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Laser Diode and Applications

Ahmed H.Almutairi

Abstract: ***This paper shows how to use the P-N Junction to generate the Laser (Laser Diode) and how we use this laser Diode in many applications.***

Index Terms: ***Introduction, P-N Junction, Biased p-n Junction, Laser diodes, Turning semiconductor amplifiers into laser diodes, Applications of Laser Diodes, Conclusion and References.***

I. INTRODUCTION

P-N Junction: It is a homo-junction between a p-type and an n-type semiconductor. It acts as a diode, which can serve in electronics as a rectifier, logic gate, voltage regulator (Zener diode), switching or tuner (varactor diode); and in optoelectronics as a light-emitting diode (LED), laser diode, photo detector, or solar cell. In a relatively simplified view of semiconductor materials, we can envision a semiconductor as having two types of charge carriers-holes and free electrons which travel in opposite directions when the semiconductor is subject to an external electric field, giving rise to a net flow of current in the direction of the electric field.

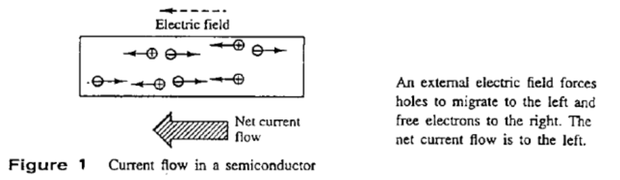

Figure 1 illustrates the concept.

A p-n junction consists of a p-type and n-type section of the same semiconductor materials in metallurgical contact. The p-type region has an abundance of holes (majority carriers) and a few mobile electrons (minority carriers); the n-type region has an abundance of mobile electrons and a few holes (Fig. 2). Both charge carriers are in continuous random thermal motion in all directions.

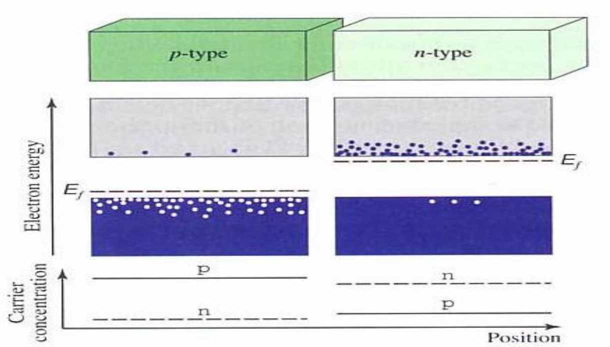

Fig. 2. Energy levels and carrier concentrations for a p-type and n-type semiconductor before contact.

When a section of p-type material and a section of n-type material are brought in contact to form a pn junction, a number of interesting properties arise. The pn junction forms the basis of the semiconductor diode. - Electrons and holes diffuse from areas of high concentration toward areas of low concentration. Thus, electrons diffuse from the n-region to the p-region., leaving behind positively charged ionized donor atoms. In the p-region the electrons recombine with the abundant holes. Similarly, holes diffuse from the p-region into the n-region, leaving behind negatively charged ionized acceptor atoms. In the n-region the holes recombine with the abundant mobile electrons. This diffusion process does not continue indefinitely, however, because it causes a disruption of the charge balance in the two regions. -So a narrow region on both sides of the junction becomes nearly depleted of the mobile charge carriers. This region is called the depletion layer. It contains only the fixed charges (positive ions on the n-side and negative ions on the p-side).

The thickness of the depletion layer in each region is inversely proportional to the concentration of dopants in the region. The net effect is that, the depletion region sees a separation of charge, giving rise to an electric field pointing from the n side to the p side. -The fixed charges create an electric field in the depletion layer that points from the n-side towards the p-side of the junction. The charge separation therefore causes a contact potential (also known as built-in potential) to exist at the junction. This built-in field obstructs the diffusion of further mobile carriers through the junction region. An equilibrium condition is established that results in a net contact potential difference VO between the two sides of the depletion layer, with the n-side exhibiting a higher potential than the p-side. This contact potential is typically on the order of a few tenths of a volt and depends on the material (about 0.5 to 0.7 V for silicon). The built-in potential provides a lower potential energy for an electron on the n-side relative to the p-side. As a result, the energy bands bend as shown in Fig. 3. In thermal equilibrium there is only a single Fermi function for the entire structure so that the Fermi levels in the p- and the n-regions must align. -No net current flows across the junction. The currents associated with the diffusion and built-in field (drift current) cancel for both the electrons and holes.

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Ahmed H.Almutairi, Higher Institute of Telecommunication & Navigation (HITN), Adailiyah, Kuwait.

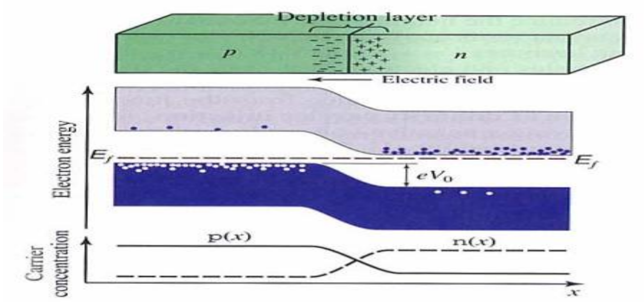

Fig. 3. A p-n junction in the Thermal equilibrium at T > 0º K. The depletion-layer, energy-band diagram, and concentrations.

- Biased p-n Junction: The externally applied potential will alter the potential difference between the p- and n-regions. This in turn will modify the flow of majority carriers, so that the junction can be used as a "gate". If the junction is forward biased by applying a positive voltage V to the p-region (Fig. 4), its potential is increased with respect to the n-region, so that an electric field is produced in a direction opposite to that of the built-in field. The presence of the external bias voltage causes a departure from equilibrium and a misalignment of the Fermi levels in the p- and n-regions, as well as in the depletion layer. The presence of the two Fermi levels in the depletion layer, Efc and Efv represents a state of quasi-equilibrium.

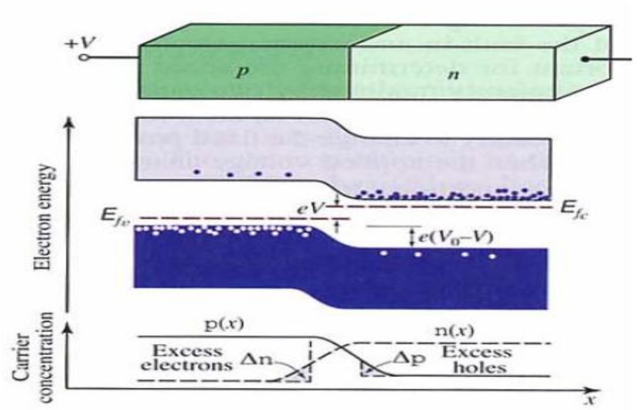

Fig. 4. Energy band diagram and carrier concentrations for a forward-biased p-n junction.

-In effect, then, if one were to connect the two terminals of the p-n junction to form a closed circuit, two currents would be present. First, a small current, called reverse saturation current, is, exists because of the presence of the contact potential and the associated electric field. In addition, it also happens that holes and free electrons with sufficient thermal energy can cross the junction. This current across the junction flows opposite to the reverse saturation current and is called diffusion current. Of course, if a hole from the p side enters, it is quite likely that it will quickly recombine with one of the n-type carriers on the n side. (Fig.4)

-The net effect of the forward bias is to reduce the height of the potential-energy hill by an amount eV. The majority carrier current turns out to increase by an exponential factor exp (eV/kT). So that the net current becomes i = is exp (eV/kT) – is, where is is nearly a constant. The excess majority carrier holes and electrons that enter the n and p regions, respectively, become minority carriers and recombine with the local majority carriers. Their concentration therefore decreases with the distance from the junction as shown in Fig. 4. This process is known as minority carrier injection.

-If the junction is reversed biased by applying a negative voltage V to the p-region, the height of the potential energy hill is augmented by eV. This impedes the flow of majority carriers. The corresponding current is multiplied by the exponential factor exp(eV/kT) where V is negative; i.e. it is reduced. The net result for the current is i = is exp(eV/kT) - is, so that a small current of magnitude ≈ is flows in the reverse direction when IVI » kT/c. A p-n junction therefore acts as a diode with a current-voltage (i-V) characteristic as illustrated.

$$i = i_s\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

II. IDEAL DIODE CHARACTERISTIC

The ideal diode characteristic equation is known as the Shockley equation, or simply the diode equation.

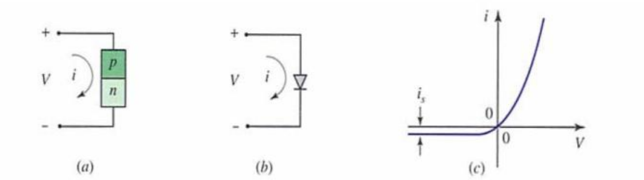

Figure 5 depicts the real diode i-V characteristic for a fairly typical silicon diode for positive diode voltages. Since the reverse saturation current, is is typically very small (10-9 to 10-15 A), the expression

$$i = i_s\left[\exp\left(\frac{eV}{kT}\right)\right]$$

is a good approximation if the diode voltage V is greater than a few tenths of a volt.

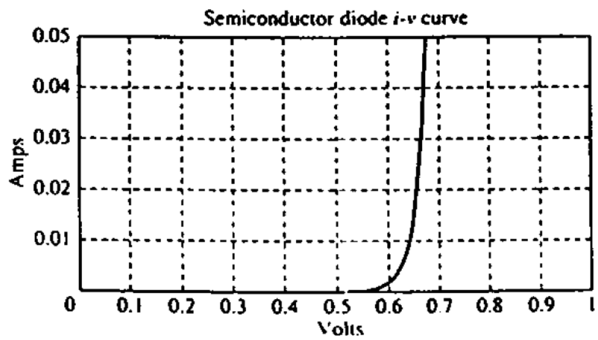

Fig. 5. i -V characteristic of a real p-n junction diode. Note that the conduction takes off for voltages larger than the contact potential.

Fig. 6 summarizes the behaviour of the semiconductor diode in terms of its i-V characteristic. Note that a third region appears in the diode i-V curve that has not been discussed yet. The reverse-breakdown region to the far left (typically > 50V) of the curve represents the behavior of the diode when a sufficiently high reverse bias is applied. Under such a large reverse bias, the diode conducts current again, this time in the reverse direction. To explain the mechanism of reverse conduction, one needs to visualize the phenomenon of avalanche

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breakdown. When a very large negative bias is applied to the p-n junction, sufficient energy is imparted to charge carriers that reverse current can flow, well beyond the normal reverse, saturation current. In addition, because of the large electric field, electrons are energized to such levels that if they collide with other charge carriers at a lower energy level, some of their energy is transferred to the carriers with low energy, and these can now contribute to the reverse conduction process, as well. This process is called impact ionization. Now, these new carriers may also have enough energy to energize other low energy electrons by impact ionization, so that once a sufficiently high reverse bias is provided, this process of conduction takes place very much like an avalanche: a single electron can ionize several others .

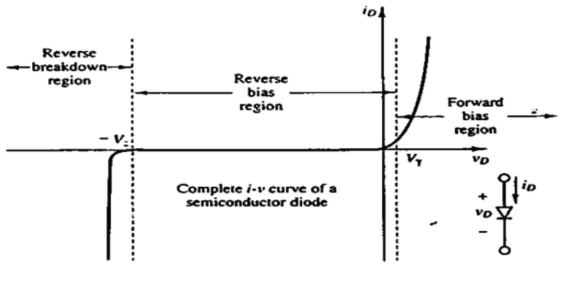


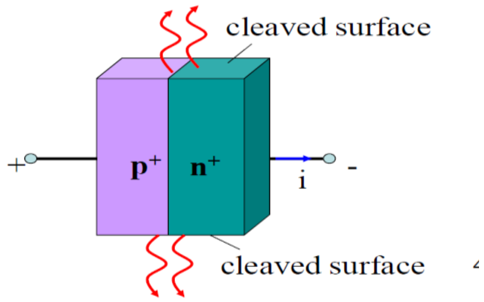
Fig. 6. The reverse breakdown region

The phenomenon of Zener breakdown is related to avalanche breakdown. It is usually achieved by means of heavily doped regions in the neighbourhood of the metal-semiconductor junction (the ohmic contact) .The high density of charge carriers provides the means for a substantial reverse breakdown current to be sustained at a much lower specific voltage than normal diode, at a nearly constant reverse bias known as the Zener voltage, Vz. This phenomenon is very useful in applications where one would like to hold some load voltage constant for example, in voltage regulators.

The response time of a p-n junction to a dynamic (ac) applied voltage is determined by solving the set of differential equations governing the processes of electrons and hole diffusion, drift (under the influence of the built-in and external electric fields), and recombination. These effects are important for determining the speed at which the diode can be operated. They may be conveniently modeled by two capacitances, a junction capacitance and diffusion capacitance, in parallel with an ideal diode. The junction capacitance for the time necessary to change the fixed positive and negative charges stored in the depletion layer when the applied voltage changes. The thickness l of the depletion layer turns out to be proportional to $\sqrt{(Vo-V)}$; it therefore increases under the reverse-bias conditions (negative V) and decreases under the forward-bias conditions (positive V). The junction capacitance C=ЄA/l (where A is the area of the junction) is therefore inversely proportional to $\sqrt{(Vo-V)}$. The junction capacitance of a reverse-biased diode is smaller (and the RC response time is therefore shorter) than that of a forward-biased diode. The dependence of C on V is used to make voltage-variable capacitors (varactors).

A. Laser diodes

laser diode (LD) is a semiconductor optical amplifier (SOA) that has an optical feedback. A semiconductor optical amplifier is a forward-biased heavily-doped p+-n+ junction fabricated from a direct-bandgap semiconductor material. The injected current is sufficiently large to provide optical gain. The optical feedback is usually implemented by cleaving the semiconductor material along its crystal planes. The sharp refractive index difference between the crystal (~3.5) and the surrounding air causes the cleaved surfaces to act as reflectors. The semiconductor crystal therefore in general can act both as a gain medium and as a Fabry-Perot optical resonator. Provided that the gain coefficient is sufficiently large, the feedback converts the optical amplifier into an optical oscillator, i.e. a laser. The device is called a laser diode or a diode laser or a semiconductor injection Laser.



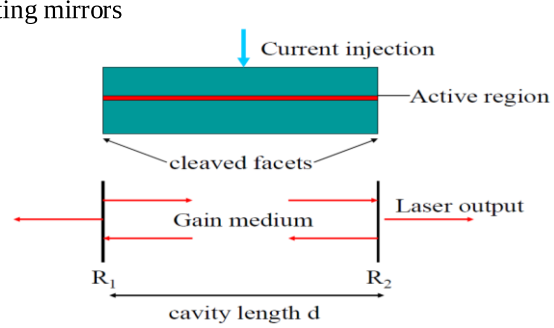
B. How The Laser Diode Works

When a diode is forward biased, holes from the p-region are injected into the n-region, and electrons from the n-region are injected into the p-region. If electrons and holes are present in the same region, they may radioactively recombine – that is the electron "falls into" the hole and emits a photon with the energy of the bandgap. This is called spontaneous emission, and is the main source of light in a light-emitting diode.

Under suitable conditions, the electron and the hole may coexist in the same area for quite some time (on the order of microseconds) before they recombine. If a photon of exactly the right frequency happens along within this time period, recombination may be stimulated by the photon. This causes another photon of the same frequency to be emitted, with exactly the same direction, polarization and phase as the first photon.

C. Turning semiconductor amplifiers into laser diodes

In the case of semiconductor lasers, external mirrors are not required as the two cleaved laser facets act as partially reflecting mirrors



D. Semiconductor as a gain medium

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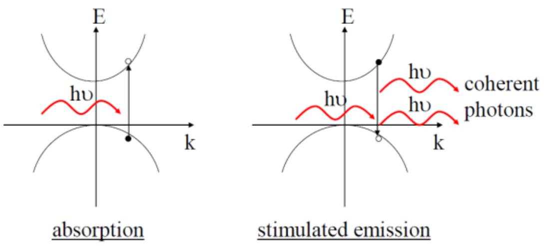
The basic principle: creation of population inversion, stimulated emission becomes more prevalent than absorption

The population inversion is usually attained by electric-current injection in some form of a p+-n+ junction diode (also possible by optical pumping for basic research) a forward bias voltage causes carrier pairs to be injected into the junction region, where they recombine by means of stimulated emission.

• Here we discuss the semiconductor gain and bandwidth upon electrical pumping scheme.

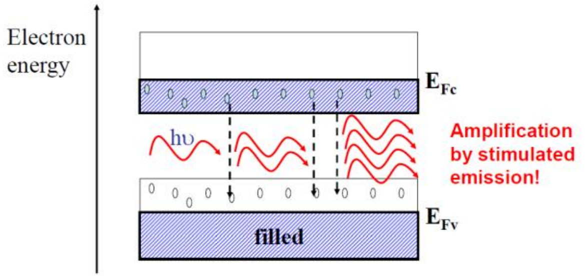
E. Absorption and stimulated emission



When stimulated emission is more likely than absorption => net optical gain (a net increase in photon flux) => material can serve as a coherent optical amplifier.

F. Population inversion by carrier injection

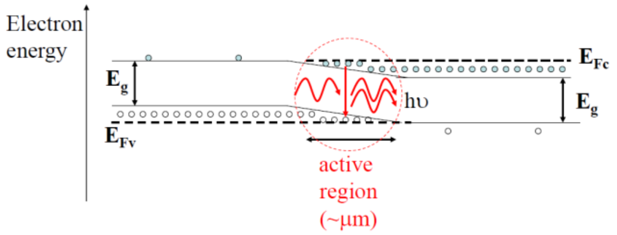
In a semiconductor, population inversion can be obtained by means of high carrier injection which results in simultaneously heavily populated electrons and holes in the same spatial region.



The condition for stimulated emission under *population inversion*:

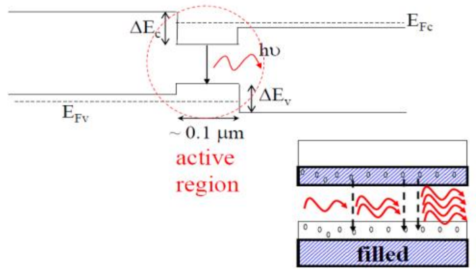
$E_{Fc} - E_{Fv} > h\upsilon > E_g$ 10

Population inversion in a forward-biased heavily doped p+-n+ junction



Upon high injection carrier density in a heavily-doped p+-n+ junction there exists an active region near the depletion layer, which contains simultaneously heavily populated electrons and holes – population inverted

Population inversion in a P+-p-N+ double heterostructure under forward bias (e.g. AlxGa1-xAs system)



The thin narrow-gap active region of a double heterostructure contains simultaneously heavily populated electrons and holes in a confined active region – population inverted.

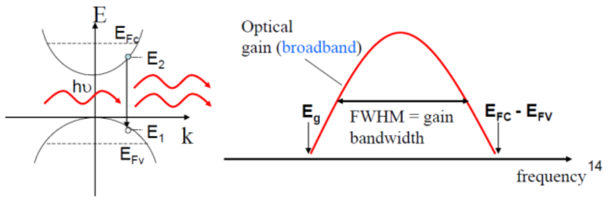
Stimulated emission is more prevalent than absorption when:

$$R_e(\upsilon) > R_a(\upsilon)$$

$$\Rightarrow P_c(E_2)\,[1 - P_v(E_1)] > P_v(E_1)\,[1 - P_c(E_2)]$$

$$\Rightarrow P_c(E_2) > P_v(E_1) \quad (E_2 < E_{Fc},\ E_1 > E_{Fv})$$

This defines the population inversion in a semiconductor. The quasi- Fermi levels are determined by the pumping (injection) level ($E_{Fc} - E_{Fv} = eV > Eg$, where V is the forward bias voltage).



Gain and absorption coefficients vs. frequency

Define the ***gain coefficient*** (cm^{-1}) in *quasi*-equilibrium ($P_c(E_2) > P_v(E_1)$, $E_g < h\upsilon < E_{Fc} - E_{Fv}$):

$$g(\upsilon) = (h\upsilon/I(\upsilon))\,[R_e(\upsilon) - R_a(\upsilon)]$$
$$= (c^2/8\pi n^2\upsilon^2\tau_{sp})\,\rho(\upsilon)\,[P_c(E_2) - P_v(E_1)]$$

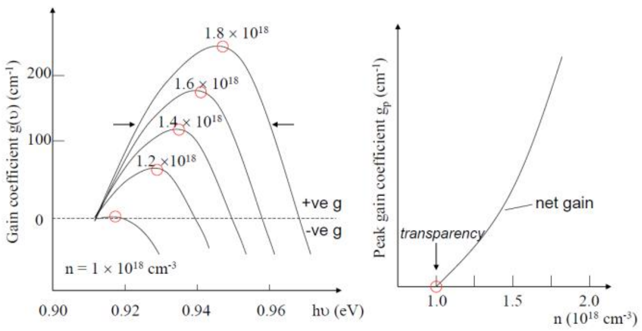
where $I(\upsilon)/h\upsilon = v_g u(\upsilon)/h\upsilon$ is the photon flux per unit *area (cm^{-2})*.

The ***absorption coefficient*** (cm^{-1}) in *thermal* equilibrium (*taking +ve sign*):

$$\alpha(\upsilon) = (c^2/8\pi n^2\upsilon^2\tau_{sp})\,\rho(\upsilon)\,[P(E_1) - P(E_2)]$$
$$\approx (c^2/8\pi n^2\upsilon^2\tau_{sp})\,\rho(\upsilon) \quad \text{where } P(E_1) \sim 1,\ P(E_2) \sim 0$$

The larger the absorption coefficient in thermal equilibrium the larger the gain coefficient when pumped

Gain coefficient g(u) for an In GaAsP SOA



Both the amplifier bandwidth and the peak value of the gain coefficient increase with injected carrier concentration n. The bandwidth is defined at the FWHM of the gain profile, also called the 3-dB gain bandwidth.

III. MATERIAL TRANSPARENCY

The semiconductor material becomes "transparent" (material transparency) when the rate of absorption just equals the rate of stimulated emission.
=> One incident photon produces exactly one photon in the output.

=> The single-pass gain must be unity, i.e. G = 1.
=> The material gain upon transparency g(n0) = 0.

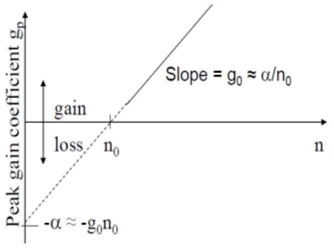
The transparency density n0 (number per unit volume) represents the number of excess conduction band electrons per volume required to achieve transparency.

A. *Differential gain*

The peak gain coefficient curves can be approximated by a straight line at n0 by making a Taylor expansion about the transparency density n0 to find

$$g_p = g_p(n) \cong g_0(n - n_0) \cong \alpha(n/n_0 - 1)$$

$g_0 = dg_p/dn$ is typically called the ***differential gain*** **(cm²)**. It has a unit of *cross section*.



- The quantity α represents the *absorption coefficient* in the absence of injection.
- n_0 represents the injected-carrier concentration at which *emission* and *absorption* just balance each other (the *transparency condition*).

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- Within the *linear approximation*, the *peak gain coefficient* is linearly related to the *injected current density* J (A cm^{-2})

$$g_p \approx \alpha(J/J_0 - 1)$$

⇒The *transparency current density* J_0 is given by

$$J_0 = (el/\eta_{int}\tau_r)\, n_0$$

where *l* is the active region thickness

- When J = 0, the peak gain coefficient $g_p = -\alpha$ becomes the *absorption coefficient*.
- When $J = J_0$, $g_p = 0$ and the material is *transparent* => exhibits *neither gain nor loss*.
- *Net gain* can be attained in a semiconductor junction *only* when $J > J_0$.

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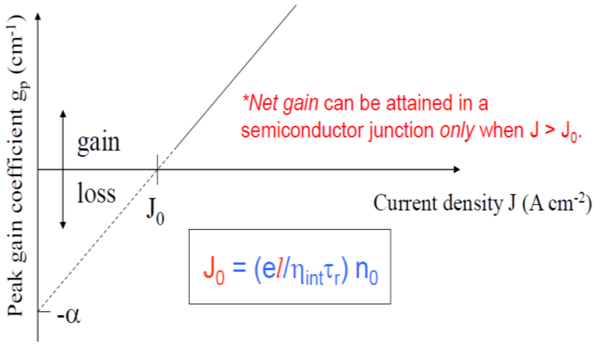
B. Injected current density

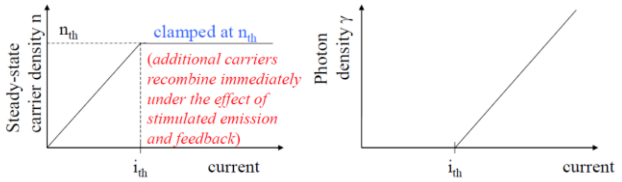
If an electric current i is injected through an area A = wd, into an active region Va = volume lA (where l is the active region thickness),the steady-state carrier injection rate is i/elA = J/el per second per unit volume, where J = i/A is the injected current density (A cm-2).
The steady-state injected carrier concentration is (recombination = injection)

Peak gain coefficient as a function of current density for the approximate linear model



Note that J0 is directly proportional to the junction thickness l => a lower transparency current density J0 is attained by using a narrower active-region thickness. (another motivation for using double heterostructures where l is ~ 0.1 mm)

Steady-state carrier density and photon density as functions of injection current



Below threshold, the laser photon density is zero; any increase in the pumping rate is manifested as an increase in the spontaneous- emission photon flux, but there is no sustained oscillation.

Above threshold, the steady-state internal laser photon density is directly proportional to the initial population inversion (initial injected carrier density), and therefore increases with the pumping rate, yet the gain g(n) remains clamped at the threshold value (g(nth)).

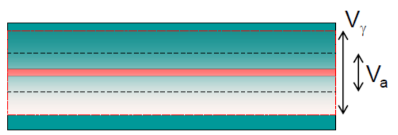
Gain at threshold

Above threshold, the gain does not vary much from gth = g(nth).
Recall the differential gain is the slope of the gain g(n)
g0(n) = dg(n)/dn
For lasing, the differential gain is evaluated at the threshold density nth.
The lowest order Taylor series approximation centered on the transparency density n0 is g(n) = g0(n – n0).
The gain at threshold must be gth = g(nth) = g0(nth – n0)

Optical confinement factor

The active region (i.e. gain region) has volume Va, which is smaller than the modal volume Vg containing the optical energy.
The simplest model assumes that the optical power is uniformly distributed in Vg and is zero outside the volume.
The optical confinement factor G specifies the fraction of the optical mode that overlaps the gain region

$$\Gamma = V_a/V_\gamma$$



Threshold current density

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Recall that within the linear approximation, the peak gain coefficient is linearly related to the injected current density J:

gp ≈ a(J/J0 – 1)

where J0 is the transparency current density.

Setting gp = gth = ar/G, the threshold injected current density Jth

Jth ≈ [(ar/G + a)/a] J0

The threshold current density is larger than the transparency current density by the factor $(a_r/G + a)/a$, which is ~ 1 – 2 for good

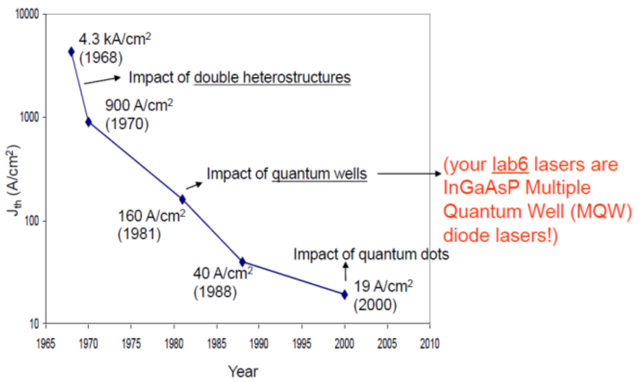
active materials with high gain (large a) in a low-loss cavity (small a_r).

The threshold injected current ith = JthA and the transparency current i0 = J0A, where A is the active region cross-sectional area.

IV. REMARKS ON THRESHOLD CURRENT DENSITY

The threshold current density Jth is a key parameter in characterizing the laser-diode performance: smaller values of Jth indicate superior performance. Jth can be minimized by (Jth → J0 and minimizing J0): maximizing the internal quantum efficiency hint; minimizing the resonator loss coefficient ar, minimizing the transparency injected-carrier concentration n0, minimizing the active-region thickness l (key merit of using double heterostructures)

A. Evolution of the threshold current density of semiconductor lasers



B. Laser Diode Rate Equations

The relationship between optical output power and diode drive current comes from the rate equations that govern the interaction of photons and electrons in the active region For a pn junction with a carrier-confinement region of depth d, the rate equations are

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}}$$

= stimulated emission + spontaneous emission + photon loss

which governs the number of photons Φ, and

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi$$

= injection + spontaneous recombination + stimulated emission

Which governs the number of electrons n.

C. Power output of injection lasers The internal laser power above threshold

$P = \eta_{int}\,(hc/e\lambda)\,(i - i_{th}) = (hc/\lambda)\,\eta_{int}\,(i - i_{th})/e$

Only part of this power can be extracted through the cavity mirrors, and the rest is dissipated inside the laser resonator The output laser power if the light transmitted through both mirrors is used (assume R = R1 = R2 => total mirror loss am = (1/d)ln(1/R))

$$P_o = \eta_{int}\,(hc/e\lambda)\,(i - i_{th}) \cdot (1/d)\ln(1/R) / \alpha_r$$

$$= \eta_e\, \eta_{int}\,(hc/e\lambda)\,(i - i_{th}) = \eta_{ext}\,(hc/e\lambda)\,(i - i_{th})$$

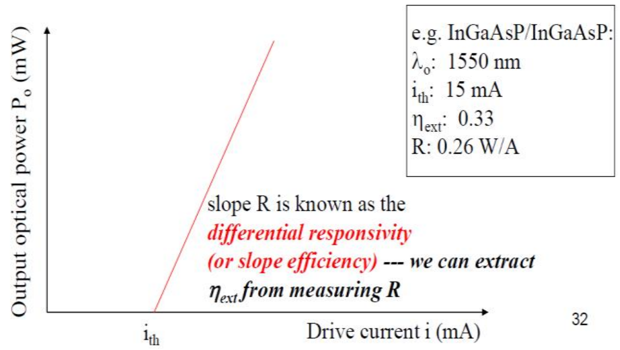
extraction efficiency (α_m/α_r) — external differential quantum efficiency

D. External differential quantum efficiency

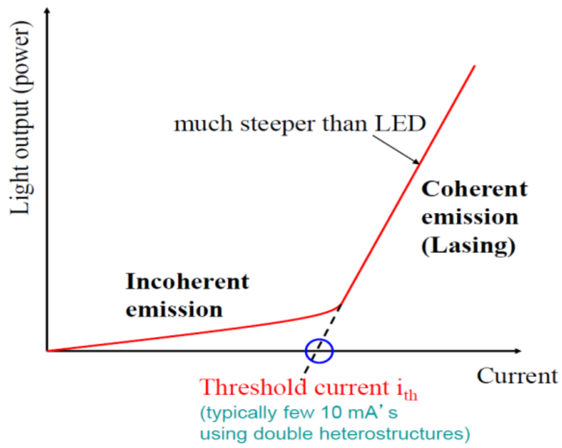
The external differential quantum efficiency hext is defined as

hext = d(Po/(hc/l)) / d(i/e)

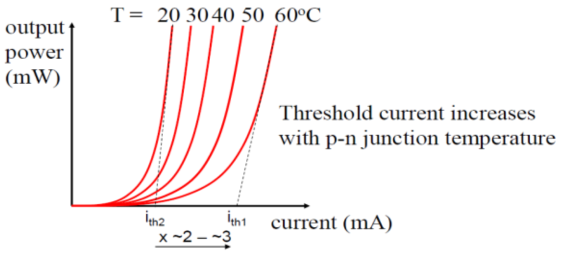
=> dPo/di = hext hc/el = hext 1.24/l ≡ R (W/A)



E. Optical output against injection current characteristics

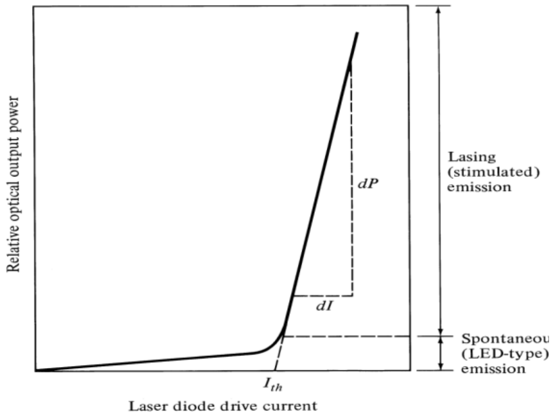


Typical laser diode threshold current temperature dependence

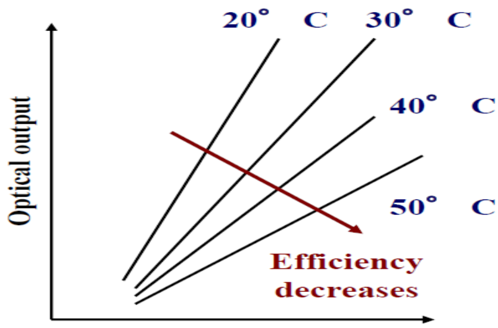


F. Laser Optical Output vs. Drive Current

Relationship between diode drive current. Below the lasing optical output and laser threshold the optical output is a spontaneous LED-type emission



Slope efficiency = dP/dI The laser efficiency changes with temperature:



G. Laser diodes temporal response

Laser diodes respond much faster than LEDs, primarily because the rise time of an LED is determined by the natural spontaneous-emission lifetime tsp of the material.

The rise time of a laser diode depends upon the stimulated-emission lifetime. In a semiconductor, the spontaneous lifetime is the average time that free charge carriers exist in the active layer before recombining spontaneously (from injection to recombination).

The stimulated-emission lifetime is the average time that free charge carriers exist in the active layer before being induced to recombine by stimulated emission.

Stimulated lifetime << spontaneous lifetime

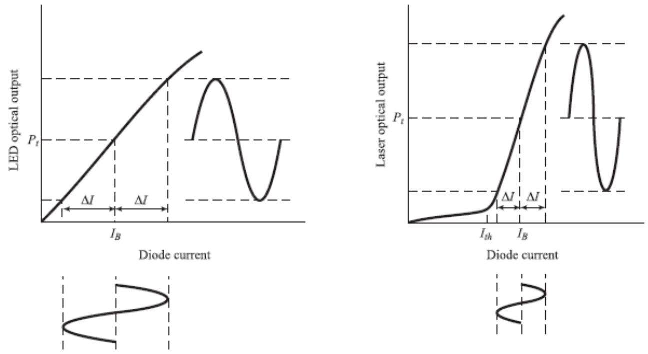
For a laser medium to have gain, the stimulated lifetime must be shorter than the spontaneous lifetime. Otherwise, spontaneous recombination would occur before stimulated emission could begin, decreasing the population inversion and inhibiting gain and oscillation. The faster stimulated-emission process, which dominates recombination in a laser diode, ensures that a laser diode responds more quickly to changes in the injected current than a LED.

H. Direct modulation

The modulation of a laser diode can be accomplished by changing the drive current. This type of modulation is known as internal or direct modulation. The intensity of the radiated power is modulated - intensity modulation **Drawbacks of direct modulation**: (1) restricted bandwidth and (2) laser frequency drift (due to the phase modulation of the semiconductor gain medium upon free-carrier density change).

I. Light Source Linearity

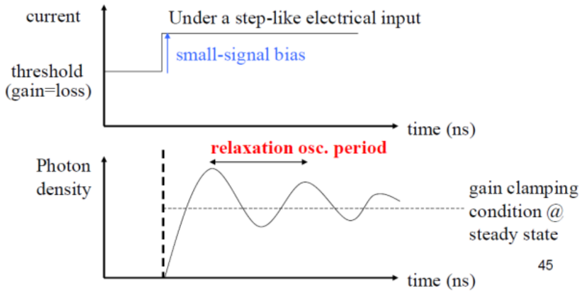
In an analog system, a time-varying electric analog signal modulates an optical source directly about a bias current IB. With no signal input, the optical power output is Pt. When an analog signal s(t) is applied, the time-varying (analog) optical output is: P(t) = Pt[1 + m s(t)], where m = modulation index



-The coupled rate equations (given by the stimulated emission term)

→ laser diode behaves like a damped oscillator (2nd-order ODE in d2F/dt2) before reaching steady-state condition

-The direct modulation frequency cannot exceed the laser diode relaxation oscillation frequency without significant power drop. (*Biasing above threshold is needed in order to accelerate the switching of a laser diode from on to off.)

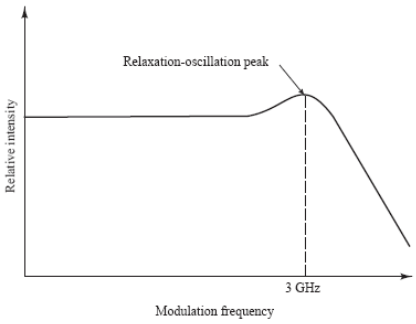


J. Modulation of Laser Diodes

For data rates of less than approximately 10 Gb/s (typically 2.5 Gb/s), the process of imposing information on a laser-emitted light stream can be realized by direct modulation. The modulation frequency can be no larger than the frequency of the relaxation oscillations of the laser field**.**

The relaxation oscillation occurs at approximately

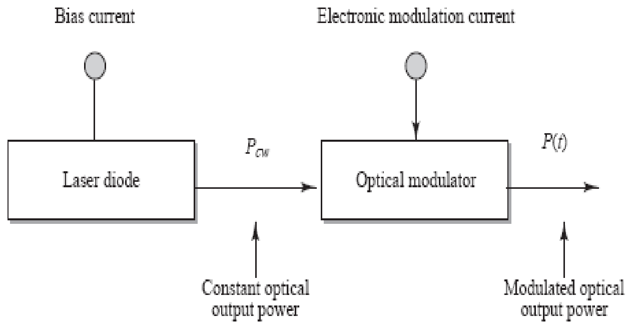
$$f = \frac{1}{2\pi}\frac{1}{(\tau_{sp}\,\tau_{ph})^{1/2}}\left(\frac{I}{I_{th}} - 1\right)^{1/2}$$



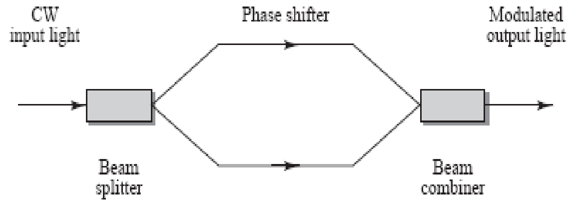
K. External Modulation

When direct modulation is used in a laser transmitter, the process of turning the laser on and off with an electrical drive current produces a widening of the laser linewidth referred to as chirp

The optical source injects a constant-amplitude light signal into an external modulator. The electrical driving signal changes the optical power that exits the external modulator. This produces a time-varying optical signal.



The electro-optical (EO) phase modulator (also called a Mach-Zehnder Modulator or MZM) typically is made of LiNbO3.



Operational concept of an electro-optical lithium niobate external modulator

L. Spatial characteristics

Like other lasers, oscillation in laser diodes takes the form of transverse and longitudinal modes.

The transverse modes are modes of the dielectric waveguide created by the different layers of the laser diode. Recall that the spatial distributions in the transverse direction can be described by the integer mode indexes (p, q).

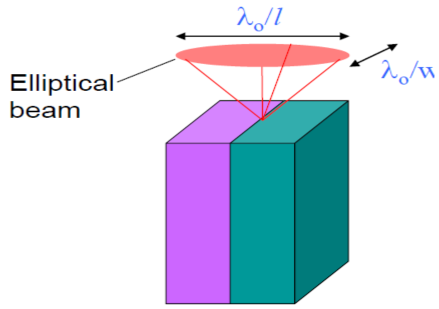
The transverse modes can be determined by using the waveguide theory for an optical waveguide with rectangular cross section of dimensions l and w. If l/lo is sufficiently small, the waveguide admits only a single mode in the transverse direction perpendicular to the junction plane.

V. ELIMINATING HIGHER-ORDER LATERAL MODES

Higher-order lateral modes have a wider spatial spread, thus less confined and has ar that is greater than that for lower-order modes some of the highest-order modes fail to oscillate; others oscillate at a lower power than the fundamental (lowest-order) mode. To achieve high-power single-spatial-mode operation, the number of waveguide modes must be reduced by decreasing the dimensions of the active-layer cross section (l and w) a single-mode waveguide; reducing the junction area also reduces the threshold current. Higher-order lateral modes may be eliminated by making use of gain- guided or index-guided LD configurations

A. Far-field radiation pattern

A laser diode with an active layer of dimensions l and w emits coherent light with far-field angular divergence ≈ lo/l (radians) in the plane perpendicular to the junction and ≈ lo/w (radians) in the plane parallel to the junction. The angular divergence determines the far-field radiation pattern. Due to the small size of its active layer, the laser diode is characterized by an angular divergence larger than that of most other lasers



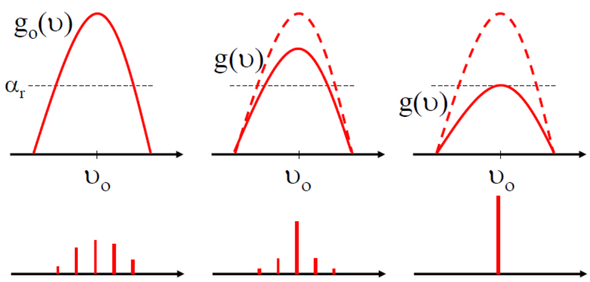
Spectral characteristics

The spectral width of the semiconductor gain coefficient is relatively wide (~10 THz) because transitions occur between two energy bands. Simultaneous oscillations of many longitudinal modes in such homogeneously broadened medium is possible (by spatial hole burning)

The semiconductor resonator length d is significantly smaller than that of most other types of lasers.

→The frequency spacing of adjacent resonator modes Du = c/2nd is therefore relatively large. Nevertheless, many such modes can still fit within the broad bandwidth B over which the unsaturated gain exceeds the loss.

-→The number of possible laser modes is M = B/Du



Growth of oscillation in an ideal homogeneously broadened medium

Immediately following laser turn-on, all modal frequencies for which the gain coefficient exceeds the loss coefficient begin to grow, with the central modes growing at the highest rate. After a short time the gain saturates so that the central modes continue to grow while the peripheral modes, for which the loss has become greater than the gain, are attenuated and eventually vanish. Only a single mode survives

B. Homogeneously broadened medium

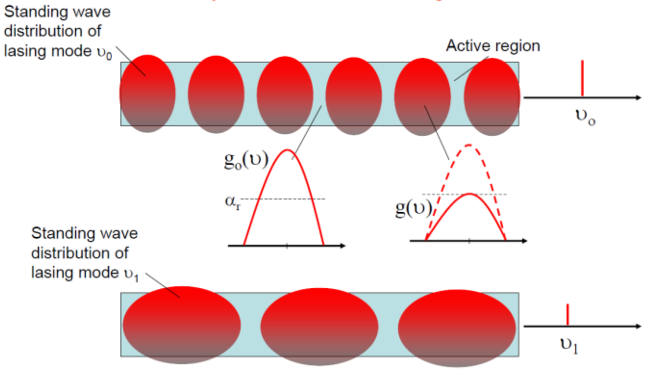
Immediately after being turned on, all laser modes for which the initial gain is greater than the loss begin to grow. => photon-flux densities f1, f2,…, fM are created in the M modes Modes whose frequencies lie closest to the gain peak frequency grow most quickly and acquire the highest photon-flux densities.

These photons interact with the medium and uniformly deplete the gain across the gain profile by depleting the population inversion.

The saturated gain:

$$g(\upsilon) = g_o(\upsilon)/[1 + \sum_{j=1}^{M} \phi_j/\phi_s(\upsilon_j)]$$

Spatial hole burning



Spatial hole burning

-This phenomenon is known as spatial hole burning. It allows another mode, whose peak fields are located near the energy nulls of the central mode, the opportunity to lase.

→permits the simultaneous oscillation of many longitudinal modes in a homogeneously broadened medium such as a semiconductor

-Spatial hole burning is particularly prevalent in short cavities in which there are few standing-wave cycles

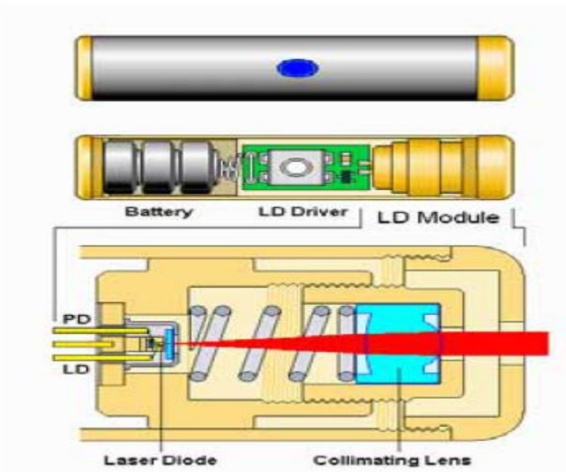
→permits the fields of different longitudinal modes, which are distributed along the resonator axis, to overlap less, thereby allowing partial spatial hole burning to occur

C. Applications of Laser Diodes

- The Red Laser Pointers

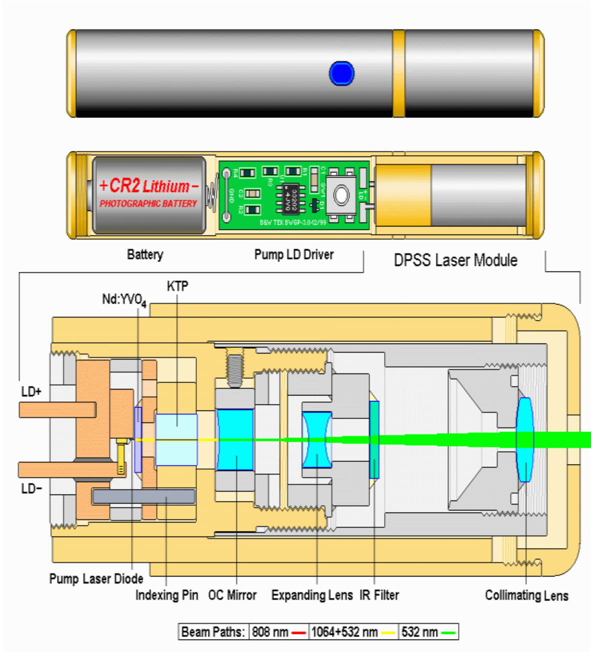
The most visible applications of laser diodes are the ever more popular laser pointers. The basic laser pointer, which can be purchased for only a few dollars, is the standard red laser pointer. The red laser pointer emits a 670 – 635nm beam. The human eye perceives the 635nm beam to be about five times brighter than the 670nm beam. The red laser pointer is quite a simple device and is very inexpensive to manufacture.

The Below Figure shows a diagram of a typical red laser pointer.



Red Laser Pointer

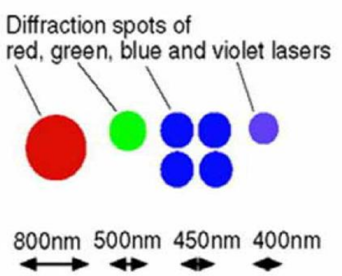
The green laser pointer is a much more complex device. The Below Figure shows a diagram of the green laser pointer. It is actually a Diode Pumped Solid State Laser (DPSS) that uses a laser diode to emit an 808nm beam that optically pumps an Nd: YVO4 crystal, which in turn emits a 1064nm beam. This beam is then processed by a KTP crystal, which halves the wavelength to 532nm. This is very close to 555nm, the wavelength to which the human eye is most sensitive. This means that at the same power as the red laser (<5mW), the green laser will appear about 30 times brighter.



Green DPSS Laser Pointer

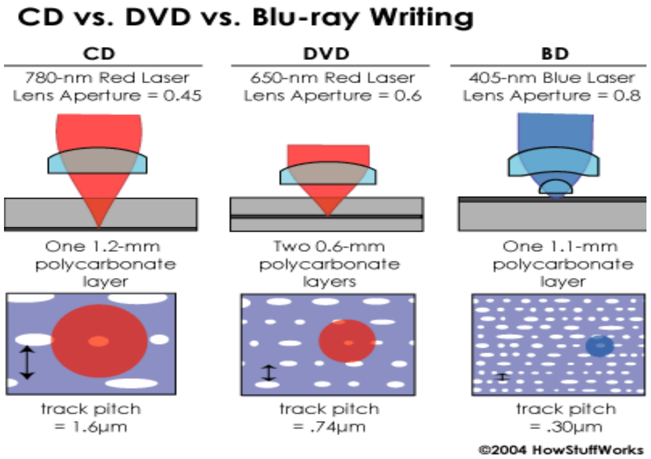
D. Optical Storage Devices

CD-ROM drives operate at a wavelength of 780nm, which is near-infrared. DVD-ROMs operate at 650nm, which is within the red spectrum. The size of the beam which can be focused from a laser diode is dependent upon the wavelength of the light that is emitted. The smaller the wavelength, the tighter the beam; and a tighter beam means a smaller diffraction spot. The belowFigure shows the relative sizes of diffraction spots for different colored laser beams.



E. Relative diffraction spot size of different colored lasers

The amount of data that can be stored using an optical system is dependent upon the size of the diffraction spot. If you want to store more data, you need a higher wavelength laser. The optical storage industry has been moving towards higher wavelength lasers over the last few years. The most prevalent high-wavelength technology is Blu-Ray laser. Blu-Ray is a copyrighted technology developed in 1997 that is being used by Dell, HP Hitachi, Sharp, Sony, Disney and many others. The Blu-Ray is a 405nm blue-violet laser that can store almost six times as much data as a standard 650nm DVD. Figure 9 diagrams the differences in beam size and data resolution for CD-ROM, DVD-ROM, and BD (Blu-Ray Disc).



VI. CONCLUSION

From the P-N Junction we built the laser diode which is a spectacularly versatile device due to both its incredibly small size and the precision with which it can be manufactured. I began this investigation of the laser diode because I was intrigued with its history. The race to be the first to bring the supposition of a semiconductor diode to fruition was fascinating. The air of competition drove the researchers to new heights faster than I would have thought possible.

Throughout this paper I have discussed the basics of laser diodes in terms of materials and physical structure. Even though my explanations may have seemed simplistic, I hope that some of the elegance of this device has shown through. The prevalence of the laser diode in modern technology cannot be overstated. Advances in material engineering are currently taking laser diodes to unforeseen achievements. Quantum advances are making laser diodes more precise and efficient that ever before. Progress is also being made at an ever increasing rate at improving the power output of laser diodes. In conclusion, the laser diode is an integral part of the laser family and is of great concern to modern physics and especially optical processes.

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