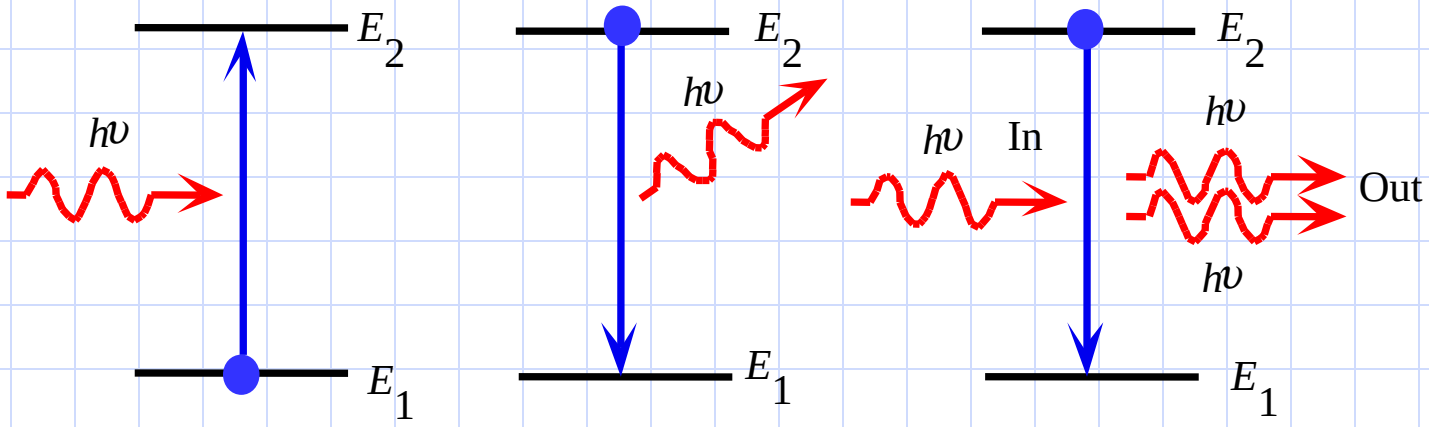
光传感系统中的重要有源光器件和无源光器件

（一）有源器件

1.1。激光与激光器

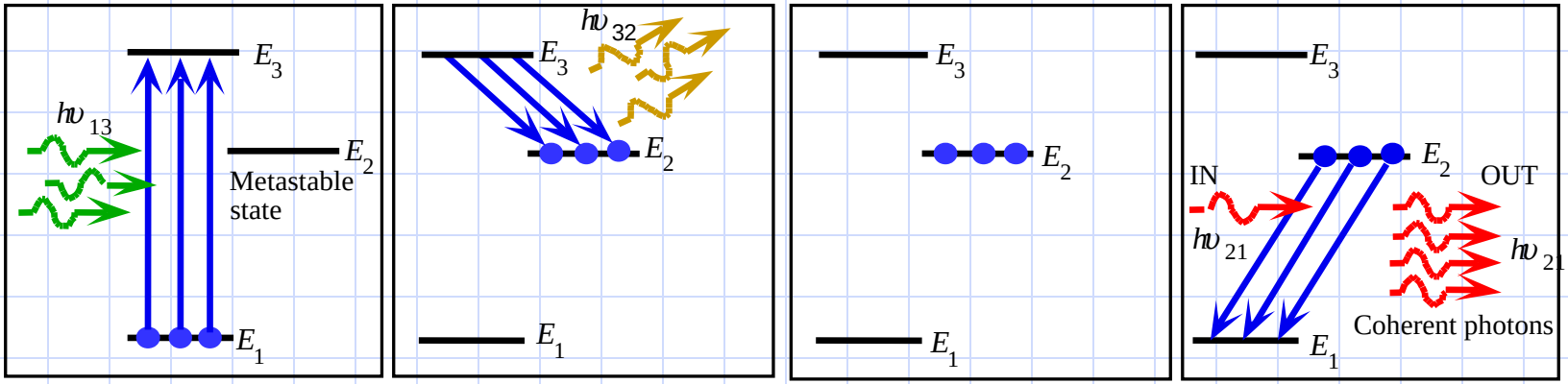
1.2。半导体光源

1.1 激光 —— 光与原子系统的相互作用



(a) Absorption (b) Spontaneous emission (c) Stimulated emission

激光的原理


E_3
$h\upsilon_{13}$
E_2
Metastable state
E_1
$h\upsilon_{32}$
E_3
E_2
E_1
E_3
E_2
E_1
E_3
IN
E_2
OUT
$h\upsilon_{21}$
$h\upsilon_{21}$
Coherent photons
E_1

红宝石激光器

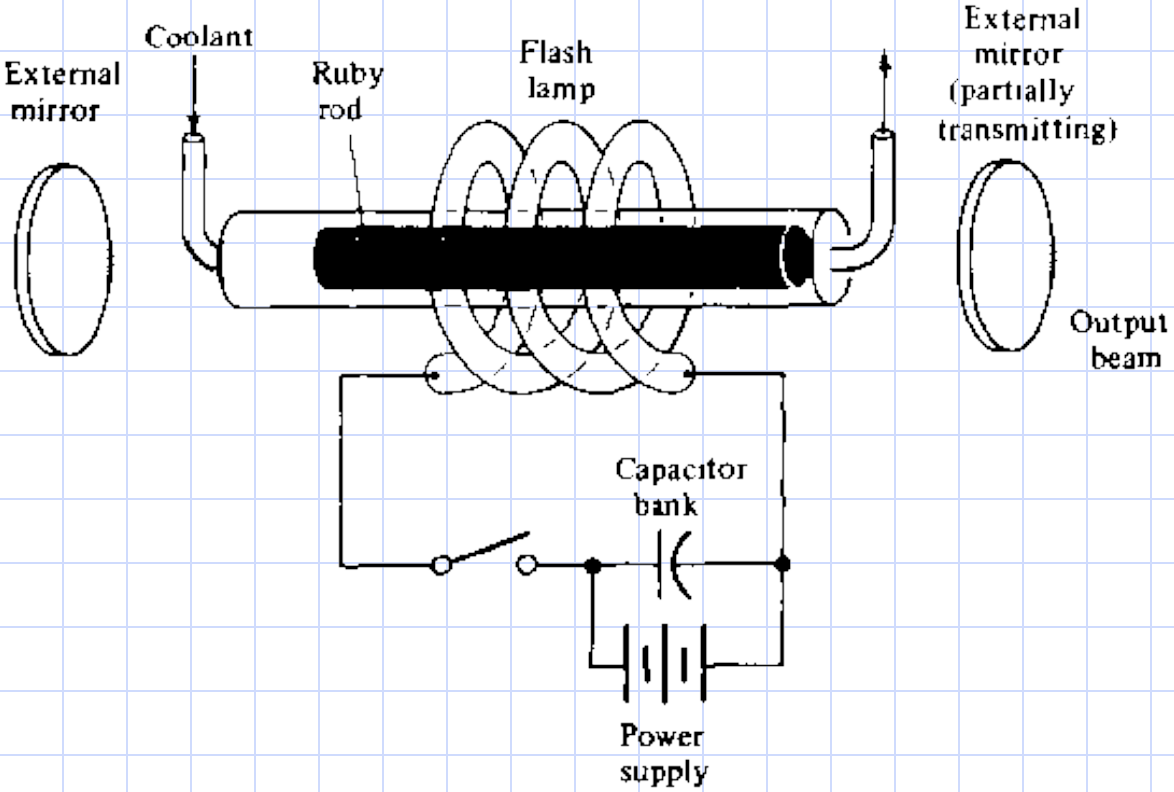


Figure 7-6 Typical setup of a pulsed ruby laser using flashlamp pumping and external mirrors.

红宝石能级图

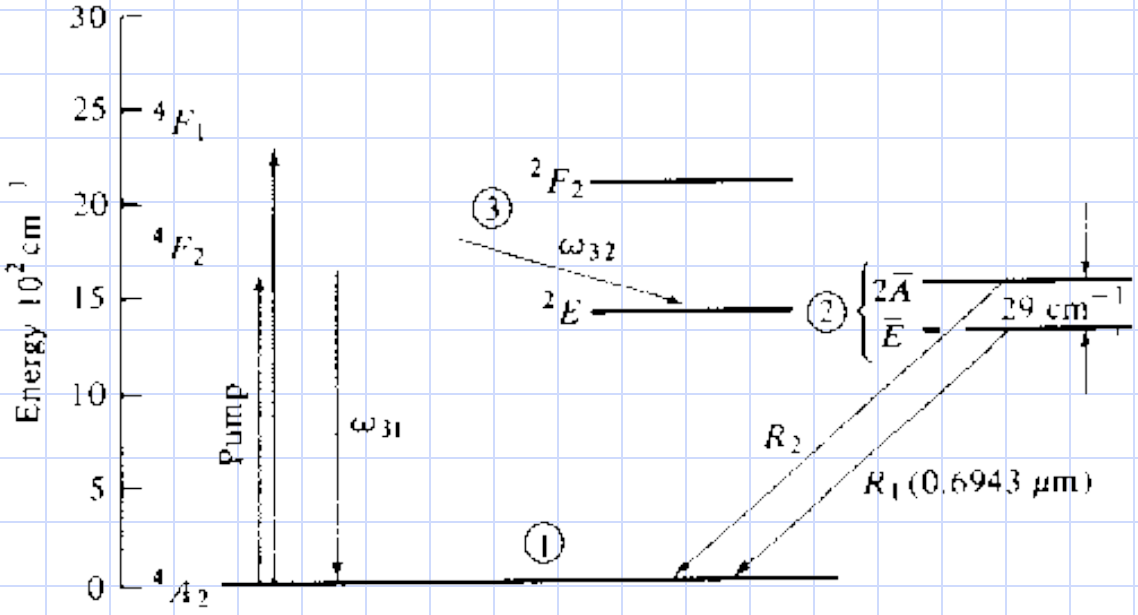
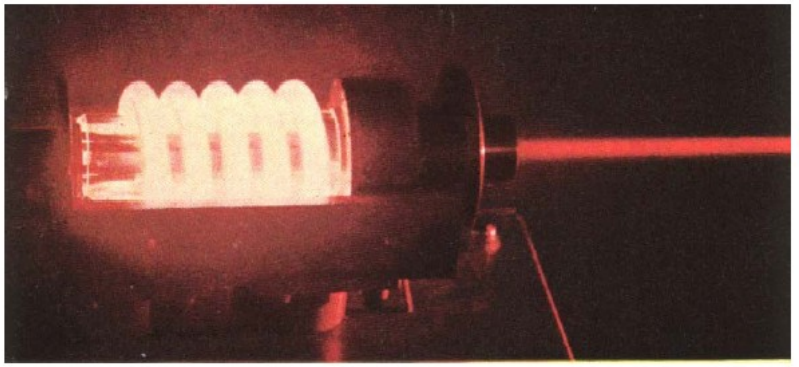


Figure 7-2 Energy levels pertinent to the operation of a ruby laser. (After Reference [2].)

"Stimulated optical radiation in ruby lasers", *Nature*, **187**, 493, 1960).

Theodore Harold Maiman

May 17, 1960: Ted Maiman's ruby laser



Nd^{3+} : YAG

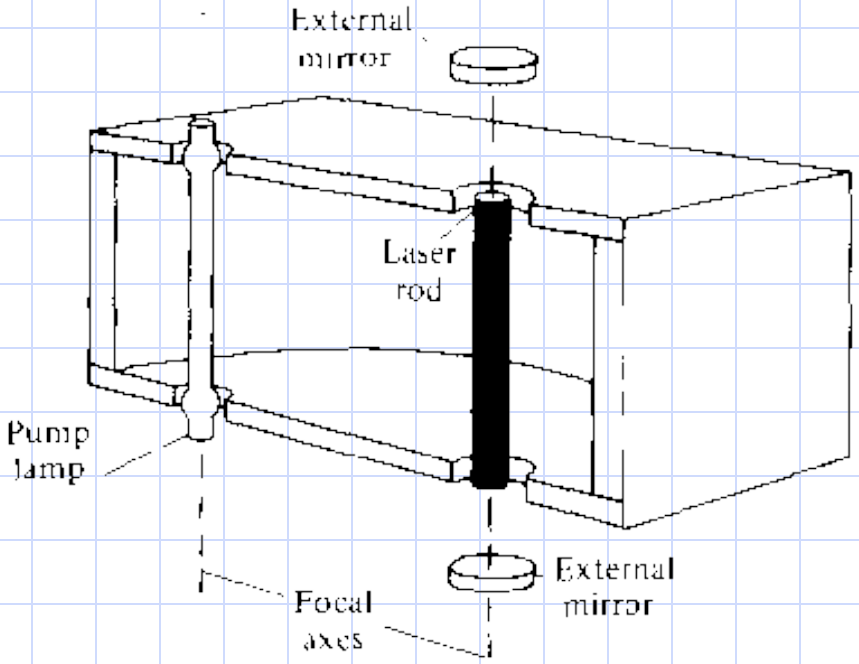


Figure 7-10 Typical continuous solid-state laser arrangement employing an elliptic cylinder housing for concentrating lamp light onto laser.

Nd^{3+} ： YAG 能级图

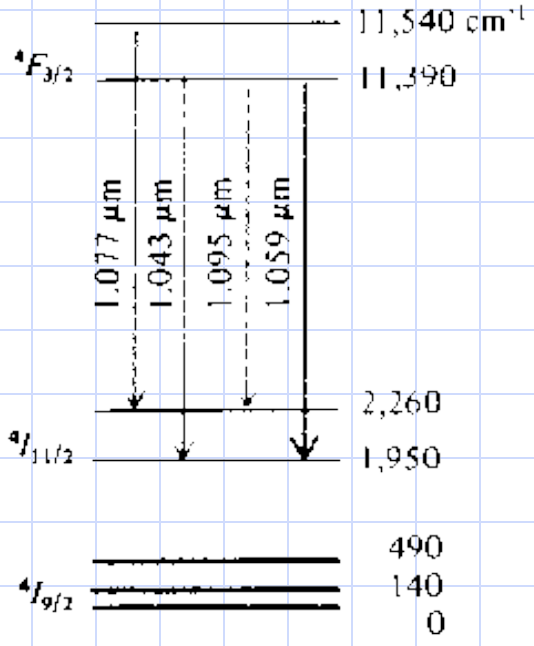
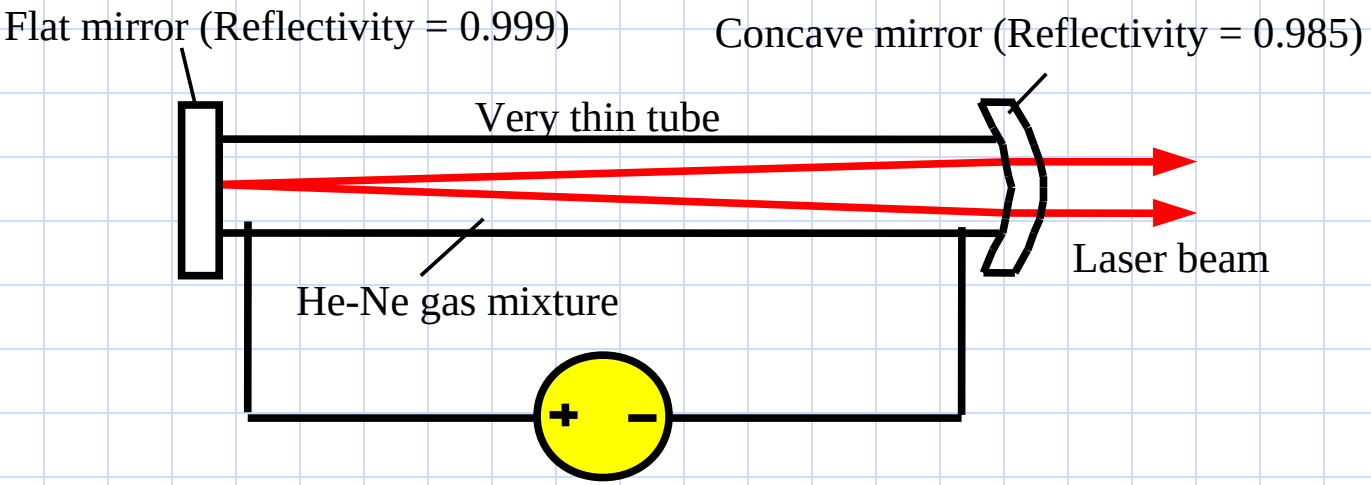


Figure 7-11 Energy-level diagram for the ground state and the states involved in laser emission at 1.059 μm for Nd^{3+} in a rubidium potassium barium silicate glass. (After Reference [8].)

氦氖激光器



Current regulated HV power supply

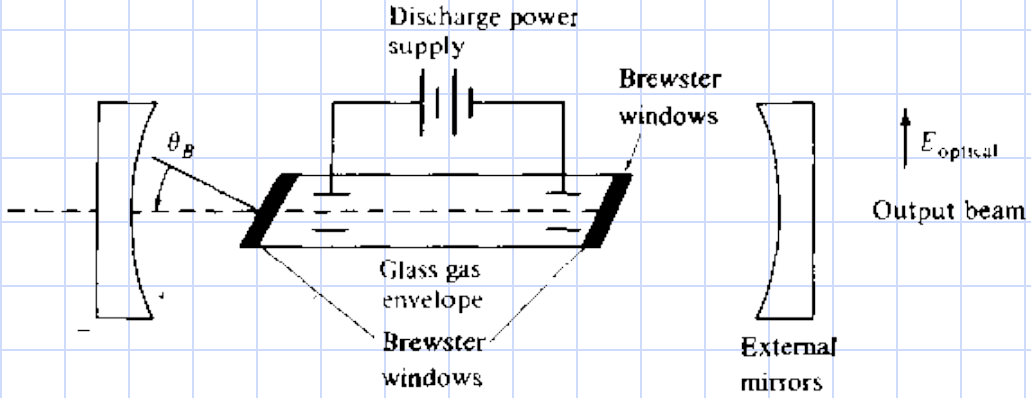
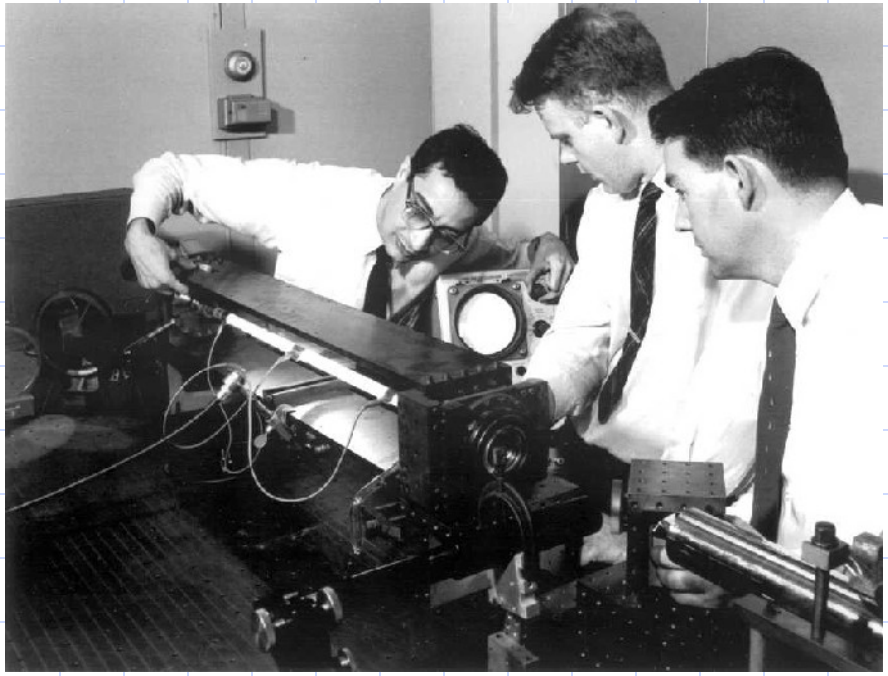


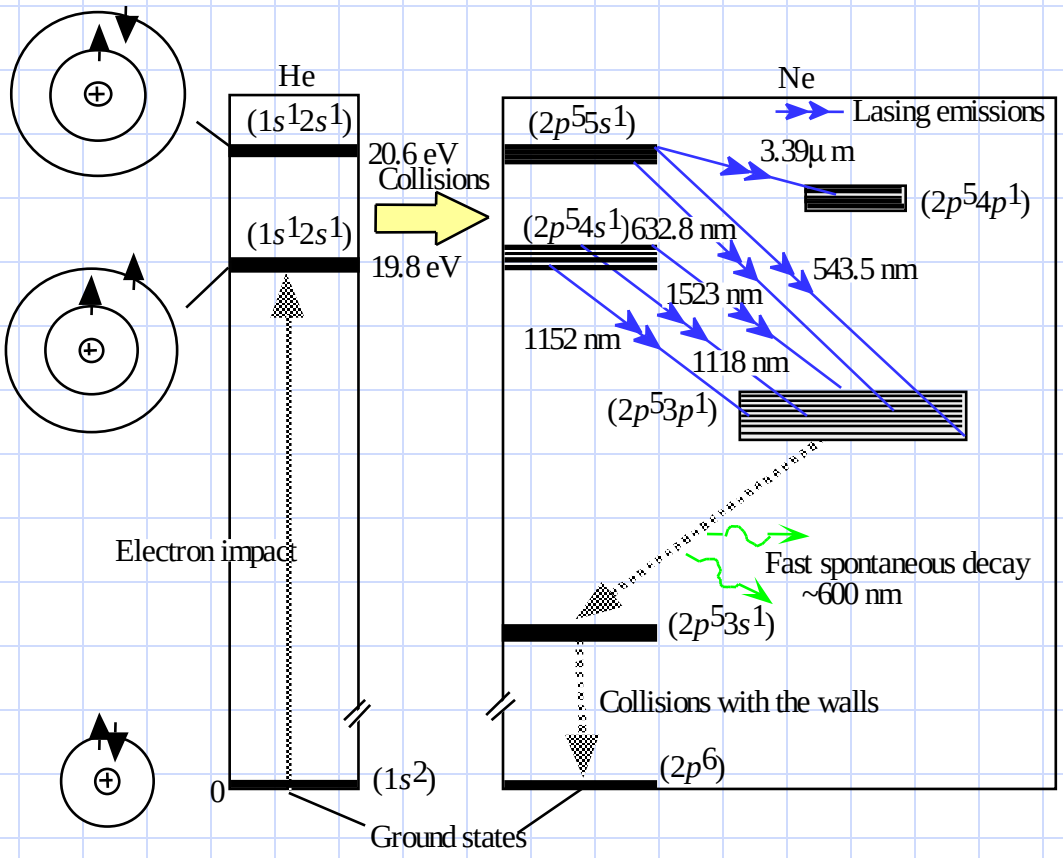
Figure 7-16 Typical gas laser.

a continuous wave (cw) helium-neon laser operation (1960-1962)

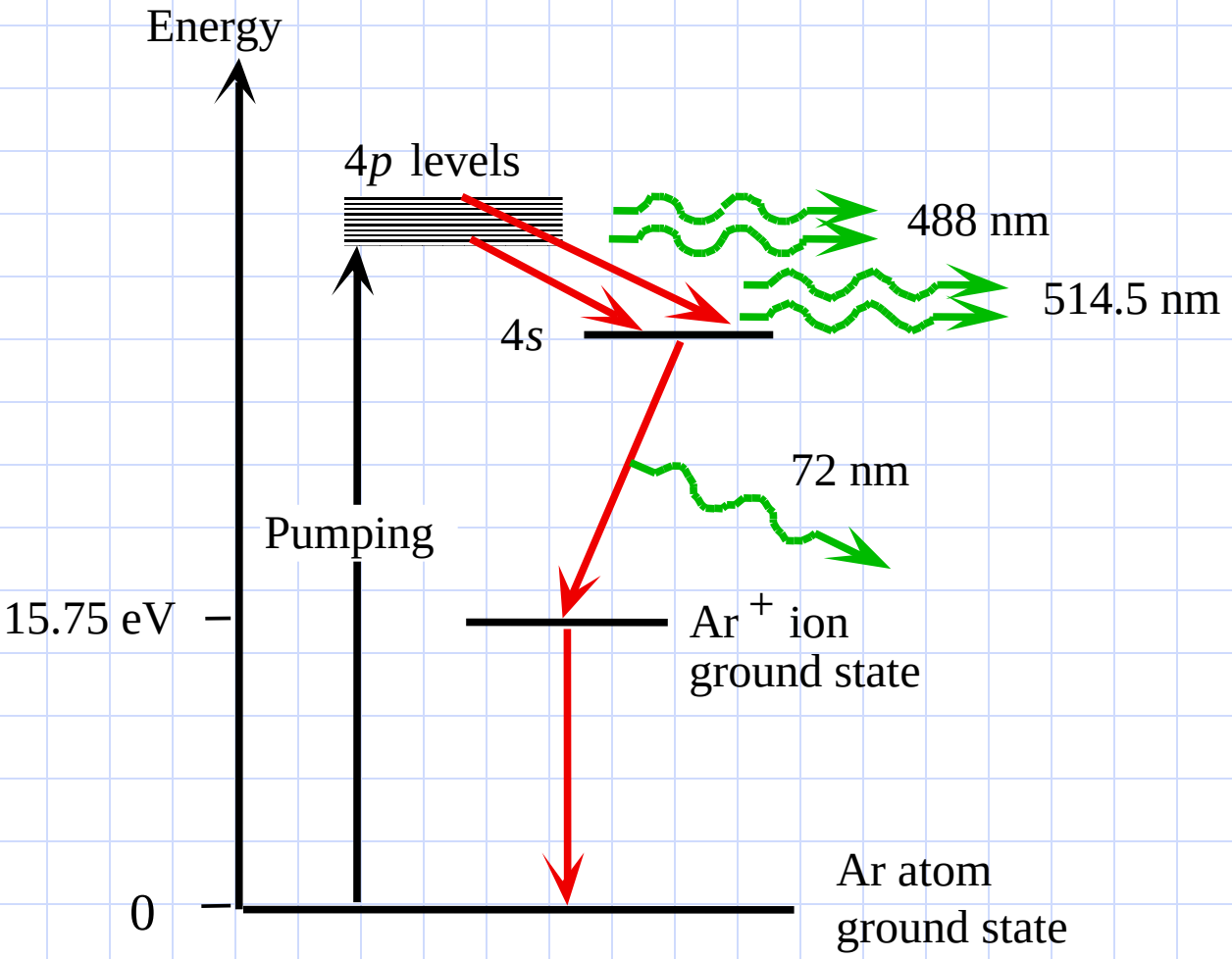


Ali Javan and his associates William Bennett Jr. and Donald Herriott at Bell Labs were first to successfully demonstrate a continuous wave (cw) helium-neon laser operation (1960-1962). (Courtesy of Bell Labs, Lucent Technologies.)

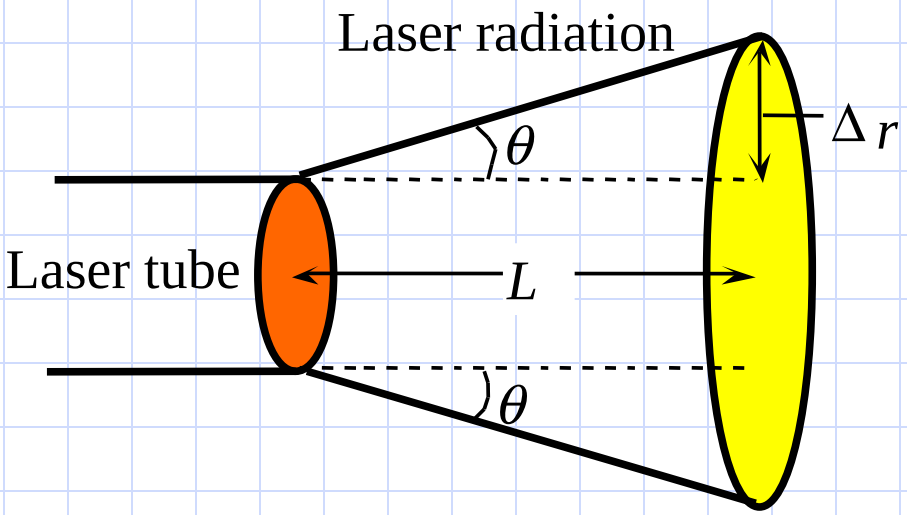
氦氖激光器的工作原理


He
Ne
$(1s^12s^1)$
$(1s^12s^1)$
20.6 eV
Collisions
19.8 eV
$(2p^55s^1)$
Lasing emissions
3.39μ m
$(2p^54p^1)$
$(2p^54s^1)$
632.8 nm
543.5 nm
1523 nm
1152 nm
1118 nm
$(2p^53p^1)$
Electron impact
Fast spontaneous decay
~600 nm
$(2p^53s^1)$
Collisions with the walls
$(2p^6)$
0
$(1s^2)$
Ground states

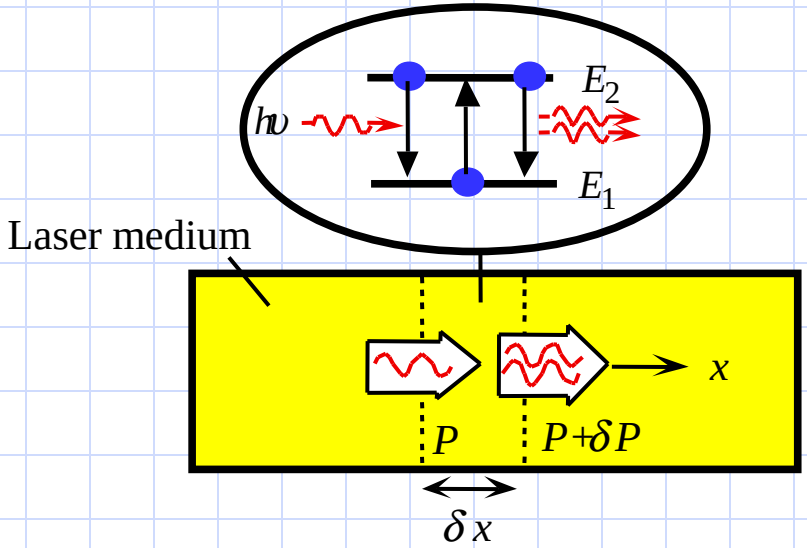
氩离子激光器的工作原理



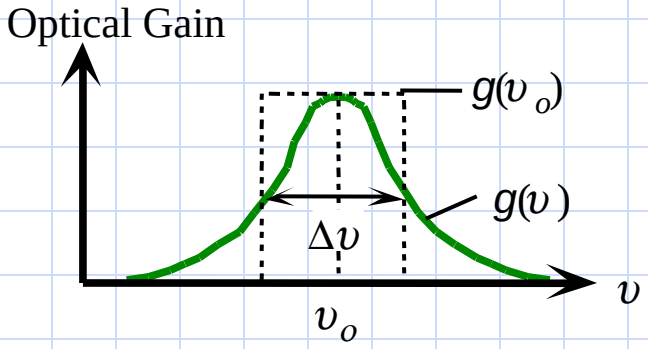
激光束的发散角



激光介质的增益特性

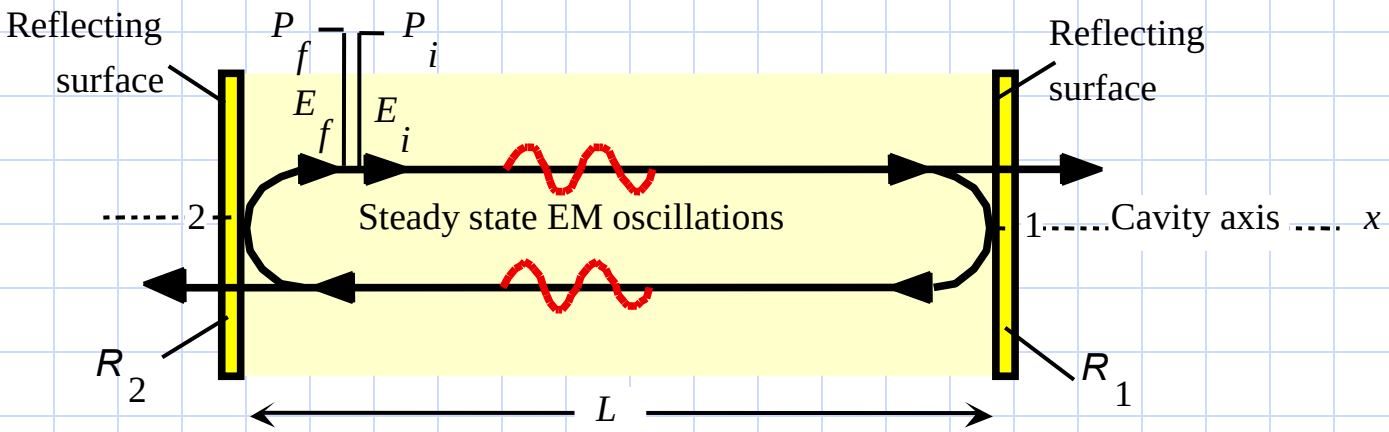


(a)

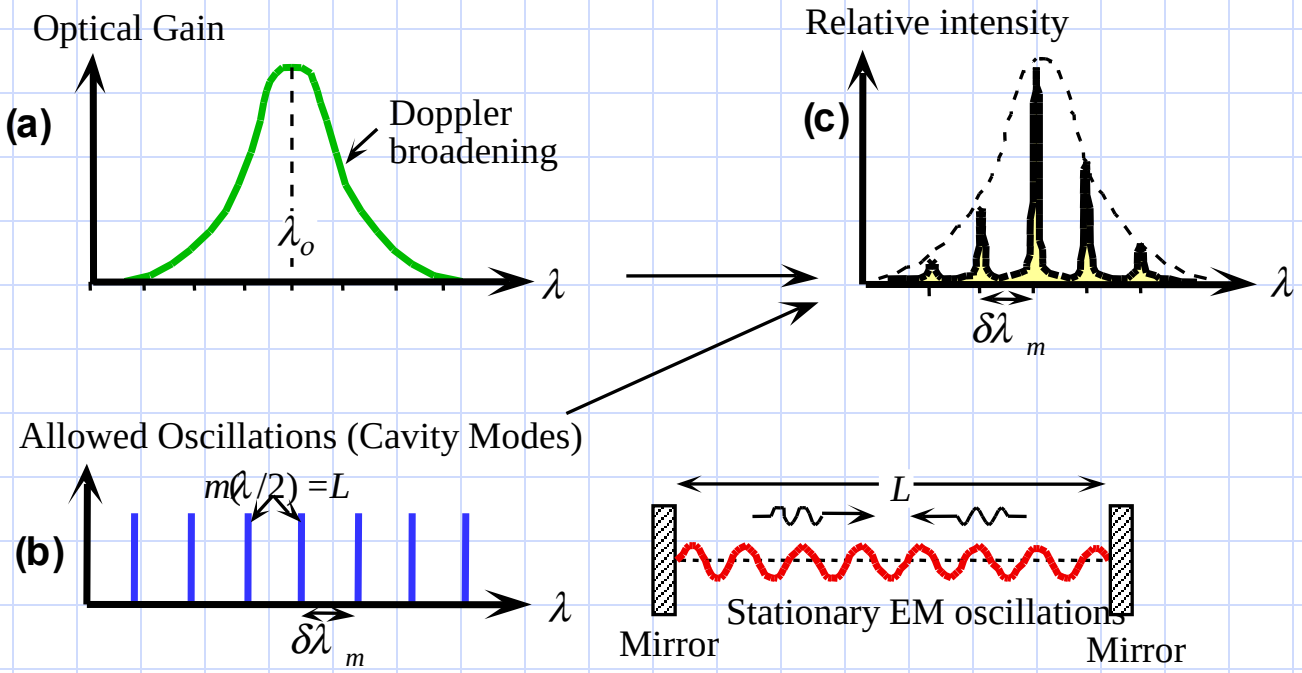


(b)

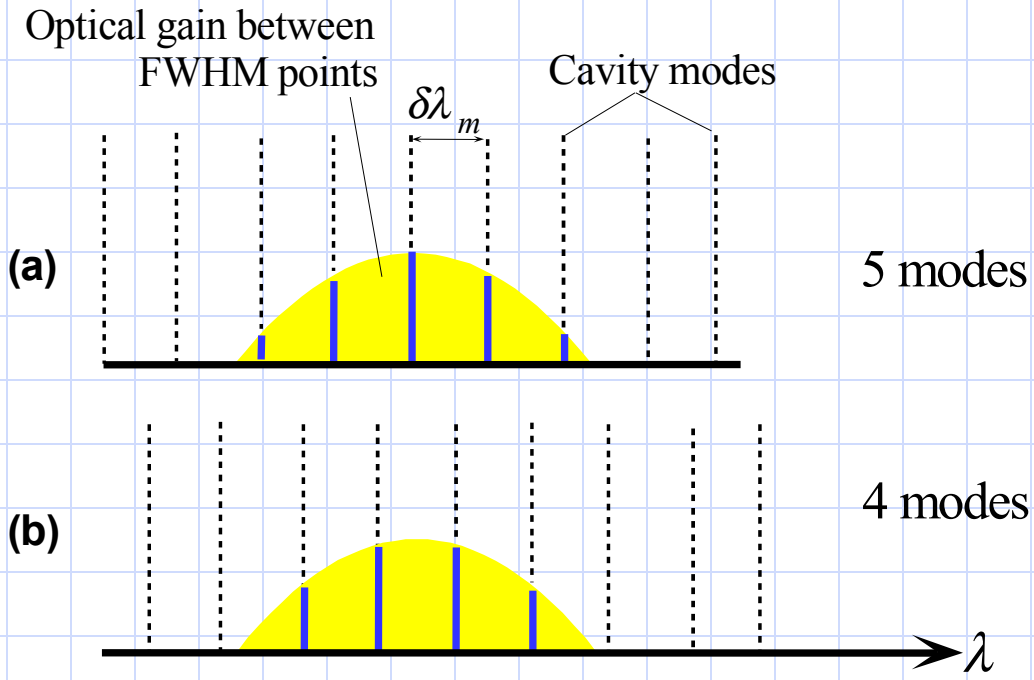
光学谐振腔


Reflecting surface
P f
P i
E f
E i
Reflecting surface
2
Steady state EM oscillations
1
Cavity axis
x
R 2
R 1
L

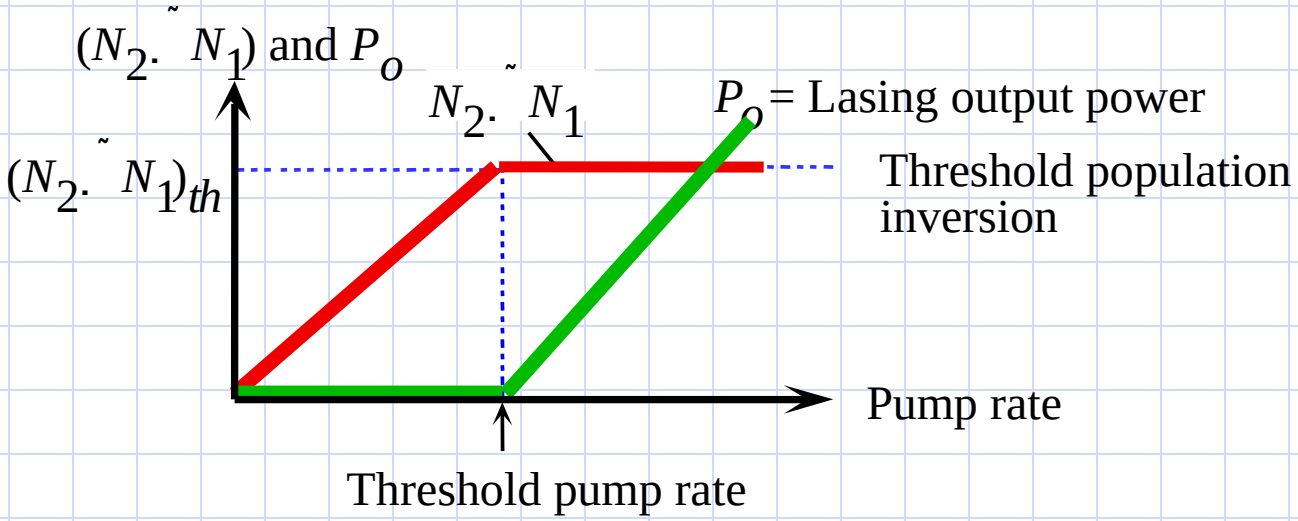
激光的波长


Optical Gain
(a)
Doppler
broadening
λ_o
λ
Relative intensity
(c)
λ
$\delta\lambda_m$
Allowed Oscillations (Cavity Modes)
$m(\lambda/2) = L$
(b)
λ
$\delta\lambda_m$
L
Stationary EM oscillations
Mirror
Mirror

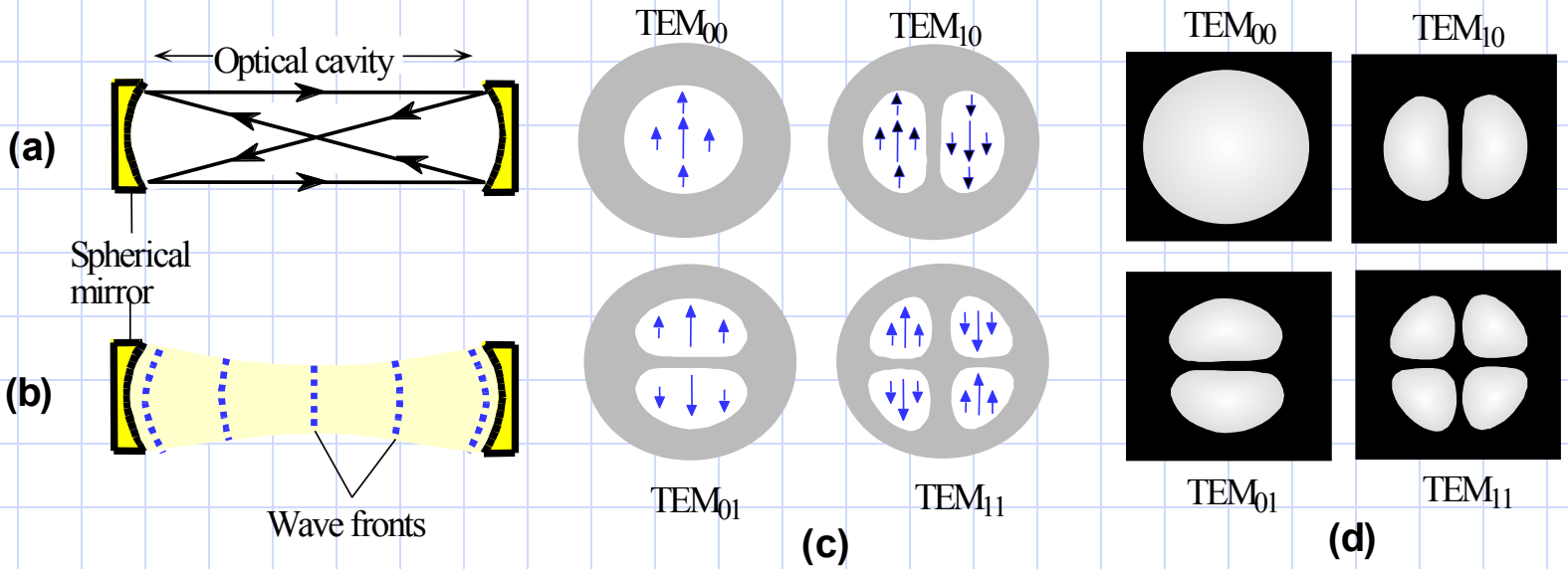
激光的模式特性（纵模）


Optical gain between
FWHM points
$\delta\lambda_m$
Cavity modes
(a)
5 modes
(b)
4 modes
λ

激光的阈值特性


$(N_2 - N_1)$ and P_o
$N_2 - N_1$
P_o = Lasing output power
$(N_2 - N_1)_{th}$
Threshold population inversion
Pump rate
Threshold pump rate

激光的模式特性（横模）


Optical cavity
(a)
Spherical mirror
(b)
Wave fronts
TEM00
TEM10
TEM01
TEM11
(c)
TEM00
TEM10
TEM01
TEM11
(d)

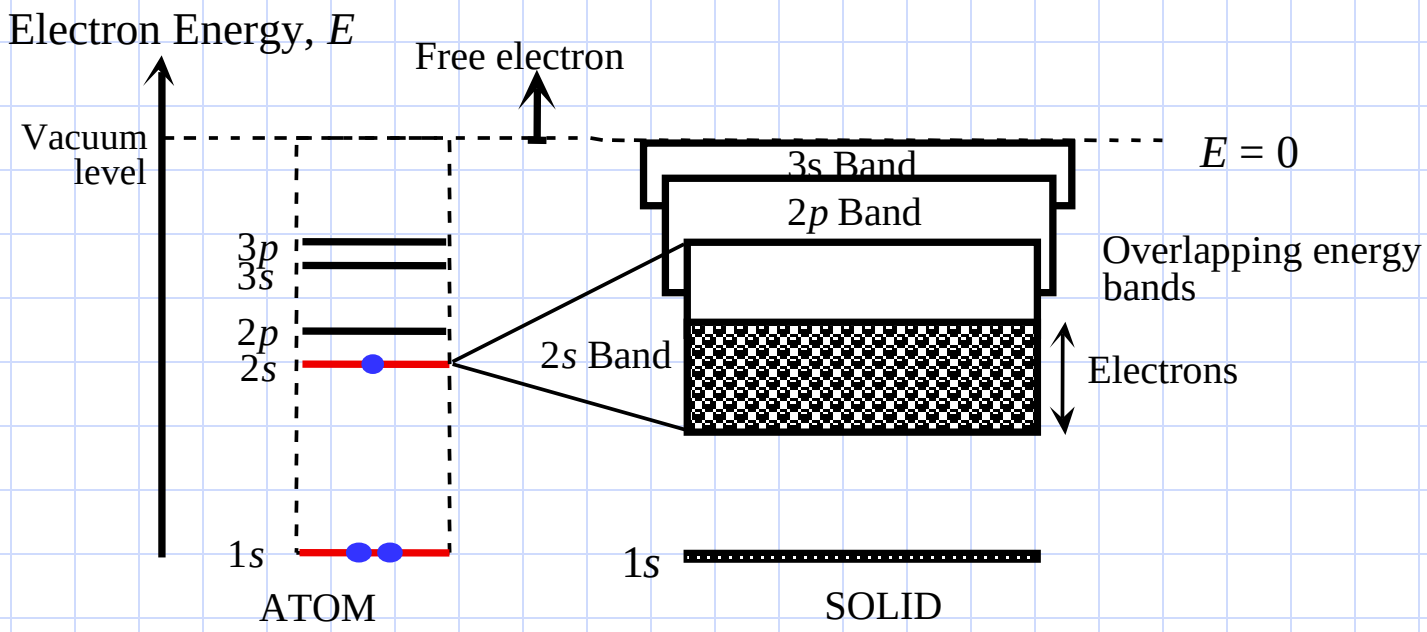
1.2 半导体光源

—— LED(半导体发光二极管)

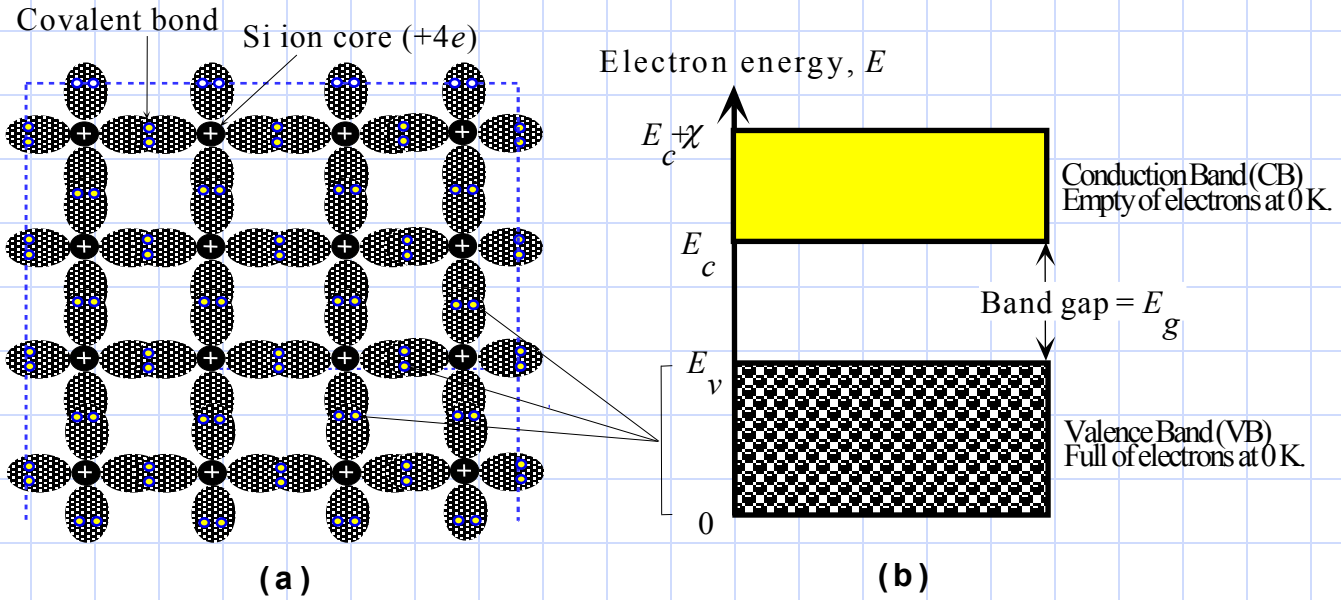
与

LD (半导体激光二极管)

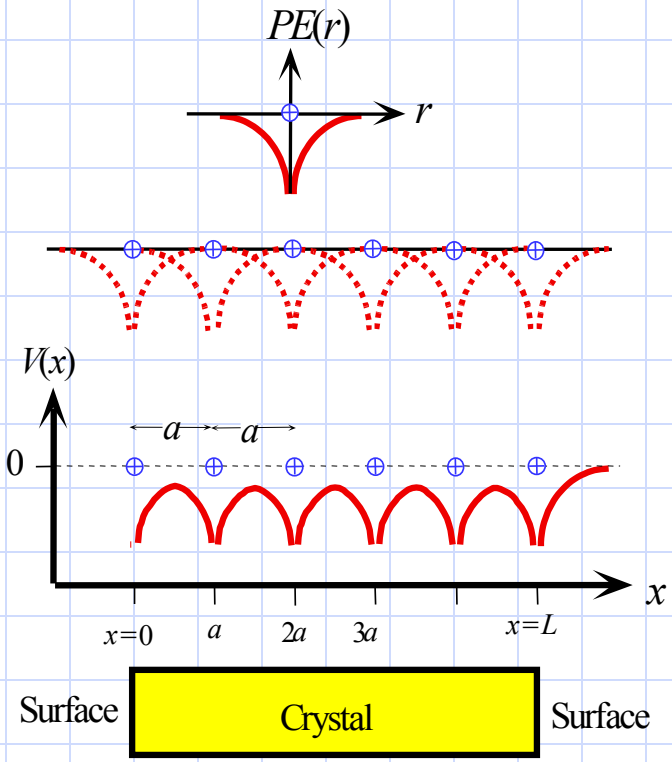
原子的能级


Electron Energy, E
Free electron
Vacuum level
E = 0
3s Band
2p Band
Overlapping energy bands
3p
3s
2p
2s
2s Band
Electrons
1s
1s
ATOM
SOLID

半导体晶体的能带结构


Covalent bond
Si ion core (+4e)
(a)
Electron energy, E
E_c + χ
E_c
Band gap = E_g
E_v
0
Conduction Band (CB)
Empty of electrons at 0 K.
Valence Band (VB)
Full of electrons at 0 K.
(b)

晶体的作用

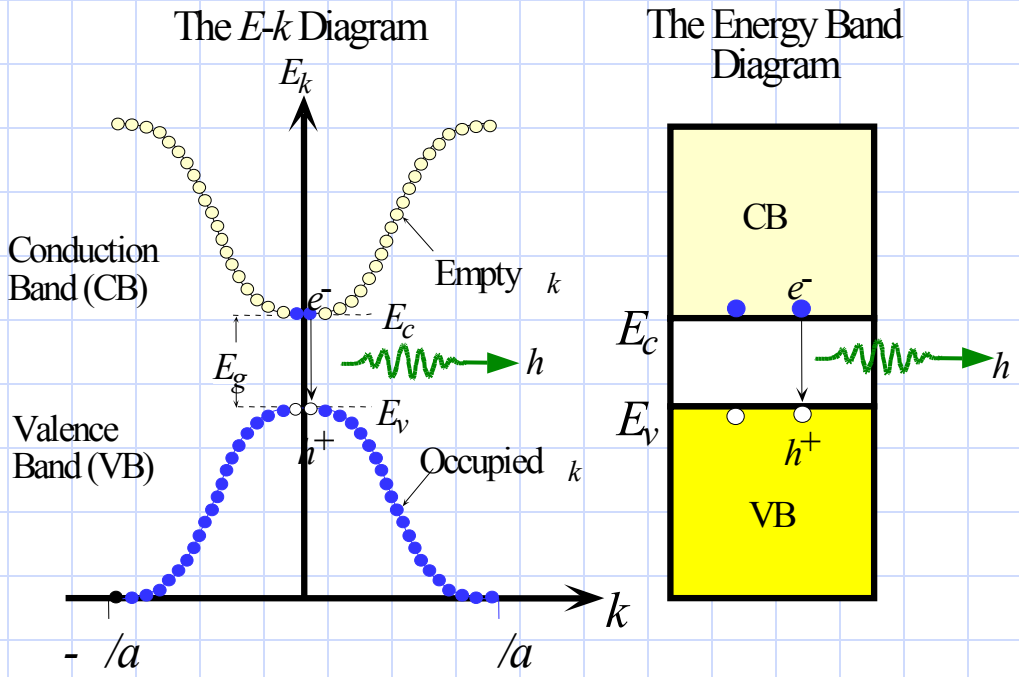


PE of the electron around an isolated atom

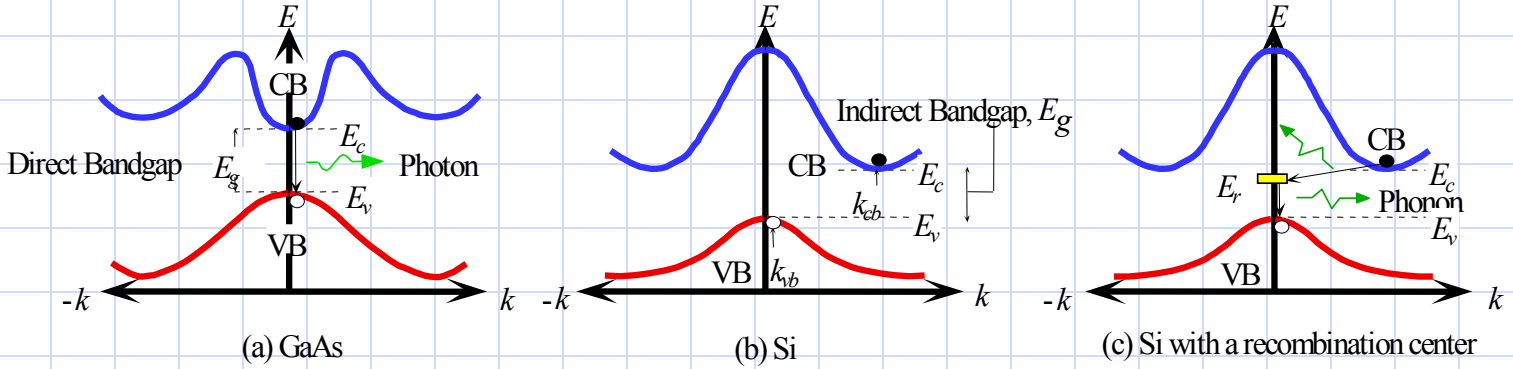
When *N* atoms are arranged to form the crystal then there is an overlap of individual electron *PE* functions.

PE of the electron, *V*(*x*), inside the crystal is periodic with a period *a*.

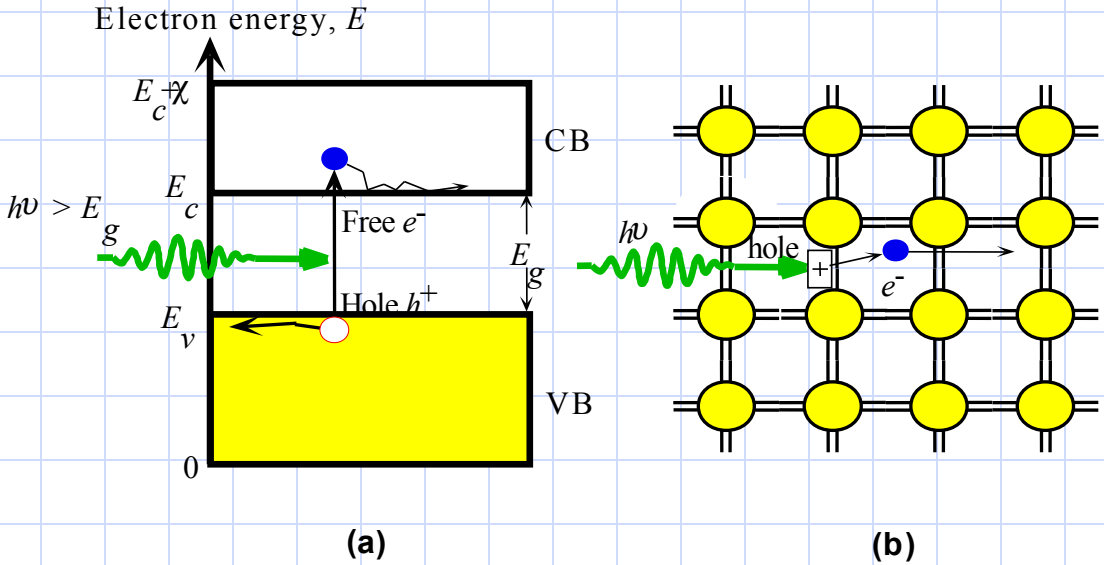
GaAs 能带结构


The E-k Diagram
The Energy Band Diagram
E_k
Conduction Band (CB)
Valence Band (VB)
Empty k
Occupied k
e^-
h^+
E_c
E_v
E_g
h
k
- /a
/a
CB
VB

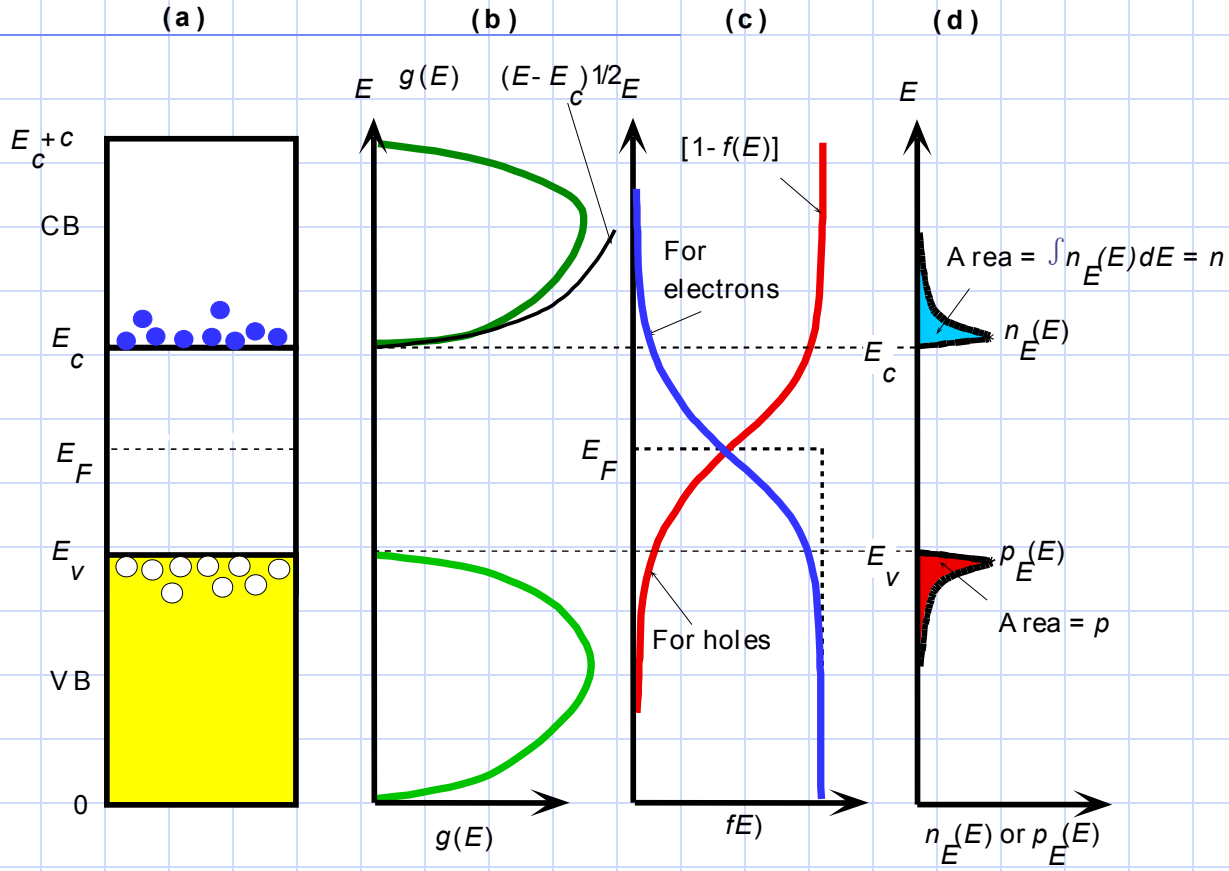
Si 和 GaAs 的比较


E
CB
Direct Bandgap
E_g
E_c
Photon
E_v
VB
-k
k
(a) GaAs
E
Indirect Bandgap, E_g
CB
E_c
k_{cb}
E_v
VB
k_{vb}
-k
k
(b) Si
E
CB
E_r
E_c
Phonon
E_v
VB
-k
k
(c) Si with a recombination center

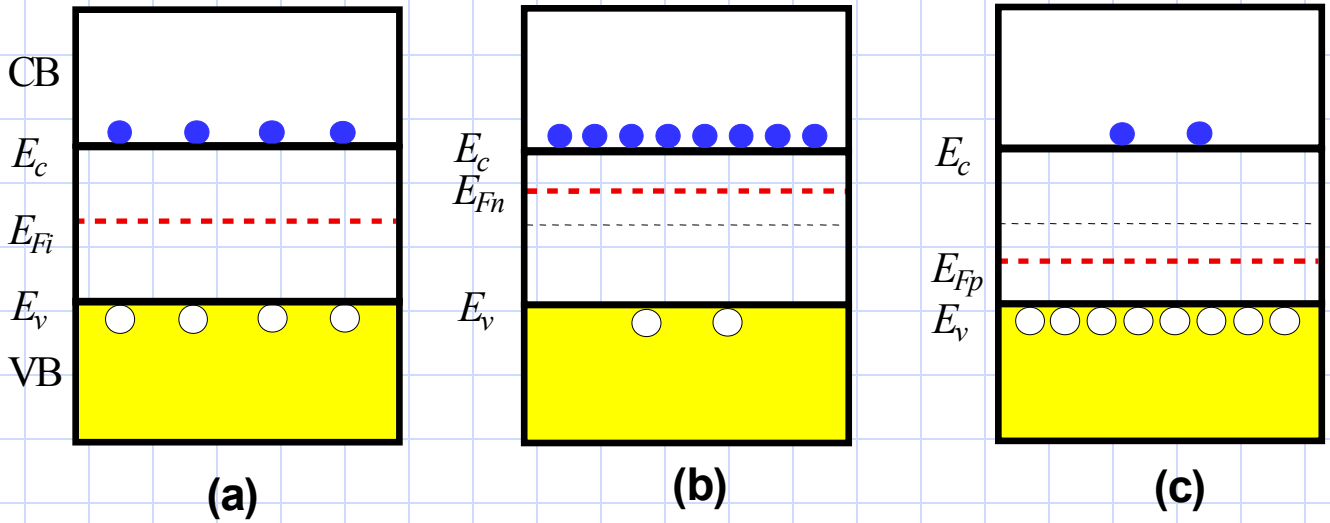
半导体的光激发


Electron energy, E
$E_c + \chi$
E_c
$h\upsilon > E_g$
Free e^-
Hole h^+
E_g
E_v
0
CB
VB
(a)
$h\upsilon$
hole
e^-
(b)

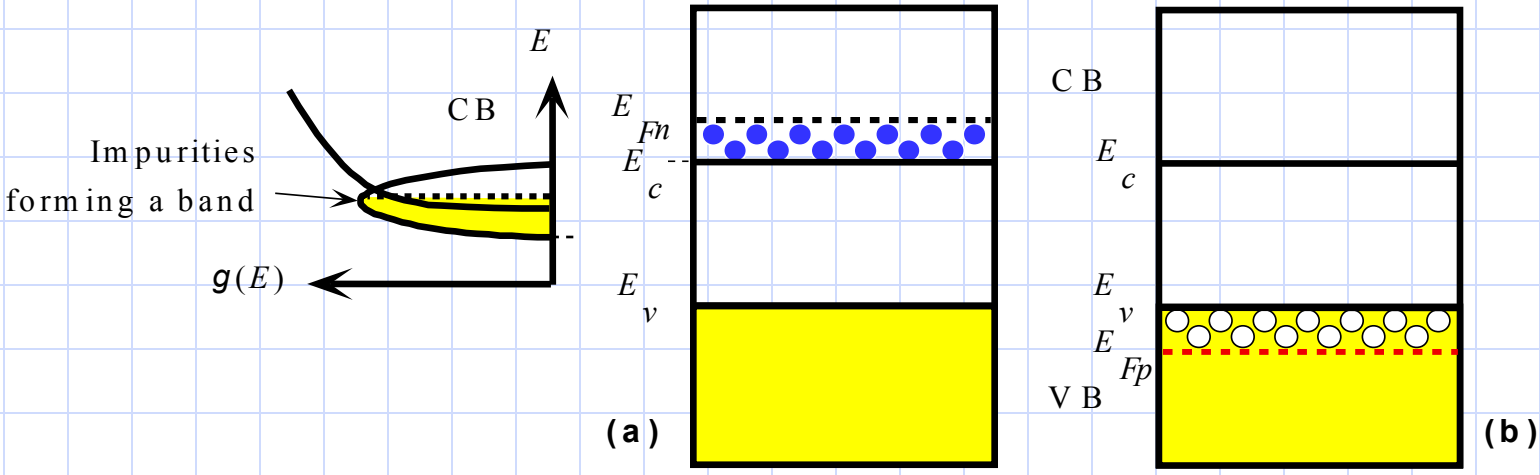
能带结构与载流子分布


(a)
(b)
(c)
(d)
$E_c + c$
CB
E_c
E_F
E_v
VB
0
E
g(E)
$(E - E_c)^{1/2}$
E
g(E)
[1- f(E)]
For electrons
E_F
For holes
fE)
E
A rea = $\int n_E(E)dE = n$
$n_E(E)$
E_c
E_v
$p_E(E)$
A rea = p
$n_E(E)$ or $p_E(E)$

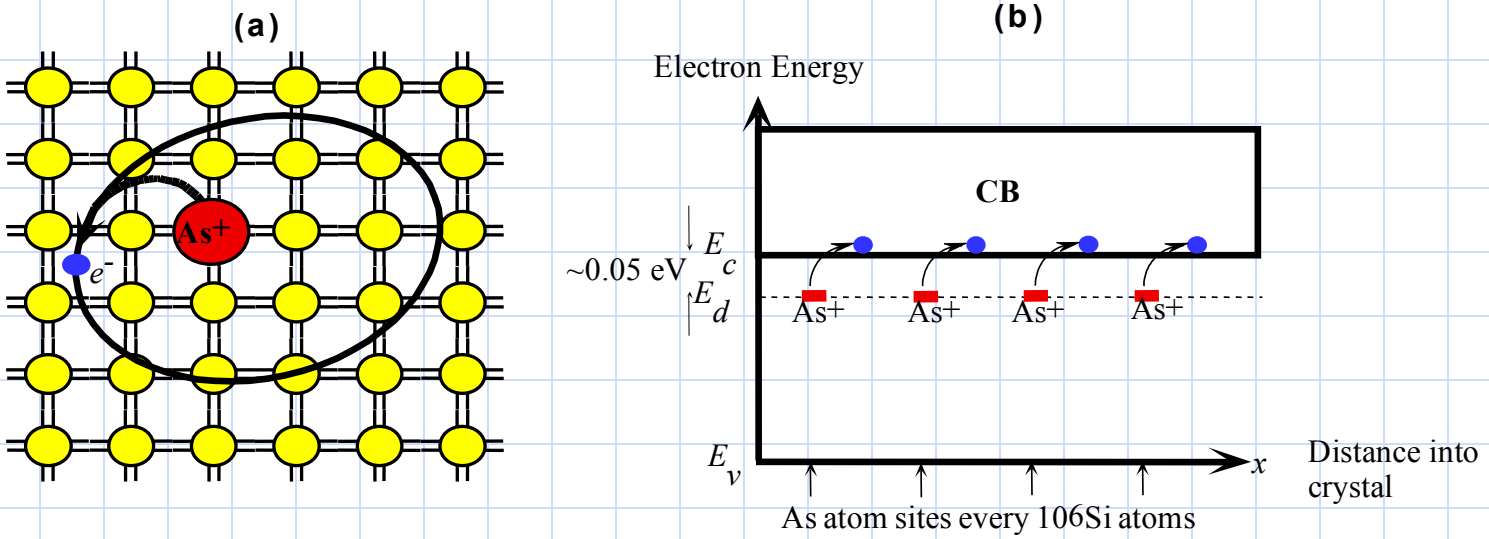
本征半导体和掺杂半导体



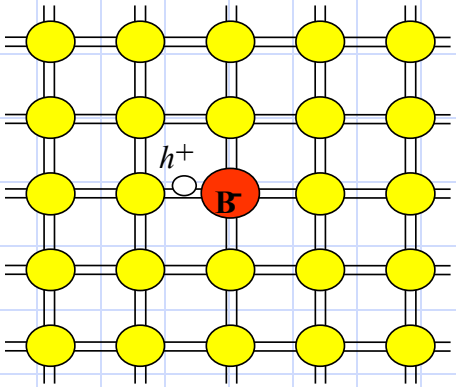
P 型简并和 n 型简并半导体



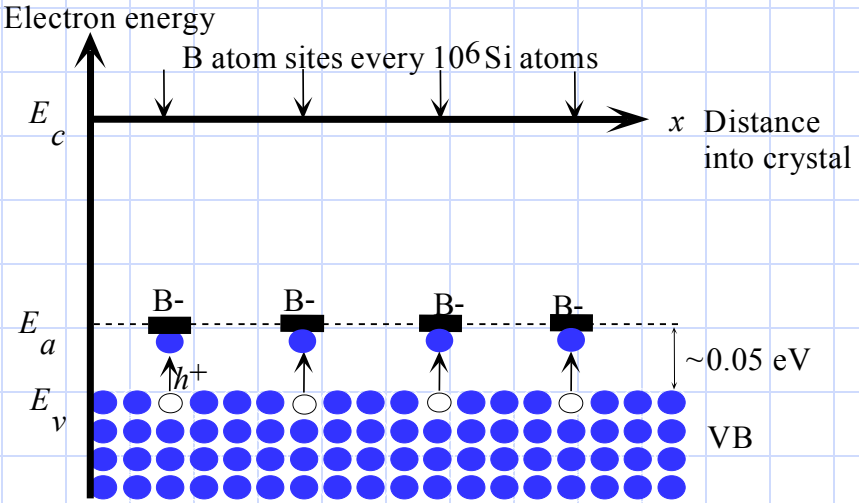
As 掺杂 Si 半导体


(a)
As+
e-
(b)
Electron Energy
CB
~0.05 eV
Ec
Ed
Ev
As+
As+
As+
As+
x
Distance into crystal
As atom sites every 106Si atoms

B 掺杂 Si 半导体

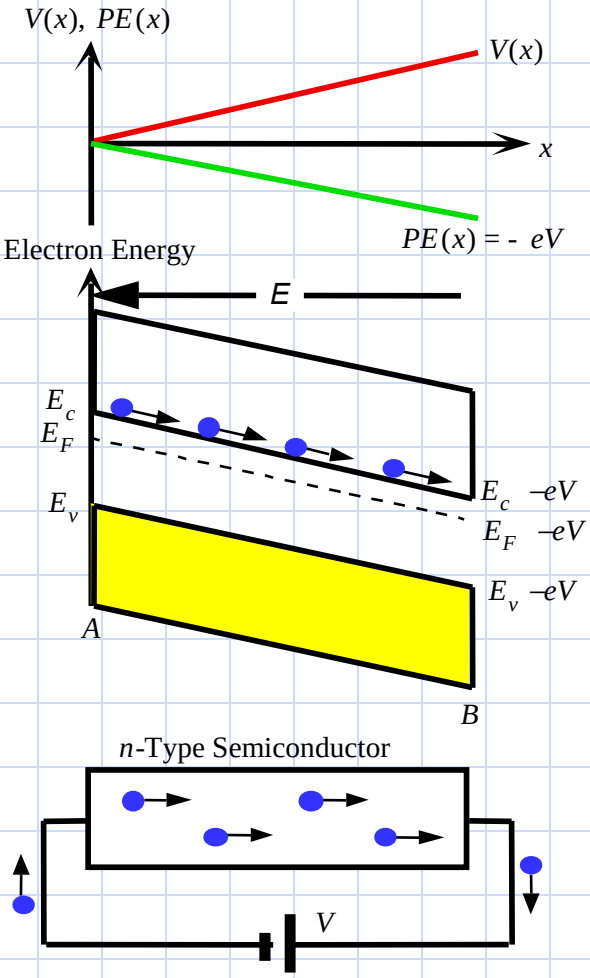

h+
B-

(a)

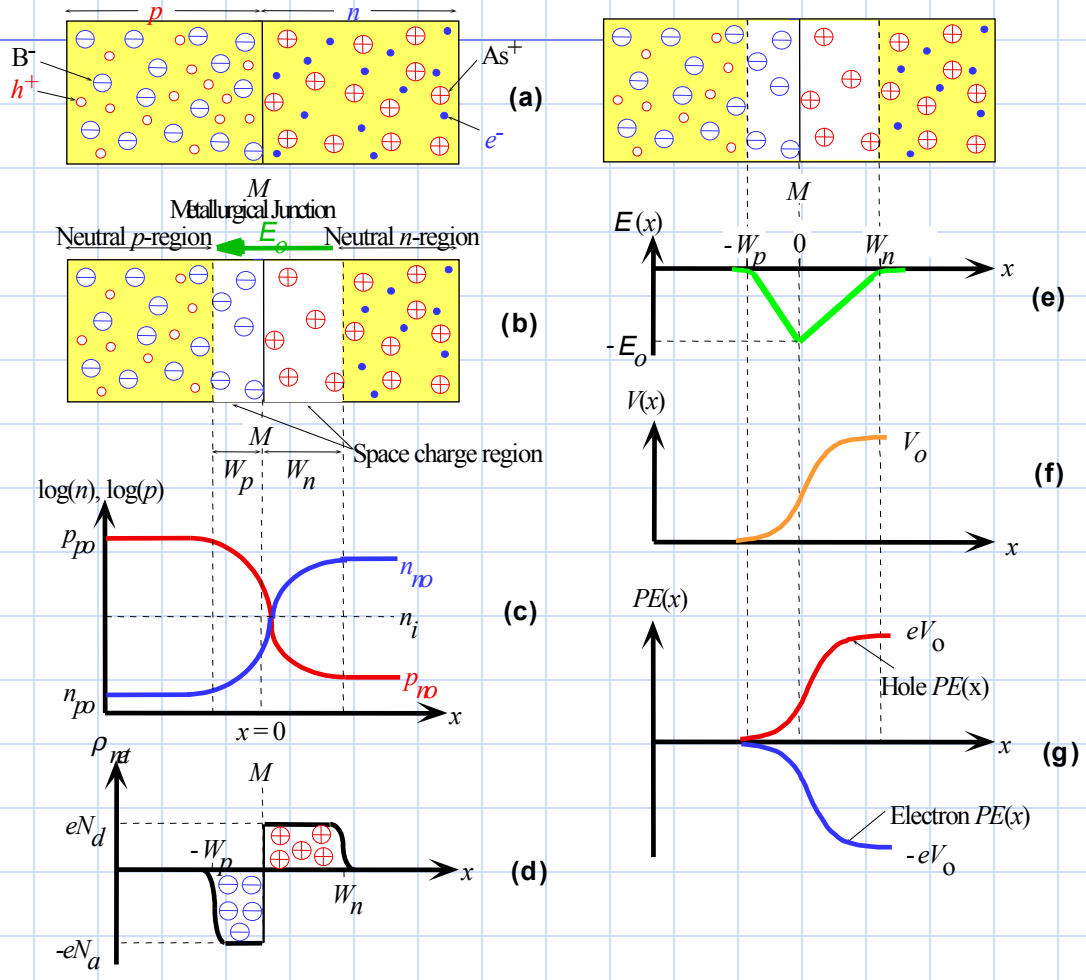

Electron energy
B atom sites every 10^6 Si atoms
E c
x Distance into crystal
B-
B-
B-
B-
E a
h+
~0.05 eV
E v
VB

(b)

n 型半导体的导电

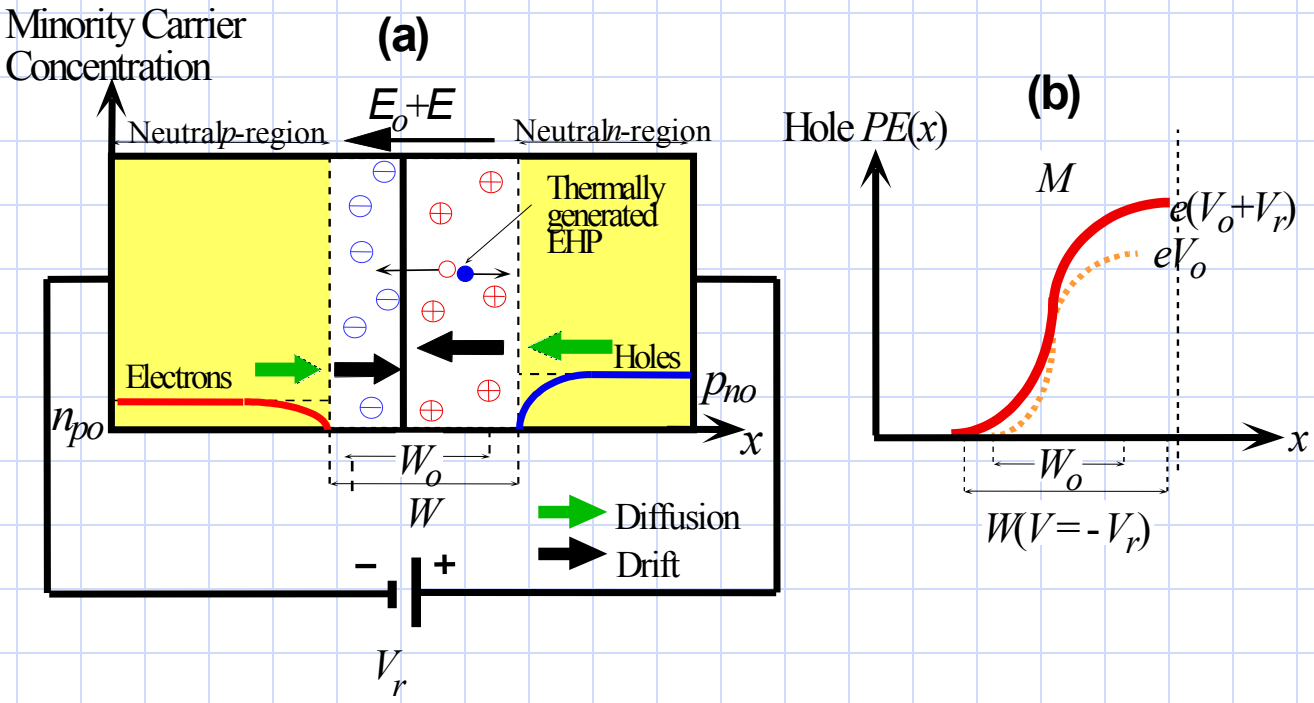

V(x), PE(x)
V(x)
x
PE(x) = - eV
Electron Energy
E
E_c
E_F
E_v
E_c –eV
E_F –eV
E_v –eV
A
B
n-Type Semiconductor
V

pn 结

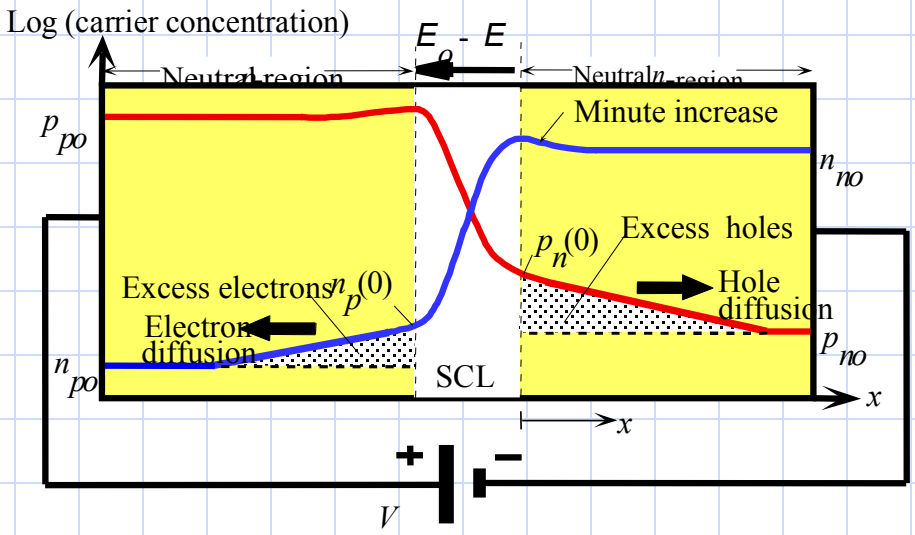


Properties of the *pn* junction.

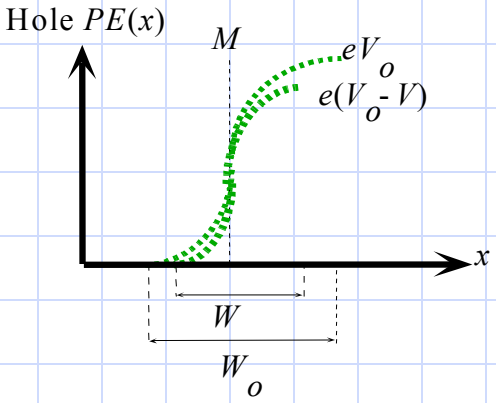
pn 结的偏压


Minority Carrier Concentration
(a)
E_o+E
Neutral p-region
Neutral n-region
Thermally generated EHP
Electrons
Holes
n_{po}
p_{no}
x
W_o
W
Diffusion
Drift
V_r
Hole $PE(x)$
(b)
M
$e(V_o+V_r)$
eV_o
x
W_o
$W(V=-V_r)$

加电压（正反向）的 pn 结

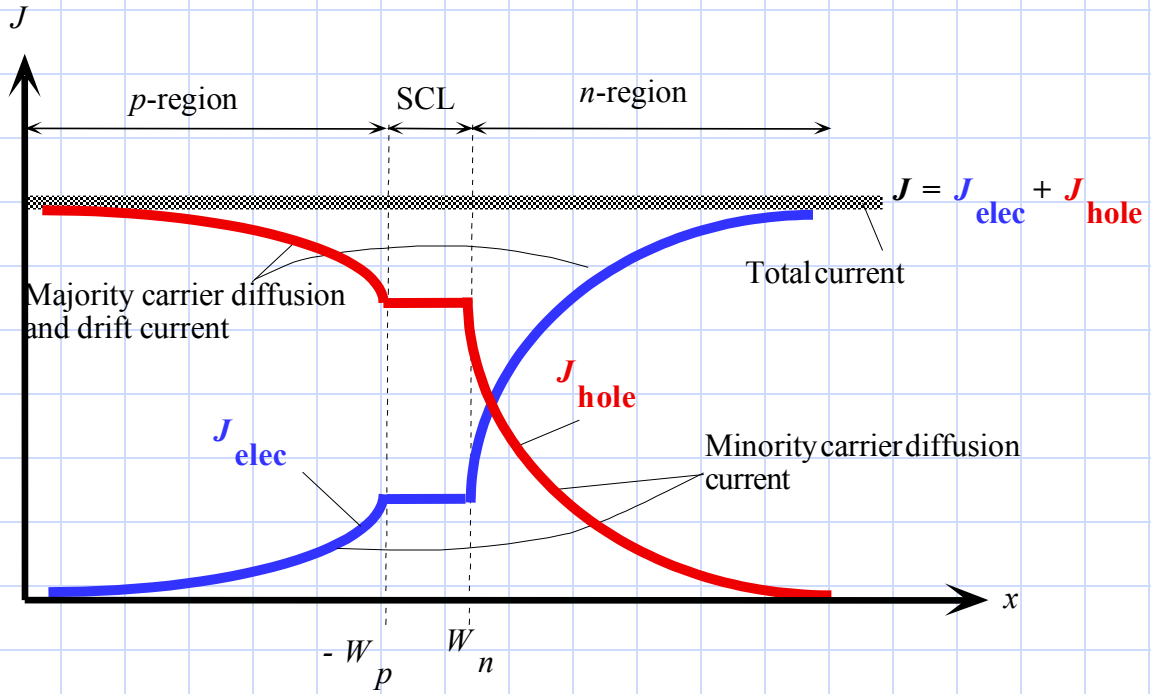


(a)

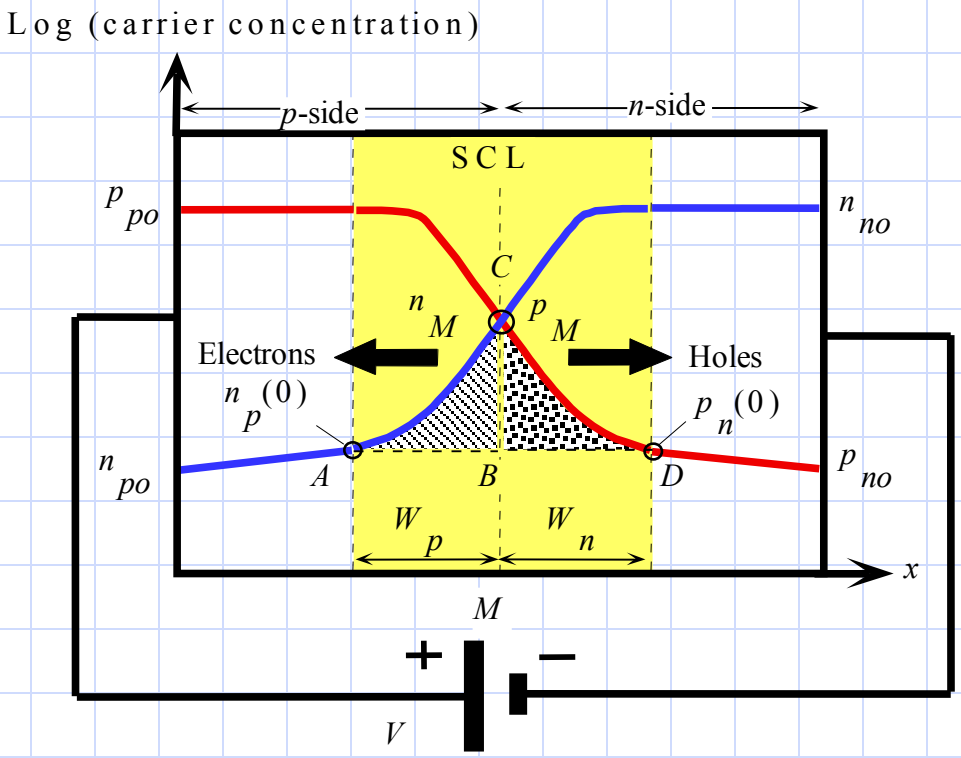


(b)

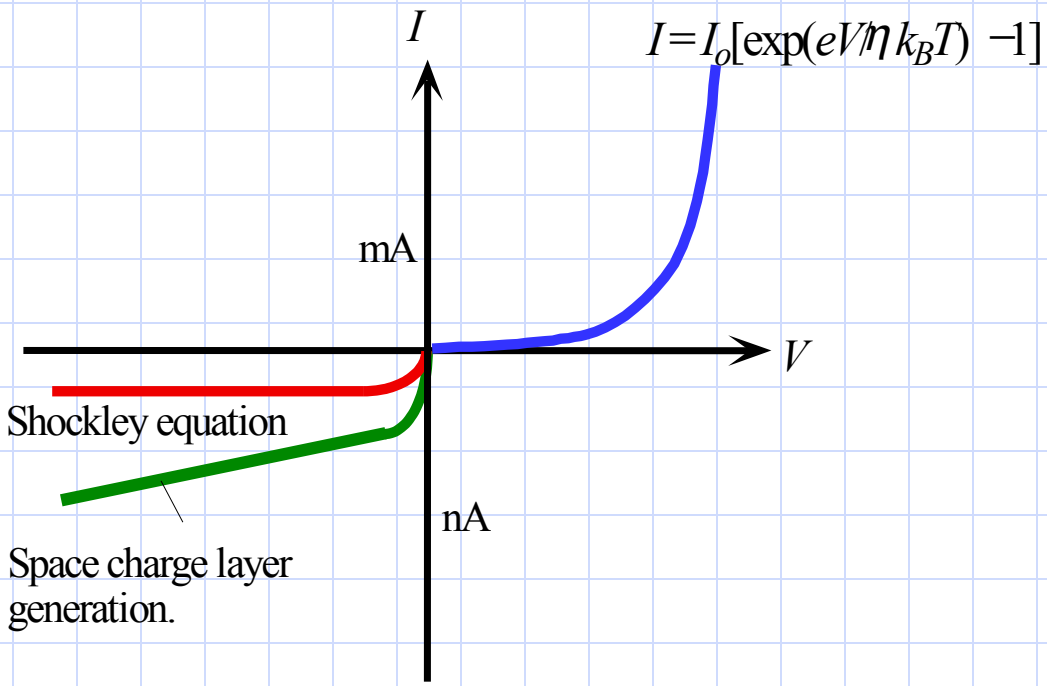
pn 结中的电流


J
p-region
SCL
n-region
J = J elec + J hole
Total current
Majority carrier diffusion and drift current
J hole
J elec
Minority carrier diffusion current
x
- W p
W n

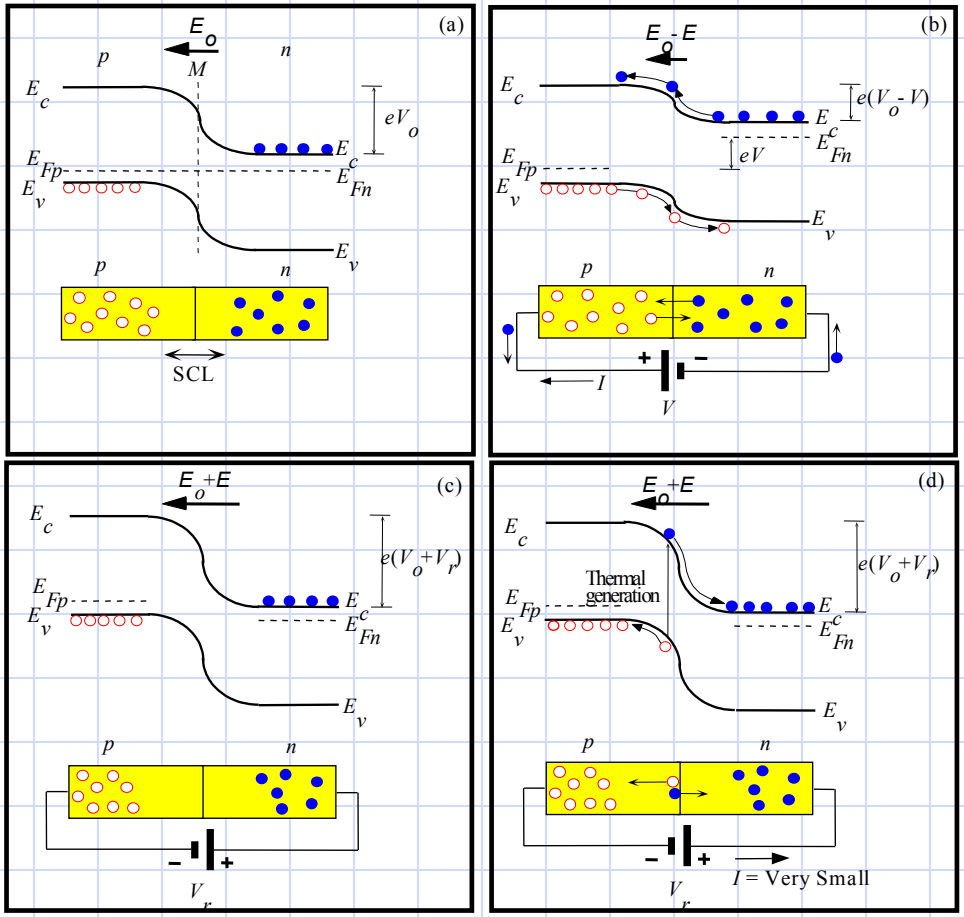
pn 结中的载流子


Log (carrier concentration)
p-side
n-side
SCL
p_{po}
n_{no}
C
n_M
p_M
Electrons
Holes
$n_p(0)$
$p_n(0)$
n_{po}
p_{no}
A
B
D
W_p
W_n
x
M
+
−
V

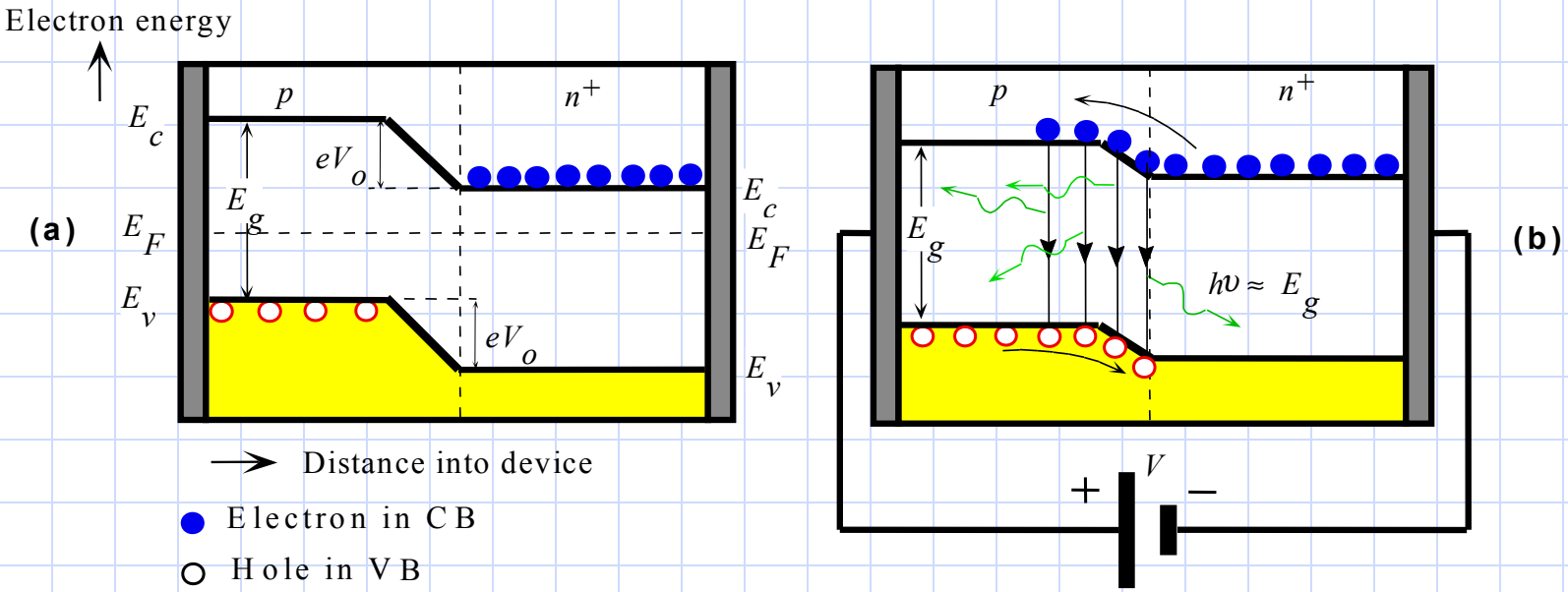
I-V 特性


I
$I = I_o[\exp(eV/\eta k_B T) - 1]$
mA
V
Shockley equation
nA
Space charge layer
generation.

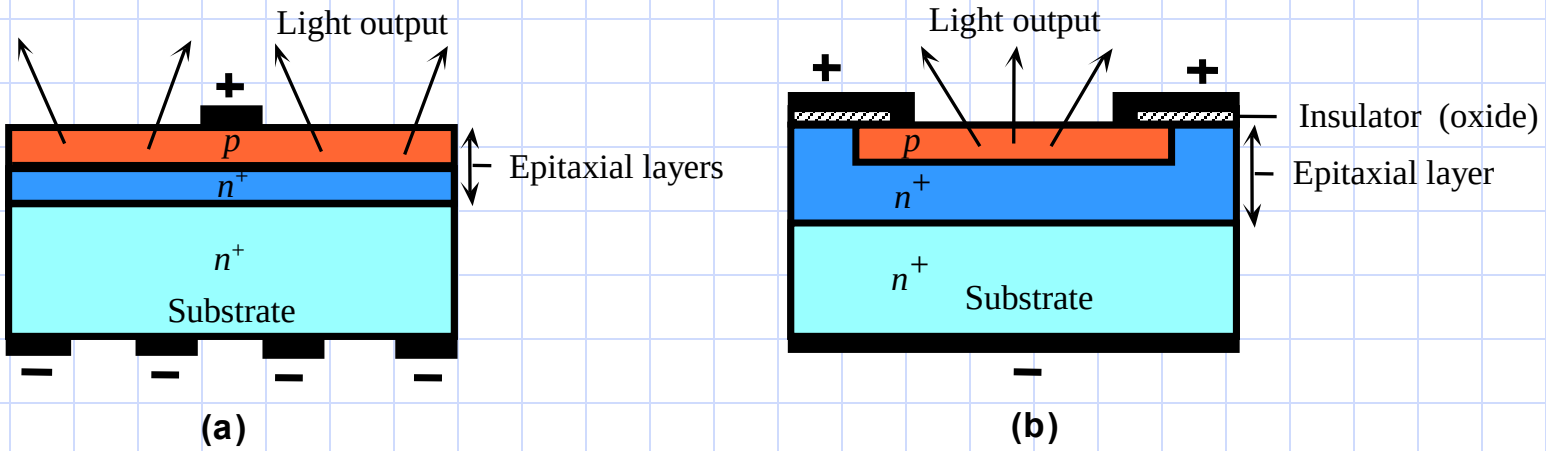
pn 结的能带结构


(a)
E_o
p
n
M
E_c
eV_o
E_{Fp}
E_v
E_c
E_{Fn}
E_v
p
n
SCL
(b)
$E_o - E$
E_c
$e(V_o - V)$
E_c
eV
E_{Fn}
E_{Fp}
E_v
E_v
p
n
I
V
(c)
$E_o + E$
E_c
$e(V_o + V_r)$
E_{Fp}
E_v
E_c
E_{Fn}
E_v
p
n
V_r
(d)
$E_o + E$
E_c
Thermal generation
$e(V_o + V_r)$
E_{Fp}
E_v
E_c
E_{Fn}
E_v
p
n
V_r
I = Very Small

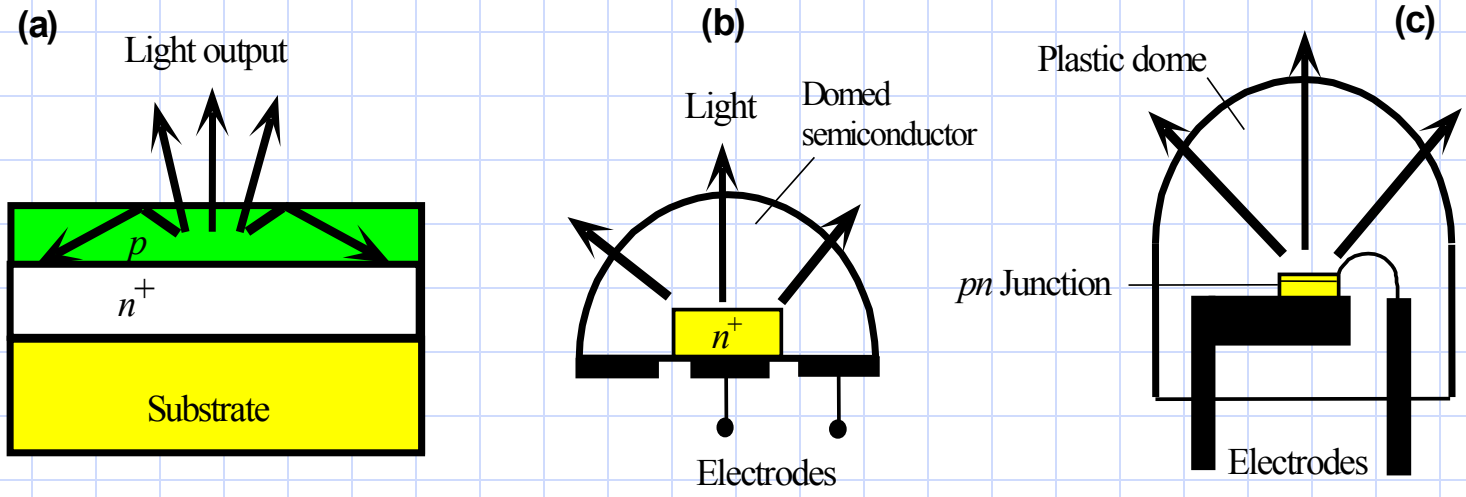
pn 结能带结构（有偏压）光的发射



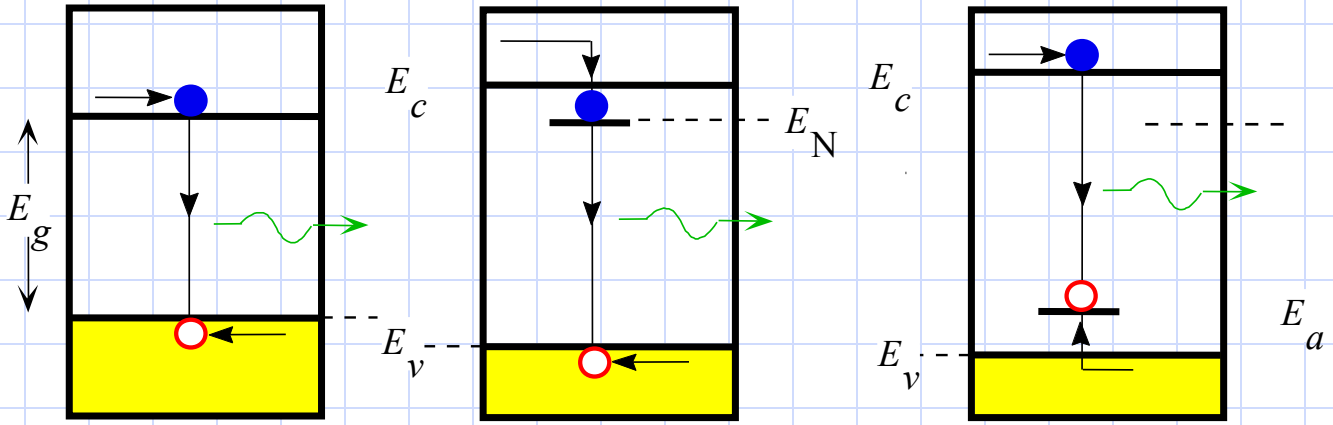
LED 原理图


Light output
p
n+
n+
Substrate
Epitaxial layers
(a)
Light output
p
n+
n+
Substrate
Insulator (oxide)
Epitaxial layer
(b)

LED 原理结构图


(a)
Light output
p
n+
Substrate
(b)
Light
Domed
semiconductor
n+
Electrodes
(c)
Plastic dome
pn Junction
Electrodes

半导体的光发射

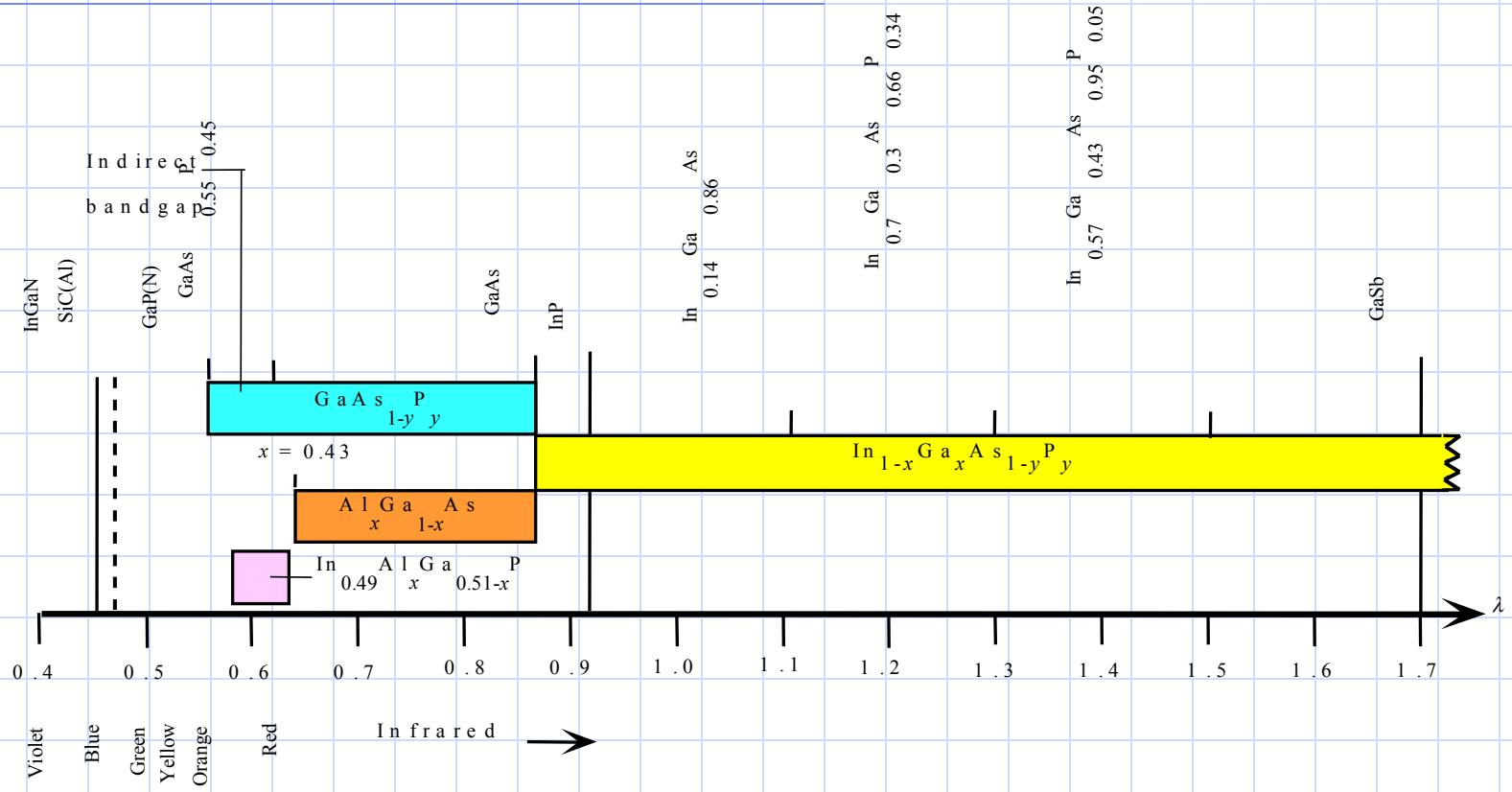


(a) $GaAs_{1-y}P_y$ $y < 0.45$

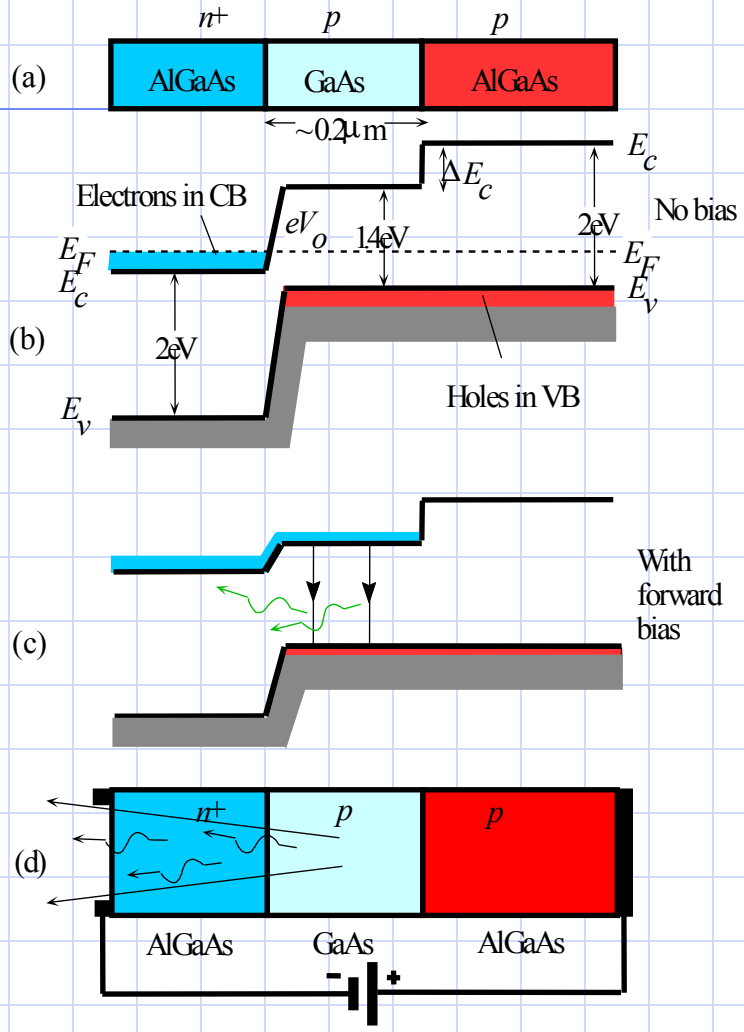
(b) N doped GaP

(c) Al doped SiC

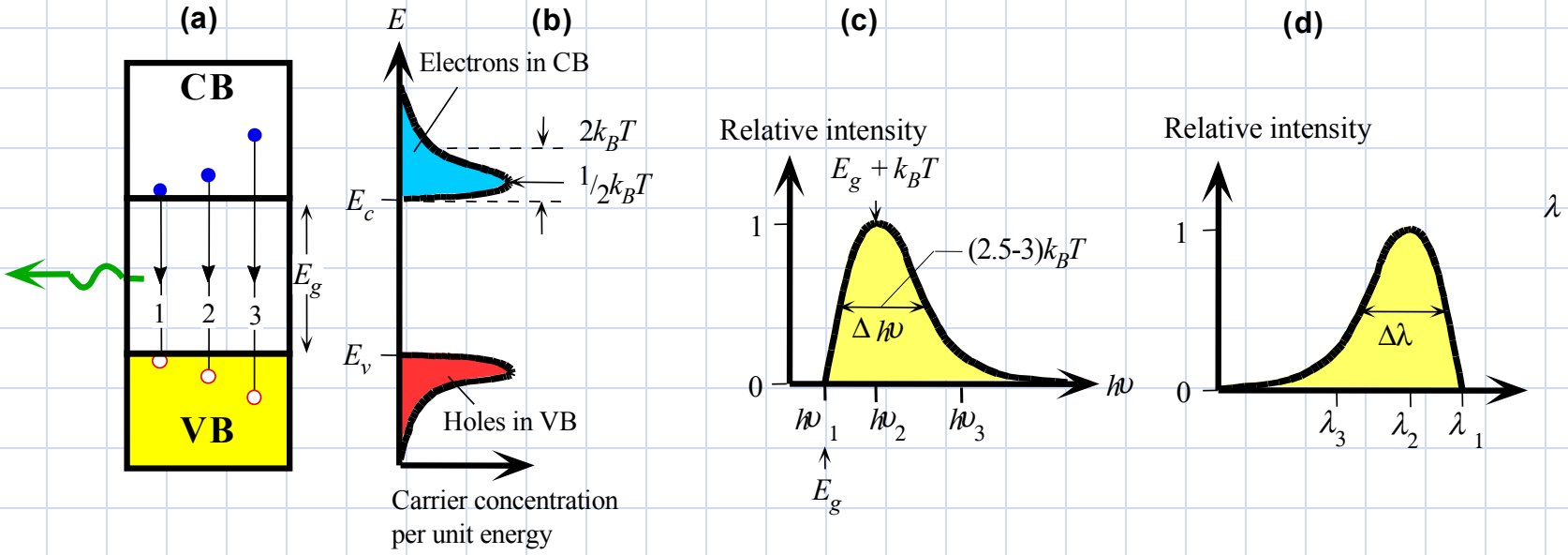
半导体的光发射


Indirect
bandgap
InGaN
SiC(Al)
GaP(N)
GaAs
GaAs
InP
In Ga As P
0.14 0.86 0.45 0.55
In Ga As P
0.7 0.3 0.66 0.34
In Ga As P
0.57 0.43 0.95 0.05
GaSb
GaAs P
1-y y
x = 0.43
In1-xGaxAs1-yPy
AlGa As
x 1-x
In AlGa P
0.49 x 0.51-x
λ
0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7
Violet
Blue
Green
Yellow
Orange
Red
Infrared

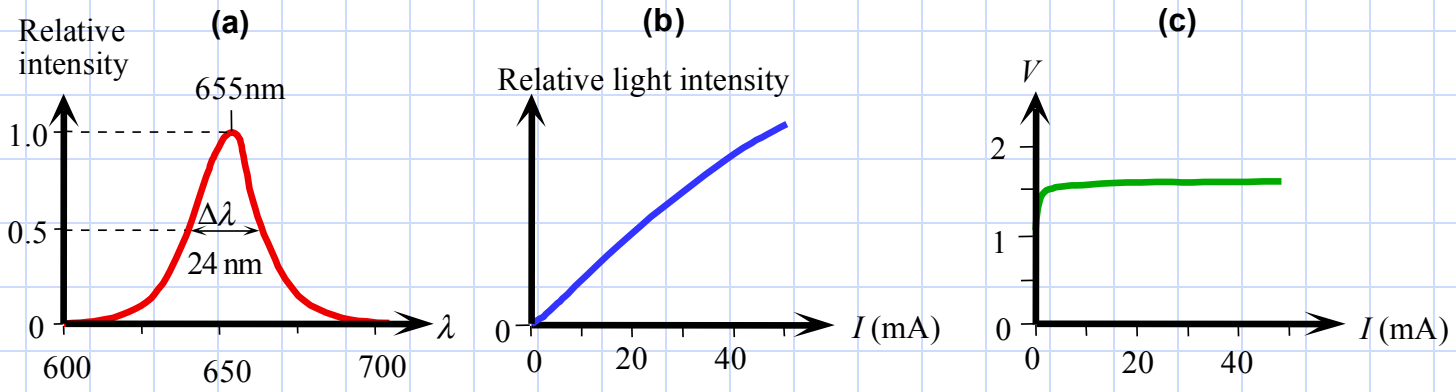
双异质结 LED


n+
p
p
(a)
AlGaAs
GaAs
AlGaAs
~0.2μm
E_c
ΔE_c
Electrons in CB
eV_o
1.4eV
2eV
No bias
E_F
E_c
E_F
E_v
(b)
2eV
E_v
Holes in VB
With
forward
bias
(c)
n+
p
p
(d)
AlGaAs
GaAs
AlGaAs
-
+

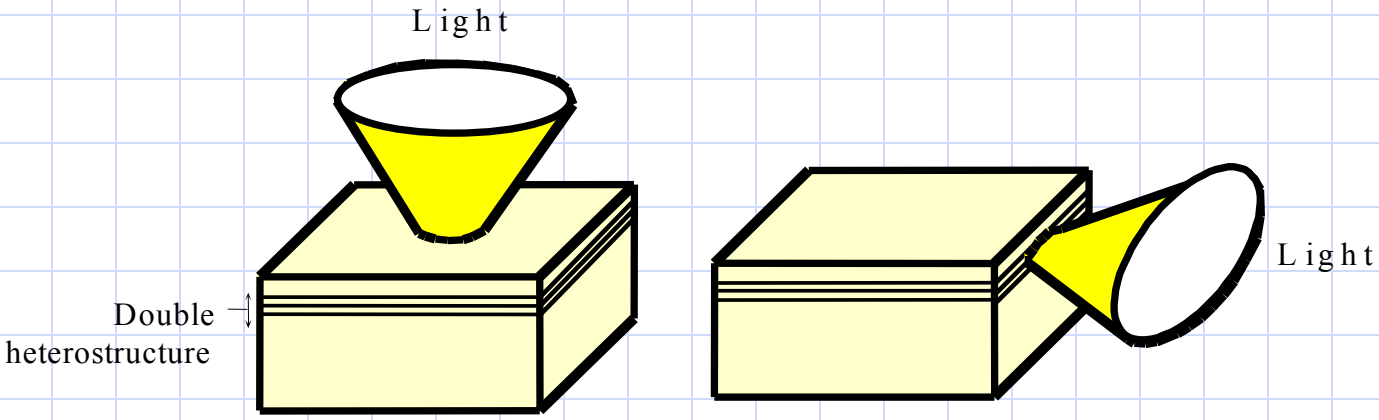
复合的过程


(a)
CB
VB
E_g
1
2
3
(b)
E
Electrons in CB
$2k_BT$
E_c
$1/2k_BT$
E_v
Holes in VB
Carrier concentration
per unit energy
(c)
Relative intensity
$E_g + k_BT$
1
$(2.5\text{-}3)k_BT$
$\Delta h\upsilon$
0
$h\upsilon$
$h\upsilon_1$
$h\upsilon_2$
$h\upsilon_3$
E_g
(d)
Relative intensity
λ
1
$\Delta\lambda$
0
λ_3
λ_2
λ_1

典型发射谱


(a)
Relative intensity
655nm
1.0
0.5
Δλ
24 nm
0
600
650
700
λ
(b)
Relative light intensity
0
0
20
40
I (mA)
(c)
V
2
1
0
0
20
40
I (mA)

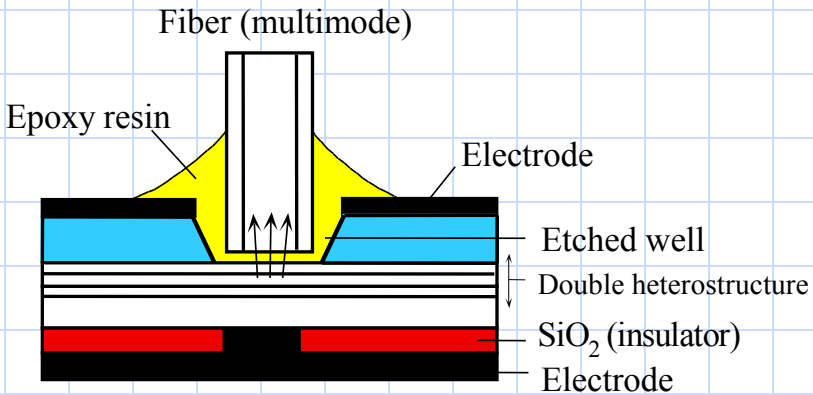
面发射和边发射结构



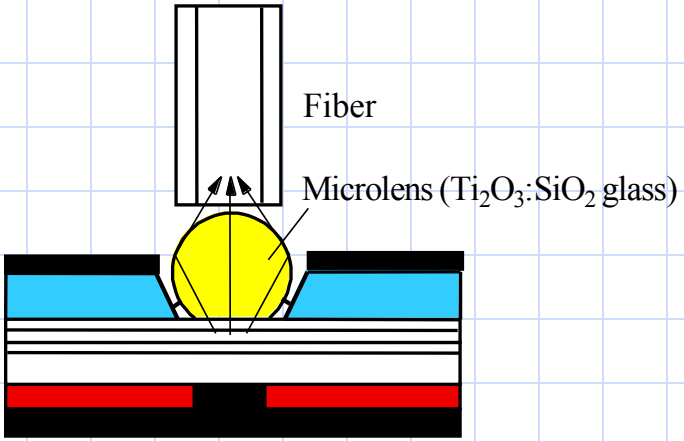
(a) Surface emitting LED

(b) Edge emitting LED

光耦合

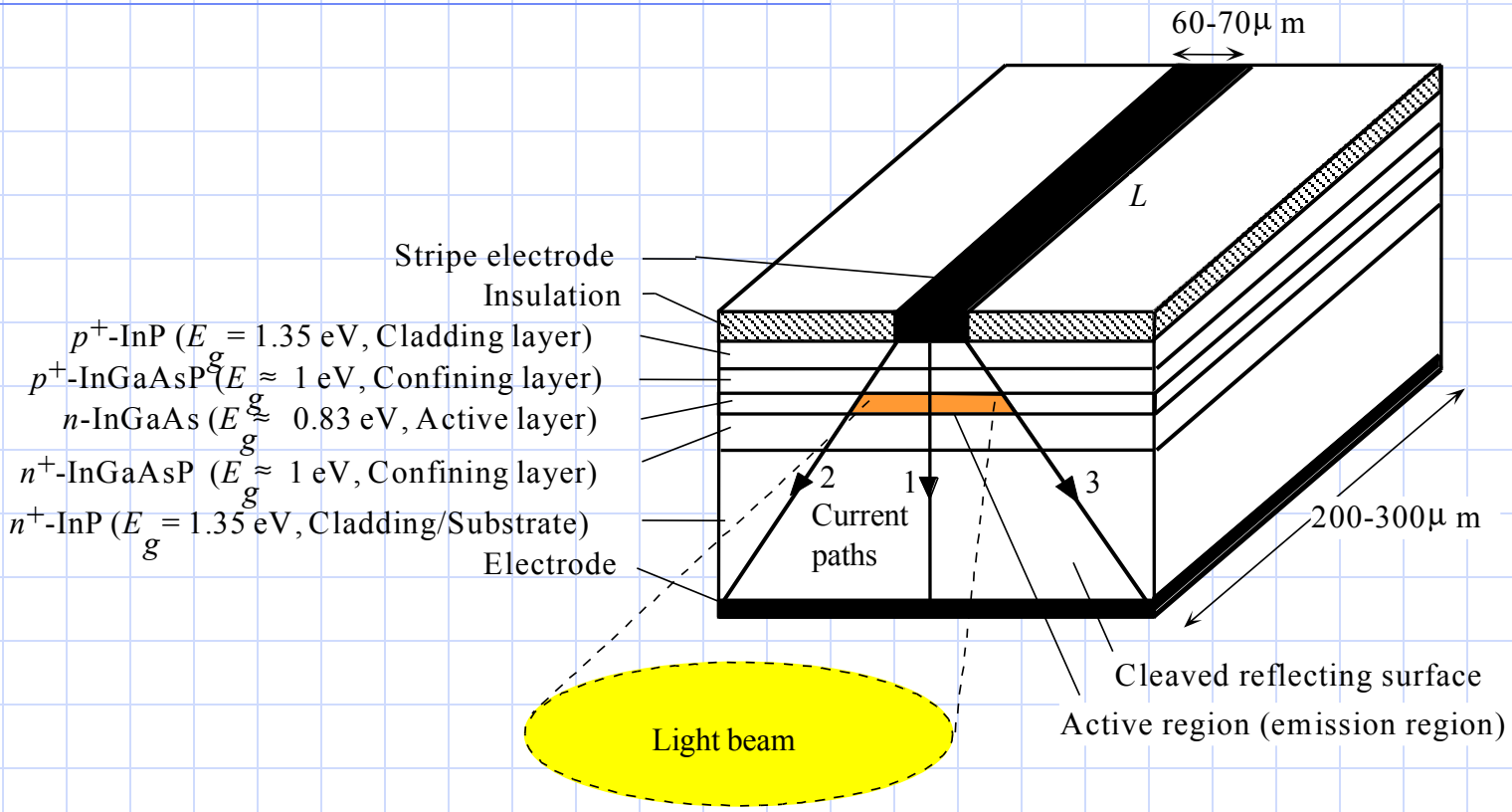

Fiber (multimode)
Epoxy resin
Electrode
Etched well
Double heterostructure
SiO_2 (insulator)
Electrode

(a)

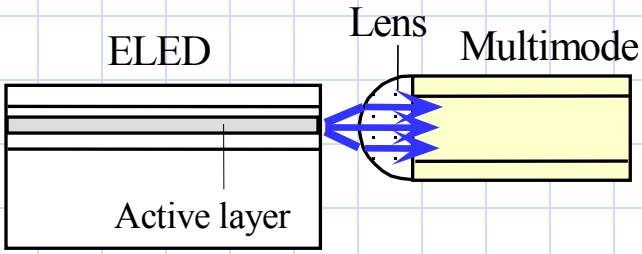

Fiber
Microlens (Ti_2O_3:SiO_2 glass)

(b)

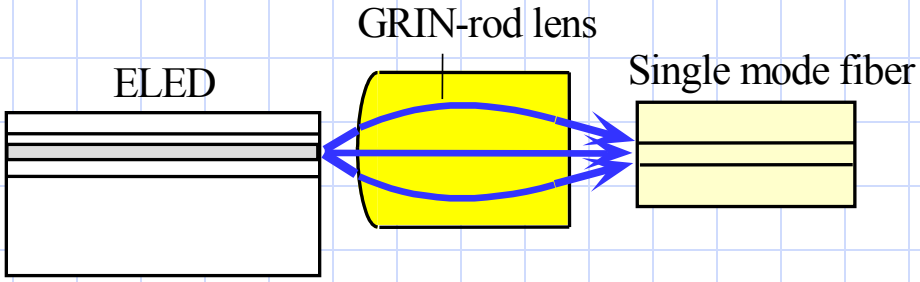
LED 典型结构


60-70μ m
L
Stripe electrode
Insulation
p^+-InP (E_g = 1.35 eV, Cladding layer)
p^+-InGaAsP ($E_g \approx$ 1 eV, Confining layer)
n-InGaAs ($E_g \approx$ 0.83 eV, Active layer)
n^+-InGaAsP ($E_g \approx$ 1 eV, Confining layer)
n^+-InP (E_g = 1.35 eV, Cladding/Substrate)
Electrode
2
1
3
Current
paths
200-300μ m
Cleaved reflecting surface
Active region (emission region)
Light beam

透镜耦合

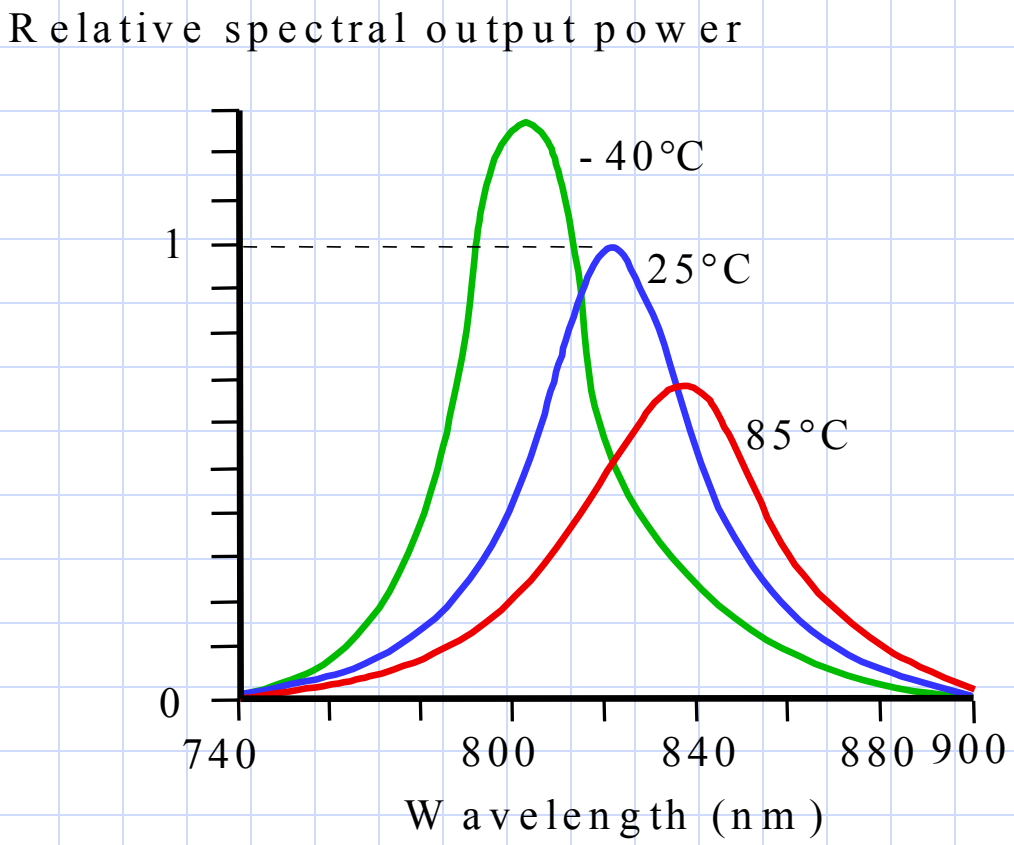

ELED
Lens
Multimode fiber
Active layer

(a)

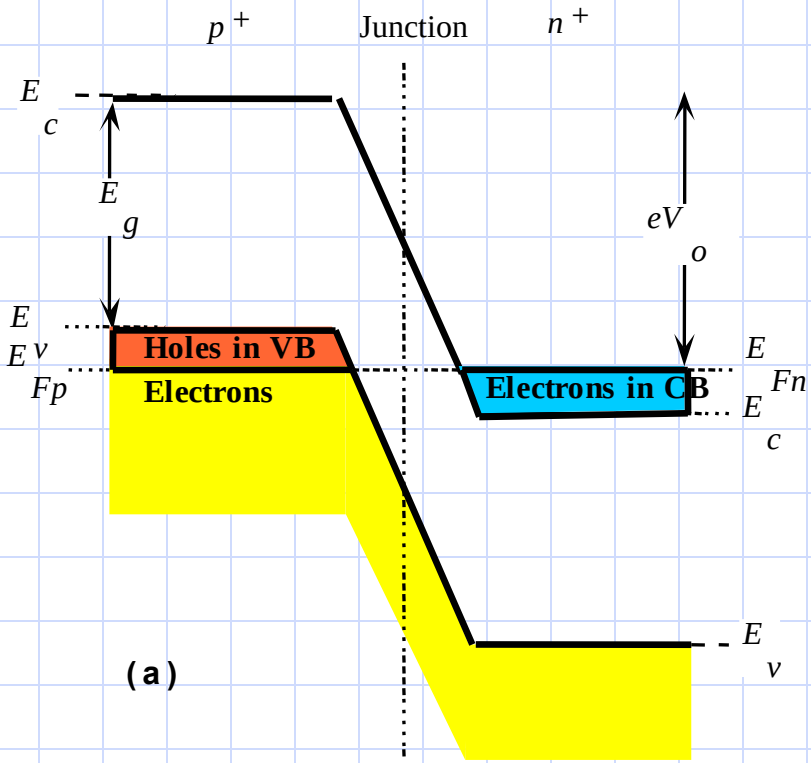

GRIN-rod lens
ELED
Single mode fiber

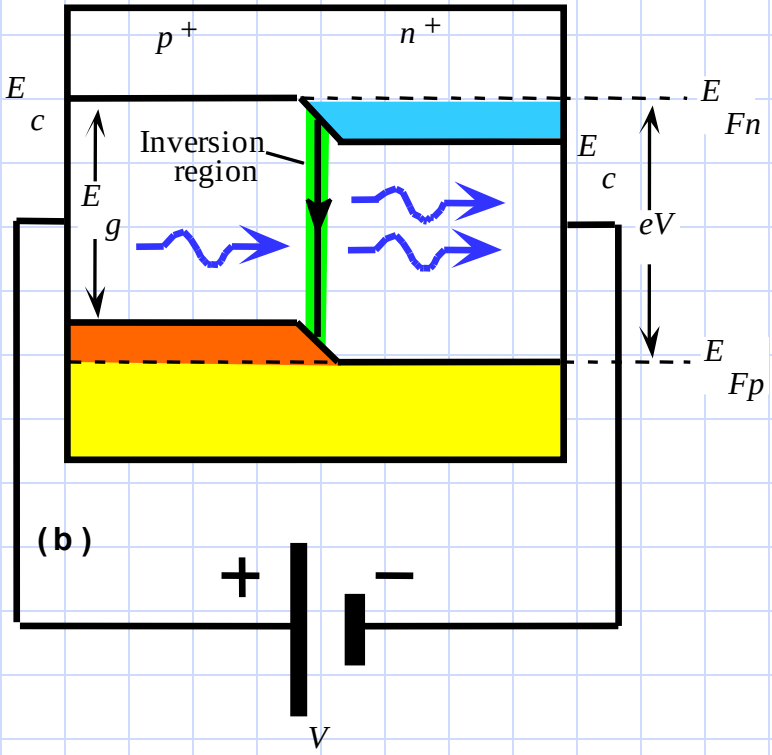
(b)

输出光谱特性

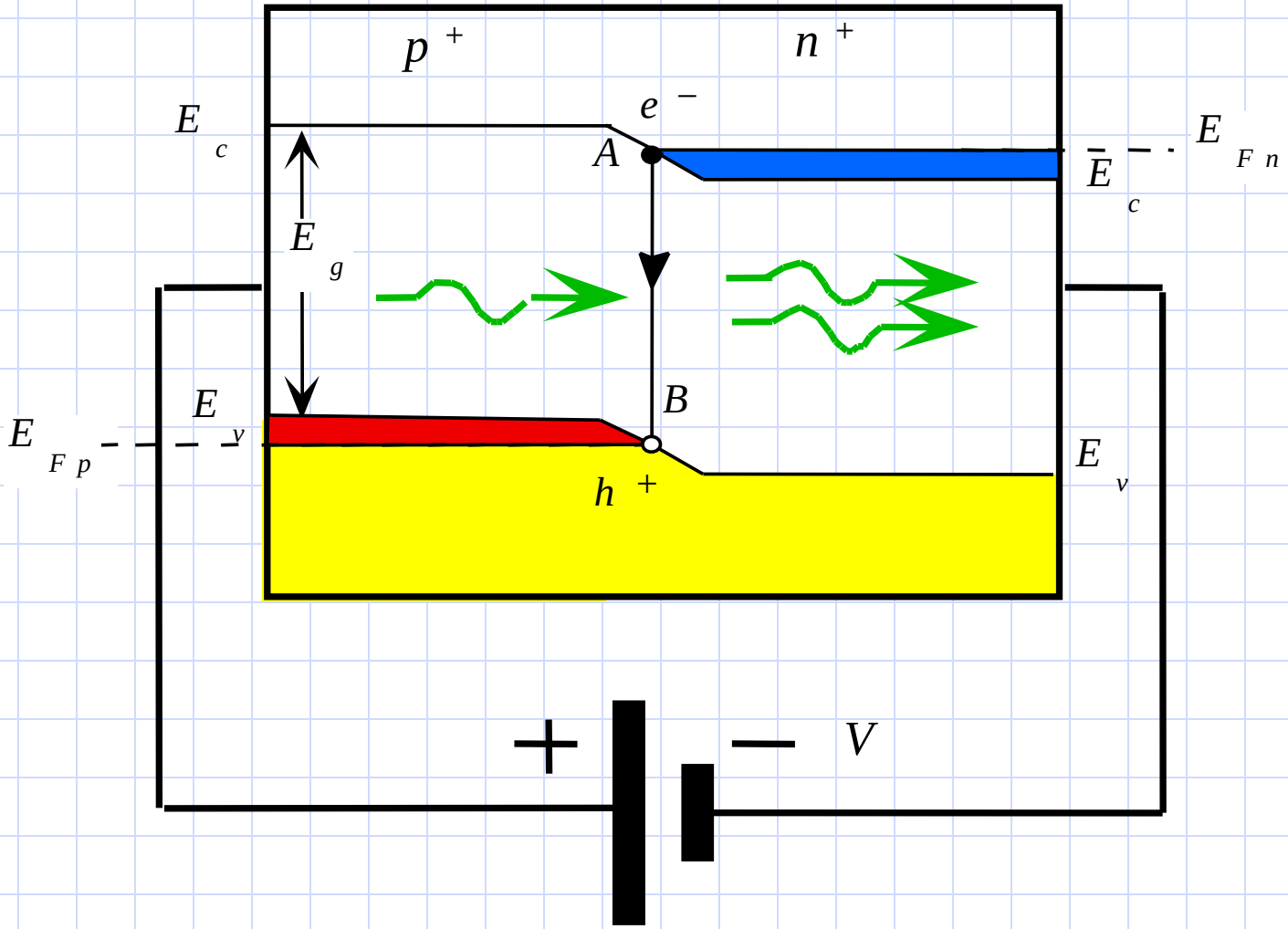

Relative spectral output power
1
0
-40°C
25°C
85°C
740
800
840
880
900
Wavelength (nm)

半导体激光器

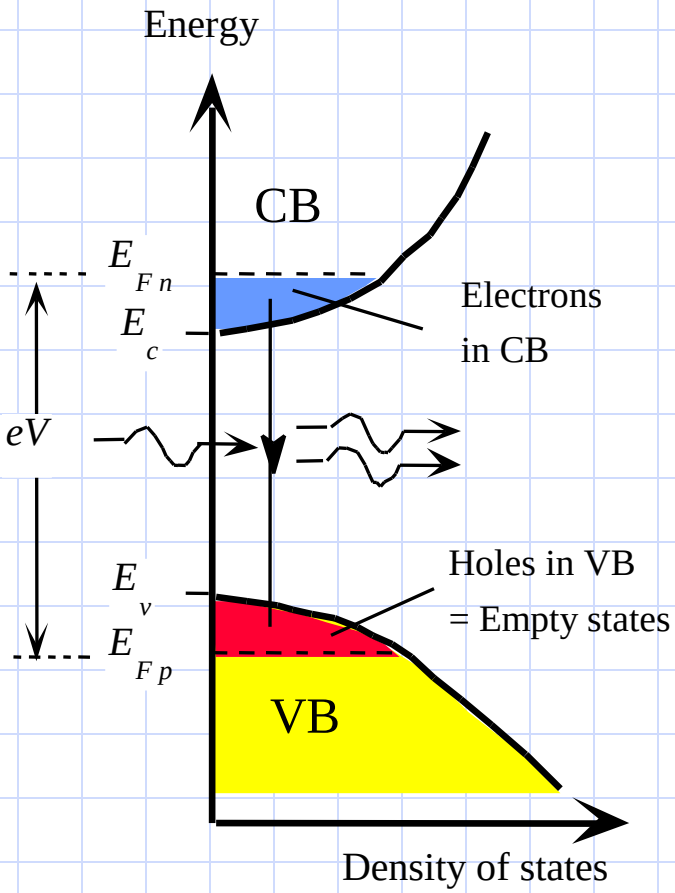

p +
Junction
n +
E
c
E
g
eV
o
E
v
Fp
Holes in VB
Electrons
Electrons in CB
E
Fn
E
c
E
v
(a)

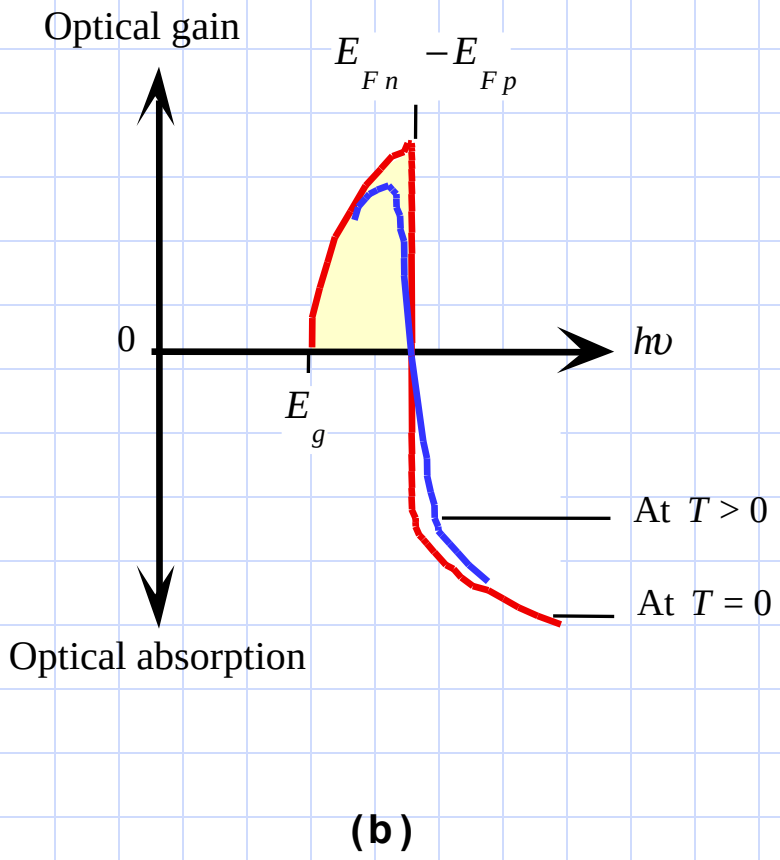

p +
n +
E
c
E
Fn
Inversion
region
E
g
E
c
eV
E
Fp
(b)
+
−
V

PN 结中的受激辐射

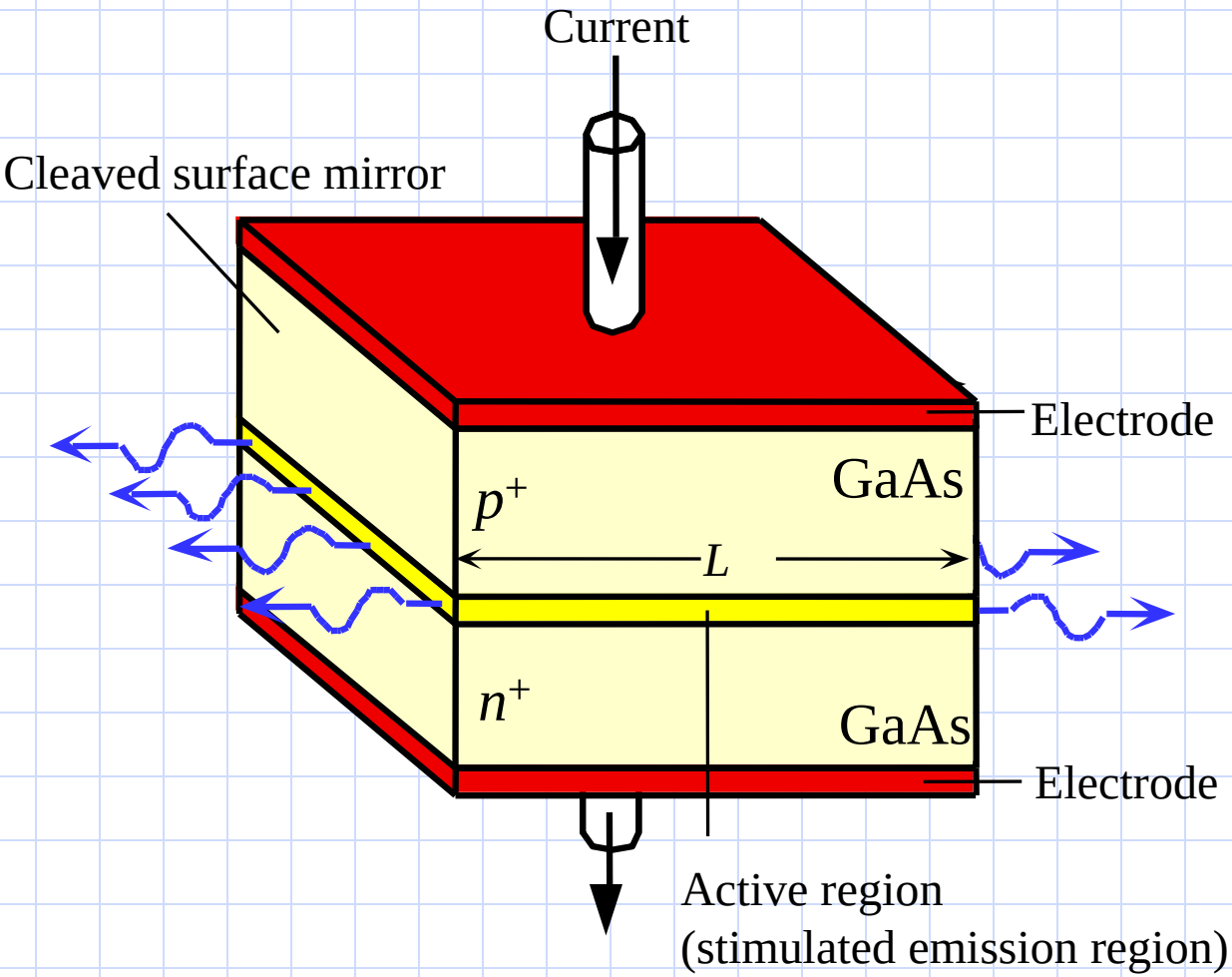


增益谱

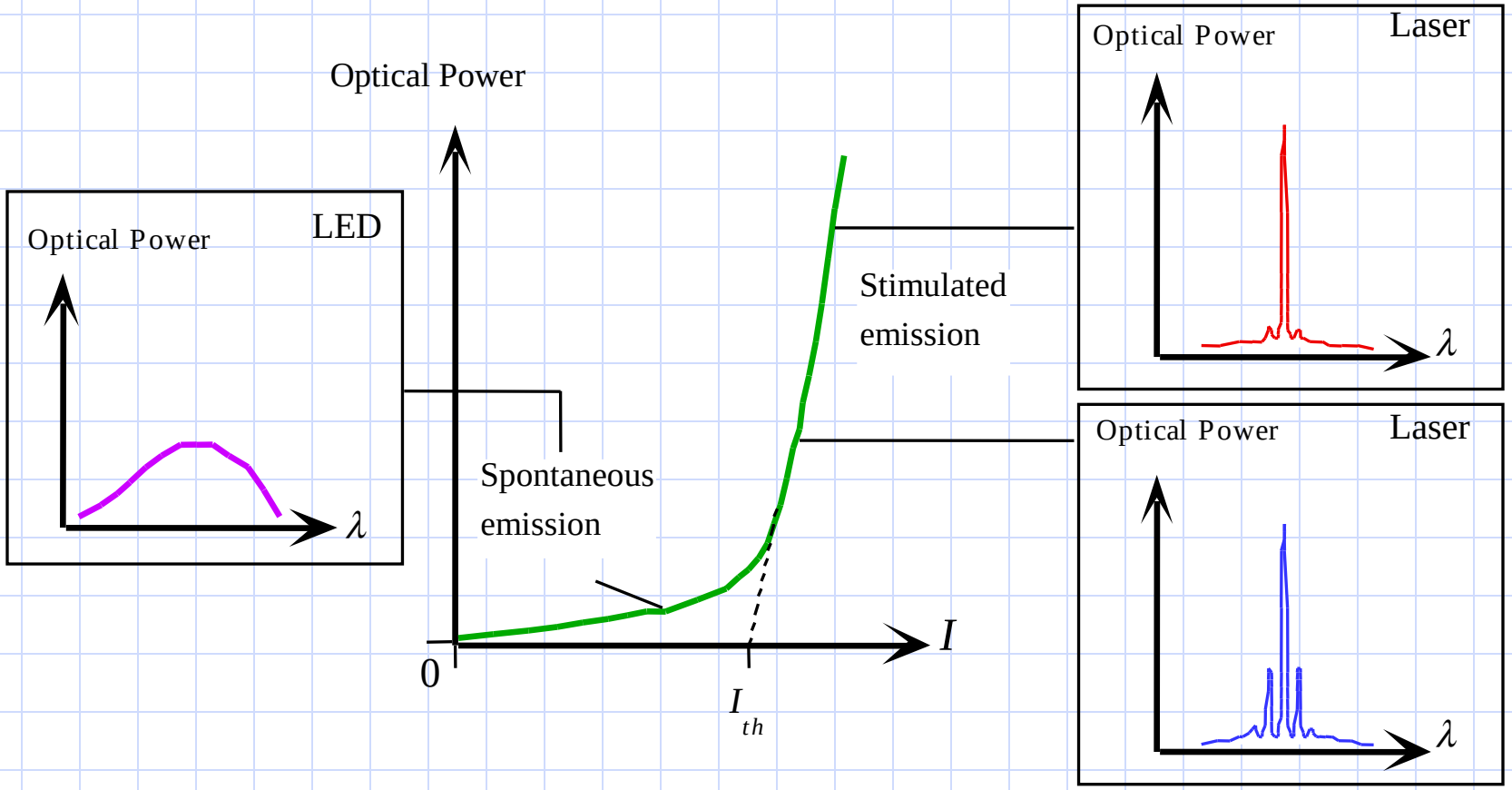

Energy
CB
E_{Fn}
E_c
Electrons
in CB
eV
Holes in VB
= Empty states
E_v
E_{Fp}
VB
Density of states
(a)


Optical gain
$E_{Fn} - E_{Fp}$
0
$h\upsilon$
E_g
At $T > 0$
At $T = 0$
Optical absorption
(b)

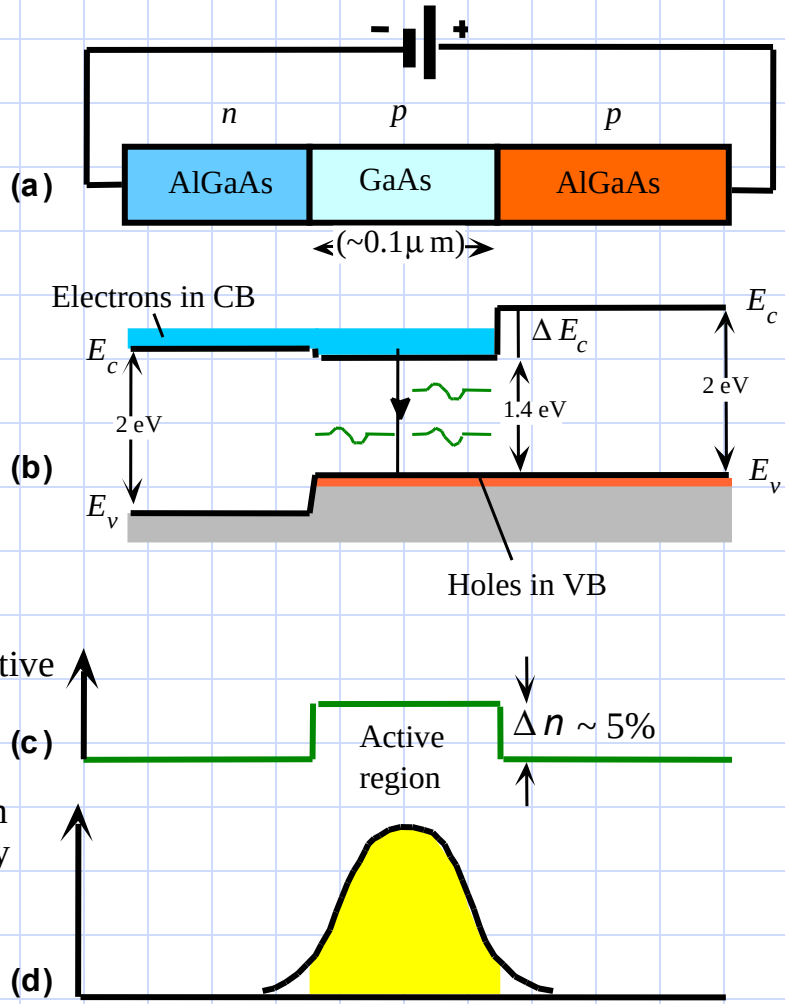
典型的半导体 LD 结构图



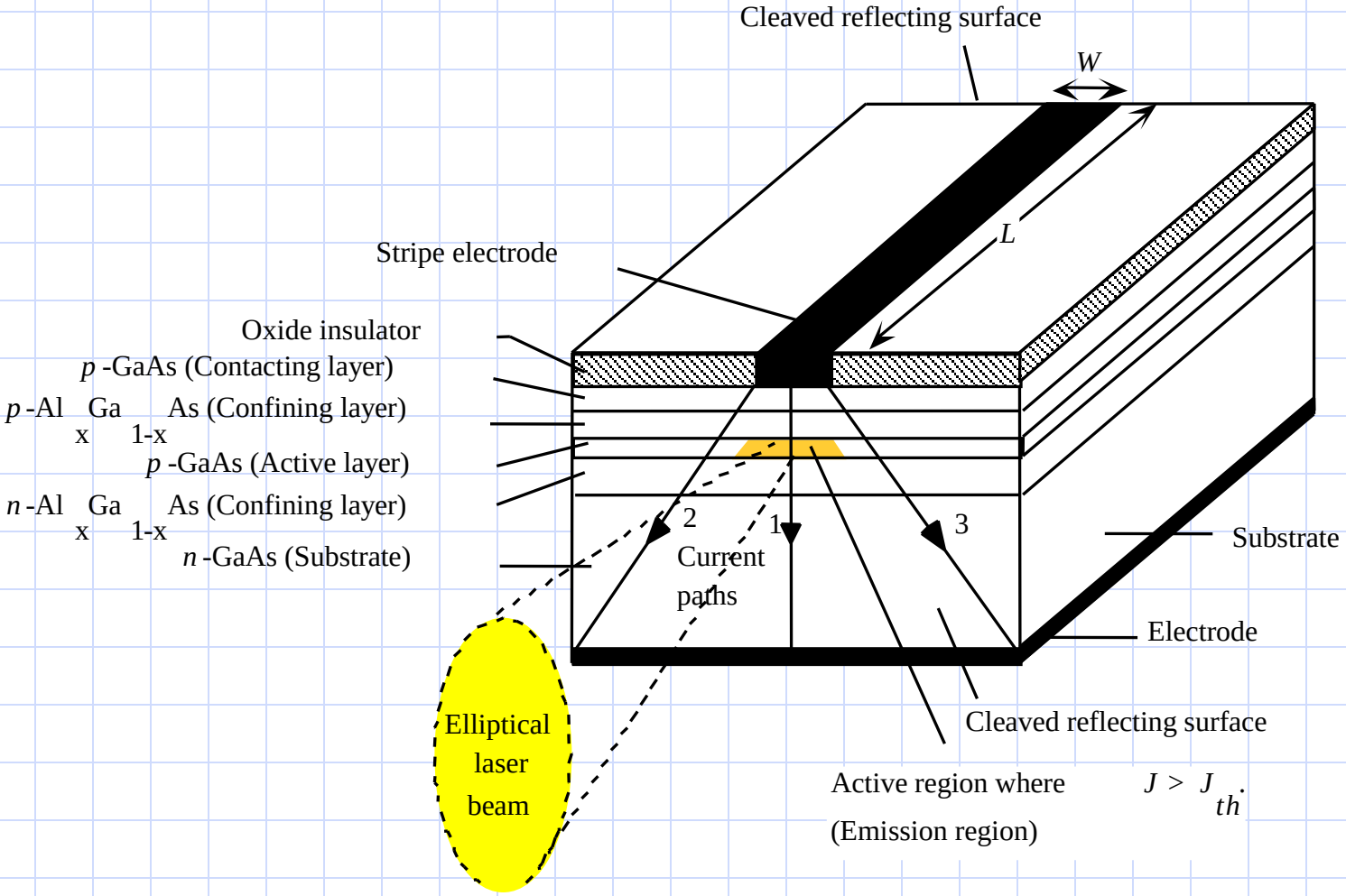
激光特性


Optical Power
LED
Optical Power
λ
Optical Power
Laser
Optical Power
λ
Optical Power
Laser
Optical Power
λ
Stimulated
emission
Spontaneous
emission
0
I
I th

砷化镓激光器


-
+
n
p
p
(a)
AlGaAs
GaAs
AlGaAs
(~0.1μ m)
Electrons in CB
E_c
ΔE_c
E_c
2 eV
1.4 eV
2 eV
(b)
E_v
E_v
Holes in VB
Refractive index
(c)
Active region
Δn ~ 5%
Photon density
(d)

砷化镓激光器结构


Cleaved reflecting surface
W
L
Stripe electrode
Oxide insulator
p -GaAs (Contacting layer)
p -Al Ga As (Confining layer)
x 1-x
p -GaAs (Active layer)
n -Al Ga As (Confining layer)
x 1-x
n -GaAs (Substrate)
2
1
3
Current paths
Substrate
Electrode
Cleaved reflecting surface
Elliptical laser beam
Active region where J > J th.
(Emission region)

砷化镓激光器结构

Oxide insulation

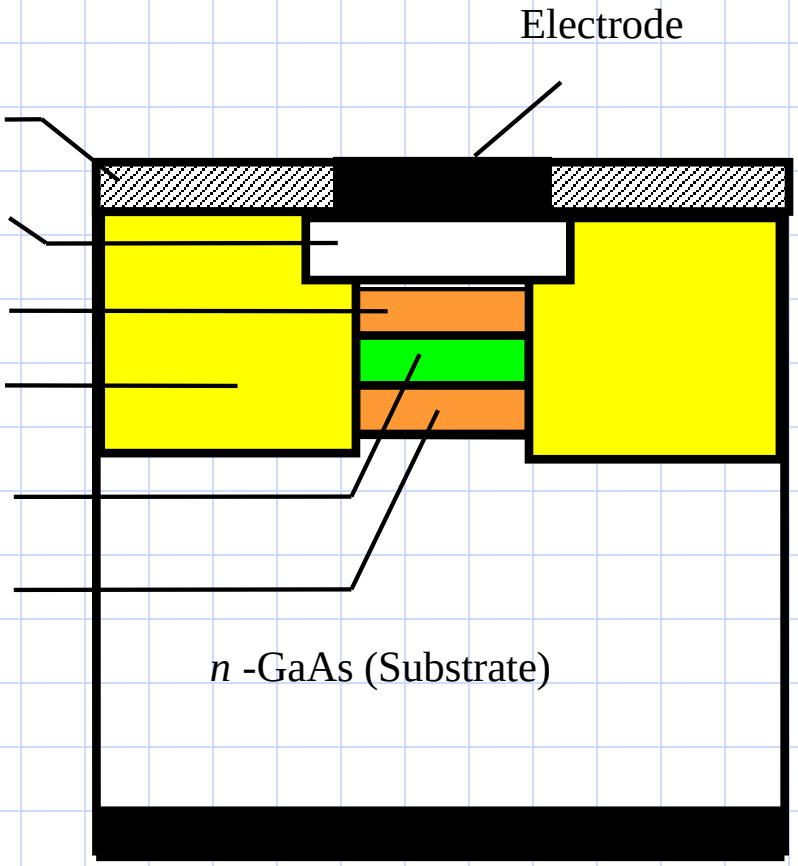
p^+-AlGaAs (Contacting layer)

p -AlGaAs (Confining layer)

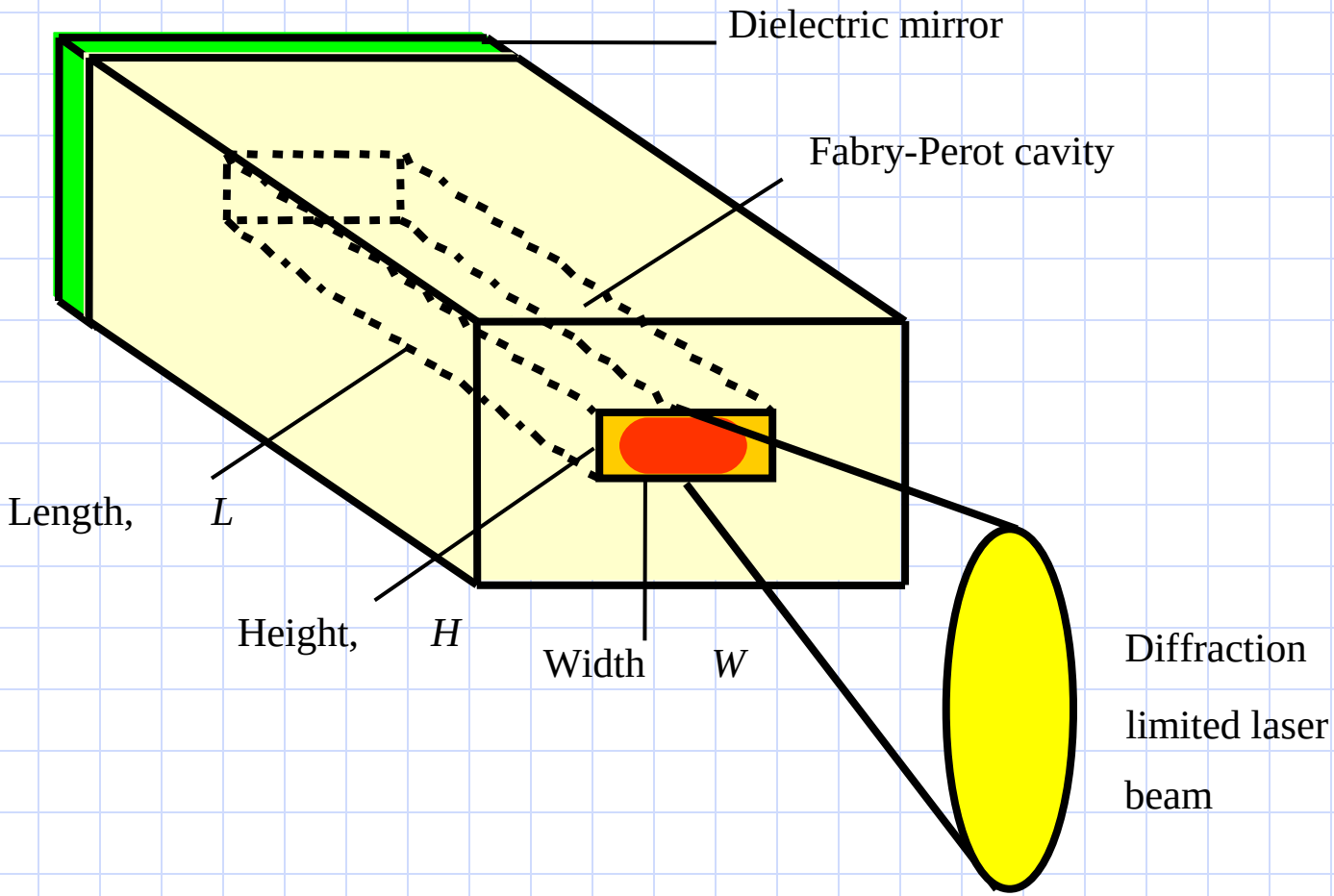
n- AlGaAs

p -GaAs (Active layer)

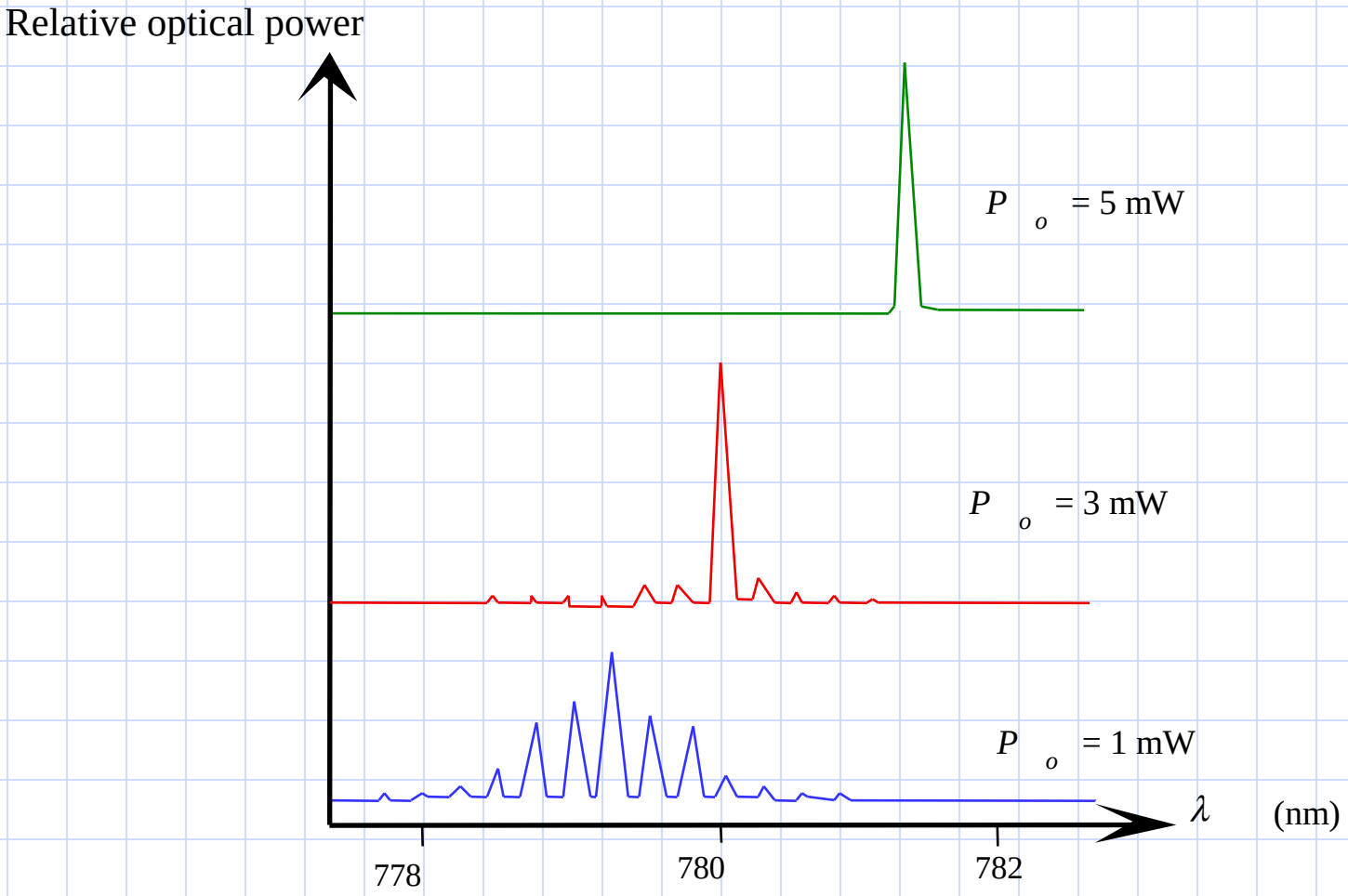
n -AlGaAs (Confining layer)



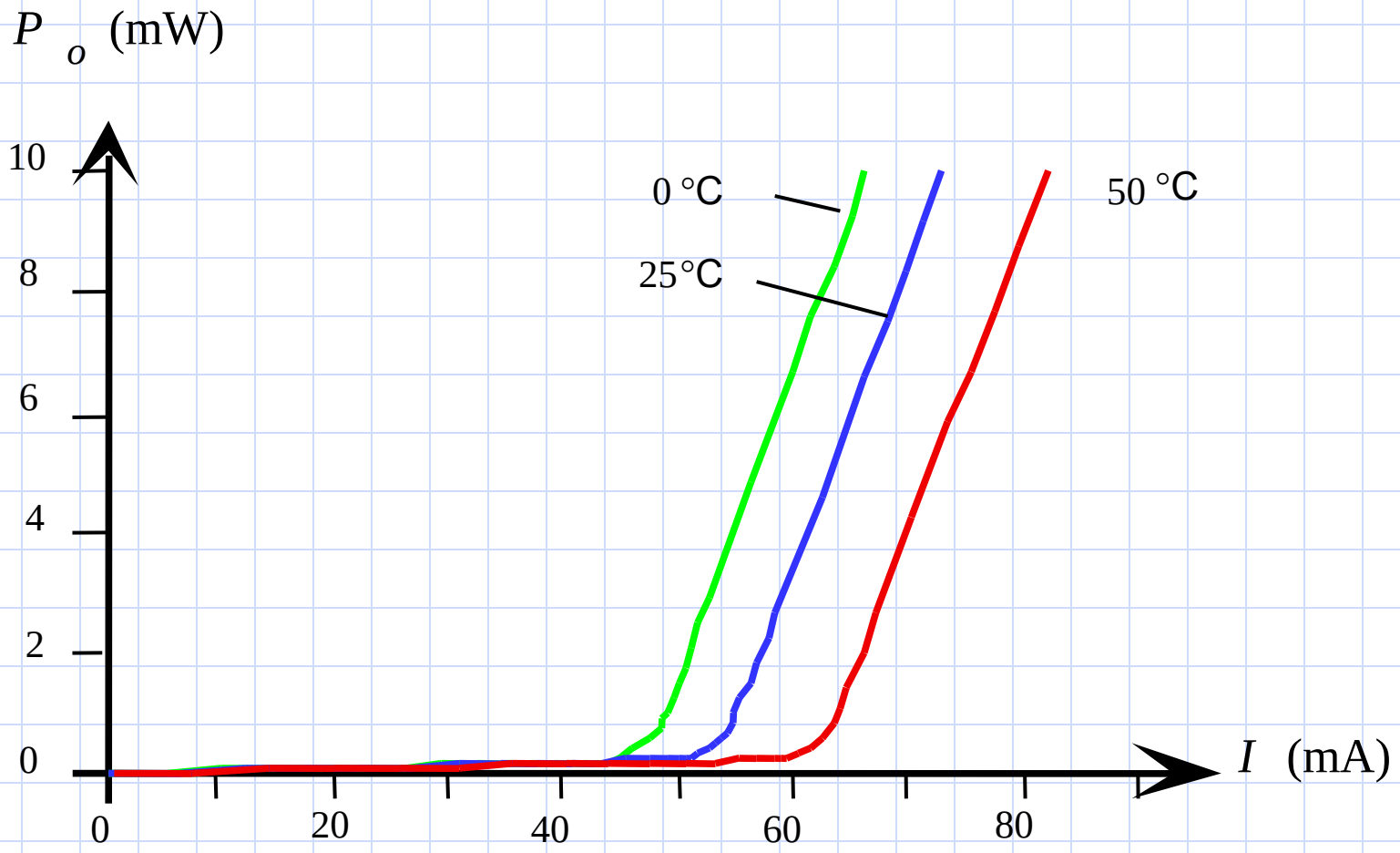
半导体激光器输出特性


Dielectric mirror
Fabry-Perot cavity
Length, L
Height, H
Width W
Diffraction limited laser beam

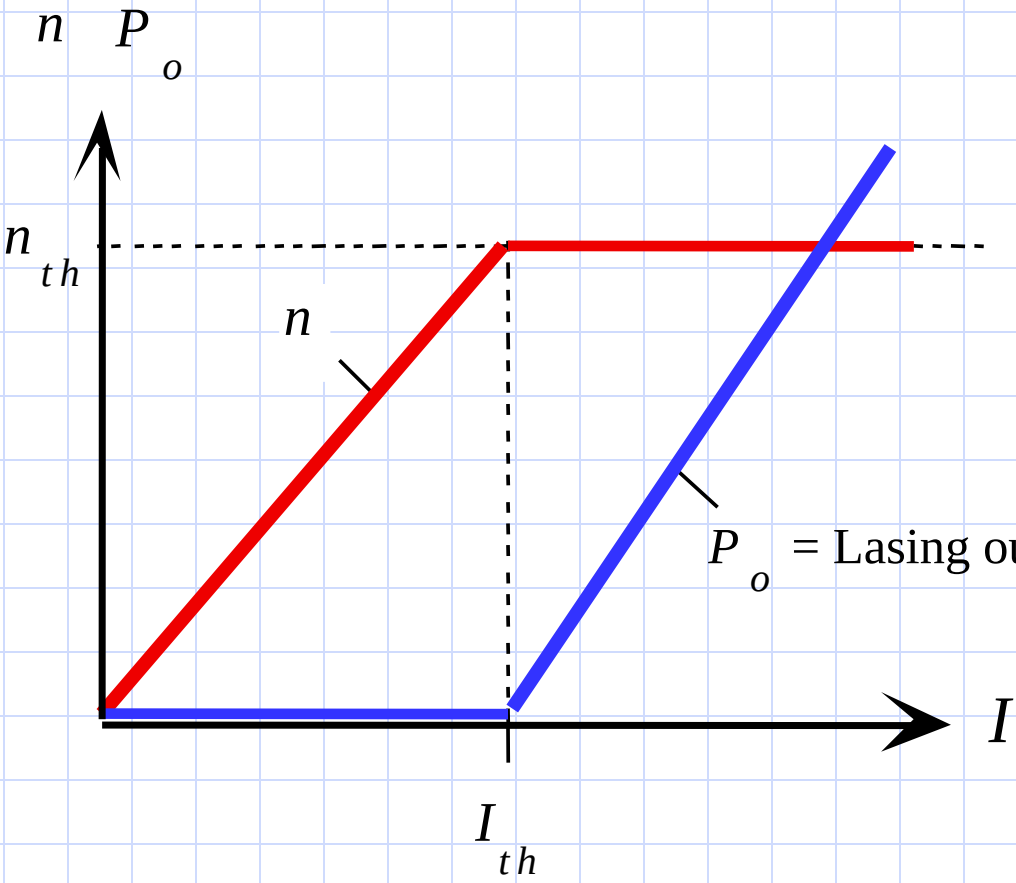
半导体激光器输出特性



半导体激光器输出特性



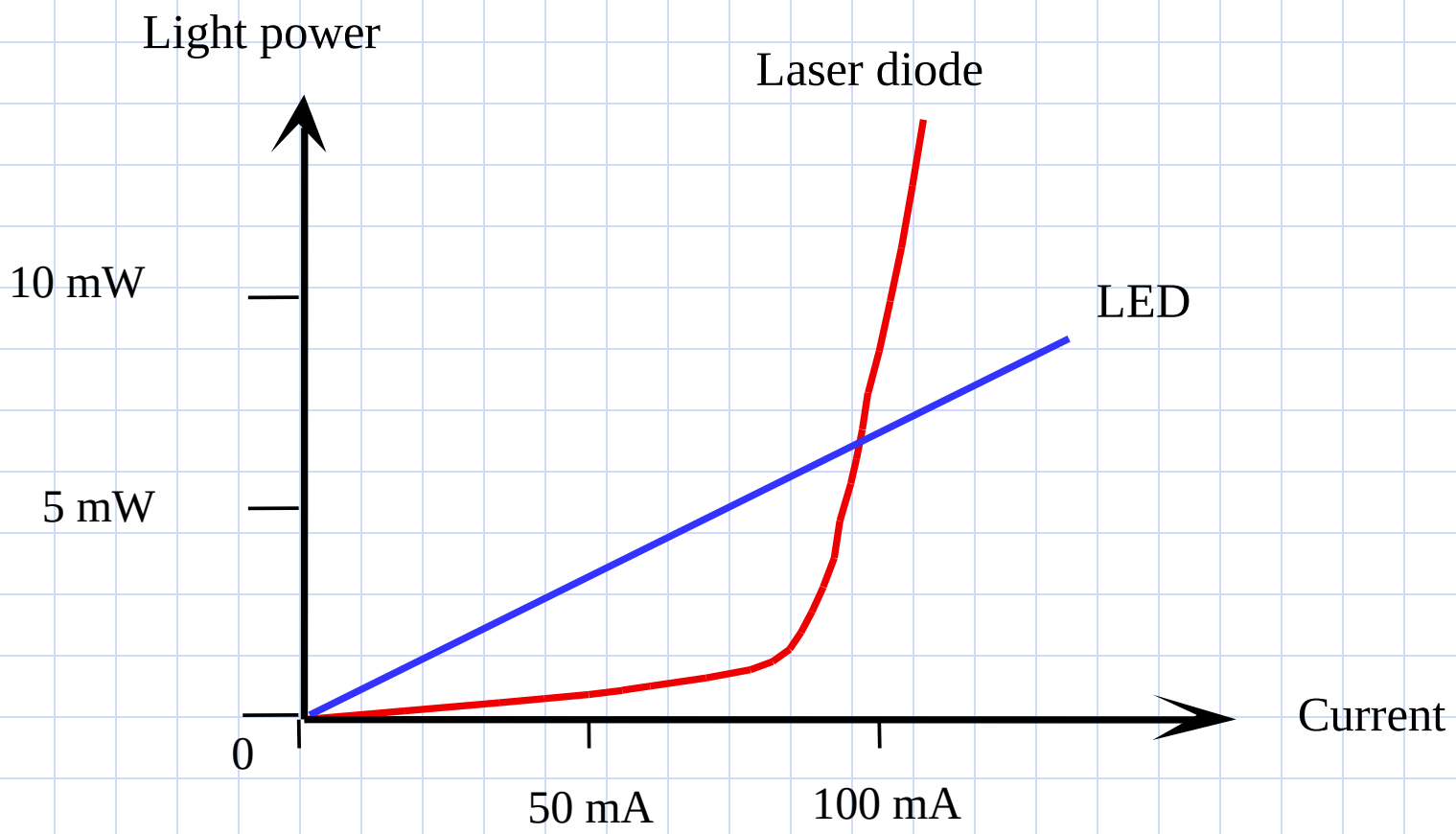
半导体激光器输出特性



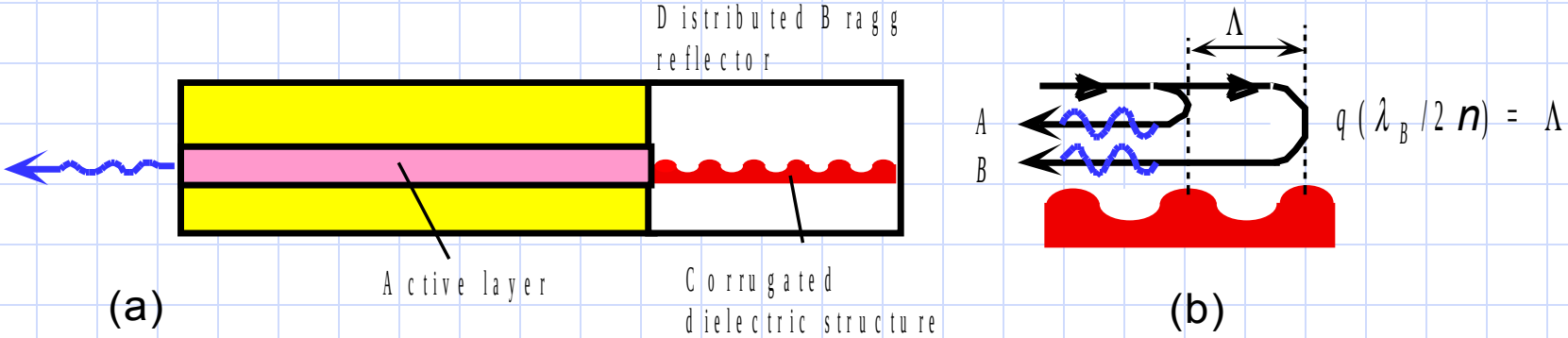
Threshold population inversion

P_o = Lasing output power $\propto N_{ph}$

LD 与 LED 的比较

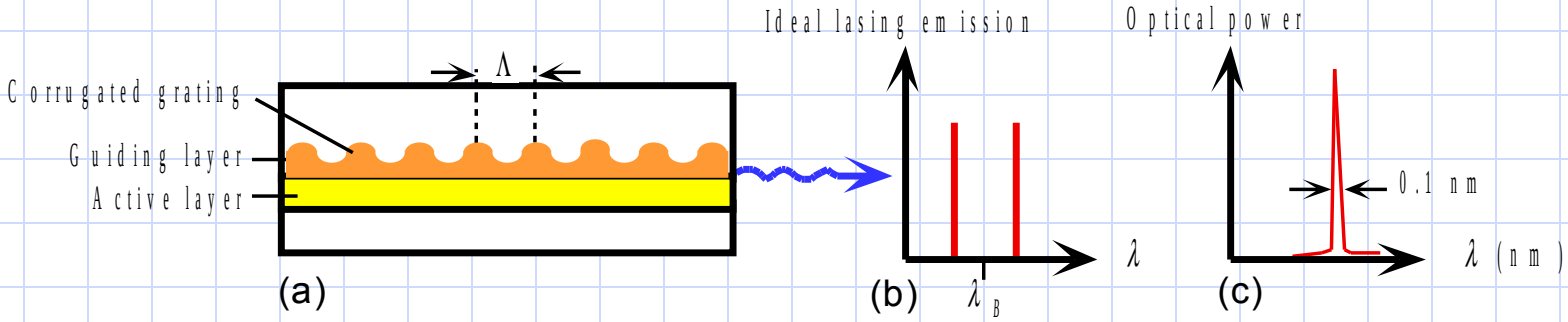


分布 BRAGG 反射半导体激光器



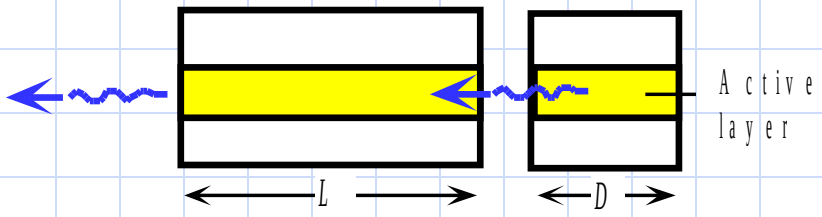
(a) Distributed Bragg reflection (DBR) laser principle. (b) Partially reflected waves at the corrugations can only constitute a reflected wave when the wavelength satisfies the Bragg condition. Reflected waves *A* and *B* interfere constructive when $q(\lambda_B/2n) = \Lambda$.

分布反馈半导体激光器

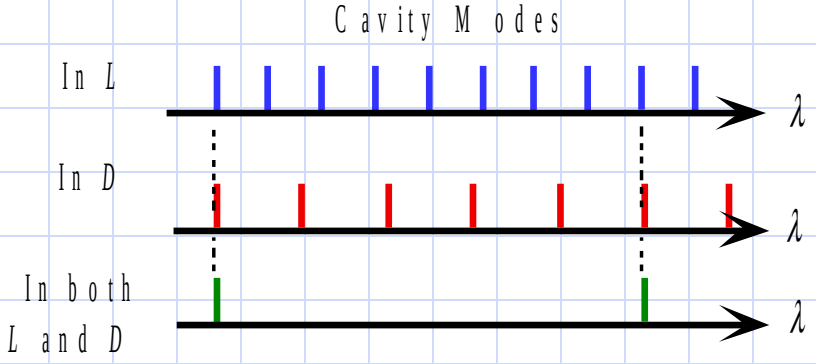


(a) Distributed feedback (DFB) laser structure. (b) Ideal lasing emission output. (c) Typical output spectrum from a DFB laser.

腔耦合半导体激光器



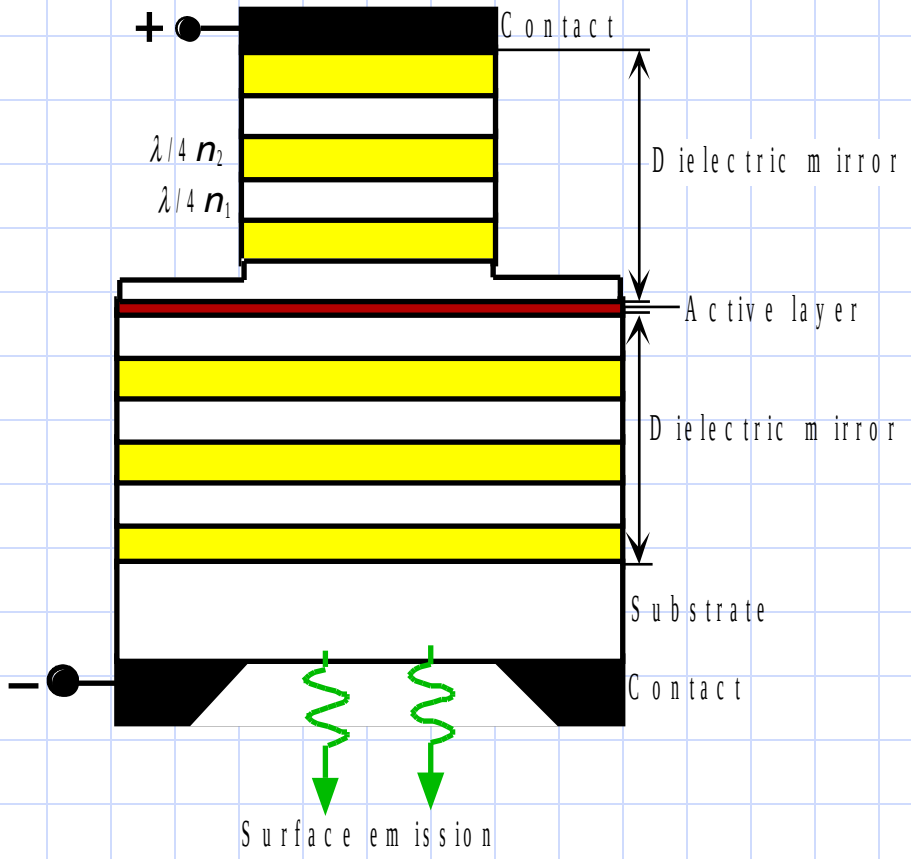
(a)



(b)

Cleaved-coupled-cavity (C^3) laser

面发射半导体激光器



A simplified schematic illustration of a vertical cavity surface emitting laser (VCSEL).