Laser Diodes
an Introduction

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Introduction

Laser diodes have grown to a key component in modern photonics technology. This article provides a general introduction in the physics and technology of laser diodes. First the physical concepts behind laser diodes are explained. In the following an example of an AlGaAs laser is given and analyzed in details. The last part introduces technological approaches to build competitive laser diodes. The focus is thereby on single mode laser diodes. We consider ways to introduce a waveguide in the laser diode and concepts to make the laser diode wavelength selective. Briefly we take a look at laser diode arrays for use in high power applications and finally we introduce the VCSEL's (Vertical Cavity Surface Emitting Lasers).

Comparison with other laser systems

The following features distinguish laser diodes from other lasers:

- Compact. They are build on one chip that contains everything necessary for a laser. This enables semiconductor lasers to be easily be inserted in other instruments.
- High efficiency up to 50%. This enables them to be driven by low electrical power compared to other lasers.
- Direct excitation with small electric currents, so that conventional transistor based circuits can supply the laser
- Possibility of direct modulation with applied current
- Small beam waist

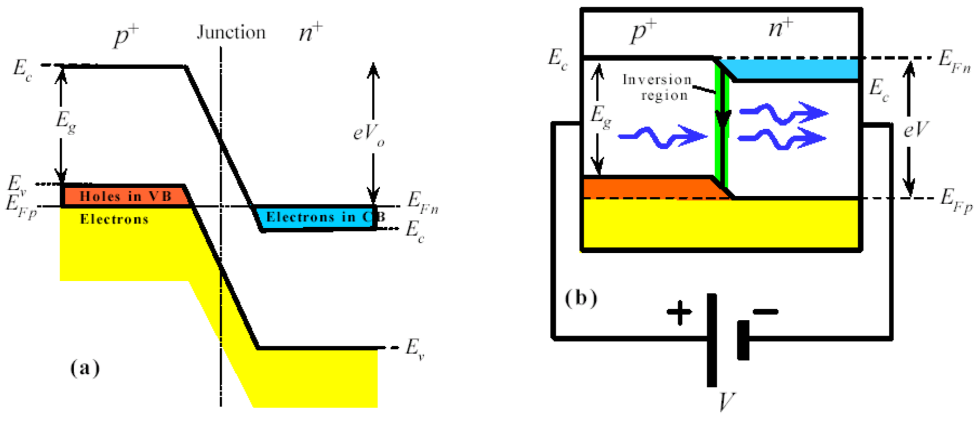
Low costs due to mass production and high reliability made them a key component in various applications. However they also have some disadvantages. They are highly sensitive to temperature. Although this allows wide wavelength tunability it is unwanted for most applications. Another important unwanted feature is their highly divergent beam. [1]

1 The physics behind laser diodes

1.1 Band structure of semiconductor

In a crystal, the discrete energy levels of the individual atom broaden into energy bands. Each quantum state of the individual atom gives rise to a certain energy band. The bonding combinations of states become the valence bands (VB) of the crystal, and the anti-bonding combinations of these states become the conduction band (CB). The energy difference between VB and CB is called energy gap. If the valence bands are partly filled, this material is p-type, if the conductive bands are partly filled, this material is n-type. Here Fermi level is used to label the occupation conditions of electrons in the semiconductor, it is the energy level to which electrons occupy. Fermi level (E_{FP}) on p-type is near the valence band and E_{FN} on the n-type is near the conductive band.

When two semiconductors with different band structures are combined, a heterojunction is formed, a p-n heterojunction is called a diode. Electrons and holes transfer to the other side, because of different Fermi levels respectively. They recombine with each other, leaving the p-side with negative charge and n-side with positive charge, this region is called space charge layer (SCL). A built-in voltage V_0 appears because of the charge transfer and recombination. When there is no applied voltage, the Fermi level is continuous across the diode $E_{FP} = E_{FN}$, as indicated in Figure 1(a). The built-in voltage prevents electrons in conduction band on n-side from diffusing into conduction band on p-side, it is similar for holes in valence band, so the majority carriers can not flow into the space charge layer. An applied voltage V can separate E_{FP} and E_{FN} by eV, and the Fermi level is not continuous across the diode. The seperate Fermi level in each side is called quasi Fermi level, as indicated in Figure 1(b).



(a) p-n junction without bias (b) p-n junction after forward bias

Figure 1: p-n junction with/without bias [2]

Due to the applied voltage, the recombination process takes place and the diode current establishs. When applied voltage is greater than built-in voltage , the space charge layer is no longer depleted. Now at the junction, more electrons are injected into the conductive band at energies near E_c than electrons in valence band at energies near E_v. This is the population inversion, and the inversion region as indicated in Figure 1(b) is called active region. In Figure 2, the carrier concentration-x is shown in two dimensional coordinate in the space charge layer (SCL). [2].

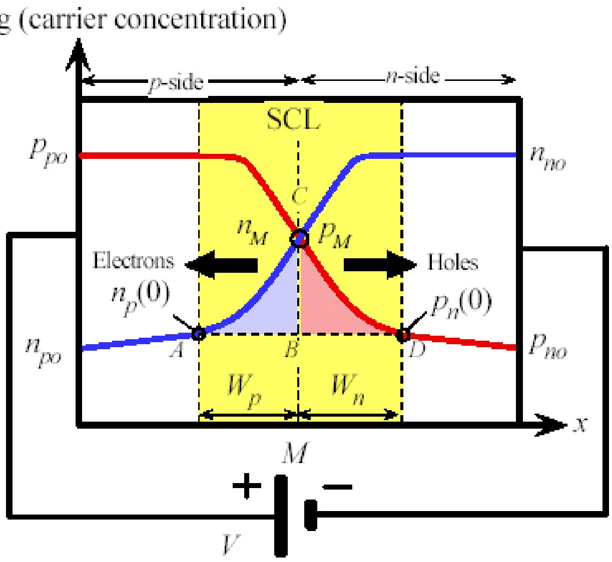
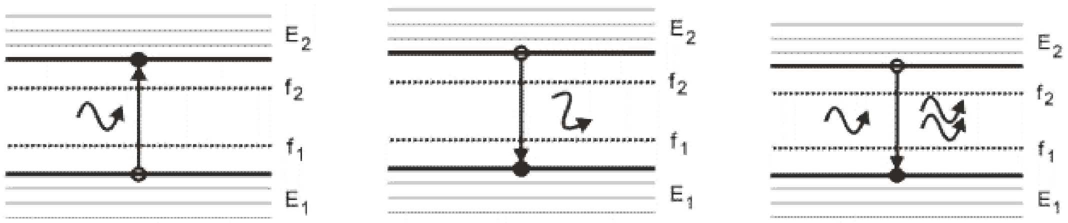


Figure 2: The carrier concentration in SCL under forward bias [2]

1.2 Recombination

There are three kinds of transitions that are important in laser diodes, which occur between the conduction and valence bands of the material. They are stimulated absorption, spontaneous emission and stimulated emission in Figure 3.



(a) Stimulated Absorption (b) Stimulated Absorption (c) Stimulated Emission

Figure 3: Recombination [3]

After defining $R_{(abs)}, R_{(spon)}, R_{(stim)}$ as the rate of absorption, spontaneous emission and stimulated emission respectively, the relationship between the three processes can be described by the following equation

$$R_{(abs)} = R_{(spon)} + R_{(stim)}$$

And the rates can be expressed by the Einstein coefficients which are defined in the following way:

$B_{(12)}$ transition probability of induced absorption
$A_{(21)}$ transition probability of spontaneous emission
$B_{(21)}$ transition probability of induced emission

Here we only cite the the ratio of spontaneous emission to stimulated emission, the deduction details can be read in website [3]

$$\frac{A_{(21)}}{B_{(21)}} = \varrho(\hbar\omega)\exp[\hbar\omega/k_B T] - 1$$

In the stimulated emission, a photon is strongly coupled with the electron, the photon can cause the electron to decay to a lower energy level, releasing a photon of the same energy. The emitted photon has the same direction and phase as the incident photon. When the stimulated emission is dominant, the light is amplified, and laser occurs. From this equation, we can see that stimulated emission is dominant when $\hbar\omega \ll k_b T$. From Fermi-Drac statistic law, under this condition, the probability of finding an electron in the conduction band has to be greater than the probability of finding an electron in the valence band, so there must be a population inversion. As mentioned before, in a laser diode, population inversion is achieved when $E_{FN} - E_{FP} > Eg$, where Eg is the bandgap energy and E_{F_c} and E_{F_v} are the Fermi levels of the conduction band and valence band, respectively. These Fermi levels can only be separated by pumping energy in the form of electrical current into the semiconductor laser. Electrons and holes are injected into the active region from n- and p-doped semiconductor cladding layers. The injection current required to achieve lasing is known as the threshold current, details will be given in section 2.2.

1.3 State density

When we calculate various optical properties, such as the rate of absorption or emission and how electrons and holes distribute themselves within a solid, we need to know the state density. The density of state is described in the number of available states per unit volume per unit energy. So in conductive band and valence band, the state density of energy is

$$\varrho_{c,v}(E)dE = \left(\frac{1}{2\pi^2}\right)\left(\frac{2m^*}{\hbar^2}\right)^{3/2}\left(E^{1/2}dE\right)$$

$m^* \rightarrow m_c$ or m_v $\quad E \rightarrow E - E_c$ or $E_v - E$

according to Fermi-Dirac statistic law, electrons in the band obey the following equations

$$f_c(E) = \frac{1}{\exp\left((E - F_n)/kT\right) + 1}$$

$$f_v(E) = \frac{1}{\exp\left((E - F_p)/kT\right) + 1}$$

so in conductive band and valence band, the electrons and holes distributions are

$$n_c(E)dE = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2} \frac{(E-E_c)^{1/2}dE}{\exp\left((E-F_n)/kT\right)+1} \qquad E > E_c$$

$$p_v(E)dE = \frac{1}{2\pi^2}\left(\frac{2m_h^*}{\hbar^2}\right)^{3/2} \frac{(E_v-E)^{1/2}dE}{\exp\left((F_p-E)/kT\right)+1} \qquad E < E_v$$

The above equations are mainly cited from website [3]

Figure 4 is the schematic graph of the distributions described by the functions above. (a) is at 0 K, and the charges first fill the lowest energy state. (b) is at a certain temperature above 0, so some charges are excited to higher energy states.

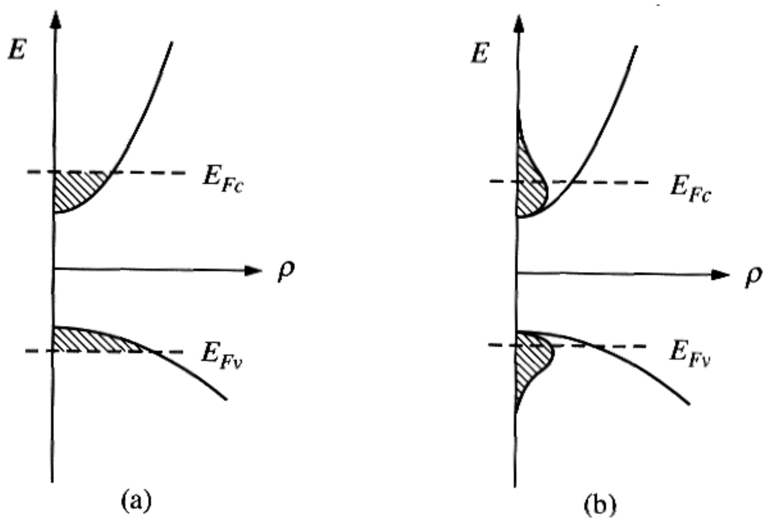
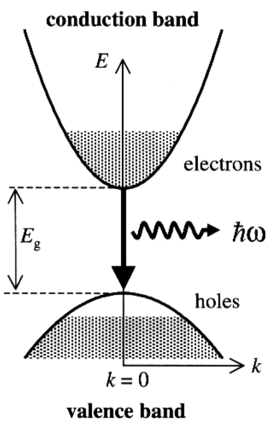


Figure 4: Electron and hole distribution [4]

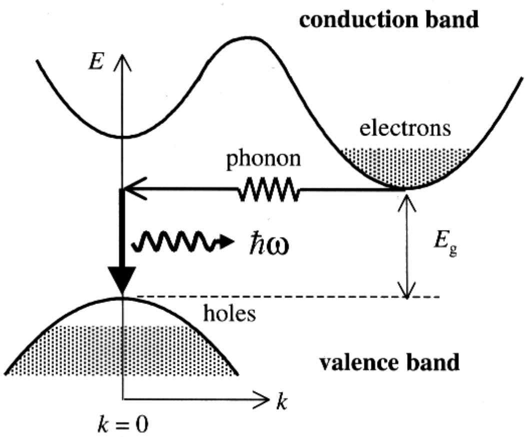
1.4 Direct band gap and indirect band gap

The recombination process mainly depends on the band structure. Generally, there are two kinds of band structure, direct band gap and indirect bandgap. Direct band gap means that in the E-k diagram, electrons at the minimum of the conduction band have the same momentum as electrons at the maximum of the valence band, and for an indirect band gap, the electrons do not have the same momentum, as indicated in Figure 5. The recombination of an electron near the bottom of the conduction band with a hole near the top of the valence band requires the exchange of energy and momentum. For indirect band gap recombination, the energy may be carried off by a photon, but one or more phonons are required to conserve momentum. This multiparticle interaction is improbable and the recombination efficiency in the indirect band gap material is lower than in the direct band gap material. [6]

The majority part of semiconductors are indirect band gap material, compared with them, direct bandgap materials are preferred for laser diodes. Direct bandgap structures



(a) direct-band-gap structure



(b) indirect-band-gap structure

Figure 5: Recombination [5]

maximize the tendency of electrons and holes to recombine by stimulated emission, thus increasing the laser effciency. For example, the direct band gap crystal aluminium gallium arsenide ($AlGaAs$) is often used for laser diodes with wavelengths between 750nm and 880nm. $Al_xGa_{1-x}As$, through changing the x, the ratio of the aluminium to gallium can be adjusted to vary the band gap and thereby control the wavelength. [7].

1.5 Optical Feedback Mechanism

In a high efficiency laser, a resonator must be formed which has the ability not only to amplify the electromagnetic wave, but also to feedback it. A laser resonator generally consists of two parallel mirrors perpendicular to the optical axis. Space between the mirrors is partially occupied by the amplifying material. This structure, called a Fabry-Perot Resonator, is obtained in a laser diode by cleaving the ends of the crystal. Because the refractive index has a jump at the interface of the crystal and other material, the mirror facet functions as a reflective surface. In some cases, special coatings are used to enhance either the reflectivity r, or transmissivity t, of the facet. When the resonator is brought to a state of population inversion, photons produced by spontaneous emission are amplified and repeatedly reflected by the front and rear facets. In homojunction LD, there is no optical confinement in the direction perpendicular to the optical axis, so the elelctromagetic waves in any direction not parallel to the optical axis of the resonator will pass through the sides of the resonator. In heterostructure LD, the waveguide will confirm the wave in the active region (see section 2). The component of the spontaneously emitted photons, which travels parallel to the optical axis, will be repeatedly reflected by the mirror facets. As the electromagetic wave travels through the semiconductor material, it is amplified by stimulated emission. At each reflection, the wave is partially transmitted through the reflective facets. Laser oscillation begins when the amount of amplification becomes equal to the total amount lost through the sides of the resonator, through the mirror facets and through absorption by the crystal. The details of Fabry-Perot can be found in the 'Protokoll laser diodes, theory part'. [8]

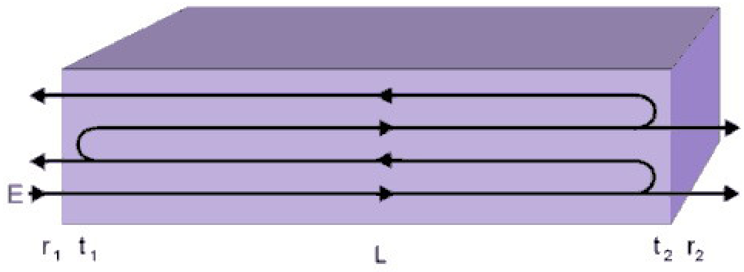


Figure 6: Light feedback [3]

2 Principles of $AlGaAs$ Laser Diodes

In the double heterostructure, stimulated emission occurs only within a thin active layer of $GaAs$, which is sandwiched between p- and n- doped $AlGaAs$ layers that have a wider band gap. Laser diodes use heterojunctions to achieve simultaneous carrier and photon confinement in the active region. A high laser efficiency demands that the light and injected charge carriers be confined as closely as possible to the same volume.

2.1 Heterostructure

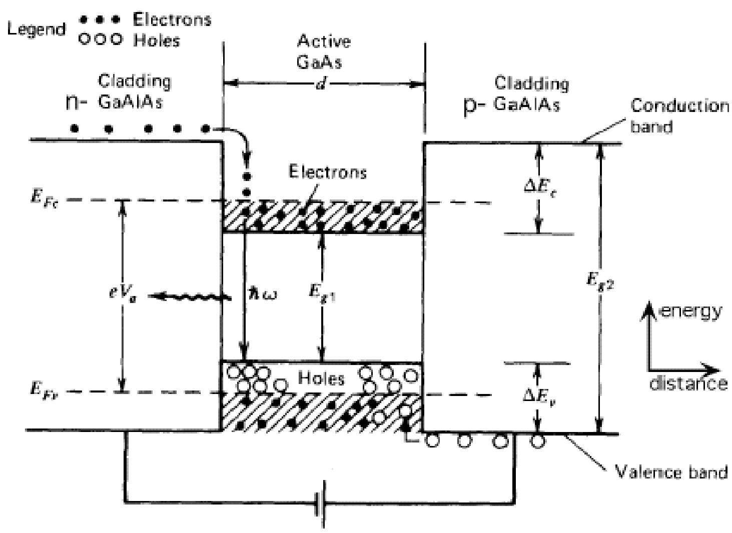
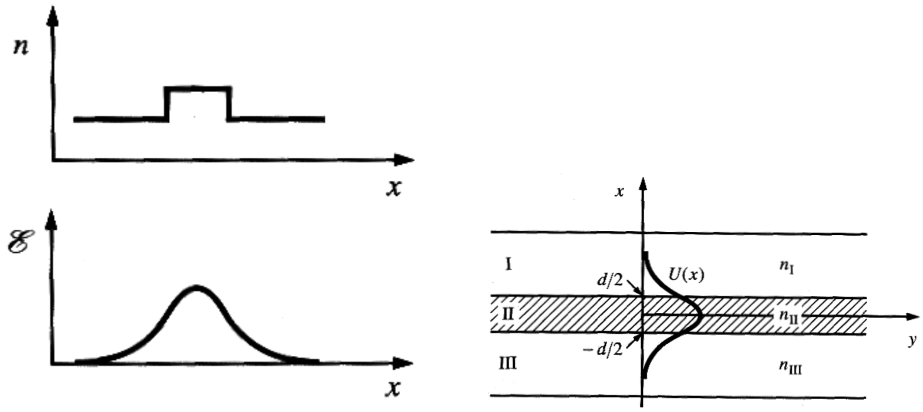


Figure 7: Double heterojunction laser diode [9]

As illustrated in Figure 7, the *AlGaAs* Laser Diode consists of a double heterojunction formed by an undoped (or lightly p-doped) active region surrounded by higher bandgap p and n $Al_xGa_{1-x}As$ cladding layers. The surrounding cladding layers provide an energy barrier to confine carriers to the active region. The actual operation wavelengths may range from 750 − 880 nm due to the effects of dopants, the size of the active region, and the compositions of the active and cladding layers. When a certain parameter is fixed, the wavelength can vary in several nanometers due to other variables. For example, when the active layer has an energy gap $E_g = 1.424$ eV, the nominal emission wavelength is $\lambda = hc/E_g = 871$ nm. 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 larger 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 (Figure 7). The electrons and holes confined to the active layer create a state of population inversion, allowing the amplification of light by stimulated emission. [9]

The cladding layers serve two functions. First, inject charge carriers. Second, light confinement. Since the active region has a smaller bandgap than the cladding layers, its refractive index will be slightly larger than that of the surrounding layers. The *GaAs* refractive index at these wavelengths is $n = 3.5$ while the refractive index of the $Al_xGa_{1-x}As$ cladding layers is slightly smaller. The Figure 8 indicates the electromagnetic field distribution due to the heterostructure. For the confinement in the



(a) Refractive index (b) Field distribution

Figure 8: Refractive index of the waveguide and the field distribution [4]

horizontal (lateral) direction, in real laser structures, index or gain guiding is always used, as mentioned in section 3.1.

The characteristics of a three-layer slab waveguide are conveniently described in terms of the normalized waveguide thickness D, defined as

$$D = \left(\frac{2\pi}{\lambda}\right) d\sqrt{\eta_a^2 - \eta_c^2}$$

where η_a and η_c are the refractive indices of the active and cladding layers respectively and d is the active layer thickness.

The confinement factor Γ, defined as the fraction of the electromagnetic energy of the guided mode that exists within the active layer, is an important parameter representing the extent to the active layer. Γ for a fundamental mode is approximately given by [1]

$$\Gamma \approx \frac{D^2}{2 + D^2}$$

For a $GaAs/Al_{0.3}Ga_{0.7}As$ waveguide with $d = 0.1\,\mu\text{m}$, $\Gamma \approx 0.27$.

2.2 Threshold current

When a sufficient number of electrons and holes are accumulated to form an inverted population, the active region exhibits optical gain and can amplify electromagnetic waves passing through it, since stimulated emission overcomes interband absorption. The wave makes a full round trip in the cavity without attenuation, which means that the optical gain should equal the losses both inside the cavity and through the partially reflecting end facets. Thus, the gain coefficient at threshold g_{th} is given by the relation

$$\Gamma g_{th} = \underbrace{\Gamma\alpha_a + (1 - \Gamma)\alpha_c + \alpha_s}_{\alpha_i} + \frac{1}{L}\ln\frac{1}{R}$$

Here, α_a and α_c denote the losses in the active and cladding layers respectively, due to free-carrier absorption. α_s accounts for scattering loss due to heterointerfacial imperfections between the active and cladding layer. The first three loss terms on the right-hand side combined are termed internal loss α_i and add up to 10 to $20\,\text{cm}^{-1}$. The reflection loss $\frac{1}{L}\ln\frac{1}{R} \approx 40\,\text{cm}^{-1}$ for $L \approx 300\,\text{mum}$, $R \approx 0.3$) due to output coupling is normally the largest among the loss terms.

There is a phenomenological linear relationship between the maximum gain g and the injected carrier density n, supposing $\frac{\partial g}{\partial n}$ and n_t are constant to a good approximation.

$$g(n) = \frac{\partial g}{\partial n}(n - n_t)$$

Here, $\partial g/\partial n$ is termed differential gain, and n_t denotes the carrier density required to achieve transparency where stimulated emission balances against interband absorption corresponding to the beginning of population inversion. Taking $GaAs$ lasers as an example, $\partial g/\partial n \approx 3.5 \times 10^{-6}\,\text{cm}^2$ and $n_t \approx 1.5 \times 10^{18}\,\text{cm}^{-3}$, and remember Γ=0.27, α=10 cm^{-1} and $L^{-1}\ln R^{-1}$=40 cm^{-1}, we get a threshold carrier density n $\approx 2 \times 10^{18}\,\text{cm}^{-3}$. The threshold current density J_{th} is expressed as

$$J_{th} = \frac{edn}{\tau_s}$$

where τ_s is the carrier lifetime due to spontaneous emission. Assuming that τ_s=3ns and d=0.1μm, we obtain a threshold current density $J_{th} \approx 1KAcm^{-2}$. [1]

2.3 Oscillation Modes

In laser diodes, length determines longitudinal modes where width and height of the cavity determines transverse or lateral modes.

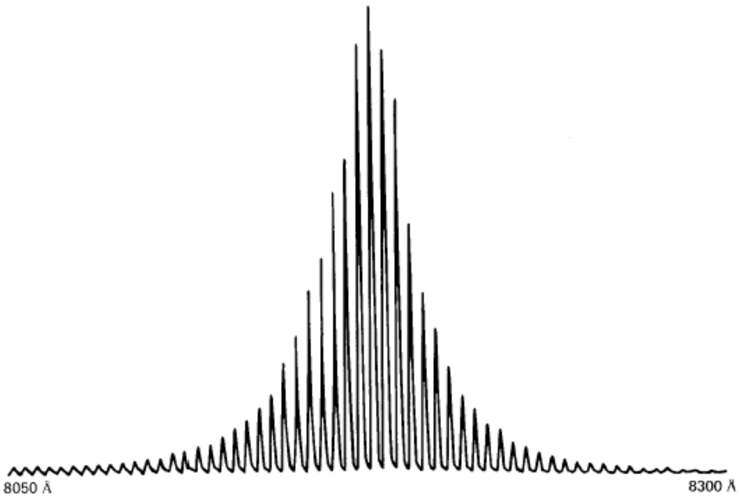


Figure 9: $AlGaAs$ LD Spectrum [9]

Longitudinal Mode The longitudinal modes, or optical resonances of the Fabry-Perot formed by the cleaved facet end mirrors, are determined by the length L of the resonator and the refractive index n of the semiconductor. For electromagnetic wave of wavelength λ, the half-wavelength in the medium is $\lambda/2n$, and for a standing wave, $q\lambda/2n = L$, q is the integral multiple. Variation of the integer q by 1, causes a wavelength variation, $\Delta\lambda$ of 0.35nm, and the laser resonator may simultaneously support several standing waves, or longitudinal modes, of slightly different wavelength. In a laser diode, the oscillation arises at the wavelength corresponding to the band gap energy of the semiconductor, the intensity decreases as the wavelength goes far away from the central wavelength, as indicated in Figure 9. Since the band gap energy varies with temperature, the wavelength with maximum intensity also varies with temperature. For example, the $AlGaAs$ laser diode, the wavelength increases by approximately 0.23nm for an increase in temperature of 1 degree. The free spectral range f_{fsr} is defined as

$$f_{\text{fsr}} = f_2 - f_1 = c\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right) = \frac{c\Delta\lambda}{\lambda^2} = \frac{c}{2nL}$$

The peak separation is defined as

$$\Delta\lambda = \lambda_2 - \lambda_1 = \lambda - \frac{c}{\frac{c}{\lambda} + f_{fsr}}$$

Figure 9 is an example with the center wavelength $\lambda = 817.5$ nm and the peak separation $\Delta\lambda = 0.45$ nm, the free spectral range $f_{\text{fsr}} = \frac{c\Delta\lambda}{\lambda^2} = 200GHz$. [9]

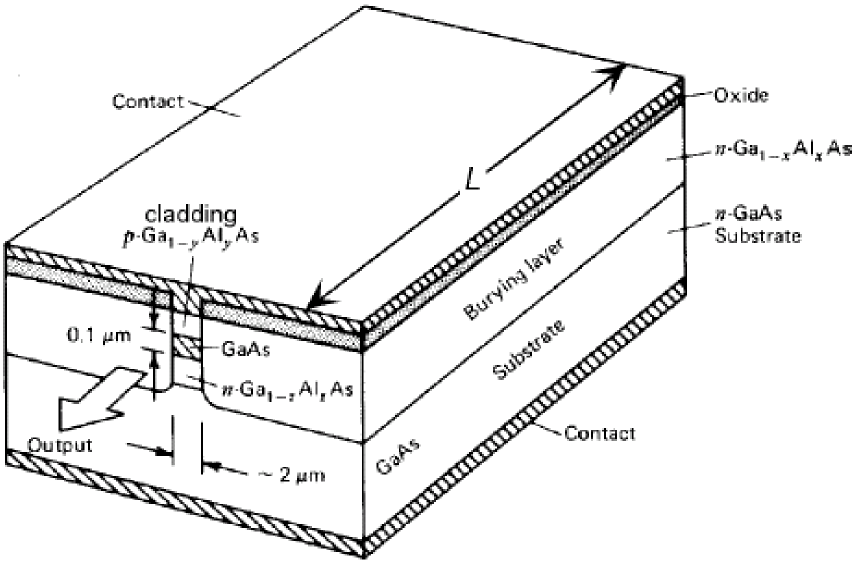


Figure 10: Index guided laser diode [9]

Transverse Modes 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. The laser beam displays a diverging field due to the diffraction at the ends of the cavity. Fig 10 shows the construction of a typical index guided laser diode with cladding layers, electrodes, and *GaAs* active region. The laser cavity mirrors are the end facets of the semiconductor crystal, which has been cleaved.

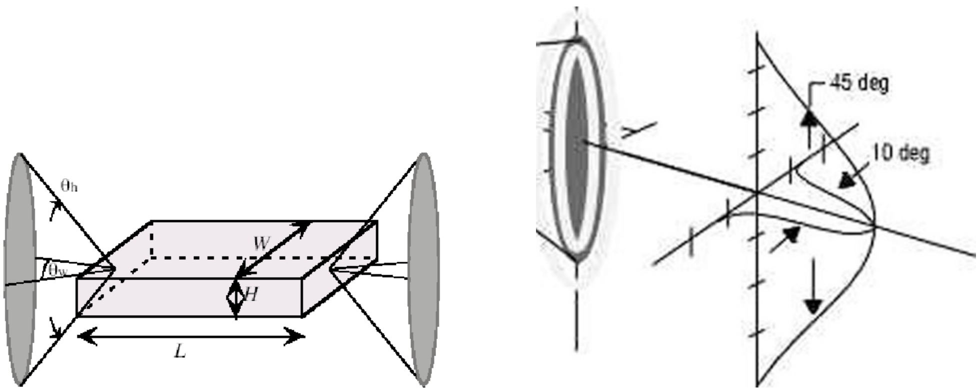


Figure 11: Beam profile from an index guided laser diode [9]

The dimensions of the crystal determine the pattern of the emitted beam (the transverse mode pattern) and also the possible laser emission frequencies (the longitudinal mode pattern). The output pattern is dominated by diffraction because the width $W \approx 10\mu$m and height $H \approx 2\mu$m of typical LDs are comparable to the emission wavelength. The divergence angle of the emission along these two directions is inversely proportional to the dimensions as shown in Fig 11. The angular width ϑ of the emission pattern from a slit or rectangular opening of width d is

$$\vartheta = 2\arcsin(\lambda/d)$$

For example, a laser wavelength of 850 nm and strip width $W = 10\mu$m has a divergence angle $\vartheta_w \approx 10$ deg, $\vartheta_H \approx 45$ deg as shown in Fig 11. The dimensions W and H of the active region of a laser diode can be determined by measuring the output emission cone angles. The smaller the aperture the greater the diffraction, with a sufficiently small W and H, only the lowest transverse mode TEM_{00} exits. [9]

3 Technology of laser diodes

In the further proceedings we are going to take a closer look at different techniques of constructing a laser diode. The focus thereby is on single mode laser diodes. Single mode waves are preferred in most cases. The realm of multimode lasers are high power lasers, where single mode operating is not of importance.

3.1 Real lasers

Most modern semiconductor lasers adopt a structure, where the current is injected only within a narrow region beneath a stripe contact several µm wide, in order to keep the threshold current low and to control the optical field distribution in the lateral direction. Compared with broad-area lasers, where the entire laser chip is excited, the threshold current of lasers with stripe geometry is reduced roughly proportional to the area of contact.

We differ mainly between two different types of structures. In case that the current injection is restricted to a small region along the junction plane these are termed *gain-guided*. Devices incorporating a built-in refractive index variation in the lateral direction are termed *index-guided* lasers. [1]

3.1.1 Gain-guided lasers

With these lasers the current injection is restricted to a narrow region beneath a stripe. The active region is planar and continuous. Lasing however occurs only in a limited region of the active layer beneath the stripe contact where high density of current flows. This horizontal confinement of the em–wave propagating through the active region is thereby accomplished by the small refractive index variation produced by the current generated population inversion. If the em–wave spreads in the horizontal plane outside of the horizontal dimensions of the stripe, it will be absorbed by the unexcited region of the active layer. In the vertical directions the lower refractive indices of the surrounding layers reflects the em–wave back into the active region. [11, 10]

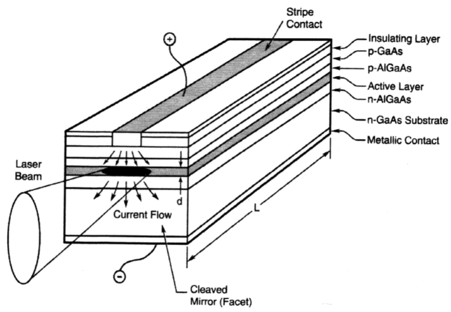


Figure 12: Gain-guided laser [10]

The current restriction serves several purposes: [11]

- it allows CW operation with reasonable low threshold currents (10-100 mA)
- it can allow fundamental-mode operation along the junction plane, which is necessary for applications where the em–wave is coupled into a single mode optical fiber
- the requirements for heat sinking are low.

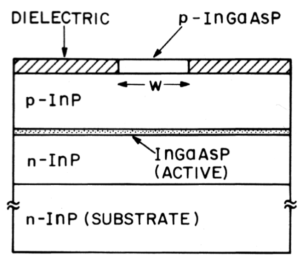


Figure 13: Cross section [11]

Such lasers are determined *gain-guided* lasers because the optical intensity distribution in the lateral direction is determined by the gain profile produced by carrier density distribution.[1]

3.1.2 Index-guided lasers

The transversal mode control in laser diodes can be achieved using index guiding along the junction plane. The mode control is necessary for improving the em–wave current linearity and the modulation response of lasers. The active region is thereby surrounded by materials with lower refractive indices in both the vertical (y) and lateral (x) transverse directions – the active region is buried in lower refractive indices layers (e.g. InP) on all sides. For this reason, these lasers are called *buried-heterostructure* lasers. [9, 1]

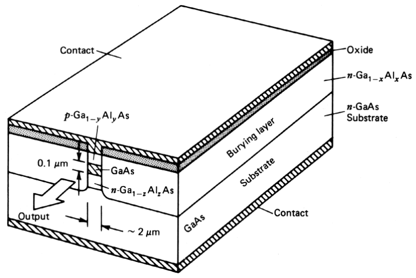


Figure 14: Index-guided laser [9]

The lateral index step along the junction plane is about two magnitudes larger than the carrier induced effects. As a result, the lasing characteristics of buried-heterostructure lasers are primarily determined by the rectangular waveguide that confines the mode inside the buried region. The transverse dimensions of the active region and the index discontinuities are chosen so that only the lowest order transverse modes can propagate in the waveguide. [9, 11]

These index guided devices produce beams with much higher beam quality, but are according to [10] typically limited in power to only a few hundred milliwatts. Another important feature of this laser is the confinement of the injected carriers to the active region. [9]

Buried Heterostructure Lasers Figure 15 shows the schematic cross sections of different types of buried-heterostructure lasers. They are (i) the buried heterostructure that is also called *etched-mesa buried-heterostructure (EMBH)* to distinguish it from other BH lasers. And (ii) the double-channel planar buried heterostructure (DCPHB) laser. [11]

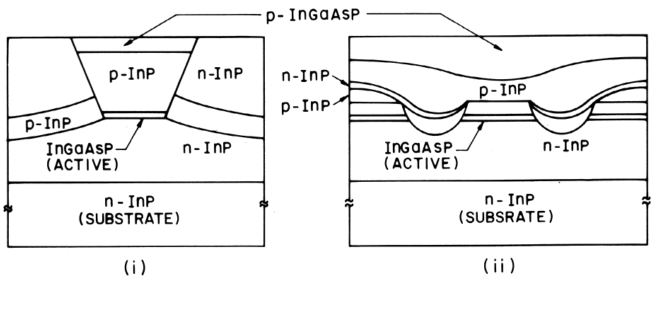


Figure 15: Schematic cross sections of buried-heterostructure lasers [11]

The fabrication of the EMBH structure is technologically complex and two epitaxial steps are necessary. Less critical is the DCPHB laser although this necessitate two epitaxial steps as well. There are other structures which are easier in fabrication, but these are not discussed here.

3.1.3 Gain vs. index-guided structure

Historically, gain-guided devices based on the stripe geometry were developed first in view of their ease of fabrication. However gain-guided lasers exhibit higher threshold currents than index-guided lasers and have other undesirable characteristics that become worse as the laser wavelength increases. [11]

In contrast, the fabrication of strongly index-guided lasers requires either a single epitaxial growth over non-planar surfaces or two epitaxial growths and, in addition, careful attention to processing. In spite of these difficulties in fabrication, their superior performance characteristics – low threshold current, stable fundamental mode operation, and good high speed modulation characteristics – make them a prime candidate for high-performance applications.[11]

3.2 DBR and DFB Lasers

The standard Fabry Perot Laser are not wavelength selective. This lead to lasing of higher modes and allows for mode jumps. So the question is, how wavelength selection can be achieved. Shorter optical cavities are not practical since it is difficult to handle very small chips. Another possible method is to insert an optical feedback in the device to eliminate other frequencies.

Periodic gratings incorporated within the lasers waveguide can be utilized as a means of optical feedback. Devices incorporating the grating in the pumped region are termed *Distributed Feedback* (DFB) lasers, while those incorporating the grating in the passive region are termed *Distributed Bragg Reflector* (DBR) Laser.

DFB and DBR lasers oscillate in a single-longitudinal mode even under high-speed modulation, in contrast to Fabry-Perot lasers, which exhibit multiple-longitudinal mode oscillation when pulsed rapidly. [1]

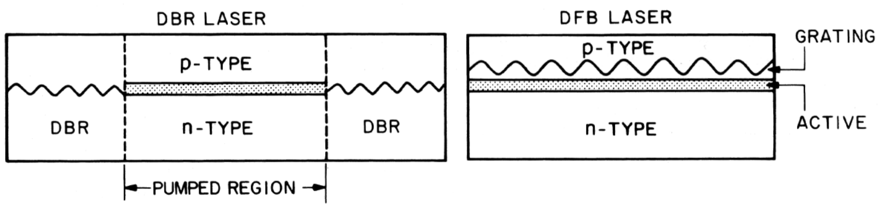


Figure 16: Schematic Illustration of DFB and DBR Lasers [11]

3.2.1 Distributed Bragg Reflector (DBR) Laser

DBR mirrors The gratings or distributed Bragg reflectors (DBRs) are used for one or both cavity mirrors. The grating thereby consist of corrugations with a periodic structure. They are used because of their frequency selectivity of single axial mode operation. The period of grating is chosen as half of the average optical wavelength, which leads to a constructive interference between the reflected beams. Significant reflections can also occur in harmonics frequencies of the medium. The corrugations are typically etched on the surface of the waveguide, and these are refilled with a different index material during a second growth. [4] This is illustrated in figure 17.

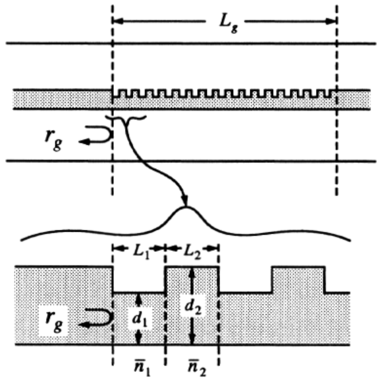


Figure 17: Schematic of a DBR mirror [4]

The concept of the grating is that many reflections can add up to a large net reflection. At the Bragg frequency the reflections from each discontinuity add up exactly in phase. As the frequency is deviated from the Bragg condition, the reflections from discontinuities further into the grating return with progressively larger phase mismatch. [4]

DBR Lasers A DBR Laser can be formed by replacing one or both of the discrete laser mirrors with a passive grating reflector. Figure 18 shows a schematic of such a laser with one grating mirror. Besides the single frequency property provided by the frequency-selective grating mirrors, this laser can include wide tunability. Since the refractive index depends on the carrier density this can be exploited to vary the refractive index electro optically on the sections by separate electrodes.

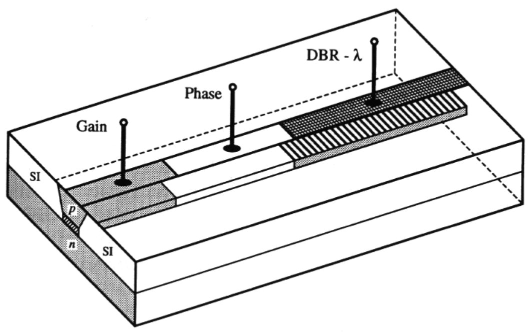


Figure 18: Schematic of a DBR Laser [4]

The potential tunability of DBR Lasers is one of the main reasons why they are of great importance. As indicated in Figure 18, there are usually three sections, one active, one passive, and the passive grating. The first provides the gain, the second allows independent mode phase control and the grating is a mode selective filter. By applying a current or voltage to the sections the refractive index changes, shifting the axial modes of the cavity. [4, 1]

3.2.2 Distributed Feedback (DFB)

A distributed feedback laser (DFB) also uses grating mirrors, but the grating is included in the gain region. Reflections from the ends are suppressed by antireflection coatings. Thus, it is possible to make a laser from a single grating, although it is desirable to have at least a fraction of a wavelength shift near the center to facilitate lasing at the Bragg frequency. The idea behind this concept is, apart from the wavelength selectivity, to improve the quality of the laser, as the active length is a quarter-wavelength long. This applies for no shift in the gratings, where the cavity can be taken to be anywhere within the DFB, since all periods look the same.

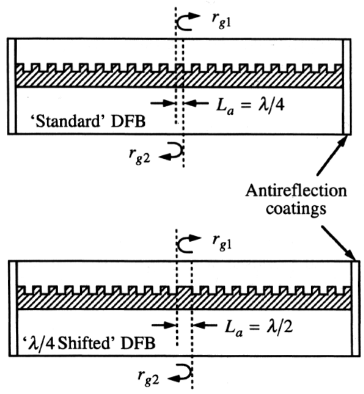


Figure 19: Standard and quarter-wave shifted DFB Lasers [4]

For the standard DFB grating, we can see that the laser is antiresonant at the Bragg frequency. The modes of this laser are placed symmetrically around the Bragg frequency. However only the modes with lowest losses will lase. With symmetrical gain profile around the Bragg frequency, this means that two modes are resonant.

To suppress one mode we need to apply additional perturbation reflections, such as from uncoated cleaves at the end. An alternative method is to introducing an extra quarter wavelength element in the grating. This quarter wave shifted grating is shown in figure 19. This however is more difficult to fabricate. [12, 4]

3.2.3 DFB vs. DBR Lasers

DFB Lasers are easier to fabricate and show less losses and therefore have a lower threshold current. The DBR is widely tunable, but relatively complex since a lot of structure must be created along the surface of the wafer. for this reason DBR Lasers are only formed when their properties are required. Both lasers however work in single mode. [4]

3.3 Laser arrays

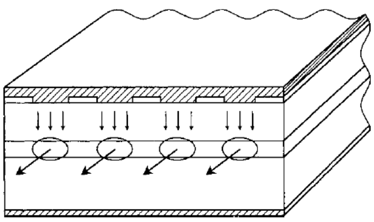


Figure 20: laser diode array [1]

Semiconductor laser structures described so far have been developed for low power applications, such as providing a source in em–wave communication system. Their limitation in the output power mainly arises form the leakage current, which increases with an increase in the applied current. [11]

The major drawbacks of semiconductor lasers, the relatively low output powers, and the high beam divergence can be lowered by integrating multiple laser stripes into an array as shown in Figure 20. The stripes are closely spaced so that the radiation from neighboring stripes is coupled to form a coherent mode of the entire array. These laser diodes operate in multimode, in contrary to those described so far.

The array modes, often referred to as supermodes, are phaselocked combinations of the individual stripe modes and characterized by the phase relationship between the optical fields supported by adjacent stripes. [1]

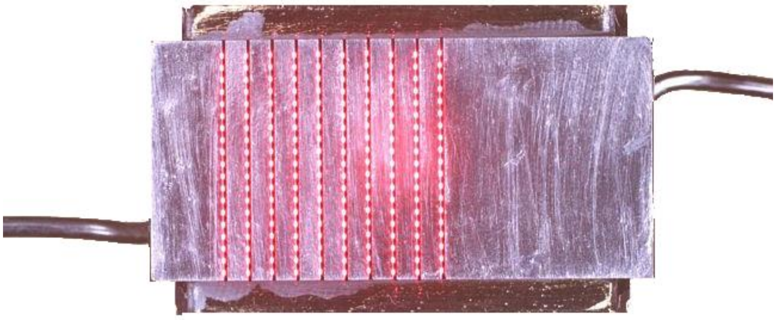


Figure 21: Laserarray with heat sink (by *Laser Diode Array Inc.*)

Laser arrays can be found in applications, where high beam powers and high beam densities are demanded. It therefore suggests itself for pumping of solid state lasers, because the wavelength range from 700 to 900 nm can be covered with appropiate semiconductor materials. [13]

The one-dimensional arrays are also referred to as laserbars. Through stacking of these bars one can build up two-dimensional arrays. With such devices powers up to a few kW have already been achieved. [10]

3.4 VCSEL (Vertical Cavity Surface Emitting Lasers)

A vertical cavity surface emitting laser (VCSEL[1]) is a specialized laser diode with improved efficiency and increased data speed.

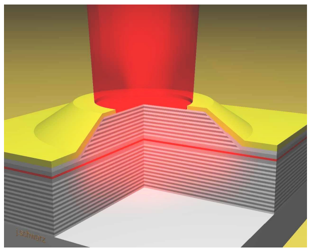


Figure 22: VCSEL laser diode Simulation [14]

Older laser diodes, called edge-emitting diodes, emit coherent em–waves parallel to the boundaries between the semiconductor layers. The VCSEL emits its coherent em–waves perpendicular to the boundaries between the layers.

The VCSEL has several advantages over edge-emitting diodes. The VCSEL is cheaper to manufacture in quantity, is easier to test, and is more efficient. In addition, the VCSEL requires less electrical current to produce a given coherent energy output. The VCSEL emits a narrow, more nearly circular beam than traditional edge emitters. And because of its short cavity length it emits only one mode. [15]

[1]The acronym VCSEL is pronounced ‘vixel’

There are many designs of VCSEL structure however, they all have certain aspects in common. The cavity length of VCSELs is very short typically 1-3 wavelengths of the emitted em–wave. As a result, in a single pass of the cavity, a photon has a small chance of triggering a stimulated emission event at low carrier densities. Therefore, VCSELs require highly reflective mirrors to be efficient. In edge-emitting lasers, the reflectivity of the facets is about 30%. For VCSELs, the reflectivity required for low threshold currents is greater than 99.9%. Such a high reflectivity can not be achieved by the use of metallic mirrors. VCSELs make use of Distributed Bragg Reflectors. (DBRs) as described on page 17. These are formed by laying down alternating layers of semiconductor or dielectric materials with a difference in refractive index. Semiconductor materials used for DBRs have a small difference in refractive index therefore many periods are required. Since the DBR layers also carry the current in the device, more layers increase the resistance of the device therefore dissipation of heat may become a problem. [3]

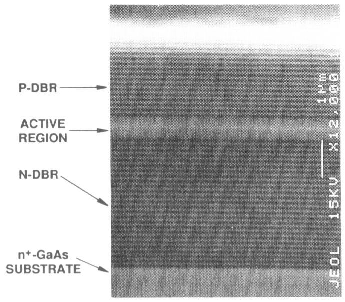
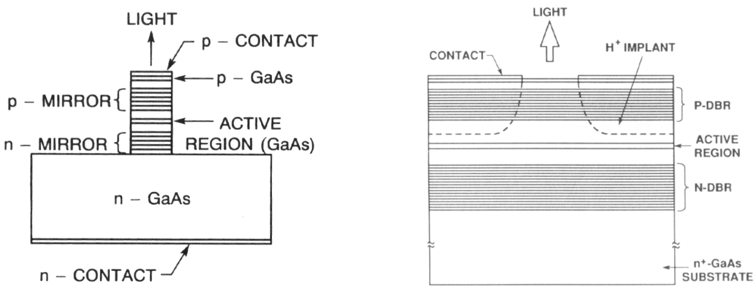


Figure 23: Layers of DBR mirrors



(a) mesa etched (b) ion implanted

Figure 24: Different designs of VCSELs [11]

As well as reducing the dimensions of the cavity one can reduce the threshold current of a VCSEL device by limiting the cross-sectional area in which gain occurs. There are a number of different types of lasers, which generally differ in the way in which high-reflectivity mirrors and current confinement is achieved.

One simple method is to etch a pillar down to the active layer. These are termed mesa[2] etched structure. Etched mesas are typically a few micrometer in diameter which allows fabrication of a large number of lasers on a single substrate. The large difference in refractive index between the air and device material also act to guide the em–wave emitted. However, for practical use a suitable bonding scheme is required. A polyamide can be used for filling up the region around the etched mesas, to allow a practical bonding scheme. Another problem with this type of structure are the loss of carriers due to surface recombination at the sidewalls and poor dissipation of heat from the laser cavity.

[2]Webster Definition for 'mesa': isolated hill having steeply sloping sides and a level top

Another technique for current confinement is ion implantation. By selectively implanting ions into a semiconductor a region of high resistivity around a 10 μm diameter opening is produced. This scheme reduces current spreading, producing a region of high gain at the center of the opening where laser action takes place.

Since the substrate is absorbing in these cases, em–waves are emitted from the top. It can also be emitted from the bottom by using a structure in which the substrate near the emitting region has been etched away. [11, 3]

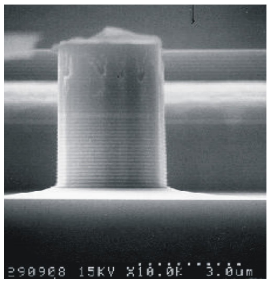
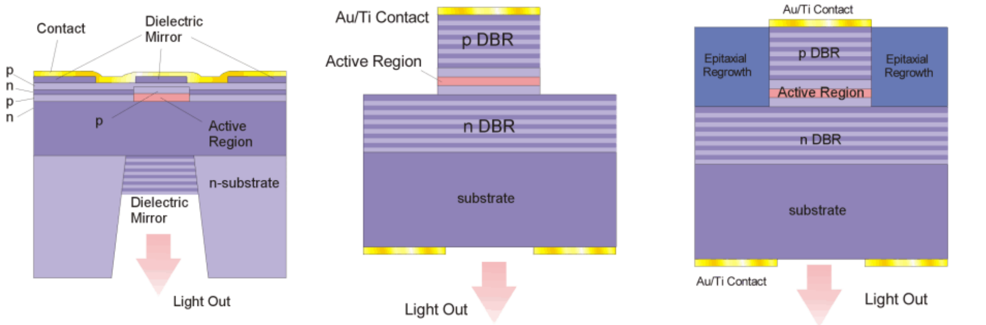


Figure 25: Etched Mesa



(a) Etched Well VCSEL (b) Air Post VCSEL (c) Burried Regrowth VCSEL

Figure 26: Other possible designs of VCSELs [3]

Appendix

Materials, wavelenght and typical applications

GaN	AlGaAs/GaAs	InGaAsP/InP	AlGaAsSb/GaSb
420 - 520 nm	780 - 870 nm	1300 - 1550 nm	1700 - 5000 nm
blue - green	near infrared	near infrared	middle/far infrared
optical datastorage	optical transimssion for short ranges	optical transmission for large ranges	research

Abbrevitations

This table provides a list of frequently used abbrevitations in the subject of laser diodes.

VB	Valance band
CB	Conduction band
SCL	space charge layer
BH	Buried Heterostructure
CW	Contiuous Wave
DBR	Distributed Bragg Reflector
DFB	Distributed Feedback Bragg
DHS	Double Heterostructure
LD	Laserdiode
MQW	Multiple Quantum Well
QW	Quantum Well
QC	Quantum Cascade
QD	Quantum Dot
VCSEL	Vertical Cavity Surface Emitting Laser

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[14] University of Stuttgart. http://www.physik.uni-stuttgart.de/ExPhys/4.Phys.Inst./Forschung/VCSEL/vcsel.html.

[15] http://whatis.techtarget.com/. vertical cavity surface emitting laser. http://whatis.techtarget.com/definition/0,,sid9_gci803517,00.html.