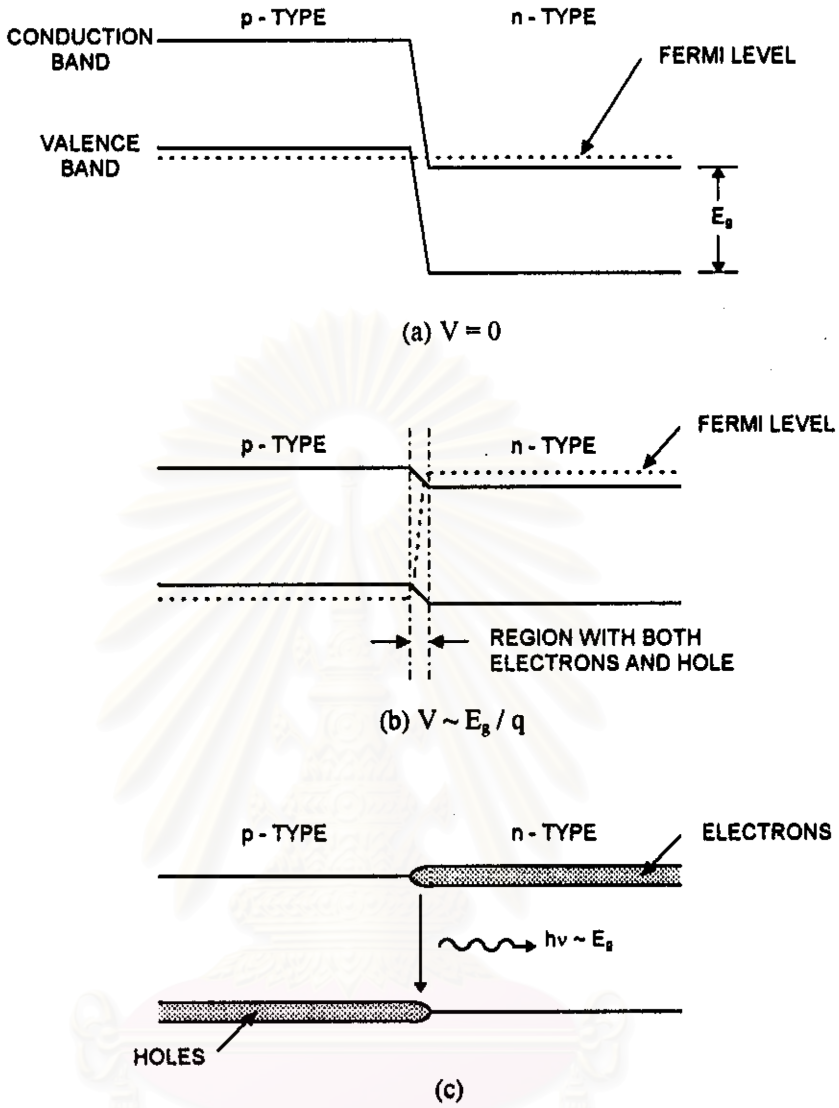
CHAPTER 2

Basic conception on laser diode structures

This chapter is intended to review the basic structures of laser diode which have been fabricated in research laboratories and commercial industries. Some of the structures are out-of-date but they are still shown for the historical investigation. This chapter consist of 12 sections containing a structure description and also providing its advantages and disadvantages. However, there is not "the best" structure for laser diode, each structure is fit to some applications and fabrication techniques which are discussed in many sections.

2.1 Homojunction laser diode

As seen in the word "diode", the heart of a laser diode is the p-n junction. The energy-band diagram and fermi level are shown in Fig. 2.1 of the p-n *homojunction*. When the p-n junction is forward-bias by applying an external voltage, the built-in electric field is reduced, making a further diffusion of electrons and holes across the junction. As Fig. 2.1b shows, in a narrow depletion region, both electrons and holes are present simultaneously and can recombine either radiatively or nonradiatively. Photons of energy $h\nu \cong E_g$ are emitted during the radiative recombination. However, these photons can also be absorbed through a reverse process that generates electron-hole pairs. When the external voltage exceeds a critical value, a condition known as *population inversion* is achieved, in which the rate of photon emission exceeds that of the absorption. The p-n junction is then able to amplify the electromagnetic radiation and exhibits *optical gain*. However, the homojunction, the thickness of the region, where the gain is sufficiently high and very small (~0.01 μm) since there is no mechanism to confine the charge carriers. Very high injected current is required for radiation which heats up the junction, then it is necessary to operate the laser under a low-temperature condition.



(a) $V = 0$

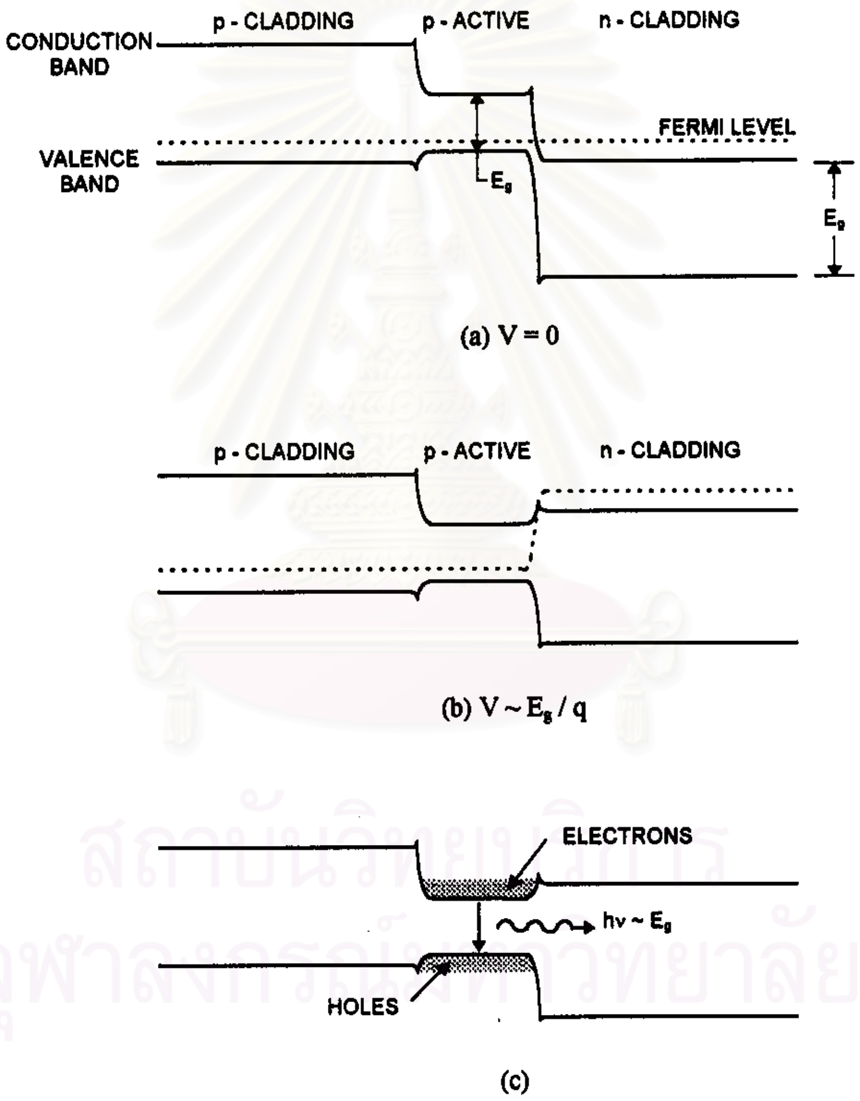
(b) $V \sim E_g / q$

(c)

Fig. 2.1 Energy-band diagram of a p-n junction at (a) zero bias and (b) forward bias. (c) Schematic representation of the electron and hole densities under forward bias. Radiative recombination of electrons and holes in the narrow overlapping region generates light.

2.2 Double heterojunction (DH) laser diode

The carrier-confinement problem can be solved by using a p-n heterojunction, Fig. 2.2 shows its energy band diagram which the thin p-type active layer has a lower bandgap compared to that of the two p-type and n-type cladding layers. Electrons and holes can move freely to the active layer under forward bias. However, once there, they can not cross over to the other side because of the potential barriers resulted from the bandgap differences. This allows for a substantial build-up of the electron and hole populations inside the active layer, where they can recombine to produce optical gain. The width of the gain region is determined by the active-layer thickness, typically 0.1~0.3 μm. The phenomenon of carrier confinement results in significantly lower threshold current density (compared with a homojunction) and lets the laser diodes to a room-temperature operation.



(a) $V = 0$

(b) $V \sim E_g / q$

(c)

Fig. 2.2 Energy-band diagram of a double-heterostructure laser diode at (a) zero bias and (b) forward bias. (c) The bandgap discontinuities at the two heterojunctions help to confine electrons and holes inside the active region, where they recombine to produce light.

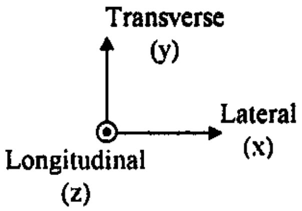
The other physical reason for the reduction in the threshold current density is an optical-mode confinement mechanism. The cladding layers surrounding the active layer have a lower refractive index compared with those of the active layer. By the refractive index difference, the photons can be transversely confined within this active layer by *index-guided* mechanism which will be discussed later in the next chapter.

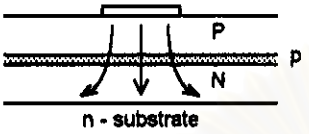
2.3 Broad-area and stripe-geometry laser diode

A double heterostructure laser diode as shown in Fig. 1.1b is sometimes called a *broad-area* laser since it does not incorporate for the lateral confinement of the injected current or the optical mode. As early as 1967, *stripe-geometry* homostructure lasers were purposed [11] to limit the lateral spread of the injected carriers inside the active layer. In these lasers, the current is injected over a narrow (~10 μm) central region using stripe contact. The stripe geometry was adapted for heterostructure [12] in 1971 as shown in Fig. 2.3a. Injected current from a top stripe contact will cross two heterojunction and spread, which leads to a bell-shaped gain distribution in the lateral direction. Therefore in this direction, light is only confined by the gain distribution and not by any index steps, as in case of the transverse direction. For this reason, these lasers are called *gain-guided* lasers [13].

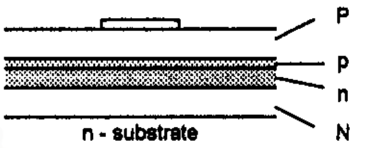
2.4 Large optical cavity (LOC) laser diode

The thickness of active layer in a DH laser determines the threshold-current density and the optical beam characteristics at the same time. In a number of cases, a reliable operation at high power output is required, however, a large spot size, so that the optical flux density is kept below levels of catastrophic mirror damage (sometimes called *catastrophic optical damage (COD)* level). One approach for increasing the laser spot size is to use the *large optical cavity (LOC)* structure. As shown in Fig. 2.3b, the optically confined layers, shaded area in the figure, is composed of the active layer and a n-type waveguiding layer. In this case, the photon confinement is uncoupled from the carrier confinement and the optical power is spread over wider region. Then the large spot size and high power operation are obtained as well as narrow beam divergence in the transverse plane [14].

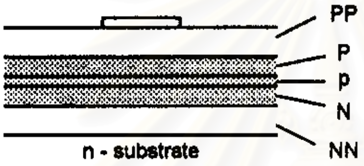




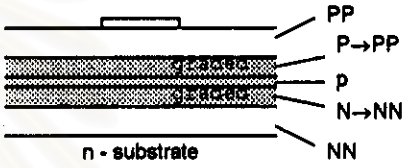
(a) Standard DH



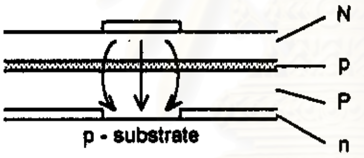
(b) LOC



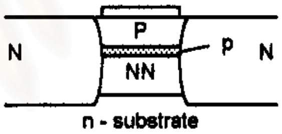
(c) SCH



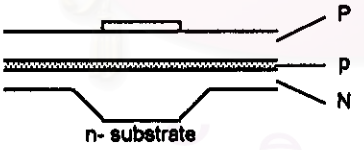
(d) GRIN-SCH



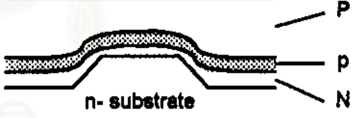
(e) DH with blocking layer



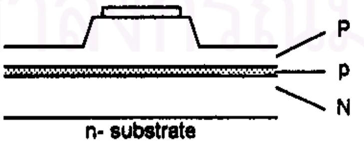
(f) BH



(g) CSP



(h) CDH



(i) Ridge Waveguide

Fig. 2.3 Various laser diode structures. The thin contacting top layer (or cap layer) has been omitted for clarity and the longitudinal direction is perpendicular to the XY plane.

2.5 Separate confinement heterostructure (SCH) laser diode

It should be realized that there is an alternative for the waveguiding structure, *separate confinement heterostructure (SCH)* laser diode (Fig. 2.3c). PP and NN in this figure designate cladding layers with higher bandgap and lower refractive index than the P and N waveguiding layers. the very thin active region is located at the center of the optically confined region. This placement minimizes the optical intensity distributions of the odd-order transverse modes [15]. As a result, all of the odd modes are completely suppressed irrespectively to the width of the optically confined region and a symmetrically optical beam in the transverse direction is obtained. Moreover, in the same width of optically confined region, the SCH laser diode also produces higher optical output than the conventional LOC ones.

2.6 Graded-index separate confinement heterostructure (GRIN-SCH) laser diode

In some cases, the P and N waveguiding layers are graded such that the bandgap increases away from the active layer while the refractive index decreases. These lasers are called *graded-index separate confinement heterostructure* or *GRIN-SCH* laser diode (Fig. 2.3d). Compared with the regular symmetrically SCH laser, The GRIN-SCH provides a lower threshold current density, due to two major reasons [16]. Firstly, the graded region acts as a "funnel" to enhance the collection of electrons in the active layer. Secondly, it efficiently guides the electromagnetic wave as in an optical fiber of graded refractive index, thereby maintaining a significant overlap of the optical and electrical distribution. The GRIN-SCH laser also offers the ability to control the transverse near- and far-field distributions of the output beam [15] to match the particular type of optical fiber in use and to suit the imaging optics in various optical systems.

According to refractive-index profile of graded region, the GRIN-SCH laser diodes can be classified as linear- and parabolic-GRIN-SCH structures shown in Fig. 2.4b and 2.4c respectively. In a GRIN-SCH with linear profile, the effective thickness of the recombination region and the recombination current in the optically confined region are significantly reduced, and thus the injection efficiency is increased from the regular SCH laser diode [17]. When a GRIN-SCH laser has a parabolic profile, the optical modes supported in the transverse direction are Hermite-Gaussian [15]. By making the very thin active layer and locating it at the center of confined region, this provides additional strong mode discrimination against higher order transverse modes for the parabolic-GRIN-SCH laser diode.

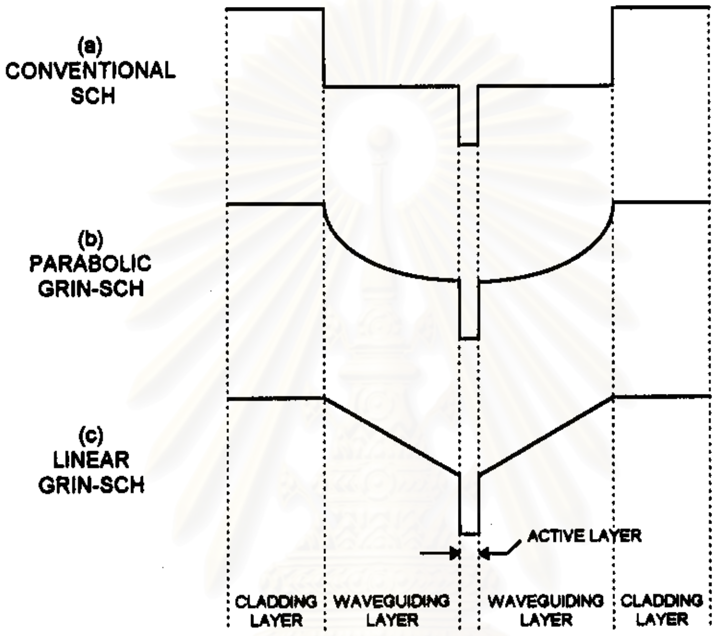


Fig. 2.4 Index profiles of SCH structures (a) conventional SCH (b) parabolic GRIN-SCH and (c) linear GRIN-SCH.

2.7 Current blocking layer included laser diode

For the striped-geometry laser diode, using the gain-guided mechanism for the lateral confinement, the bell-shaped current spreading is not ideal for high efficiency. The use of a *blocking layer* (Fig. 2.3e) will confine the current at the interface between substrate and cladding layer [13]. It is advantageous to make use of an inverted dopant type structure here (p-type substrate), since an n-type blocking layer between p-layers is allowed to be much thinner than a p-type blocking layer in the opposite situation due to the difference in minority carrier diffusion lengths. A disadvantage using a blocking layer is of course the necessity for two epitaxy growth runs.

2.8 Buried heterostructure (BH) laser diode

As mentioned before, the optical field is not truly guided in the lateral direction. In the *buried heterostructure (BH)* laser diode (Fig. 2.3f), this problem is solved through a two-step epitaxy process in which the active layer is totally embedded in a lower refractive-index material as in the optical fibers. In this way, true index-guiding both in the transverse and lateral direction is obtained. By optimization of the design parameters such as material compositions and doping concentrations, the structure can provide both carrier and optical confinement as well.

The proposed structure of a BH laser will produce some unique features as following : (i) extremely low threshold current comparing with gain-guided lasers, due to excellent current confinement in the stripe region [18], (ii) stable transverse mode, symmetrically beam profile and non-astigmatic beam pattern [19], (iii) quite high modulation bandwidth of ~21 GHz [20], (iv) output stability during accelerated aging [21], (v) low COD level [19], and (vi) fewer longitudinal modes (often only one) in laser spectrum [13]. For these reasons, BH laser diode is suitable for imaging applications and long distance fiber optic communication. This does not mean that the BH laser is a *true dynamic single mode (DSM)* laser, because longitudinal-mode hopping is very likely to occur under modulating [13]. The other disadvantage is that the higher order mode is likely to lase at high output power level [19].

2.9 Channeled substrate planar (CSP) laser diode

For BH laser diode, two-step epitaxy growth is necessary. It is possible to obtain index-guiding in the lateral direction by only one epitaxy growth process, such as in *channeled substrate planar (CSP)* structure [22,23] (Fig. 2.3g) which has the planar layers grown on a grooved-channel substrate. In this non-planar structure, there is not a true lateral change in refractive index but the optical field see an effective refractive index change as a result of the lateral variation in the optical confinement factor and the active layer thickness.

It should be noted that an advantageous performance of CSP compared with BH laser is the more stable fundamental-mode operation. The CSP laser diode can has a stable operation at the high output power level [9,19] because of the suppression of the higher order modal gain by the light absorption into the substrate outside the channel. Then the light-output vs. current (L-I) characteristic can reveal the "kinkless" or linearity over the whole range of emitted power [22]. The "kinks" in L-I curves are the phenomenon occurred in many stripe-geometry laser diodes [24,25]. They are usually accompanied with unfavorable anomalous lasing characteristics such as increased noise, beam direction shifts, and deterioration of modulation characteristics [22]. The other advantage of CSP over BH laser diode is the higher COD level. However, it still has a problem in the astigmatism which is not excellent as BH laser.

2.10 Constricted double heterostructure (CDH) laser diode

The stable single-mode operation can be achieved by an alternative of a *constricted double heterostructure (CDH)* [14,26,27] laser diode (Fig. 2.3h). In contrast to the CSP structure, the curved epitaxy are grown on a mesa-cross-section substrate. The CDH laser diode also produces lateral index change via effective refractive index which index-guiding mechanisms in both transverse and lateral directions are obtained. Although only one epitaxy growth process is more simple than the BH laser, a tight control of curved-epitaxy thickness and shape in growth process is required for a reproducible fabrication of CDH laser diode.

2.11 Ridge waveguide (RW) laser diode

Presently, the most popular structure used for lateral confinement is *ridge waveguide (RW)* laser diode (Fig. 2.3i). In this structure, the electrical confinement is achieved by limiting the current flow to a narrow stripe window opened in an insulator on the top surface of the device. The lateral optical confinement is provided by etching the part of the material outside the ridge (wing regions) in order to obtain a sufficient refractive index decrease in the etched region, thus creating an optical waveguide. The waveguiding mechanism is determined by the effective index approximation method.

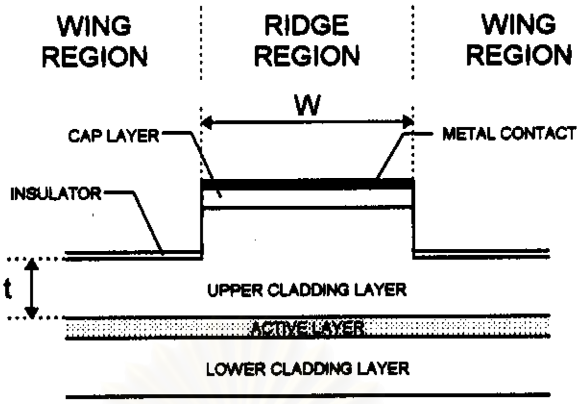


Fig. 2.5 Cross-section schematic of ridge waveguide (RW) laser diode.

The need to accurately control the ridge dimension and shape is very important. (i) In case of ridge height, if the wings are not etched deeply enough, the laser is gain-guided, and the high degree of antiguiding in this system increases the threshold current density by more than an order of magnitude [28]. If the wings are etched too deeply, the laser will exhibit multiple lateral (spatial) modes. The etch-stop layer has been used for precise control of the etch depth [28,29] which implies to the thickness of residual upper cladding layer outside the ridge (t) shown in Fig. 2.5. (ii) In case of ridge width (w), if the ridge is too wide, the multiple modes are occurred. If the ridge is too narrow, less optical confinement is obtained. It can be achieved the high optical confinement and the single fundamental mode operation by the optimum dimension of the residue thickness (t) and the width (w) of ridge [30] which will be discussed in next chapter. (iii) At last, the ridge with rectangular cross section is the most desired shape. By wet chemical etching, it can not produce this ultimate shape, its cross-section patterns of the etched shape are mesa, inverse-mesa and waist [31]. The waist structure is an unpleasant shape due to the polarization bistability issue [32].

Like CSP and CDH laser diode, the stable mode operation is obtained at the high output level [33] but the RW laser diode has simpler growth processing because the planar epitaxy growth is more controllable than the curved growth in CDH and CSP.

The RW lasers containing the undoped active layer can produce the high modulation bandwidth of 20-24 GHz [20,34], while those containing the p-doped active layer can achieve 33 GHz bandwidth [34]. Both the undoped and p-doped RW laser diode also demonstrate the best modulation current efficiency factors exceeding 5 GHz/mA$^{1/2}$ [34]. Not only have very high modulation bandwidths been achieved, but also very high relaxation frequencies of the RW structure have been reported [35].

Although the BH structure is providing the lowest threshold current, it has so far an almost inevitably irregular surface with steep mesa steps which degrade the reproducibility of the fine lithographic patterns involved in the subsequent process steps. Then the BH structure is obviously not suitable to be integrated into a monolithic optoelectronics integrated circuits (OEIC's) anymore [36]. Several attempts have already been made to employ ridge waveguide lasers as optical sources for OEIC's [37,38]. This structure has the advantages of being easy to fabricate and compatible to many applications such as in the OEIC's, as it requires only one epitaxy growth step and one accurately etching process.

2.12 Other structures

Fig. 2.6 shows the summary classification of the laser diode structure which have been described in this chapter. However, all of the laser diode fabricated today are the combinations of the transverse and lateral confinement structures, for example, CDH-LOC [27] and LCSP [39]. Moreover, a number of modified structures have been reported such as buried-RW [40], IID-RW [41], tapered/flared waveguide [42,43], BH on ridge [44], inverted-RW [45] and PIN-SCH [46,47]. It is likely that the regular active layer with ~0.1-0.3 μm thickness is converted to the very thin active layer with less than 10 nm leading to the quantum size effect, then a laser containing this layer are called a *quantum well (QW)* laser which have been published by many groups [16,34,35,38,41,48]. Sometimes the single longitudinal modes operation is achieved in a *distributed-feedback (DFB)* laser diode [30,48,49] which apply the grating layer into the laser structure.

The described laser diodes are known as the *edge-emitting lasers* which their resonance cavities are in the longitudinal direction which parallel to the junction plane. The *vertical-cavity surface-emitting lasers (VCSEL's)* have been proposed [50-53] which have been developed for a two-dimensional laser array or monolithic integration of lasers with electronic components.

Anyway, in this chapter could not collect the whole of laser structures established in the world, but it might be an initial idea for further developments of laser diode structures.

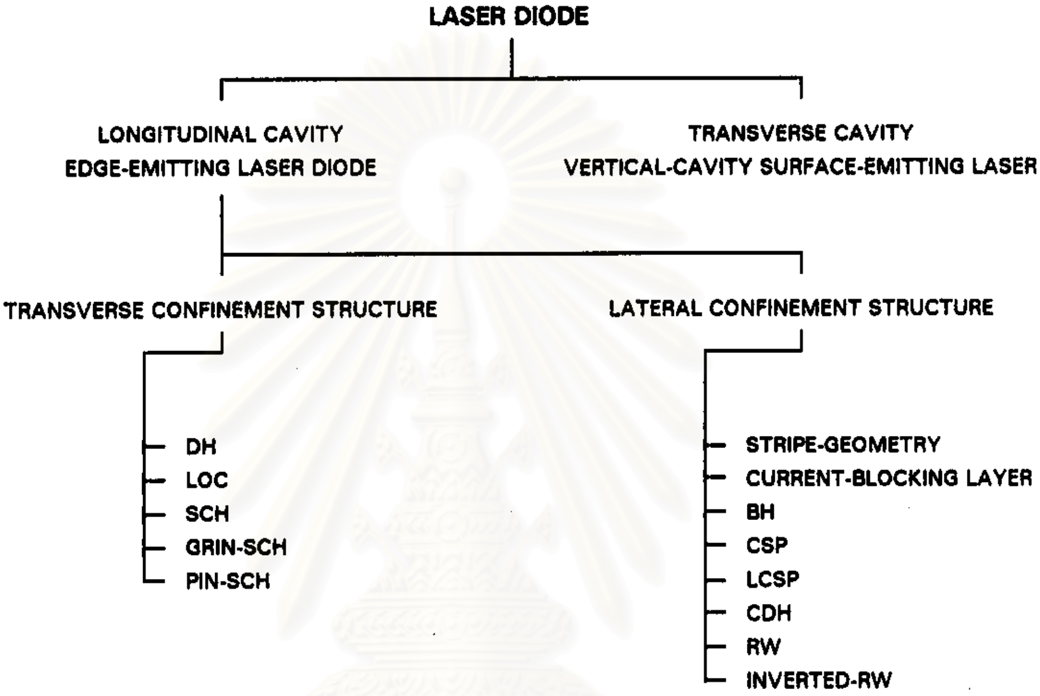


Fig. 2.6 Summary classification of laser diode structures.