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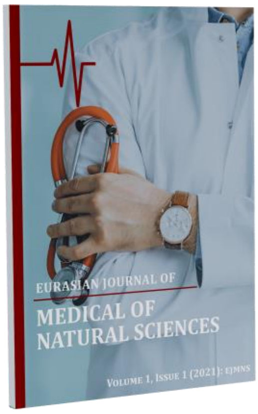

FEATURES OF SEMICONDUCTOR LASERS

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ABSTRACT

This article discusses the operation principle of semiconductor lasers. With the help of the band diagram, a distinctive feature of all semiconductor laser materials is explained, which is a very high gain of electromagnetic radiation compared to other laser materials (crystals, glasses, liquids, gases). Due to this, it is possible to fulfill the generation condition for miniature semiconductor samples.

The energy spectrum of an ideal semiconductor crystal (a crystal without defects and impurities) consists of wide bands of allowed states of electrons - the conduction band and the valence band, separated by a band of forbidden states (forbidden band). In the valence and conduction bands, the energy states of electrons form an almost continuous spectrum.

In an ideal semiconductor at T=0°K, all electrons are in the valence band. The conduction band is completely free of electrons. In this case, the semiconductor cannot conduct electricity and is an insulator. At a non-zero temperature, part of the electrons, due to thermal motion, passes from the valence band to the conduction band. As a result of such a transition, free places appear in the valence band - holes. A hole is equivalent to a particle with a positive charge.

In a semiconductor in which some of the atoms of the original substance are replaced by atoms of other elements (the so-called impurity semiconductor), in addition to the valence band and the conduction band, additional energy levels appear that lie within the band gap. Impurities and their corresponding energy levels are divided into donor and acceptor. Donors are impurities whose energy levels are located close to the conduction band (donor levels). Donors easily donate electrons to the conduction band. Acceptors are impurities whose energy levels are closer to the valence band. Acceptors easily capture electrons from the valence band, leaving holes there. The energy spectrum of an impurity semiconductor is shown in Fig. 1. Depending on the type of charge carrier (electron or hole), semiconductors are of two types: n-type (charge carriers are electrons) and p-type (charge carriers are holes).

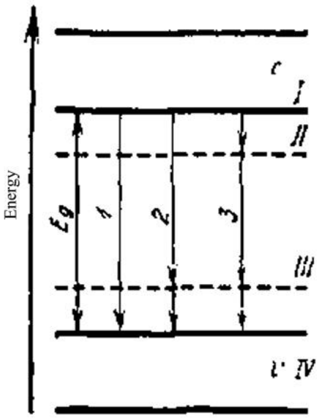

Fig. 1. Energy spectrum and radiative transitions in a semiconductor: Eg is the band gap; I - conduction band: II - donor level; III-acceptor level; IV - valence band

In order for a system to radiate, it must be brought into a nonequilibrium state. And to bring the semiconductor into such a state, the following methods are used: 1) irradiation of the semiconductor with external radiation of a sufficiently high frequency (optical excitation method); 2) irradiation of the semiconductor with an electron beam; 3) use of an external electric field. The transition to an equilibrium state occurs due to recombination. The energy released during recombination is realized in the form of one of three main processes: the production of a photon (radiative, or photon recombination), lattice heating, i.e., the formation of phonons (phonon recombination), and an increase in the kinetic energy of free carriers (nonradiative recombination).

Naturally, we will be interested only in radiative recombination, which in a semiconductor can occur as a result of interband transitions (arrow 1 in Fig. 1) and transitions from the band to the impurity level (arrow 2) or through both impurity levels (arrow 3).

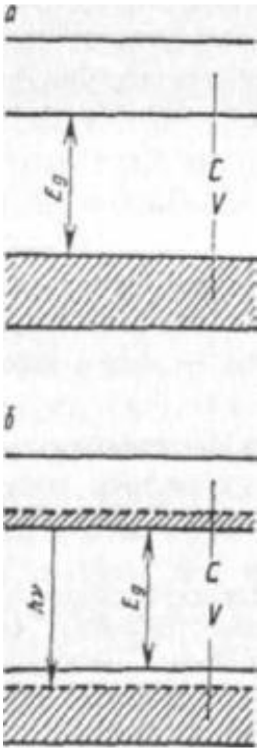

Fig. 2. Operating principle of a semiconductor laser

When determining the conditions for the formation of population inversion in a semiconductor, for simplicity, we consider an ideal semiconductor at a temperature T=0°K. The shaded area in Fig. 2(a) corresponds to completely filled energy states. Let us assume that electrons somehow get from the valence band to the conduction band. In this zone, during a very short time interval (about 10-13 s), electrons relax to its lowest level. Near the maximum of the valence band, electrons also pass to the lowest of the unoccupied levels, thus filling the maximum of the valence band with holes. This means that a population inversion occurs between the valence and conduction bands in Fig. 2(b). Since electrons tend to move from zone C to zone V (ie, recombine with a hole), by placing such a semiconductor in an appropriate resonator, it is possible to obtain generation. This means that the most suitable active medium for a semiconductor laser will be substances in which the probability of electron transition from the conduction band to the valence band with the emission of a photon is sufficiently high.

The first semiconductor laser was made on gallium arsenide (GaAs) by Hall in 1962. This laser had a very high probability of radiative recombination. The gallium arsenide laser ($\lambda=0.84$ μm) belongs to the so-called p-n-junction injection lasers. Usually, smooth p-n transitions are created by diffusion of acceptor impurities (zinc, cadmium, etc.) into a material doped with donor impurities (tellurium, selenium, etc.).

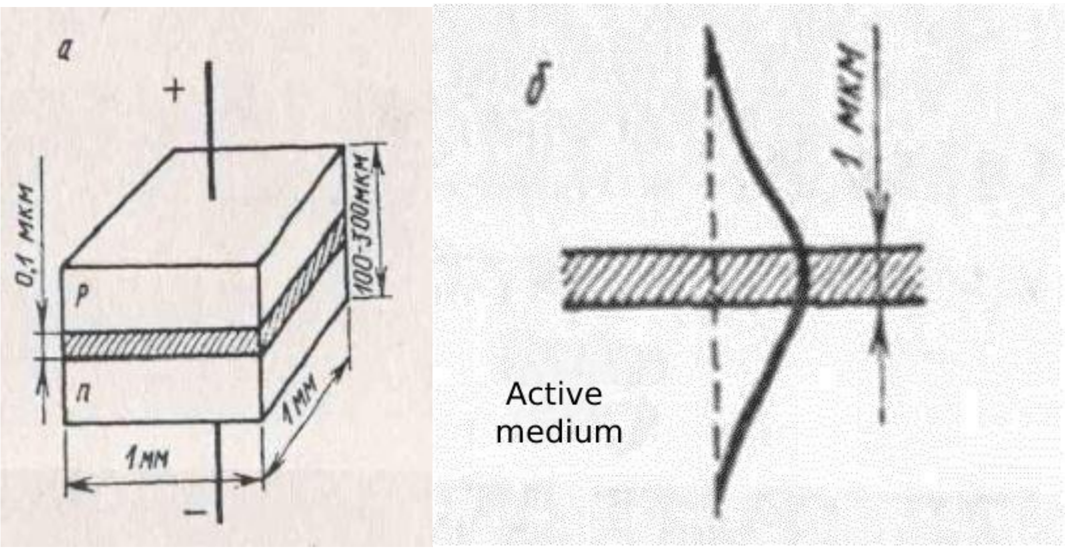

Fig.3. Scheme of the device of a semiconductor laser (a) and the distribution of the laser radiation intensity in the cross section (b)

A distinctive feature of all semiconductor laser materials, including gallium arsenide, is a very high gain of electromagnetic radiation compared to other laser materials (crystals, glasses, liquids, gases). Due to this, it is possible to fulfill the generation condition for miniature semiconductor samples. A typical gallium arsenide laser is shown in Fig. 3(a). To obtain lasing, two opposite semiconductor surfaces are polished and made plane-parallel, while the other two are left roughly machined to prevent lasing in undesirable directions. Usually, both reflective surfaces do not have reflective coatings, since the refractive index of the semiconductor is quite high and the polished ends reflect approximately 35% of the incident radiation. The active region is a layer about 1 μm thick, i.e. slightly larger than the barrier layer (approximately 0.2 μm). In turn, the transverse dimensions of the laser beam are much larger (about 40 μm) than the thickness of the active region in Fig. 3(b). Consequently, the laser beam occupies a fairly large space in the p- and n-regions. However, since the transverse dimensions of the beam are still relatively small, the output radiation has a large divergence (several degrees).

In addition to the gallium arsenide laser, other types of semiconductor lasers are used. Major advances in the development of semiconductor lasers are associated with the advent of injection lasers based on heterojunctions. So called complex p-n-structures, consisting of semiconductor materials with different band gaps.

This concludes our discussion of various types of lasers. We have discussed only some of the most widely used lasers. In reality, their number is much higher. To illustrate this, Fig. 4 shows the wavelength ranges in which generation was obtained with lasers of various types. This figure also shows the areas where there is a potential possibility of obtaining generation. It should be noted that, in general, these regions cannot be covered in a continuous manner, with the exception of dye lasers. We also note that based on lasers generating at a certain frequency, it is possible to create sources of coherent radiation at other frequencies using nonlinear optical effects.

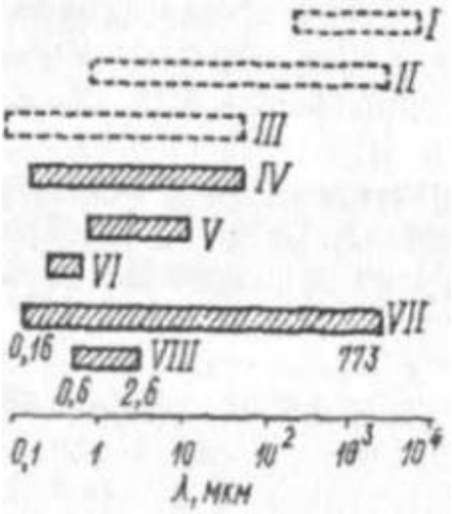

Fig. 4. Diagrams of lasing wavelengths overlapped by active lasers: I is the possible region of lasing at rotational transitions; II - possible region of generation on vibrational-rotational transitions; III—possible region of generation on electronic transitions; IV - semiconductor lasers; V—chemical lasers; VI, dye lasers; VII - gas lasers; VIII - solid state lasers

Semiconductor lasers differ from gas and solid-state lasers in that radiant transitions occur in a semiconductor material not between discrete energy states of an electron, but between a pair of wide energy bands. Therefore, the transition of an electron from the conduction band to the valence band with subsequent recombination leads to radiation that lies in a relatively wide spectral range and amounts to several tens of nanometers, which is much wider than the emission band of gas or solid-state lasers.

2. Creation of population inversion in semiconductors

Consider our own semiconductor. Under conditions of thermodynamic equilibrium, the valence band of a semiconductor is completely filled with electrons, and the conduction band is empty. Let us assume that a flux of electromagnetic radiation quanta falls on the semiconductor, the energy of which exceeds the band gap $h\nu>Eg$. Incident radiation is absorbed in matter, as electron-hole pairs are formed. Simultaneously with the process of formation of electron-hole pairs, the process of their recombination proceeds, accompanied by the formation of a quantum of electromagnetic radiation. According to the Stokes rule, the energy of the emitted quantum is less than the energy of the generating quantum. The difference between these energies is converted into the energy of the vibrational motion of the atoms of the crystal lattice. Under conditions of thermodynamic equilibrium, the probability of a transition with the absorption of a photon (valence band - conduction band) is equal to the probability of a radiative transition (conduction band - valence band).

Let us assume that, as a result of some external influence, the semiconductor is brought out of the state of thermodynamic equilibrium, and high concentrations of electrons in the conduction band and holes in the valence band are simultaneously created in it. The electrons pass into a state with some energy F_n near the top of the valence band.

The situation under consideration is illustrated by the diagrams shown in Fig.5.

Since all states near the bottom of the conduction band are filled with electrons, and all states with energies near the top of the valence band are filled with holes, transitions with the absorption of photons accompanied by an increase in the energy of electrons become impossible. The only possible transitions of electrons in a semiconductor under the conditions under consideration are transitions between the conduction band and the valence band, accompanied by the recombination of electron-hole pairs and the emission of electromagnetic radiation. In a semiconductor, conditions are created under which an amplification of an electromagnetic wave occurs. In other words, the absorption coefficient turns out to be negative, and the situation under consideration corresponds to a state with an inverse population density.

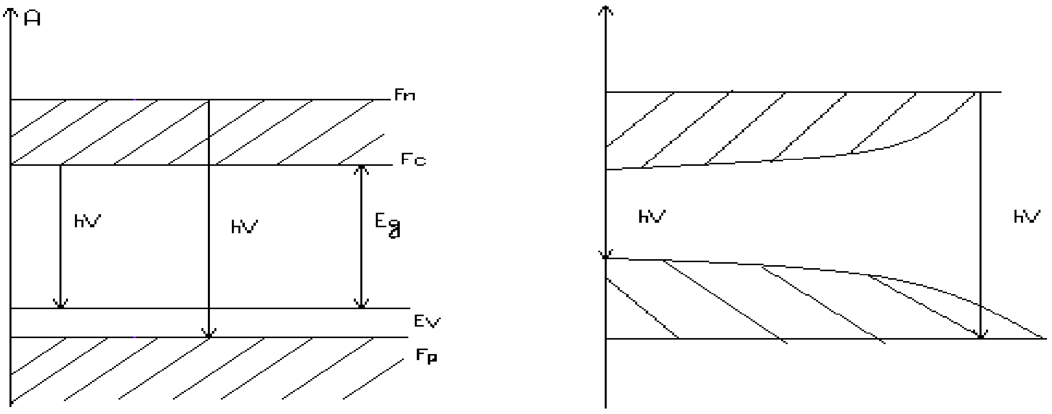

Fig. 5. Conduction band - valence band transitions, accompanied by recombination of electron-hole pairs and emission of electromagnetic radiation

The flux of radiation quanta, the energy of which is in the range from
$h\nu=E_c-E_v$ to $h\nu=F_n-F_p$
propagates through the excited semiconductor unhindered.

To implement the process of radiative recombination, two conditions must be met. First, the electron and hole must be localized at the same point in the coordinate space. Second, the electron and hole must have the same and oppositely directed velocities. In other words, the electron and hole must be localized at the same point in k-space. Since the momentum of the photon formed as a result of recombination of an electron-hole pair is much smaller compared to the quasi-momenta of an electron and a hole, in order to fulfill the law of conservation of the quasi-momentum, it is necessary to ensure that the quasi-momenta of the electron and hole involved in the act of radiative recombination are equal.

Optical transitions with conservation of quasi-momentum correspond to vertical (direct) transitions in k-space. Conservation of the quasi-momentum during the radiative transition can be considered as a quantum-mechanical selection rule (in the case when third particles, for example, phonons or impurity atoms, do not take part in the radiative recombination act). Non-vertical in k-space (indirect) transitions have a much lower probability compared to direct transitions, since in this case it is required to balance some difference quasi-momentum dk Fig.6.

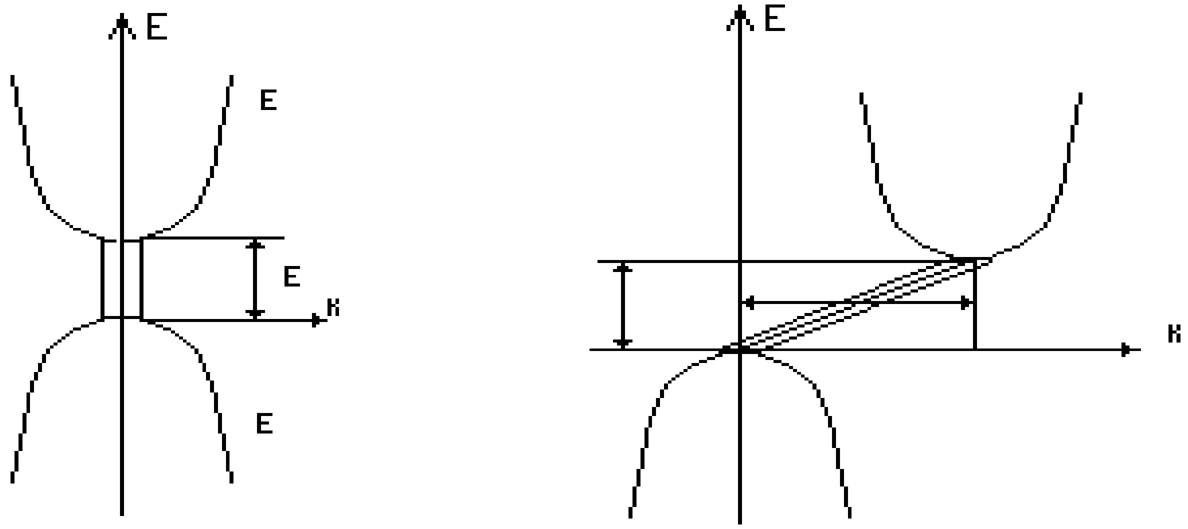

Fig.6. Vertical in k-space (direct) and non-vertical in k-space (indirect) transitions

Thus, to obtain radiative recombination, a direct-gap semiconductor, such as GaAs, is required. In general, adhering to a rigorous theory, one can prove that the inverse population is possible only under the condition $E_c - E_g < F_n - F_p$.

The methods widely used in practice to create an inverse population are: 1) excitation due to the injection of minority carriers through a p-n junction; 2) excitation by an electron beam; 3) excitation in a strong electric field.

Conclusion

Studies of the interaction of laser radiation with matter are of exceptionally great scientific interest. Semiconductor lasers are widely used in modern physical, chemical and biological research of a fundamental nature. A striking example is research in the field of nonlinear optics. As already noted, laser radiation with a sufficiently high power can reversibly change the physical characteristics of a substance, which leads to various nonlinear optical phenomena.

Semiconductor lasers make it possible to carry out a strong concentration of light power within very narrow frequency intervals: in this case, smooth frequency tuning is also possible. Therefore, lasers are widely used to obtain and study the optical spectra of substances. Laser spectroscopy has an exceptionally high degree of accuracy (high resolution). Semiconductor lasers also make it possible to carry out selective excitation of certain states of atoms and molecules, selective breaking of certain chemical bonds. As a result, it becomes possible to initiate specific chemical reactions, control the development of these reactions, and study their kinetics.

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