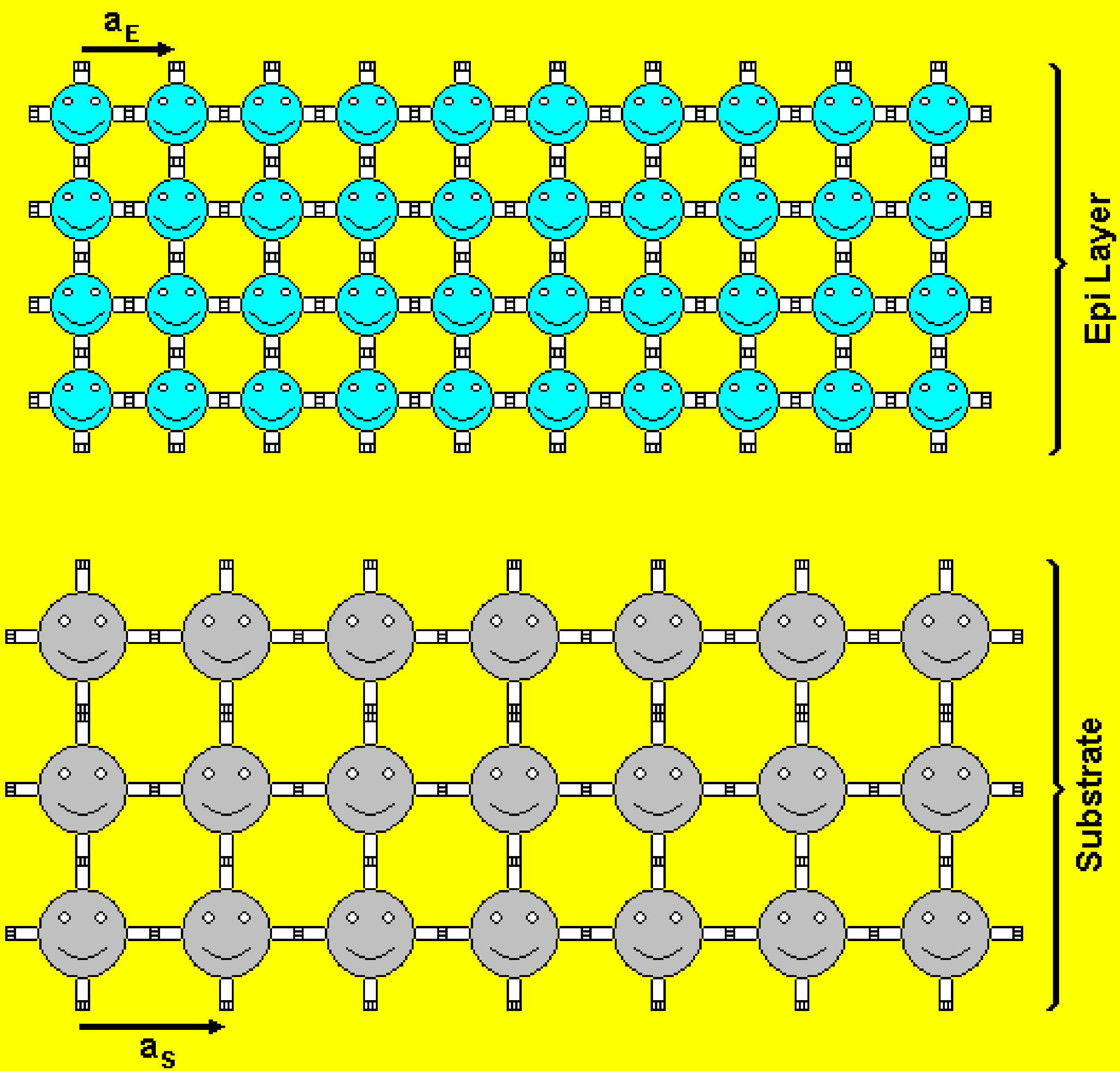
- Pseudomorphic growth occurs when the epi-layer is not lattice matched with the substrate and it is comparatively thin.

- As a result, the epi-layer strains to match the substrate

- Lateral Strain in Epi-Layer : $\boxed{\varepsilon = \dfrac{a_s - a_e}{a_e}}$

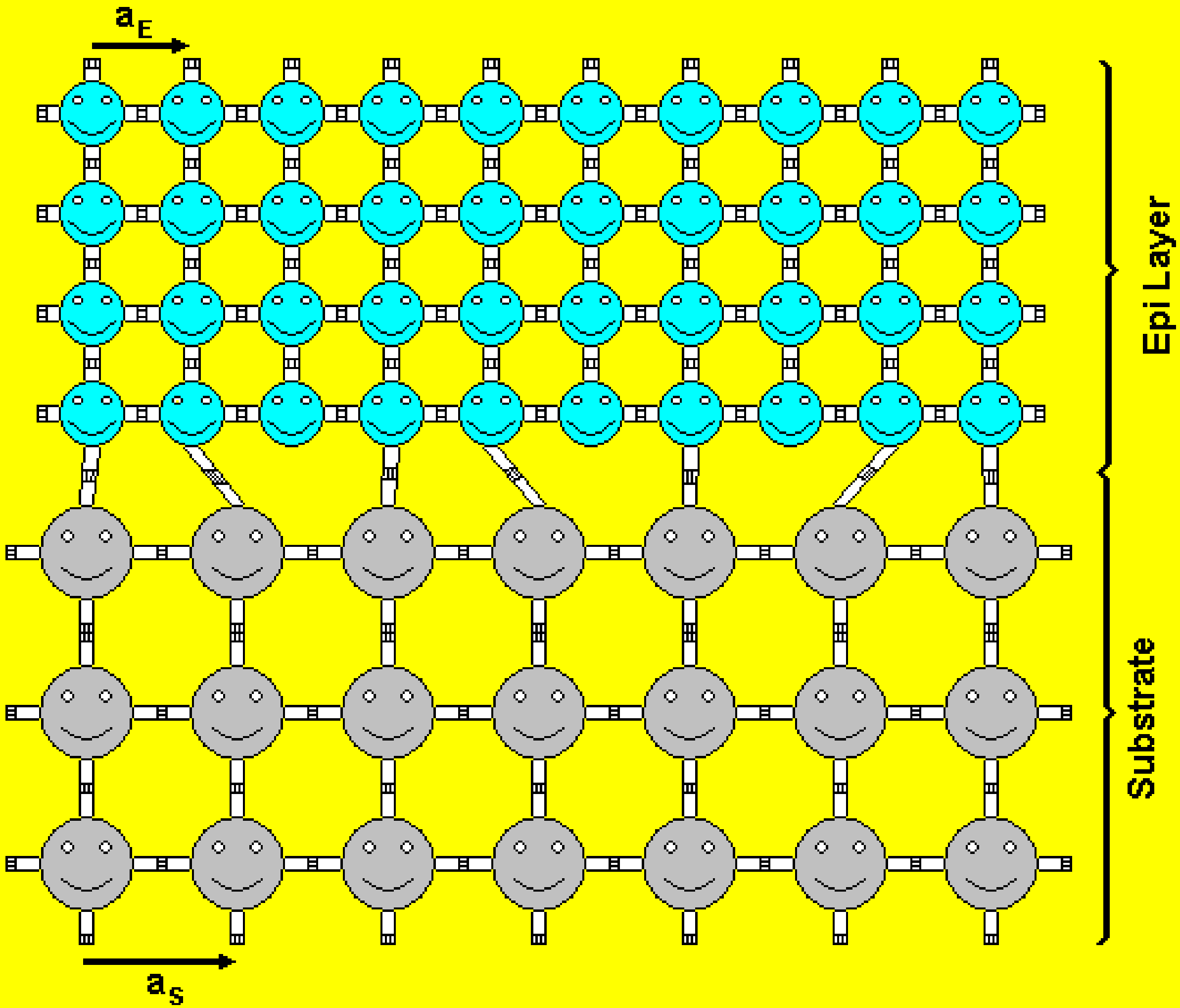
Georgia
Tech

c. Incommensurate Structure



Georgia Tech

c. Incommensurate Structure



Observation:

- Incommensurate growth is the production of thick layers that are not lattice matched to the substrate
- Misfit between two crystals must be accommodated by defects at or near the interface
- These defects may propagate into the epi-layer

Methods to Overcome Lattice Mismatch:

a. Confine epi-layer to Critical Thickness

b. Gradual change in Lattice Constant by depositing more than one layers

c. Multi-Layer Strain Balancing

Critical Thickness:

Force exerted by misfit dislocation:

$$F_{\varepsilon} = \frac{2G(1+\nu)}{(1-\nu)} bh\varepsilon \cdot \cos\lambda$$

- **Tension in dislocation line:**

$$F_{l} = \frac{Gb^2}{4\pi(1-\nu)}(1-\nu \cdot \cos^2 a)\left(\ln\frac{h}{b}+1\right)$$

- **Where:**

Assumption: Elastic constants of both materials are same and isotropic

G = Shear Modulus of each layer (same)

ν = Poisson Ratio

b = Length of Burgers Vector

h = Thickness of each layer (same)

ε = Strain in each layer (same)

λ = Angle between Slip Direction and Film Plane

α = Angle between dislocation line and Burgers Vector

Critical Thickness (Contd.):

- **If $F_\varepsilon < F_\lambda$, then growth is Pseudomorphic and dislocation line in substrate is not translated to epi-layer**

- **If $F_\varepsilon > F_\lambda$, then epi-layer becomes relaxed and translates dislocation lines from the substrate**

- **If $F_\varepsilon = F_\lambda$, then the corresponding thickness is known as 'Critical Thickness'**

Critical Thickness (Contd.):

- **Expression for Critical Thickness:**

$$hc = \frac{b}{2\pi F}\,\frac{(1-\nu\cdot\cos^2\alpha)}{(1+\nu)\,\cos\lambda}\left(\ln\frac{hc}{b}+1\right)$$

- **Where:**

Assumption: Elastic constants of both materials are same and isotropic

h_c= Critical Thickness of each layer (same)

F = Force exerted by misfit dislocation = tension on dislocation line

ν = Poisson Ratio

b = Length of Burgers Vector

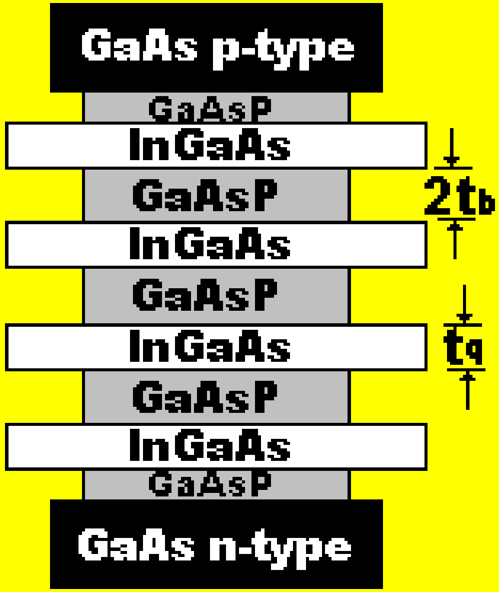
λ = Angle between Slip Direction and Film Plane

α = Angle between dislocation line and Burgers Vector

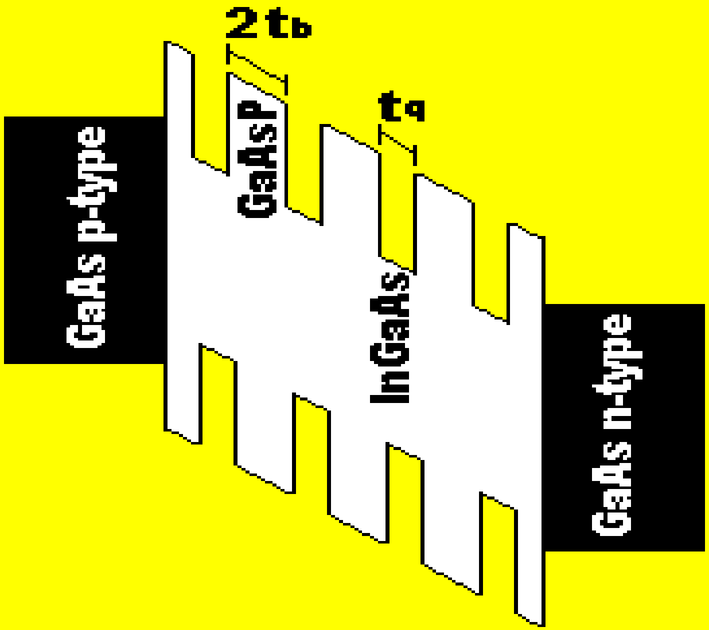
Multi-Layer Strain Balancing:

- **It is possible to grow alternate layers of tensile and compressively strained material**
- **These structures, are locally strained, but over one period, exert no net force on the substrate**
- **Such structures are known as 'Strain Balanced' or 'Strain Compensated' structures**

Example of Strain Balancing:



Strain Balanced
Multi-Quantum Well
P-i-N Diode



Band Diagram of
Strain Balanced
Multi-Quantum Well
P-i-N Diode

Strain Balancing Calculation:

- **Average Lattice Parameter across the Strain Balanced (i) Structure:**

$$\boxed{\langle a \rangle = \frac{2t_b\, a_{GaAsP} + t_q\, a_{InGaAs}}{2t_b + t_q}}$$

- **Average Strain in Substrate:**

$$\boxed{\langle f \rangle = \frac{\langle a \rangle - a_{GaAs}}{a_{GaAs}}}$$

- **Strain Balance Condition is met when:**

$$\boxed{\langle f \rangle = \langle a \rangle}$$

Application of Strain Balanced Structures:

- Recently, Strain Balancing has been applied to Quantum Well Devices like:

a. Lasers

b. (Infrared) Photodetectors

c. Photovoltaic Devices

References:

[1] S.A. Campbell, The Science and Engineering of Microelectronic Fabrication, 2nd Edition, Oxford University Press ,2001, New York, pp. 370.

[2] R. People, J.C.Bean, Calculation of critical layer thickness versus lattice mismatch for GeSi/Si strained-layer hetereostructure, Appl. Phys. Lett. 47, 322 (1985)

[3] J.W. Matthews, A.D. Blakeslee, Defects in epitaxial multilayers, J. of Crystal Growth 27, 118 (1974)

[4] N.J. Ekins-Daukes, J. Zhang, D. Buschnell, K.W.J. Barnham, M. Mazzer, J.S. Roberts, Strain-balanced materials for high-efficiency solar cells, Proceedings of the 28th IEEE PV Specialists Conference, IEEE Press, New York, USA,, 1273 (2000)

[5] K.W.J. Barnham, http://www.ess.ph.ic.ac.uk/~q_pv/ingaas.html

Questions?