Operating Principles of Laser Diodes

"LASER" is an acronym for "Light Amplification by Stimulated Emission of Radiation." A laser is a device which uses one of a large number of solid, liquid, or gaseous materials to generate light and amplify it through the process of stimulated emission. The term "LASER DIODE" denotes a device which uses a semiconductor p-n junction in a LASER system

Theory

Atoms and molecules possess Internal energy The value of this internal energy is restricted to specific discrete values, or energy levels. Fig. 12-1 illustrates the energy levels which the electrons in a typical atom may possess. Each electron will always be found in one of these allowed energy states The transition of an electron from one energy level to another is made possible by the absorption or emission of light.

Light is absorbed or emitted in Individual units called photons. Each photon is an electromagnetic wave which has a specific wavelength and travels in a specific direction.

For the transition between the energy levels E_1 and E_2, as shown in Fig. 12-1, a photon is either absorbed, for the E_1 to E_2 transition, or emitted, for the E_2 to E_1 transition The energy of the photon must correspond exactly to the energy difference between the two energy levels. The wavelength of the photon can be calculated from its energy by using the equation 1.

There are three types of energy transition (Fig 12-2), The first transition process occurs when a photon of light, with the wavelength given by equation 1, strikes an atom which has an electron in the energy level E_1. The photon is absorbed, and the electron is left in the energy level E_2. This phenomena is called Induced Absorption (Fig. 12-2a).

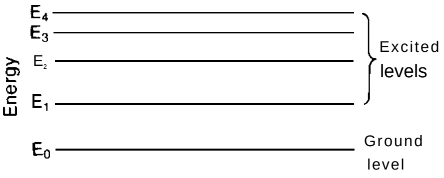
The second transition process occurs when an atom, which has an electron in the energy level E_2, emits a photon with the wavelength given by equation 1 The electron is left in the energy level E_1 This phenomena is called Spontaneous Emission (Fig.1 2-2 b), The light emitted by one atom within a material has no phase relationship to the light emitted by any other atom. Light is emitted in all directions. Random independent transitions of this type produce the incoherent light characteristic of most light sources.

The third transition process occurs when a photon with the wavelength given by equation 1 interacts with an atom which has an electron in the energy level E_2. The atom is stimulated to emit a second photon with the same wavelength, the same phase, and traveling in the same direction as the Incident photon, leaving the electron in the energy level E_1. This phenomena is called Stimulated Emission (Fig. 12-2c). The constructive interference of many photons travelling in the same direction with a common phase and a common wavelength produces the powerful, coherent beam commonly associated with a laser.

In a state of thermal equilibrium, the number of atoms within a material which have an electron in the energy level E_1 is always greater than the number of atoms which have an electron in the energy level E_2 As a result, more light is absorbed than is emitted In order to achieve light amplification, there must be more electrons in the E_2 energy level than in the E_1 energy level This population inversion is achieved in a laser diode by applying an injection current to a p-n junction. In this so called population inversion state, stimulated emission predominates over induced absorption, allowing for the amplification of light.

Solid laser such as ruby and YAG, and gaseous lasers such as He-Ne also use light emission resulting from the transition of electrons between discrete energy levels In laser diodes, light emitted from the transition of electrons from the conduction band of the semiconductor to the valence band is used The electrons in the conduction band, corresponding to the excited levels, recombine with holes in the valence band, corresponding to the ground level, and photons with energy equal to the band gap are emitted As shown in Fig. 12-3a, semiconductors with a band structure in which the extreme values of the bands have corresponding momenta are called direct-gap semiconductors In this type of semiconductor, electron transitions between bands preserve the momentum of the electrons, so that light is readily emitted On the other hand,

Fig. 12-1 **Electron Energy Levels**



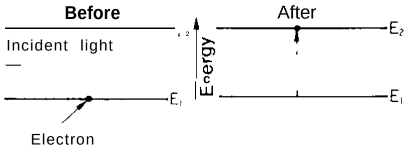
Equation 1.

$$\lambda = \frac{c}{|E_2 - E_1|/h} = \frac{1.2398}{|E_2 - E_1|}$$

Where λ = Wavelength (μm)
c = Velocity of light ($2.998\times10^{8}\,m\cdot s^{-1}$)
h = Planck's constant (4.135×10^{-15} eV Hz^{-1})
$|E_2 - E_1|$ = Energy difference between states (eV)

Fig. **12-2 Electron Energy Level Transition Processes**

(a) Induced Absorption



(b) Spontaneous Emission

(c) Stimulated Emission

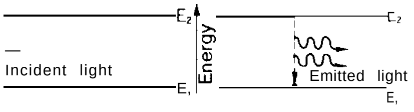
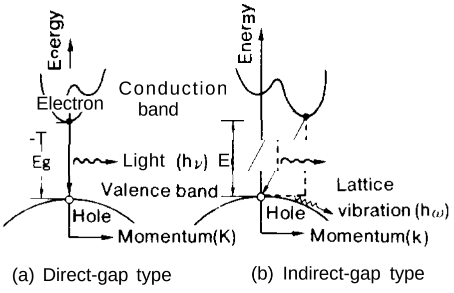


Fig. 12-3 Basic Transition Mechanism in a Semiconductor



(a) Direct-gap type (b) Indirect-gap type

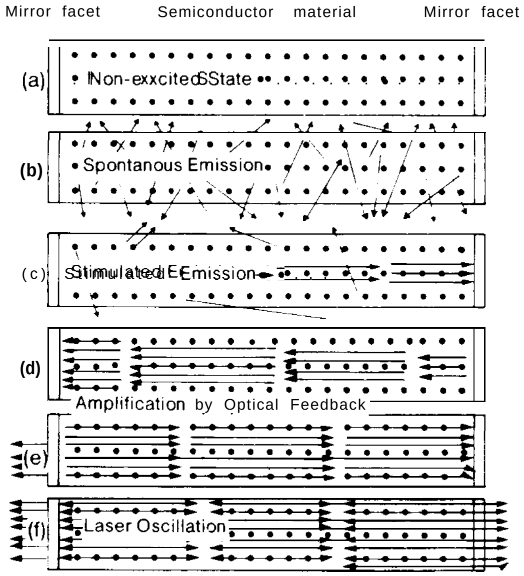
Indirect-gap semiconductors have a band structure as shown in Fig 12-3b and do not readily permit electron transition between bands.

Laser diodes with wavelengths between 750 and 830nm use a direct-gap gallium aluminum arsenide (GaAlAs) crystal In this type of semiconductor, the ratio of the gallium to aluminum can be adjusted to vary the band gap width and thereby control the wavelength

In order to produce a useful laser beam, a laser oscillator must be formed which has the ability not only to amplity light, but also to feedback light A laser oscillator generally consists of two confronting mirrors with the space between mirrors occupied by the light amplifying material This structure, called a Fabry-Perot Resonator, is obtained in a laser diode by cleaving the ends of the semiconductor crystal to form two parallel reflective crystal surfaces (Fig. 13-1 a). In some cases, special coatings are used to enhance either the reflectivity or transmissivity of the mirror facet

When the semiconductor material forming the resonator is brought to a state of population Inversion, light produced by spontaneous emission is amplified and repeatedly reflected by the front and rear reflective facets Light emitted in any direction not parallel to the optical axis of the resonator will pass through the sides of the resonator (Fig 13-1 b). The component of the spontaneously emitted light which travels parallel to the optical axis, will be repeatedly reflected by the mirror facets (Fig 13-1c). As the light travels through the semiconductor material, it is amplified by stimulated emission (Fig 13-1 d, e) At each reflection, the beam is partially transmitted through the reflective facets Laser oscillation begins when the amount of amplified light becomes equal to the total amount lost through the sides of the resonator, through the mirror facets, and through absorption by the semiconductor material (Fig. 13-1 f).

Fig. 13-1 Laser Oscillation



Principles of GaAlAs Laser Diodes

The GaAlAs Laser Diode consists of a double hetero junction formed by a $Ga_{1-y}Al_yAs$ active layer surrounded by P-type and N-type $Ga_{1-x}Al_xAs$ cladding layers, where $x > y$ (Fig. 14-l a), When a bias voltage is applied in the forward direction, electrons and holes are Injected into the active layer. Since the band gap energy is greater in the cladding layers than in the active layer, the injected electrons and holes are prevented from diffusing across the junction by the potential barriers formed between the active layer and cladding layers (Fig. 14-1 b). The electrons and holes confined to the active layer create a state of population Inversion, allowing the amplification of light by stimulated emission. Fig.14-1 c illustrates the light amplification gain across the hetero juction. The high refractive index of the active layer, as compared to the cladding layers, serves to confine the emitted light to propagation within the active layer (Fig. 14-ld,e).
The confinement of the charge carriers and the emitted light are the keys to highly efficient laser diodes.

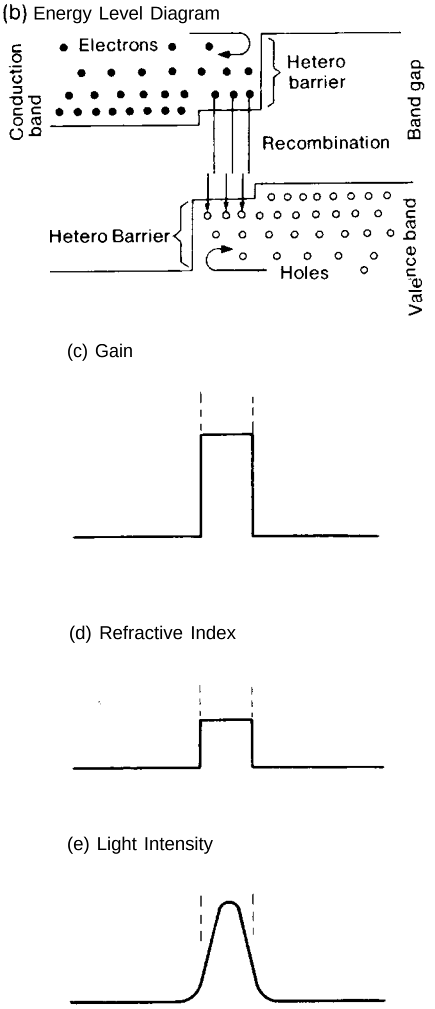
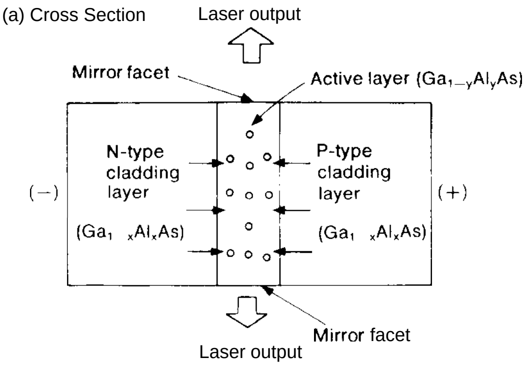


Fig. 14-1 Structure of GaAlAs Laser Diodea



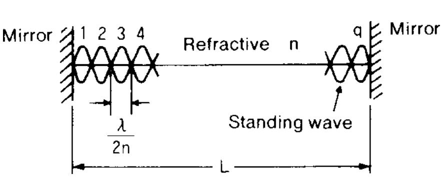
Oscillation Modes

(a) Longitudinal Mode

During laser oscillation, constructive Interference allows the creation of a standing wave within the Fabry-Perot resonator (Fig. 14-2). For light of wavelength λ traveling in a medium of refractive index n, the half-wavelength in the medium is $\lambda/2n$. As the condition for a standing wave. an integral multiple, q, of the half-wavelength must be equal to the resonator length, L

$$q \cdot \frac{\lambda}{2n} = L$$

Fig. 14-2 Standing Wave in Laser Resonator



In the case of the laser diode with, for example $\lambda = 780nm$, $n = 3.5$ and $L = 250\mu m$, q takes on a value of greater than 2000 ($q \doteqdot 2240$) Variation of the Integer q by 1 causes a wavelength variation, $\Delta\lambda$, of 0.35nm Because of its relative long length as compared to the light wavelength, the laser resonator may simultaneously support several standing waves, or longitudinal modes, of slightly different wavelength.
In a laser diode, laser oscillation arises at the wavelength with the maximum gain, which is determined by the band gap energy of the semiconductor since the band gap varies with temperature, so too does the oscillation wavelength For the GaAlAs laser diode, the wavelength Increases by approximately 0.23 nm for an Incremental Increase-In temperature of 1 ‘C

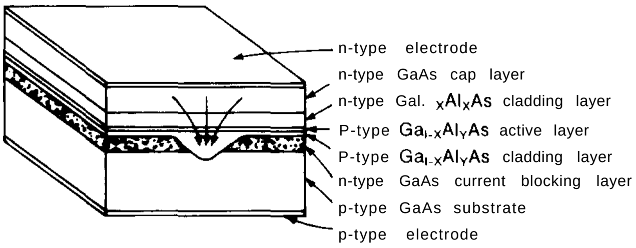
(b) Transverse Mode

The transverse mode represents the state of the electromagnetic standing wave in the direction perpendicular to the optical axis of the laser resonator. The transverse mode has two components, one parallel and the other perpendicular to the active layer of the laser. As stated above, there exist steps in the refractive index on each side of the active layer which serve to confine the light to the active layer. An appropriately thin active layer supports only the fundamental value of the transverse mode perpendicular to the active layer Because the transverse spatial extent of the beam within the laser material is comparable to the wavelength of the light, the beam becomes widely dispersed when exitting the resonator.

Originally, there were no means for restricting the transverse mode in the direction parallel to the active layer. As a feature of Sharp's Laser Diodes, a V-shaped groove is formed in the substrate (Fig.1 5-1), which serves to confine the injection current and the laser oscillation to a narrow strip. In this stripe structure laser, current flow is restricted outside of the V-channel by an n-type current blocking layer. Also in this region, any light leaking out of the active layer is absorbed by the substrate, thus suppressing laser oscillation and controlling the parallel transverse mode,

The V-channeled substrate inner stripe laser structure, based on Sharp's original technology, insures stable single fundamental transverse mode operation.

Fig. 15-1 VSIS Laser Diode



Laser Beam Characteristics

Because of the randomness of the energy states of the electrons in most materials there is no correlation between the individual waves of light produced by a conventional source through spontaneous emission A conventional light source can be likened to dropping a handful of pebbles into a pond The waves formed on the surface of the water appear to be random and it is difficult to capture their energy A conventional light source is called Incoherent because it emits waves of light with no common phase relationship and with a broad range of wavelengths A laser is a coherent source emitting waves of light that are in phase with each other and are of nearly the same wavelength It is the coherence of a laser which allows it to be used in many applications where conventional sources are unsuitable

The general term coherence Includes temporal coherence and spatial coherence Temporal coherence describes the monochromaticity of a wave, *and its continuity in the direction* of travel Temporal coherence depends on the spectral bandwidth of the souce In a typical single mode laser diode, the spectral bandwidth is at least several megahertz due to temperature variations, variations in carrier density, and other factors The spectral bandwidth may vary up to several gigahertz or even higher in multi-mode laser diodes The temporal coherence of a laser beam is often expressed in terms of its coherence length, which indicates the length, measured parallel to the beam, over which it can be considered a continuous wave Coherence length, L_C is determined as,

$$L_C = c/2\pi n\Delta f = \lambda^2/2\pi n\Delta\lambda$$

Where Δf, or $\Delta\lambda$ is the spectral bandwidth, c is the speed of light in vacuum, and n is the index of refraction of the propagation medium Laser diodes with coherence lengths of up to several dozen meters are suitable for applications in interferometry In compact disc and video disc players, a high degree of temporal coherence causes poor noise characteristics In laser diodes for these applications, the coherence length is deliberately shortened to as little as 1 millimeter

Spatial coherence describes the continuity and uniformity of a wave in the direction perpendicular to the direction of travel A spatially coherent beam can be focused to a much smaller spot than can the beam from an Incoherent source In theory a beam of light with uniform wavefronts can be focused to a diameter roughly equal to the wavelength of the light This feature is utilized by high power CO_2 and Nd YAG lasers to achieve high optical power densities for material processing and ablative surgery High density data storage on compact discs, video discs, and of her optical media is made possible by the extreme focusability of the beams from laser diodes Another measure of spatial coherence is directivity The collimated beam from a laser can travel great distances with minimal angular dispersion For example, it is possible to collimate a laser beam to a diameter of 1 mm, direct it towards the moon, and achieve a beam diameter of about 200 mm on the surface of the moon When combined with the laser's high luminance per *unit* bandwidth*, *this* feature makes lasers ideal for long distance optical communications

* The light from a typical 1 mW GaAlAs laser diode is 10 thousand times brighter than the red light from the sun al the corresponding wavelength

Fig. 15-2 **Temporal Coherence**

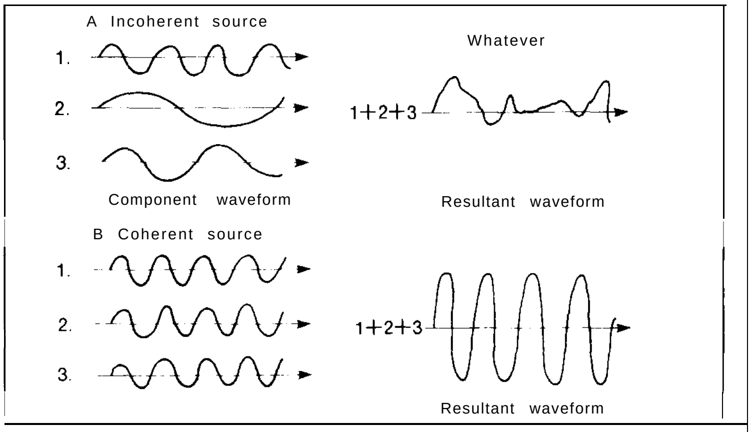


Fig. 15-3 **Spatial Coherence**