Lasers

lecture 10

Czesław Radzewicz

energy band structure in semiconductors

crystal lattice ⇒ periodic potential

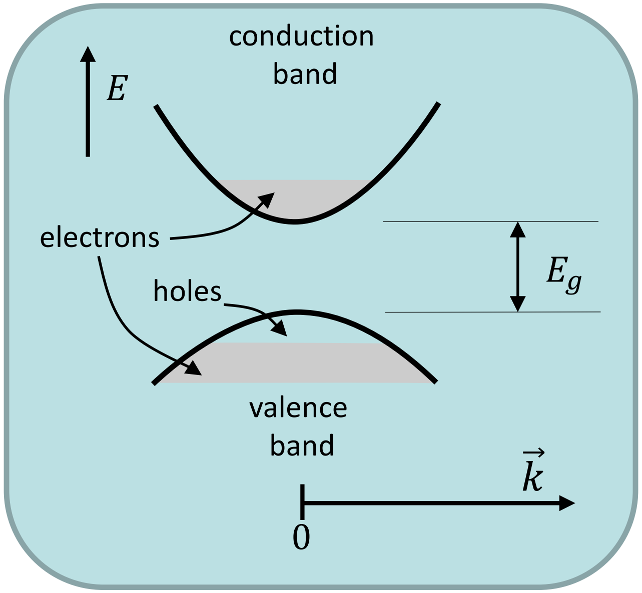
electron wave function

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

↖ periodic function

....

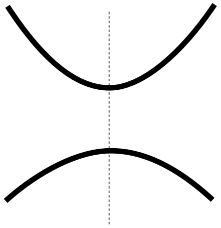
consequences:



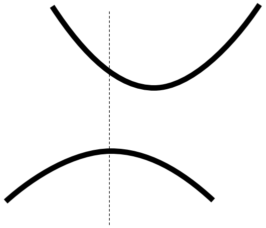
	E_g (eV)
C (diam.)	5.47
GaP	2.26
GaAs	1.43
Si	1.12
InSb	0.17

important distinction:

direct bandgap

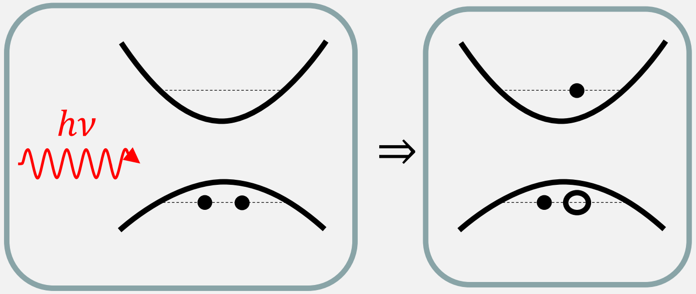


indirect bandgap

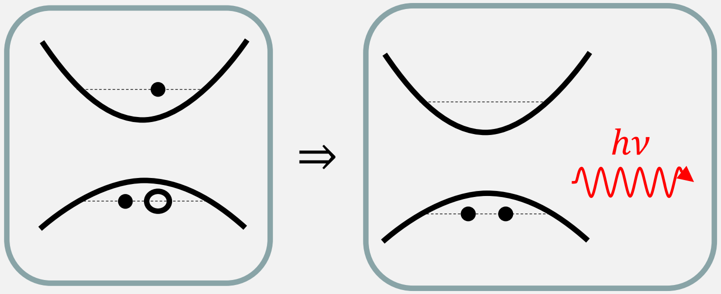


radiative processes in semiconductors

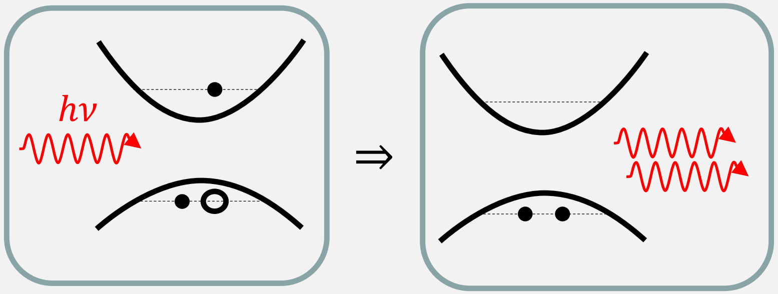
absorption



spontaneous emission



stimulated emission



conservation principles

energy and momentum:

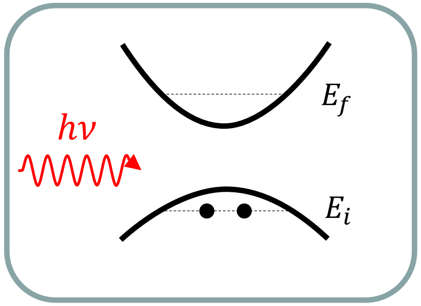
$$E_i + h\nu = E_f$$

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

momentum before absorption

photon momentum

momentum after absorption



numbers:

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

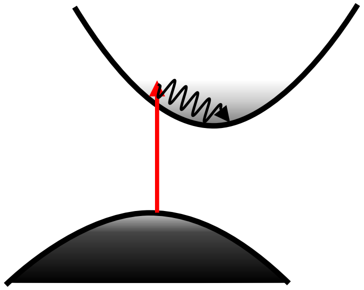
photon $\quad |\hbar\vec{k}_p| = \frac{h}{\lambda} \approx 8\cdot 10^{-28}$ kgm/s $\quad$ (λ=800nm)

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

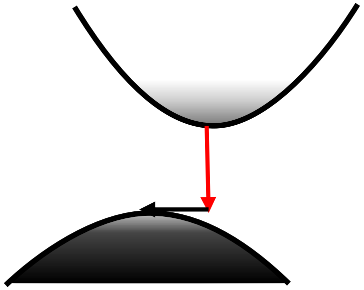
$$\vec{k}_f \cong \vec{k}_i$$

radiative transitions in semiconductor are „vertical”

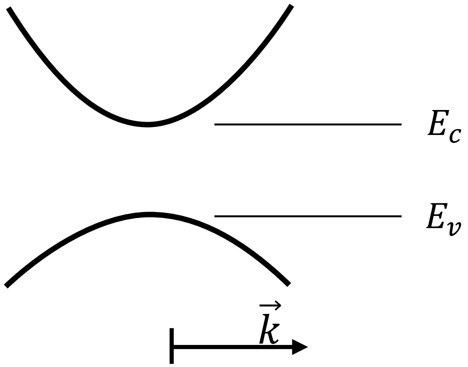
in semiconductors with indirect band gap, e.g. Si absorption is allowed. We can build very good photodetectors out of Si.

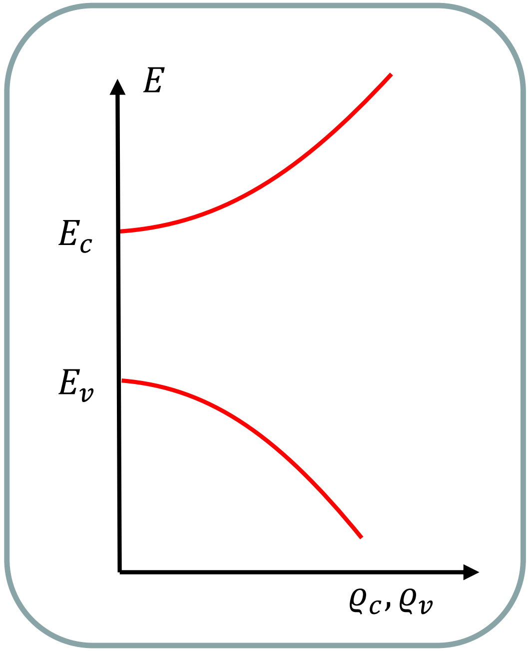


in semiconductors with indirect band gap radiative electron-hole recombination requires a photon to fulfill the momentum conservation rule. Thus radiative recombination has little probability – we cannot have light gain and thus build lasers.



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):

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

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

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

ϱ_v and ϱ_c have units $\frac{1}{\mathrm{m^3 J}}$

interpretation:

- for given ΔE 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

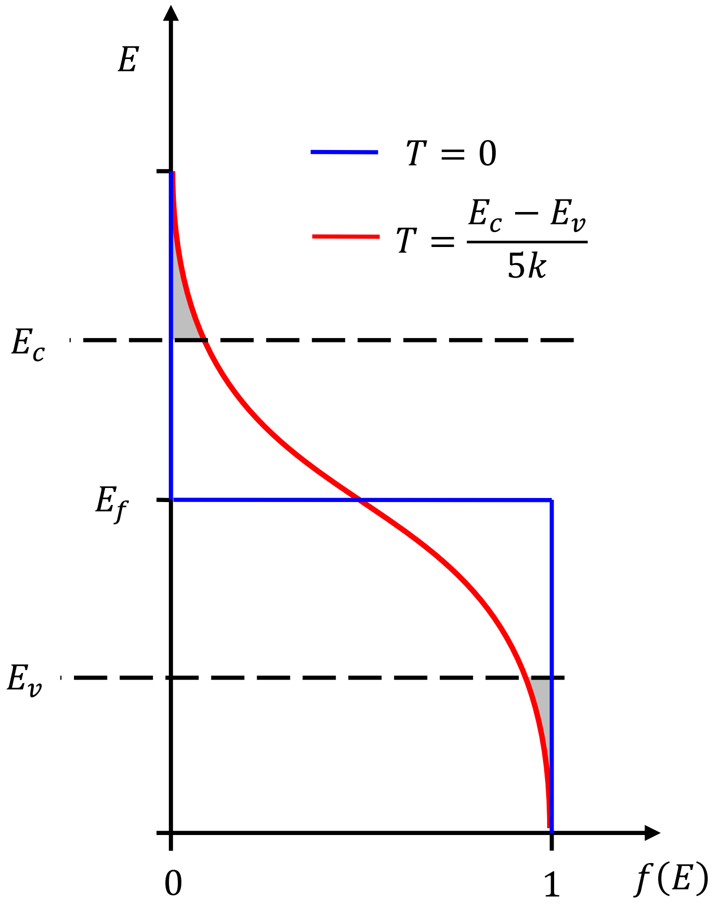
electrons are fermions

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

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

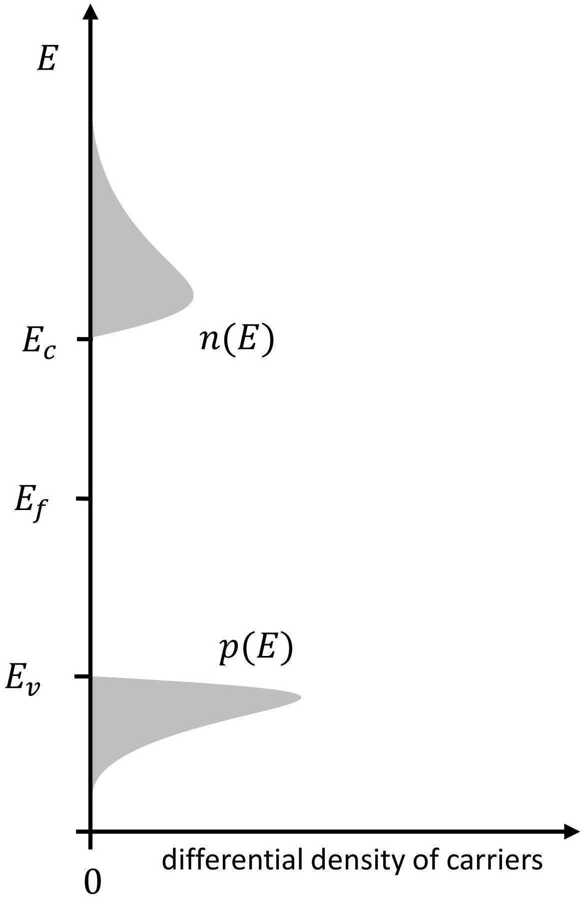
$$\frac{1}{\mathrm{m^3}}$$

$$n = \int_{E_c}^{\infty} n(E)dE$$

density of holes

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

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

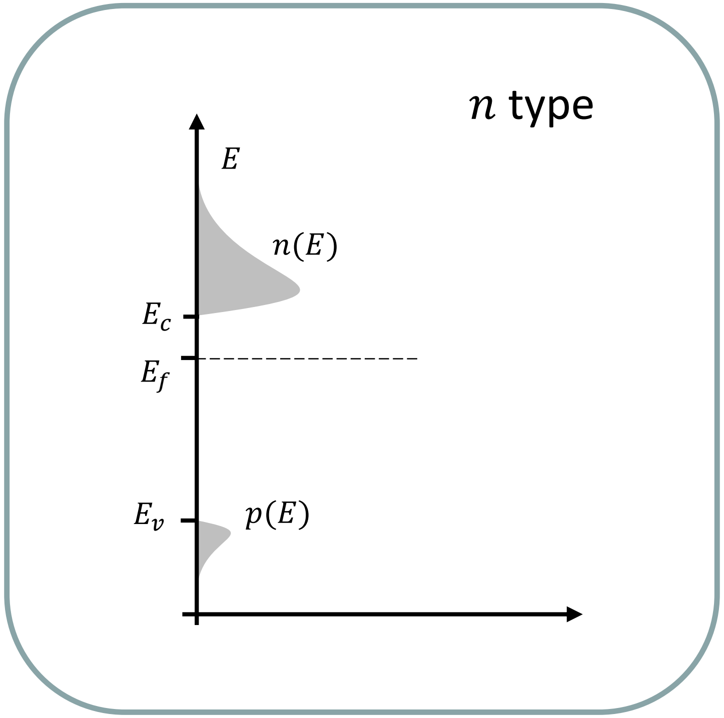


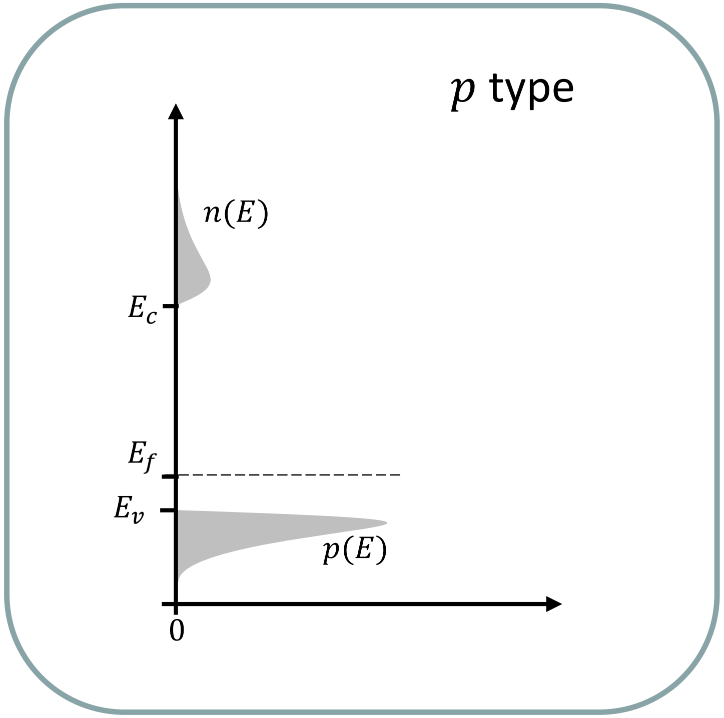
doped semiconductors

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.

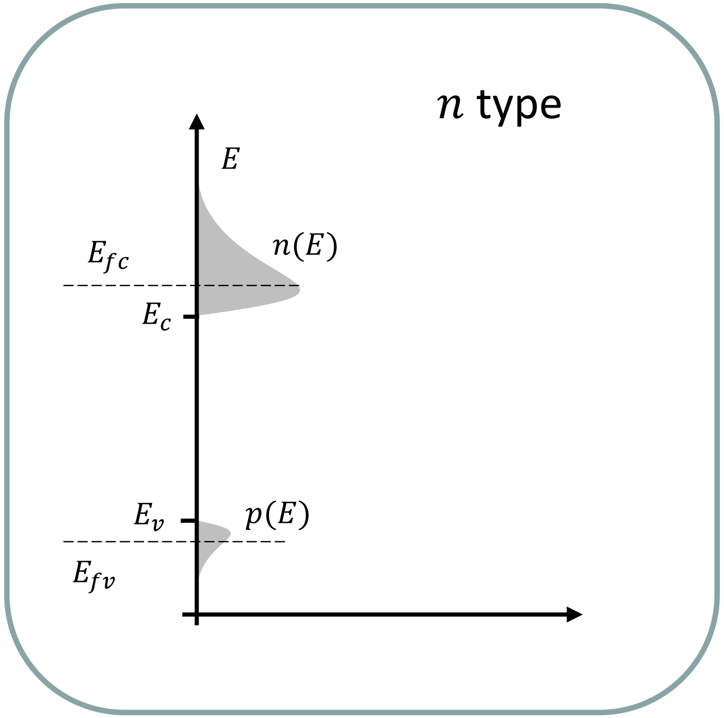


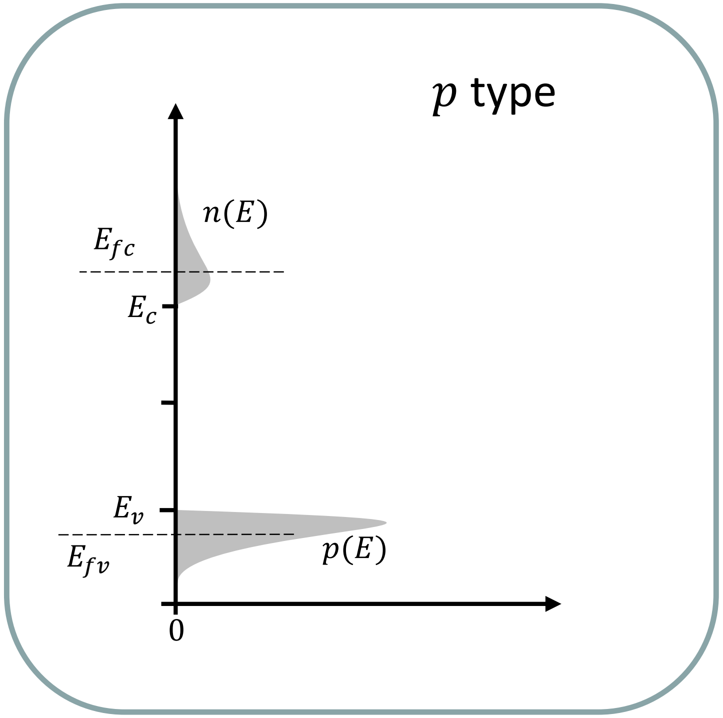


doped semiconductors with optical pumping or current injection

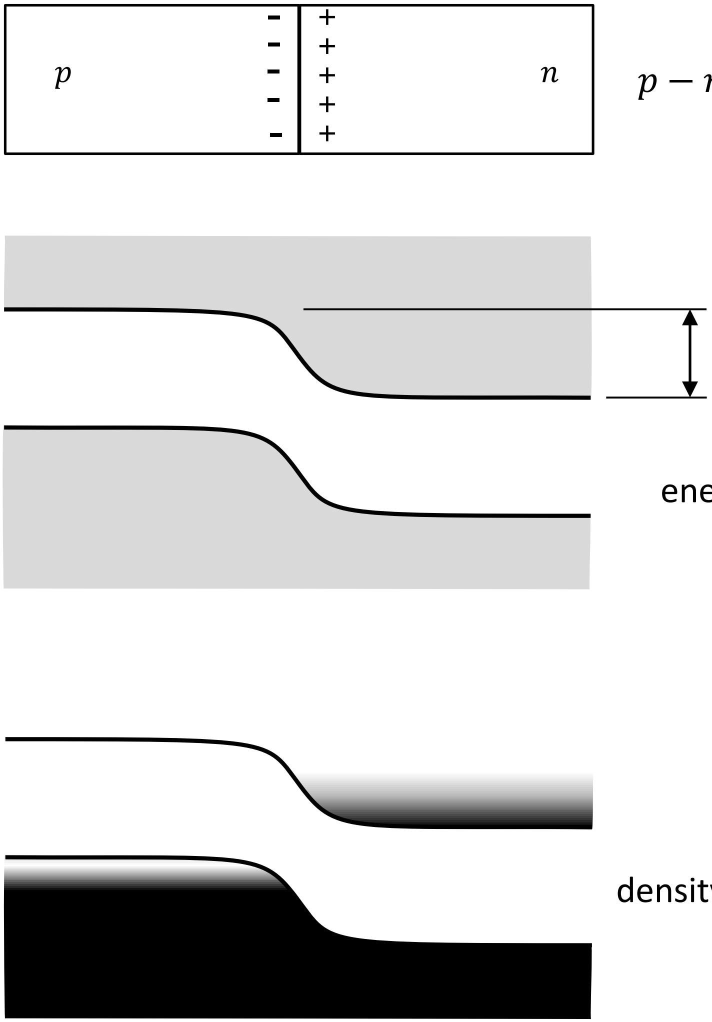
Two types of dopants: n (excessive number of electrons) and p (excessive number of holes) $n \neq p$

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}


n type


p type

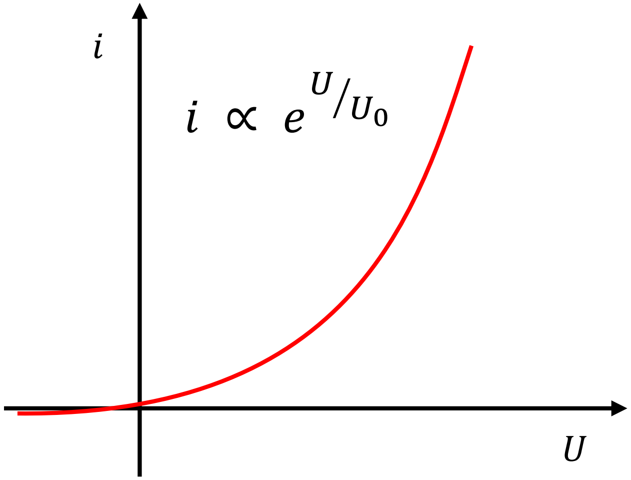
$p-n$ junction



$p-n$ junction

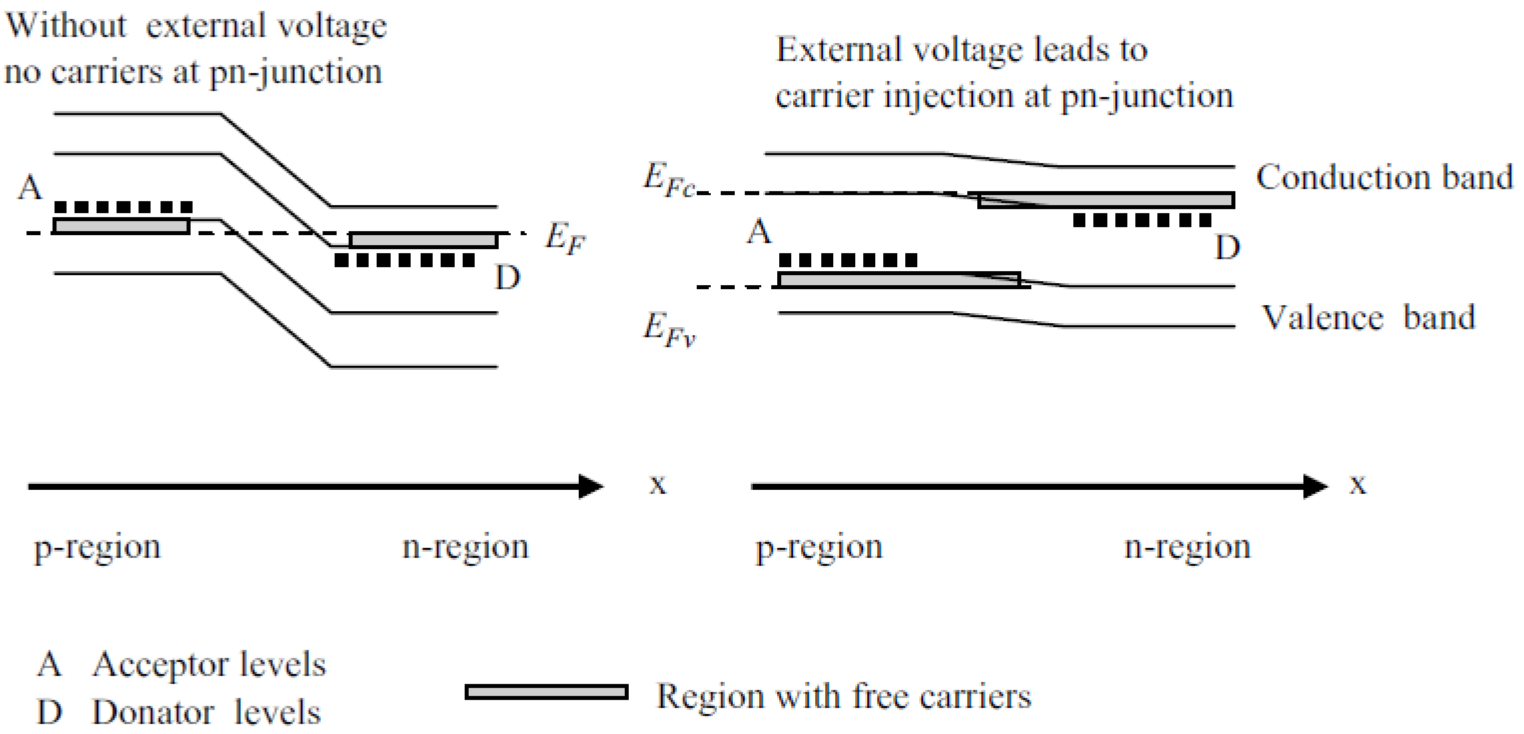
energy bands

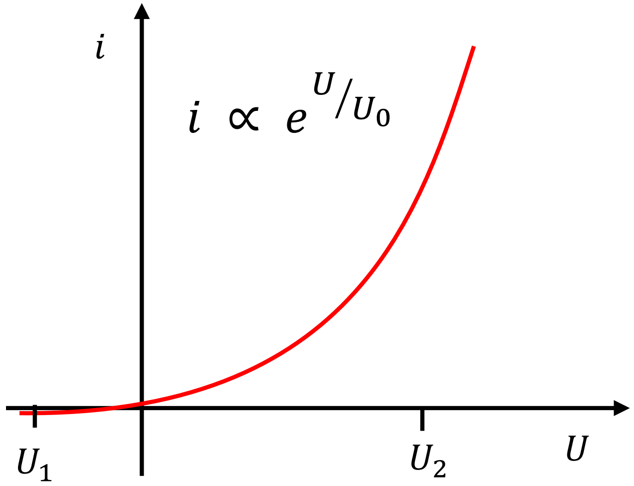
density of carriers



$i \propto e^{U/U_0}$

polaryzacja złącza $p - n$

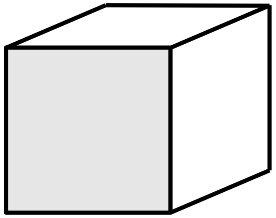




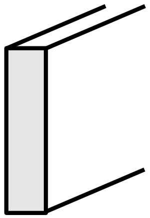
W łączu są obecne równocześnie dziury i elektrony –
możliwa jest rekombinacja promienista –
wzmacnianie światła

energia fotonu ≈ szerokość przerwy energetycznej

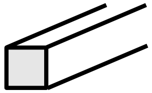
low-D structures



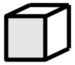
volume crystal
(3D)



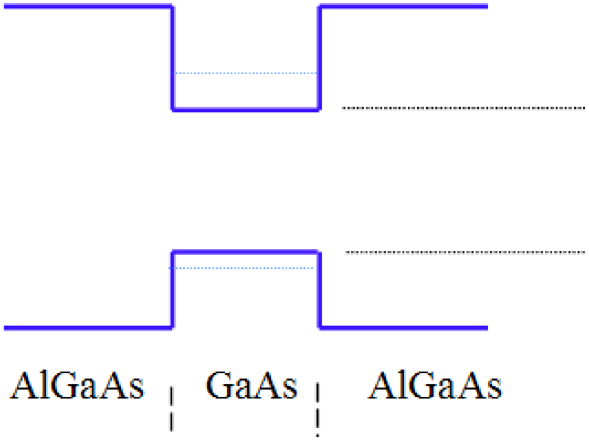
quantum well
(2D)



quantum wire
(1D)



quantum dot
(0D)

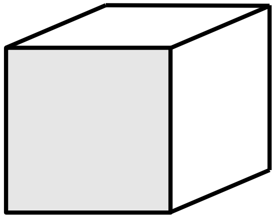


- In a quantum well the motion of electron along the direction normal to the well is quantized – the energy levels corresponding to this motion are discrete.
- The number of bound levels depends on the width and depth of the well
- The total energy of the carrier is the sum of the energy of discrete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

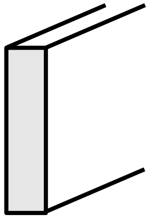
How can we build low-D structures? – semiconductor alloys

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

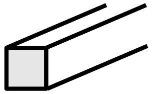
densities of electron states in low-D structures



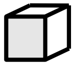
volume crystal
(3D)



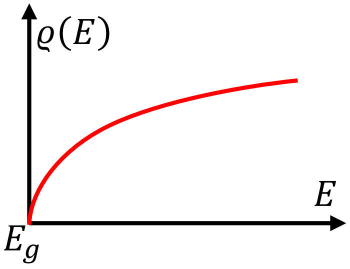
quantum well
(2D)

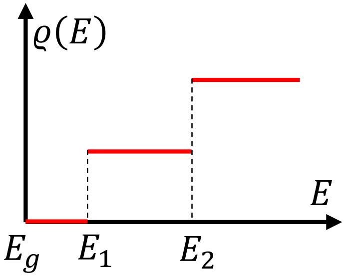


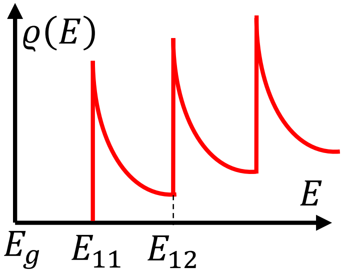
quantum wire
(1D)

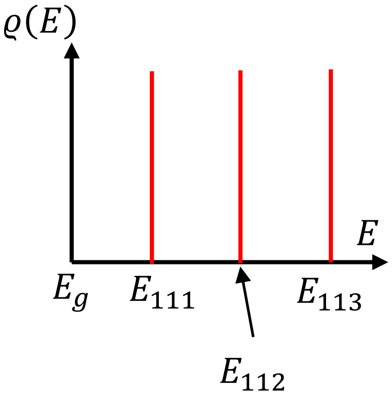


quantum dot
(0D)









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

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

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

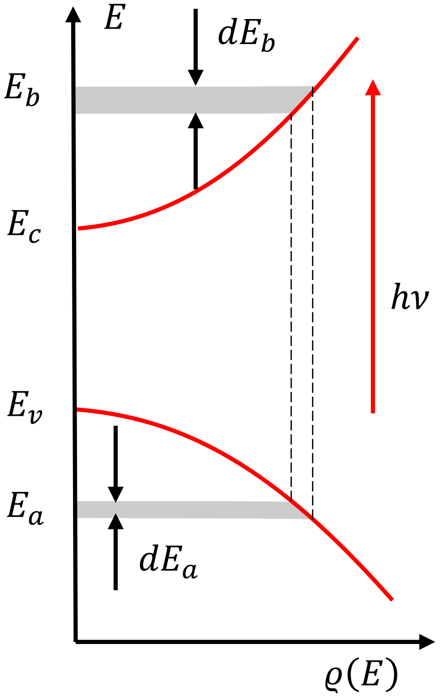
$$\varrho(E) = \frac{m}{2\pi\hbar^2}\frac{1}{L_z}$$

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

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

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

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 $T = 0$.

$$0 \leq f_c, f_v \leq 1$$

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.

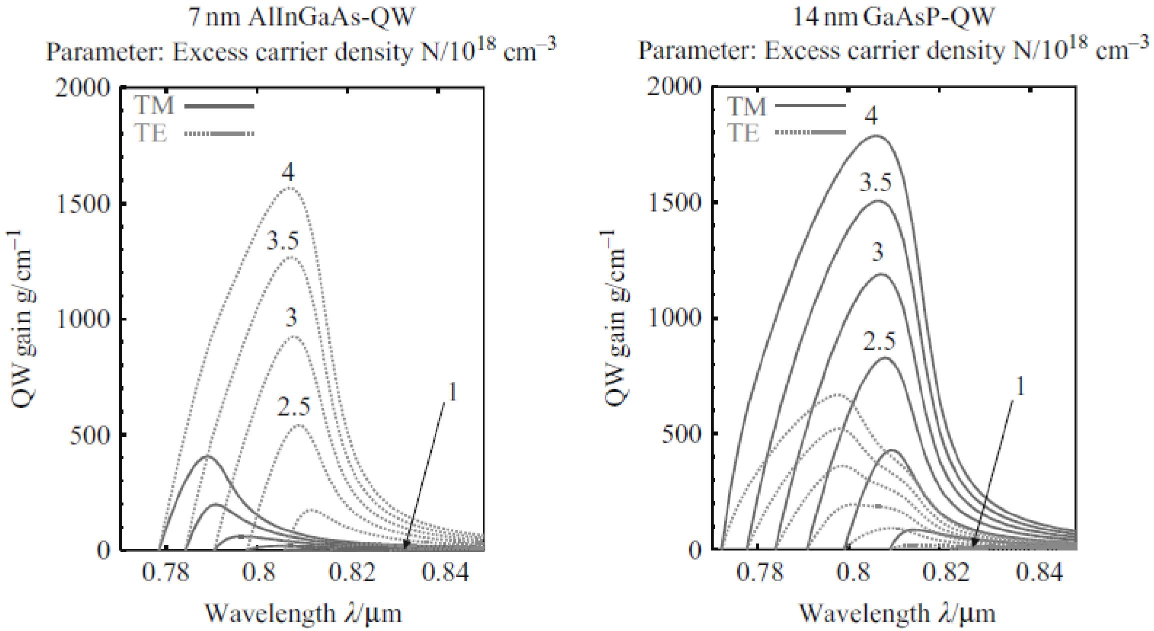


FIGURE 2.6. Calculated optical gain versus wavelength at different excitation levels for a compressively strained AlInGaAs-QW and a tensile-strained GaAsP-QW at 810 nm

semiconductor alloys

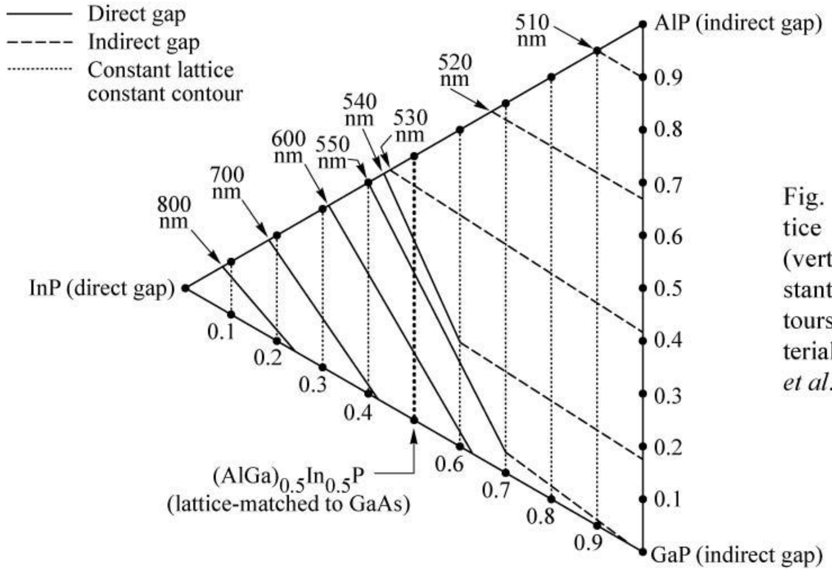
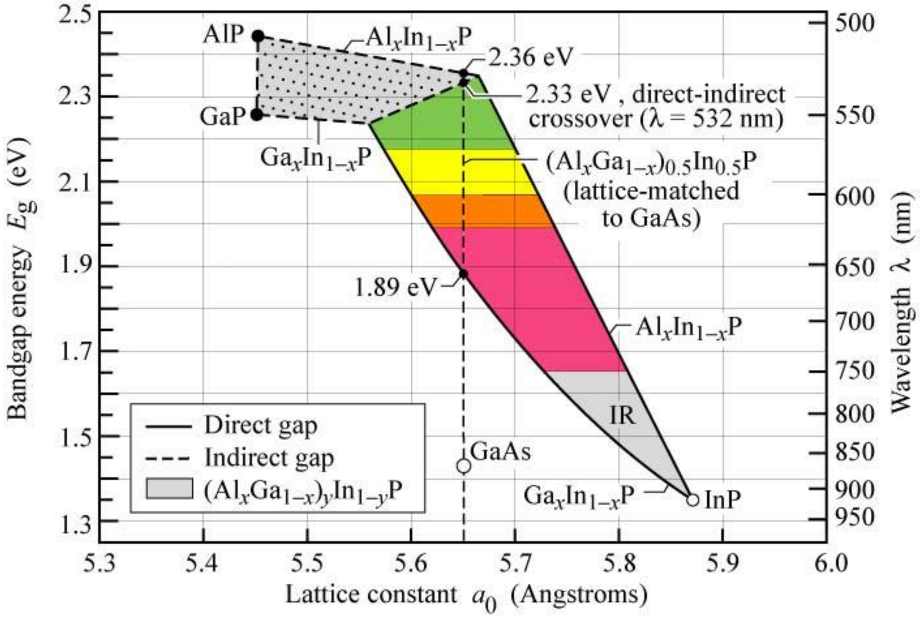


Fig. 12.11. Constant lattice constant contours (vertical lines) and constant emission line contours of the AlGaInP materials system (after Chen *et al.*, 1997).



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

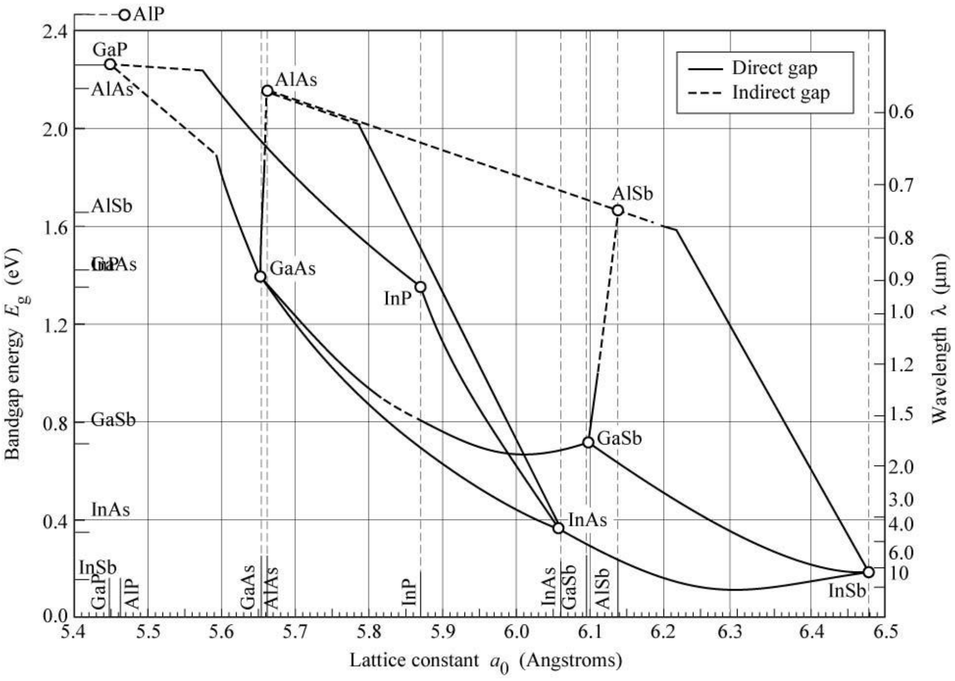
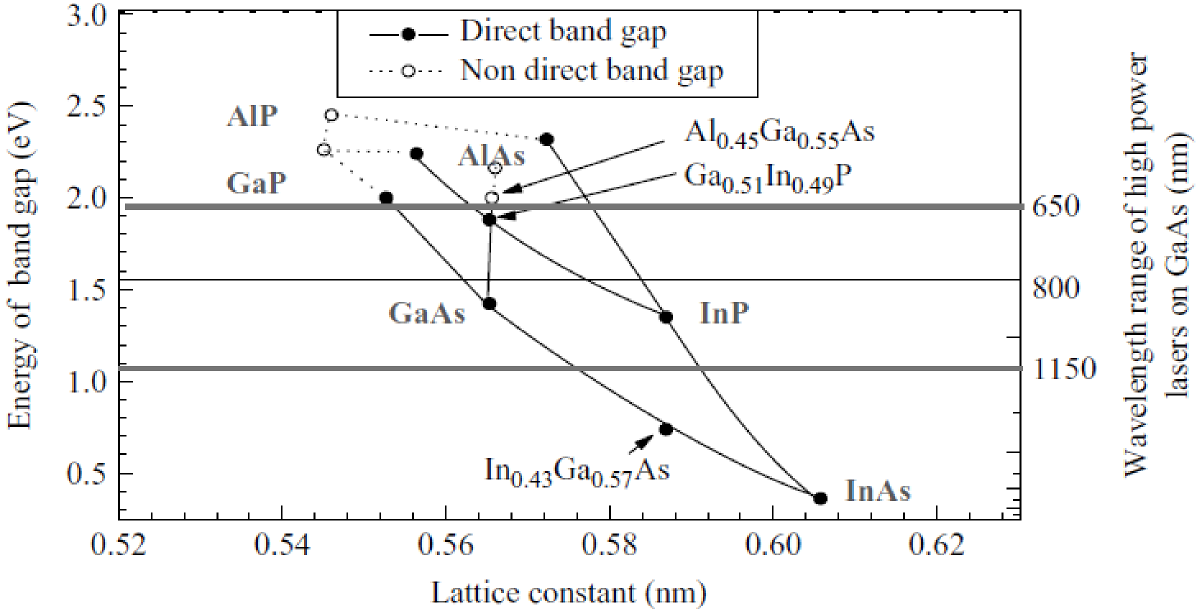


Fig. 12.6. Bandgap energy and lattice constant of various III–V semiconductors at room temperature (adopted from Tien, 1988).



Light Emiiting Diode (LED)

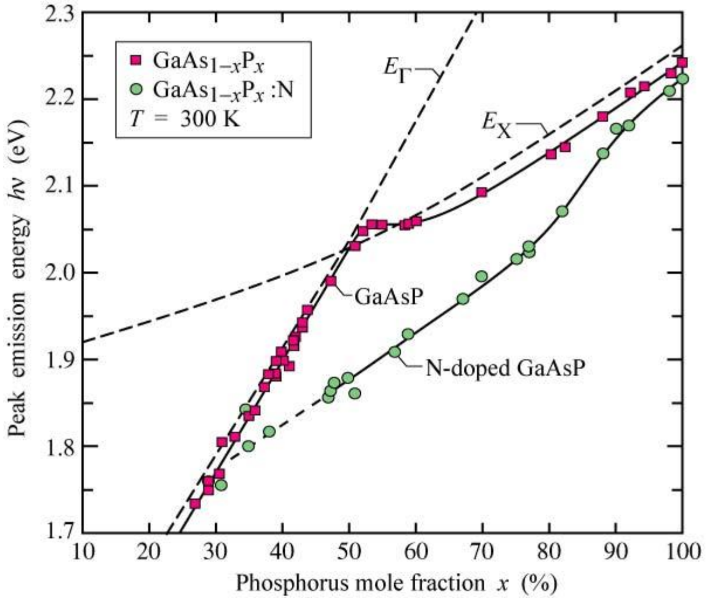


Fig. 12.2. Room-temperature peak emission energy versus alloy composition for undoped and nitrogen-doped GaAsP LEDs injected with a current density of 5 A/cm^2. Also shown is the energy gap of the direct-to-indirect (E_Γ-to-E_X) transition. The direct–indirect crossover occurs at $x \approx 50\,\%$ (after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

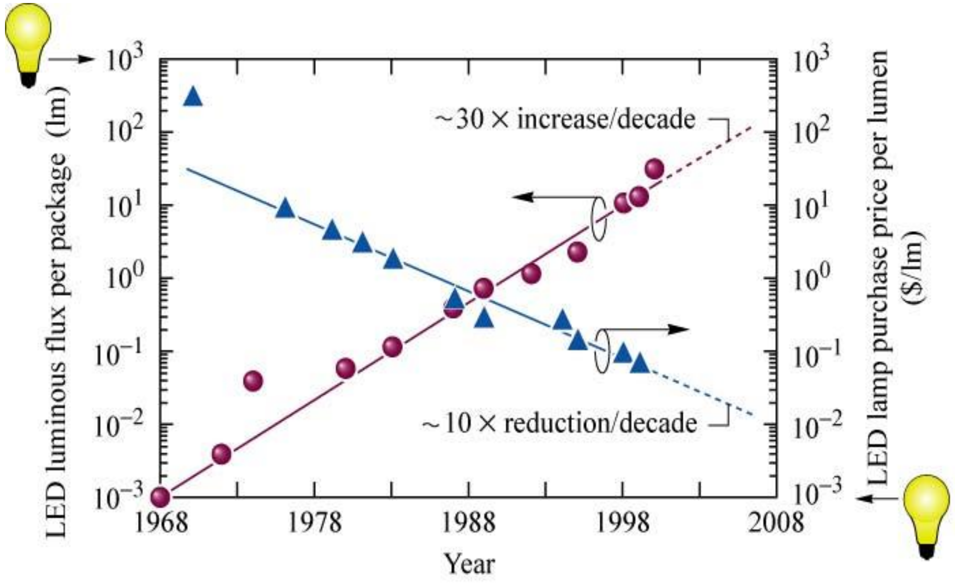


Fig. 12.15. LED luminous flux per package and LED lamp purchase price per lumen versus year. Also shown are the values for a 60 W incandescent tungsten-filament light bulb with a luminous efficiency of ~17 lm/W and a luminous flux of 1000 lm with an approximate price of 1.00 US$ (after Krames *et al*.,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

laser cavities for semiconductor lasers

Two major groups:

1. Lasers emitting at the edges, Fresnel reflections of the surfaces that form flat mirrors, eventually Bragg

advantage: large powers possible

disadvantage : strongly astigmatic output beam

Note that the dimensions of the structures are, typically, μm

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

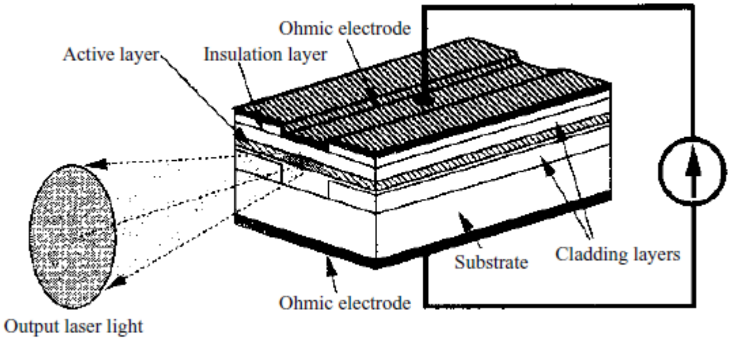
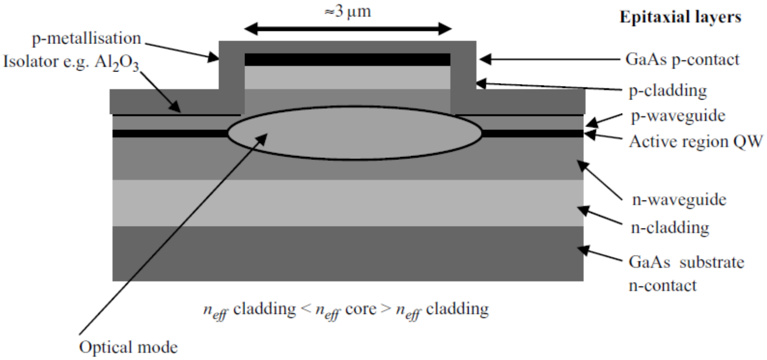
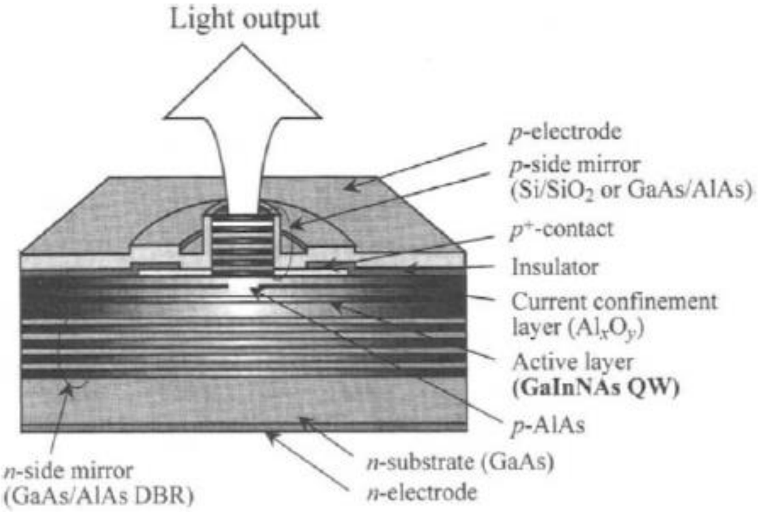


Figure 6.1 Schematic illustration of a double-heterostructure (DH) FP semiconductor laser.

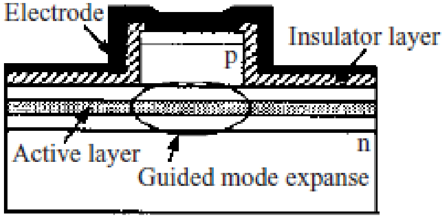




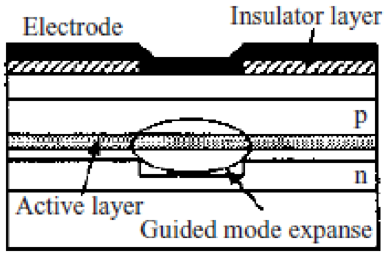
laser resonators for edge emitting lasers

Two methods for creating waveguides:

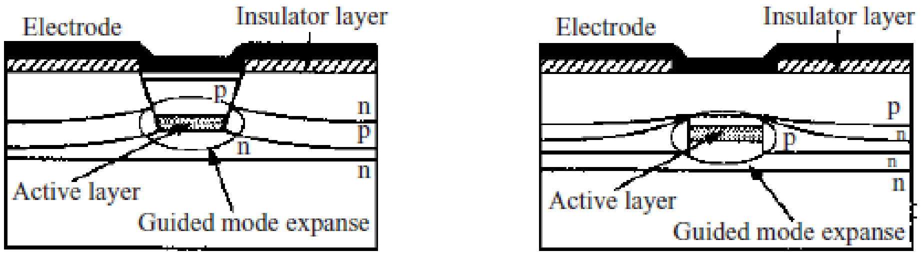
1. index guiding – the structure of the laser chip forms a waveguide which, together with end mirrors forma resonator



Ridge waveguide type



Rib waveguide type



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

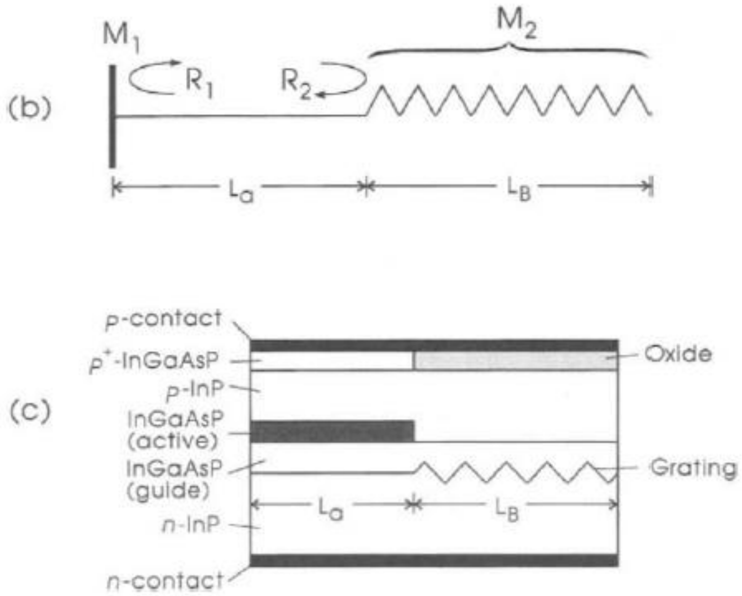
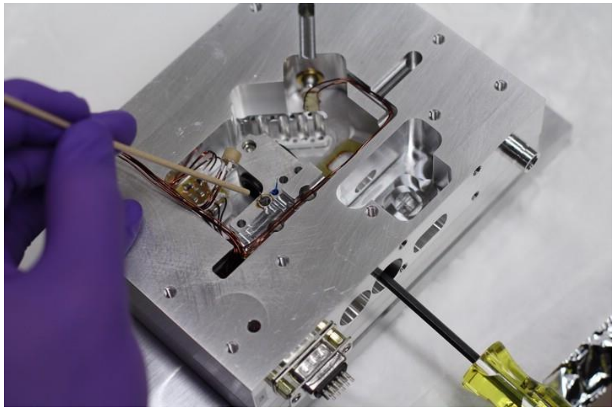


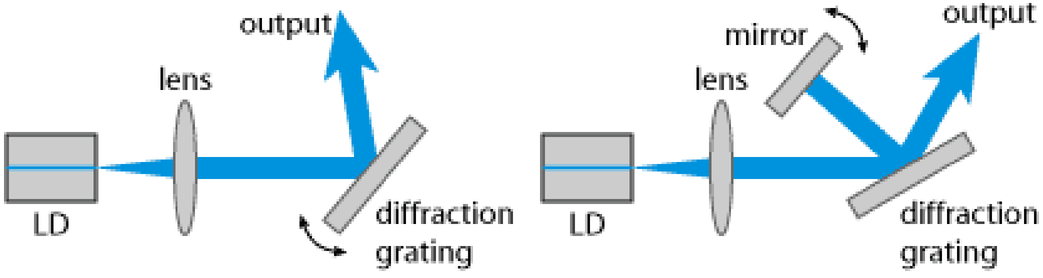
Figure 3.8: Distributed Bragg reflector (DBR) laser: (a) Both mirrors replaced by Bragg gratings. (b) One mirror replaced by a Bragg grating. (c) Schematic longitudinal view of InGaAsP/InP DBR laser.

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



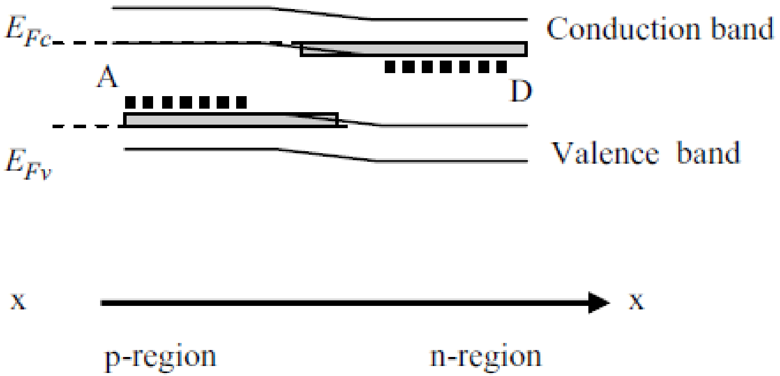


a) Littrow configuration

b) Littman-Metcalf configuration

from RP Photonics Encyclopedia

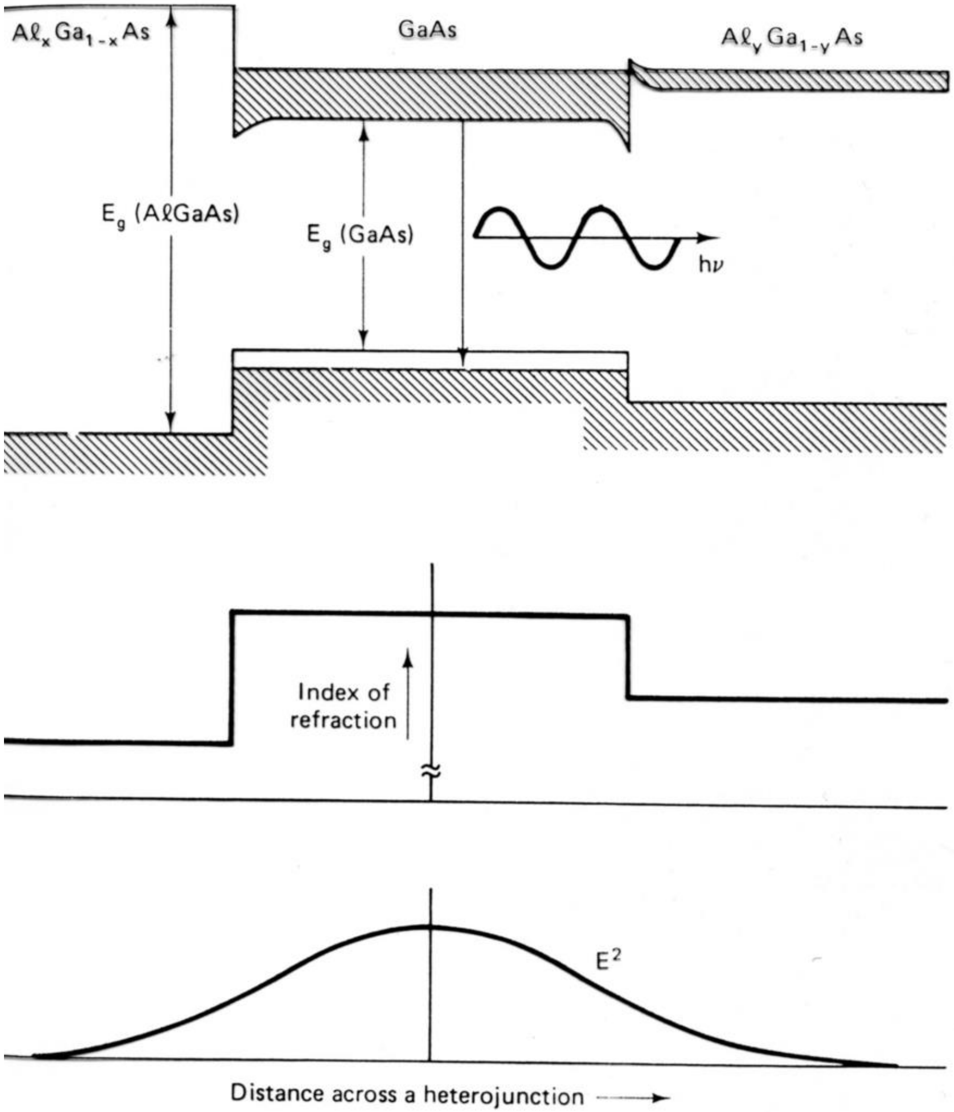
$n-p$ junction lasers



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.

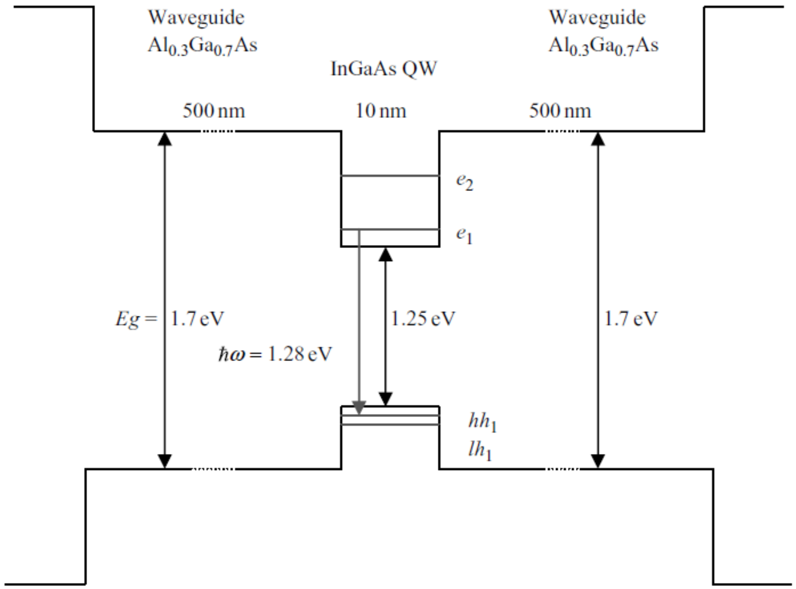
double heterojunction structure lasers



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

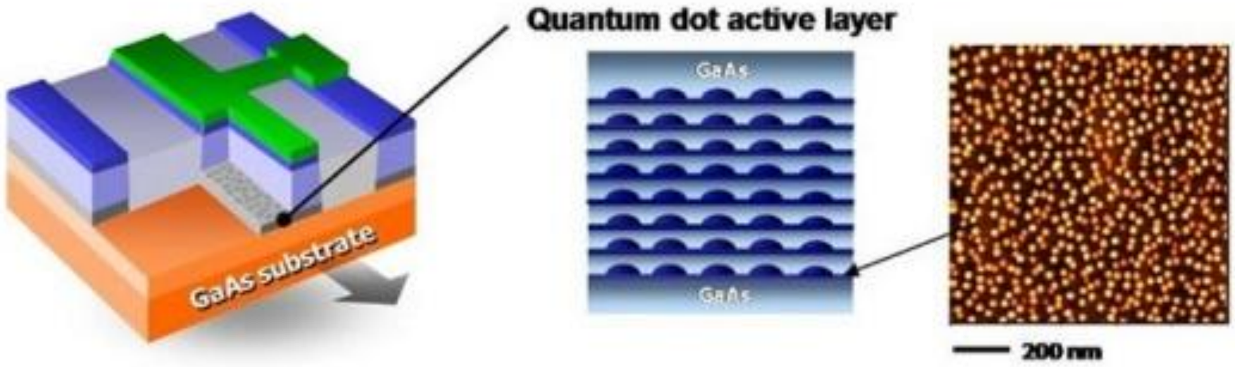


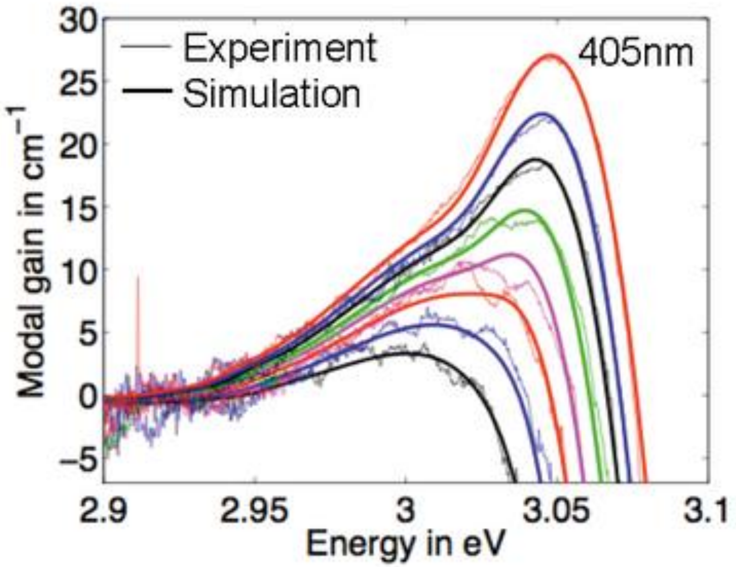
An example:

gain medium 10nm InGaAs quantum well

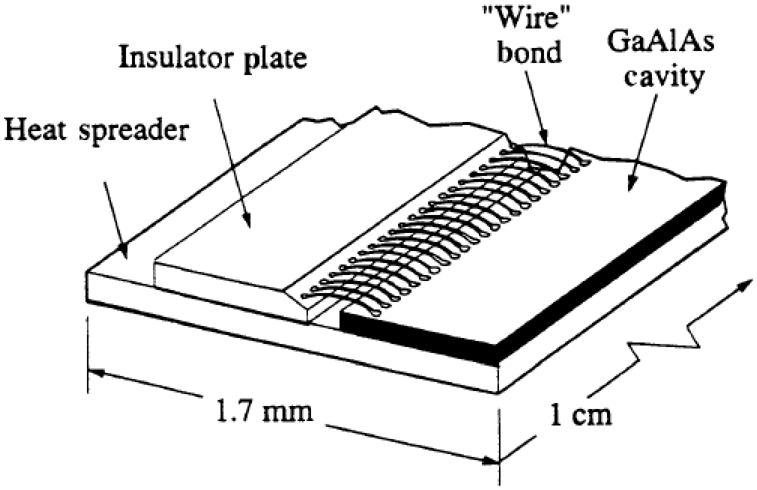
waveguide – double heterojunction

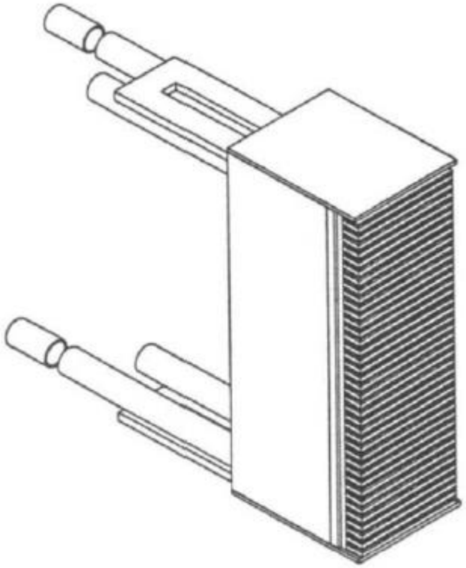
quantum dot semiconductor lasers



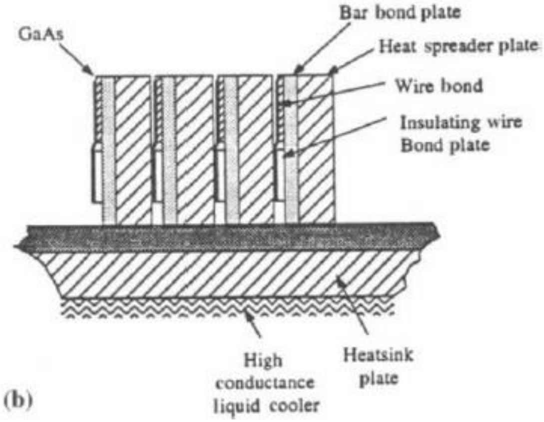


laser diode bar

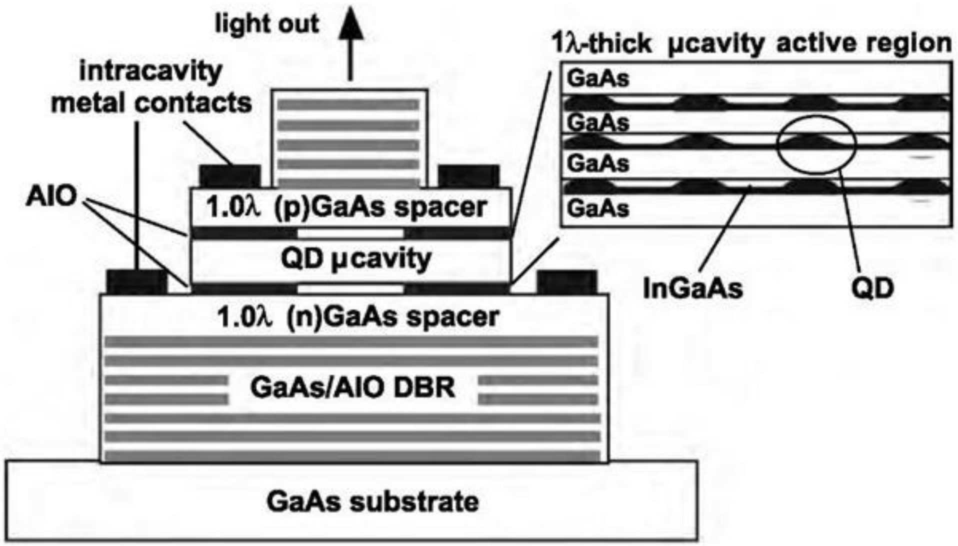




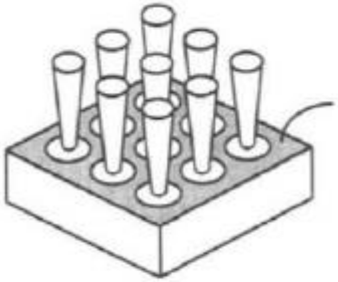
The power of a single diode laser is limited mostly by the limited ability to remove heat. Higher powers are achieved by stacking many chips and providing efficient cooling to each individual laser.



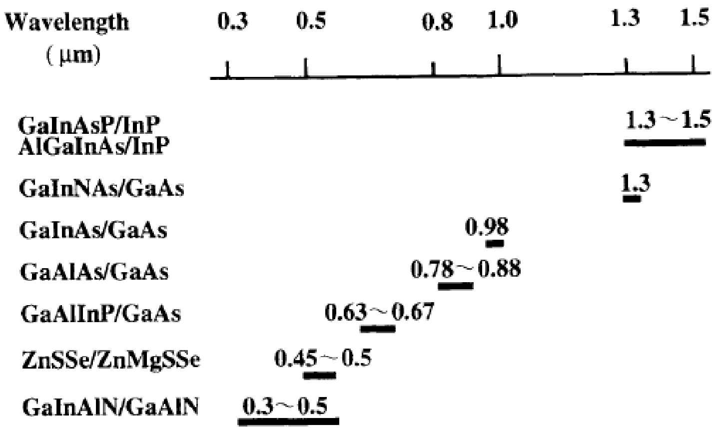
Vertical Cavity Surface Emitting Laser (VCSEL)



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

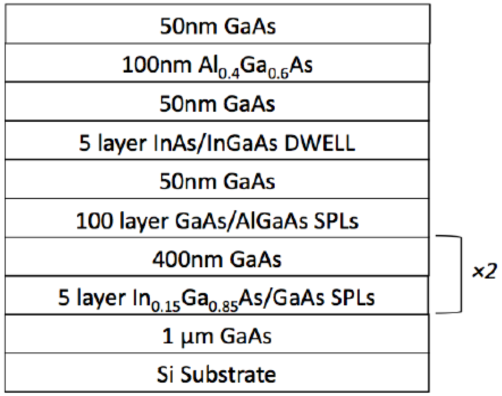


VCSEL laser matrices



hybrid technologies

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

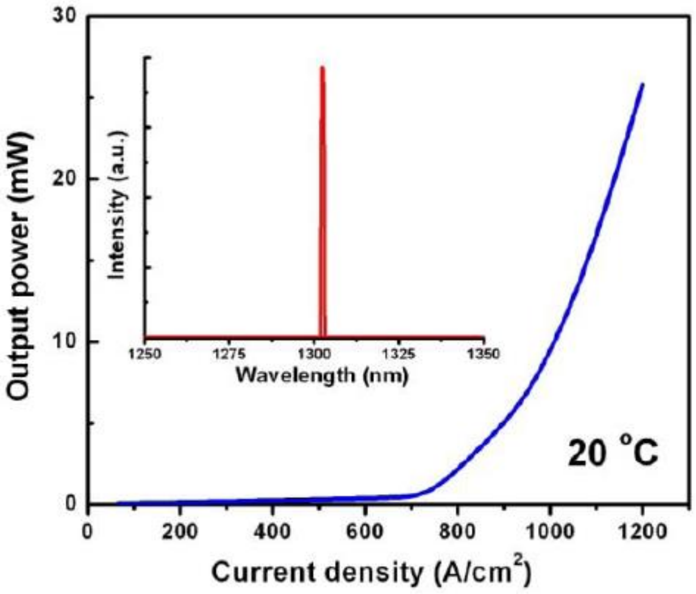


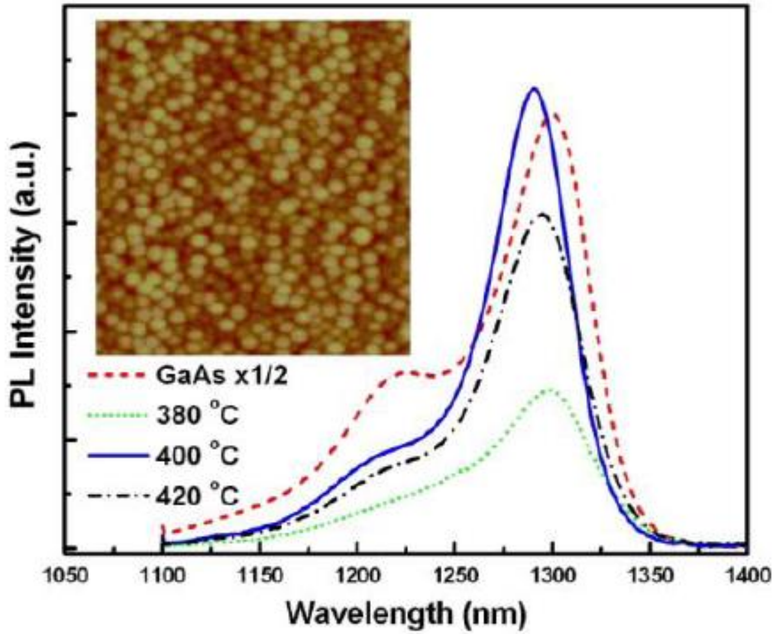
50nm GaAs
100nm $\mathrm{Al_{0.4}Ga_{0.6}As}$
50nm GaAs
5 layer InAs/InGaAs DWELL
50nm GaAs
100 layer GaAs/AlGaAs SPLs
400nm GaAs
5 layer $\mathrm{In_{0.15}Ga_{0.85}As}$/GaAs SPLs
1 µm GaAs
Si Substrate

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



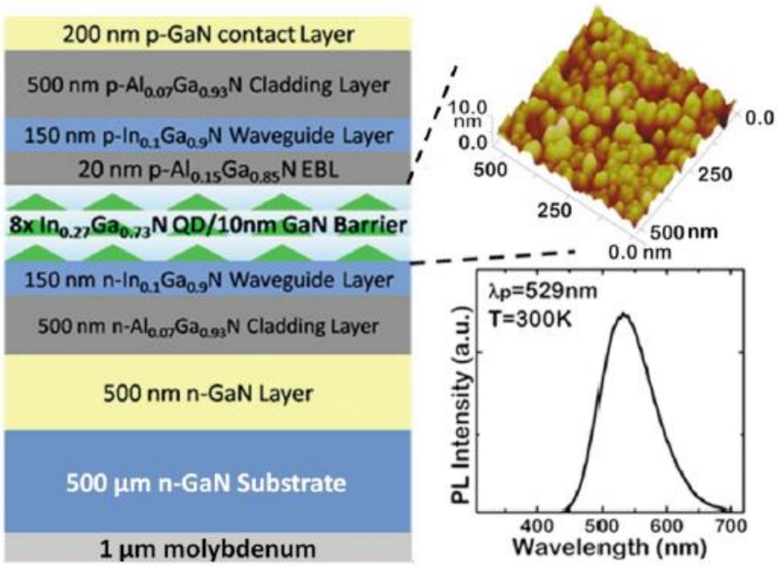


green semiconductor laser

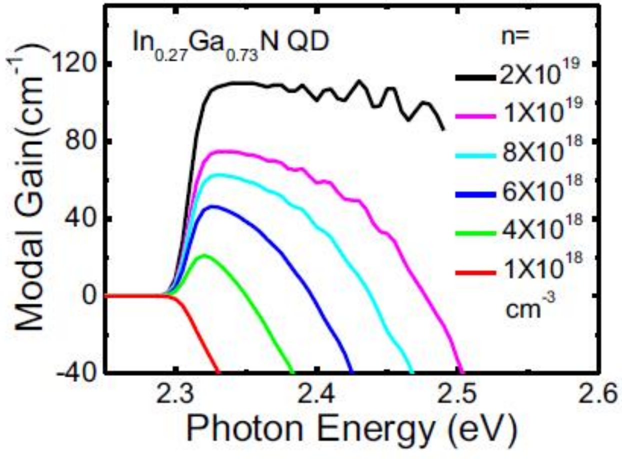
APPLIED PHYSICS LETTERS **98**, 221104 (2011)

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

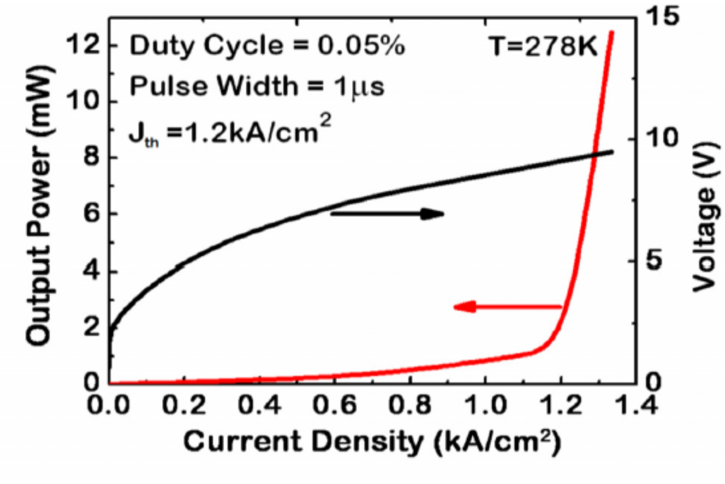
Meng Zhang, Animesh Banerjee, Chi-Sen Lee, John M. Hinckley, and Pallab Bhattacharya[a)]



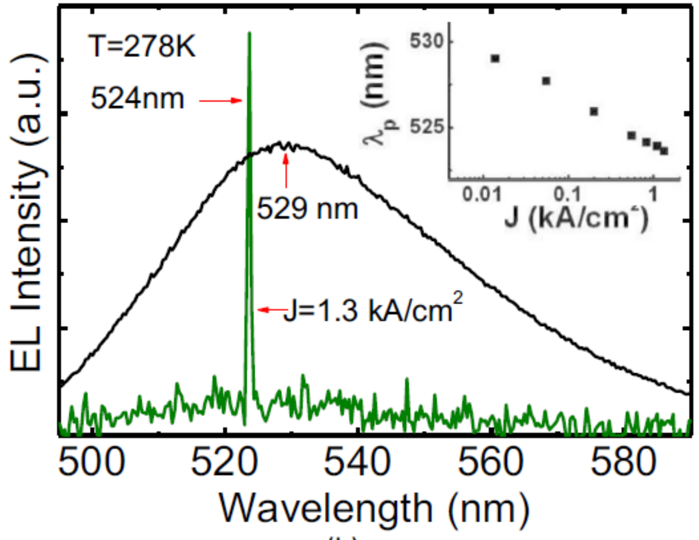
(a)



(b)

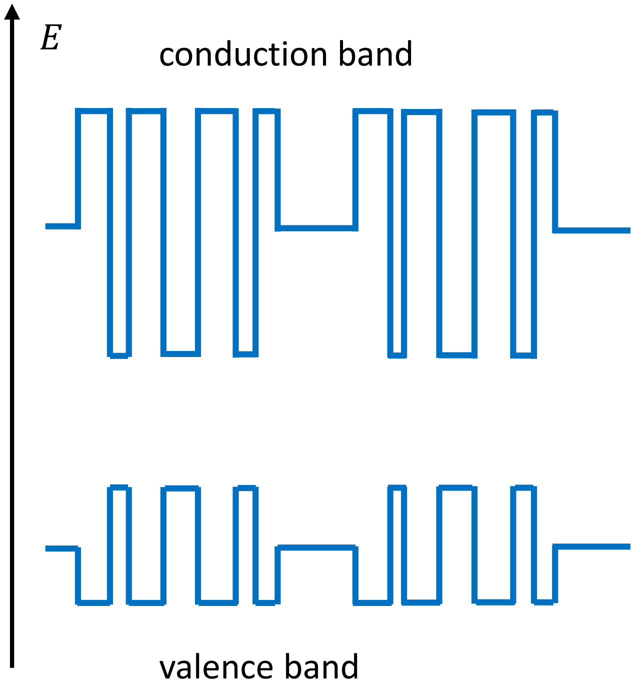


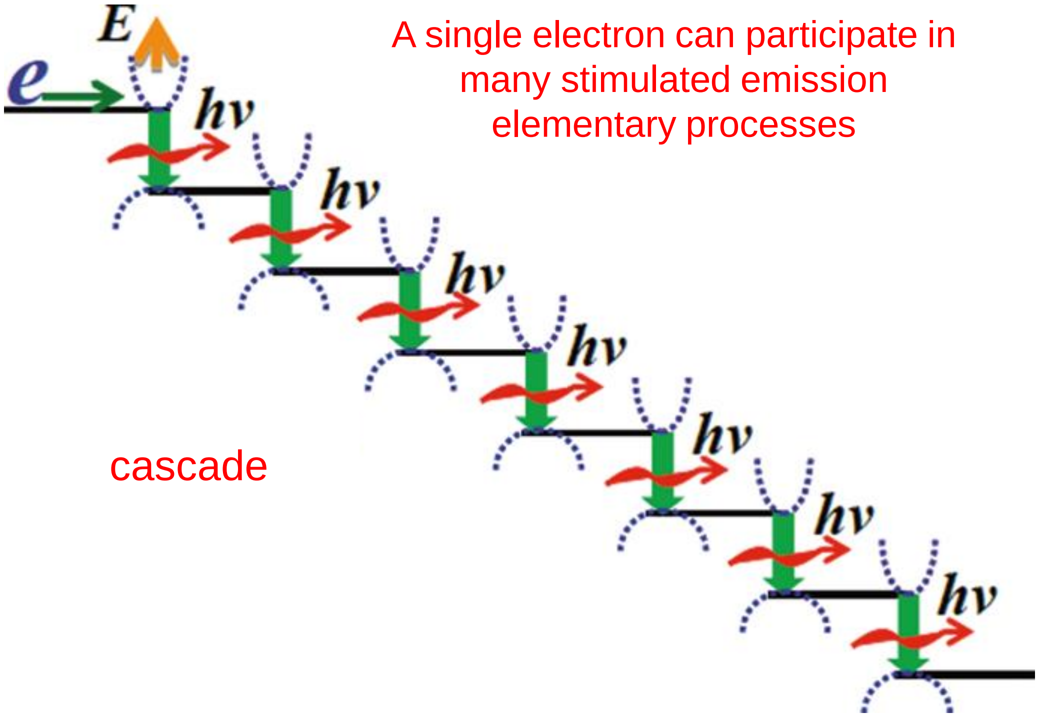
(a)



(b)

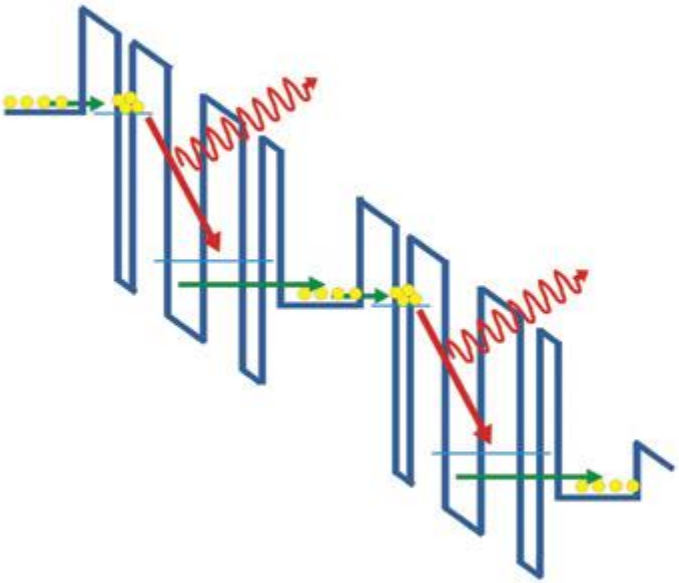
quantum cascade laser





A single electron can participate in many stimulated emission elementary processes

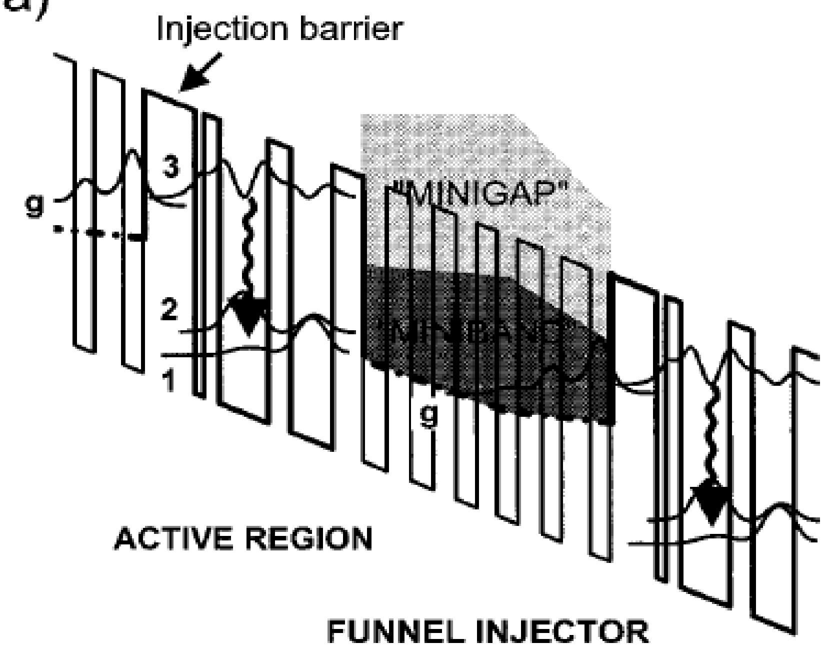
cascade



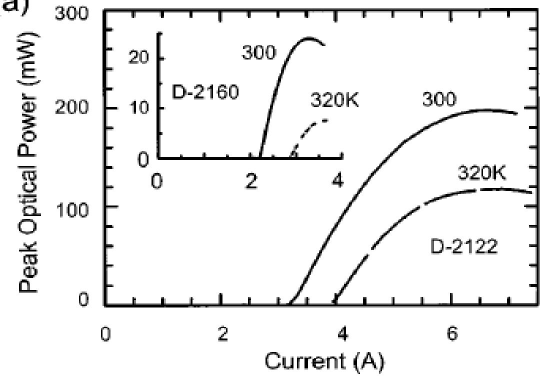
quantum cascade laser, 2

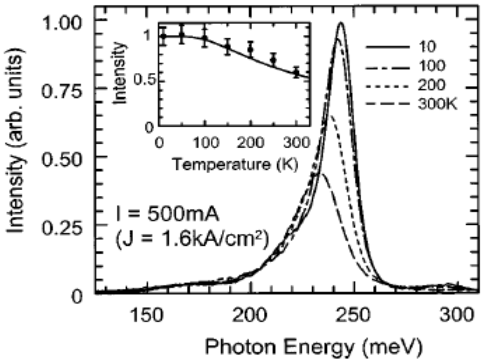
Appl. Phys. Lett. **68** (26), 24 June 1996

(a)



(a)



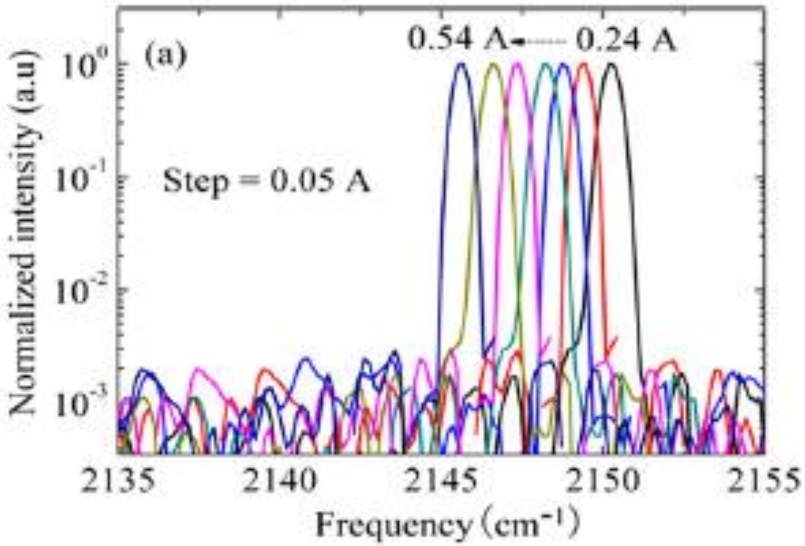


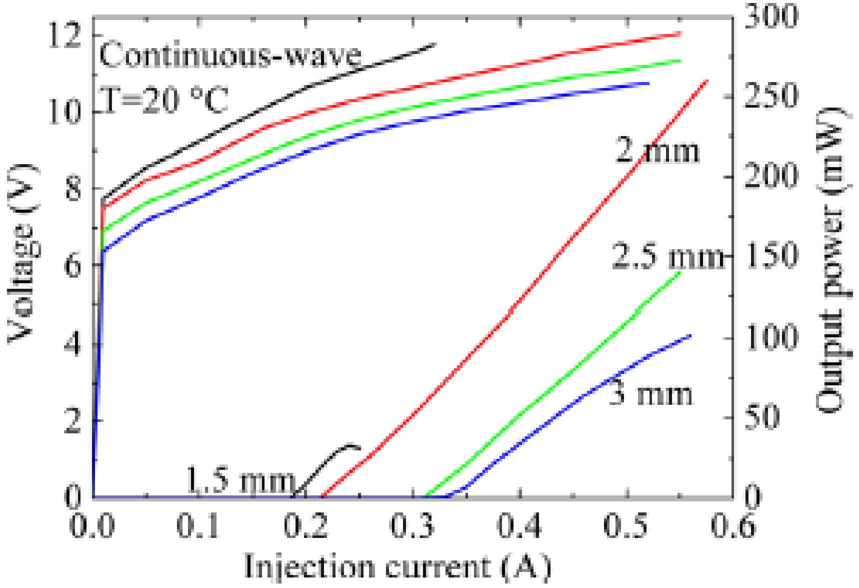
lasery z kaskadą kwantową (ang. quantum cascade laser)

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

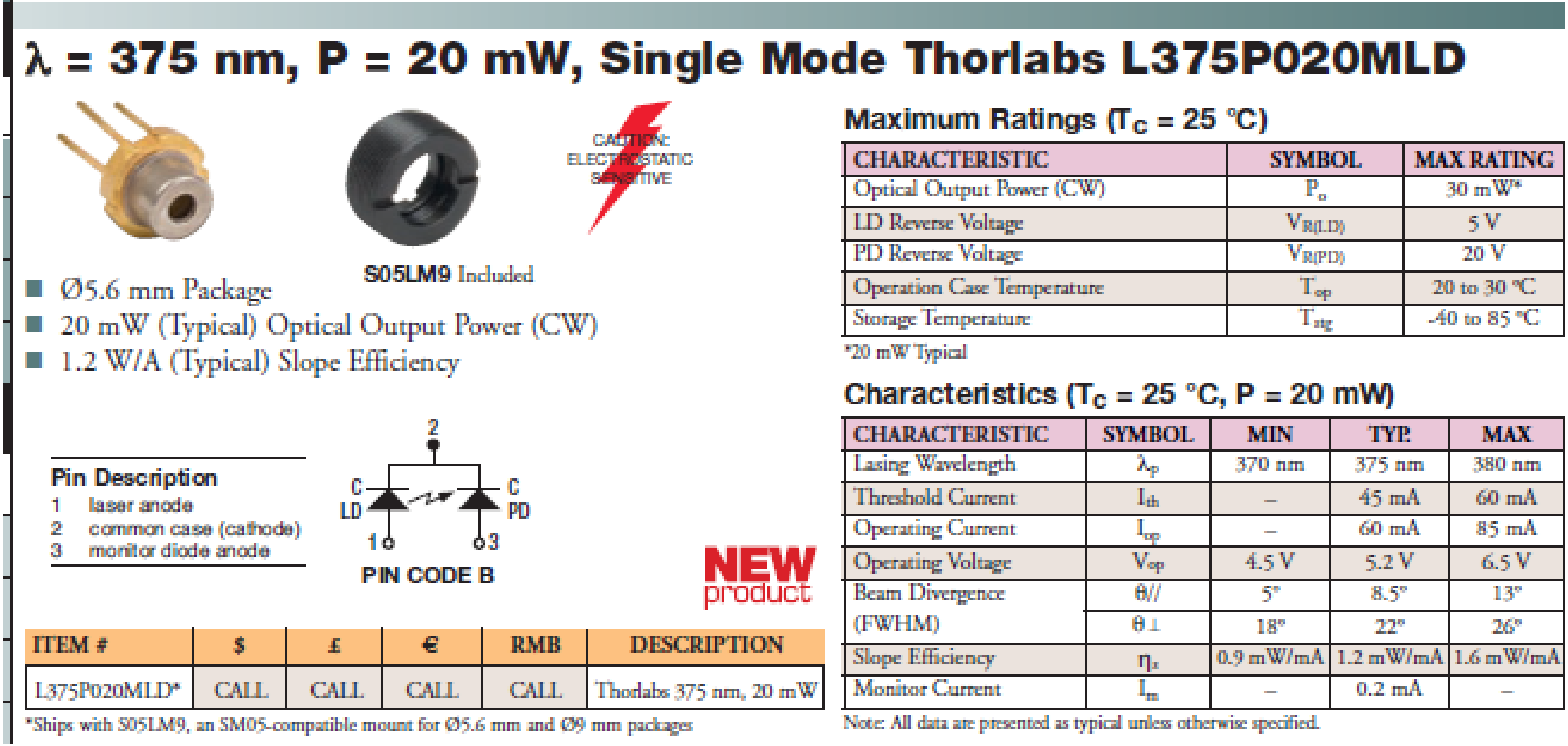
J. C. Zhang,[1,2] F. Q. Liu,[1,a)] S. Tan,[1] D. Y. Yao,[1] L. J. Wang,[1,b)] L. Li,[1] J. Q. Liu,[1]
and Z. G. Wang[1]

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





UV semiconductor lasers



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

S05LM9 Included

- 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

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

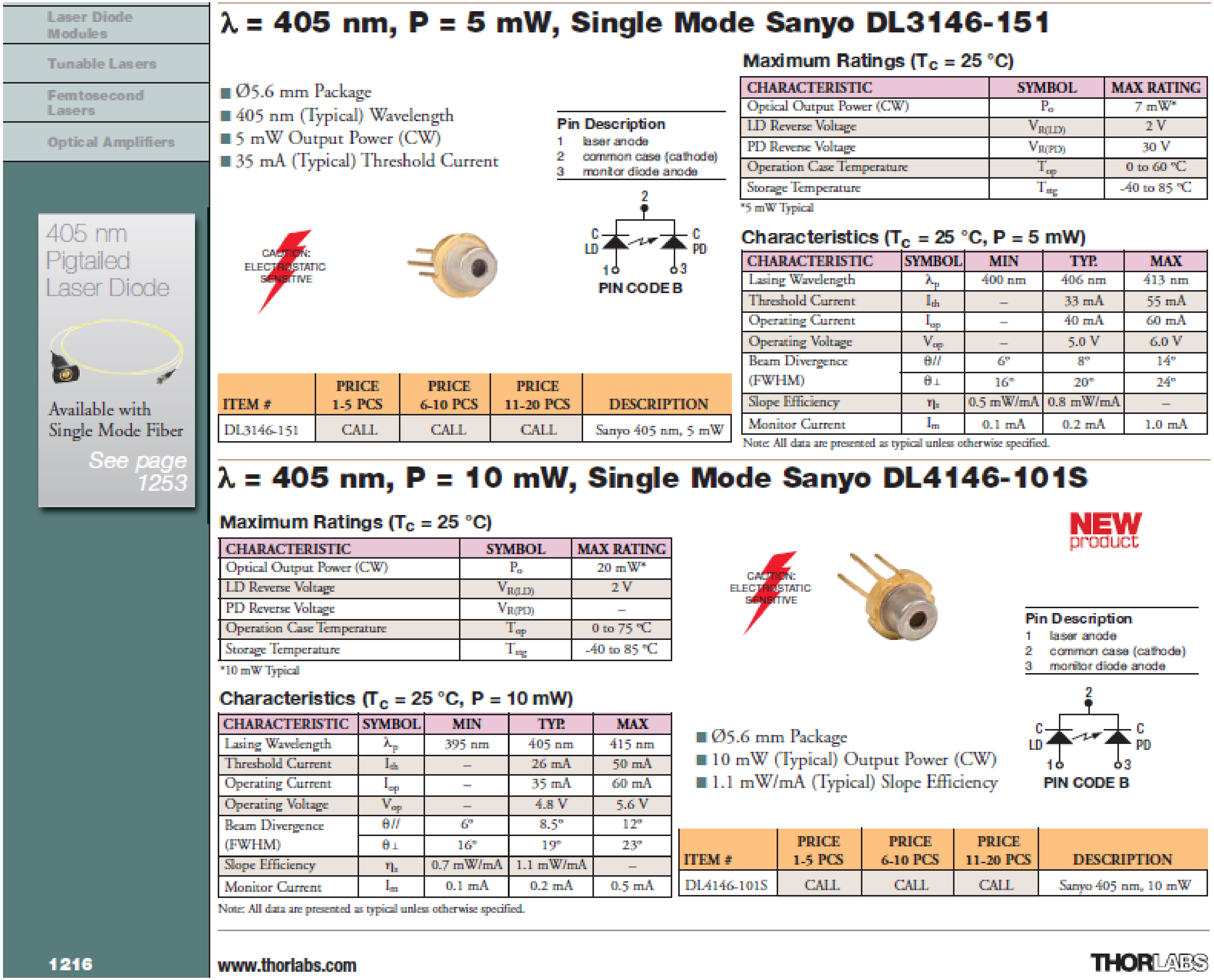
*20 mW Typical

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

CHARACTERISTIC	SYMBOL	MIN	TYP.	MAX
Lasing Wavelength	λ_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	η_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



405 nm Pigtailed Laser Diode

Available with Single Mode Fiber

See page 1253

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

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	λ_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	η_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.

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

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)

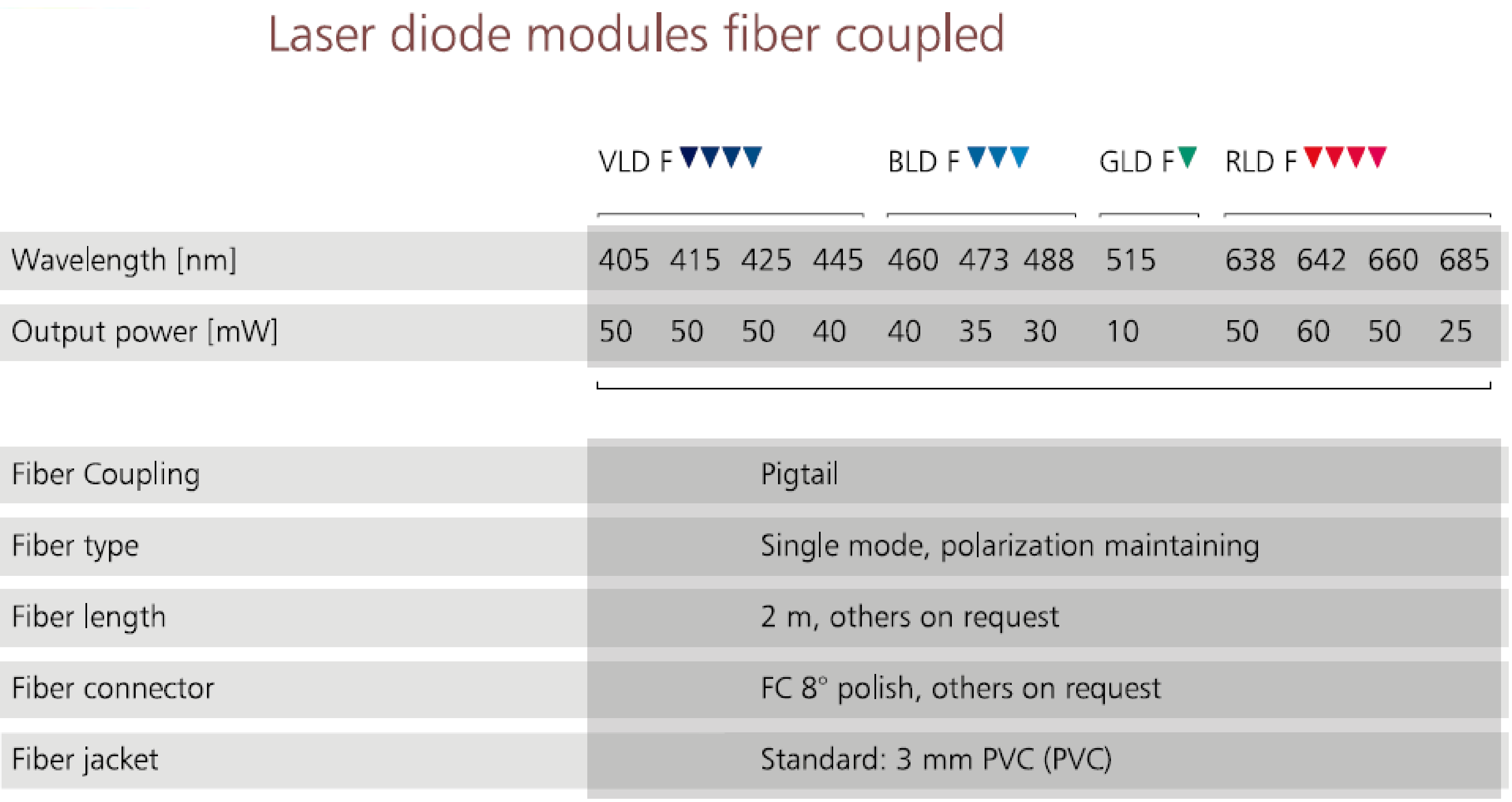
CHARACTERISTIC	SYMBOL	MIN	TYP.	MAX
Lasing Wavelength	λ_p	395 nm	405 nm	415 nm
Threshold Current	I_{th}	–	26 mA	50 mA
Operating Current	I_{op}	–	35 mA	60 mA
Operating Voltage	V_{op}	–	4.8 V	5.6 V
Beam Divergence	θ//	6°	8.5°	12°
(FWHM)	θ⊥	16°	19°	23°
Slope Efficiency	η_s	0.7 mW/mA	1.1 mW/mA	–
Monitor Current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

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

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

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)