# Lasers

lecture 10

Czesław Radzewicz

# energy band structure in semiconductors

crystal lattice ⇒ periodic potential

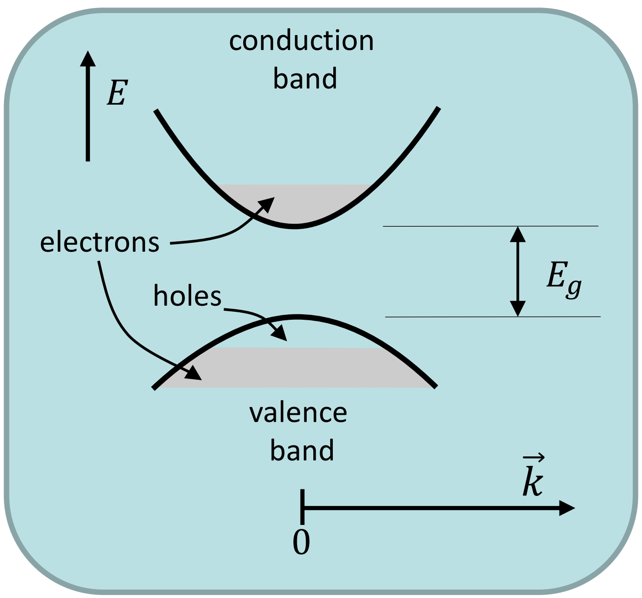
electron wave function

$$\psi(\vec{r}) = u(\vec{r})e^{-i\vec{k}\cdot\vec{r}}$$

periodic function

....

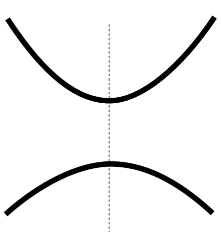
consequences:



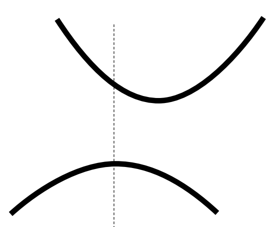

| | $E_g$ (eV) |
|---|---|
| C (diam.) | 5.47 |
| GaN | 3.4 |
| GaP | 2.26 |
| GaAs | 1.43 |
| Si | 1.12 |
| InSb | 0.17 |

important distinction:

direct bandgap

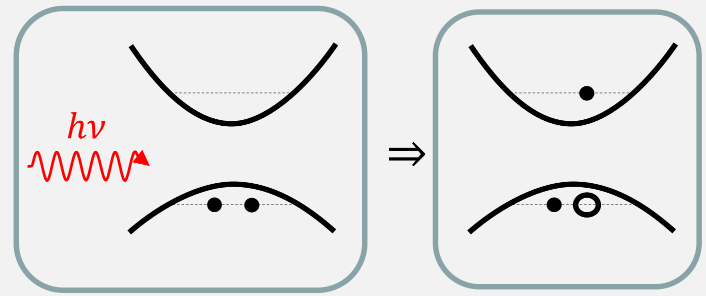


indirect bandgap

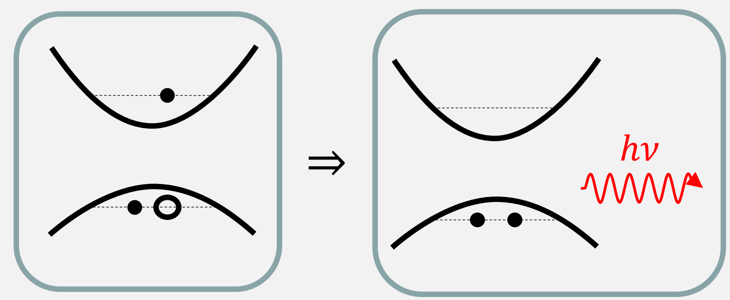


## radiative processes in semiconductors

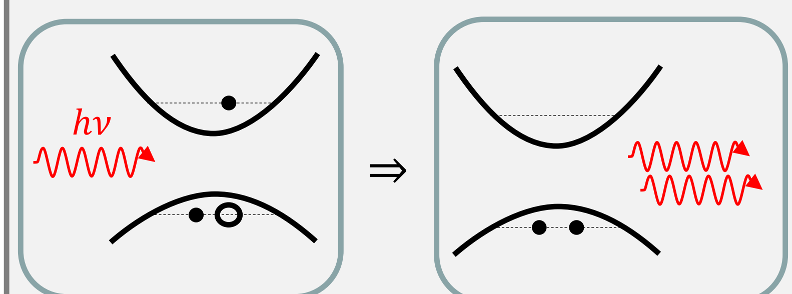
absorption




spontaneous emission




stimulated emission



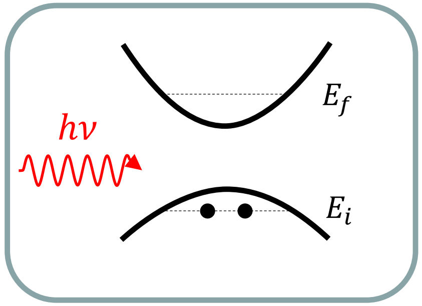
# conservation principles

for absorption:

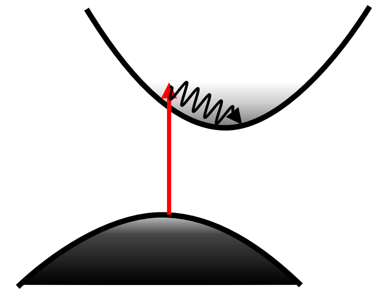
$$E_i + h\nu = E_f$$

$$\hbar\vec{k}_i + \hbar\vec{k}_p = \hbar\vec{k}_f$$

momentum before absorption; photon momentum; momentum after absorption




in semiconductors with indirect band gap, e.g. Si absorption is allowed. We can build very good photodetectors out of Si.



numbers:

electron $\quad \left|\hbar\vec{k}_e\right| = \left|m_e{}^* \sqrt{\frac{3kT}{m_e{}^*}}\right| \approx 1{,}6 \cdot 10^{-26}$ kgm/s for GaAs

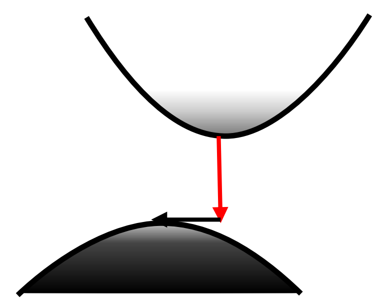
photon $\quad \left|\hbar\vec{k}_p\right| = \frac{h}{\lambda} \approx 8 \cdot 10^{-28}$ kgm/s $\quad$ ($\lambda$=800nm)

$\left|\hbar\vec{k}_p\right| \ll \left|\hbar\vec{k}_i\right|$ and

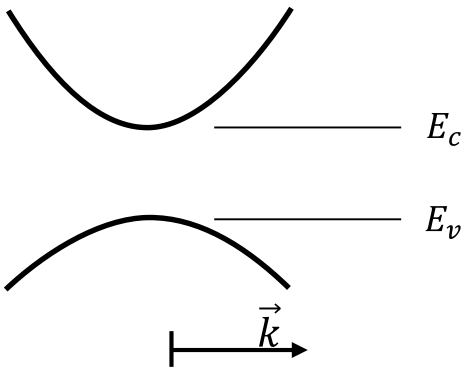
$$\vec{k}_f \cong \vec{k}_i$$

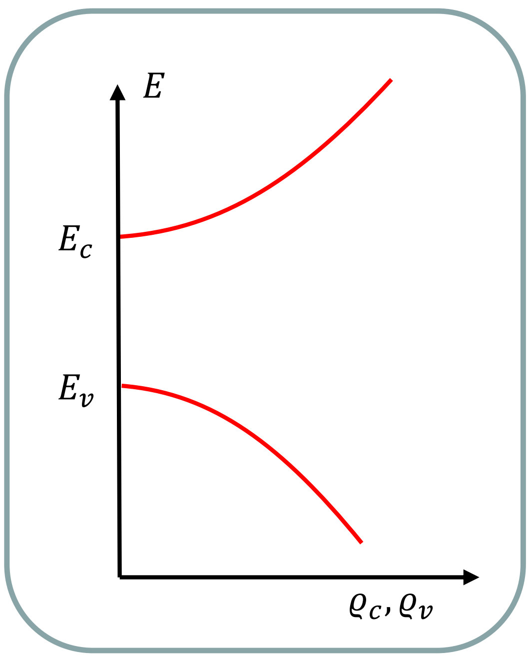
radiative transitions in semiconductor are „vertical"

in semiconductors with indirect band gap radiative electron-hole recombination requires a photon to fulfill the momentum conservation rule. Thus radiative recombination has little probability – we cannot have light gain and thus build lasers.



# differential density of electron states




Pauli's principle!

if we approximate the shape of the bands around $k = 0$ by parabolas then (no proof given here):

$$\varrho_c(E) = \frac{(2{m_e}^*)^{3/2}}{2\pi^2\hbar^3}\sqrt{E - E_c}$$

$$\varrho_v(E) = \frac{(2{m_h}^*)^{3/2}}{2\pi^2\hbar^3}\sqrt{E_v - E}$$

${m_e}^*$ electron effective mass
${m_h}^*$ hole effective mass

$\varrho_v$ and $\varrho_c$ have units $\frac{1}{\mathrm{m^3 J}}$

interpretation:

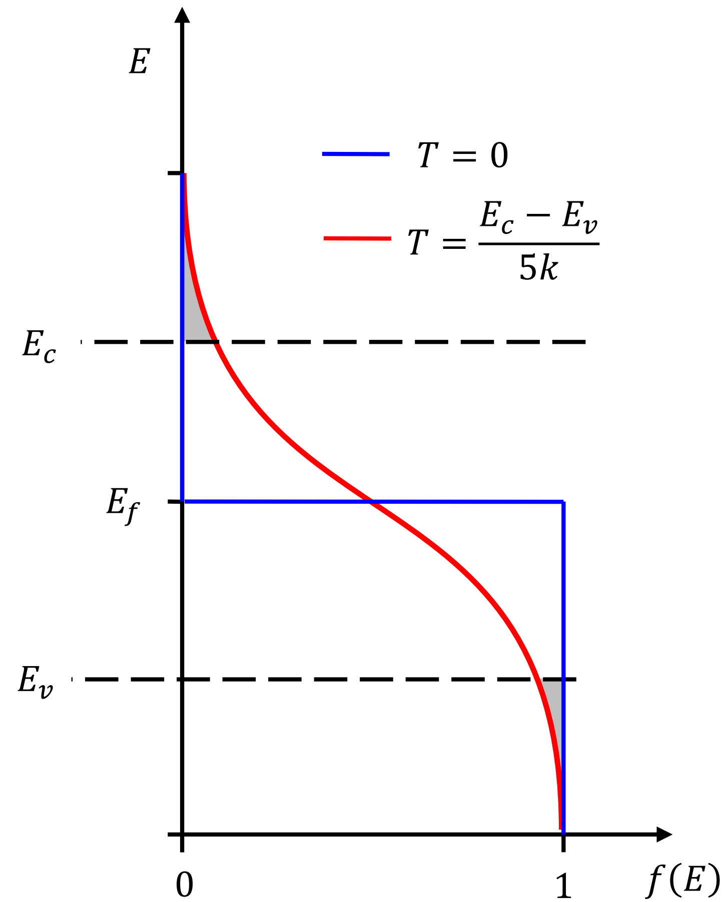
- for given $\Delta E$ the product $\varrho_c(E)\Delta E$ is equal to maximum density of electrons with energy from $E - \Delta E/2 \div E + \Delta E/2$ range.
- the same applies to holes

# Fermi's distribution

electrons are fermions

$$f(E) = \frac{1}{e^{\frac{E-E_f}{kT}} + 1}$$

$E_f$ - Fermi's energy
$T$ – temperature
$k$ –Boltzman's constant




for $E > E_c$ $f(E)$ - probability of finding an electron at a level with energy $E$
for $E < E_v$ $1 - f(E)$ - probability of finding hole at a level with energy $E$

# differential density of carriers

differential density of electrons – number of electrons in a unit volume (density) per unit energy band

$n(E) = \varrho_c(E)f(E) \qquad \frac{1}{\mathrm{m^3 J}}$

differential density of holes

$p(E) = \varrho_v(E)[1 - f(E)]$

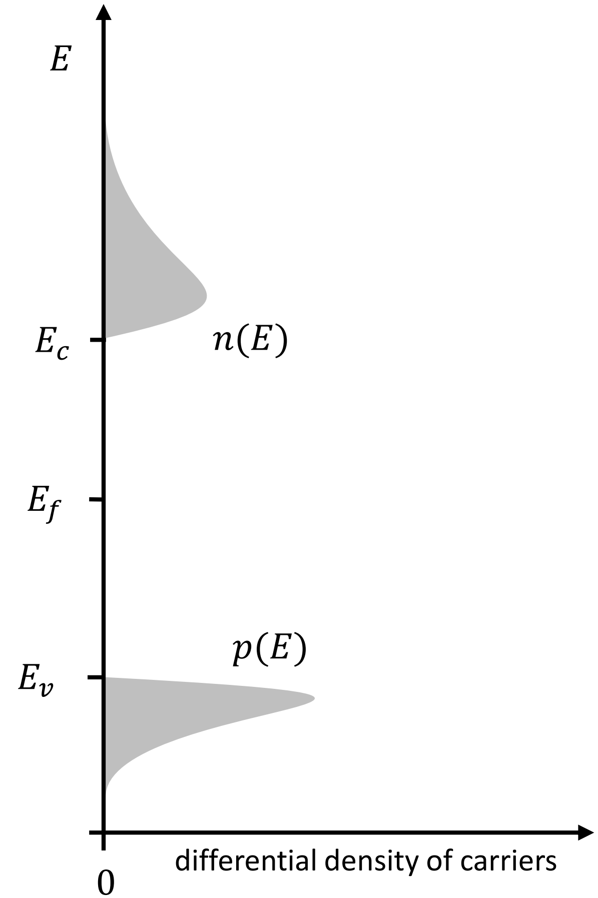
density of electrons

$$n = \int_{E_c}^{\infty} n(E)dE \qquad \frac{1}{\mathrm{m}^3}$$

density of holes

$$p = \int_{-\infty}^{E_v} p(E)dE$$

in a pure (no doping) semiconductor $n = p$.

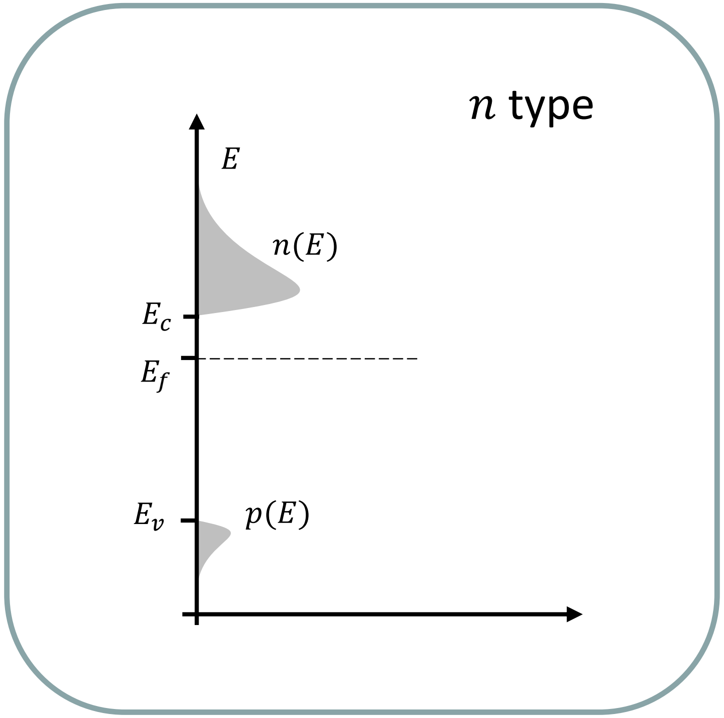


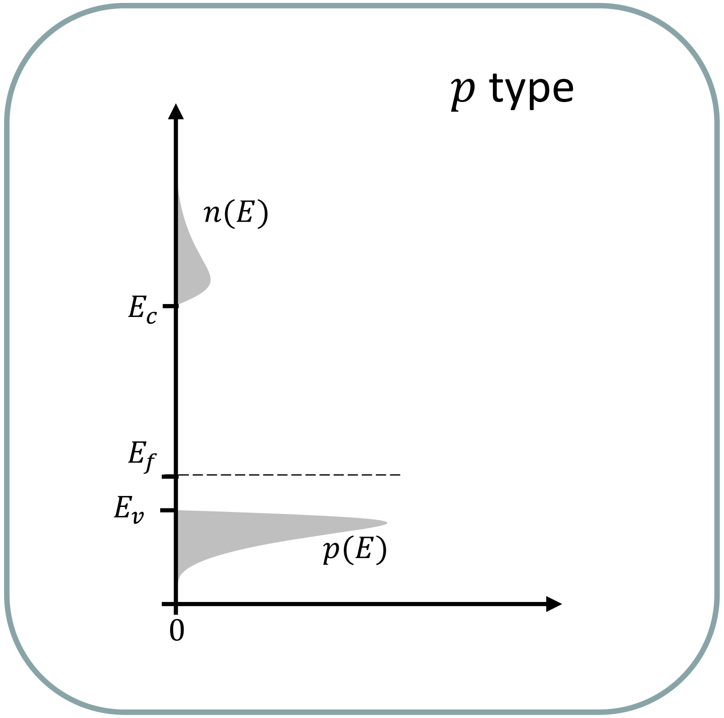
# doped semiconductors

Two types of dopants: $n$ (excessive number of electrons) and $p$ (excessive number of holes)

$n \neq p$

In doped semiconductors the Fermi's level is no longer half-way between valence and conduction bands.

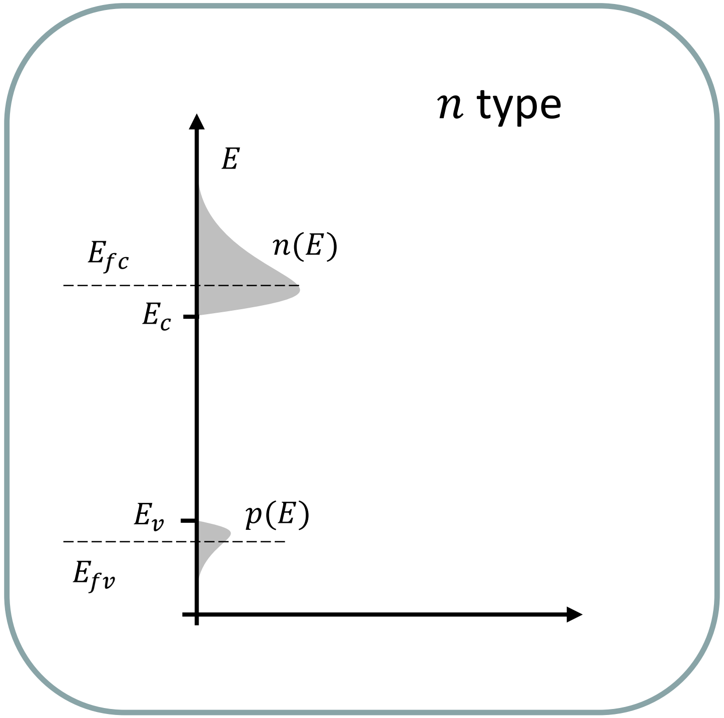


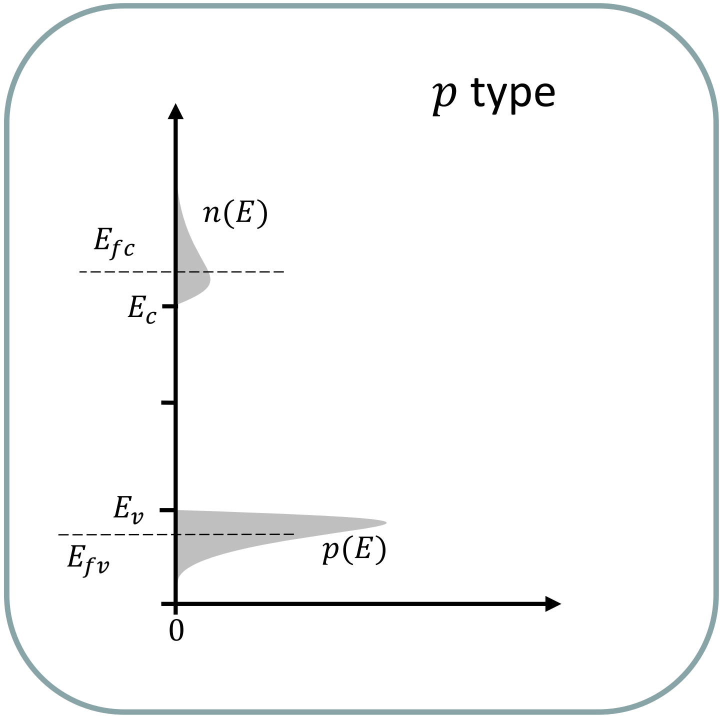



# doped semiconductors with optical pumping or current injection

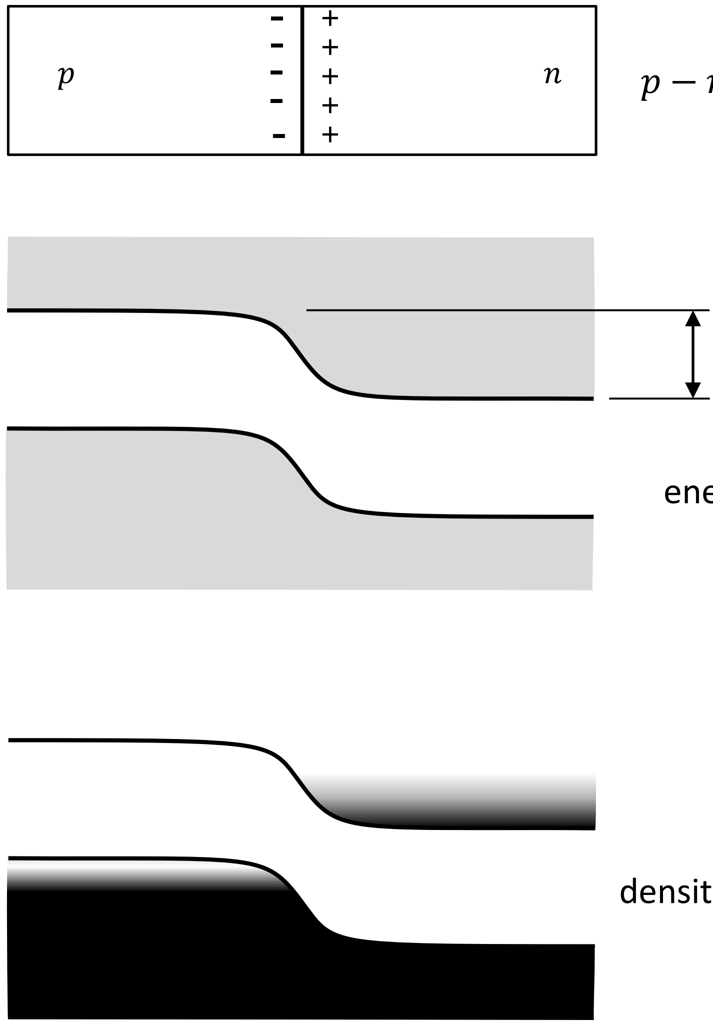
Two types of dopants: $n$ (excessive number of electrons) and $p$ (excessive number of holes) $n \neq p$

interband relaxation is much faster than the decay of electrons from the conduction band. Local thermodynamic equilibrium in any of the two bands is reached very quickly. We can define local Fermi's energies: $E_{fv}$ and $E_{fc}$



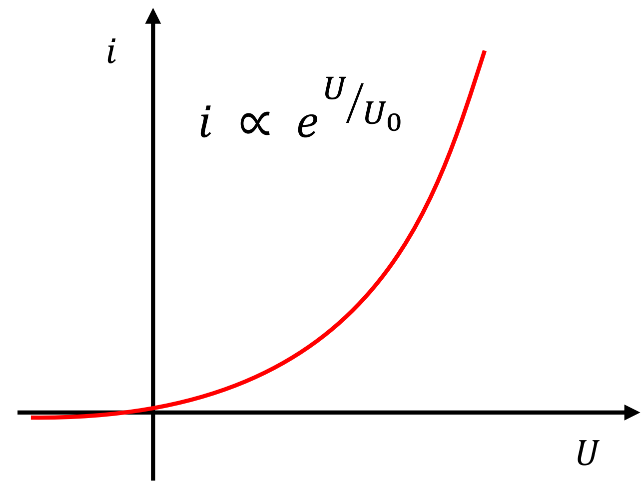
# $p - n$ junction



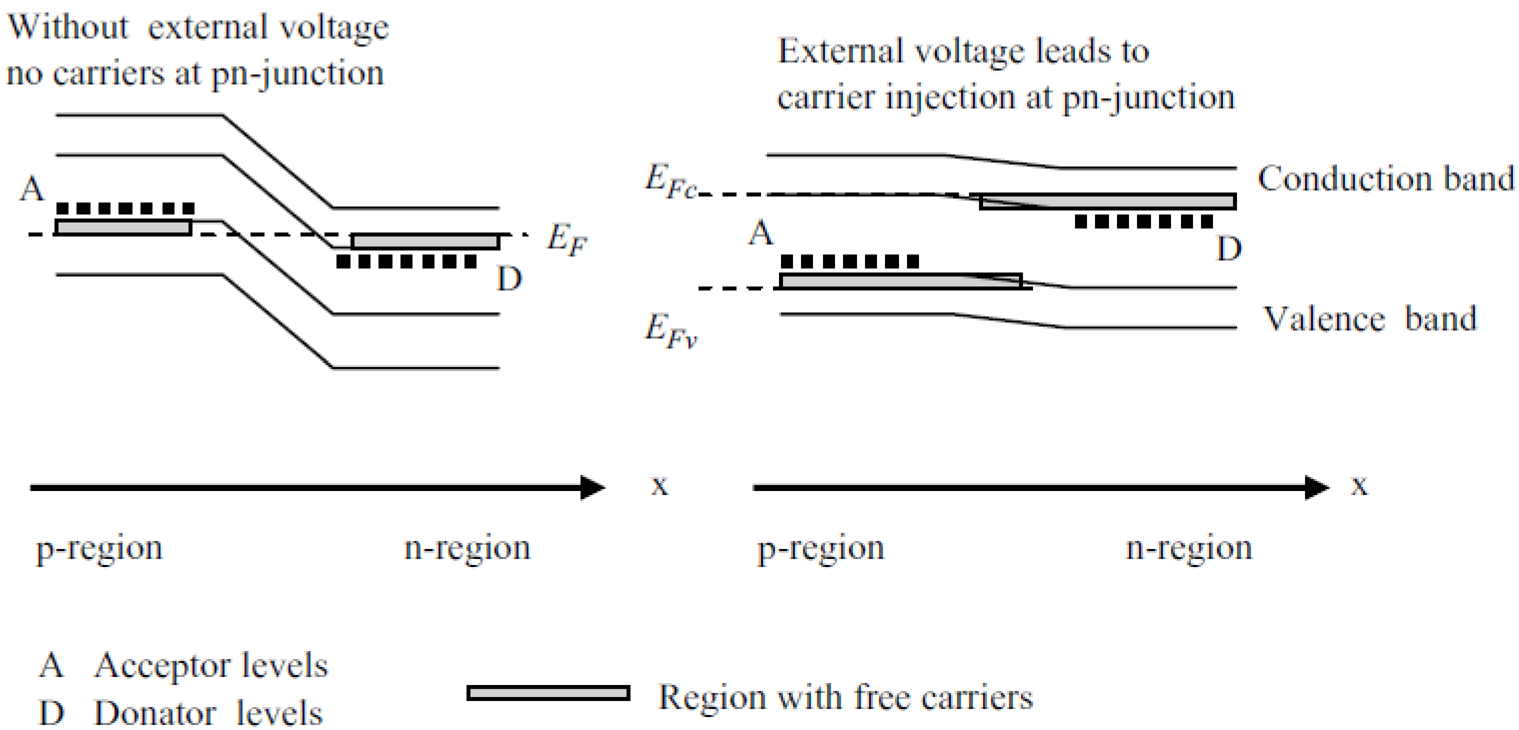

$p - n$ junction

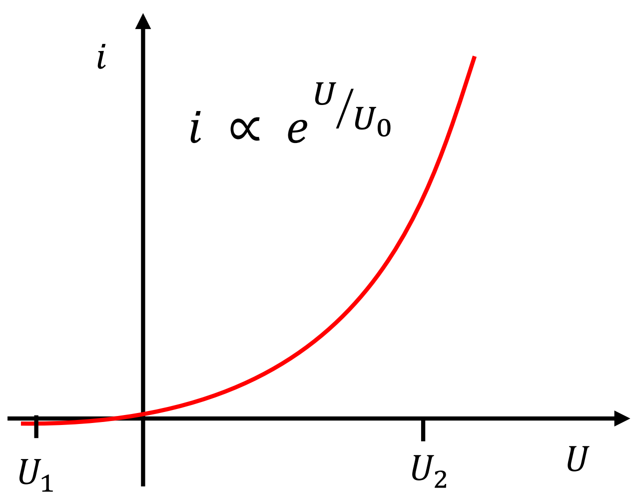
energy bands

density of carriers



# $p-n$ junction polarization

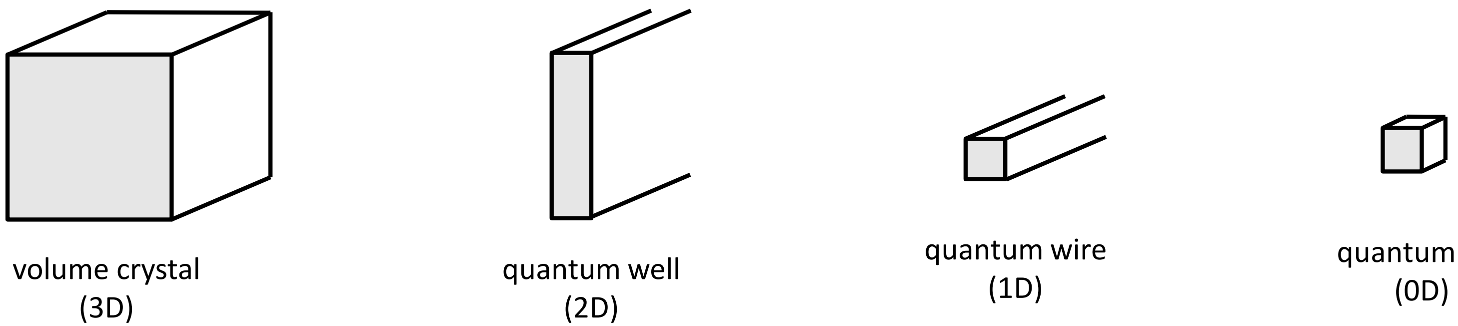


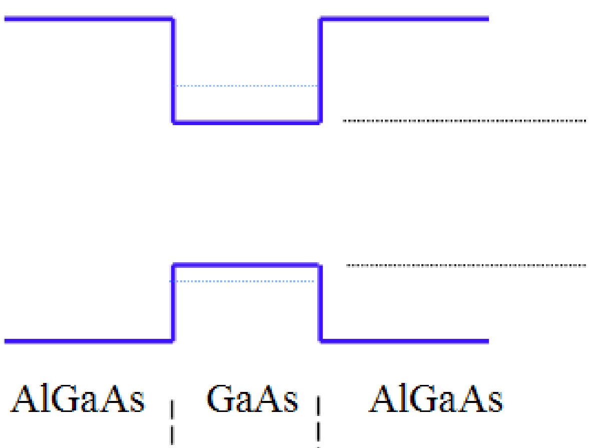




Both electrons and holes are present in the junction
– radiative recombination and thus gain are possible

photon energy ≈ bandgap

# low-D structures



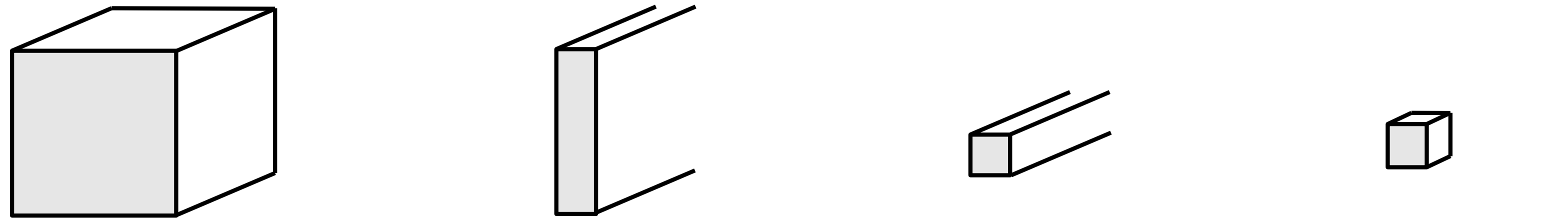




- In a quantum well the motion of electron along the direction normal to the well is quantized – energy levels corresponding to this motion are discrete.
- The number of bound levels depends on the width and depth of the well
- The total energy of the carrier is the sum of the energy of discrete levels and the Energy of free motion in the two directions parallel to the well.

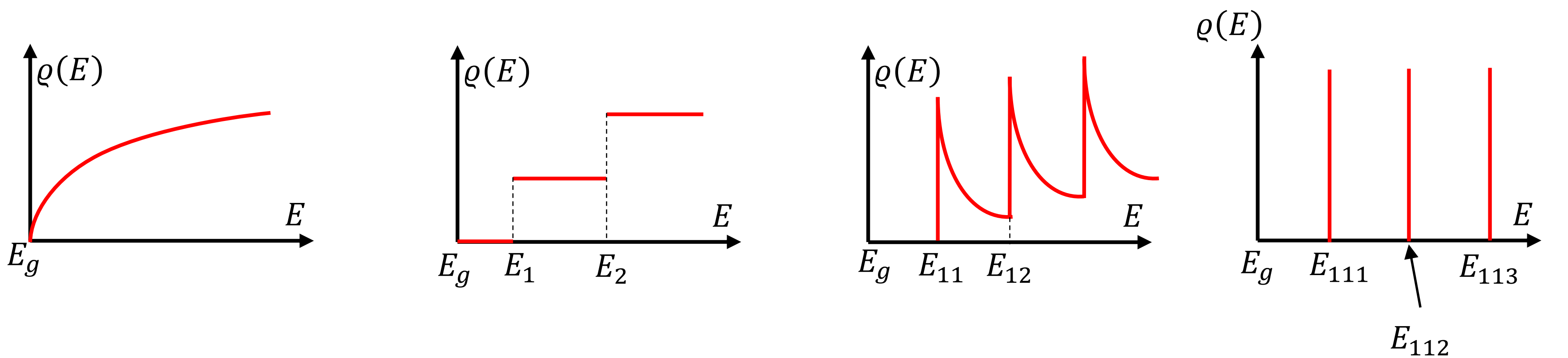
How can we build low-D structures? – semiconductor alloys

- ……
- For quantum dot all the energy levels are discrete

# densities of electron states in low-D structures



volume crystal (3D) | quantum well (2D) | quantum wire (1D) | quantum dot (0D)




**3D:**

$$\varrho(k) = \frac{k^2}{2\pi^2}$$

$$\varrho(E) = \frac{(2m)^{3/2}}{2\pi^2\hbar^3}\sqrt{E}$$

**2D:**

$$\varrho(k) = \frac{k}{2\pi}\left(\frac{1}{L_z}\right)$$

$$\varrho(E) = \frac{m}{2\pi\hbar^2}\frac{1}{L_z}$$

**1D:**

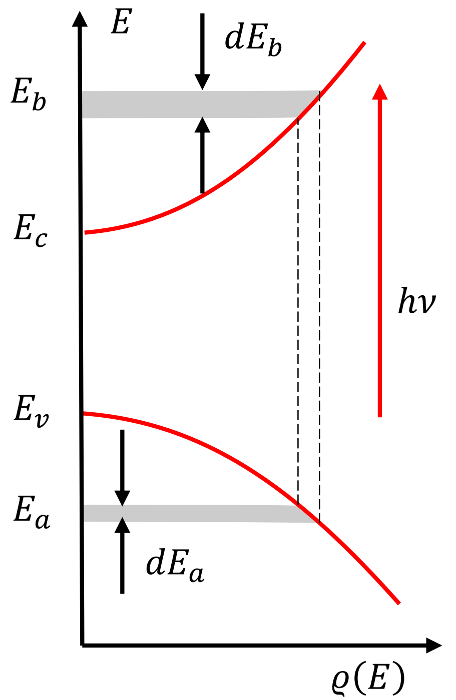
$$\varrho(k) = \frac{1}{\pi}\left(\frac{1}{L_x L_y}\right)$$

$$\varrho(E) = \frac{\varrho(k)\sqrt{2m}}{2\hbar}\frac{1}{\sqrt{E}}$$

**0D:**

$$\varrho(E) \propto \delta(E - E_{ikl})$$

## gain lineshape




**bulk (3D)**

momentum conservation

$$\sqrt{2m_e^*(E_b - E_c)} = \sqrt{2m_h^*(E_v - E_a)}$$

gives

$$E_b - E_c = \frac{m_h^*}{m_e^*}(E_v - E_a)$$

and

$$dE_b = -\frac{m_h^*}{m_e^*}dE_a$$

calculations …

give reduced density of states

$$\varrho_r(\nu) = \frac{1}{4\pi^2}\left(\frac{2m_r}{\hbar^2}\right)^{3/2}\sqrt{h\nu - E_g}$$

calculations …

$$\gamma(\nu) = B_{21}\frac{n}{c}\varrho_r(\nu)[f_c(E_b) - f_v(E_a)] =$$
$$= \alpha_0(\nu)[f_c(E_b) - f_v(E_a)]$$

absorption lineshape at $T = 0$.

$$0 \le f_c, f_v \le 1$$

the gain is possible only when $f_c(E_b) > f_v(E_a)$

this is an analogue of the population inversion ($\Delta N > 0$) in atoms/ions.

We need both types of carriers: electrons and holes to be present. This is consistent with the stimulated emission picture – in order to produce extra photon the hole and electron have to be annihilated.

# gain lineshape, 2

**low-D materials**

- different formulas for reduced density of states, still the result is proportional to the densities of carriers
- result: higher densities of states leads to higher gain.

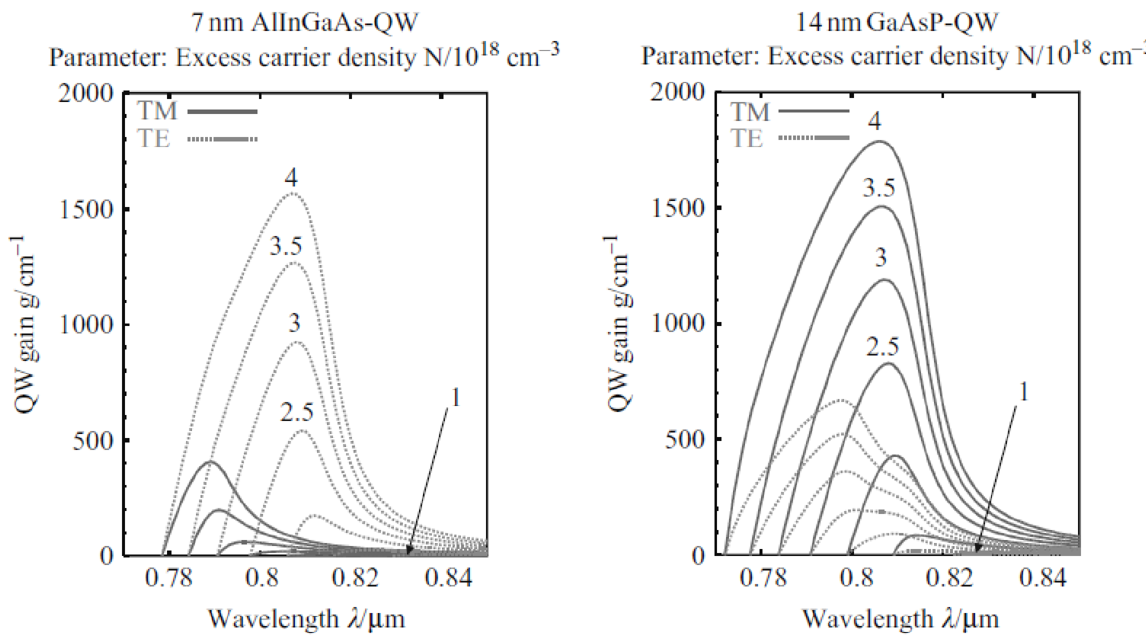



FIGURE 2.6. Calculated optical gain versus wavelength at different excitation levels for a compressively strained AlInGaAs-QW and a tensile-strained GaAsP-QW at 810 nm

# semiconductor alloys

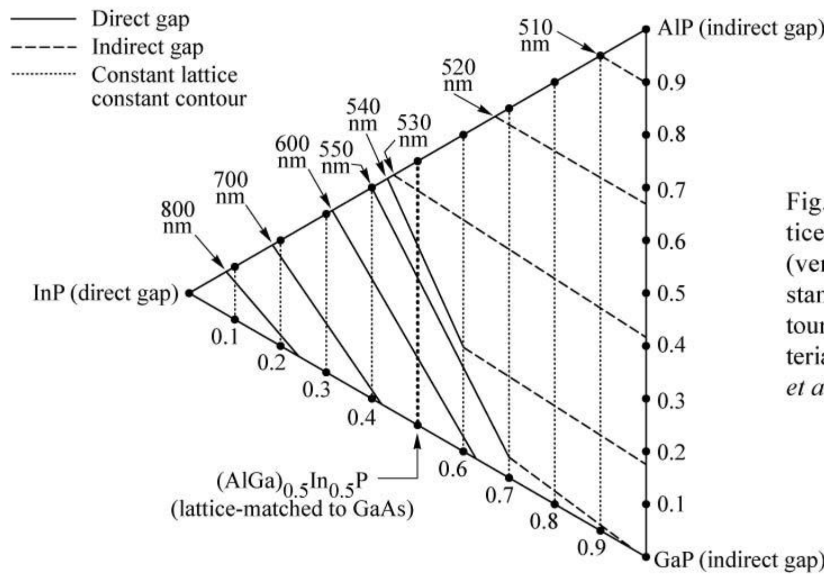
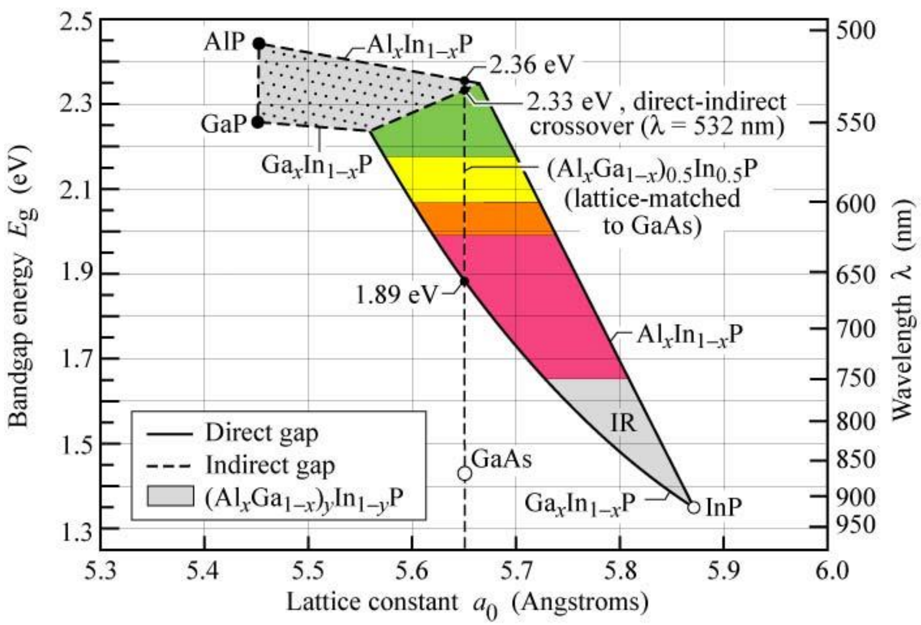



Fig. 12.11. Constant lattice constant contours (vertical lines) and constant emission line contours of the AlGaInP materials system (after Chen *et al.*, 1997).




AlP
$E_g = 2.45$ eV
$a_0 = 5.4510$ Å

GaP
$E_g = 2.26$ eV
$a_0 = 5.4512$ Å

InP
$E_g = 1.35$ eV
$a_0 = 5.8686$ Å

GaAs
$E_g = 1.424$ eV
$a_0 = 5.6533$ Å

Fig. 12.9. Bandgap energy and corresponding wavelength versus lattice constant of $(Al_xGa_{1-x})_yIn_{1-y}P$ at 300 K. The dashed vertical line shows $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ lattice matched to GaAs (adopted from Chen *et al.*, 1997).

# semiconductor alloys, 2

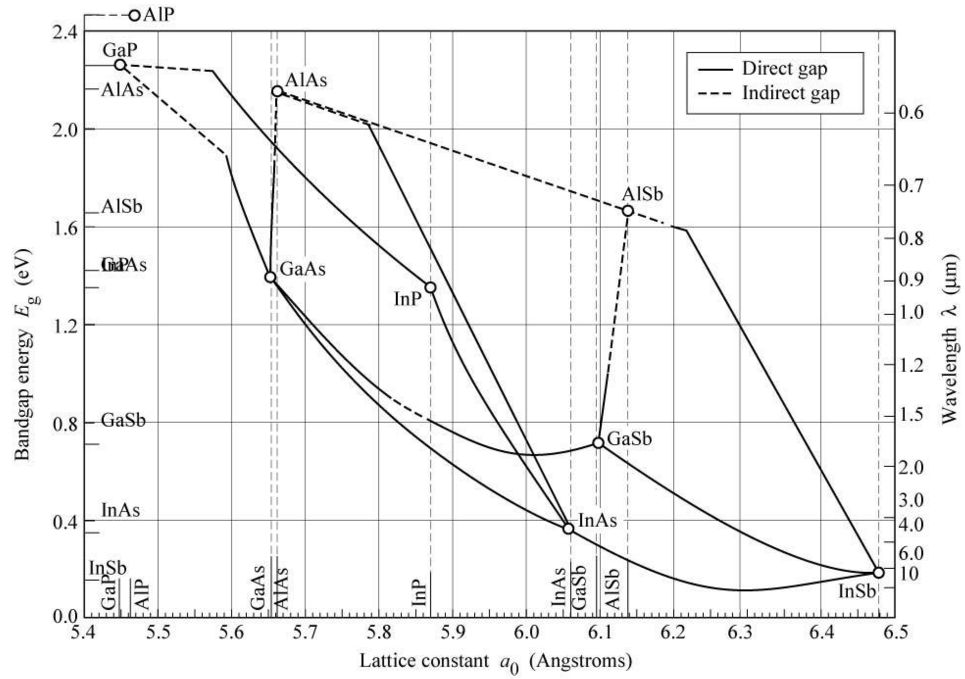
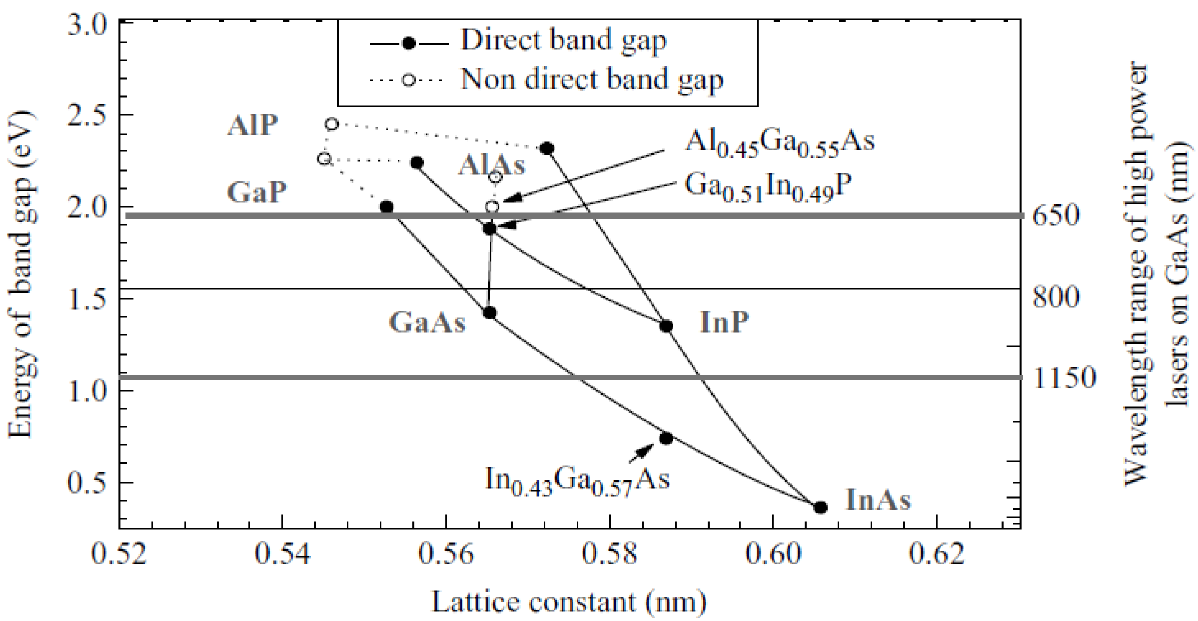



Fig. 12.6. Bandgap energy and lattice constant of various III–V semiconductors at room temperature (adopted from Tien, 1988).



# Light Emiiting Diode (LED)

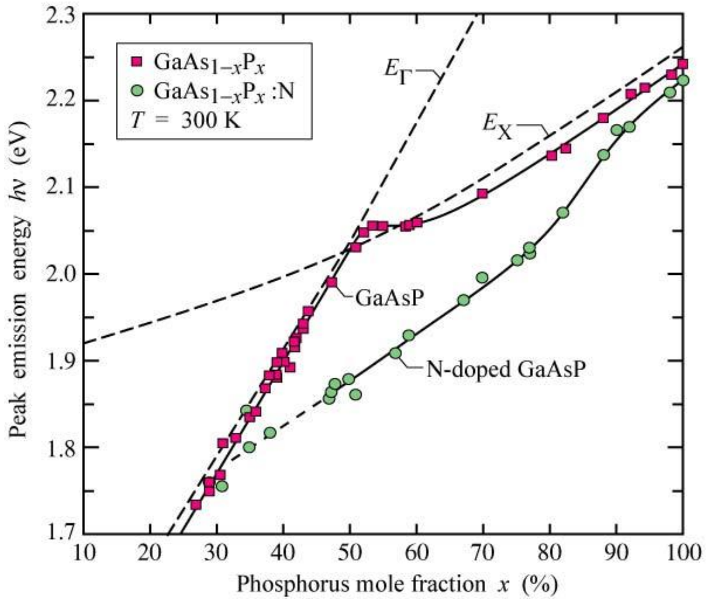



Fig. 12.2. Room-temperature peak emission energy versus alloy composition for undoped and nitrogen-doped GaAsP LEDs injected with a current density of 5 A/cm$^2$. Also shown is the energy gap of the direct-to-indirect ($E_\Gamma$-to-$E_X$) transition. The direct–indirect cross-over occurs at $x \approx 50\,\%$ (after Craford *et al*., 1972).

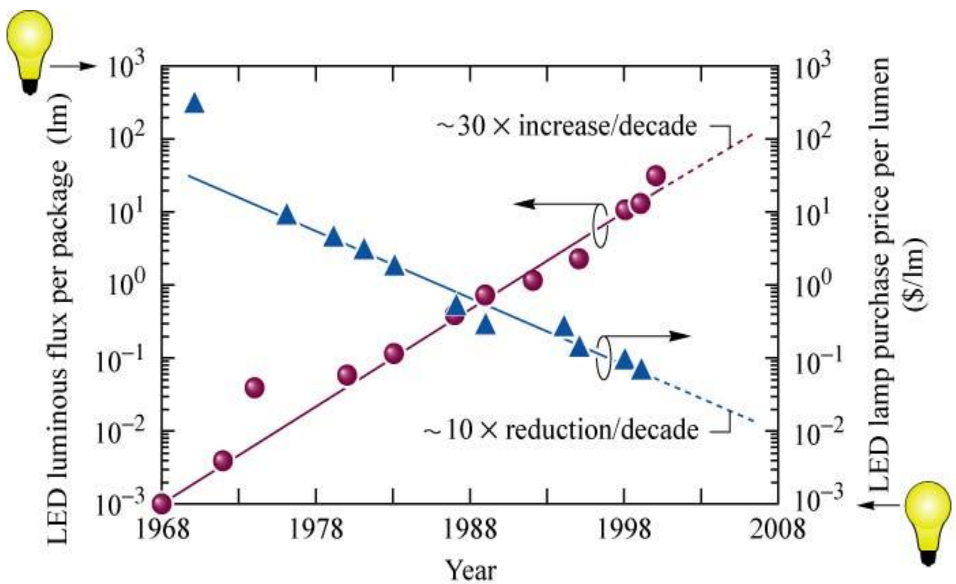



Fig. 12.15. LED luminous flux per package and LED lamp purchase price per lumen versus year. Also shown are the values for a 60 W incandescent tungsten-filament light bulb with a luminous efficiency of ~17 lm/W and a luminous flux of 1000 lm with an approximate price of 1.00 US$ (after Krames *et al*., 2000).

# laser cavities for semiconductor lasers

Two major groups:

1. edge emitting lasers, Fresnel reflections of the surfaces that form flat mirrors, eventually Bragg

advantage: large powers possible

disadvantage : strongly astigmatic output beam

Note that the vertical dimensions of the structures are, typically, $\mu$m

2. surface emitting lasers, Bragg mirrors are grown using MBE

disadvantage: low powers

advantage: high beam quality, large 2D matrices can be grown on a single wafer

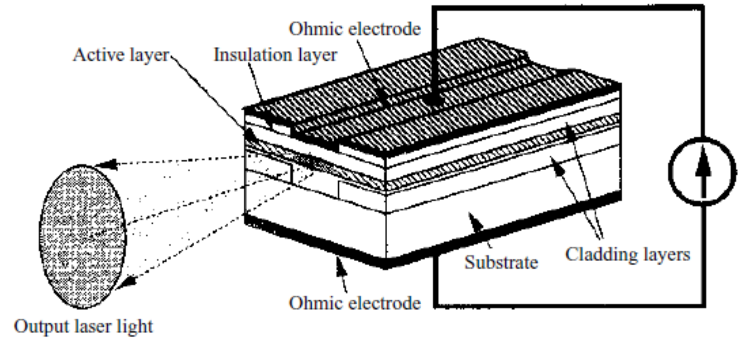
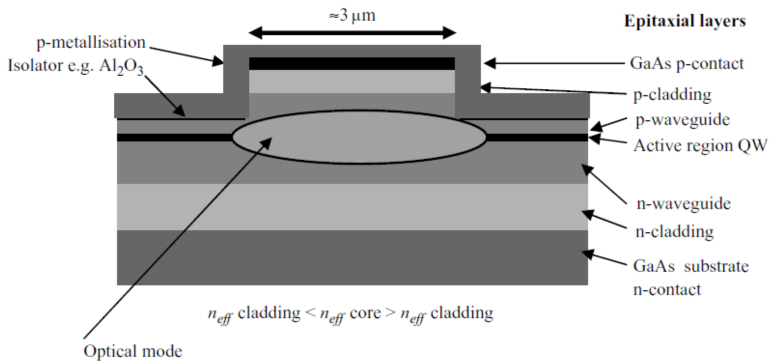
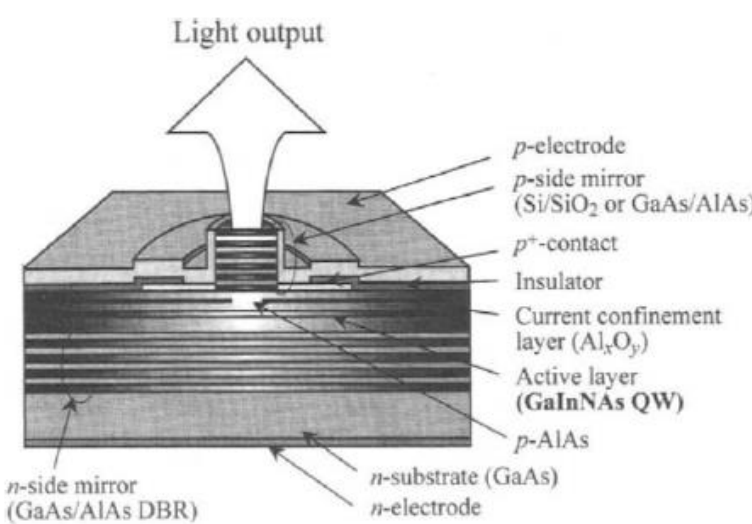



**Figure 6.1** Schematic illustration of a double-heterostructure (DH) FP semiconductor laser.

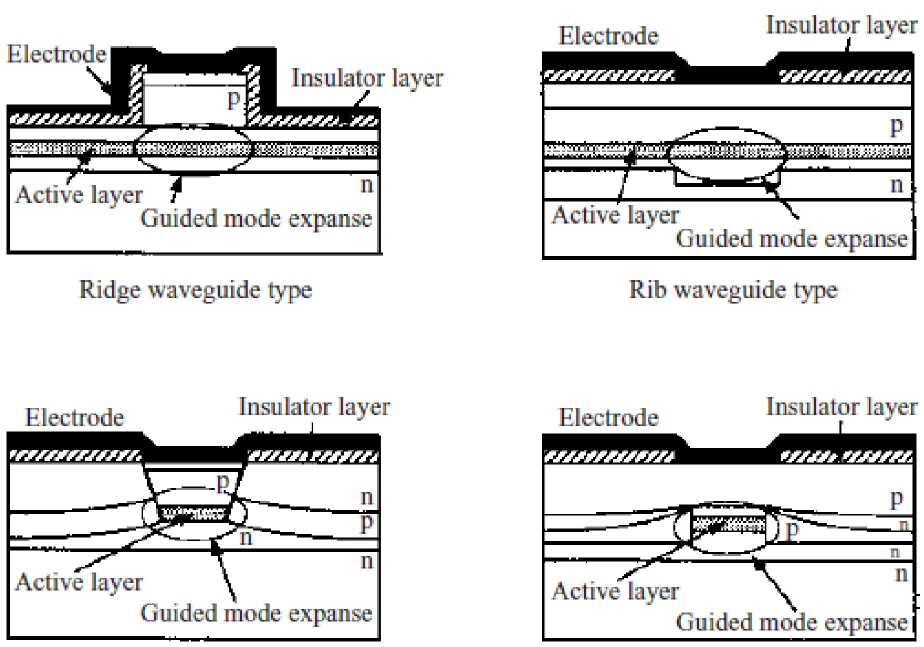


# laser resonators for edge emitting lasers

Two methods for creating waveguides:

1. index guiding – the structure of the laser chip forms a waveguide which, together with end mirrors forma resonator




Buried heterostructure waveguide type

2. gain guiding – the waveguide does not exist without pumping, the shape of the gain region guides some waves by providing them with the gain larger than for other (nonguided) waves.

# narrowband and tuned semiconductor lasers

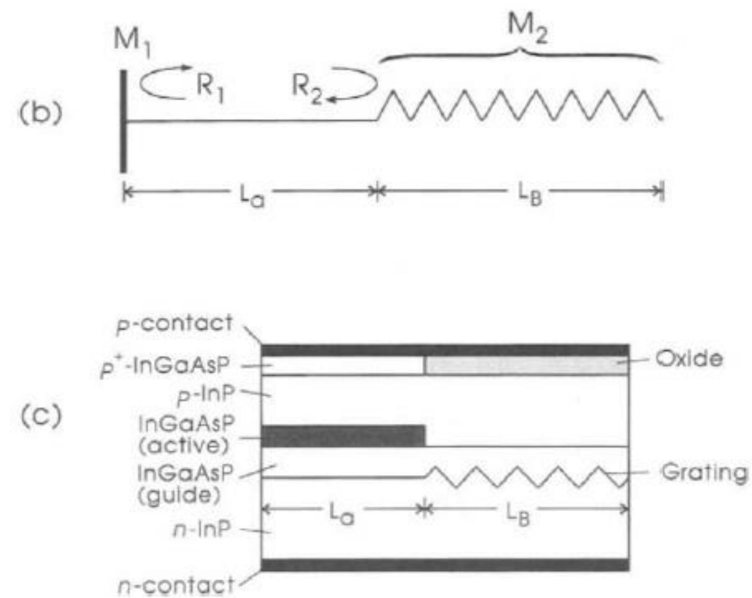
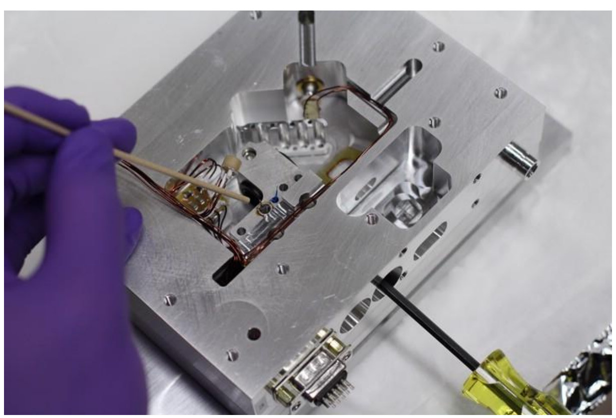


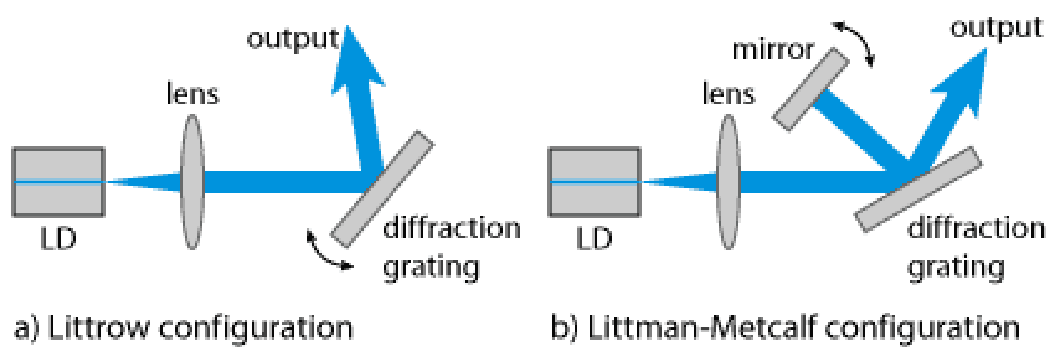

**Figure 3.8:** Distributed Bragg reflector (DBR) laser: (a) Both mirrors replaced by Bragg gratings. (b) One mirror replaced by a Bragg grating. (c) Schematic longitudinal view of InGaAsP/InP DBR laser.

1. The tuning components (1D Bragg grating) is formed next to gain region on the laser chip.

optical telecommunications!!!

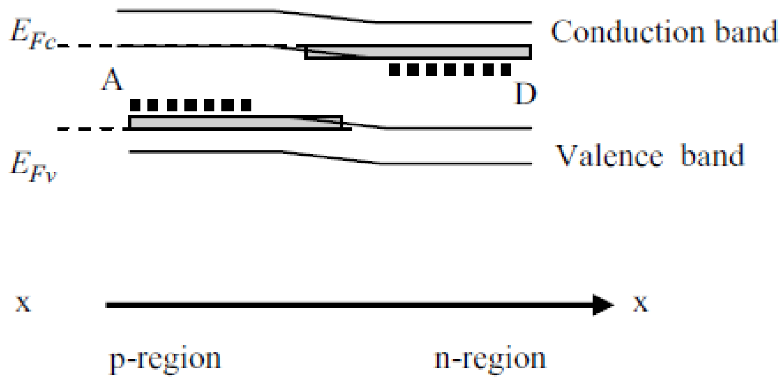
2. External cavity line narrowing and tuning






from RP Photonics Encyclopedia

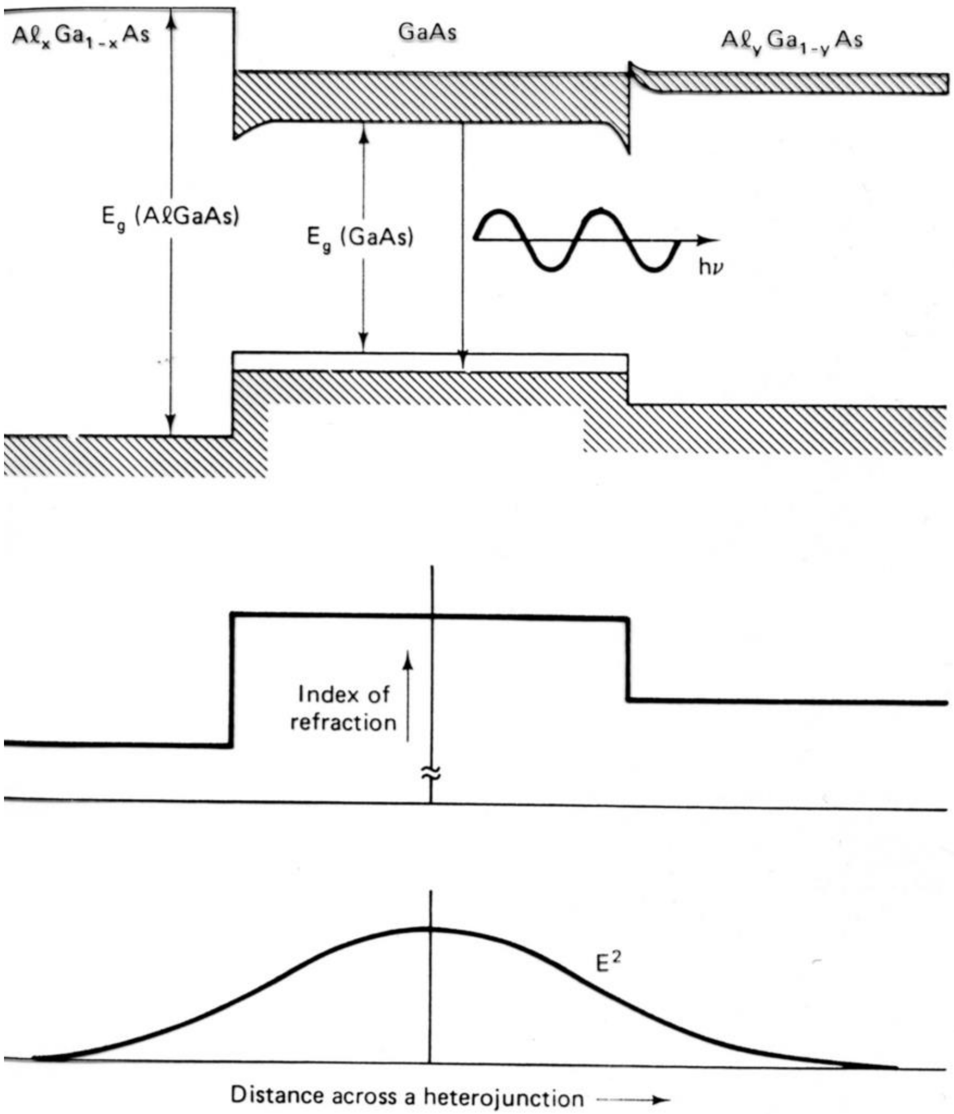
# $n - p$ junction lasers




Historical value only.
If we apply voltage in the conduction direction a current will flow through the junction the band structure will be deformed in such a way that both types of carriers can be present in the junction at the same time (condition for gain).

Because of the carriers diffusion those lasers required very high currents, typically >10kA/cm$^2$ which results in very strong heating.

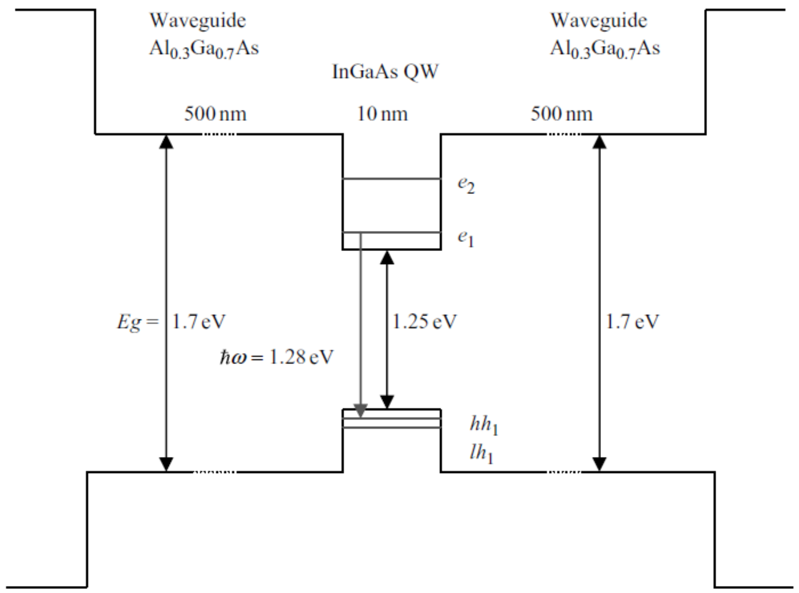
# double heterojunction structure lasers




The heterojunction plays two roles

1. Carrier trapping – the electrons and holes are trapped in the potential minima which facilitates radiative recombination and by many orders of magnitude lowers the electrical current required
2. Different materials with different indices of refraction form a waveguide.

# quantum well semiconductor lasers

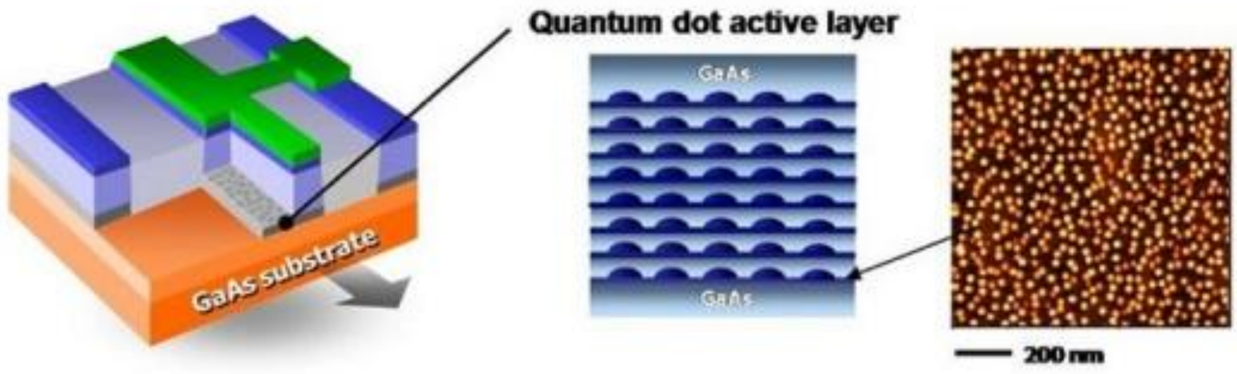


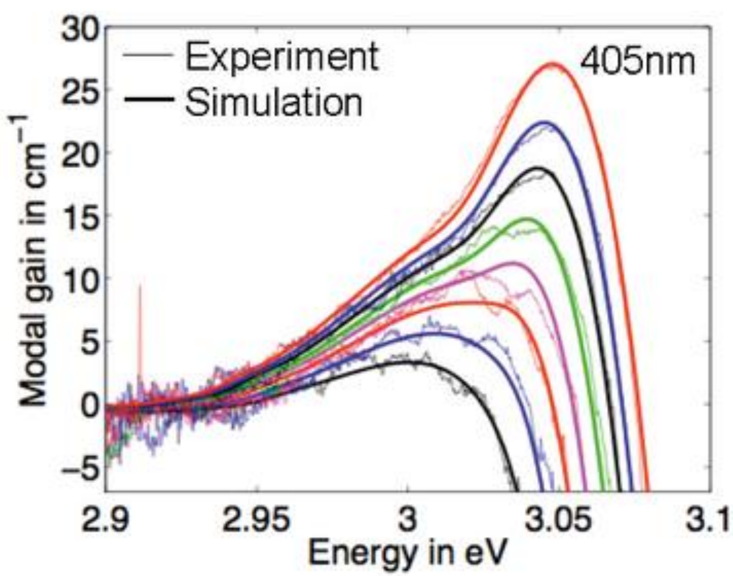

An example:

gain medium 10nm InGaAs quantum well

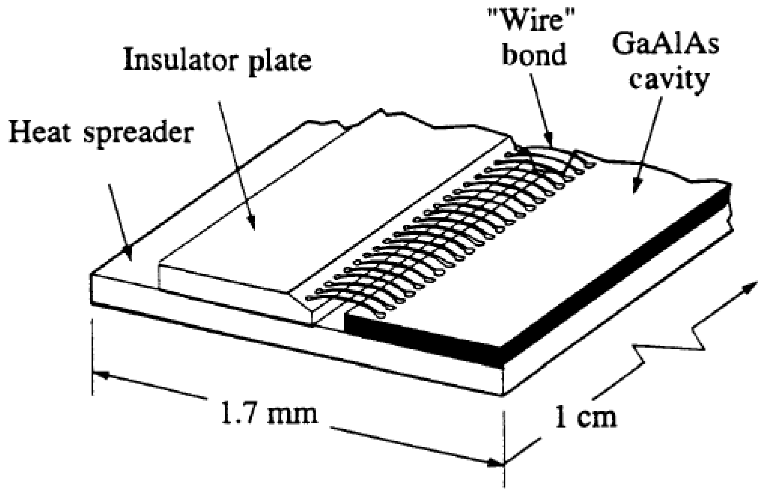
waveguide – double heterojunction

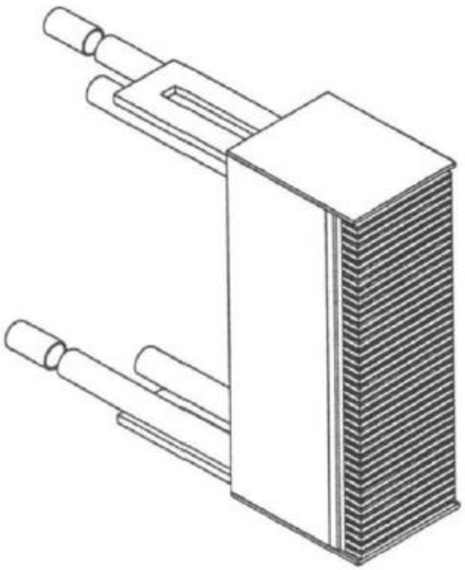
# quantum dot semiconductor lasers



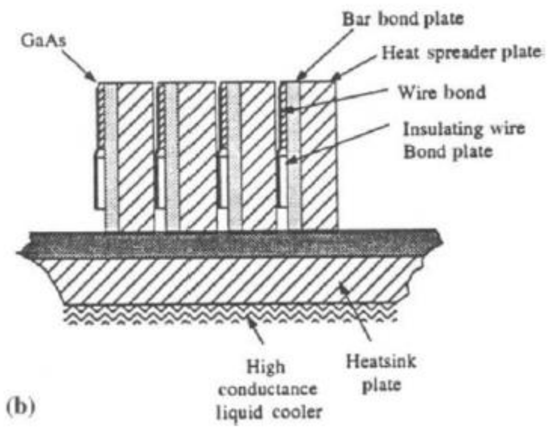



# laser diode bar

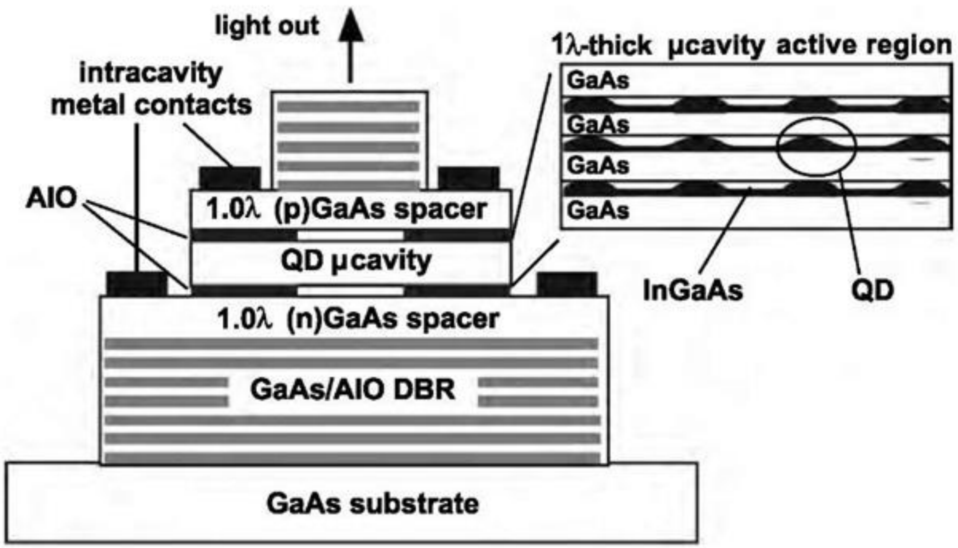


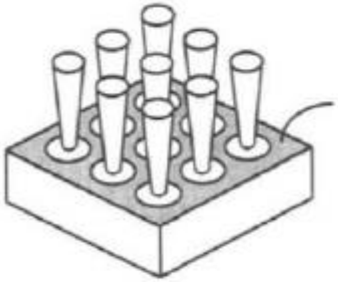
The power of a single diode laser is limited mostly by the limited ability to remove heat. Higher powers are achieved by stacking many chips and providing efficient cooling to each individual laser.



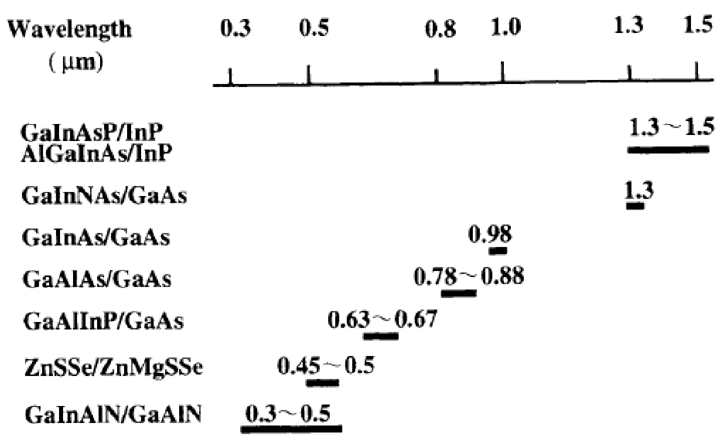
# Vertical Cavity Surface Emitting Laser (VCSEL)




- excellent beam quality ($TEM_{00}$)
- easy to run in a single mode regime



VCSEL laser matrices



# hybrid technologies

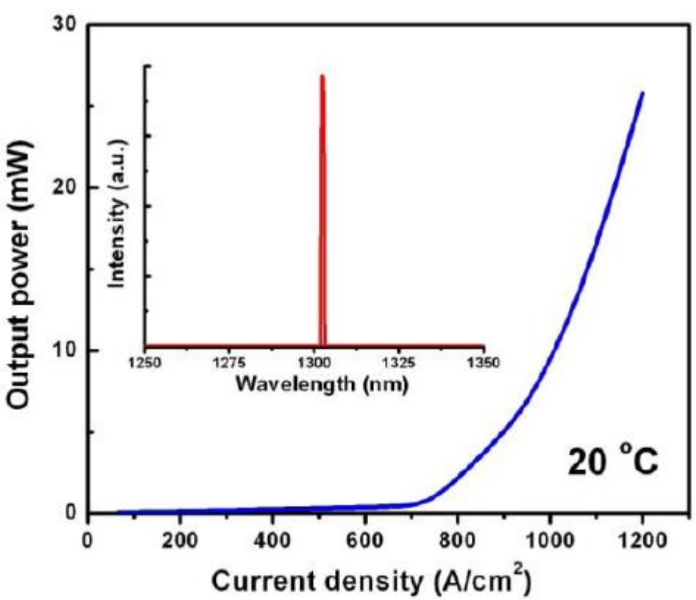
Dilemma: silicon electronics dominates but one cannot build a laser with a silicon crystal because it has indirect gap.

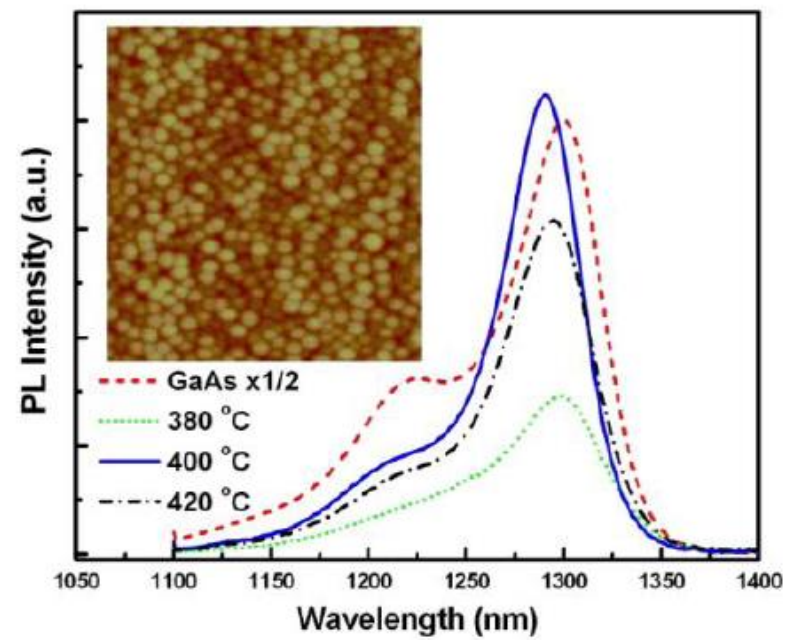
| | |
|---|---|
| 50nm GaAs | |
| 100nm $Al_{0.4}Ga_{0.6}As$ | |
| 50nm GaAs | |
| 5 layer InAs/InGaAs DWELL | |
| 50nm GaAs | |
| 100 layer GaAs/AlGaAs SPLs | |
| 400nm GaAs | ×2 |
| 5 layer $In_{0.15}Ga_{0.85}As$/GaAs SPLs | ×2 |
| 1 µm GaAs | |
| Si Substrate | |

## 1.3-µm InAs/GaAs quantum-dot lasers monolithically grown on Si substrates

Ting Wang, Huiyun Liu,* Andrew Lee, Francesca Pozzi, and Alwyn Seeds

6 June 2011 / Vol. 19, No. 12 / OPTICS EXPRESS 11381



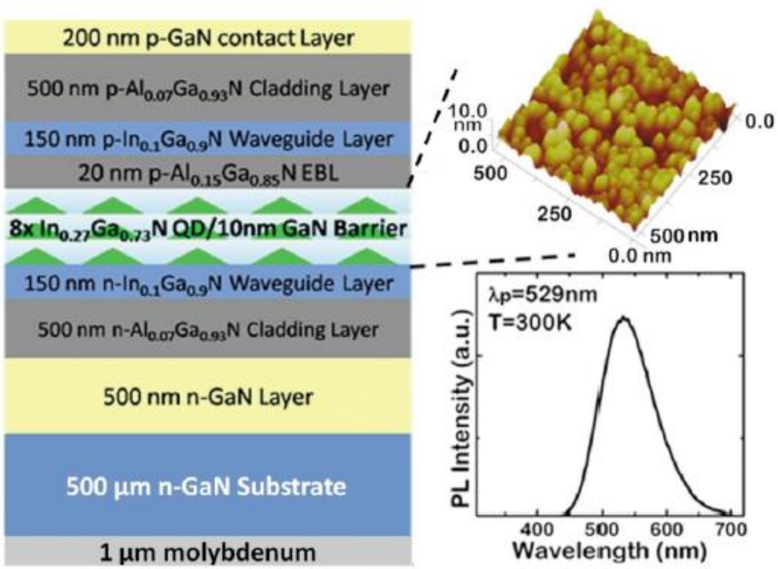



green semiconductor laser

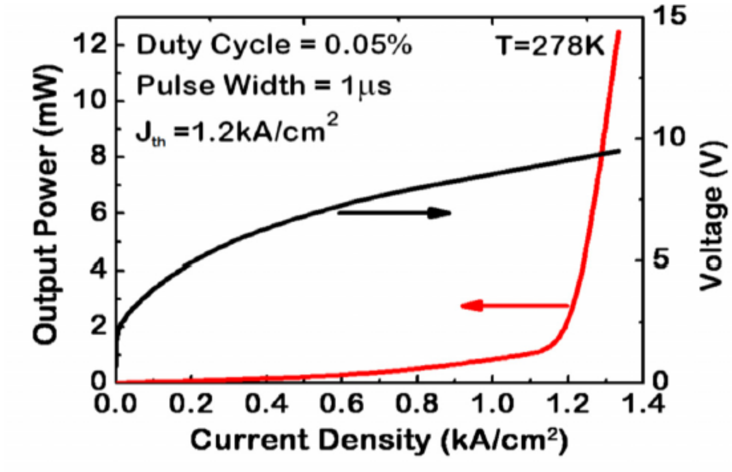
APPLIED PHYSICS LETTERS 98, 221104 (2011)

# A InGaN/GaN quantum dot green (λ=524 nm) laser

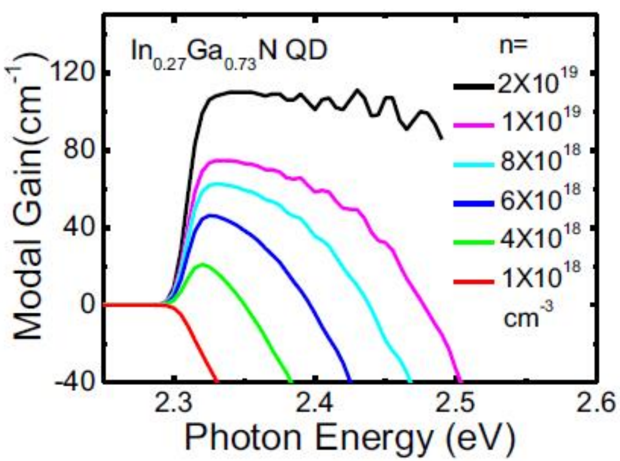
Meng Zhang, Animesh Banerjee, Chi-Sen Lee, John M. Hinckley, and Pallab Bhattacharya[a)]



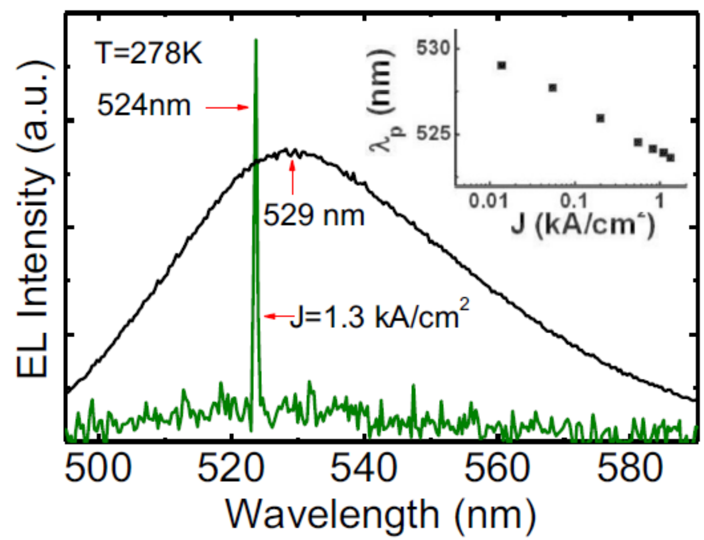

(a)




(a)

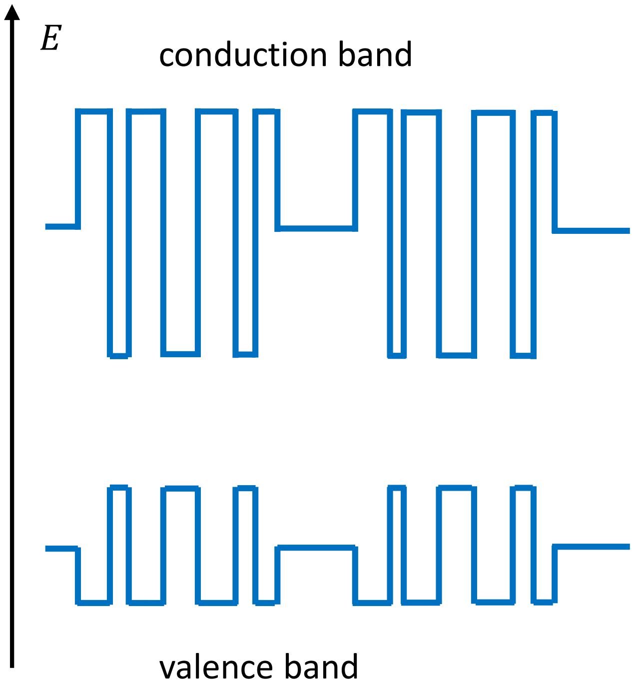


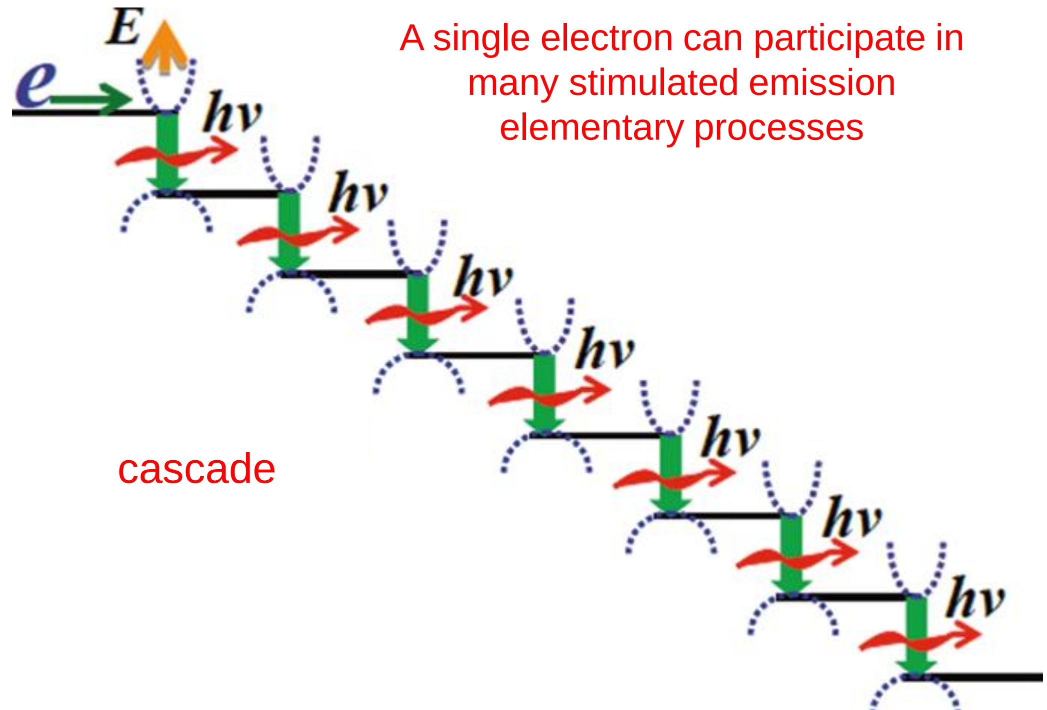

(b)




(b)

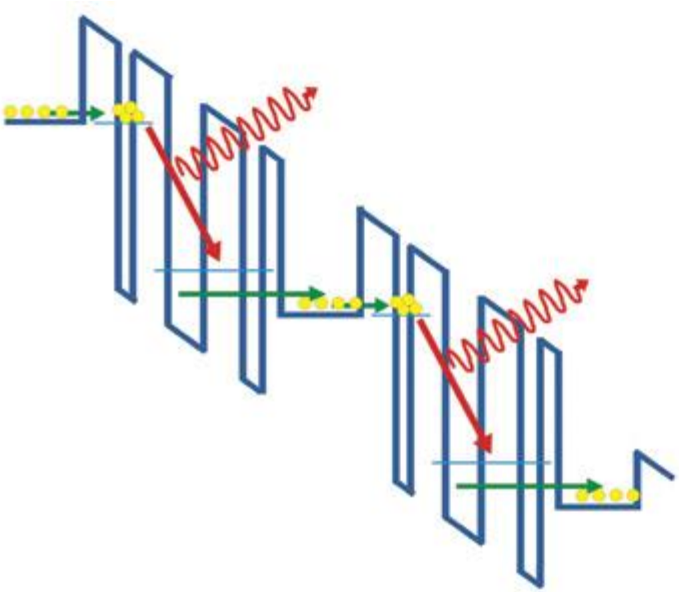
# quantum cascade laser



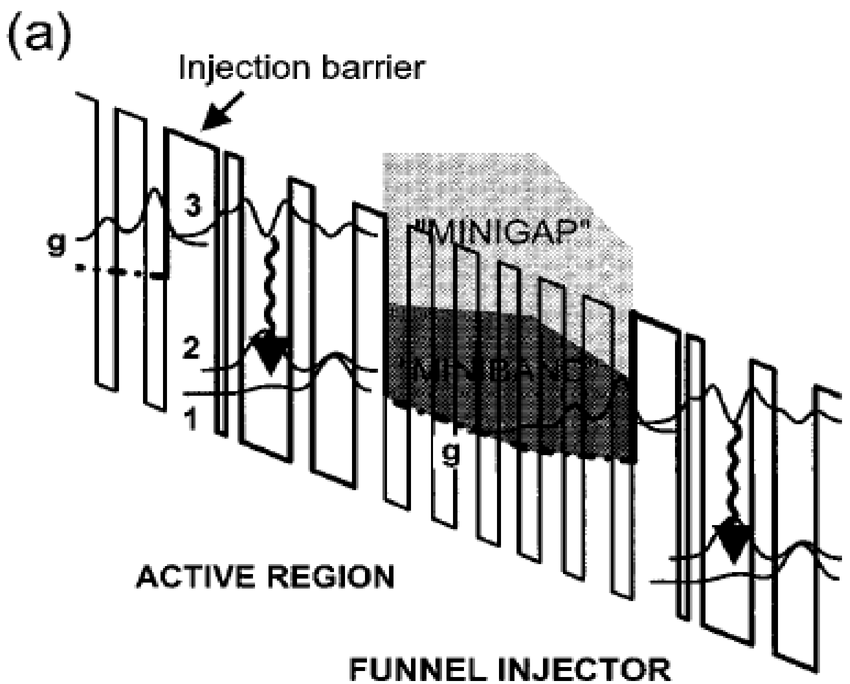

A single electron can participate in many stimulated emission elementary processes

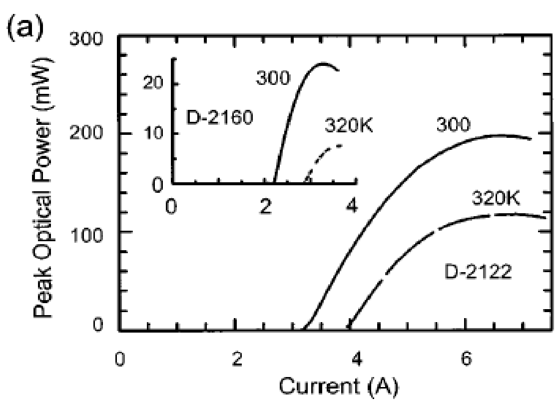
cascade

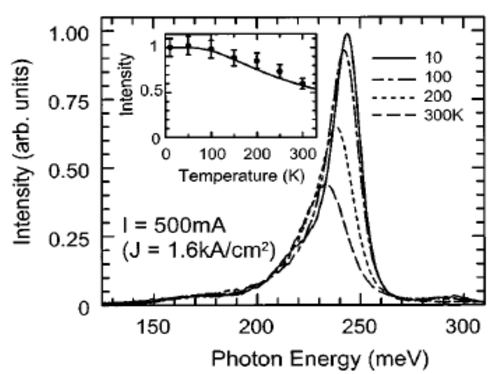


# quantum cascade laser, 2

Appl. Phys. Lett. 68 (26), 24 June 1996



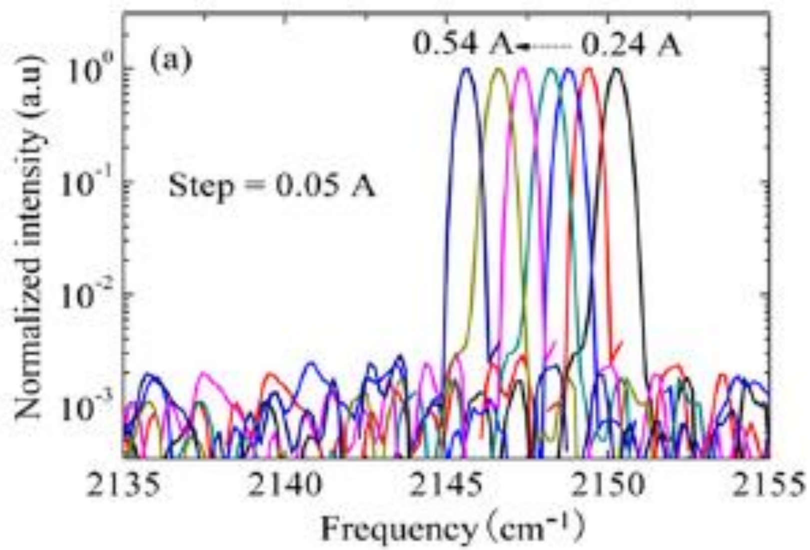



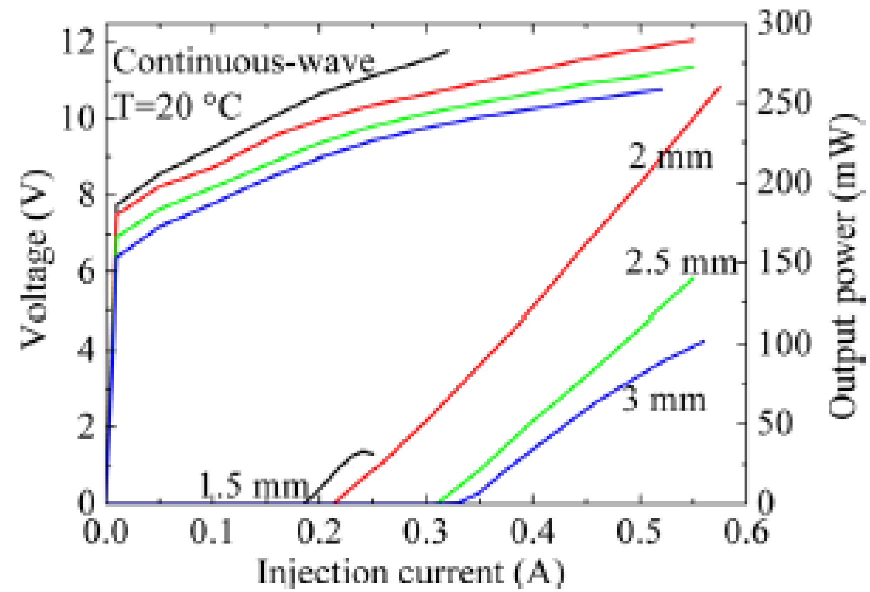



## High-performance uncooled distributed-feedback quantum cascade laser without lateral regrowth

J. C. Zhang,[1,2] F. Q. Liu,[1,a)] S. Tan,[1] D. Y. Yao,[1] L. J. Wang,[1,b)] L. Li,[1] J. Q. Liu,[1] and Z. G. Wang[1]

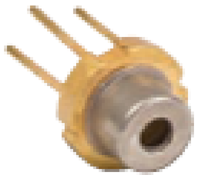
APPLIED PHYSICS LETTERS **100**, 112105 (2012)



# UV semiconductor lasers

## λ = 375 nm, P = 20 mW, Single Mode Thorlabs L375P020MLD

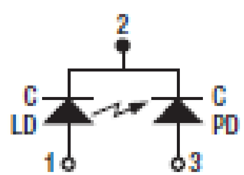


**S05LM9** Included

CAUTION: ELECTROSTATIC SENSITIVE

- Ø5.6 mm Package
- 20 mW (Typical) Optical Output Power (CW)
- 1.2 W/A (Typical) Slope Efficiency

**Pin Description**
1 laser anode
2 common case (cathode)
3 monitor diode anode




PIN CODE B

NEW product

| ITEM # | $ | £ | € | RMB | DESCRIPTION |
|---|---|---|---|---|---|
| L375P020MLD* | CALL | CALL | CALL | CALL | Thorlabs 375 nm, 20 mW |

*Ships with S05LM9, an SM05-compatible mount for Ø5.6 mm and Ø9 mm packages

### Maximum Ratings ($T_C$ = 25 °C)

| CHARACTERISTIC | SYMBOL | MAX RATING |
|---|---|---|
| Optical Output Power (CW) | $P_o$ | 30 mW* |
| LD Reverse Voltage | $V_{R(LD)}$ | 5 V |
| PD Reverse Voltage | $V_{R(PD)}$ | 20 V |
| Operation Case Temperature | $T_{op}$ | 20 to 30 °C |
| Storage Temperature | $T_{stg}$ | -40 to 85 °C |

*20 mW Typical

### Characteristics ($T_C$ = 25 °C, P = 20 mW)

| CHARACTERISTIC | SYMBOL | MIN | TYP. | MAX |
|---|---|---|---|---|
| Lasing Wavelength | $\lambda_p$ | 370 nm | 375 nm | 380 nm |
| Threshold Current | $I_{th}$ | – | 45 mA | 60 mA |
| Operating Current | $I_{op}$ | – | 60 mA | 85 mA |
| Operating Voltage | $V_{op}$ | 4.5 V | 5.2 V | 6.5 V |
| Beam Divergence (FWHM) | $\theta_{//}$ | 5° | 8.5° | 13° |
| | $\theta_{\perp}$ | 18° | 22° | 26° |
| Slope Efficiency | $\eta_s$ | 0.9 mW/mA | 1.2 mW/mA | 1.6 mW/mA |
| Monitor Current | $I_m$ | – | 0.2 mA | – |

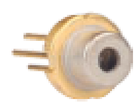
Note: All data are presented as typical unless otherwise specified.

# UV semiconductor lasers



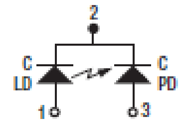
## λ = 405 nm, P = 5 mW, Single Mode Sanyo DL3146-151

- Ø5.6 mm Package
- 405 nm (Typical) Wavelength
- 5 mW Output Power (CW)
- 35 mA (Typical) Threshold Current

**Pin Description**

1 laser anode
2 common case (cathode)
3 monitor diode anode




PIN CODE B

| ITEM # | PRICE 1-5 PCS | PRICE 6-10 PCS | PRICE 11-20 PCS | DESCRIPTION |
|---|---|---|---|---|
| DL3146-151 | CALL | CALL | CALL | Sanyo 405 nm, 5 mW |

### Maximum Ratings ($T_C$ = 25 °C)

| CHARACTERISTIC | SYMBOL | MAX RATING |
|---|---|---|
| Optical Output Power (CW) | $P_o$ | 7 mW* |
| LD Reverse Voltage | $V_{R(LD)}$ | 2 V |
| PD Reverse Voltage | $V_{R(PD)}$ | 30 V |
| Operation Case Temperature | $T_{op}$ | 0 to 60 °C |
| Storage Temperature | $T_{stg}$ | -40 to 85 °C |

*5 mW Typical

### Characteristics ($T_C$ = 25 °C, P = 5 mW)

| CHARACTERISTIC | SYMBOL | MIN | TYP. | MAX |
|---|---|---|---|---|
| Lasing Wavelength | $\lambda_p$ | 400 nm | 406 nm | 413 nm |
| Threshold Current | $I_{th}$ | – | 33 mA | 55 mA |
| Operating Current | $I_{op}$ | – | 40 mA | 60 mA |
| Operating Voltage | $V_{op}$ | – | 5.0 V | 6.0 V |
| Beam Divergence | θ// | 6° | 8° | 14° |
| (FWHM) | θ⊥ | 16° | 20° | 24° |
| Slope Efficiency | $\eta_s$ | 0.5 mW/mA | 0.8 mW/mA | – |
| Monitor Current | $I_m$ | 0.1 mA | 0.2 mA | 1.0 mA |

Note: All data are presented as typical unless otherwise specified.

## λ = 405 nm, P = 10 mW, Single Mode Sanyo DL4146-101S

**NEW product**

### Maximum Ratings ($T_C$ = 25 °C)

| CHARACTERISTIC | SYMBOL | MAX RATING |
|---|---|---|
| Optical Output Power (CW) | $P_o$ | 20 mW* |
| LD Reverse Voltage | $V_{R(LD)}$ | 2 V |
| PD Reverse Voltage | $V_{R(PD)}$ | – |
| Operation Case Temperature | $T_{op}$ | 0 to 75 °C |
| Storage Temperature | $T_{stg}$ | -40 to 85 °C |

*10 mW Typical


**Pin Description**

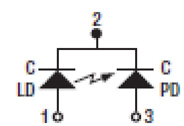
1 laser anode
2 common case (cathode)
3 monitor diode anode

### Characteristics ($T_C$ = 25 °C, P = 10 mW)

| CHARACTERISTIC | SYMBOL | MIN | TYP. | MAX |
|---|---|---|---|---|
| Lasing Wavelength | $\lambda_p$ | 395 nm | 405 nm | 415 nm |
| Threshold Current | $I_{th}$ | – | 26 mA | 50 mA |
| Operating Current | $I_{op}$ | – | 35 mA | 60 mA |
| Operating Voltage | $V_{op}$ | – | 4.8 V | 5.6 V |
| Beam Divergence | θ// | 6° | 8.5° | 12° |
| (FWHM) | θ⊥ | 16° | 19° | 23° |
| Slope Efficiency | $\eta_s$ | 0.7 mW/mA | 1.1 mW/mA | – |
| Monitor Current | $I_m$ | 0.1 mA | 0.2 mA | 0.5 mA |

Note: All data are presented as typical unless otherwise specified.

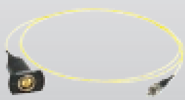
- Ø5.6 mm Package
- 10 mW (Typical) Output Power (CW)
- 1.1 mW/mA (Typical) Slope Efficiency




PIN CODE B

| ITEM # | PRICE 1-5 PCS | PRICE 6-10 PCS | PRICE 11-20 PCS | DESCRIPTION |
|---|---|---|---|---|
| DL4146-101S | CALL | CALL | CALL | Sanyo 405 nm, 10 mW |

405 nm Pigtailed Laser Diode



Available with Single Mode Fiber

See page 1253

# **VIS semiconductor lasers** example LASOS

## Laser diode modules fiber coupled

| | VLD F | | | | BLD F | | | GLD F | RLD F | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wavelength [nm] | 405 | 415 | 425 | 445 | 460 | 473 | 488 | 515 | 638 | 642 | 660 | 685 |
| Output power [mW] | 50 | 50 | 50 | 40 | 40 | 35 | 30 | 10 | 50 | 60 | 50 | 25 |

| | |
|---|---|
| Fiber Coupling | Pigtail |
| Fiber type | Single mode, polarization maintaining |
| Fiber length | 2 m, others on request |
| Fiber connector | FC 8° polish, others on request |
| Fiber jacket | Standard: 3 mm PVC (PVC) |

# 1kW, Fiber-Coupled, Multi-Bar Module

DILAS
The diode laser company.

| Electrical Parameters[1] | | |
|---|---|---|
| Power Conversion Efficiency | % | 35% |
| Threshold Current ($I_{TH}$) | A | <8 |
| Operating Current ($I_{OP}$) | A | <75 |
| Operating Voltage ($V_{OP}$) | V | <48 |

| Thermal Parameters | | |
|---|---|---|
| Operating Temperature[2, 3, 4] | °C | +20 to +25 |
| Storage Temperature | °C | 0 to +55 |
| Flow | L/h | 500 |
| Operating Water Temperature | °C | 20 to 25 |
| Purity | µm | 10 / deionized |
| Recommended Cooling Capacity | W | 2500 |

# 1kW, Fiber-Coupled, Multi-Bar Module

DILAS
The diode laser company.


| Optical Parameters | Units | |
|---|---|---|
| Center Wavelength (Range)[1, 3] | nm | 976 |
| Center Wavelength Tolerance | nm | ±3 |
| Output Power[3] | W | 1000 |
| Spectral Width (FWHM) | nm | 5 |
| Slope Efficiency | W/A | 16 |
| Wavelength Temp. Coefficient[2] | nm/°C | ~0.38 |

| Fiber Parameters | | | |
|---|---|---|---|
| Numerical Aperture | NA | 0.2 | 0.12 |
| Fiber Core Diameter | µm | 400 | 800 |
| Fiber Connector | | QBH or LLK-HP (Q5) | QBH or LLK-HP (Q5) |