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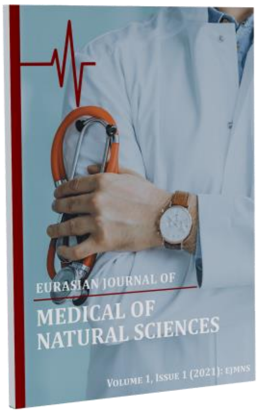

HETEROJUNCTION LASERS

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ABSTRACT

The main parameters of a heterojunction laser diode, such as the emission frequency spectrum (optical modes), threshold current, output radiation power, and operating efficiency, are considered. A simplified formula for the radiation intensity of a heterostructure laser is obtained. It is shown that, due to reflection from the ends, the light repeatedly passes through the active region and is predominantly amplified by stimulated emission. A standing wave is established inside the laser diode with an integer number of half-waves between the end surfaces.

It is known that population inversion is achieved most easily and efficiently in p–n junctions due to electron injection. In heavily doped (degenerate) semiconductors, when different electronic or hole states correspond to the same energy value, the Fermi levels in the p- and n-regions are within the allowed bands, and at thermal equilibrium these levels for electrons and holes coincide (fig.1 a). In the region of the p–n junction, a potential barrier is formed that does not allow the transition of the main carriers from zone to zone. If, on the other hand, a voltage U is applied to the junction in the forward direction, then the potential barrier in the region of the p–n junction decreases by the value of the energy corresponding to this voltage. As a rule, this voltage is applied to the junction, as a result of which the equilibrium of current carriers is disturbed. If at thermal equilibrium the distribution of electrons and holes could be described using the quasi-Fermi level, then in the presence of an applied electric field, the occupation of states should be considered separately for the conduction band and separately for the valence band. When the forward bias is turned on, a diffusion flow of electrons through the p–n junction arises, which tends to raise the quasi-Fermi level Fn for electrons in the p–n region to its level in the n region.

The injected electrons, after diffusing over a short distance determined by the diffusion length, recombine with holes; as a result, a steady state arises, in which the rate of electron recombination is exactly balanced by the rate of their injection. The arguments are completely analogous for holes in the valence band. In the presence of a stationary state, the position of quasi-Fermi levels for two types of carriers in the transition region changes Fig. 1(b). The majority carriers are pulled out of contact to provide a neutral condition. Currently, laser diodes are mainly made from GaAs or $Ga_{1-x}Al_xAs$.

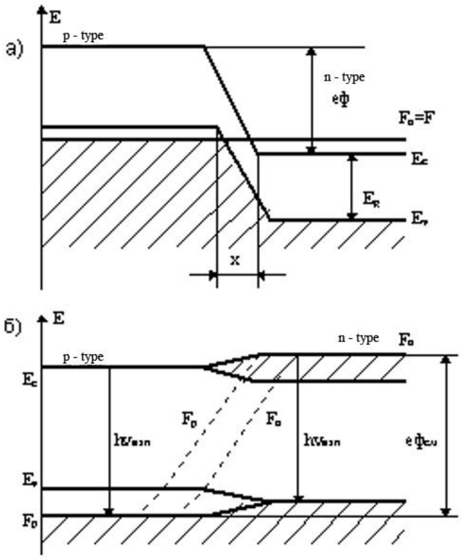

Fig.1. Band diagram of a heavily doped (degenerate) semiconductor

The structure of a laser diode based on a p–n junction is shown in Fig. 2. The p–n junction is usually formed by growing a p-type layer on an n-type substrate by epitotsia. The electric current is the source of the pump energy necessary to create a population inversion in the active zone adjacent to the p–n junction. Two parallel end surfaces are made by cleaving along the crystallographic axis to act as resonator mirrors and create positive optical feedback necessary for generating radiation. Due to the high refractive index of the semiconductor material, the reflection coefficient from the faces is 30–35%. The side faces of the laser crystal are roughened in order to suppress unwanted transverse propagation of light.

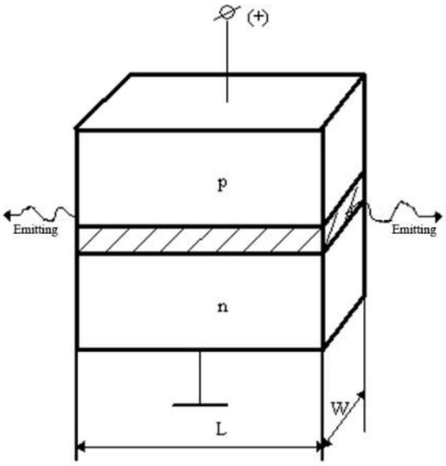

Fig. 2 Laser structure

The main parameters of a laser diode include the emission frequency spectrum (optical modes), threshold current, output radiation power and operating efficiency. When current is passed through a laser diode, then light is generated by population inversion through spontaneous and stimulated emission. Due to reflection from the ends, the light repeatedly passes through the active region and is predominantly amplified by stimulated emission.

Inside the laser diode, a standing wave is established with an integer number of half-waves between the end surfaces. The mode number m is given by the number of half-waves

$m=2Ln/L_w$,

where L is the distance between the ends; n is the refractive index; L_w is the wavelength of radiation in vacuum. The mode separation can be established by taking the derivative dm/dL_w . Then

$dm/dL_w=-2Ln/ L_w^2+(2L/ L_w)(dn/ dL_w)$.

With dm=-1, which corresponds to the loss of one half-wave in the resonator, we obtain an expression for mode separation:

$dL_w= dL_w^2/\{2L[n- L_w(dn/ dL_w)]\}$.

The emission spectrum of the laser diode is shown in Fig.3. Usually there are several longitudinal modes having wavelengths near the spontaneous emission peak. The mode separation for a semiconductor laser based on GaAs is $dL_w=0.3$ nm. In order for the laser to operate in a single-mode mode, it is necessary to suppress unwanted side modes in some way, leaving the main central one.

The laser diode does not immediately begin to radiate when a voltage is applied to it from an external source. At a low current, spontaneous emission takes place (Fig. 3) with a width of the emission spectrum of several hundred micrometers.

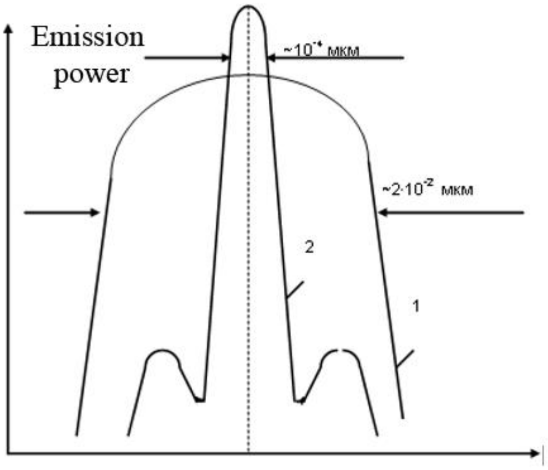

Fig. 3 A sharp change in the shape of the spectral distribution curve from a wide spontaneous emission distribution curve 1 to a curve with several narrow modes 2

As the pump current increases, a high degree of population inversion is created in the region of the p–n junction and more light is emitted. Individual photons repeatedly pass strictly in the plane of the p-n junction and are amplified perpendicular to the ends of the diode. With an increase in the pump current, the radiation emitted by the diode is significantly narrowed simultaneously in the width of the spectrum and in the spatial divergence. When stimulated emission occurs, the intensity of the emission increases due to the formation of a large number of electron-hole pairs per unit time. Spontaneous emission is suppressed due to the fact that the initially formed photons repeat themselves when passing through the active region. The radiation of a laser diode, obtained at current densities above the threshold, is coherent. In this case, the shape of the spectral distribution curve changes sharply from a broad spontaneous emission distribution curve 1 to a curve with several narrow modes 2 (Fig. 3).

The value of the threshold current, depending on the nature of the material and geometrical parameters, can be obtained from the following reasoning. Let there be a light-emitting layer of thickness D in the region of the p–n junction, which is greater than the thickness d of the layer with inverse population. Then it can be assumed that of all the existing electron-hole pairs, only a fraction of d/D remains in the active region and can participate in induced emission.

Let us assume that a light wave propagates in a crystal and a light flux of power Ps falls on each end surface, and the reflection coefficient from the end is p. In the presence of laser radiation, the product pPs increases exponentially as a function of the core length L. The existing losses of the light wave are significantly offset by laser amplification due to stimulated emission. Each end of the diode emits light with a power

$P_{out}/2=(1-p)P_s$.

If μ [cm^{-1}] is the loss factor for the wave during its propagation in the crystal, H[cm^{-1}] is the amplification factor, then the power, depending on the distance traveled by the wave along the active region, will be

$P=pP_s\exp[H(d/D)-\mu]z$.

The amplification of the wave occurs only in the region with inverse population, so the value of H must be multiplied by d/D, while losses occur throughout the volume and therefore the coefficient μ does not have such a factor. Then, when passing through a crystal of length L, we will have:

$P=pP_s\exp[H(d/D)-\mu]L$; $\log(1/p)=[H(d/D)-\mu]L$.

Thus, the condition for laser radiation has the form

$H(d/D)=\mu+(1/L)\ln(1/p)$. (1)

The gain H is related to the injected current density. The expression for the value of H will be

$H=gL_w^2I/(8en^2dV)$, (2)

where for GaAs at room temperature the quantum efficiency is g=0.7 , the radiation wavelength in vacuum is $L_w=9\cdot 10^{-6}$ cm, the refractive index is n=3.34 at L_w ; V is the spontaneous emission bandwidth, $V=1.5\ 10^{13}\ s^{-1}$; e is the electron charge; d is the thickness of the active region, $d=10^{-4}$ cm; I is the injected current density.

Expression (2) is valid for subthreshold current. Substituting (2) into (1), we learn $(gL_w^2I)/(8en^2VD)=\mu+(1/L)\ln(1/p)$ (3)

The left side in expression (3) describes the amplification of the wave in one pass, and the right side describes the losses . From (3) we find the value of the threshold current sufficient to cover the losses:

$I=(8en^2VD)/(gL_w^2I)(\mu+(1/L)\ln(1/p))$ (4)

The term (1/L) ln(1/p) determines the radiation losses. The reflection coefficient can be expressed in terms of the transmittance T=1-p, and then the expansion of ln[1/(1-T)] into a series has the form

$(1/L)\ln(1/p)=(1/L)\ln[1/(1-T)]=(1/L)[T-(T^2/2)+(T^3/3)-(T^4/4)+\ldots]$.

Neglecting the higher order terms in T, we find

$(1/L)\ln(1/p)=T/L$.

Then we represent expression (4) in the form

$I=(8en^2VD)/(gL_w{}^2I)(\mu+T/L)$ (5)

Formula (5) is valid for approximate calculations. It also follows from formula (5) that in order to decrease I, it is necessary to decrease D and the most optimal condition will be D=d . However, this condition is difficult to implement in practice on a conventional laser diode, since the light wave generated in the vicinity of the p–n junction propagates not only in the active region, but also outside it, where the population inversion conditions are not satisfied. Another reason is that some of the injected electrons, having a long mean free path, drag through the active part of the p–n junction and do not participate in the formation of electron–hole pairs. For these reasons, it is necessary to limit the propagation zone of the generated light and injected electrons and to ensure that these processes occur only in the active region. Desired optical confinement properties can be obtained on heterojunction structures. The simplest of them is a laser with a single heterojunction (SH) shown in Fig. 4(a). An emitting p–n junction is formed between GaAS and $Ga_{(1-x)}Al_xAs$ through special technological processing. If the impurity concentrations are approximately the same on both sides of the p–n junction, then the injection current will exist due to the electrons injected into the p-type layer, since the effective mass of electrons is almost an order of magnitude less than the effective mass of holes. Therefore, a layer with an inverse population will be located in p-GaAs, the thickness of which is commensurate with the long diffusion of injected electrons. Thus, the region of population inversion is limited by the thickness, where the recombination of electrons with subsequent emission occurs mainly.

In a SH laser, optical limitation occurs on one side, hence the desired result, i.e., an increase in the efficiency of the heterolaser, is partially realized, and therefore the threshold current value for a SH laser is higher than for a laser with a double heterostructure Fig. 4, (b) . Since it was possible to reduce the threshold current of the SH laser, this made it possible to use its operation at room temperature, but only in the pulsed pumping mode. Double heterostructure (DH) lasers operate in the continuous pumping mode at room temperature.

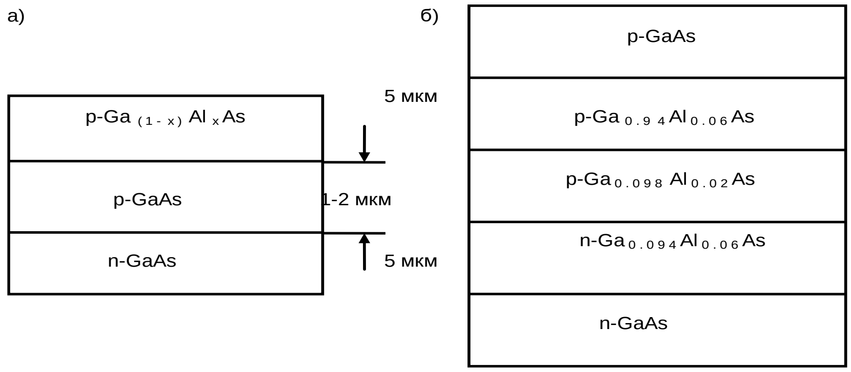

Fig.4 Laser with a single heterojunction a) (SH) and double heterojunction b) (DH)

The thickness of the active layer of a DH laser is no less than 1 μm. In this case, an inverse population is created over the entire layer. If in SH lasers the thickness of the active layer is commensurate with the long diffusion of the injected electron, then in DH lasers the thickness is less than this length. In addition, in DH lasers, optical confinement is provided on both sides of the active zone. These circumstances lead to the fact that DH lasers are highly efficient devices and are characterized by a minimum threshold current, which allows continuous electric current pumping at room temperature.

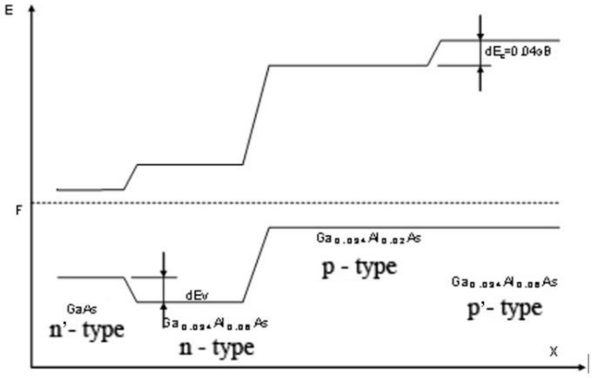

Fig.5 Energy band diagram for the structure shown in figure 4 (b)

To improve the output characteristics of a heterostructure laser, in the process of obtaining a heterostructure, conditions are created that ensure the limitation of charge carriers in the active region. For the structure shown in Fig.4(b), the energy band diagram is shown in Fig. 5. Due to the fact that the band gap of a semiconductor is larger in the region with an increase in the concentration of Al atoms, mixing occurs in the conduction band at the p−p+ junction (dE_c) and in the valence band at n−p and n+−p junctions (dE_v).

When a forward bias voltage is applied to such a structure, electrons are injected from the n- to the p-region. A jump in the conduction band at the p-p+ interface at dEc provides an energy barrier for the injected electrons, thereby confining them in the p-region and increasing the probability of their recombination with holes. The jump of the valence band at the n−p junction dE_c increases the already existing potential barrier that prevents the injection of holes into the n region, thereby improving the injection efficiency.

Resume

Thus, the dual heterostructure tends to restrict both majority and injected minority carriers in the core. This provides good conditions for obtaining a more efficient population inversion. This means that DH lasers provide higher output characteristics in comparison with SH lasers, and even more so in comparison with homojunction lasers. Comparison of technical characteristics shows that if the threshold current density of a homostructure laser is 104 A/cm^2 with a quantum efficiency of 10%, then for SH lasers the threshold current density is 103 A/cm^2 with a quantum efficiency of 40%. These lasers operate only in pulsed mode. For DH lasers, the threshold current density is 700-800 A/cm^2, and the quantum efficiency is 55%. These lasers operate continuously.

However, DH lasers have a large angular beam divergence (20–40°) in a plane perpendicular to the transition plane due to light diffraction in a thin active layer, while homostructure and SH lasers have an angular divergence of 15–20° . For all considered types of lasers, the angular divergence of the beam in the transition plane is no more than 10°.

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