

Fig.1. Energy-level diagram. (a) For atoms with two energy levels; (b) for semiconductors.

significantly less than the energy difference between the conduction and valent bands, then practically all electrons will be found in the valent band, filling its levels, while practically all levels of the conduction band remain free (Fig. 2a). In such a state the semiconductor cannot conduct electric current and becomes an insulator, since the electric field applied to the semiconductor is unable to change the motion of the electrons in the valent band (all energy levels are occupied).

If the energy of thermal motion is sufficient, then a part of the electrons are thrown into the conduction band. Such a system may serve as a conductor of electric current. Current is able to flow both due to variation of the electron energy under the action of the external field, as well as due to changes in the electron distribution within the valent and conduction bands. Current within the valent band behaves as if those places free from electrons (holes) moved in a direction opposite to that of the electrons. A vacant place or « hole » is entirely equivalent to a positively charged particle (Fig. 2b).

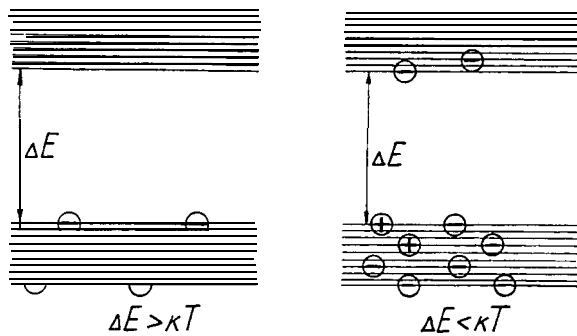


Fig. 2. Distribution of the electrons on energy levels.

levels is greater than that of finding them on the lower levels^{1,3}. It is very difficult to disturb the distribution inside a band because of the strong interaction between the electrons and the lattice of the semiconductor: it is restored in 10^{10} to 10^{12} sec. It is much simpler to disturb the equilibrium between the bands, since the lifetime of electrons and holes is considerably greater in the bands. It depends on the semiconductor material and lies in the interval of 10^{-3} to 10^9 sec.

Due to the fact that electrons and holes move in semiconductors, in addition to the law of the conservation of energy, the law of the conservation of momentum should be fulfilled during emission. Since the photon impulse is extremely small, the law of the conservation of momentum, approximately speaking, requires that the electrons and holes must have the same velocity during the emission (or absorption) of a light quantum. Fig. 4 shows graphi-

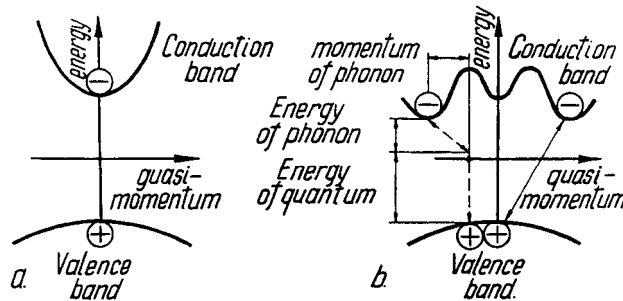


Fig. 4. Diagram of the electron-hole energy dependence on the quasi-momentum. (a) Direct transitions; (b) indirect transitions.

cally the dependence of energy on momentum. There are two types of semiconductors. For one group of semiconductors, the minimum of electron energy in the conduction band is exactly equal to the maximum of hole energy in the valent band. In such semiconductors there may take place so called « direct transitions ». An electron having minimum energy may recombine with a hole having maximum energy. For another group of semiconductors, the minimum energy in the conduction band does not coincide with the maximum energy in the valent band. In this case the process of emission or absorption of a light quantum should be accompanied by a change in the amplitude of the oscillatory state of the crystal lattice, that is by the emission or absorption of a phonon which should compensate for the change in momentum. Such processes are called indirect transitions. The probability of indirect transitions is usually less than that of direct transitions.

Table 1
Semiconductor lasers

The semi - <i>conductor</i> material	The wave range of the radiation (in microns)	The method of the excitation	References
CdS	0.5	high speed electron beam	15
CdTe	0.8	high speed electron beam	30
GaAs	0.85	p-n junction	17,18
		high speed electron beam	29
		optical excitation	23
InP	0.9	p-n junction	31
GaSb	1.6	p-n junction	32
		high speed electron beam	33
InAs	3.2	p-n junction	34
		high speed electron beam	35
InSb	5.3	p-n junction	36
		high speed electron beam	6
PbTe	6.5	p-n junction	24
PbSe	8.5	p-n junction	24
GaAs-GaP	0.65-0.9	p-n junction	37
InAs-InP	0.9-3.2	p-n junction	25
GaAs-InAs	0.85-3.2	p-n junction	38

ty. Even now it has become possible to make diodes with an efficiency²⁶ of 70430%.

Lasers with monochromatic optical pumping should also have a very high efficiency, since the pumping frequency may be made close to the emission frequency¹¹.

The efficiency of lasers with electron excitation cannot be higher¹² than about 30%, since two thirds of the energy is spent on heating of the lattice during the production of electron-hole pairs. However, such lasers may be rather powerful. This type of excitation will evidently make it possible to create sources of coherent emission working in the far ultraviolet range.

Another characteristic of semiconductors is a high coefficient of amplification, attaining a value of several thousands of reverse centimeters, which makes possible to construct lasers with dimensions measured in microns, that is, with cavity dimensions close to the length of the emission wave. Such cavities should have a very short setup time, of the order of 10^{-12} - 10^{-13} sec, which opens the way for the control of high frequencies by using the oscillations in semiconductor lasers, and for the creation of superfast-operating circuits on

the basis of lasers, such as components for superfast-operating electronic computers. Q-switch lasers giving very short light pulses may be built out of semiconducting materials.

The small dimensions of semiconductor lasers make it possible to construct quantum amplifiers with an extremely high sensitivity, since sensitivity increases with a decrease in the number of modes of oscillation which may be excited in the cavity. For the first time light amplifiers with an amplification index of about 2000 cm^{-1} have been produced²⁸.

The high amplification index in semiconductor lasers makes it possible to create for them a new type of cavity—the cavity with emitting mirrors (Fig. 8)²⁷.

A silver mirror is covered by a thin semiconductor film which is then covered by a transparent film. If one produces in the semiconducting film a state with negative temperature which can compensate for the mirror losses, such a mirror may be used in the construction of a laser. As in the case of a gas laser, one may expect to observe very high monochromaticity and spatial coherence in the emission. A significant advantage of such a system is the simplicity of removing heat from the thin semiconducting film, which indicates that it should be possible to obtain considerable power.

In order to produce negative temperature in a semiconducting film, one may use electronic excitation or optical pumping. The utilization of semiconductor lasers with *p-n* junctions for optical pumping makes it possible to attain high efficiency in the system as a whole.

The question as to the maximum power which may be obtained using semiconductor lasers is not quite clear at present. However, the employment of emitting mirrors of sufficiently large area will make it possible, apparently, to utilize a considerable quantity of semiconducting material. The maximum value of a mirror's cross-section is determined by such factors as the precision of its manufacture and the homogeneity of its semiconducting layer. Various deviations from optical homogeneity will produce the highest modes of oscillations.

Among the disadvantages of semiconductor lasers are their relatively small power, their large spatial divergence and their insufficiently high monochromaticity.

However, in speaking about those disadvantages one should keep in mind that the field of semiconductor quantum electronics is still in its infancy. Furthermore, the means of overcoming these disadvantages are already in sight. It is quite clear in what directions to proceed in order to develop semi-

conductor quantum electronics, and to increase the sphere of application of semiconductor lasers. All of this gives reason to hope that semiconductor quantum electronics will continue to play a fundamental role in the development of lasers.

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