

Optoelectronic Semiconductor Devices - Principals and Characteristics.

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**Submitted in partial fulfillment
of the requirements
for the course ENGR-797**

Contents

- [1 PREFACE](#)

- [2 ENERGY LEVELS AND BANDS IN SOLIDS](#)
 - [2.1 PHOTON EMISSION IN SEMICONDUCTORS: THE CREATION OF LIGHT](#)
 - [2.2 SEMICONDUCTOR MATERIALS FOR DIODE LASERS](#)
 - [2.3 BASIC SEMICONDUCTOR LUMINESCENT DIODE STRUCTURES](#)
 - [2.4 SUMMARY ON THE BASIC STRUCTURE OF MODERN ILD, LED AND SLD](#)

- [3 LASER DIODES](#)
 - [3.1 BROAD AREA LASERS](#)
 - [3.2 STRIPE GEOMETRY LASERS](#)
 - [3.3 SINGLE-FREQUENCY SINGLE-MODE INJECTION LASERS: FABRY-PEROT LASERS](#)
 - [3.4 BASIC CHARACTERISTICS OF LASER DIODES](#)
 - [3.5 DIFFERENCES OF ILD FROM GAS, LIQUID DYE AND SOLID STATE LASERS](#)
 - [3.6 RECENT DEVELOPMENTS](#)

- [4 LIGHT-EMITTING DIODES](#)
 - [4.1 TWO BASIC LED STRUCTURES](#)
 - [4.2 BASIC CHARACTERISTICS OF LED](#)

- [5 SUPERLUMINESCENT DIODES](#)

- [6 COMPARISON OF ILD, LED AND SLD](#)

- [7 PHOTODIODES](#)
 - [7.1 BASICS OF PHOTODIODES](#)

- [8 DEVICE FABRICATION](#)
 - [8.1 CRYSTAL GROWTH](#)
 - [8.2 DEVICE FABRICATION PROCESSES](#)
 - [8.3 PACKAGING](#)

- [9 REFERENCES](#)
- [About this document ...](#)

1 PREFACE

Optical semiconductor devices are widely used, in fields ranging from optical fiber communication systems to consumer electronics, and have become indispensable devices in the equipment and systems making up the infrastructure of our society. Most optical semiconductor devices are optoelectronic *pn*-junction devices, such as laser diodes, light-emitting diodes, and photodiodes.

The main interest in the field of optoelectronic devices has shifted from device physics and operation principles to device applications. That is why we require a wide range of knowledge related to optoelectronic semiconductor devices.

In this project, I will try to provide an introduction to optoelectronic *pn*-junction devices from the point of view of semiconductor materials' properties, operating principles, applications and fabrication.

Most semiconductor optoelectronic devices are *pn*-junction diodes, and their performance depends on the properties of the *pn*-junction and of the semiconductor material.

To better describe the operation of laser diodes, LEDs, photodiodes, etc., it is necessary to understand the basics of the processes involved.

2 ENERGY LEVELS AND BANDS IN SOLIDS

In order to understand how gain is accomplished in lasers, we must have some knowledge of the energy levels that electrons can occupy in the gain medium.

In a covalently bonded solid like the semiconductor materials we use to make diode lasers, the uppermost energy levels of individual constituent atoms each broaden into bands of levels as the bonds are formed to make the solid.

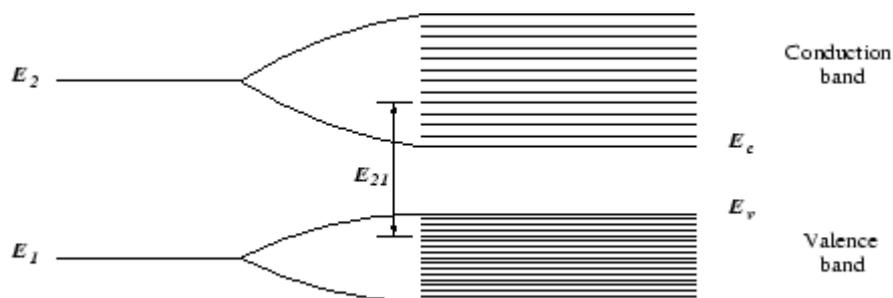


Figure 1.: Illustration of how two discrete energy levels of an atom develop into bands of many levels in a crystal. [2]

Figure 1. schematically illustrates the energy levels that might be associated with optically induced transition in both an isolated atom and in a semiconductor solid.

In covalently bonded solids, the outer valence electrons are shared by many atoms, and they develop wave functions that extend throughout the crystal.

The isolated energy level of the electron is now split into two levels due to the two ways the electron can arrange itself around the two atoms. The splitting is a fundamental phenomenon associated with solutions

to the wave equation involving two coupled systems and applies equally to probability, electromagnetic or any other kind of waves. [2]

The electrons of the two atoms both occupy the lower energy bonding level (provided they have opposite spin), while the higher energy antibonding level remains empty.

In our linear chain of atoms, spin degeneracy allows all N electrons to fall into the lower half of the energy band, leaving the upper half of the band empty.

In typical semiconductor crystals, there are two atoms per primitive unit cell. Thus the first atom fills the lower half of the energy band, while the second atom fills the upper half, such that the energy band is entirely full.

The semiconductor valence band is formed by the multiple splitting of the highest occupied atomic energy level of the constituent atoms. In semiconductors, the valence band is by definition entirely filled with no external excitation at $T = 0 K$.

Likewise, the next higher-lying atomic level splits apart into the conduction band which is entirely empty in semiconductors without any excitation.

The imposition of momentum conservation in addition to energy conservation limits the interaction to a fairly limited set of state pairs for a given transition energy.

2.1 PHOTON EMISSION IN SEMICONDUCTORS: THE CREATION OF LIGHT

In the electron-hole recombination process, electrons drop from the conduction band to the valence band. The energy difference can be released as photons, phonons, or both.

Figure 2. illustrates the different kinds of electronic transitions that are important, emphasizing those that involve the absorption or emission of photons (light wave quanta).

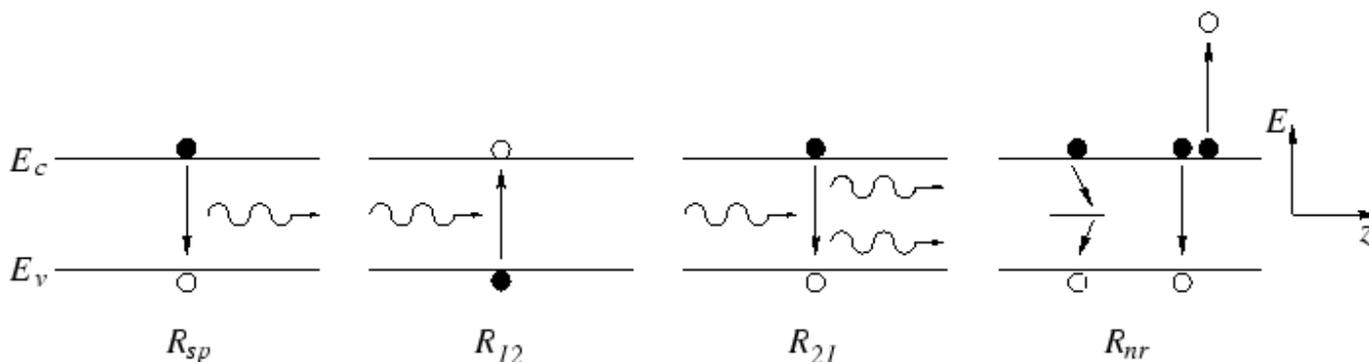


Figure 2.: Electronic transitions between the conduction and valence bands. The first three represent radiative transitions in which the energy to free or bind an electron is supplied by or given to a photon. The fourth illustrates two non radiative processes. [2]

Momentum conservation selects only a limited number of pairs of levels from conduction and valence bands for a given transition energy. In fact, if it were not for finite bandwidth of interaction owing to the finite state lifetime, a single pair of states would be correct.

The procedure to calculate gain and other effects will be to find the contribution from a single state pair and then integrate to include contributions from other pairs.

As illustrated, (Fig. 2.), four basic electronic recombination/generation mechanisms must be considered separately:

1. Spontaneous recombination (photon emission) - represents the case of an electron in the conduction band recombining spontaneously with a hole (missing electron) in the valence band to generate a photon. If a large number of such events should occur, relatively incoherent emission would result, since the emission time and direction would be random and the photons would not tend to contribute to a coherent radiation field. This is the primary mechanism within a light emitting diode (LED), in which photon feedback is not provided.
2. Stimulated generation (photon absorption) - outlines photon absorption, which stimulates the generation of an electron in the conduction band while leaving a hole in the valence band.
3. Stimulated recombination (coherent photon emission) - is the same as the second, only the sign of the interaction is reversed. Here an incident photon perturbs the system, stimulating the recombination of an electron and hole and simultaneously generating a new photon. This is the all-important positive gain mechanism that is necessary for lasers to operate.
4. Non radiative recombination - represents the several non radiative ways in which a conduction band electron can recombine with a valence band hole without generating any useful photons. Instead, the energy is dissipated as heat in the semiconductor crystal lattice. These effects are to be avoided if possible. In practice, there are two general non radiative mechanisms for carriers:
 1. non radiative recombination centers, such as point defects, surfaces and interfaces in the active region of the lase.
 2. Auger recombination, in which the electron-hole recombination energy E_{21} is given to another electron or hole in the form of kinetic energy. Auger recombination tends to be proportional to N^3 .

Photon energies tend to be only slightly larger than the band-gap, i.e., $E_{21} = h\nu \sim E_g$.

The effects involving electrons in the conduction band are all enhanced by the addition of some pumping means to increase the electron density to above the equilibrium value there.

Because spontaneous recombination requires the presence of an electron-hole pair, the recombination rate tends to be proportional to the product of the density of electrons and holes. In undoped active regions, charge neutrality requires that the hole and electron densities be equal. The spontaneous recombination rate becomes proportional to N^2 . In a similarly undoped active region, net stimulated recombination (photon emission) depends upon the existence of photons in addition to a certain value of electron density to overcome the photon absorption.

The rate of radiative recombination R , defined as the number of photons emitted per volume per second, is proportional to Δn and p as follows:

$$R = B_{rec} p \Delta n \quad (1)$$

Where

p - majority carrier concentration;

n - minority carrier concentration;

B_{rec} - recombination coefficient.

We see that the radiative recombination rate increases with the minority carrier density, and the majority carrier concentration. The majority carrier concentration p may be increased by increasing the impurity concentration. The minority carrier density may be increased by injection of the charge carrier.

Table 1. shows the recombination coefficient for several semiconductors. Recombination coefficient B_{rec} (Formula (1)) of indirect band-gap semiconductors (example Ge, Si and GaP) is smaller by three to five orders of magnitude than that of direct band-gap.

Table 1.: Recombination coefficients for several semiconductors. [6]

Material	Band-gap type	B_{rec} in cm^3/s
Si	Indirect	$1.79 \cdot 10^{-15}$
Ge	Indirect	$5.25 \cdot 10^{-15}$
GaP	Indirect	$5.37 \cdot 10^{-14}$
InSb	Direct	$4.58 \cdot 10^{-11}$
InAs	Direct	$8.5 \cdot 10^{-11}$
GaSb	Direct	$2.39 \cdot 10^{-10}$
GaAs	Direct	$7.21 \cdot 10^{-10}$

Each elemental and binary semiconductor has a specific band-gap at a given temperature. If the choice of semiconductors were restricted to elemental and binary semiconductors (Binary semiconductors - compounds made from the elements of two different groups of the periodic table (For example: III and V, II and IV, etc.)) only, then the available wavelengths would be rather limited.

But as we know, light is emitted by solid solutions of semiconductors as well. By mixing two or more binary semiconductors, we can create ternary or quaternary crystalline solid solutions. The energy band-gap, refractive index, and lattice constant of such solid solutions can be adjusted by varying the composition of the contributing materials and the growth conditions of the solutions.

2.2 SEMICONDUCTOR MATERIALS FOR DIODE LASERS

The successful fabrication of a diode laser relies very heavily upon the properties of the materials involved. There is very limited set of semiconductors that possess all of the necessary properties to make a good laser. For the desired DH (double heterostructure) at least two compatible materials must be found, one for the cladding layers and another for the active region. In more complex geometries, three or four different band-gaps may be required within the same structure.

The fundamental requirement for these different materials is that they have the same crystal structure and nearly the same lattice constant (Lattice Constant - a length that denotes the size of the unit cell in a crystal lattice. With respect to the cubic crystal, this is the length of the side of the unit cell. However, a simple definition of the term is difficult, and the lattice constant must be considered with the geometry of the structure in each case.), so that single-crystal, defect-free films of one can be epitaxially grown on the other.

We need to understand how to select materials that meet these fundamental boundary conditions.

2.2.1 III-V SEMICONDUCTOR

They consist of the elements from columns III and V of the periodic table, (Table 2.) and of the form of $A_xB_{1-x}C$, where x - the mole fraction in range from 0 to 1.

Table 2.: Periodic Table.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
H 1.00794																	He 4.002602	
Li 6.941	Be 9.012182											B 10.811	C 12.011	N 14.007	O 15.999	F 18.998	Ne 20.180	
Na 22.990	Mg 24.305											Al 26.982	Si 28.086	P 30.974	S 32.06	Cl 35.453	Ar 39.948	
K 39.098	Ca 40.078	Sc 44.956	Ti 47.88	V 50.942	Cr 51.996	Mn 54.938	Fe 55.845	Co 58.933	Ni 58.693	Cu 63.546	Zn 65.38	Ga 69.723	Ge 72.64	As 74.922	Se 78.96	Br 79.904	Kr 83.80	
Rb 85.468	Sr 87.62	Y 88.906	Zr 91.224	Nb 92.906	Mo 95.94	Tc 98.906	Ru 101.07	Rh 102.91	Pd 106.42	Ag 107.87	Cd 112.41	In 114.82	Sn 118.71	Sb 121.76	Te 127.6	I 126.905	Xe 131.29	
Cs 132.905	Ba 137.327	* 87.62	Lu 174.967	Hf 178.49	Ta 180.948	W 183.84	Re 186.207	Os 190.23	Ir 192.222	Pt 195.084	Au 196.967	Hg 200.59	Tl 204.384	Pb 207.2	Bi 208.980	Po 209	At 210	Rn 222
Fr 223	Ra 226	** 87.62	Lr 260.106	Rf 261.108	Db 262.109	Sg 263.109	Bh 264.109	Hs 265.109	Mt 266.109	Uun 267	Uuu 268	Uub 269	Uuq 270	Uuh 271	Uu 272	Uu 273	Uu 274	Uu 275
		† lanthanoids										† actinoids						
		La 138.905	Ce 140.12	Pr 140.908	Nd 144.24	Pm 144.913	Sm 150.36	Eu 151.964	Gd 157.25	Tb 158.925	Dy 162.50	Ho 164.930	Er 167.259	Tm 168.930	Yb 173.054			
		Ac 227	Th 232.038	Pa 231.036	U 238.029	Np 237.048	Pu 244.064	Am 243.061	Cm 247.070	Bk 247.070	Cf 251.08	Es 252.083	Fm 257.095	Md 258.10	No 259.108			

These III-V compounds have emerged as the materials of choice for lasers that emit in the 0.7-1.6 μm wavelength range. This range includes the important fiber-optic communication bands at 0.85, 1.31 and 1.55 μm, the pumping bands for fiber amplifiers at 1.48 and 0.98 μm, the the window for pumping Nd-doped YAG (yttrium-aluminum-garnet) at 0.81 μm and the wavelength currently used for optical disk players at 0.78 μm.

Most of these materials have a direct gap in *E-k* space, which means that the minimum and maximum of the conduction and valence bands, respectively, fall at the same *k*-value. (Figure 3).

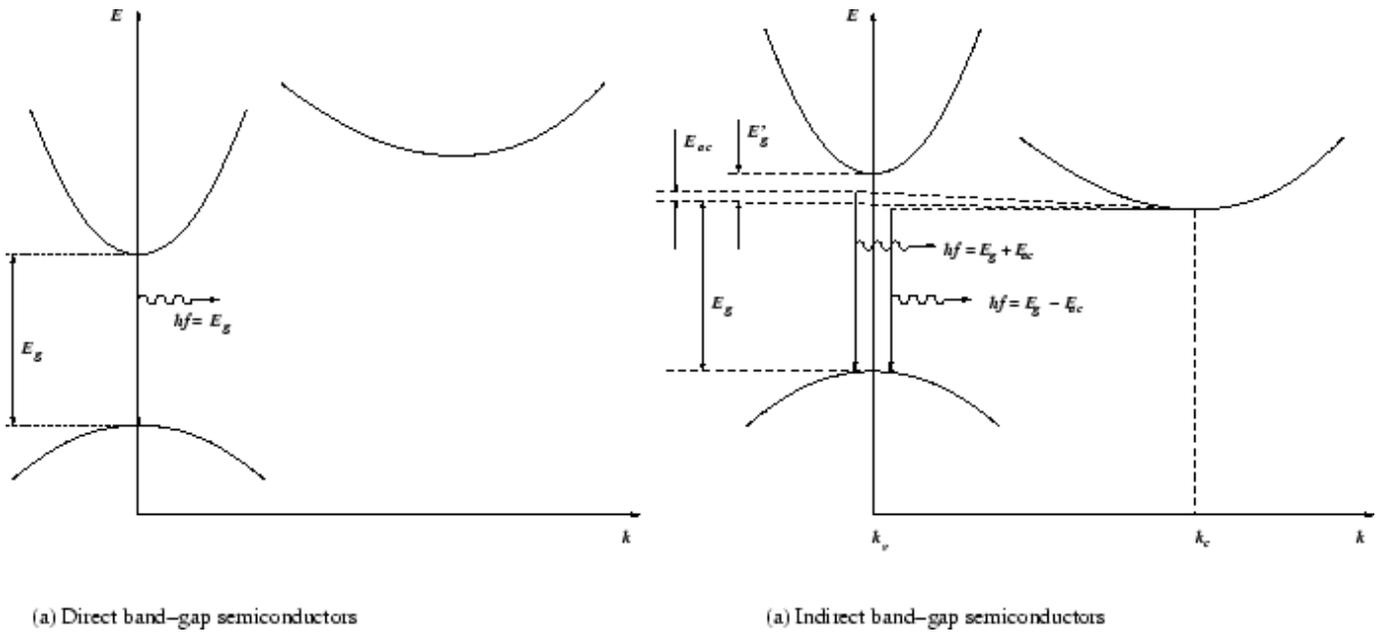


Figure 3.: Photon emission in direct and indirect band-gap semiconductors.[1]

Since there are three group III atoms (Al, Ga and In) and three group V atoms (P, As and Sb), there are 18 possible ternary III-V solutions.

Some of the III-V solid solutions have direct band-gap and others have indirect. This means that not all ternary semiconductors are good optical materials.

With quite a good precision, the lattice constant of quaternaries can be calculated from Vegard's law, which gives a value equal to the weighted average of all of the four possible constituent binaries. For example, in $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$, we obtain

$$a(x, y) = xya_{\text{GaAs}} + x(1-y)a_{\text{GaP}} + (1-x)ya_{\text{InAs}} + (1-x)(1-y)a_{\text{InP}} \quad (2)$$

Similarly, the lattice constant for other alloys can be calculated using Formula (2).

In addition to the usual III-V compounds, Table 3. also lists some of the nitride compounds. These have gained an attention because of a success in demonstrating LEDs emitting at high energies in the visible spectrum.

III-V Compounds	a (Å)	E_g (eV) 0°K	E_g (eV) 300°K	m_c	m_{HH}	m_{LH}	m_{SH}	$\epsilon@$ dc	$n@$ E_g	$n@$ λ (μm)				
GaAs	5.6533	1.519	1.424	0.067	0.380	0.090	0.15	13.20	3.62	3.52(0.98)				
AlGaAs (0.2)	5.6548	1.769	1.673	0.084	0.390	0.100	0.16	12.50	3.64	3.46(0.87)				
										3.39(0.98)				
AlAs*	5.6600	2.228	2.153	0.190	0.480	0.200	0.29	10.06	3.20	2.98(0.87)				
										2.95(0.98)				
InGaAs (0.2) comp.strained on GaAs	5.6533	1.296	1.215	0.059	0.370	0.062	0.11	13.60	3.60					
					0.078 [†] 3.1890	3.500	3.390	0.20				8.90	2.67	2.33(1 eV)
	$c=$ 5.1850													
AlN (hexagonal)	$a=$ 3.1120	6.280	6.200					8.50		2.15(3eV)				
	$c=$ 4.9820													

*Indirect gap

[†] In-plane masses

Solid solutions are good optical quality only if the lattice constant of the constituent binary semiconductors match very well (within 0.1 percent up to a certain thickness, ~20nm). Without a good lattice match, excessive crystal defects appear and distribute themselves randomly throughout the material. As a result, material becomes too lossy to be useful for optical applications. Therefore, a comprehensive knowledge of various semiconductor properties is extremely useful.

2.2.2 II-VI SEMICONDUCTORS

The energy gap ranges from a very wide value to a very narrow or even negative value. All II-VI binary semiconductors have direct band-gaps.

The main drawback for II-VI materials is the difficulty in forming *n*-type and *p*-type II-VI semiconductors on the same substrate. Also quite difficult to form good ohmic contact.

Some of the basic characteristics for different groups of semiconductors are shown on Table 4.

Table 4.: Selected semiconductor characteristics. [1]

Type	Semiconductor	E_g at 300°K, eV	Dir/ind band-gap	Index n	Relative dielectric constant ϵ_r	Lattice constant a nm	Electron mobility μ_e cm^2/Vs	Hole mobility μ_H cm^2/Vs	Electron affinity χ eV
IV	Si	1.11	ind 100	3.44	11.7	0.5430	1350	480	4.01
IV	Ge	0.67	ind 111	4.00	16.3	0.5660	3900	1900	4.13
III-V	AlAs	2.16	ind	2.90	12.0	0.5660	1000	~100	2.62
III-V	AlSb	1.60	ind 100	3.40	11.0	0.6135	50	400	3.60
III-V	GaP	2.25	ind 100	3.37	10.0	0.5450	120	120	4.00
III-V	GaAs	1.43	dir 000	3.40	12.0	0.5653	8600	400	4.07
III-V	GaSb	0.69	dir 000	3.90	15.0	0.6095	4000	650	4.06
III-V	InP	1.28	dir 000	3.37	12.1	0.5869	4000	650	4.40
III-V	InAs	0.36	dir 000	3.42	12.5	0.6058	30000	240	4.90
III-V	InSb	0.17	dir 000	3.75	18.0	0.6479	76000	5000 [†]	4.59
II-VI	ZnO	3.2	dir 0000	2.02	7.9	a0.3250 c0.2065	180 180		
II-VI	ZnSe	2.58	dir 000	2.89	8.1	0.5667	100		4.09
II-VI	ZnTe	2.28	dir 000	3.56	9.7	0.6101		7	3.53
II-VI	CdS	2.53	dir 0000	2.50	8.9	a0.4136 c0.6713	210		4.79
II-VI	CdSe	1.74	dir 0000		10.6	a0.4299 c0.7010	500		4.95
II-VI	CdTe	1.50	dir 000	2.75	10.9	0.6477	600		4.28
IV-VI	PbS	0.37	dir 111	3.70	170.0	0.5936	550	600	3.30
IV-VI	PbSe	0.26	dir 111		250.0	0.6124	1020	930	
IV-VI	PbTe	0.29	dir 111	3.80	412.0	0.6460	1620	750	4.60

[†] at 78°K

The energy band-gaps and lattice constant of common elemental III-V and II-VI semiconductors are shown on the picture, (Figure 4.):

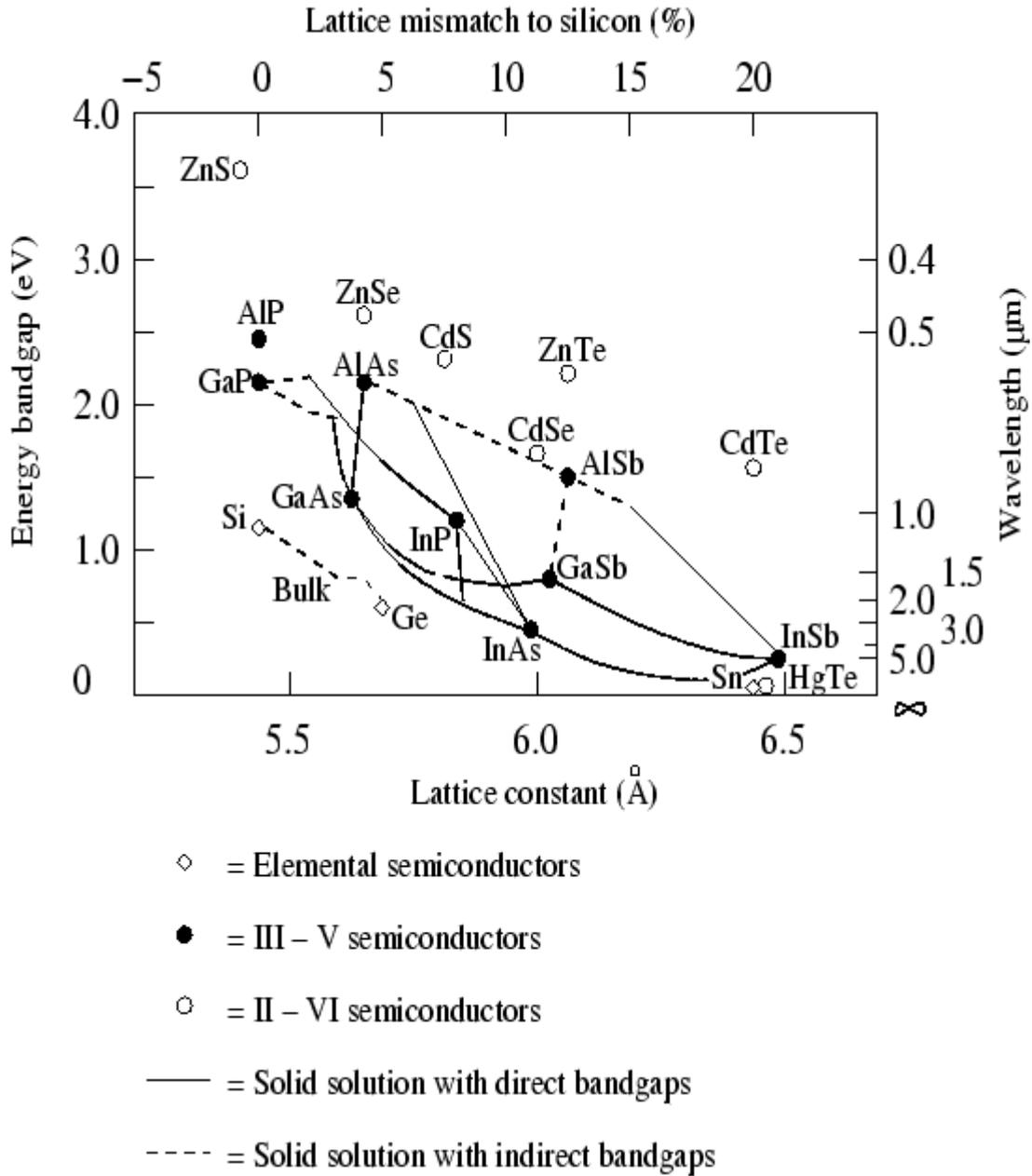


Figure 4.: Energy band-gap versus lattice constant for common semiconductors. Squares correspond to elemental semiconductors, filled circles to III-V semiconductors, and unfilled circles to II-VI semiconductors. Solid and dashed lines are for solid solutions with direct and indirect band-gaps, respectively. [1]

The lines on this diagram represent ternary compounds which are alloys of the binaries labeled at their end-points. The dashed lines represent regions of indirect gap. The triangular areas enclosed by the lines between three binaries represent quaternaries, which obviously have enough of freedom that the energy gap can be adjusted somewhat without changing the lattice constant.

In general, a quaternary compound is required in a DH laser to allow the adjustment of the energy gap while maintaining lattice matching.

There are some unique situations which allow the use of more simple ternaries. As we can see, the AlGaAs ternary line is almost vertical. That means that the substitution of Al for Ga in GaAs does not change the lattice constant very much.

The AlGaAs/GaAs system provides lasers in the 0.7-0.9 μm wavelength range. For DH structures in this system, about two-thirds of the band offset occurs in the conduction band.

2.2.3 IV-VI SEMICONDUCTORS

The band-gaps of IV-VI semiconductors are very narrow and the emission wavelengths are long. E_g can be tuned over a wide range by controlling the temperature of, the pressure on, or the magnetic fields applied to the semiconductor.

Tunable semiconductor light sources based on these materials are useful for high-resolution spectroscopy applications.

Most light-emitting IV-VI semiconductor devices operate at cryogenic temperatures, typically 50°K.

Stable IV-VI crystals exist in various stoichiometric compositions. They have an interesting property: excess Pb atoms in PbSe act as electron donors, and excess Se atoms act as electron acceptors. By simply changing the proportional composition, we can change a IV-VI semiconductor from n-type to a p-type.

The emission wavelength of various semiconducting materials are summarized in Figure 5.

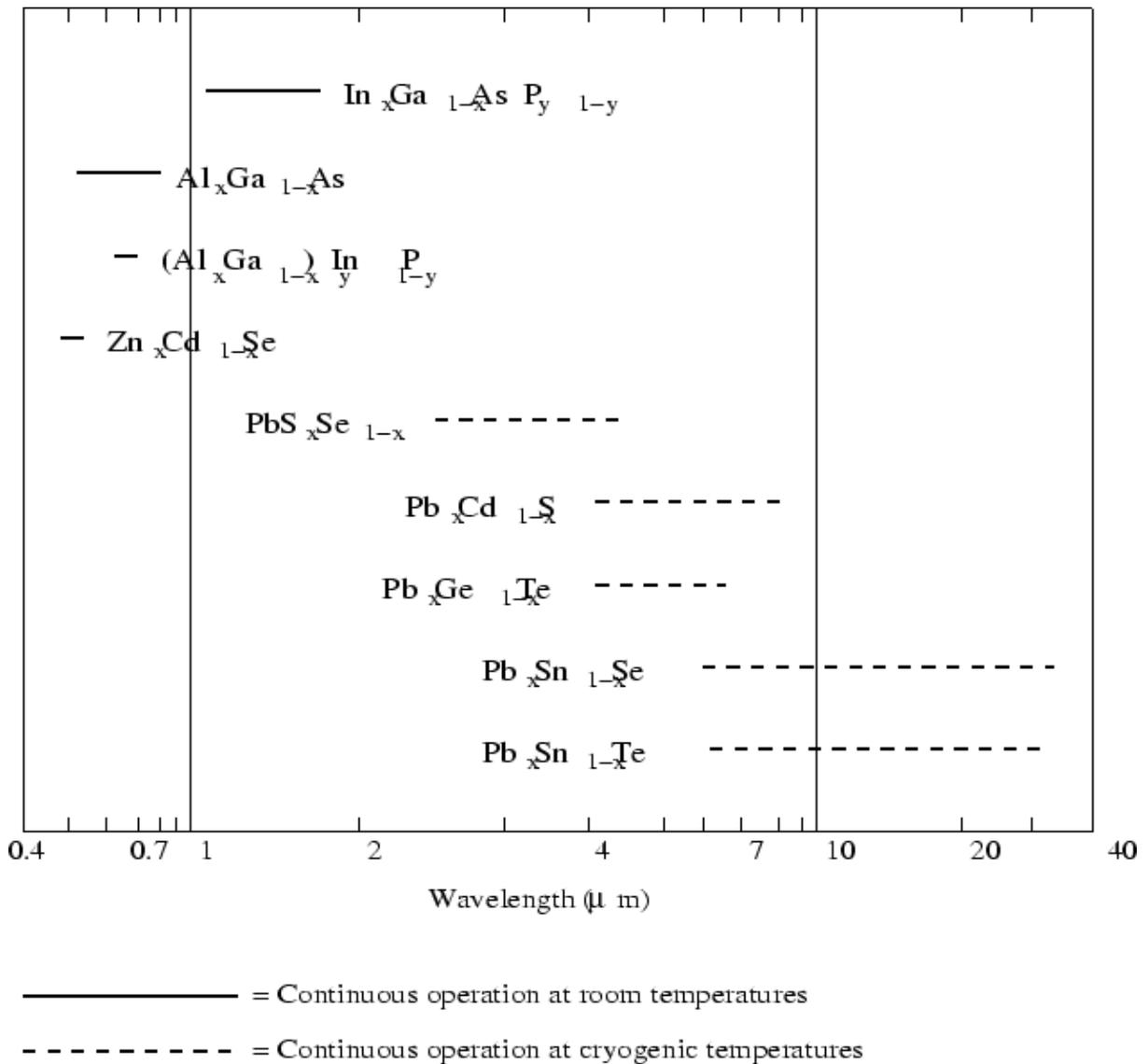


Figure 5.: Emission wavelengths of selected semiconductor ILDs. Solid and dashed lines represent continuous operation at room temperature and cryogenic temperature. [1]

For a thin active region, one can move slightly left or right of the lattice matching condition, as it was mentioned above. In this case, the lattice of the deposited film distorts so as to fit the substrate lattice in the plane, but it also must distort in the perpendicular direction to retain approximately the same unit cell volume it would have without distortion.

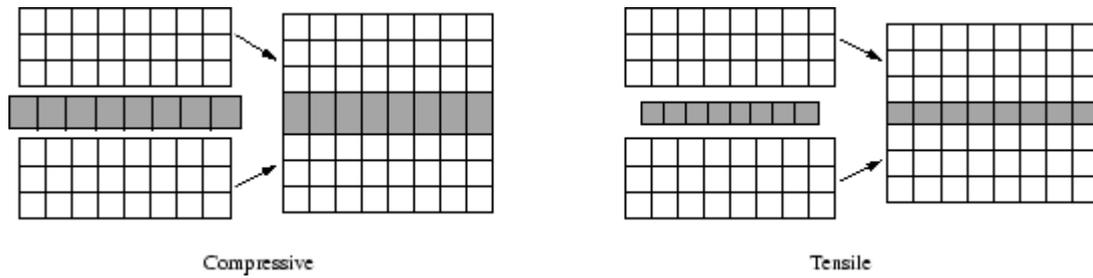


Figure 6.: Schematic of sandwiching quantum wells with either a larger or smaller lattice constant to provide either compressive or tensile strain, respectively.[2]

Figure 6. shows a cross section of how unit cells might distort to accommodate a small lattice mismatch.

It turns out that such strained layers may have more desirable optoelectronic properties than their unstrained counterparts. Plus, quantum-well active regions, which are thinner than typical critical thicknesses, are desirable in diode lasers for reduced threshold and improved thermal properties.

2.3 BASIC SEMICONDUCTOR LUMINESCENT DIODE STRUCTURES

The heart of the semiconductor luminescent diode is an active semiconducting layer, which is sandwiched between two cladding layers. There are two junctions, one on each side of the active layer.

In order for the gain material in a semiconductor laser to function, it must be pumped or excited with some external energy source. A major attribute of diode lasers is their ability to be pumped directly with an electrical current. Of course, the active material can also be excited by the carriers generated from absorbed light, and this process is important in characterizing semiconductor material before electrical contacts are made.

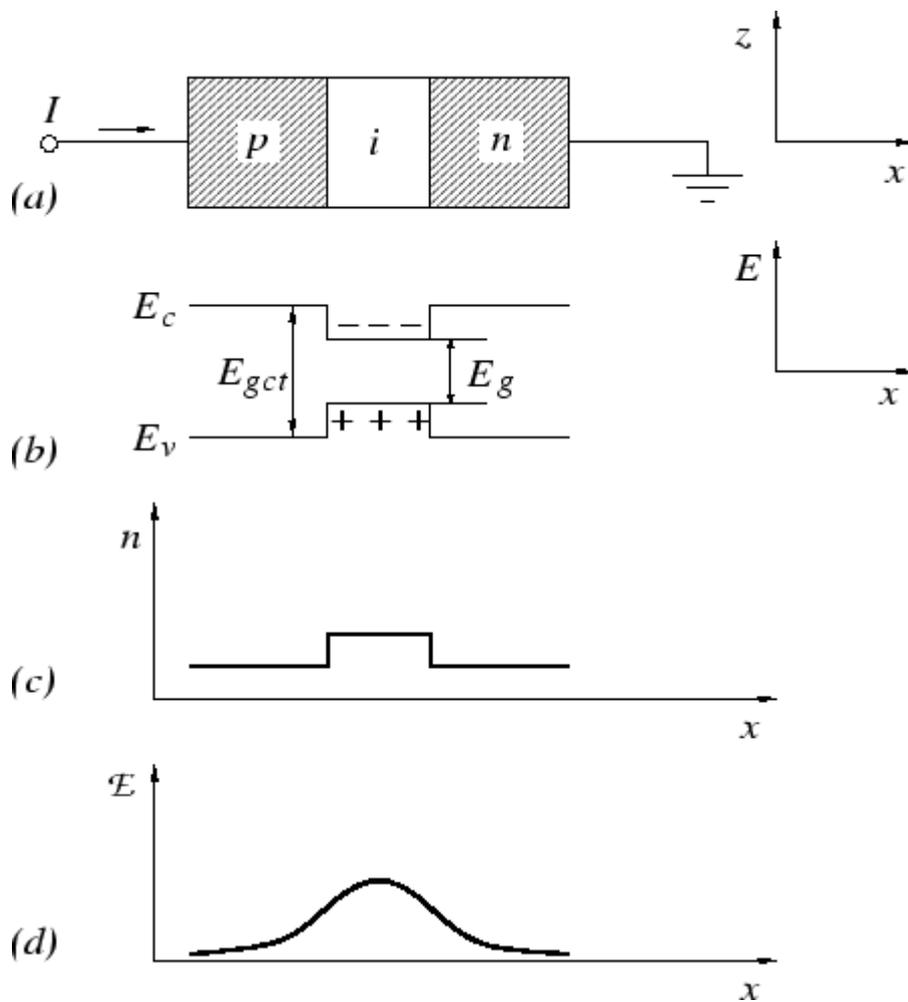
The first ILDs and LEDs were homojunction diodes. Most modern electro luminescent diodes have one or two heterojunctions.

SH - single heterostructure diode: has two different materials and has both a homojunction and heterojunction.

DH - double heterostructure diode: formed with three materials and two heterojunctions.

After many early efforts that used homojunctions or single heterostructure, the advent of the DH structure made the diode laser truly practical for the first time.

To form the necessary resonant cavity for optical feedback, simple cleaved facets can be used, since the large index of refraction discontinuity at the semiconductor-air interface provides a reflection coefficient of ~30%. The lower band-gap active region also usually has a higher index of refraction, n , than the cladding.



- (a) a schematic of the material structure;
 (b) an energy diagram of the conduction and valence bands vs. transverse distance;
 (c) the refractive index profile;
 (d) the electric field profile for a mode traveling in the z-direction. [2]

Figure 7.: Aspects of the DH diode laser:

Figure 7. gives a schematic of a broad-area *pin* DH laser diode, along with transverse sketches of the energy gap, index of refraction and resulting optical mode profile across the DH region. A thin slab of undoped active material is sandwiched between *p* and *n*-type cladding layers, which have a higher conduction-valence band energy gap. Typical thickness of the active layer for this simple three-layer structure are $\sim 0.1\text{-}0.2\ \mu\text{m}$. Because the band-gap of the cladding layers is larger, light generated in the active region will not have sufficient photon energy to be absorbed in them, i.e. $E_{21} = h\nu < E_{gcl}$.

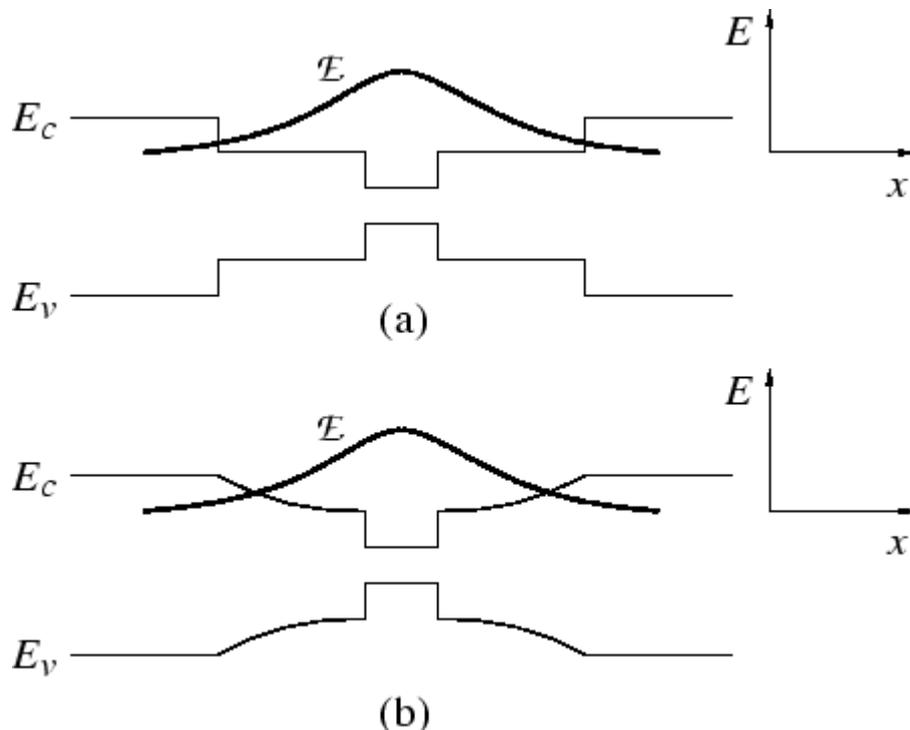
For this DH structure, a transverse (*x*-direction) potential well is formed for electrons and holes that are being injected from the *n*- and *p*-type regions, respectively, under forward bias. They are captured and confined together, thereby increasing their probability of recombining with each other.

Unlike in most semiconductor diodes or transistors that are to be used in purely electronic circuits, it is desirable to have all of the injected carriers recombine in the active region to form photons in a laser or LED. Unfortunately, there is always a possibility of the "leakage current", which results from some of the carriers being thermionically emitted over the heterobarriers before they can recombine.

One should also realize that if the end facet reflections are suppressed by antireflection coating, the device would then function as an LED.

Many modern diode lasers involve a little more complexity in their transverse carrier and photon confinement structure as compared on Figure 7., but the fundamental concepts remain valid.

Figure 8. illustrates transverse band-gap profiles for such separate-confinement heterostructure, single quantum-well (SCH-SQW) lasers. The transverse optical energy density is also overlaid to show that the photons are confined primarily by the outer heterointerfaces and the carriers by the inner quantum well.



(a) standard SCH;
(b) Graded-index SCH (GRINSCH).

The electric field (photons) are confined by the outer step or graded heterostructure; the central quantum well confines the electrons. [2]

Figure 8.: Transverse band structures for two different separate-confinement heterostructures (SCHs):

In order to be able to compare the performances of various diodes, it is customary to use the threshold current density J_{th} .

When the injection current is less than threshold value, the radiation of the ILD is mainly broadband, incoherent, spontaneous emission.

For current greater than the threshold current, the emission becomes mostly coherent and has a narrow spectral width.

The first-generated ILDs were fabricated by diffusion techniques and had homojunctions. All layers in these diodes were made of GaAs. As we know properties of the diffusion techniques used in fabrication, one side of the active region was not well defined. Which means that the injected charge carriers were not confined in the narrow active region. The index difference Δn between various layers was very small. J_{th} of these ILDs was as high as $100kA/cm^2$.

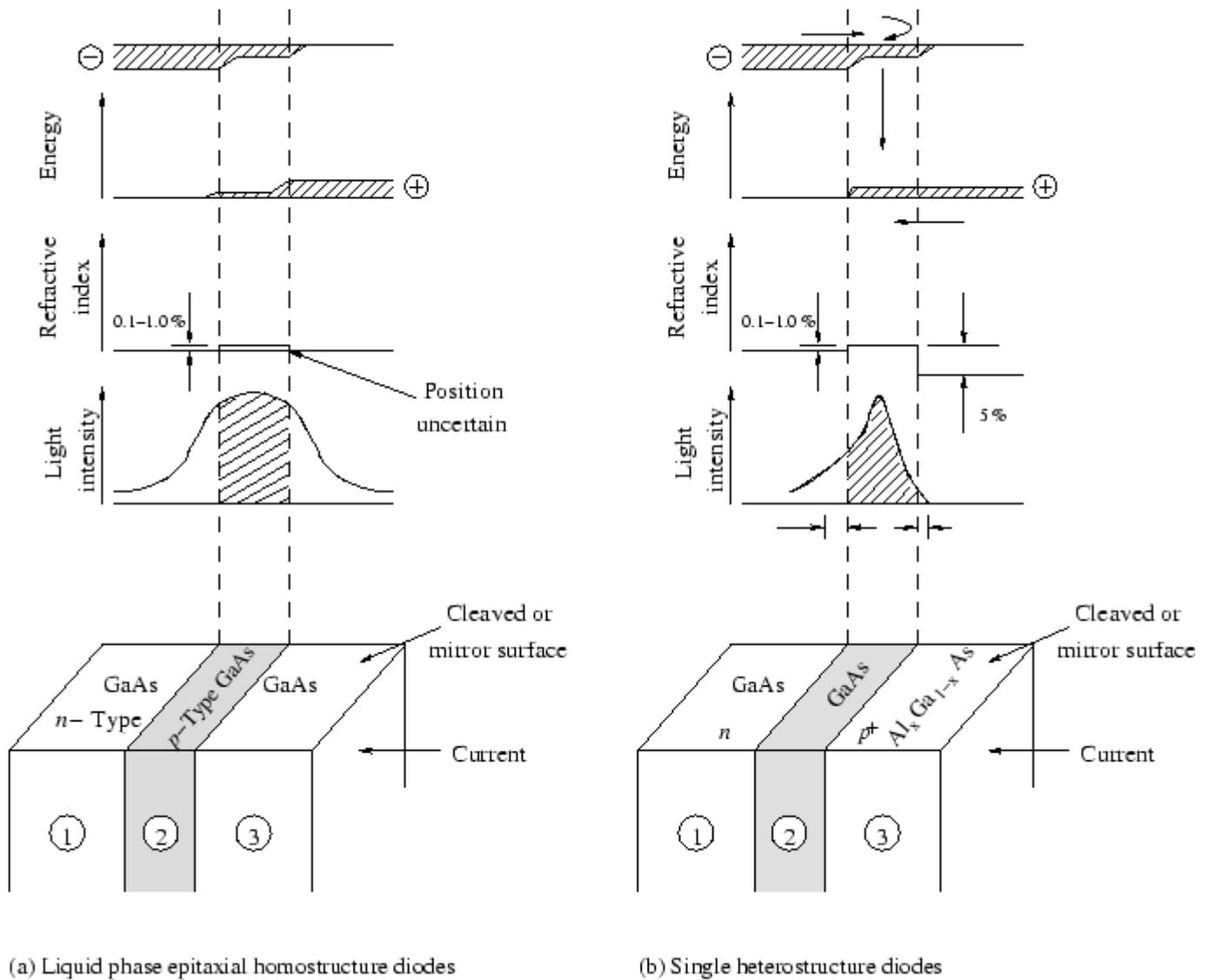


Figure 9.: Schematic representation of energy band diagram, refractive index profile, and optical field distribution of homostructure, and single heterostructure LEDs and ILDs. [1]

The second generation laser diodes were made by liquid phase epitaxy techniques. The boundaries between layers were well defined. Since all layers were based on GaAs, the energy band-gap difference was very small and junctions were homojunctions.

Because of the sharp junction interfaces, charge carriers were weakly confined in the active region. J_{th} was reduced to $40kA/cm^2$.

For charge carrier and optical beam confinement was proposed use of heterostructures.

A comparison of Figure 9.(a) and Figure 9.(b) shows that the p^+ - GaAs layer of Figure 9.(a) has been replaced by a p^+ - $Al_xGa_{1-x}As$ layer. Since the band-gap of $Al_xGa_{1-x}As$ is wider than that of p -GaAs, the junction between p -GaAs and p^+ - $Al_xGa_{1-x}As$ is a single heterojunction, forming SH diode.

This heterojunction serves two functions:

1. Confines the optical power in the active layer, which minimizes the optical loss in the cladding layer;
2. Provides a potential barrier at the heterojunction that confines the charge carriers in the active region.

J_{th} decreases to about $10kA/cm^2$.

Further improvement was achieved by incorporating a second heterojunction, resulting in DH lasers.

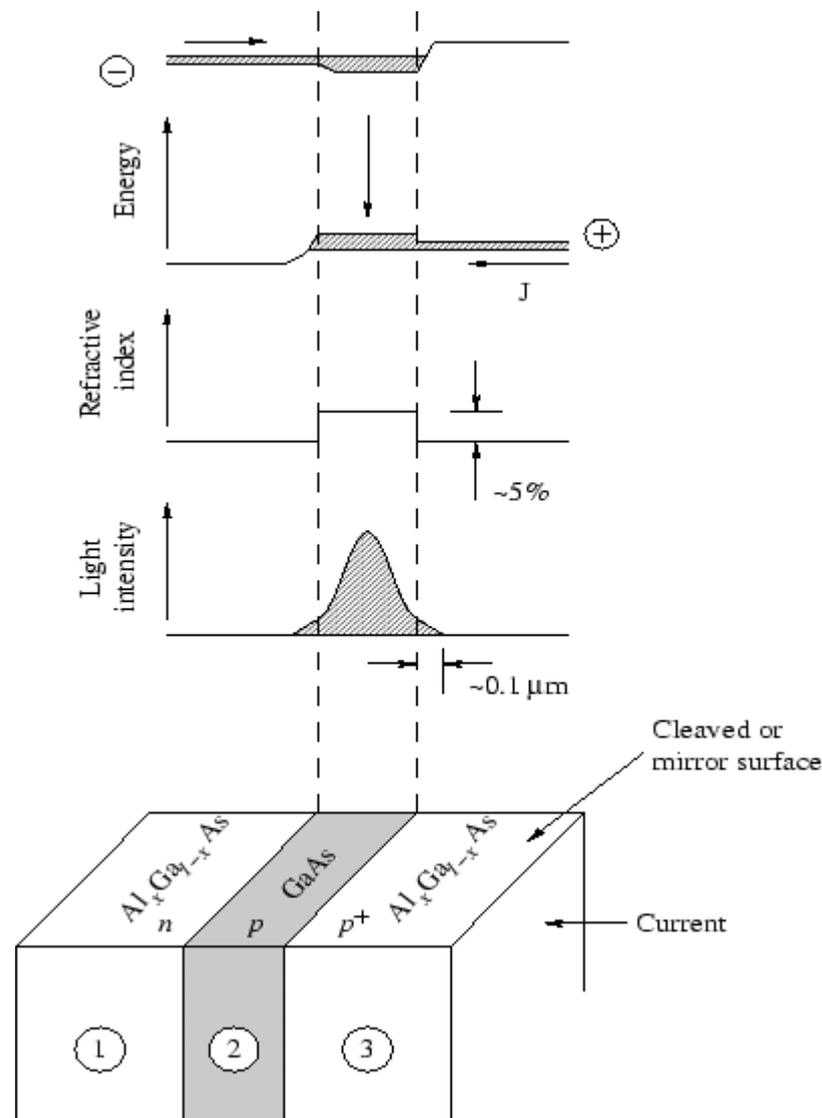


Figure 10.: Schematic representation of energy band diagram, refractive index profile, and optical field distribution of double heterostructure LEDs and ILDs. [1]

Figure 10. shows the schematic of the DH diode.

Difference with the SH diodes:

- potential barrier for holes at pN junction and for electrons at the Pp junction;
- the index difference between the active layer and surrounding cladding layers also acts as a guide for the resulting optical waves.

Because of these improvements, J_{th} can be reduced further to $0.5kA/cm^2$ at the room temperature.

Further reduction of the threshold current density is possible by using very thin layers which are known as quantum wells (In the thin layer, carrier motion perpendicular to the layer is restricted, and the kinetic energy is quantized into discrete energy levels. Structures consisting of such extremely thin layers having quantized energy levels are called quantum well structures), the thin layer is called potential well, and one of the neighboring layers with wide band-gap energies is called a potential barrier. One of the key results

of the potential well is that electrons in solids can behave much like free electrons with plane wave solutions and a parabolic $E-k$ relationship.

2.4 SUMMARY ON THE BASIC STRUCTURE OF MODERN ILD, LED AND SLD

All modern ILDs, LEDs and SLDs consist of an active layer and two cladding layers, surrounded by a substrate on one side and a contact layer on the other side. (Figure 11.).

- [1]The active layer is the light generating medium of the diode. It should be a direct band-gap material, with E_g corresponding to the desired emission wavelength. The band-gap should be narrower and the refractive index greater than those of the surrounding cladding regions.
- [2]The cladding layers restrict the motion of the charge carriers and confine the optical power in the active layer. The band-gap must be wider than band-gap of the active layer in order to prevent the charge carriers from diffusing away from the active layer. Index of refraction must be lower than that of the active layer in order to confine the optical power in the active region. Since no photons are emitted from the cladding layers, materials used can have direct or indirect band-gap.
- [3]The substrate provides mechanical support, heat dissipation capability and electrical contact. Proper crystal symmetry and lattice constant of the substrate are necessary for the growth of the succeeding compound semiconductor layers or solid solutions.
- [4]The contact layer provides electrical contact. In the case of surface emitting diodes, this layer should also be transparent to the emission wavelength.

Layer	Wavelength	
	0.7 to 0.87 μ m	1.1 to 1.67 μ m
Contact layer	GaAs	$\text{In}_{1-y}\text{Ga}_y\text{As}_z\text{P}_{1-y}$
Cladding layer	$\text{Ga}_{1-y}\text{Al}_y\text{As}$	InP
Active layer	$\text{Ga}_{1-x}\text{Al}_x\text{As}$	$\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$
Cladding layer	$\text{Ga}_{1-z}\text{Al}_z\text{As}$	InP
Substrate	GaAs	InP
	$y > x, z > x$	$x > u, y > v$

Figure 11.: Basic structure and material composition of LEDs and ILDs. [1]

Depending on the geometrical structures normal to the junction layers, ILDs can be further classified as broad area or stripe geometry lasers.

3 LASER DIODES

Laser diodes are typical *pn*-junction devices used under a forward bias. Laser is an acronym for Light Amplification by Stimulated Emission of Radiation.

The basic operating mechanism of laser diodes are based on the electrical and optical properties of *pn*-junctions and semiconductor materials.

Laser diodes are devices emitting coherent light produced in a stimulated emission process. The light emission process in laser diodes is more complicated than that in LEDs, where light produced in a spontaneous emission process.

The lasing wavelength ranges from the visible to the infrared wavelength range depending on the material of the active layer.

The 850 nm-band AlGaAs/GaAs and 1300/1550 nm-band InGaAs(P)/InP material systems are commonly used in optical fiber communication systems, Whereas AlGaAs/AlGaAs, group-III nitrides, and other materials are used in the visible wavelength range.

On the developmental stage of laser diodes, continuous-wave (cw) lasing at room temperature was achieved in an AlGaAs/GaAs double-heterostructure laser in 1970, and since then the double heterostructure has been a common one for laser diodes.

3.1 BROAD AREA LASERS

Broad area lasers are injection lasers of the most rudimentary form.

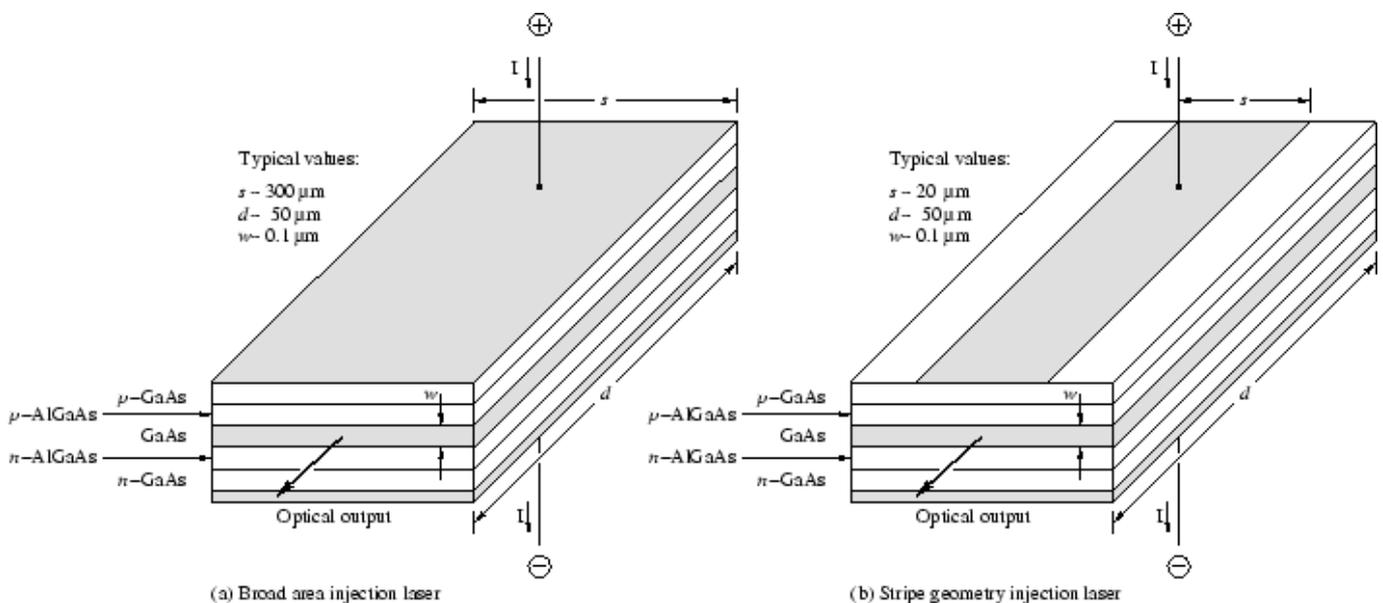


Figure 12.: Geometry of broad area injection lasers and stripe geometry injection lasers. [1]

Since the width is much larger than the thickness, (as we can see on Figure 12.) we can assume that the optical fields and injection current are distributed uniformly in the y direction and many transverse modes can be supported by the structure, if they are not suppressed.

The disadvantage of broad area lasers :

- since material non homogeneities and fabrication imperfections are inevitable, the current distribution is not necessarily uniform throughout the width in the y direction. As a result, the local current density may exceed the threshold level in some regions and may be below that level elsewhere.
- there may be excessive strain near imperfections, which leads to an increase in the refractive index, which in turn causes fields to concentrate in the high index region. As a result, light appears in a filamentary form. This filaments are unstable and may vary with the injection current.

As a result, broad area ILDs are inefficient, unstable and obsolete.

3.2 STRIPE GEOMETRY LASERS

Instead of trying to suppress the instabilities associated with filaments, which are typically 10 to 20 μm wide, it is better to forcibly control filament formation. This can be done by restricting the current to a narrow strip 10 to 20 μm wide. ILDs with this type of lateral current confinement are known as **stripe geometry injection lasers**.

One way to achieve this objective is to use a narrow conducting strip 10 to 20 μm in width as one of the electrodes. With the current confined to the emission region, recombination of the injected electrons with holes is more efficient and threshold current density is reduced.

3.2.1 GAIN-GUIDED STRIPE GEOMETRY LASERS

There are few different schemes to restrict current in a narrow region:

- the laser with an oxide insulating stripe;
- ion implantation techniques;
- internally striped structure.

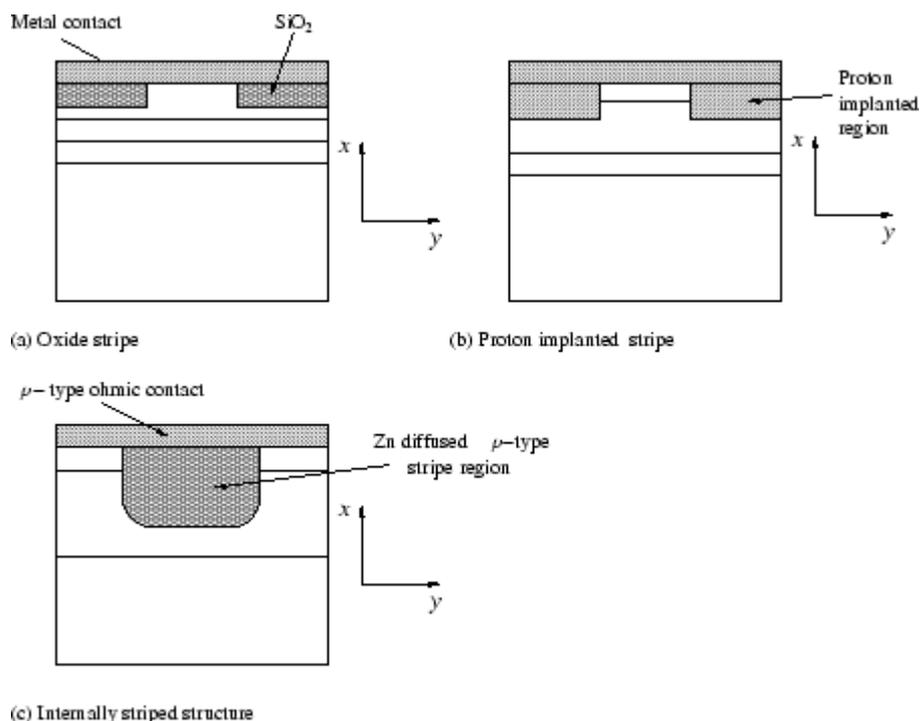


Figure 13.: Schematic cross section of three gain-guided stripe geometry ILDs. [1]

If the stripe is much narrower than 10 μm , the fraction of current confined in the stripe region will be too small to be effective.

For stripes much narrower than 10 μm , the threshold current density increases due to current spreading.

Since the current is confined to the stripe region, gain in the narrow region is high. Examples of these gain-guided structures are shown on Figure 13. The optical gain is related to the imaginary part of the refractive index.

3.2.2 INDEX-GUIDED STRIPE GEOMETRY LASERS

As we can see on the Figure 13., there is a large index change in the lateral dimension. Because of this, lateral optical confinement is built into the laser structure.

Example: the regions outside the stripe in the mesa isolated stripe are removed completely and the index for that region outside the stripe is reduced to that of air ($n=1$).

The disadvantage of this particular structure is that the index difference between the stripe region and the surrounding region is too large and many higher-order transverse modes are exited unless the active stripe is very narrow.

An alternative techniques help to get read of this disadvantage.

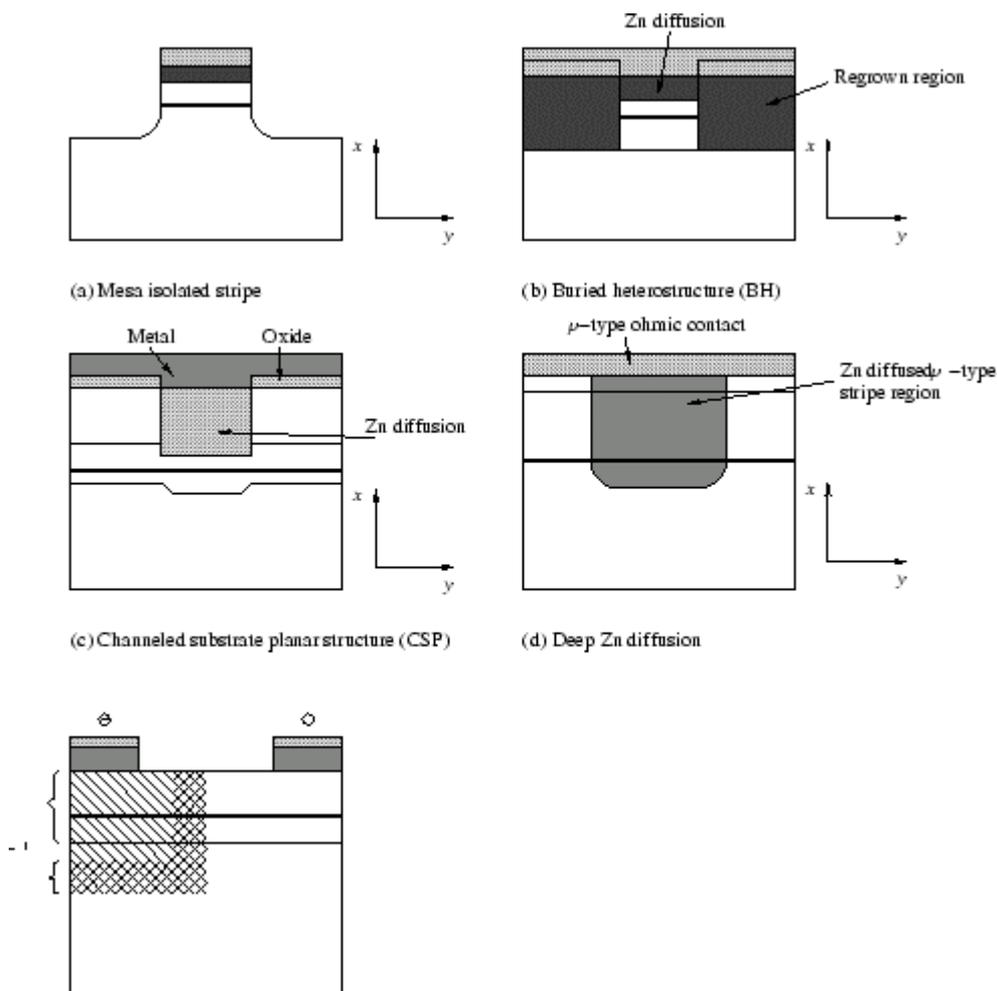


Figure 14.: Schematic cross section of five index-guided stripe geometry ILDs. [1]

TJS (transverse junction stripe) laser is quite different from other diode structures. Impurity diffusion is performed twice. Two heterojunctions are formed. Lateral confinement in the x direction is provided by the two heterojunctions and in the y direction it is provided by the two homojunctions. Current is injected laterally into the active region (horizontally), when in other stripe geometry laser diodes current flows across the active region.

3.3 SINGLE-FREQUENCY SINGLE-MODE INJECTION LASERS: FABRY-PEROT LASERS

The basic structure of the Fabry-Perot type of DH laser diodes is illustrated in Figure 15.

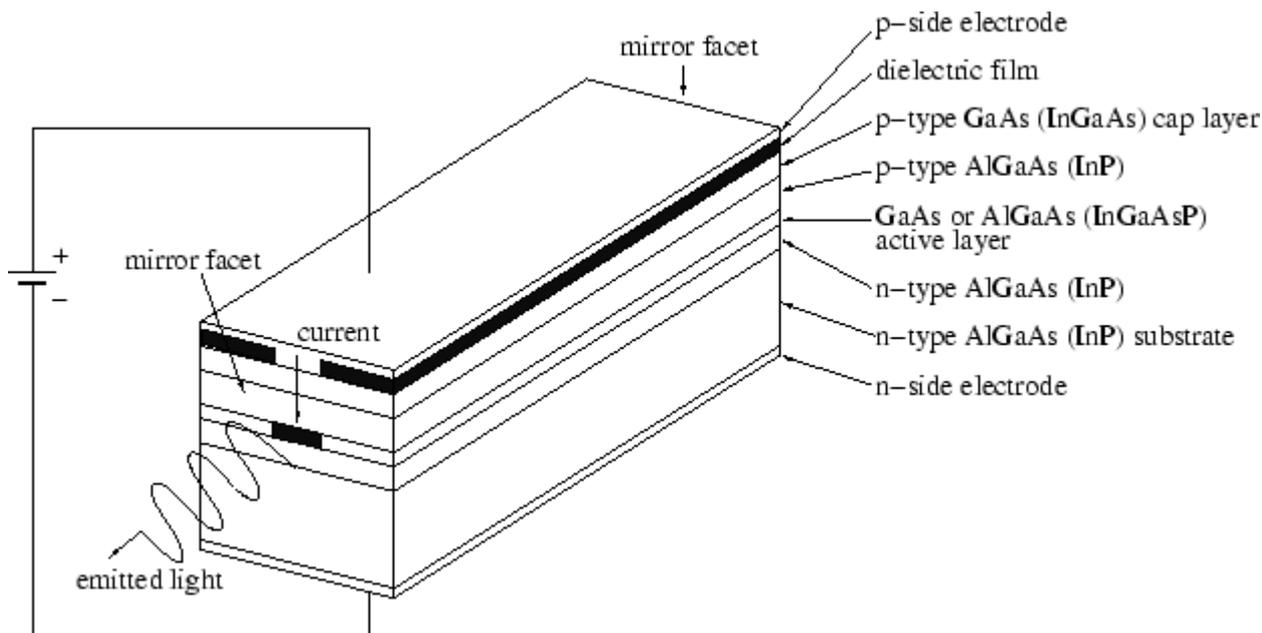


Figure 15.: Basic structure of a Fabry-Perot laser diode. [4]

It has two mirror facets - which are usually (110) cleaved facets - one at each end of the active layer. The mirror facets are parallel to each other and perpendicular to the active layer. This structure forms a Fabry-Perot (FP) type of optical cavity for lasing, and this type of laser is called the Fabry-Perot type laser.

The coherent light from the stimulated emission process in the active layer is emitted from the facets in opposite directions.

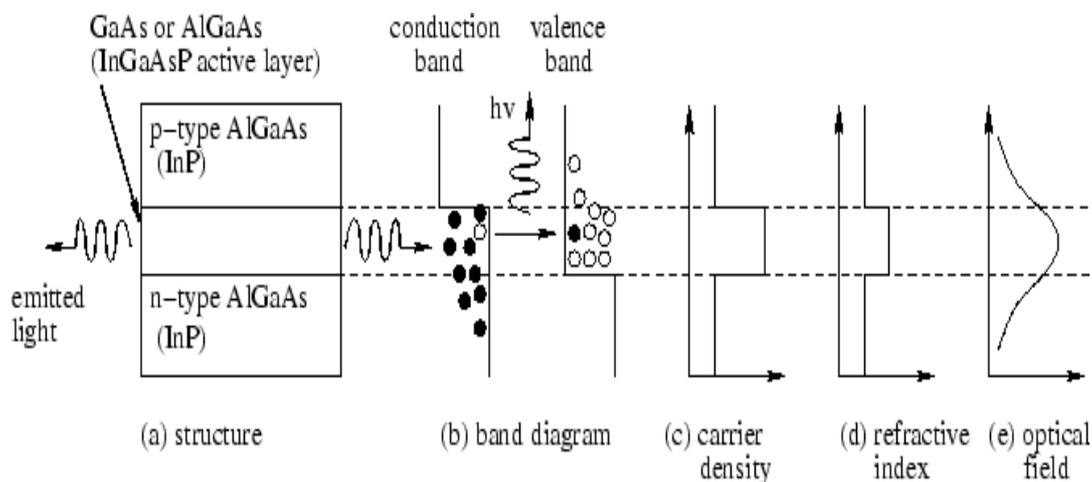


Figure 16.: Basic configuration of double heterostructure laser diodes. [4]

The basic configuration of double heterostructure lasers is shown in Figure 16., where AlGaAs/GaAs and InGaAs/InP lasers are used as typical examples. Under the forward bias condition the minority carriers are injected into the active layer through the pn -junction. Because of the requirement for electrical neutrality, what actually occurs is double injection (majority carriers also diffuse into the active layer). For stimulated emission, a very high density of injected carrier (over 10^{18} cm^{-3}) is required to form a population inversion. Such a high density of the injected carriers is attained by making the active layer less than 150 nm thick. To confine the carriers and photons within the active layer, we can set the refractive index the way as in shown on the Figure 16. This confinement will result in the occurrence on the stimulated emission at a high rate leading to lasing at a low input power.

We can show that the separation of longitudinal modes of a Fabry-Perot cavity of length d is

$$\Delta\lambda \approx \frac{\lambda^2}{2d \left[n - \lambda \frac{dn}{d\lambda} \right]} \quad (3)$$

Where

n - refractive index of the material

$\frac{dn}{d\lambda}$ - is the material dispersion (Source of time dispersion arising from the fact that the refractive index is indeed a function of wavelength might well be called chromatic dispersion but it is most commonly referred to as material dispersion).

For GaAs, material dispersion is between -1.5 and -2. Thus for a diode with length d of 500 μm , the longitudinal mode separation is in the range of 0.1 to 0.3 nm. The spectral separation of transverse modes is even narrower. However, higher-order transverse modes can be suppressed by introducing excessive losses to the higher-order modes, which is done by the index variation or gain stripes.

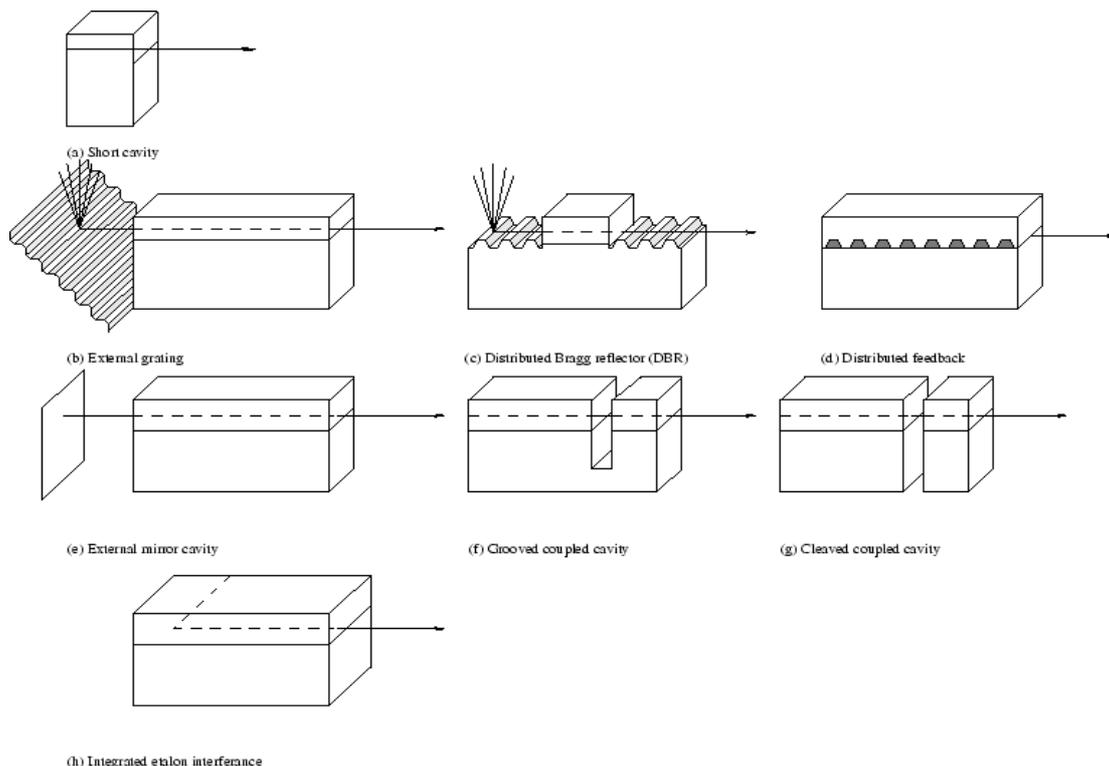


Figure 17.: Methods for controlling longitudinal modes of ILDs [1]

The discrimination of longitudinal modes is much more difficult. In order to restrict or select longitudinal modes, three basic schemes have been devised, (Figure 17.).

- [1]Geometry Control - since the longitudinal mode separation is inversely proportional to the cavity length d (Formula (3)) only one longitudinal mode can fit within the gain bandwidth if d is sufficiently small.
 - short cavity laser.
- [2]Frequency-Selective Feedback. In the usual Fabry-Perot cavities, broadband reflectors are used and the frequency selectivity is mainly due to the large mirror separation. Alternative - use of the gratings with a large number of grooves. For such gratings, the reflectivity is frequency dependent.
 - external grating laser;
 - distributed Bragg reflector (DBR) laser;
 - distributed feedback laser.
- [3]Coupled Cavities. Instead of having a single optical cavity, a laser diode can have two coupled cavities with slightly different cavity lengths. If one set is tuned such that the two wavelength sets have one wavelength in common, the laser diode will lase at that particular wavelength.
 - external mirror cavity;
 - grooved coupled cavity;
 - cleaved coupled cavity;
 - integrated etalon interference structure.

Table 5.: Evolution of laser diode structure and geometries. [1]
I. Layer structures
1.Homojunctions [by diffusion or liquid phase epitaxial (LPE) techniques]
Example: $n\text{-GaAs}/p\text{-GaAs}/\text{GaAs}$
2. Single heterojunctions (by LPE techniques)
Example: $n\text{-GaAs}/p\text{-GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$
3. Double heterostructures (by various epitaxial methods)
Example: $n\text{-Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}/p\text{-Al}_x\text{Ga}_{1-x}\text{As}$
4.Quantum wells
II. Geometry in the transverse direction
1. Broad area lasers: multiple longitudinal modes and multiple transverse modes
2. Stripe geometry lasers (single-mode lasers): single transverse mode and multiple longitudinal modes
i. Gain-guided stripe geometry lasers
ii. Index-guided stripe geometry lasers
III. Optical cavity (single-mode single frequency)
1. Short cavity lasers
2. Lasers with distributed Bragg reflectors, distributed feedback, or external grating reflectors
3. Lasers with external mirrors, grooved couple cavity, cleaved coupled cavity, or integrated etalon interference

To our reference is useful to present the evolution of laser diodes into the Table 5.

3.4 BASIC CHARACTERISTICS OF LASER DIODES

The three essential components in a laser system are an amplifying medium, an optical feedback and a pumping source.

The operation of an ILD can be described as follows:

- [1]Electrons are injected from the n -side of a junction to the p -side and holes - from the opposite direction.
- [2]In the depletion region, electrons are near the bottom of the conduction band, while holes are near the top of the valence band.
- [3]Photons are emitted when electrons and holes recombine. The injected current above the threshold induces stimulated emission, and coherent light is emitted from the laser diode.
- [4]Electric charges return through the external circuit.

Lasers are classified as three-level or four-level systems. To determine how ILDs should be classified, consider a DH injection laser with an energy diagram as shown in Figure 18.

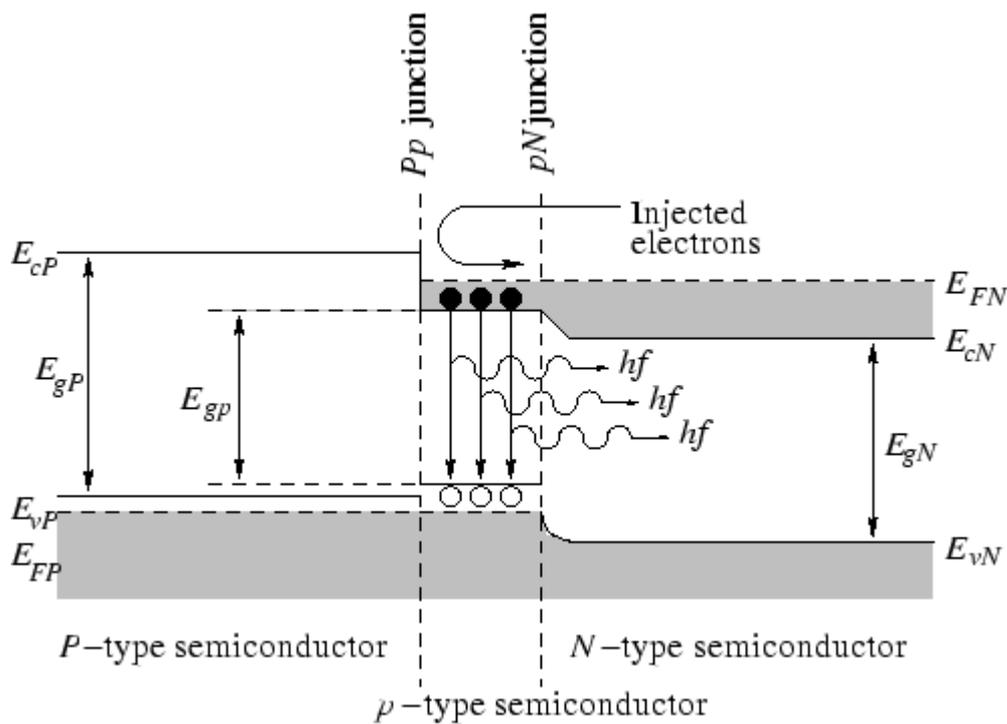


Figure 18.: Energy diagram of heterostructure ILD. [1]

As we can see from the Figure 18., lasing occurs in the narrow band-gap semiconducting layer sandwiched between two wide band-gap semiconductors. The difference between three- and four-level systems involves whether level E_a is normally occupied. Since in an ILD, the top of the valence band in the active region is normally vacant, ILDs are considered four-level systems.

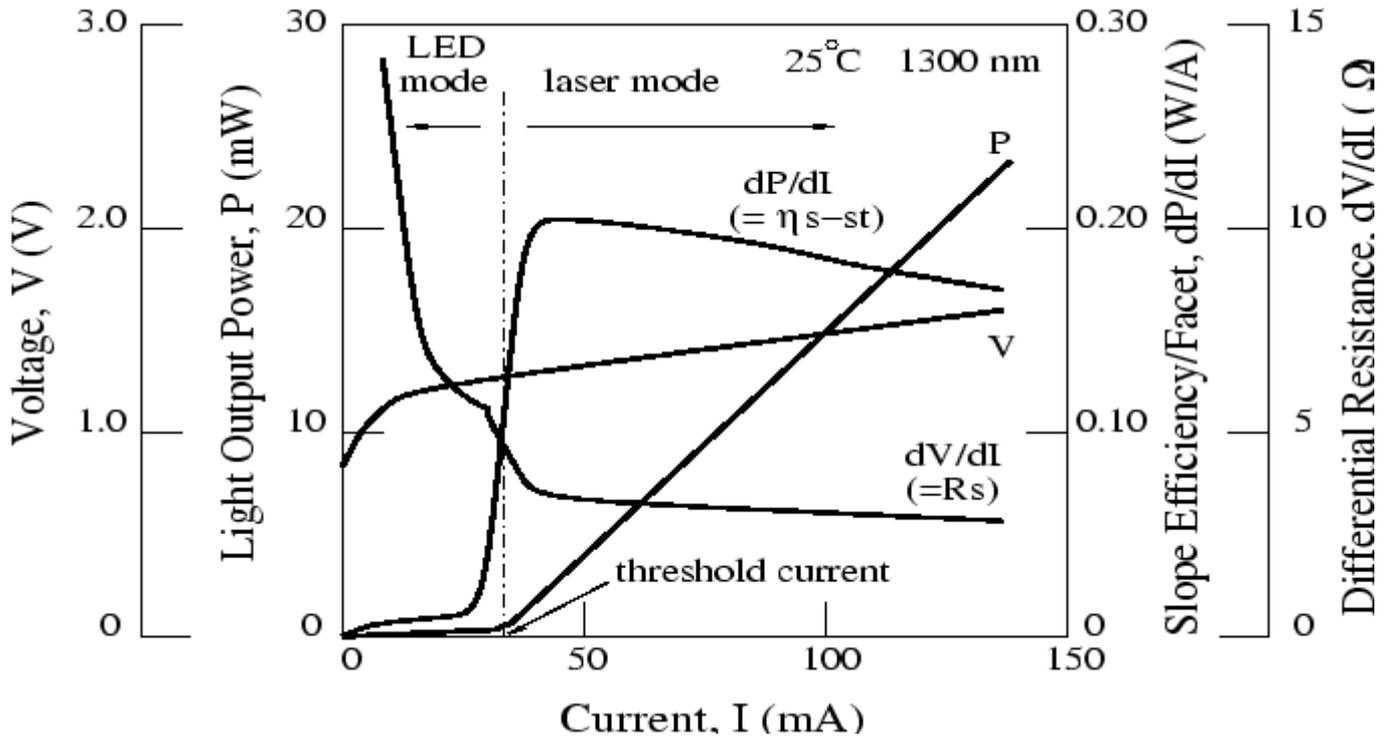


Figure 19.: Typical device characteristics for a 1300 nm-band InGaAsP/InP laser diode with cleaved facets. [4]

The operating characteristics of a typical 1300 nm-band InGaAsP/InP FP laser diode are shown in Fig 19.

In the low bias range - that is, the low excitation range - spontaneous emission is dominant because the carrier density in the active layer is not high enough for forming a population (When there are external means available whereby the upper state may be populated preferentially, it is sometimes possible to create situations in which n_1 can be made greater than n_2 (where n_1 and n_2 are the number of atoms per unit volume), then a population inversion is said to exist.). As the bias is increases, the population inversion occurs in the active layer.

Stimulated emission thus becomes dominant at a certain bias. This bias point is called the lasing threshold, and the corresponding current is called the threshold current.

3.4.1 THRESHOLD GAIN AND CURRENT

Threshold current is the most important and basic parameter of the laser diodes. Below the threshold, the emitted light in the active layer propagates along the layer because the refractive index of the active layer is higher than that of the cladding layers. Partially the propagating light is reflected at the mirror facet and the rest of it is emitted outside from the facet. Propagation and reflection of the light is repeated within the optical cavity formed by the active layer and the two mirror facets. As a result, the light is lost and gained.

The loss of the light is combined of the cavity loss (the absorption losses in the active layer and the cladding layers), the mirror loss caused by the mirror facet reflectivity being less than 100% (about 30% just after cleavage) and scattering loss caused by structural inhomogeneities (roughness of the heterointerface).

The gain originates from the injection excitation.

The gain coefficient at the threshold (threshold gain) can be given by Formula (4)

$$g_{th} = \alpha_i + \left(\frac{1}{2L}\right) \ln\left(\frac{1}{R_1 R_2}\right) \quad (4)$$

where

α_i - the internal cavity loss and is dominated by free carrier absorption in the active layer,

L - an active layer length,

R_1 and R_2 - the reflectivities of two mirror facets. (Figure 20.).

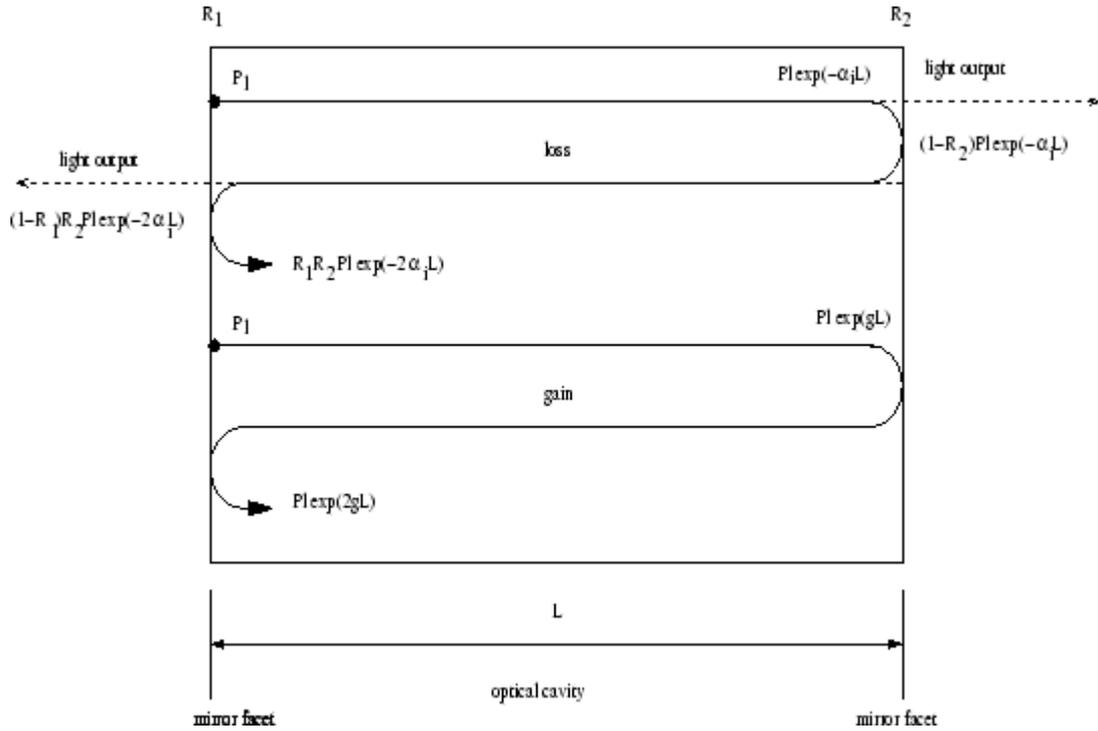


Figure 20.: Gain and loss in the optical cavity.

The second term on the right-hand side indicates the mirror loss and is inversely proportional to the cavity length, because photons related to stimulated emission can stay within the cavity for a time proportional to the cavity length.

If we define the reflectivity of the facet by formula (5)

$$R_1 = R_2 = R_{cleavage} = \left[\frac{n_r - 1}{n_r + 1} \right]^2 \quad (5)$$

where n_r is the refractive index of material of the laser diode, the equation (4) can be simplified in this case as

$$g_{th} = \alpha + \left(\frac{1}{L}\right) \ln\left(\frac{1}{R}\right) \quad (6)$$

As an example, for AlGaAs/GaAs and InGaAs/InP lasers with a 300 μm -long cavity, a bulk active layer and two cleaved facets, the refractive index of the active region under operation is about 3.3. The power

reflectivity is about 31% from formula (5), and the mirror loss in formula (5) is calculated to be about 40 cm^{-1} . The internal cavity loss in the normal bulk active layer is between 10 and 20 cm^{-1} . Then for lasing in such laser diodes a threshold gain is needed between 50 to 60 cm^{-1} .

Gain becomes high as the injected current (carrier density) increases.

The maximum gain coefficient, g_{max} , is also a function of injected carrier density:

$$g_{max} = \beta \left(\frac{J}{d} - J_0 \right)^m \quad (7)$$

where

β - the gain constant of gain factor,

J/d - the normalized current per unit active layer thickness, $A/\text{cm}^2/\mu\text{m}$, corresponds to the injected carrier density,

J_0 - the transparency current - the current required to compensate the cavity loss for a transparent cavity, $A/\text{cm}^2/\mu\text{m}$.

The ratio of light confined within the active layer to the total light is given by the optical confinement factor, Γ_a , ($0 \leq \Gamma_a \leq 1$). This factor is a function of active layer thickness and the refractive indexes of the active layer and the adjacent layers. Now, we can derive the absorption coefficient as

$$\alpha_i = \Gamma_a \alpha_a + (1 - \Gamma_a) \alpha_{ad} \quad (8)$$

where

α_a and α_{ad} are the absorption coefficients of the active layer and the adjacent layers.

The light confined within the active layer can be related to the optical gain and formula (4) can be rewritten as

$$g_{th} = \left(\frac{1}{\Gamma_a} \right) \left[\alpha_i + \left(\frac{1}{L} \right) \ln \left(\frac{1}{R} \right) \right] \quad (9)$$

Now, using formulas (7) and (9), the approximate threshold current density, J_{th} , (A/cm^2), can be written as

$$J_{th} = d \left\{ \frac{1}{\beta \Gamma_a} \left[\alpha_i + \frac{1}{L} \ln \left(\frac{1}{R} \right) \right] \right\}^{1/m} + d J_0 \quad (10)$$

where d - the active layer thickness in micrometers.

The threshold carrier density corresponding to the threshold current, n_{th} , can be found from

$$n \approx \Delta n = \tau_c J / qd \quad (11)$$

and

$$p \approx \Delta p = \tau_h J / qd \quad (12)$$

that will give as

$$n_{th} = \tau_c J_{th} / qd \quad (13)$$

where τ_c - the lifetime of the injected minority carriers.

3.4.2 PHASE CONDITION

The relationship between gain and loss described in the previous section does not completely determines the lasing conditions. The emission spectra are closely related to lasing, and only spontaneous emission corresponding to the lasing mode makes a contribution to the lasing. The phase of the propagating light after a round trip is required to coincide with the initial phase.

The following phase condition has to be satisfied (determined by a Fabry-Perot geometry):

$$m\lambda_m = 2L, \quad (m = 1, 2, 3, \dots) \quad (14)$$

where

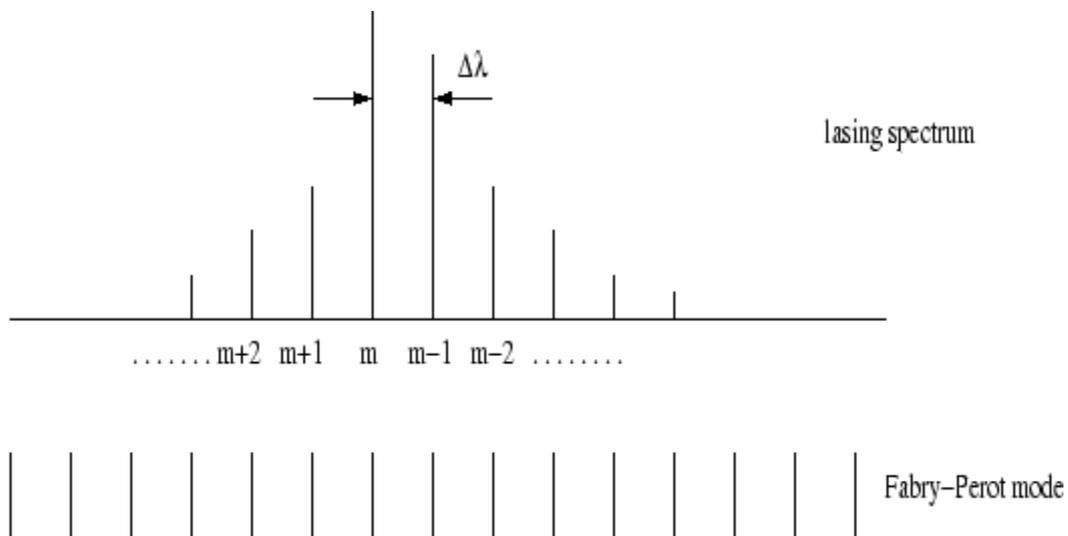
m - the mode index or mode number,

λ_m - the wavelength of the mode in the optical cavity.

If we define the refractive index of the active region as n_r , formula (14) can be rewritten as:

$$m \left(\frac{\lambda_0}{n_r} \right) = 2L \quad (15)$$

where λ_0 - the wavelength in a vacuum.



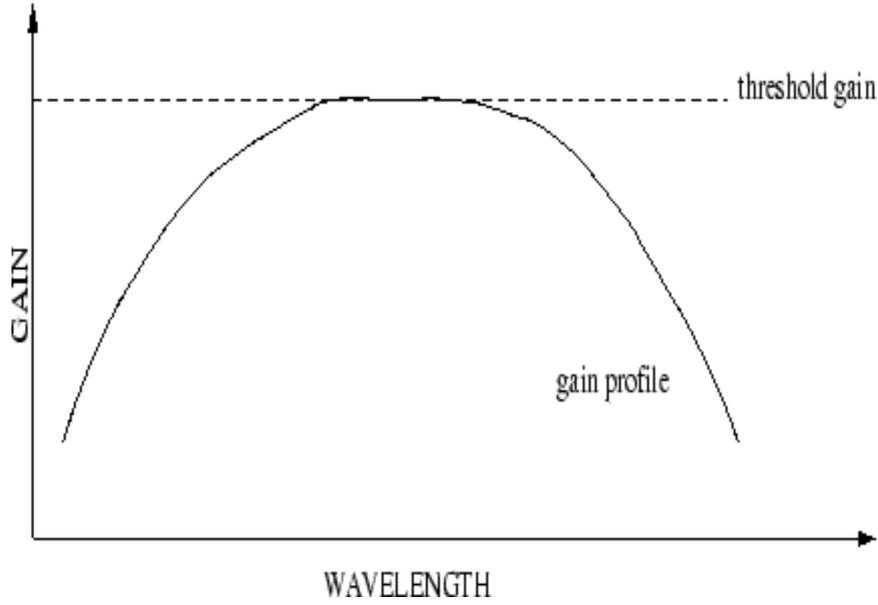


Figure 21.: Illustration of gain profile and emission spectra (longitudinal modes).

Lasing occurs every wavelength mode as we can see from the formula (14) and the Figure 21. By using formula (15) and considering the next mode, $(m+1)$ mode, we can find the mode spacing $\Delta\lambda_m$ as

$$(m+1) \left[\frac{\lambda_0 - \Delta\lambda}{n_r} \right] = 2L \quad (16)$$

and then

$$\Delta\lambda_m = \lambda_0^2 / 2n_{eff}L \quad (17)$$

where n_r is replaced by the effective refractive index, n_{eff} , which given by:

$$n_{eff} = n_r \left[1 - \left(\frac{\lambda_0}{n_r} \right) \left(\frac{dn_r}{d\lambda_0} \right) \right] \quad (18)$$

When the gain reaches the threshold level, lasing occurs at the wavelength satisfying formula (14).

3.4.3 EFFICIENCY AND OUTPUT POWER

The behaviors of laser diodes are quite similar to the edge-emitting LEDs, and a part of the spontaneous emission power in the active layer is emitted from both facets. the efficiency is quite low, and the total output power from both facets is less than a few percent of the power emitted in the active layer.

At the lasing threshold, stimulated emission exceeds spontaneous emission, and above the threshold, the efficiency increases. The output power corresponds to the mirror loss from the viewpoint of the gain-loss relation shown in Figure 21. and the current injected through the pn -junction induces gain.

Taking output power from both mirror facets into consideration, the external quantum efficiency, η_d , %, is given by

$$\eta_d = \eta_{id} \frac{\frac{2\Delta P_{out-st}}{h\nu}}{\frac{\Delta I}{q}} = \eta_{id} \left\{ \frac{\left(\frac{1}{2L}\right) \ln\left(\frac{1}{R_1 R_2}\right)}{\alpha_i + \left(\frac{1}{2L}\right) \ln\left(\frac{1}{R_1 R_2}\right)} \right\} \quad (19)$$

where η_{id} is called the internal differential quantum efficiency, %, and is given by

$$\eta_{id} = \frac{\Delta P_{act-st} / h\nu}{\Delta I / q} \quad (20)$$

where P_{act-st} is the lasing power due to the stimulated emission within the active layer. By using the external differential quantum efficiency, the lasing output power per facet (in W or mW) can be given as

$$P_{out-st} = \frac{1}{2} h\nu \eta_d S_{act} \frac{J - J_{th}}{q} = \frac{1}{2} h\nu \eta_d \frac{I_F - I_{th}}{q} \quad (21)$$

where

S_{act} - the area of the active layer,

I_F - the forward injected current,

I_{th} - the threshold current observed.

In addition to the external differential quantum efficiency, the slope efficiency (or responsivity) of laser diodes, η_{s-st} , is also used quite often and is given by the first derivative of the output power with respect to the current, I_F :

$$\eta_{s-st} = \frac{dP_{out-st}}{dI_F} = \frac{1}{2} \eta_d h\nu / q = 0.62 \frac{\eta_d}{\lambda (\mu m)}, \quad (W/A \text{ or } mW/mA) \quad (22)$$

Now, if we use the slope efficiency, lasing output power from formula (21) is simplified:

$$P_{out-st} = \frac{1}{2} h\nu \eta_d \frac{I_F - I_{th}}{q} = \eta_{s-st} (I_F - I_{th}) \quad (23)$$

The formulas (21) and (23) are showing the ideal increase of the optical input power above the lasing threshold.

3.4.4 CURRENT-VOLTAGE CHARACTERISTICS

The current-voltage characteristics are basically given by

$$I_F \propto \exp\left(\frac{gV_F}{a_f k_B T}\right) \quad (24)$$

except for those due to lasing.

In the bias range below that in which lasing occurs, the diffusion current is approximately given by formula

$$I_F = S_{act} J_{s0} \exp\left(q \frac{V_b - R_s I_F}{k_B T}\right) \quad (25)$$

As shown on the Figure 22., the injection carrier density in the active layer increases rapidly.

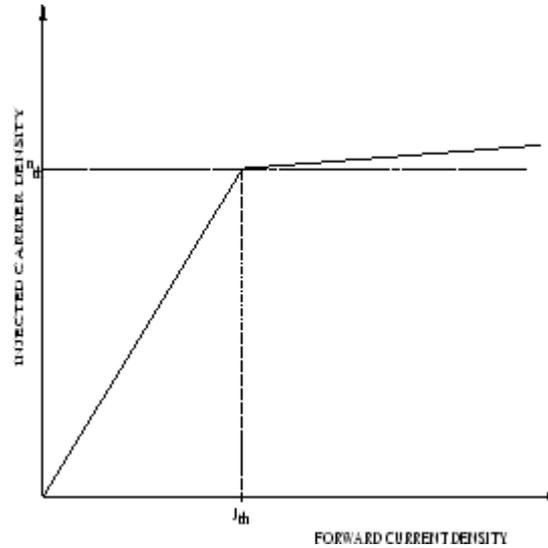


Figure 22.: Injected carrier density as a function of injected (forward) current. [4]

The differential resistance is given by:

$$\frac{dV_b}{dI_F} = \frac{k_B T}{q} \frac{1}{I_F} + R_s \quad (26)$$

In the LED-mode operation before lasing, the differential resistance decreases rapidly with injected current and approaches the series resistance, R_s . At the lasing threshold current the differential resistance corresponding to the slope of current-voltage characteristics becomes constant as shown in Figure 22.

Most of the injected carrier is converted to lasing output power. As a result of such rapid carrier recombination, the carrier density on the active layer becomes constant (Figure 22.).

The junction voltage is given by

$$V_j = V_b - R_s I_F \quad (27)$$

by taking $\frac{dV_j}{dI_F} \approx 0$, we get:

$$\frac{dV_b}{dI_F} = R_s \quad (28)$$

We can see that the differential resistance changes rapidly from the value given by formula (26) to that given by formula (28).

When the bias is low, laser diodes operate in a manner similar to LEDs.

3.5 DIFFERENCES OF ILD FROM GAS, LIQUID DYE AND SOLID STATE LASERS

- [1] Lasing transition in ILDs are between the valence and conduction bands of semiconductors rather than between the discrete energy levels of isolated atoms or ions in solid-state host materials.
- [2] The energy diagram of semiconductors depends on the orientation with respect to the crystal axis. The energy levels in gases or liquids are independent of direction or orientation.
- [3] Direct, high-speed amplitude modulation of ILDs is possible by controlling the current injected into the semiconductor junction. For other lasers, direct amplitude modulation is extremely difficult.
- [4] The overall size of ILDs, including the active medium and the optical cavity, is very small in comparison with other lasers. Because ILDs are small, the output is not as well confined spatially or spectrally, as in other lasers that are larger.

Diode lasers are distinguished from these other types primarily by their ability to be pumped directly by an electrical current. This results in much more efficient operation. Overall power conversion efficiencies of ~50% are not uncommon for a diode laser. But for gas and solid state lasers, which generally pumped by plasma excitations or an incoherent optical flash lamp source respectively, efficiencies on the order of 1% are common.

Because of their longer cavities and more narrow gain bandwidth, gas and solid state lasers also tend to have more coherent outputs than simple semiconductor lasers. However, more advanced and sophisticated single frequency diode lasers can have comparable line widths in the low megahertz range.

Another difference between semiconductor and other lasers is the net size. Gas and solid state lasers are typically tens of centimeters in length, diode laser chips generally about the size of the grain of salt and increased to the order of a cubic centimeter mostly for the purpose of handling (mounting and packaging).

Diode lasers, due to their high reliability or useful lifetime, find a widespread use in such an applications as fiber-optic communication systems.

The useful life of gas or solid state lasers is typically measured in thousands of hours, diode lasers - hundreds of years.

The characteristics of semiconductor injection lasers may be described by six parameters:

- radiation wavelength;
- threshold current density;
- external quantum efficiency;
- power efficiency;
- far-field radiation pattern;
- spectral width.

3.6 RECENT DEVELOPMENTS

Quantum Well Lasers. The basic structure of a DH laser is a narrow-band-gap semiconductor layer sandwiched between two wide-band-gap materials. The active layer thickness is in order of $0.1 \mu\text{m}$. With this kind of thickness electrons are free to move in all directions. However, if we reduce the layer thickness to 20 nm or less, electron motion in the direction normal to the layer structure is allowed only if electron wave functions satisfy conditions dictated by quantum mechanics. This is because the electrons in the narrow-band-gap material are trapped by the potential barriers due to the wide-band-gap materials on both sides. This is a "potential well" problem.

Double heterostructure lasers with a single active layer 20 nm thick or less are known as single quantum well lasers and those with several thin active layers are known as multiple quantum well lasers.

$J_{th}=80 \text{ A/cm}^2$ for a very long cavity $d=3.3 \mu\text{m}$.

Two key features of quantum well lasers are:

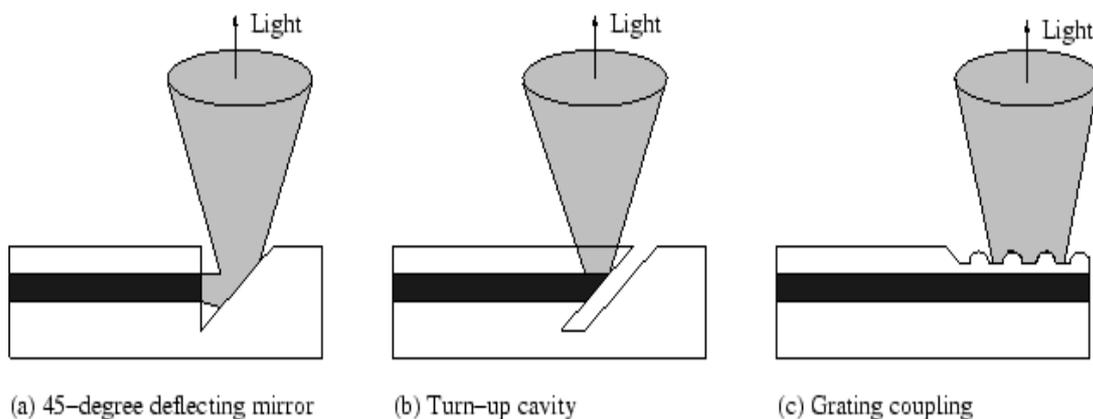
1. reduction of the threshold current density;
2. possibility of tuning the emission wavelength by controlling the thin layer thickness.

Surface-Emitting Semiconductor Injection Lasers. For basic laser diode structures, an active layer is surrounded by cladding layers on either side. Reflecting mirrors normal to the layers are made by cleaving the semiconductor and light is emitted from one or both of the cleaved edges. We refer to these ILDs as conventional of edge-emitting. They are used mostly in the CD players and optical communication.

Disadvantages

- [1]The radiated beam is elliptical and diverges quickly (especially in the plane normal to the junction).
- [2]ILDs are quite large compared to other semiconductor diodes, transistors and integrated circuit components. (High electrical power).
- [3]ILDs are not amenable to mass production, since most cavity mirrors are formed by cleaving.
- [4]It is rather difficult to form two dimensional laser arrays, particularly the densely packed ones that are needed in many optical image and signal processing applications. (ability to electronically control the emission from each emitter independently).

To avoid these shortcomings, a new type of ILD has been conceived: surface-emitting ILD. An edge-emitting ILD can be converted to a surface emitting by the incorporation of deflecting mirrors, gratings or intra cavity bent waveguides. (Figure 23).



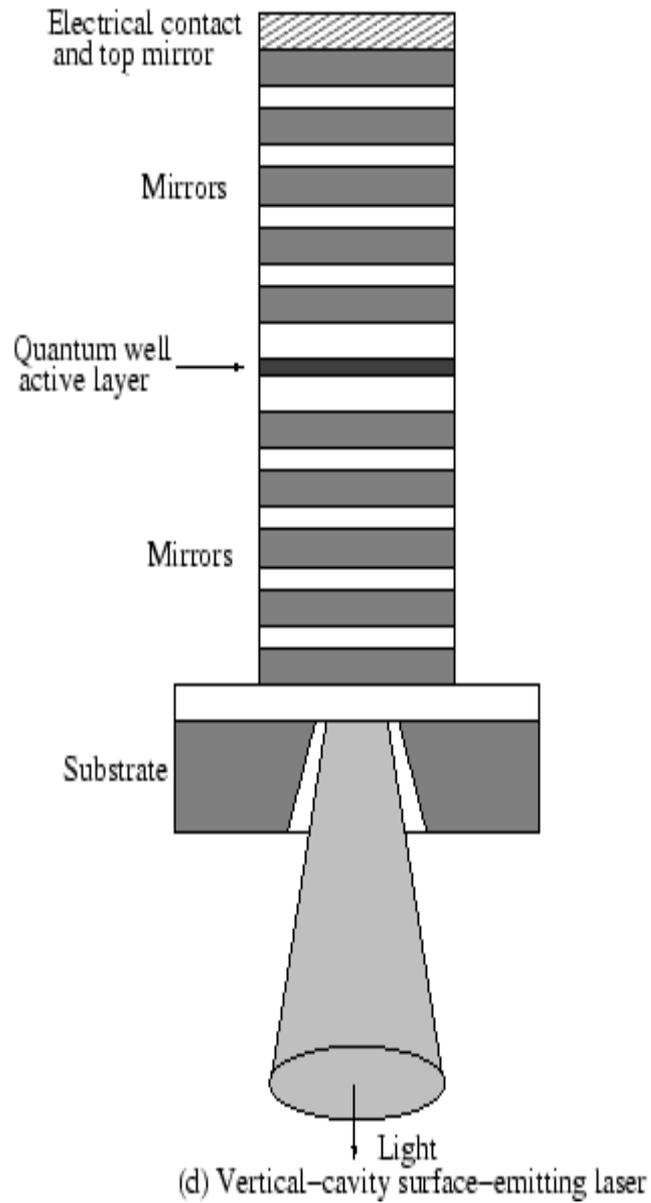


Figure 23.: Types of surface-emitting injection lasers. [1]

These lasers are quite small. Typically, each emitter is about 6 to 10 μm long and 10 μm in diameter. They are often referred to as microlasers.

4 LIGHT-EMITTING DIODES

Light-emitting diodes (LEDs) are a typical *pn*-junction device used under a forward bias that emit incoherent light when current passes through the semiconductor junction. When the minority charge carriers recombine radiatively with the majority charge carriers, photons are emitted. This is the basic light generation process in semiconductors.

Depending on the semiconductor material used in the light-emitting layer (active layer), the wavelength of the emitted light can be anywhere within the range from visible to infrared.

Most commercially available LEDs are made from III-V compound semiconductors. Some II-VI compound semiconductors such as ZnS and AnSe are used in a few LEDs emitting visible light though these materials are not used frequently because of the difficulty of *pn*-junction formation.

LEDs have been widely used in various kinds of equipment and systems. LEDs composed of a combination of InGaAsP and InP cover the wavelengths from the 1300 to 1550 nm band and are the ones usually used in optical fiber communication systems.

A combination of GaAs and AlGaAs of a combination of different compositions of AlGaAs has been used to make LEDs emitting in the 780 to 900 nm band, and those LEDs have been used in optical fiber communication systems, data links, remote controllers, etc.

For display and indicator applications, LEDs emitting from blue to red light are usually applied.

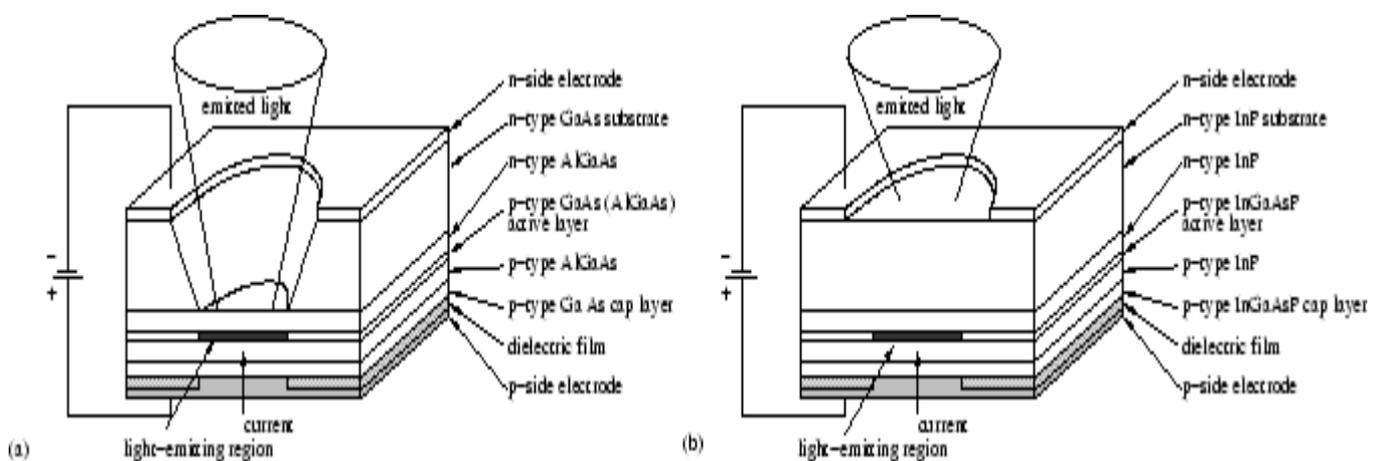
In a typical display LED, the current density is on the order of 10 A/cm^2 . This corresponds to an injection of approximately 6×10^{19} carriers/cm²s.

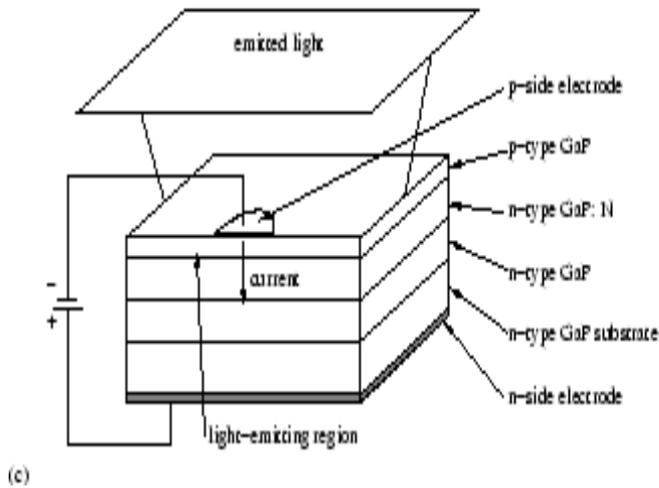
Even for a moderate current injection, such as 10 A/cm^2 , the number of injected minority charge carriers far exceeds that of minority charge carriers in thermal equilibrium at room temperature.

For LEDs designed for communications applications, the current density is typically 10^3 A/cm^2 or higher. This means that the injected minority charge carrier density in these LEDs is about two orders of magnitude greater than typical display LEDs.

4.1 TWO BASIC LED STRUCTURES

The basic structures of various kinds of LEDs are illustrated in Figure 24.





(c)

- a) Burrus type;
 b) surface-emitting type (double heterostructure type);
 c) surface-emitting type (homojunction type). [5]

Figure 24.: Cross-section illustration of the basic surface-emitting types of LEDs:

In LEDs used in optical fiber communication systems, efficient spontaneous emission originating from the injection excitation is favorable to reduce input power, and thus a *pn*-heterojunction - usually DH - is used.

A *pn*-homojunctions (as well as *pn*-heterojunctions) is still used in LEDs emitting red or yellow light because it is easy to fabricate.

The light originating in the spontaneous emission process is emitted from the light-emitting region (active layer) in all directions. Consequently, several structures restricting the emitted light to a certain directions have been developed. These LED structures are basically divided into two groups: The surface-emitting and Edge-emitting types.

4.1.1 SURFACE-EMITTING LED

The surface-emitting LEDs emit the light in a direction perpendicular to the *pn*-junction plane. Figure 24. shows three surface-emitting types of LEDs.

The general idea is that a narrow active layer is sandwiched between two cladding layers. Because of heterojunctions on either side of the active layer, injected carriers are confined within the thin active region. The thick substrate is used to provide mechanical support and electrical contacts.

In the Burrus type, the emitted light is absorbed in the substrate. If the wavelength (photon energy) of the emitted light is shorter (higher) than the fundamental absorption edge (band-gap energy) of the substrate, most of the emitted light is absorbed in the substrate. In such case, a part of the substrate corresponding to the light-emitting region is etched off to prevent the absorption.

The light-emitting region is usually limited in order to keep the operating current low and, for LEDs used in optical fiber communication systems, to facilitate the coupling of the light to a fiber. The emitting region is limited by confining the injected current to a part of the electrode. The electrode is in contact with a cap layer, usually 30 to 50 μm in diameter, and is limited by a dielectric film such as SiO_2 .

If the emitted light is transparent in the substrate, the substrate can be chemically or physically etched down to lens structure to improve the light-emitting pattern.

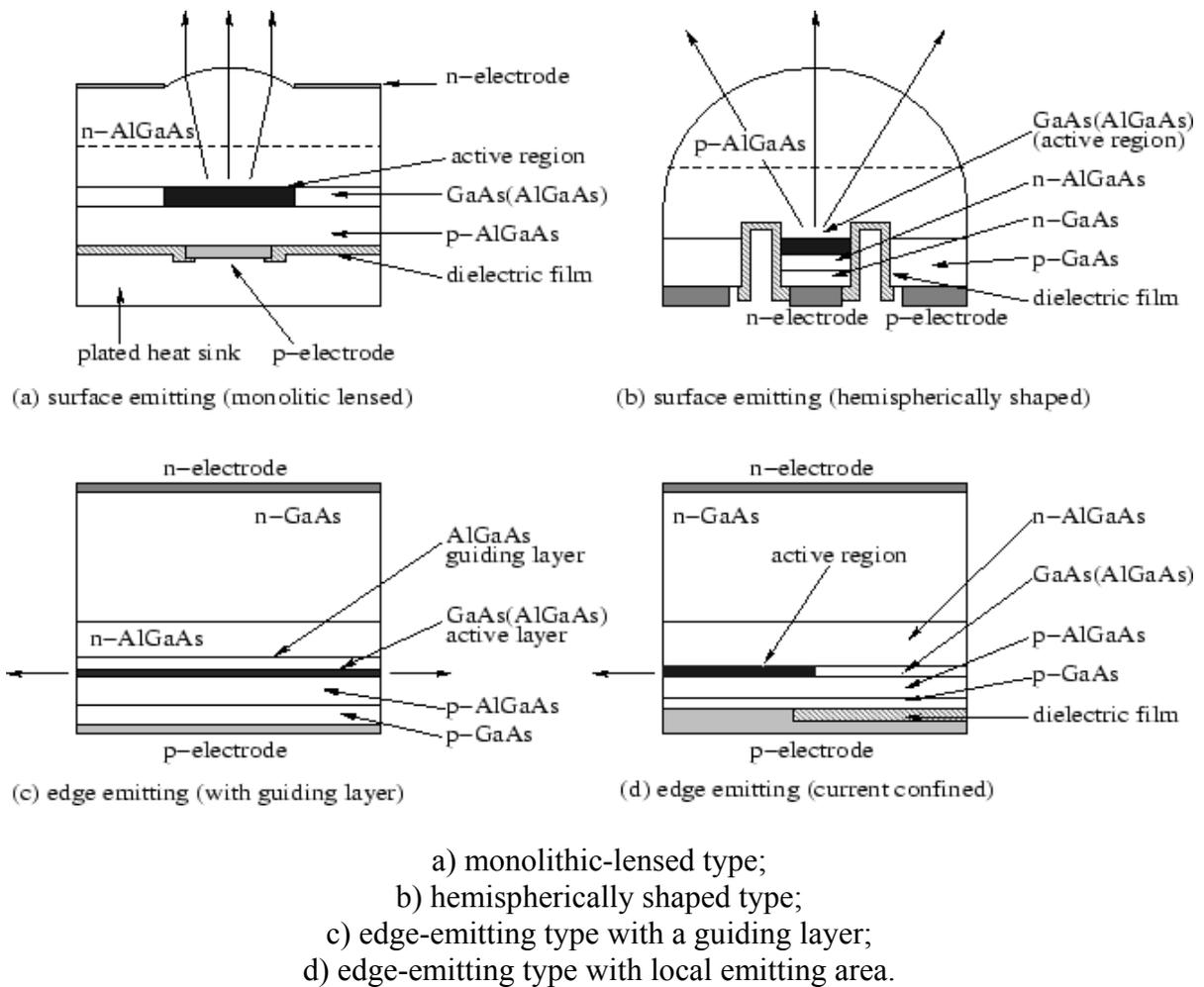


Figure 25.: Cross-sectional views of some widely used LEDs:

Because radiative recombination is more probable in direct-band-gap semiconductors than in indirect-band-gap semiconductors, direct-band-gap materials are preferred for the light emitting layers.(Figure 25.).

For typical surface-emitting LED designed for optical fiber communication purposes, the active area, defined for example by an oxide stripe, has a width of 20 to 50 μm , which matches the core diameter of typical multimode fibers.

4.1.2 EDGE-EMITTING LED

The structure is very similar to that of ILDs.(Figure 26.)

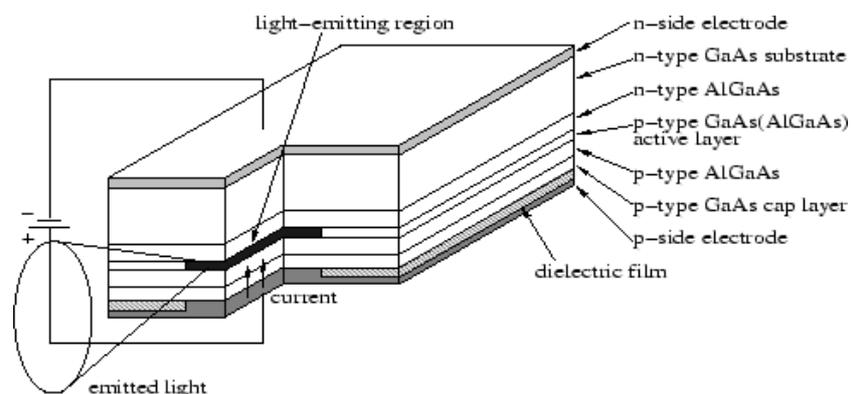


Figure 26.: Cross-section illustration of the basic edge-emitting type of LEDs. [5]

The light is emitted in a direction parallel to the pn -junction plane. The current is restricted, by a dielectric film, to within a stripe having a width less than several tens of micrometers and then the light-emitting regions is formed along the current injected (stripe) region.

The cladding layers are chosen to provide carrier confinement, as well as optical guidance. since the index of the cladding layers is slightly lower than that of the active layer, rays with a large incident angle are total reflected internally by the boundaries between the two layers. This means that light is trapped inside the high-index light-emitting layer and emerges only from the diode edge.

Edge-emitting LEDs have an elliptical pattern.

In some edge-emitting LEDs, current injection in the region near the rear facet is reduced by an electrically resistive region, which means that the region near the rear facet absorbs rather than generates light.

This edge-emitting type of LEDs is used in the optical sources of fiber communication systems, but not often.

4.2 BASIC CHARACTERISTICS OF LED

The output light of the LEDs originates from the spontaneous emission in the active layer, which in turn is a product of the radiative recombination of the injected electrons and holes.

The band structure and the distribution of injected carrier density under a forward bias are shown schematically in Figure 27. for a p -type/ p -type/ n -type DH composed of direct band-gap semiconductors.

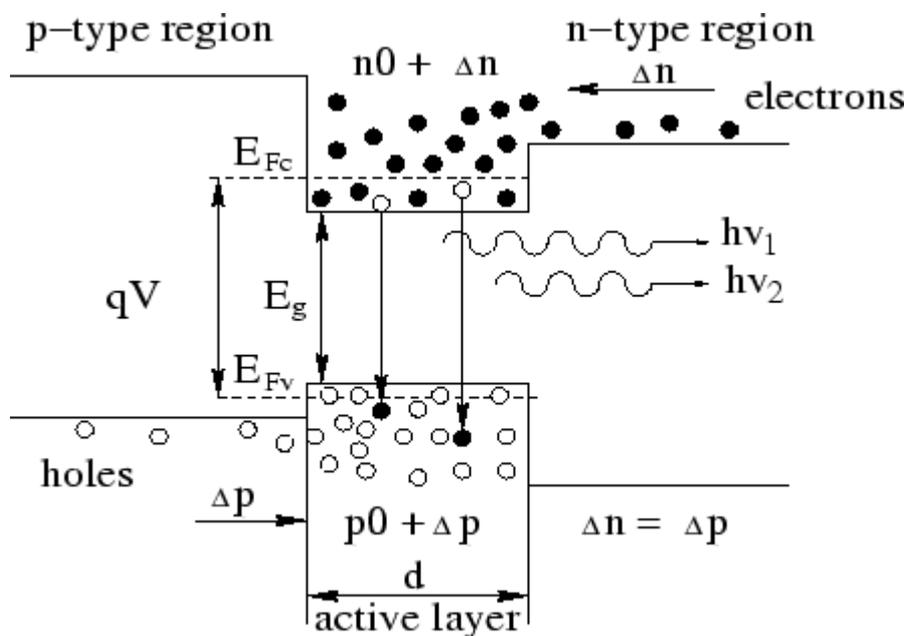


Figure 27.: Energy band diagram and injected carrier distribution for a double heterostructure under a forward bias. [4]

Injected carriers distribute uniformly in the active layer because its thickness is less than the carrier diffusion length (a few μm). The thickness of the active layer in LEDs is ordinarily between 0.5 and 2 μm .

The electron and hole densities in the active layer under the injection excitation can be expressed with the equations:

$$n = n_0 + \Delta n \quad (29)$$

$$p = p_0 + \Delta p \quad (30)$$

and

$$\Delta n = \Delta p \quad (31)$$

where

Δn and Δp - are the injected electron and hole densities.

n_0 and p_0 - are the electron and hole densities in the active layer in a thermal equilibrium state and $n_0 p_0 = n_i^2$.

Current-light output power and current-voltage characteristics for 1550 nm-band InGaAsP/InP surface-emitting LED are shown in Figure 28.

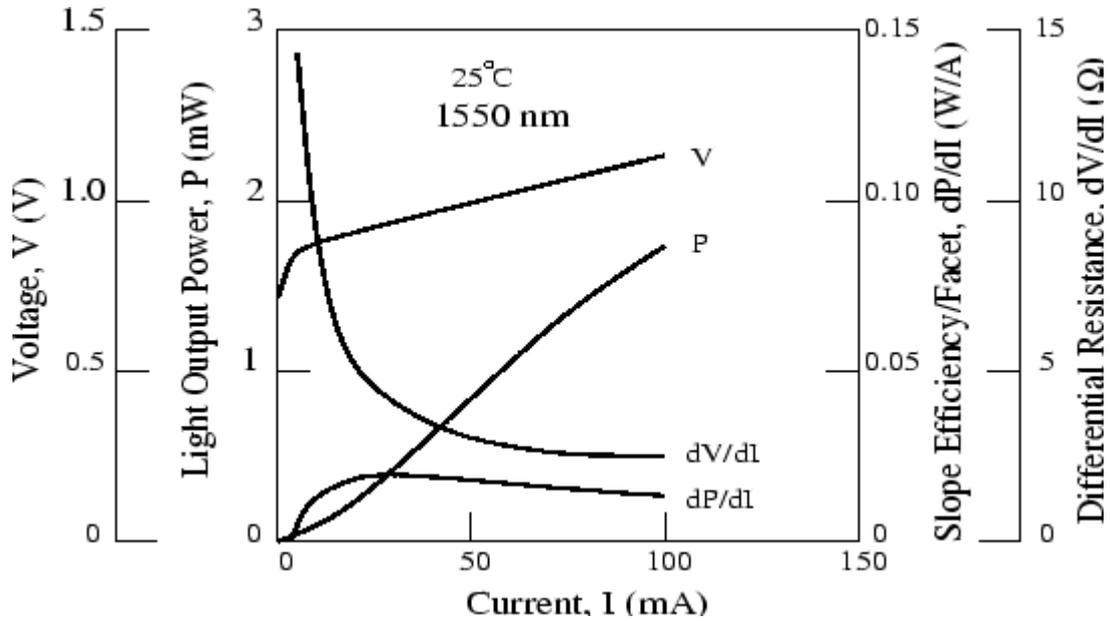


Figure 28.: Typical device characteristics of a surface-emitting 1550 nm-band InGaAsP/InP LED. [4]

The light power emitted in the active layer is given by the product of the number of photons emitted and the photon energy, $h\nu$.

Consequently, the light output power of the active layer is proportional to the injected current density in the low-excitation range, while in the high-excitation rate it is proportional to the square of the injected current density if the lifetimes are constant.

4.2.1 POWER AND LIGHT EXTRACTION EFFICIENCY: SURFACE-EMITTING LED

We have to introduce two terms in order to be able to quantify optical power. (Figure 29).

H - irradiance - the optical power ΔP per unit area received by the receiver

$$H = \frac{\Delta P}{\Delta S_r} \quad (32)$$

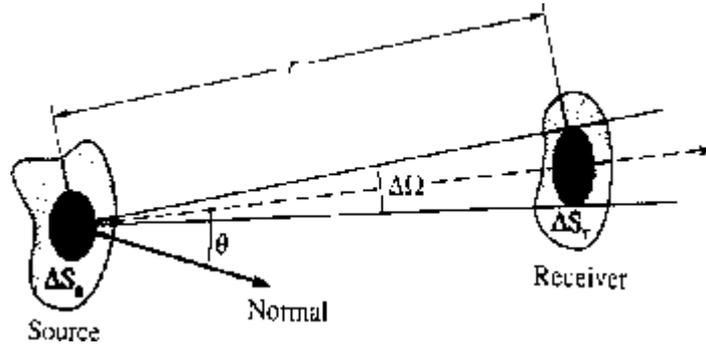


Figure 29.: Geometry for defining irradiance, radiant intensity, and radiance. [1]

J - radiant intensity

$$J = r^2 \frac{\Delta P}{\Delta S_r n} = \frac{\Delta P}{\Delta S_r n \frac{1}{r^2}} = \frac{\Delta P}{\Delta W} \quad (33)$$

Where $\Delta W = \Delta S_r n / r^2$ is the solid angle of the power impinging on the receiver surface element.

We can interpret J as the power ΔP contained in a solid angle ΔW .

The light output power is nearly proportional to the injected current in the low-current range. The light power emitted in the active layer is given by the product of the number of photons emitted and the photon energy, $h\nu$. The product of the injected carrier density, J/qd , and the internal quantum efficiency gives us the number of photons created by the spontaneous recombination processing a unit volume of the active layer. Now, we can see that the light power emitted from a unit volume of the active layer is given by

$$P_{act} = h\nu \frac{\eta_i J}{qd} \quad (34)$$

where η_i - the internal quantum efficiency corresponding to the ratio of emitted photons to injected electrons:

$$\eta_i = B_{sp} \tau_n (p_0 + n_0 + \Delta n) \quad (35)$$

If we substitute formula (35) into (34) and using equations (29) and (30),

$$P_{act} = h\nu \frac{J}{qd} B_{sp} \tau_n \left(p_0 + n_0 + \tau_n \frac{J}{qd} \right) \quad (36)$$

where τ_n - the injected carrier lifetime.

Under low-injection conditions, p_0 and $n_0 \gg \tau_n \frac{J}{qd}$, and the formula (36) can be rewritten for the p -type active layers ($p_0 > n_0$) as

$$P_{act-p} = h\nu B_{sp} p_0 \tau_e \frac{J}{qd} \quad (37)$$

and for the n -type layers as

$$P_{act-n} = h\nu B_{sp} n_0 \tau_h \frac{J}{qd} \quad (38)$$

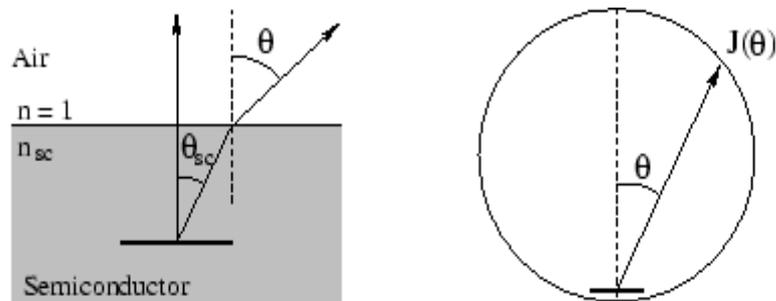
Under high-injection conditions, for $\tau_n \frac{J}{qd} \gg p_0$ and n_0 , we get:

$$P_{act} = h\nu B_{sp} \left(\tau_n \frac{J}{qd} \right)^2 \quad (39)$$

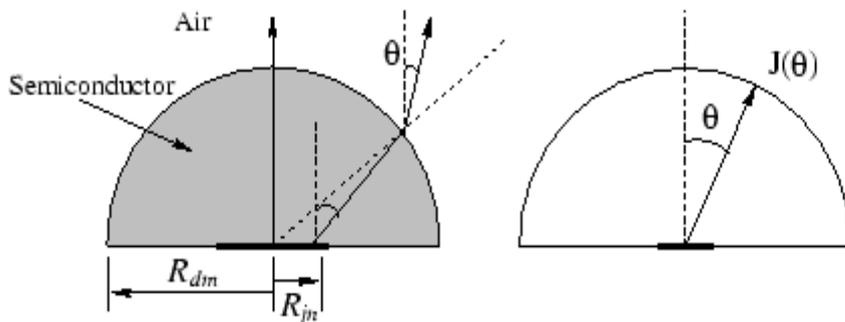
In the last three formulas the variables only τ_n and J . The light output power of the active layer then is proportional to the injected current density in the low-excitation range and to the square of the injected current density in the high-excitation range.

4.2.2 RADIATION INTENSITY PATTERN: SURFACE-EMITTING LED

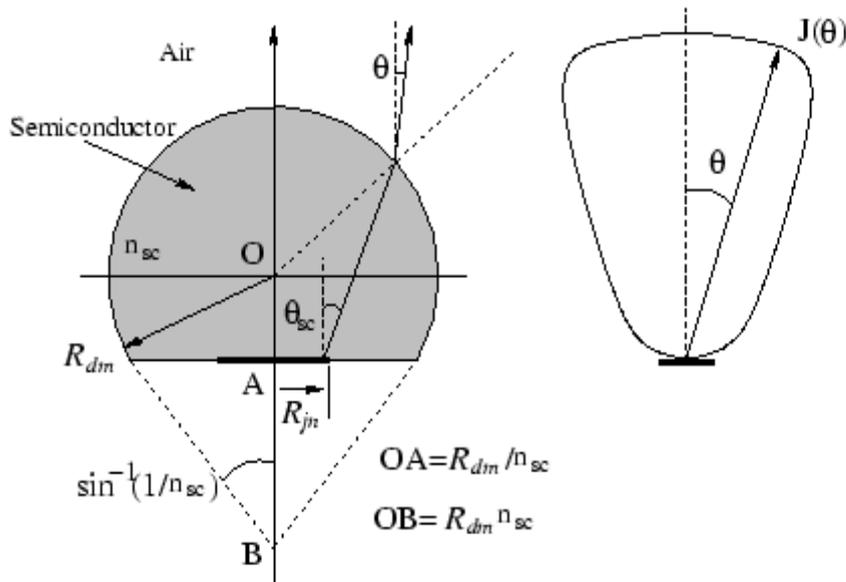
The radiant intensity pattern $J(q, f)$ of an LED depends not only on the characteristics of the semiconductor junction, but also on the diode geometry and the dome. (Figure 30.)



(a) Planar LED and its radiant intensity pattern



(b) LED with hemispherical dome and its radiant intensity pattern



(c) LED with Weierstrass spherical dome and its radiant intensity pattern

Figure 30.: Surface-emitting LEDs with and without high index domes. [1]

The radiation from a planar, undomed surface-emitting LED approximately follows Lambert's cosine law, which states that the radiant intensity pattern of any incoherent emitter is given by a cosine function if every point on the emitting surface radiates uniformly in all directions.

Many LEDs have a high-index dome. The function of a dome is to reduce the loss due to total internal reflection and to modify the radiant intensity pattern.

4.2.3 RADIATION INTENSITY PATTERN: EDGE-EMITTING LED

The radiant intensity pattern of an edge-emitting LED is quite different from that of a surface-emitting LED. An edge-emitting LED has an elliptical radiant intensity pattern. (Figure 31.).

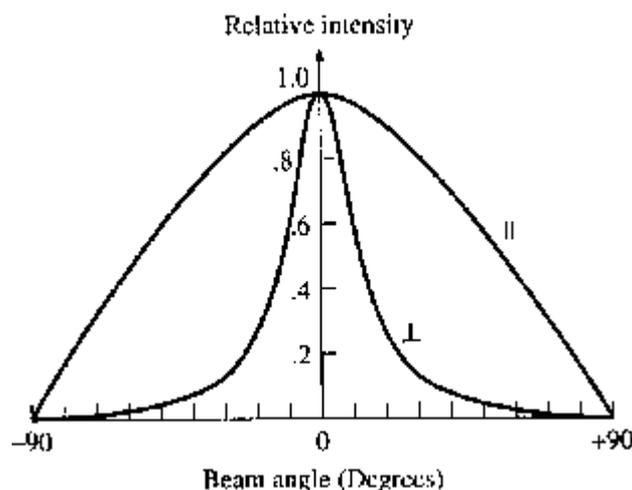


Figure 31.: Radiant intensity patterns of an edge-emitting LED in the planes normal and perpendicular to the junction. [1]

The radiation in the plane perpendicular to the junction is strongly influenced by the index difference between the active layer and the cladding layers and is concentrated more in the forward direction.

4.2.4 CURRENT-LIGHT OUTPUT CHARACTERISTICS

The total light output power from an LED is never equal to the light power emitted from the active layer for the reason of the emission of the light (due to spontaneous emission) in a random direction. Therefore, the light from a defined surface is only a part of the total emitted power. Meaning that we get a very low slope efficiency (~ 0.02 W/A in Figure 28.), which is the ratio of the output power from a defined surface to the injected current.

The light output power is expressed with several kinds of terms related to the efficiency. The conversion efficiency (also called device efficiency or power efficiency), η_{cv} , is defined as the ratio of the optical output power from LEDs, P_{out} , to the electrical input power, P_{e-in} ,

$$\eta_{cv} \equiv \frac{P_{out}}{P_{e-in}} \times 100 \quad (40)$$

Ordinarily, η_{cv} is less than 5%.

Another efficiency that is also often used in evaluating light-emitting devices is the external quantum efficiency, η_{ext} :

$$\eta_{ext} = \frac{P_{out}/h\nu}{I_F/q} = \left(\frac{P_{out}}{I_F E_g} \right) \times 100 \quad (41)$$

where

I_F - the injected current,

$E_g (=h\nu/q)$ - the band-gap energy of the active layer, *electron-volts*.

Relation between the conversion efficiency, η_{cv} , and the external quantum efficiency, η_{ext} , is expressed by:

$$\eta_{cv} = \eta_{ext} \left(\frac{E_g}{V_j} \right) \quad (42)$$

Where $P_{e-in} = I_F V_j$ and $V_j = V_b - R I_F$ is the bias voltage on the *pn*-junction (V_b - the applied bias voltage, and R - the total series resistance of bias circuit).

The external quantum efficiency, η_{ext} , may be given by the product of the internal quantum efficiency, η_i , and the extraction efficiency, η_{out} :

$$\eta_{ext} = \eta_i \eta_{out} \quad (43)$$

where the extraction efficiency is the ratio of the power emitted from the active layer to the power emitted from the LED, P_{out} .

$$P_{out} = \eta_{out} (S_{act} d_{act}) P_{act} \quad (44)$$

where

S_{act} - the area of the light-emitting region,

d_{act} - the thickness of the active layer.

The slope efficiency, η_s , shown on the Figure [28](#), is given by:

$$\eta_s = \frac{dP_{out}}{dI_F} = \eta_{out} \frac{dP_{act}}{dI_F} = \eta_{out} \eta_i h\nu (S_{act} d_{act}) \frac{d(J/qd_{act})}{dI_F} = \eta_{ext} \frac{h\nu}{q} = 1.24 \frac{\eta_{ext}}{\lambda(\mu m)} (W/A) \quad (45)$$

where we used formulas (43) and (44).

For example, in the case of the 1550 nm LED, whose characteristics are shown in Figure [28](#), the slope efficiency is 0.02 W/A.

4.2.5 CURRENT-VOLTAGE CHARACTERISTICS

The current-voltage characteristics of LEDs are basically given by formula (46). In the operating bias range of LEDs, the diffusion current is dominant and the radiative current is given by

$$I_F = S_{act} J_{s0} \exp\left(\frac{V_b - R_s I_F}{k_B T}\right) \quad (46)$$

where R_s - the series resistance.

As shown in Figure [28](#), the current increases rapidly when the applied voltage exceeds the band-gap of the active layer. (0.8 V in the Fig. [28](#)).

5 SUPERLUMINESCENT DIODES

The structure of a SLD is very similar to that of an ILD of edge-emitting LED. All lasers have three basic components:

- an amplifying medium;
- an optical feedback mechanism;
- a means to receive power from external sources.

An SLD does not have an optical feedback or cavity, which is the main difference between SLD and ILD.

The front surface on an SLD is coated with an antireflection material, which may consist of several dielectric layers. In some SLDs, the back surface is also coated. (Figure 32.).

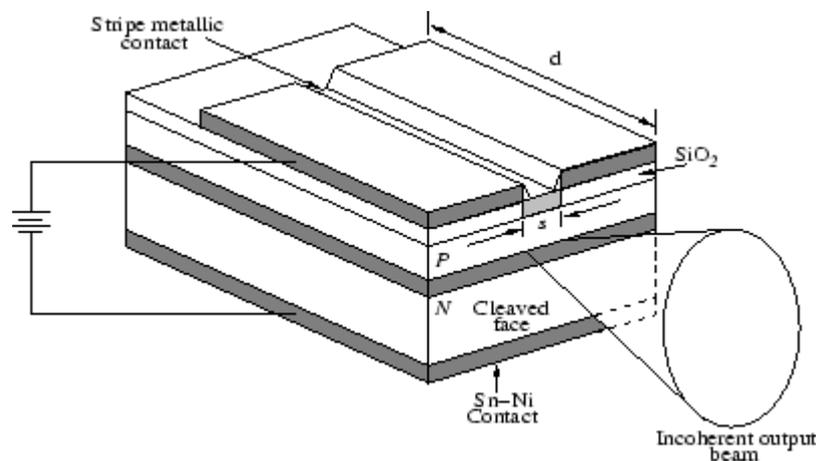


Figure 32.: Geometry of a superluminescent diode. [1]

Because of the antireflection coating on the back facet and/or the lossy segment near the rear end of an SLD, optical feedback and stimulated emission are greatly suppressed.

The radiation emitted by an SLD is amplified spontaneous emission.

Since the optical amplification occurs only in a single pass in the forward direction, the realizable gain is limited. In general, the current density required for SLD operation is much higher than that required for LEDs or ILDs. (Figure 33.).

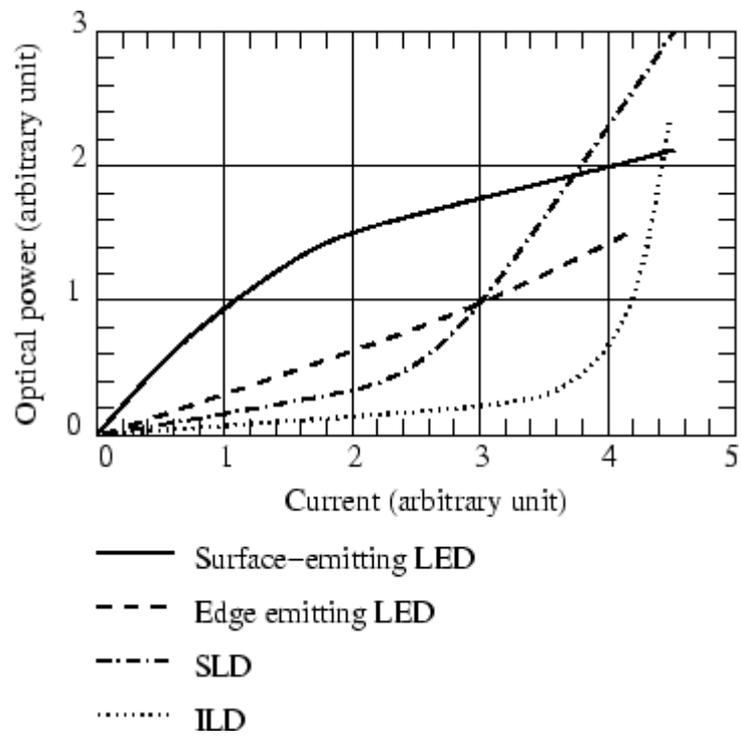


Figure 33.: Comparison of the PI characteristics of surface-emitting and edge-emitting LEDs, ILDs, and SLDs. [\[1\]](#)

6 COMPARISON OF ILD, LED AND SLD

On Figure [33](#), we see the optical power versus current characteristics of a typical surface-emitting LED, an edge-emitting LED, an SLD and an ILD.

Optical power of an LED increases linearly with the input current until saturation sets in. The saturation is due to the junction heating.

In contrast, the PI characteristic of an ILD has a sharp knee that corresponds to a threshold for stimulated emission.

Another way to differentiate between various semiconductor sources is to compare the spectral widths of their outputs.

For surface-emitting and edge-emitting LEDs with center wavelengths near 0.85 μm , the spectral width (FWHP) $\Delta\lambda$ is about 40 nm and 15 nm, respectively.

However, the spectral width of SLDs is only 25 % of that of surface-emitting LEDs.

For ILDs, the spectral width is on the order of few nanometers or less.

An idealized light emitting diode (LED) emits incoherent spontaneous emission over a wide spectral range into a large solid angle. The unamplified light emerges in one pass from a depth limited by the material absorption. The output is unpolarized and increases linearly with input current. The modulation bandwidth is limited by the spontaneous lifetime.

An idealized laser diode (LD) emits coherent stimulated emission (and negligible spontaneous emission) over a narrow spectral range and solid angle. The light emerges after many passes over an extended length with intermediate partial mirror reflections. The output is usually polarized and increases abruptly at a threshold current that provides just enough stimulated gain to overcome losses along the round-trip path at the mirrors.

In an idealized superluminescent diode (SLD), the spontaneous emission experiences stimulated gain over an extended path and, possibly, one mirror reflection, but no feedback is provided. The output is incoherent but the stimulated emission narrows the spectral width and solid angle and increases the modulation bandwidth. Thus, the SLD has optical properties, bounded by LED and LD, that can be adjusted by changing the driving current. The output, which may be polarized, increases superlinearly with current with a knee that occurs near the current providing a significant net positive gain.

An actual SLD will have some feedback because it is not possible to make a perfect antireflection (AR) coating. An actual LED will have some stimulated gain (particularly an edge-emitter) if its length is greater than approximately 1 mm, the typical absorption length. An actual LD has relatively weak feedback from the cleaved mirrors and depends on the amplification of spontaneous emission continuously coupled into the laser mode. Thus, in practice these three devices form a continuum with no sharp boundaries.

For multimode fiber applications, the high output power and coupling efficiency of the LD are attractive but its high coherence can be a source of modal, partition, and feedback noise. On the other hand, the LED has too low output power, too low coupling efficiency, and too low modulation bandwidth for many applications. And in some cases its very wide spectral width may cause material dispersion to limit repeater spacing. By contrast, an SLD can be designed to give a combination of properties tailored to a given system. [\[3\]](#)

From a practical point of view:

1. Since LEDs are relatively simple and the operating current density is relatively low, LEDs can tolerate variations in the fabrication processes. They can operate over a wide range of temperatures, and they require only a simple circuit to maintain a stable output. In contrast, ILDs must be fabricated precisely. Also, the PI characteristic of an ILD changes abruptly beyond the threshold level, and its spectral and spatial characteristics are critically dependent on the operating current and temperature. This means that provisions must be made to maintain a stable operating environment for ILDs.
2. Emission from LEDs are broadband, unpolarized, incoherent light. The optical output can be amplitude modulated to a few hundred megahertz. In contrast, the output from ILDs is narrow band, polarized, and mainly coherent light. Direct-amplitude modulation of ILDs at 20 GHz has been achieved.
3. Radiation from surface-emitting LEDs is not very well confined spatially, and only a small fraction of the output can be coupled into a multimode fiber. Radiation from edge-emitting LEDs is better confined spatially and spectrally. By comparison, the directional characteristics of conventional ILDs are much better, and coupling from ILDs to fibers can be done more efficiently. [\[1\]](#)

7 PHOTODIODES [4]

Photodiodes are typical optoelectronic *pn*-junction devices used under a reverse bias. their operating mechanisms are based on the electrical and optical properties of the *pn*-junction and semiconductor material. Their functions are, however, quite different from those of LEDs and laser diodes, and in the photodiodes the optical absorption processes are used.

The light absorption is the opposite of the stimulated and spontaneous emission process, and the operating wavelength therefore essentially depends on the band-gap energy of the material.

The materials mostly used in photodiodes are elementary semiconductors such as Si and Ge, and III-V and II-VI compound semiconductors such as GaAs, InP and CdTe.

Photodiodes composed of Si are mainly used in consumer electronics, while those composed of Ge and InGaAs(P)/InP are used in optical fiber communication systems.

In the longer-wavelength range, InAs and InSb are also used as photodiode materials.

7.1 BASICS OF PHOTODIODES

When a semiconductor is illuminated by light having an energy greater than its band-gap energy, the light is absorbed in the semiconductor and electron-hole pairs are generated. (Figure 34.).

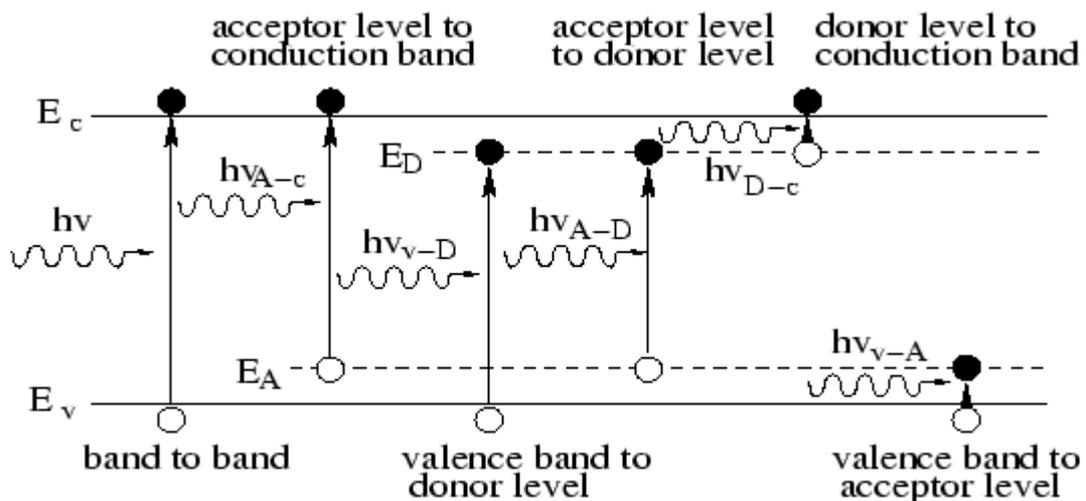


Figure 34.: Simplified illustration of the optical absorption process in direct band-gap semiconductors.

[4]

Those photoinduced electrons and holes recombine radiatively (photoluminescence) and non radiatively. If an electrical field is applied to the semiconductor, some of the induced carriers take part in electric conduction and this leads to a decrease in electrical resistance of the semiconductor. This is called photoconduction.

If there is a *pn*-junction in the illuminated area, the electrons and the holes are separated by the electrical field at the *pn*-junction without any electric bias, and an electromotive force between the *p*- and *n*-side semiconductors is generated. This is called the *photovoltaic effect*, and with regard to the effect there is basically no difference between a *pn*-junction and a *pn*-heterojunction.

Based on the phenomena described above, light power can be converted into electrical power in photodiodes.

A bias circuit for photodiodes and current-voltage characteristics under light illumination are shown schematically in Figure 35.

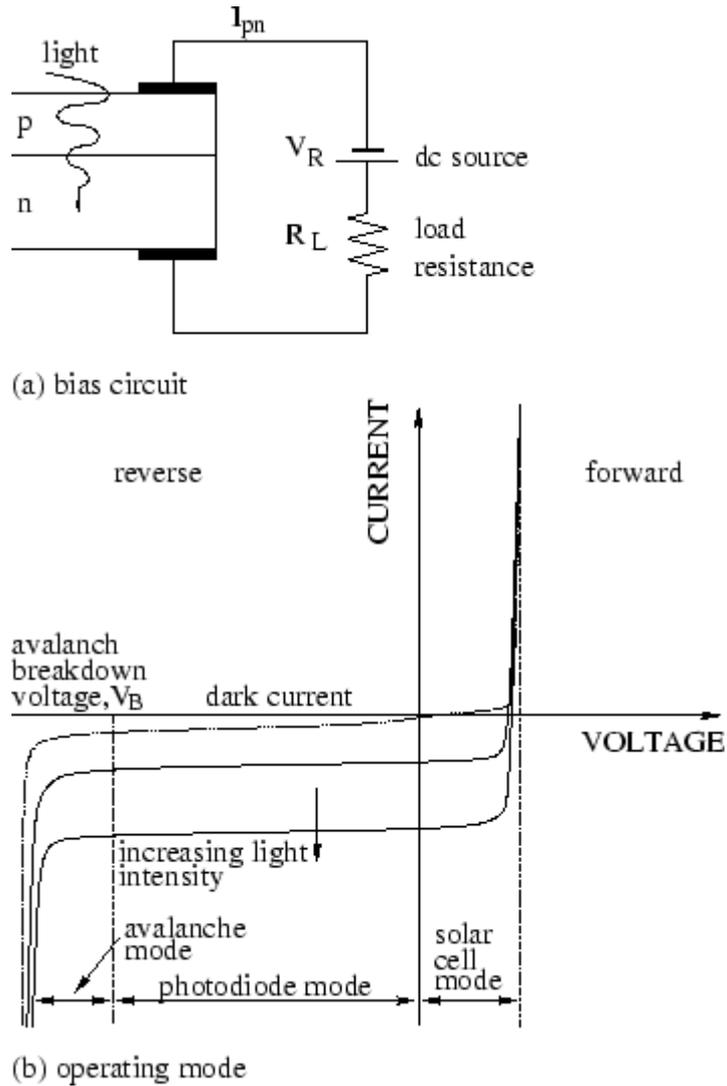


Figure 35.: Photodiode (a) bias circuit and (b) operation modes.

When light is absorbed, the current-voltage characteristics change as shown in Figure 35.(b), and the reverse current increases because of the generation of photo current. depending on the reverse voltage biased to the *pn*-junction, the operation behaviors of photodiode can be divided into solar cell, photodiode, and avalanche photodiode modes.

7.1.1 *pn*-JUNCTION UNDER REVERSE BIAS AND REVERSE CURRENT

The diffusion current appears ideally under forward and reverse bias, and the diffusion current under reverse bias is called the saturation current. There are several kinds of current going through the *pn*-junction in the forward and reverse directions. The main components of the additional currents are: surface leakage current, I_{ds} , generation-recombination current, I_{dg-r} , and tunneling current, I_{dt} . The reverse current is not constant at the saturation current but gradually increases because of those additional currents. The total, called dark current, is given approximately by formula (47)

$$I_d = I_{dd} + I_{ds} + I_{dg-r} + I_{dt} \tag{47}$$

where I_{dd} is the diffusion current in the reverse direction and ideally corresponds to the saturation current.

Important of these currents that they result in the dark current and noise, which strongly influence device reliability.

It is important to remember that the dark current increases with increase of the temperature. The quantum-mechanical tunneling is itself independent of the temperature, but increases as a result of the temperature dependence of the band-gap energy. The tunneling current is given by formula (48):

$$I_{dt} = A_{pn} \left[2^{1/2} q^3 F_{max} |V_b| / \pi h^2 \right] (m_e / E_g)^{1/2} \times \exp \left(-\pi^2 m_e^{1/2} E_g^{2/3} / 2^{1/2} h q F_{max} \right) \quad (48)$$

where

F_{max} is the maximum electric field in the pn -junction,

m_e is the effective electron mass, and

h is Plank's constant.

In the photodiode mode the generation-recombination current and diffusion current are dominant and mainly determine the temperature dependence of the dark current.

It is important to remember that the dark current has an influence on the noise behavior of the photodiode, increasing it at the higher temperature.

7.1.2 OPTICAL ABSORPTION AND QUANTUM EFFICIENCY

The photo-induced carriers are created under light incidence by the intrinsic and extrinsic process (electrons are excited from a deep level to the conduction band and then contribute to photocurrent). The light having an energy lower than the band-gap energy can be converted into electrical power. (Example: photoconductors composed of CdS, PbS, An-doped Ge, Ga, Sb, etc., in the wavelength range over 5 μm but quite low responsivity and operating speed). The photoconductor detects light by monitoring the change in resistivity of the semiconductor.

The commonly used photodetector is an intrinsic type and detects light at wavelengths close to and shorter than that corresponding to the band-gap energy of the semiconductor.

the quantum efficiency, η_{ph} , of a photodiode is defined by:

$$\eta_{ph} = \frac{\text{number of electron-hole pairs contributing to photo-induced current}}{\text{number of incident photons}}$$

$$\eta_{ph} = \left[\frac{I_{photo} / q}{P_{inc} / h\nu} \right] \times 100 \quad (49)$$

where

I_{photo} - the photoinduced current,

P_{inc} - the incident optical power.

Quite often instead of the quantum efficiency, used the responsivity, $S(A/W)$

$$S = \frac{I_{photo}}{P_{inc}} = \frac{q\eta_{ph}}{h\nu} = \frac{\eta_{ph}\lambda(\mu m)}{1.24} \quad (50)$$

The quantum efficiency is influenced by the reflection of incident light at the surface of the photodiode, the recombination of photo-induced carriers at the surface and in the depletion layer, and the optical absorption outside of the depletion layer. Important to know that about 30% of the incident light is reflected at the surface because the refractive index of the semiconductor material is about 3.5. For this reason an antireflective dielectric film is deposited onto the surface to suppress the reflection, which can be reduced to less than 1%.

8 DEVICE FABRICATION

For the devices discussed in the previous sections various kinds of technologies required. These optoelectronic devices are made of semiconductor materials, packaged, installed, and then used in equipment and systems.

Each technology influences the performance of the device. The device characteristics depend on the quality of semiconductor crystal, the surface and interface state density, parasitic capacitance of package, etc.

8.1 CRYSTAL GROWTH

Crystal growth is the first step in device fabrication. There are different techniques that are used depending on the costs and needs for the quality of the crystal.

8.1.1 LIQUID-PHASE EPITAXY

Used in making various semiconductor devices, and the crystal growth occurs near thermal equilibrium. When a supersaturated solution of semiconductor material comes into contact with a single-crystalline substrate, a lattice-matched epitaxial layer grows on the substrate. For forming multilayer structures such as DHs, graphite sliders often used. The substrate set on the slide in a quartz reactor and lid under the solutions corresponding to each layer (see Figure 36.).

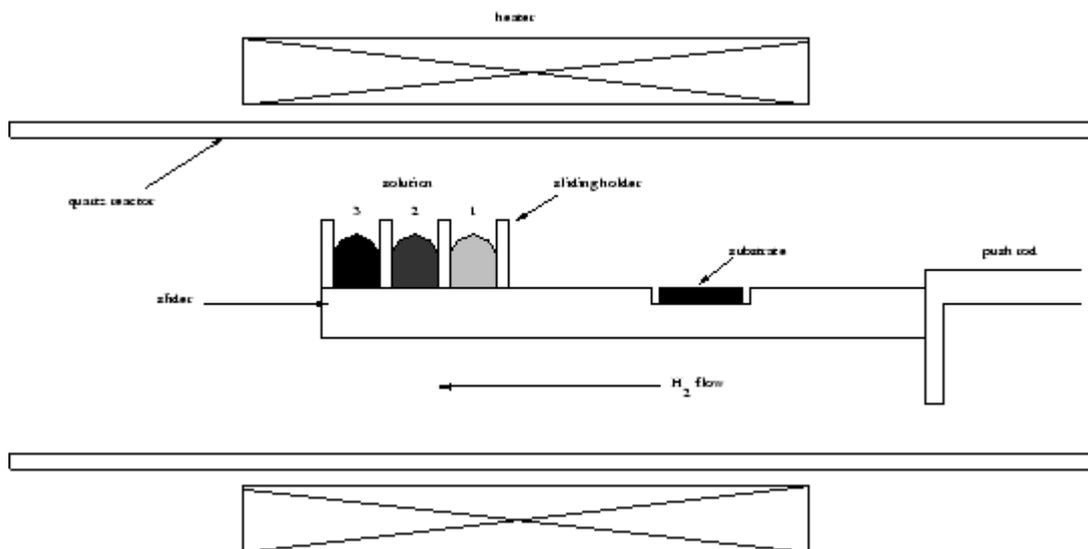


Figure 36.: Basic setup for LPE. [4]

A flow of H_2 prevents oxidation of the solutions and the substrate, and the growth is terminated by sliding the substrate out from under the solution. Extremely important the control of the temperature for the growth rate, crystal quality. (Example: for the length of about 30 cm, the temperature in the reactor must be controlled with a precision of about $\pm 0.1^\circ C$.)

The thickness of a grown layer is determined by the temperature and the length of time in which the substrate and solution are in contact.

8.1.1.1 Advantages.

- The LPE technique allows to produce high quality (low-defect density and homogeneous composition) crystals and interfaces between the epitaxial layers, mainly because the crystal growth is going under conditions close to thermal equilibrium.
- The LPE process is particularly suitable for regrowth on a chemically or physically damaged surface, such as one that has been etched. The damaged layer on a slightly damaged surface is wiped off by the solution and then high quality crystal grows on the cleaned surface.
- The high growth rate makes the LPE process suitable for growing thick epitaxial layers quickly.

8.1.2 METAL-ORGANIC VAPOR-PHASE EPITAXY

Metal-Organic Vapor-Phase Epitaxy (MOVPE) occurs far from the thermal equilibrium state. There are two possibilities of the MOVPE: atmospheric-pressure and low-pressure. In Figure 37, we can see a basic setup for low-pressure MOVPE.

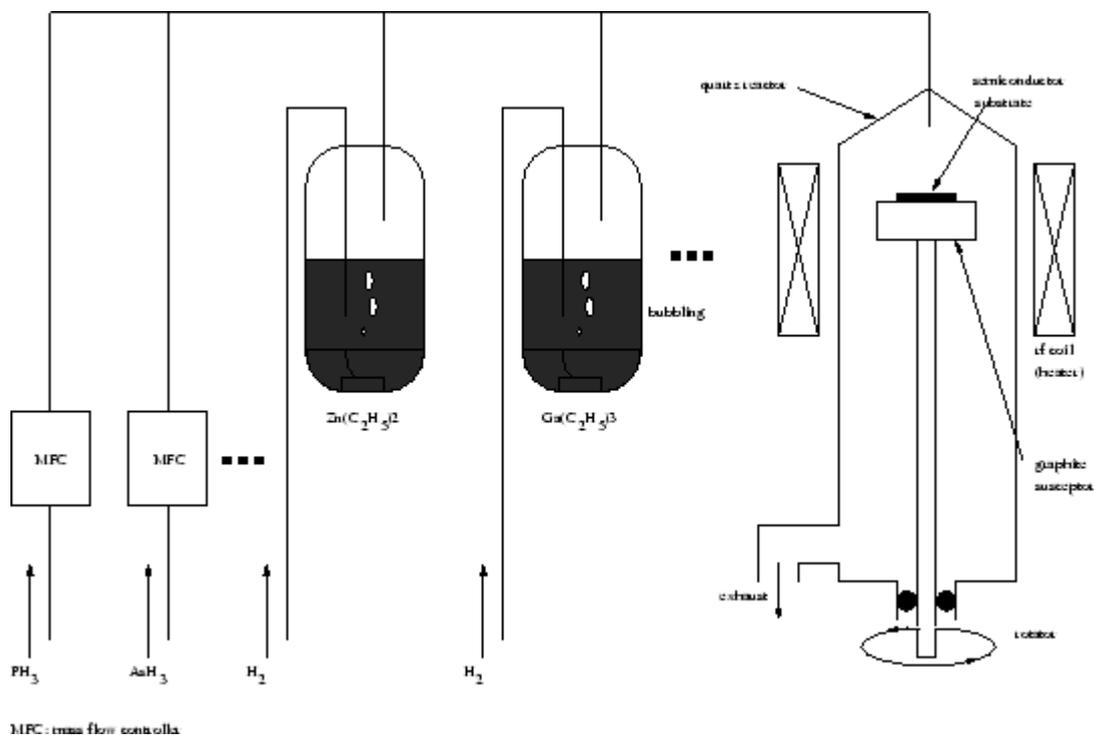


Figure 37.: Basic setup for low-pressure MOVPE. [4]

8.1.2.1 Advantages

- Large-scale epitaxial growth (on 2-inch or 3-inch wafer) of an epitaxial layer of uniform composition can be easily accomplished.
- MOVPE is suitable for the growth of thin epitaxial layers, such as those of quantum well structures and also suitable for the mass production.
- The interfaces between the epitaxial layers are excellent if the layers are grown sequentially.

8.1.2.2 Disadvantage

- Regrowth on a chemically or physically damaged surface often results in a defective interface. The epitaxial layer grows on such defective surfaces because MOVPE occurs far from the thermal equilibrium and this often causes problems, reducing the reliability of the buried heterostructure type of laser diodes.

8.1.3 MOLECULAR BEAM EPITAXY

Molecular Beam Epitaxy (MBE) also occurs far from the thermal equilibrium state. Figure 38. shows a basic idea for the MBE. Atoms or molecules in the effusion cells are evaporated by heating and shot up to the substrate, where they are directly deposited on the heated substrate in a high vacuum.

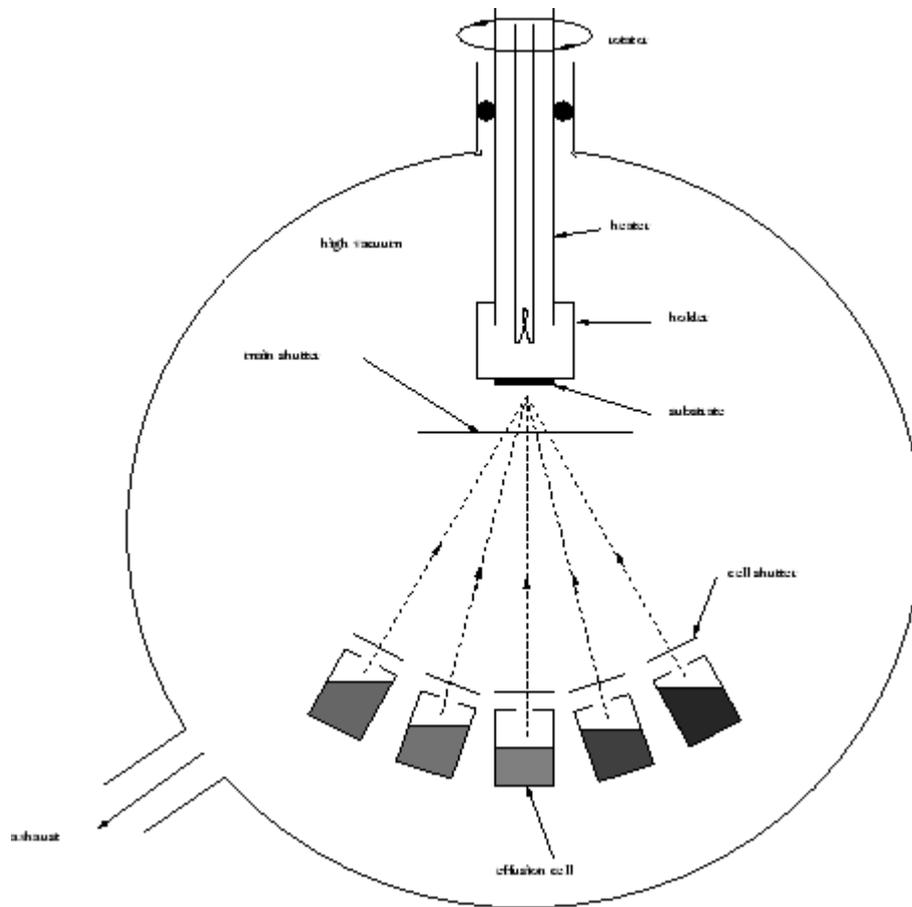


Figure 38.: Basic setup for MBE. [4]

The high vacuum is needed to lengthen the mean free path of the atoms or molecules and the base pressure is controlled at about 10^{-7} Pa. The epitaxial layers grow on the substrate, and the doping and the composition of the layers are changed by controlling deposited atoms or molecules - opening or closing shutters near the effusion cells.

8.1.3.1 Advantages

- MBE can produce sharp interfaces and thin layers with a precision of atomic monolayer.
- Since MBE is carried out under high vacuum conditions, observations can be done by using Auger electron spectroscopy, electron probe microanalysis, reflection high energy electron diffraction, etc.

When compared with LPE, rest of advantages and disadvantages of MBE are similar to those of MOVPE.

8.2 DEVICE FABRICATION PROCESSES

After creation of the active region for the device by the epitaxial growth, we start the fabrication process. The damage introduced during the process often determines device performance and reliability.

8.2.1 ELECTRODE FORMATION

Optoelectronic devices need the ohmic contact as *p*-side and *n*-side electrodes. The electrical and thermal resistance of those contacts must be low as to maintain the little electrical input power and have a high frequency response, and there is little Joule's heating (suppression of the heating in the active region).

Difference between the work functions of the metal and semiconductor determines the potential barrier between the metal and the semiconductor.

$$\phi_B = \phi_m - \phi_s \tag{51}$$

If $\phi_s > \phi_m$, there is no potential barrier at the heterojunction for *n*-type semiconductors, and we can form an ideal ohmic contact.

If $\phi_m > \phi_s$, we get the condition for an ideal ohmic contact for the *p*-type semiconductor.

Unfortunately, most of semiconductors for optoelectronic devices do not satisfy the above conditions because of the surface states. For this reason we have to use some treatment in order to reduce the size of the potential barrier between the metal and the semiconductor. That is where we introduce the alloy type and the nonalloy type (or Schottky type) ohmic contacts.

Table 6.: Some typical metals used for optoelectronic devices. [\[4\]](#)

Group A		Group B
.....Ti Cr Ni	Cu
..... Mo	Ag
.....(W) Pt	Au
Early transition metals	Near-noble metals (electronegative)	Noble metals (very electronegative)
Schottky type (inert interface)		Alloy type

Table [6](#). shows some typical metals used for the ohmic contacts.

Metals from the Group A for an inert interface between the metal and the semiconductor and thus form Schottky-type electrodes. If the metal is selected from this group and the semiconductor is heavily doped ($\geq 10^{19} \text{ cm}^{-3}$), an inert interface with a thin depletion layer is formed between the deposited metal and the semiconductor. This type of contact shows ohmic characteristics and is called the Schottky-type ohmic contact.

Typical Schottky-type electrodes are Ti/Pt/Au and Cr/Au, in which Pt is the barrier metal that prevents the diffusion of Au toward the semiconductor under operation and during bonding of the device chip. The thicker Au layer is required for easy bonding of wire.

Metals from Group B easily interact with semiconductors having band-gap energies less than 2.5 eV at room temperature and thus form alloy-type electrodes. When we choose the metal from this group, and alloying is carried out under a relatively high temperature (around 400°C), the width of the depletion layer decreases enough to be comparable to the extent of the diffuse conductor-semiconductor interface and the

barrier decreases. Then, when bias is applied, current can easily flow over the reduced barrier by the thermionic emission.

Typical alloy-type electrodes for *p*-type and *n*-type semiconductors are AuZnNi and AuGeNi, respectively.

8.2.2 DIELECTRIC FILM DEPOSITION

The dielectric films are widely used as masks for impurity diffusion and for chemical and physical etching during the process of fabrication, as an electrical insulator between an electrode and a semiconductor, as passivation films for device surfaces, and as film for controlling reflectivity.

Popular materials for dielectric films used for optoelectronic devices are SiO₂ and SiN_x. Al₂O₃ is also used as passivation film as well as antireflective and highly reflective films.

There are several kinds of methods used to deposit dielectric films:

- **radio-frequency sputtering:**

- (i) a cation such as Ar⁺ is formed by glow discharge excited with radio-frequency waves in a vacuum chamber;
- (ii) the ions collide with the target composed of the dielectric material and the target material is sputtered;
- (iii) the sputtered material is deposited on the semiconductor.

The use of radio-frequency waves is required in order to prevent the dielectric target from being positively charged.

- **chemical vapor deposition (CVD):**

dielectric film deposition with CVD is carried out by the chemical reaction of material gases in a vacuum chamber. The chemical reaction is enhanced by excitations such as heating, light incidence, and electrical discharges. The material gases for SiN_x films, for example, are SiH₄ and N₂.

- **plasma CVD.**

Mechanical stress due to the deposited dielectric film has to be taken into consideration. If the stress is severe, slip dislocation or cracks are induced and degrade device performance.

The reflectivity of the optical input and output ports is easily controlled by coating them with dielectric films. By adjusting the thickness of the dielectric film, we can control the reflectivity.

The minimum reflectivity gives the condition for the antireflective film coating. The minimum reflectivity would be strictly zero at

$$n_{rf} = (n_{r1}n_{r2})^{1/2} \quad (52)$$

The dielectric material having a refractive index close to that given by formula (52) is therefore chosen for an antireflective film. For example, an Al₂O₃ film with thickness of $m\lambda_0/4n_{rf}$ and refractive index of about 1.7 (n_{rf}) is a very popular antireflective coating for AlGaAs and InGaAsP surfaces exposed to air ($n_{r2}=1$) because each of these materials has a refractive index of about 3.5 (n_{r1}).

The highly reflective films are formed by multilayers of two kinds of dielectric materials, (see Figure 39.), in which the thickness of each layer is usually set at the quarter-wavelength, $\lambda_0/4n_{rf}$, to increase the tolerance for thickness fluctuation.

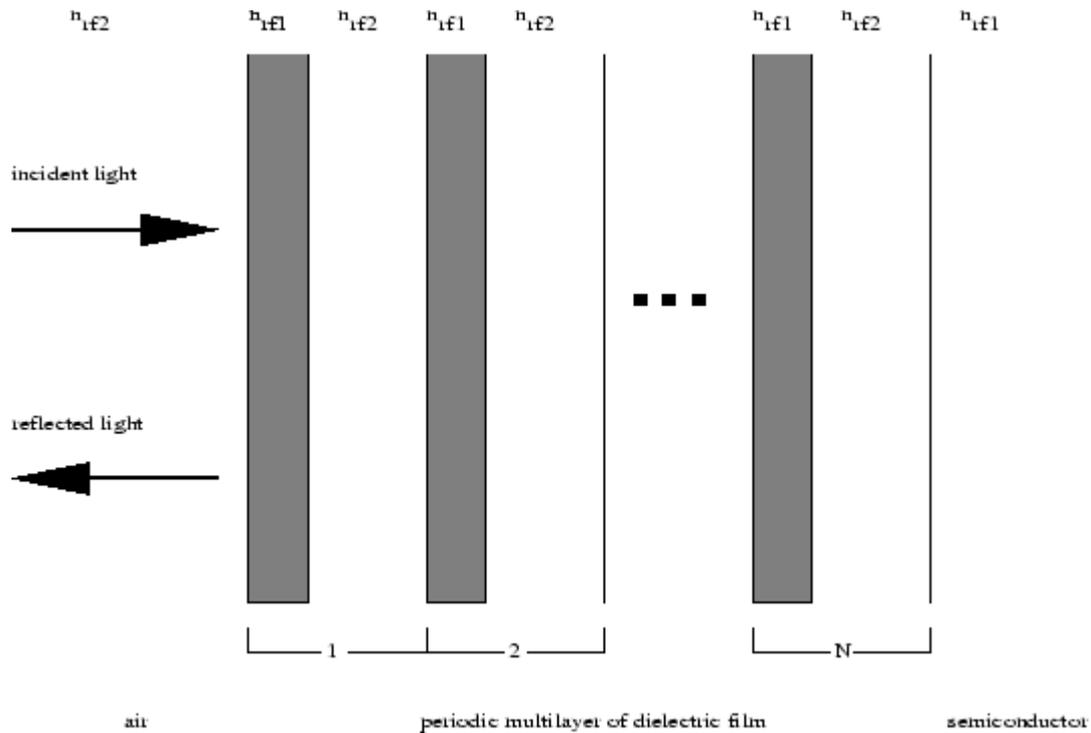


Figure 39.: A periodic multilayer (highly reflective film). [4]

Typical pairs for highly reflective films used in optoelectronic devices Si/SiO₂ (3.4/1.4) and TiO₂/SiO₂ (2.5/1.4). One of two pairs is usually coated onto the semiconductor surface such as facets of laser diodes, and the material with the lower refractivity is deposited first. For example, in air ($n_{r2}=1$) one pair of amorphous Si/SiO₂ layers and one pair of TiO₂/SiO₂ layers deposited on AlGaAs and InGa AsP ($n_{rf}\approx 3.5$) give reflection of a 83% and 70%, respectively.

8.2.3 LITHOGRAPHY AND CHEMICAL AND PHYSICAL ETCHING

The photolithography is carried out as follows:

- formation of a photoresist (PR) film on the dielectric or metal film deposited on the semiconductor;
- exposure of the PR through a patterned mask by photoexposure or by electron-beam exposure without any mask (direct writing);
- developing of the PR;
- rinsing of the PR.

The dielectric (or metal) film is then chemically or physically etched through the patterned PR.

There are two types of etching: wet and dry.

The etching rate and shape of the etched pattern depends on combination of semiconductor materials and etchants. The etched shapes and patterns for the wet etching are determined by the combination and depend on the crystal orientation of the semiconductor. There is little process damage and the defect density in the processed devices is low.

Physical etching can be used to form relatively fine patterns. Typical kind of physical etching is dry etching, in which semiconductor materials are sputtered by collisions of particles. But a damaged layer is formed and the etched surface contains a large number of defects. (See Figure 40.). This damage affects the device performance and reduces reliability. After dry etching, the etched surface is therefore lightly etched chemically to eliminate the damaged layer.

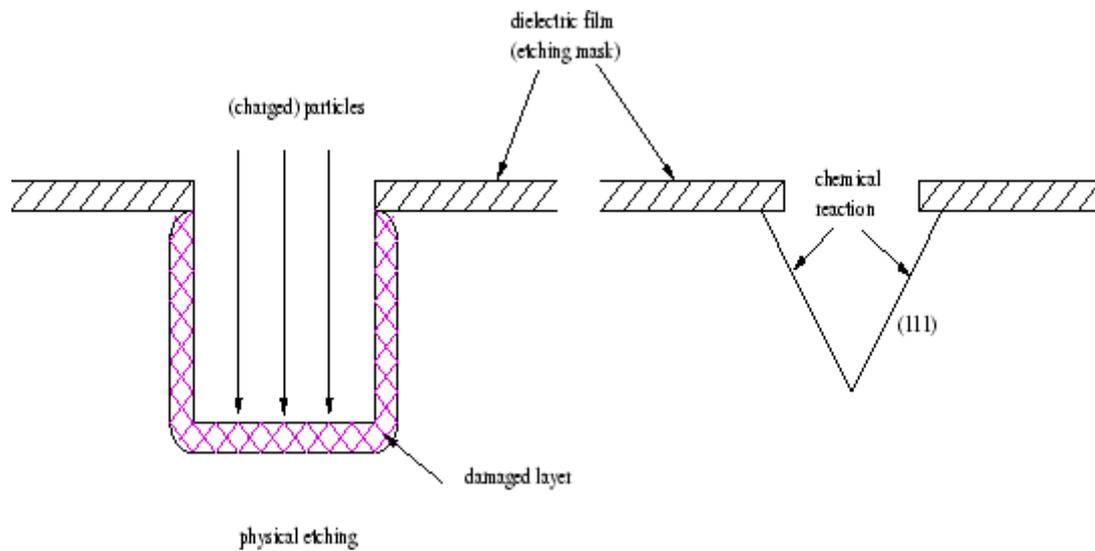


Figure 40.: Schematic illustration of chemical and physical etching. [4]

8.3 PACKAGING

Packaging is indispensable when optoelectronic devices are applied to equipment and systems. After packaging, optical input and output as well as electrical input and output can be performed via the optical ports and the electrical terminals. During packaging, bonding of the device chip on a heat sink or stem, for example, determines thermal conductance (or resistance), and the optical coupling between the device chip and the waveguide/fiber mainly determines the performance and reliability.

The long-term stability of the plastic packages is determined by the properties of plastic materials. Various plastics for packaging optical devices have been developed and some have been used in the modules for data links.

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Optoelectronic Semiconductor Devices - Principals and Characteristics.

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2002-02-17