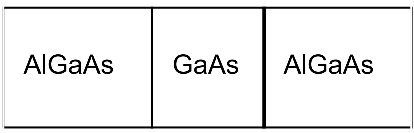
3.46 PHOTONIC MATERIALS AND DEVICES

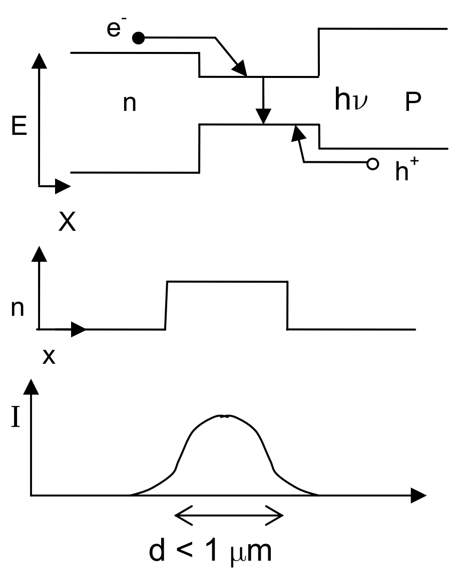
Lecture 15: III-V Processing

Lecture	Notes

Double Hetero structure laser

(band structure engineering)





1. Large refractive index active region
2. Low E_g active region

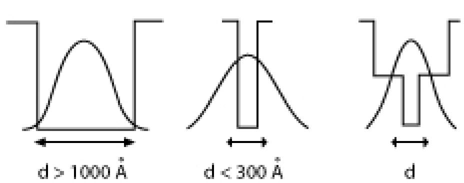
light (guided) confinement
carrier (electron and hole) confinement

η_i is increased

- faster inversion for same injection current
- light concentrated for stimulated emission

$100\times \downarrow$ of J_{th}

Confinement Γ

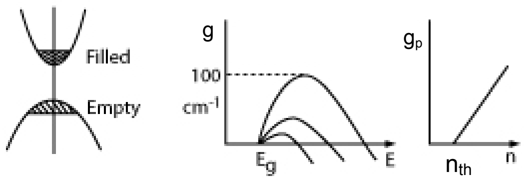


DH	SQW	SCH
$\Gamma = 1$	$\Gamma \propto \Delta nd^2$	$\Gamma \propto \Delta nd$

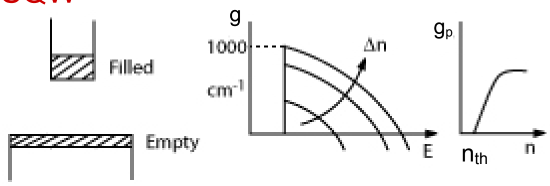
DH: Double Heterostructure
SQW: Single Quantum Well
SCH: Separate Confinement Heterostructure

Lecture

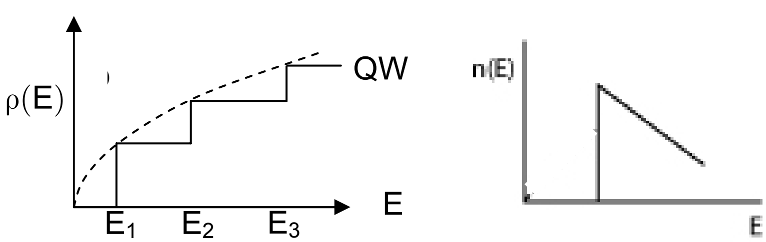
DH



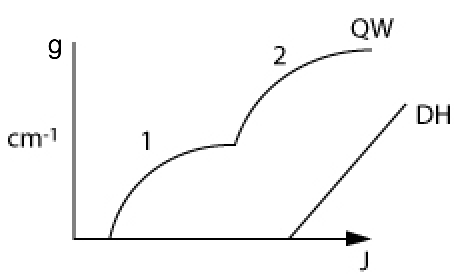
SQW



Density of States of QW



$$g_P = \frac{\lambda^2 m_r}{2\tau_r hd} @ \text{ threshhold}$$



Threshhold current density

$$J_{th} = e\underbrace{R_{th}}_{\;}$$

$$\downarrow \rightarrow C_R np$$

$$10^{-10}\,cm^3 s^{-1} \cdot (2\times 10^{18}\,cm^{-3})^2 = 4\times 10^{26}\,cm^{-3}s^{-1}$$

$$= 1.6\times 10^{-19}\cdot R_{th}$$

$$J_{th} \approx 6.4 \text{ kA } \underbrace{cm^{-2}}_{l\times w}\cdot \underbrace{\mu m}_{d}$$

Notes

$n_{th} \downarrow$ as $d \downarrow$

$g(\nu) \propto f_g(\nu)\cdot \rho_{bulk}(\nu)$

g_p :peak gain

higher T stability

$g(\nu) \propto f_g(\nu)\cdot \rho_{QW}(\nu)$

$$\rho(\nu) = 10^{12}\,\text{states}/cm^2 \text{ for } dE = kT$$

$$= \frac{2m_r}{\hbar d}$$

multilevel gain

R_{th} = threshold recombination rate

J_{th} decreases with d

Lecture

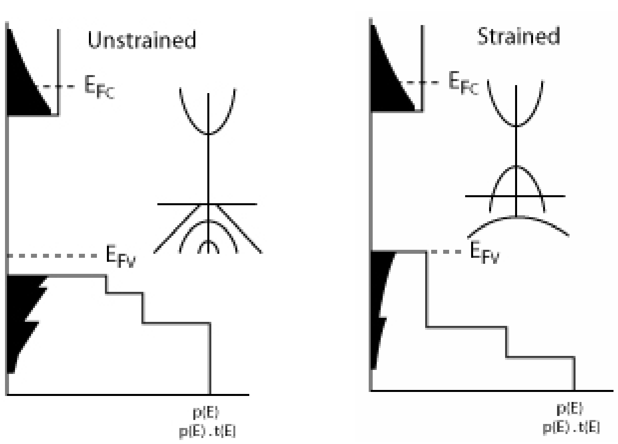
DH: $\boxed{\begin{array}{l} d \simeq 0.2\ \mu m \\ J_{th} = 1.2\ kA/cm^2 \\ I_{th} \simeq 10 - 20\ mA \end{array}}$

SQW: $\boxed{\begin{array}{l} d < 300\ Å \\ J_{th} < 180\ A/cm^2 \end{array}}$

SQW
1. E levels quantized → lasing @ QW transitions
2. $\rho(\nu)(2D)$ more efficient, $g_P = const(\nu)$
3. g saturates
4. QW $\simeq 10^{12}$ states/cm^2
   DH $\simeq 10^{13}$ states/cm^2 in $d = 1000Å$
5. Confinement optimized by separation SCH

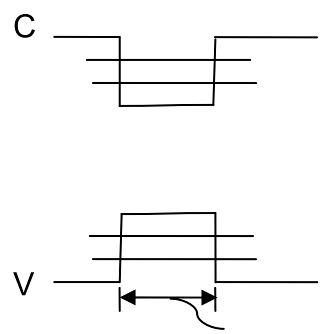
Strained Layers

Strain (compressive)
- raises the LH sub band
- reduces carriers to invert $\Rightarrow J_{th} \downarrow$
  $\Rightarrow \eta_d \uparrow$



(a)

Notes



d<300Å

with band filling, transition not @ g_p are useless

Lecture

Notes

III-V Compound Semiconductor Processing

1. Substrate Preparation
   GaAs, InP
2. Epitaxial layer growth
   LPE, MBE, MOCVD, CVD
3. Etch
   Dry (RIE), wet
4. Contacts
   Au, silicides, metals

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1. Process Constraints
   A. CSBH laser provides (CSBH: Channeled-Substrate Buried Heterostructure) lateral optical and electrical confinement.
      i. grow InP:Fe SI layer
      ii. etch channel
      iii. grow InP/InGaAsP/InP DH in channel
   B. APD detector (SAM)
      i. grow InGaAs/InP het.
      ii. SiNx dielectric deposition
      iii. etch contact window
      iv. diffuse p+ contact/junction
      v. implant p- guard ring

Both devices employ deposited dielectrics for AR coatings (APD) and facet reflectors (laser).

2. Issues
   A. Groups V volatility
      i. incongruent vaporization of P from InP @ T > 360°C
      ii. as from GaAs @ T > 600°C

   Solution: group V overpressure or stable dielectric cap layer.

      iii. RIE creates group III rich suffice

   Solution: lower T, lower E, high Z (Z: atomic number)

Lecture

Notes

B. Preferential etch of V groove
Solution: surface prep.

C. Metallization reactions
Solution: barriers or stable phases

D. Degradation of η_i
Solution: defect control, life testing

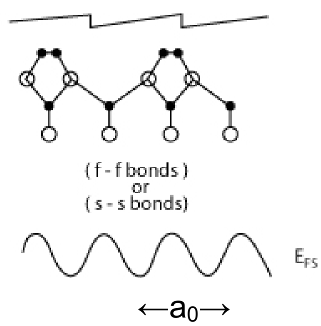
3. Epitaxial Growth

A. Dislocation density
B. Stoichiometry

Concept: Single crystal film bonded to a single crystal substrate with a common interface and the lattice of the film having a definite orientation w.r.t. the substrate lattice.

Substrate: semi infinite thickness

Surface: atomically flat
(ledges)
(bond reconstruction)



Si(100) 2 × 1
or
GaAs(100)
→ rows of AS
V-termination
→ flat surface

Film: homogeneous, 2D (x, y >> t)
(phase separation?)

Interface: sharp (interdiffusion)

Tangential forces: sinusoidal in a_0

Growth Modes

E_{fs} = film/substrate bond strength
E_{ff} = film/film bond strength

$$W = \frac{E_{fs}}{E_{ff}} = \text{relative strength of bonds to substrate}$$

$$\eta = \text{lattice misfit} = \frac{a_s - a_f}{a_f}$$

Lecture

Epitaxy

equilibrium:

- low deposition rate
- high T (surface diffusion)
- minimize $\dfrac{\Delta G \text{ (system energy)}}{N_f \text{ (film atoms)}}$

Coherency (dislocations)

1. 1. variables: a, E_{ff}, h
2. minimize energy

$$E_\epsilon = \underbrace{\epsilon^2}_{\text{strain}}\,\underbrace{B}_{\text{elastic constant}}\,\underbrace{h}_{\text{Film thickness}}$$

Coherent: $\eta = \epsilon$ (strained)
Incoherent: $\eta = \epsilon + \delta$ (relaxed)

separation of parallel misfit dislocations:

$$S = \frac{|\vec{b}|}{\delta}$$

$$\eta \text{ (relaxed)} = \epsilon + \frac{1}{S}|\vec{b}|\cos\underline{\lambda}$$

projection of $\vec{b}$ on plane of interface

Critical h_c

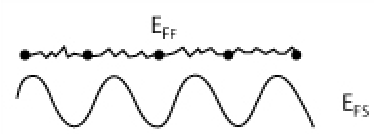
minimize E_ϵ vs. $E_{dislocation}$

Matthews–Blakelee

$$h_c = \frac{b}{8\pi\eta(1+\upsilon)}\left[\ln\left(\frac{h_c}{b}\right)+1\right]$$

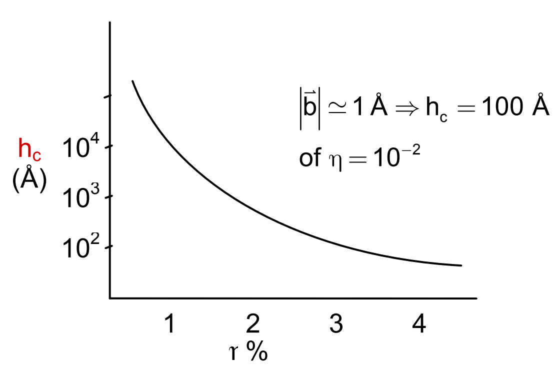
$$h_c \approx \frac{b}{4\eta}$$

Notes



Frank-Vander Merwe 1D harmonic chain

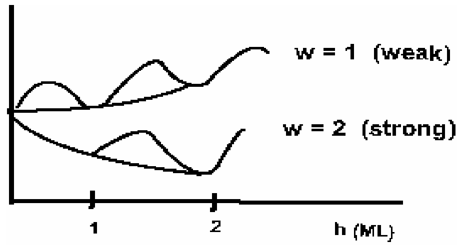
$\delta =$ strain relief by dislocations



Lecture

Morphology (wetting)

$$\mu_f = \frac{\partial G}{\partial N}$$



ML: monolayers

Nucleation barrier to clustering

$$\Delta G^* = \frac{8\pi}{3}\frac{\gamma_{c/v}^3}{\rho_0{}^2\left[\Delta F(\eta)\right]^2}$$

ρ_0 ← density of unstrained film

$$N^* = \frac{16\pi\gamma_{c/v}^3}{3\left[\Delta F(\eta)\right]^3 \rho_0{}^2}$$

$$I = N_s \Gamma \exp\left(-\Delta G^* / RT\right)$$

Morphology + Coherency are determined by nucleation barriers ΔG^* for dislocation formation clustering

Metastability is common

Notes

Deposition

w = 1

$\mu_{0-1} \Rightarrow$ monolayer coverage G ↓

$\mu_{1-2} \Rightarrow$ f-f clustering G ↑

w = 2

$\mu_{1-2} \Rightarrow$ layer growth G ↓

Stronski-Kranstanov: G ↑ after one monolayer

Volmer-Weber: G ↑ initially (no wetting)

$$\Delta F(\eta) \propto \eta^2$$

Lecture

4. Contacts

- stable
- selective
- low R_c
- low T deposition
- adhesion

Eutectics

- Au(Be) P
- Au(Ge) n

- small process window
  - o RTA
- unreliable

Silicides

- Stable
  - o undefined interface
    $\rightarrow R_c \uparrow$

Metals

- reactive with compounds
  $\rightarrow$ defects, dissociation
  $\rightarrow$ phase stability

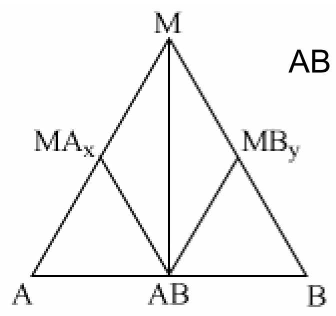
Notes

$R_c < 10^{-5}\,\Omega\cdot cm^2$

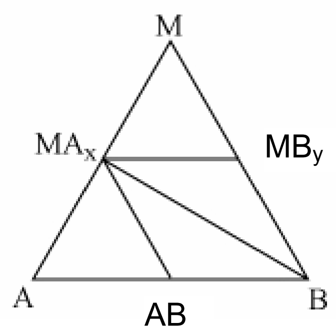
for lasers

surface defects pin E_F
$\rightarrow$ contact resistance
(Schottky Barrier)
for n-GaAs
p-InP
$\Rightarrow$ heavily doped epilayer under contact

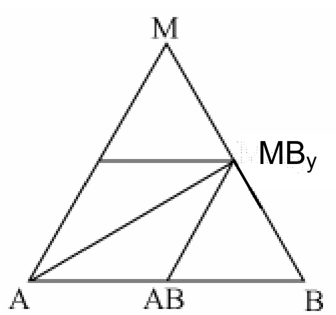
Lecture	Notes



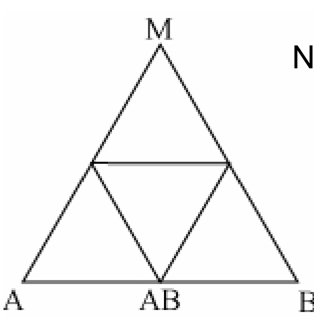
AB dominant



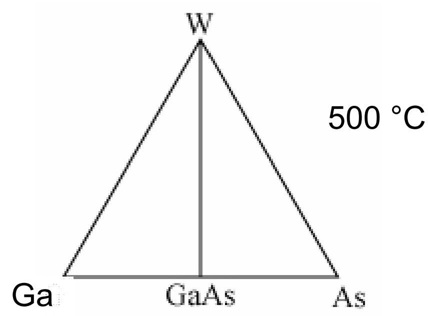
dominant

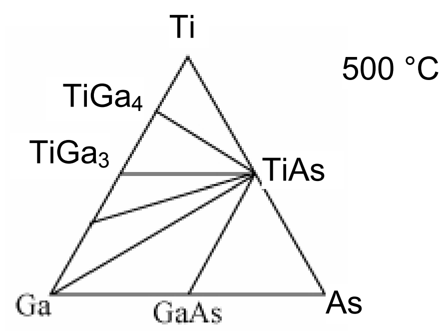


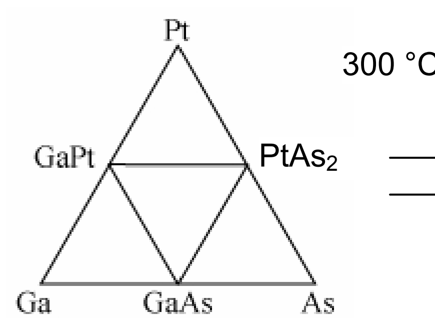
dominant



No phase dominant







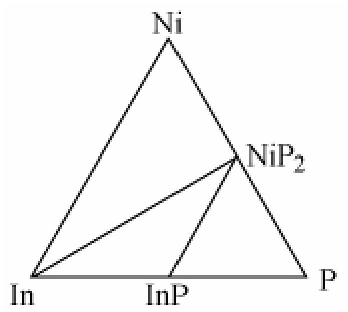
$PtGa_3$

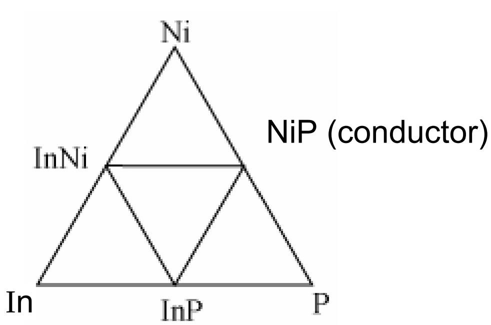
$PtAs_2$ + PtGa

GaAs

Lecture

Notes





Lecture

Adhesion:

- local structural relaxation
- ion beam mixing
- chemical bonding
  $\left(Cu/Al_2O_3 \text{ with excess } \quad _2\right)$

Interdiffusion

- Polycrystal: grain boundary diffusion

$D_{bulk} = E_a \qquad D_{disloc} \simeq \frac{3E_a}{4}$

$D_{gb} \sim \frac{E_a}{2}$

$D = D_{bulk} + f \cdot \quad _{gb}$

- Diffusion Barrier $(Ti/Pt)Au$
  - high T_{MP}
  - chemically stable
- Intermetallic Compound
- Coherent Interface

Dielectric Deposition

SiO_2, SiO_xN_y, SiN_x

- sputter
- PECVD
- e-beam

facets, isolation, diffusion masks

Etch

- Wet etch ($Br:CH_3OH$, HCl)
  - layer stop $\quad H_2SO_4 : H_2O_2 : H_2O$
  - v-groove
- Dry etch (CF_2Cl_2), (HBr, HI)
  - Anisotropy
  - Photoelectrochemical etch anisotropy

Notes

$D_{bulk}\left(T_{MP}\right) \simeq D_{gb}\left(\frac{1}{2}T_{MP}\right)$

refractory TM: Cr, Ni, Ta, Ti, Hf