Injection Laser

The electroluminescent properties of the forward-biased *p–n* junction diode have been considered in the preceding sections. Stimulated emission by the recombination of the injected carriers is encouraged in the semiconductor injection laser (also called the injection laser diode (ILD) or simply the injection laser) by the provision of an optical cavity in the crystal structure in order to provide the feedback of photons. This gives the injection laser several major advantages over other semiconductor sources (e.g. LEDs) that may be used for optical communications. These are as follows:

1. High radiance due to the amplifying effect of stimulated emission. Injection lasers will generally supply milliwatts of optical output power.

2. Narrow linewidth on the order of 1 nm (10 Å) or less which is useful in minimizing the effects of material dispersion.

3. Modulation capabilities which at present extend up into the gigahertz range and will undoubtedly be improved upon.

4. Relative temporal coherence which is considered essential to allow heterodyne (coherent) detection in high-capacity systems, but at present is primarily of use in single-mode systems

5. Good spatial coherence which allows the output to be focused by a lens into a spot which has a greater intensity than the dispersed unfocused emission.

This permits efficient coupling of the optical output power into the fiber even for fibers with low numerical aperture. The spatial fold matching to the optical fiber which may be obtained with the laser source is not possible with an incoherent emitter and, consequently, coupling efficiencies are much reduced

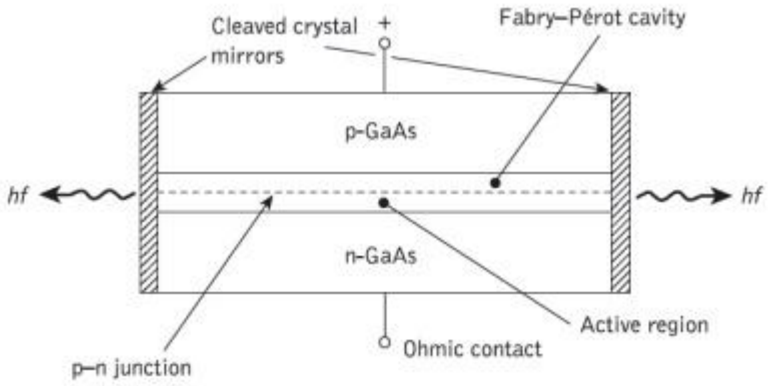


Figure 3.4 Schematic diagram of a GaAs homojunction injection laser with a Fabry–Pérot cavity

[Source: htpp://img.brainkart.com]

These advantages, together with the compatibility of the injection laser with optical fibers (e.g. size), led to the early developments of the device in the 1960s. Early injection lasers had the form of a Fabry–Pérot cavity often fabricated in gallium arsenide which was the major III–V compound semiconductor with electroluminescent properties at the appropriate wavelength for first-generation systems. The basic structure of this homojunction device is shown in Figure 3.4, where the cleaved ends of the crystal act as partial mirrors in order to encourage stimulated emission in the cavity when electrons are injected into the *p*-type region. However, as mentioned previously these devices had a high threshold current density (greater than 104 A cm−2) due to their lack of carrier containment and proved inefficient light sources.

High current densities required dictated that these devices when operated at 300 K were largely utilized in a pulsed mode in order to minimize the junction temperature and thus avert damage. Improved carrier containment and thus lower threshold current densities (around 103 A cm−2) were achieved using heterojunction structures.

The DH injection laser fabricated from lattice-matched III–V alloys provided both carrier and optical confinement on both sides of the *p*–*n* junction, giving the injection laser a greatly enhanced performance. This enabled these devices with the appropriate heat sinking to be operated in a CW mode at 300 K with obvious advantages for optical communications (e.g. analog transmission). However, in order to provide reliable CW operation of the DH injection laser it was necessary to provide further carrier and optical confinement which led to the introduction of stripe geometry DH laser configurations. Prior to discussion of this structure, however, it is useful to consider the efficiency of the semiconductor injection laser as an optical source.

Stripe Geometry

The DH laser structure provides optical confinement in the vertical direction through the refractive index step at the heterojunction interfaces, but lasing takes place across the whole width of the device. This situation is illustrated in Figure 3.5 which shows the broad-area DH laser where the sides of the cavity are simply formed by roughening the edges of the device in order to reduce unwanted emission in these directions and limit the number of horizontal transverse modes. However, the broad emission area creates several problems including difficult heat sinking, lasing from multiple filaments in the relatively wide active area and unsuitable light output geometry for efficient coupling to the cylindrical fibers.

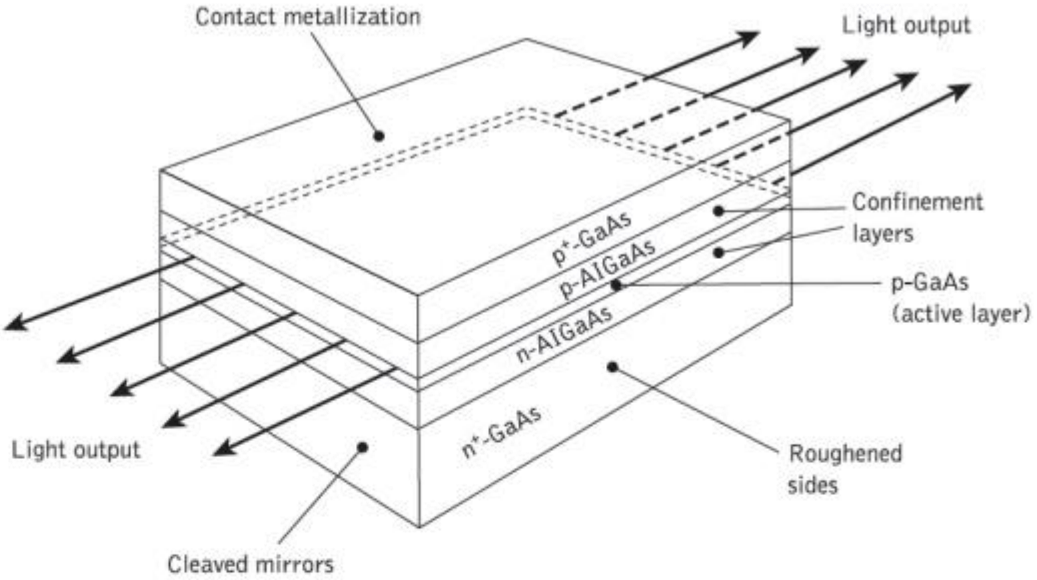


Figure 3.5 A broad-area GaAs/AlGaAs DH injection laser

[Source: htpp://img.brainkart.com]

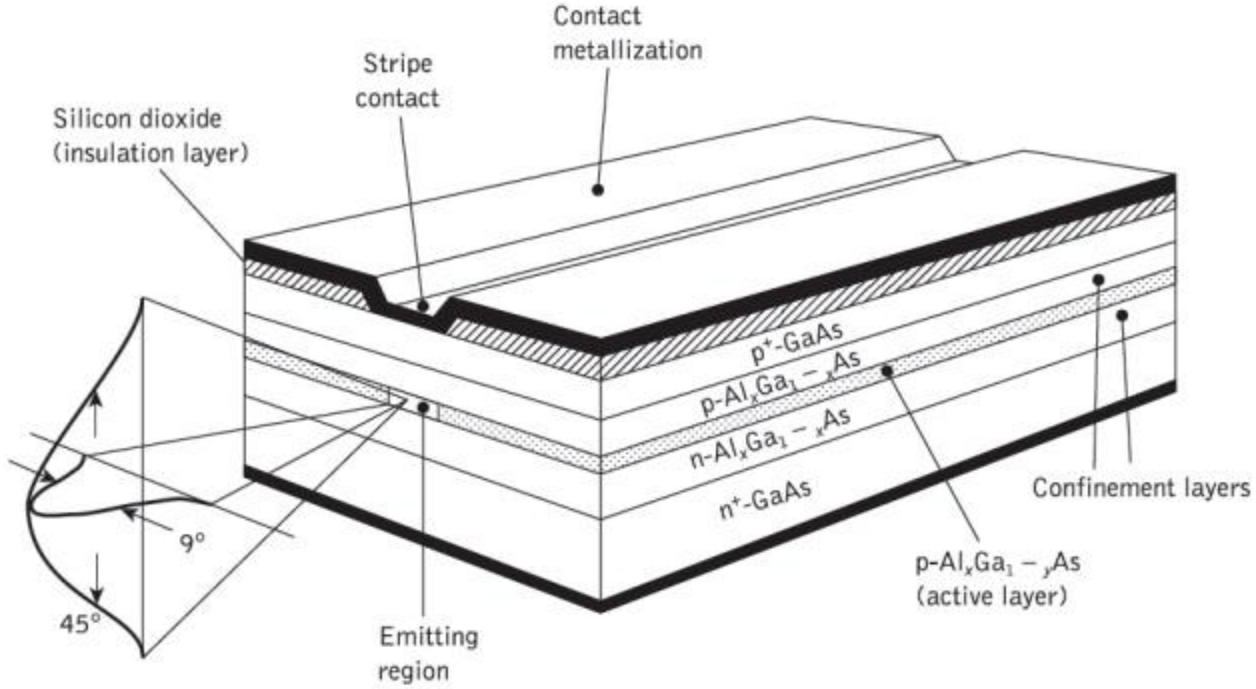


Figure 3.6 Schematic representation of an oxide stripe AlGaAs DH injection laser

[Source: htpp://img.brainkart.com]

To overcome these problems while also reducing the required threshold current, laser structures in which the active region does not extend to the edges of the device were developed. A common technique involved the introduction of stripe geometry to the structure to provide optical containment in the horizontal plane. The structure of a DH stripe contact laser is shown in Figure 3.6 where the major current flow through the device and hence the active region is within the stripe. Generally, the stripe is formed by the creation of high-resistance areas on either side by techniques such as proton bombardment or oxide isolation.

The stripe therefore acts as a guiding mechanism which overcomes the major problems of the broad-area device. However, although the active area width is reduced the light output is still not particularly well collimated due to isotropic emission from a small active region and diffraction within the structure. The optical output and far-field emission pattern are also illustrated in Figure 6.21. The output beam divergence is typically 45° perpendicular to the plane of the junction and 9° parallel to it. Nevertheless, this is a substantial improvement on the broad-area laser.

Injection Laser Structures

1. Gain-Guided Lasers.

Fabrication of multimode injection lasers with a single or small number of lateral modes is achieved by the use of stripe geometry. These devices are often called gain-guided lasers. The constriction of the current flow to the stripe is realized in the structure either by implanting the regions outside the stripe with protons (proton isolated stripe) to make them highly resistive, or by oxide or *p–n* junction isolation. The structure for an aluminium gallium arsenide oxide isolated stripe DH laser was shown in Figure 3.6. It has an active region of gallium arsenide bounded on both sides by aluminium gallium arsenide regions. This technique has been widely applied, especially for multimode laser structures used in the shorter wavelength region. The current is confined by etching a narrow stripe in a silicon dioxide film.

Two other basic techniques for the fabrication of gain-guided laser structures are illustrated in Figure3.7(a) and (b) which show the proton-isolated stripe and the *p*–*n* junction isolated stripe structures respectively. In Figure 3.7(a) the resistive region formed by the proton bombardment gives better current confinement than the simple oxide stripe and has superior thermal properties due to the absence of the silicon dioxide layer; *p*–*n* junction isolation involves a selective diffusion through the *n*-type surface region in order to reach the *p*-type layers, as illustrated in Figure 1(b). None of these structures confines all the radiation and current to the stripe region and spreading occurs on both sides of the stripe.

With stripe widths of 10 μm or less, such planar stripe lasers provide highly efficient coupling into multimode fibers, but significantly lower coupling efficiency is achieved into small-core-diameter single-mode fibers. However, with certain practical laser diodes the characteristic is not linear in the simulated emission region, but exhibits kinks. This phenomenon is particularly prevalent with gain-guided injection laser devices. The kinks may be classified into two broad categories.

The first type of kink results from changes in the dominant lateral mode of the laser as the current is changed. The output characteristic for laser *A* in Figure 3.8(a) illustrates this type of kink where lasing from the device changes from the fundamental lateral mode to a higher order lateral mode (second order) in a current region corresponding to a change in slope. The second type of kink involves a ‘spike’, as observed for laser *B* of Figure 3.8(a). These spikes have been shown to be associated with filamentary behaviour within the active region of the device. The filaments result from defects within the crystal structure.

Both these mechanisms affect the near- and far-field intensity distributions (patterns) obtained from the laser. A typical near-field intensity distribution corresponding to a single optical output power level in the plane of the junction is shown in Figure 3.8(b).

As this distribution is in the lateral direction, it is determined by the nature of the lateral waveguide. The single intensity maximum shown indicates that the fundamental lateral mode is dominant. To maintain such a near-field pattern the stripe geometry of the device is important. In general, relatively narrow stripe devices (< 10 μm) formed by a planar process allow the fundamental lateral mode to dominate.

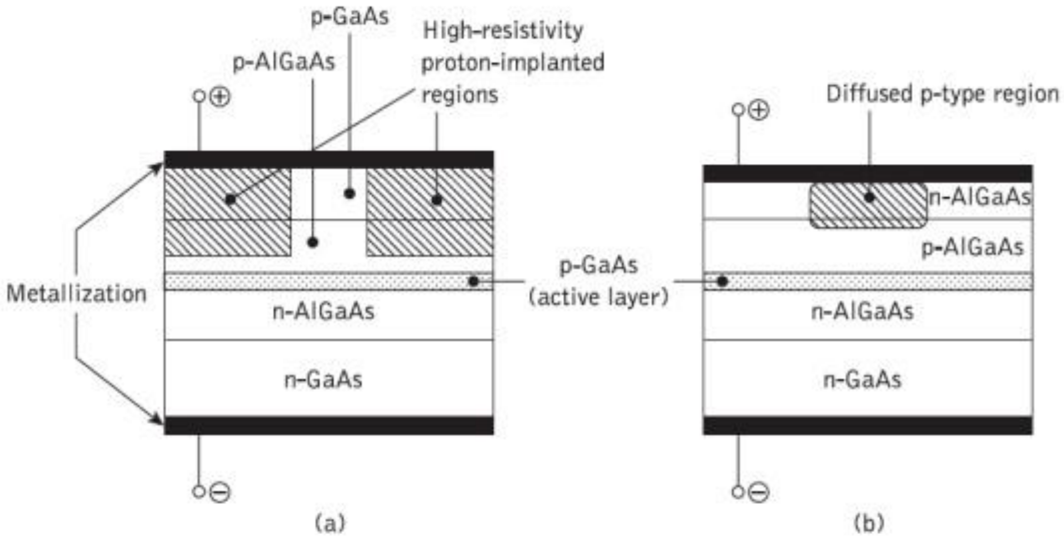


Figure 3.7 Schematic representation of structures for stripe geometry injection lasers: (a) proton-isolated stripe GaAs/AlGaAs laser; (b) *p–n* junction isolated (diffused planar stripe) GaAs/AlGaAs laser

[Source: htpp://img.brainkart.com]

This is especially the case at low power levels where near-field patterns similar to Figure 3.8(b) may be obtained. Although gain-guided lasers are commercially available for operation in both the shorter wavelength range (using GaAs active regions) and the longer wavelength range (using InGaAsP active regions) they exhibit several undesirable characteristics.

Apart from the nonlinearities in the light output versus current characteristics discussed above, gain-guided injection lasers have relatively high threshold currents (100 to 150 mA) as well as low differential quantum efficiency. These effects are primarily caused by the small carrier-induced refractive index reduction within the devices which results in the movement of the optical mode along the junction plane. The problems can be greatly reduced by introducing some real refractive index variation into the lateral structure of the laser such that the optical mode along the junction plane is essentially determined by the device structure.

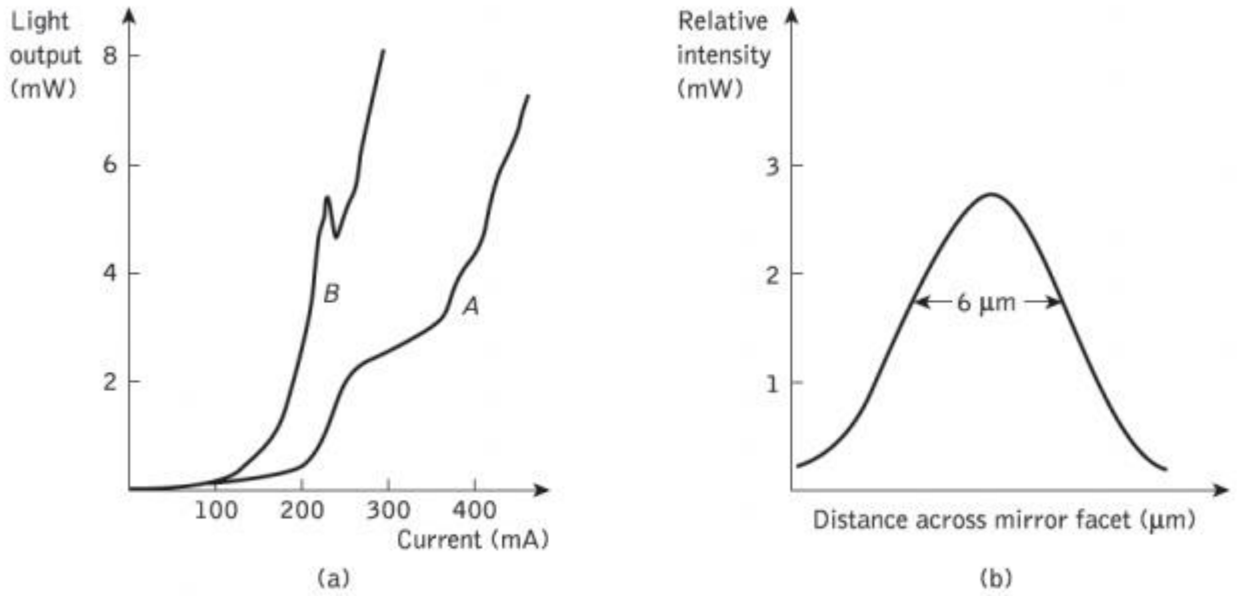
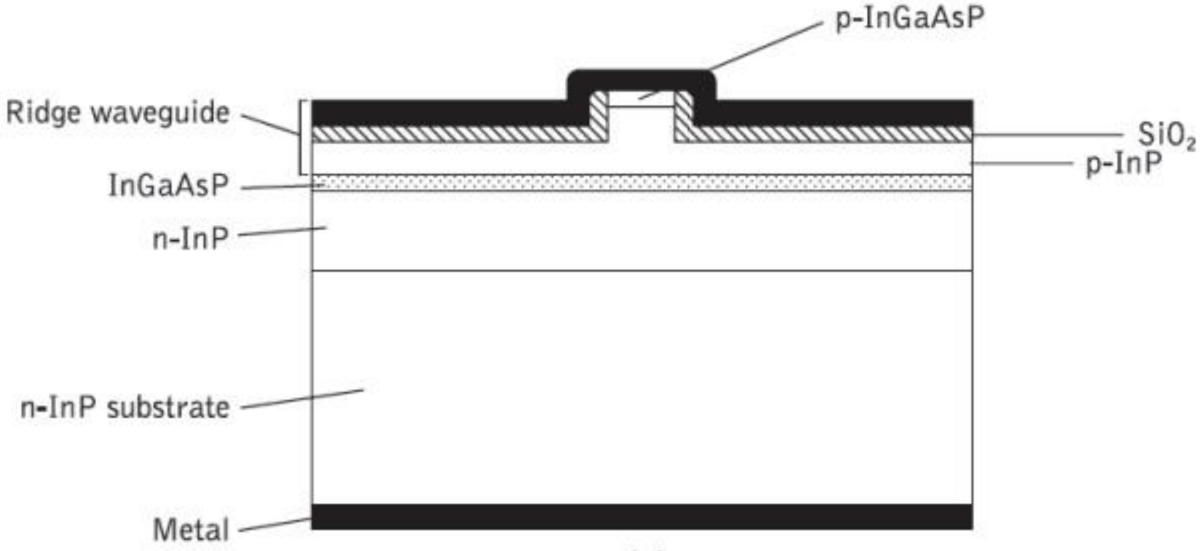


Figure 3.8 (a) The light output against current characteristic for an injection laser with nonlinearities or a kink in the stimulated emission region. (b) A typical near-field intensity distribution (pattern) in the plane of the junction for an injection laser

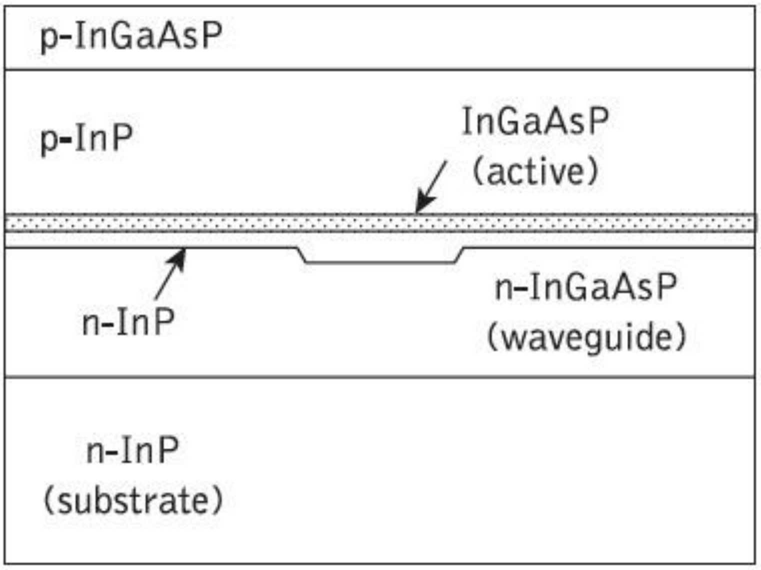
[Source: htpp://img.brainkart.com]

2. Index-Guided Lasers

The drawbacks associated with the gain-guided laser structures were largely overcome through the development of index-guided injection lasers. In some such structures with weak index guiding, the active region waveguide thickness is varied by growing it over a channel or ridge in the substrate. A ridge is produced above the active region and the surrounding areas are etched close to it (i.e. within 0.2 to 0.3 μm). Insulating coatings on these surrounding areas confine the current flow through the ridge and active stripe while the edges of the ridge reflect light, guiding it within the active layer, and thus forming a waveguide. Hence in the ridge waveguide laser shown in Figure 3.9 (a), the ridge not only provides the location for the weak index guiding but also acts as the narrow current confining stripe. These devices have been fabricated to operate at various wavelengths with a single lateral mode, and room temperature CW threshold currents as low as 18 mA with output powers of 25 mW have been reported.



(a)



(b)

Figure 3.9 Index-guided lasers: (a) ridge waveguide injection laser structures; (c) rib (plano-convex) waveguide injection laser structure

[Source: htpp://img.brainkart.com]

More typically, the threshold currents for such weakly index-guided structures are in the range 40 to 60 mA, which compares a light output versus current characteristic for a ridge waveguide laser with that of an oxide stripe gain-guided device. Alternatively, the application of a uniformly thick, planar active waveguide can be achieved through lateral variations in the confinement layer thickness or the refractive index. However, room temperature CW threshold currents are between 70 and 90 mA with output powers of around 20 mW for InGaAsP devices operating at a wavelength of 1.3 μm.

3. Quantum-Well Lasers

DH lasers have also been fabricated with very thin active layer thicknesses of around 10 nm instead of the typical range for conventional DH structures of 0.1 to 0.3 μm. The carrier motion normal to the active layer in these devices is restricted, resulting in a quantization of the kinetic energy into discrete energy levels for the carriers moving in that direction. This effect is similar to the well-known quantum mechanical problem of a one dimensional potential well and therefore these devices are known as quantum well lasers. In this structure the thin active layer causes drastic changes to the electronic and optical properties in comparison with a conventional DH laser.

These changes are due to the quantized nature of the discrete energy levels with a step-like density of states which differs from the continuum normally obtained. Hence, quantum-well lasers exhibit an inherent advantage over conventional DH devices in that they allow high gain at low carrier density, thus providing the possibility of significantly lower threshold currents. Both single-quantum-well (SQW), corresponding to a single active region, and multiquantum-well (MQW), corresponding to multiple active regions, lasers are utilized. In the latter structure, the layers separating the active regions are called barrier layers. Energy band diagrams for the active regions of these structures are displayed in Figure 3.10. It may be observed in Figure 3.10(c) that when the bandgap energy of the barrier layer differs from the cladding layer in an MQW device, it is usually referred to as a modified multiquantum-well laser.

Better confinement of the optical mode is obtained in MQW lasers in comparison with SQW lasers, resulting in a lower threshold current density for these devices. A substantial amount of experimental work has been carried out on MQW lasers using the AlGaAs/GaAs material system. It has demonstrated the superior characteristics of MQW devices over conventional DH lasers in relation to lower threshold currents, narrower line widths, higher modulation speeds, lower frequency chirp and less temperature dependence.

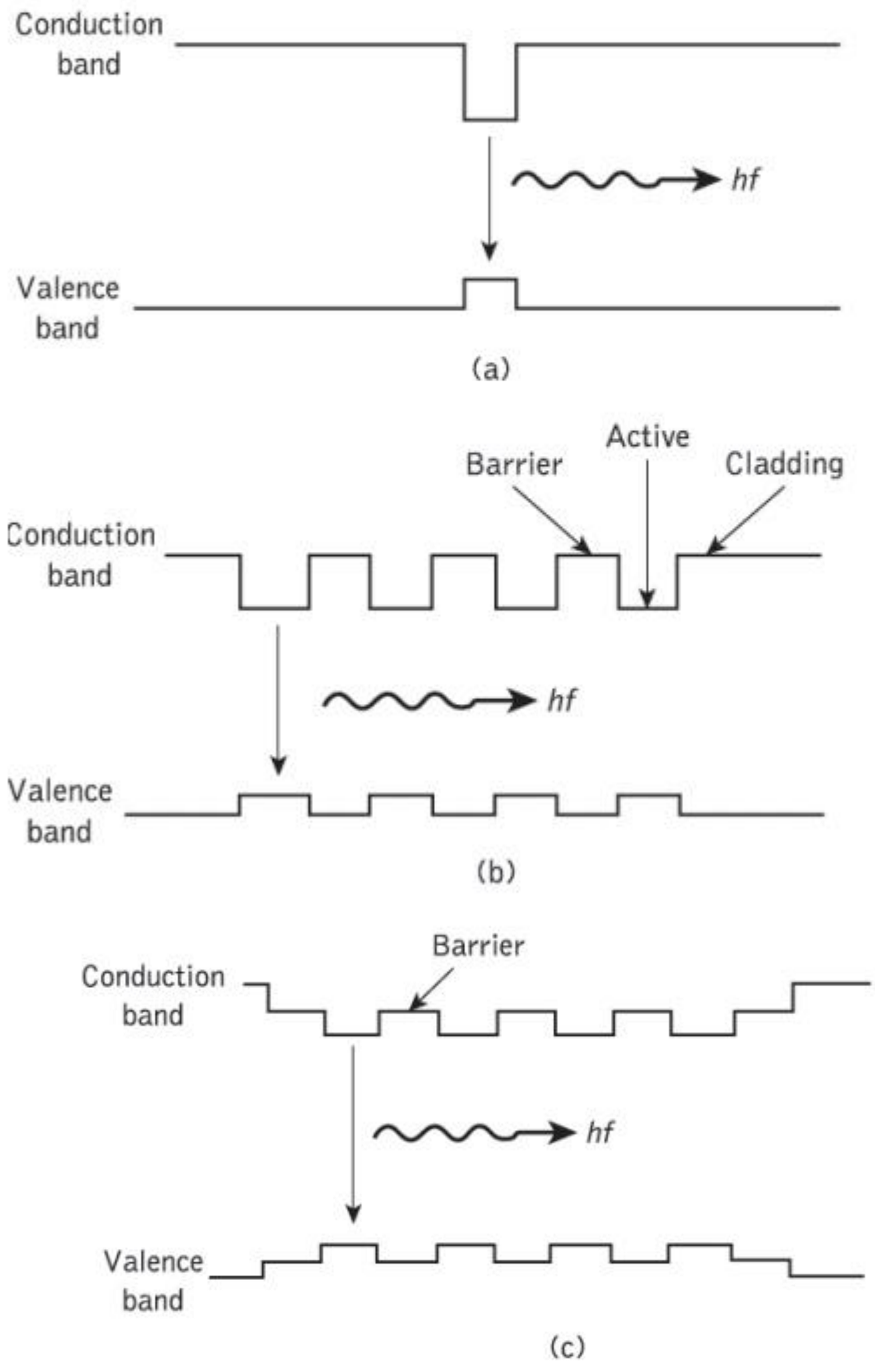


Figure 3.10 Energy band diagrams showing various types of quantum-well structure: (a) single quantum well; (b) multiquantum well; (c) modified multiquantum well

[Source: htpp://img.brainkart.com]