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Semiconductor lasers

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In modern physics, and perhaps this was true earlier, there are two different trends. One group of physicists has the aim of investigating new regularities and solving existing contradictions. They believe the result of their work to be a theory; in particular, the creation of the mathematical apparatus of modern physics. As a by-product there appear new principles for constructing devices, physical devices.

The other group, on the contrary, seeks to create physical devices using new physical principles. They try to avoid the inevitable difficulties and contradictions on the way to achieving that purpose. This group considers various hypotheses and theories to be the by-product of their activity.

Both groups have made outstanding achievements. Each group creates a nutrient medium for the other and therefore they are unable to exist without one another; although, their attitude towards each other is often rather critical. The first group calls the second « inventors », while the second group accuses the first of abstractness or sometimes of aimlessness. One may think at first sight that we are speaking about experimentors and theoreticians. However, this is not so, because both groups include these two kinds of physicists.

At present this division into two groups has become so pronounced that one may easily attribute whole branches of science to the first or to the second group, although there are some fields of physics where both groups work together.

Included in the first group are most research workers in such fields as quantum electrodynamics, the theory of elementary particles, many branches of nuclear physics, gravitation, cosmology, and solid-state physics.

Striking examples of the second group are physicists engaged in thermonuclear research, and in the fields of quantum and semiconductor electronics.

Despite the fact that the second group of physicists strives to create a physical device, their work is usually characterized by preliminary theoretical analysis. Thus, in quantum electronics, there was predicted theoretically the possibility of creating quantum oscillators: in general, also, there were predicted the high monochromaticity and stability of the frequency of masers, the high sensitivity of quantum amplifiers, and there was investigated the possibility of the creation of various types of lasers.

This lecture is devoted to the youngest branch of quantum electronics - semiconductor lasers, which was created only two years ago, although a theoretical analysis started already in 1957 preceded the creation of lasers[1].

However, before starting to discuss the principles of operation of semiconductor lasers we would like to make some remarks of the theoretical « by-products » of quantum electronics. There are many of them but we shall consider only three:

(I) The creation of quantum frequency oscillators of high stability and the transition to atomic standards of time made it possible to raise the question of solving the problem of the properties of atomic time.

Dicke[2] in his paper at the first conference on quantum electronics pointed out the possibility of an experimental check of the hypothesis on the variation of fundamental physical constants with time on the basis of studying changes in frequencies of different quantum standards with time. There arises the question about the maximum accuracy of atomic and molecular clocks depending on the nature of quantum of emission, especially about the accuracy of the measurement of short time intervals.

(2) Due to quantum electronics there was started an intensive investigation of a new « super non-equilibrium state of matter » - the state with negative temperature, which in its extreme state of negative zero is close in its properties to the absolute ordering intrinsic for the temperature of absolute zero. It is just this property of high ordering of a system with negative temperature which makes it possible to produce high-coherent emission in quantum oscillators, to produce high sensitive quantum amplifiers, and to separate the energy stored in the state with negative temperature in a very short time, of the order of the reciprocal of the emission frequency.

(3) Quantum electronics gives examples of systems in which there occurs radiation with a very small value of entropy. For instance, spontaneous low temperature radiation from flash tubes, distributed through very large number of degrees of freedom is converted with the help of a system in a state of negative temperature (quantum oscillators) into high-coherent laser emission, the temperature of which in present experiments already attains a value of 10^{20} degrees.

Apparently, the regularities established by quantum electronics for radiation may be generalized for other natural phenomena. The possibility of obtaining a high degree of organization with the help of feed-back systems may be of interest for chemical and biological research, and for cosmology. The question arises as to whether or not the maser principle is used in Nature.

We believe that the above questions need attention from physicists of the first group, because these questions go beyond the limits of the theory of oscillations, the theory of radiation and usual optics which form the basis of modern quantum electronics.

I. Conditions for the Production of Negative Temperature in Semiconductors

Investigations of semiconductor quantum oscillators were a direct continuation of research on molecular oscillators and paramagnetic amplifiers. One should note that at the beginning of research on semiconductor lasers, due to investigations in the field of semiconductor electronics, there became known the physical characteristics of semiconductors, which were essential in the development and practical realization of lasers; such as, optical and electric characteristics, structure of energy bands, and relaxation time.

Various pure and alloyed semiconductors were made, and the technique of measurements of their various properties and the technology of making *p-n* junctions were worked out. All of this considerably simplified investigations of semiconductor lasers. Semiconductors were very intriguing because of the possibility of using them for making oscillators with a frequency range from the far-infrared region to the optical or even to the ultraviolet range, as well as because of the variety of methods by means of which states with negative temperatures may be obtained within them and because of their large factor of absorption (amplification). As the following studies have shown, semiconductor lasers may have extremely high efficiency, in some cases approximating 100 percent.

In contrast to an isolated atom, in semiconductors there do not exist separate energy levels, but rather there exist groups of energy levels arranged very close to one another, which are called bands (Fig. 1). The upper group of levels, called the conduction band, and a lower group of excited levels, called the valent band, are divided by a band of forbidden energy (Fig. 1).

The distribution of electrons on energy levels is described by the Fermi function: each level is occupied by two electrons, the electrons being distributed in the energy range of the order of the energy of kT thermal motion; and, the probability of finding an electron beyond the kT interval sharply decreases when the energy level increases. If the energy of thermal motion is

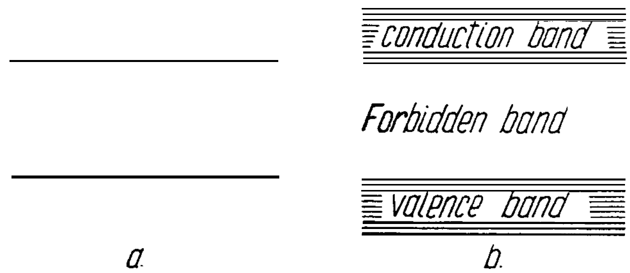

Fig.1. Energy-level diagram. (a) For atoms with two energy levels; (b) for semiconductors.

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).

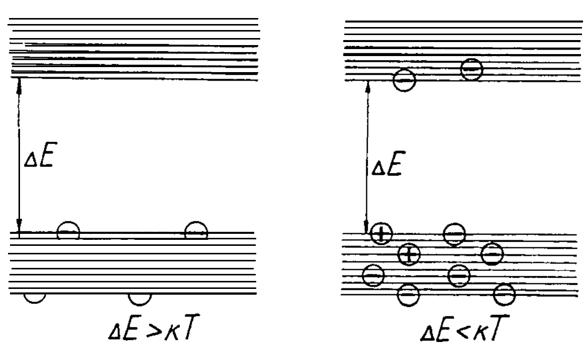

Fig. 2. Distribution of the electrons on energy levels.

During interaction with light, a semiconductor, similar to an isolated atom, may undergo three processes:

(1) A light quantum may be absorbed by the semiconductor: and, in this case an electron-hole pair is produced. The difference in energy between the electron and the hole is equal to the quantum energy. This process is connected with the decrease in energy of the electromagnetic field and is called *resonance absorption* (Fig. 3a).

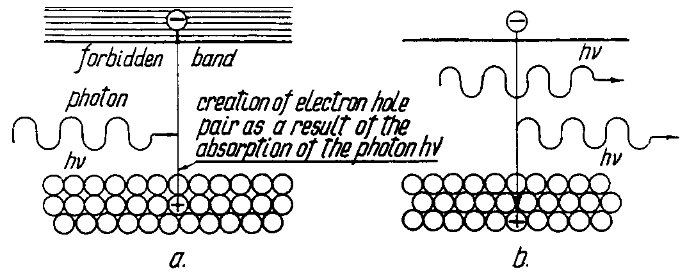

Fig. 3. Processes of the interaction with light. (a) Resonance absorption; (b) stimulated emission.

(2) Under the influence of a quantum, an electron may be transferred from the conduction band to a vacant place (hole) on the valent band. Such a transfer will be accompanied by the emission of a light quantum identical in frequency, direction of propagation and polarization to the quantum which produced the emission. This process is connected with an increase of the field energy and is called *stimulated emission* (Fig. 3b). We recall that stimulated emission was discovered by A. Einstein in 1917 during an investigation of thermodynamical equilibrium between the radiation field and atoms.

(3) Besides resonance absorption and stimulated emission, a third process may take place - *spontaneous emission.* An electron may move over to a vacant place-hole (recombine with the hole) in the absence of any radiation quanta.

Since the probabilities of stimulated radiation and resonance absorption are exactly equal to one another, a semiconductor in an equilibrium state at any temperature may only absorb light quanta, because the probability of finding electrons at high levels decreases as the energy increases. In order to make the semiconductor amplify electromagnetic radiation, one must disturb the equilibrium of the distribution of electrons within the levels and artificially produce a distribution where the probability of finding electrons on higher energy 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-

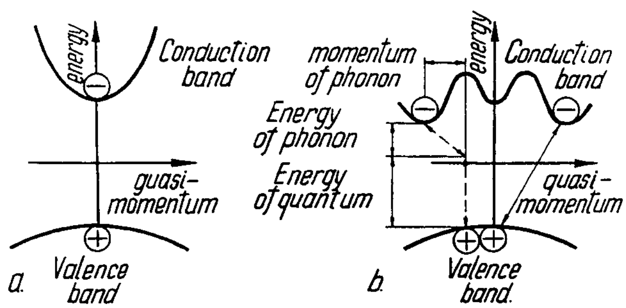

Fig. 4. Diagram of the electron-hole energy dependence on the quasi-momentum. (a) Direct transitions; (b) indirect transitions.

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.

In order to make a semiconductor amplify incident radiation under inter-band transitions, one should distinguish two cases:

(a) In the case of direct transitions

It is necessary to fill more than half of the levels in the band of the order of kT near the band's edge with electrons and holes. Such states, both for atoms and molecules, came to be called states with inverse populations, or states with negative temperature. The distribution of electrons when all levels in the kT zone of the conduction band are occupied by electrons, and in the valent band - by holes, corresponds to the temperature minus zero degrees. In this state (in contrast to the state of plus zero degrees), the semiconductor is only able to emit (stimulated and spontaneous) light quanta and is unable to absorb emissions.

The state of a semiconductor when most levels in a certain energy band are occupied by electrons or holes was named the *degenerated state.*

Thus, for the creation of negative temperature there must occur degeneration of electrons and holes in the semiconductor. With a given number of electrons and holes it is always possible to produce degeneration by means of lowering the semiconductor's temperature; since, as the temperature decreases the energy band width occupied by the electrons also decreases. At the temperature of liquid nitrogen for degeneration to take place it is necessary to have an electron concentration[3] of 10^{17}-10^{18} $1/cm^3$.

(b) *In the case of indirect transitions*

Degeneration is not necessary for the creation of negative temperature. This is connected with the fact that when indirect transitions occur, the probability of quantum-stimulated emission may not be equal to the probability of resonance absorption,

Consider, for instance, an indirect transition in which a quantum and a phonon are emitted simultaneously. The process of the simultaneous absorption of a quantum and a phonon is the inverse of that process.

The probability of absorption is proportional to the number of phonons in the crystal lattice. The number of phonons decreases with a lowering of temperature. At low temperature phonons are absent. Therefore, by means of lowering the temperature of the sample one may make the probability of emission much greater than the probability of absorption. This means that with indirect transitions negative temperature may be attained with a considerably lower concentration of electrons and holes[4].

One should note that the absorption and emission of quanta during transitions within a band also takes place due to indirect transitions. When negative temperature is created between bands, the distribution of electrons (and holes) within a band corresponds to a positive temperature and leads to the absorption of emission.

In the case of direct transitions, when the probability of interband transitions is much greater than that of innerband transitions, one may neglect the innerband transitions; that is, states with negative temperature can be used for the amplification of emission.

In the case of indirect transitions for amplification to take place it is not sufficient to attain negative temperature. It is necessary that the probability of interband transitions be greater than that of innerband transitions. The necessity of fulfilling this condition makes it difficult to utilize indirect transitions. According to Dumke's estimate, this condition cannot be fulfilled for germanium[5]. However, it may be fulfilled for other semiconductors[6].

In a number of cases in semiconductors, an electron and a hole form an interconnected state something like an atom-exciton. The excitons may recombine, producing an emission. They may be also used to obtain quantum amplifiers, but we shall not consider this in detail.

We have studied conditions for the production of negative temperature in semiconductors possessing an ideal lattice. In a non-ideal crystal there occur additional energy levels connected with various disturbances in the crystalline lattice (impurities, vacancies, dislocations, etc.). As a rule, these states are localized near the corresponding centre (for instance, near an impurity atom) and in this they differ from those states in the valent and conduction bands which belong to the crystal as a whole.

In an ideal crystal the number of electrons in the conduction band is exactly equal to the number of holes in the valent band. However, in an actual crystal the number of current carriers - electrons and holes - is determined, mainly, by the existence of impurities (Fig. 5).

There are two kinds of impurities: one type has energy levels arranged near the conduction band and creates excess electrons due to thermal ionization. These are called « donor » impurities. Other impurities having energy levels near the valent band are able of removing electrons from the valent band and thus producing an excess number of holes in it. These impurities are called « acceptors ».

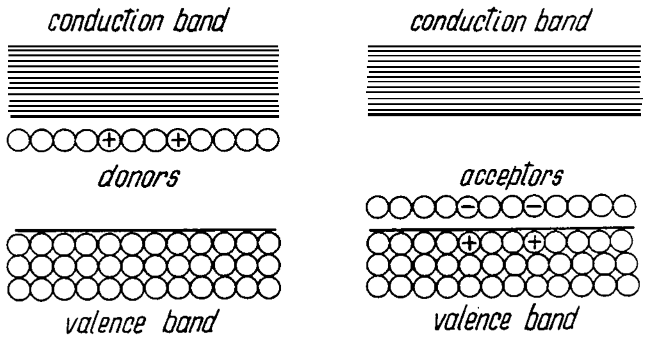

Fig. 5. Donor and acceptor levels.

One should note that a semiconductor with an equal number of donor and acceptor impurities behaves as if it were a pure semiconductor, since the holes produced by acceptors recombine with the electrons produced by donors.

In a number of cases, transitions of electrons between bands, between impurity atoms or between other levels may also be accompanied by emission of photons. One may likewise use these transitions for the creation of negative temperature. However, because of time limitations, we shall not discuss this question.

II. Methods of Obtaining States with Negative Temperature in Semiconductors

(a) The method of optical pumping

In the case of semiconductors one may utilize the « three-level » scheme[7] which has been used successfully for paramagnetic quantum amplifiers[8] and optical generators based on luminescent crystals and glasses[9] (Fig. 6).

Since the relaxation time of electrons and holes in the band levels[10] is much less than the lifetime of electrons and holes in the corresponding bands, one may obtain an inverse population by means of optical pumping.

Semiconductors have a very large absorption index which sharply increases as the radiation frequency increases. Therefore, to obtain an inverse population in samples of relatively large thickness, it is reasonable to use monochromatic radiation with a frequency close to that of the interband transitions[11]. In the case when the frequency of the exciting radiation is greater than the width of the forbidden band, a state with negative temperature is produced in a narrow band, several microns deep (on the order of the electrons' diffusion length)

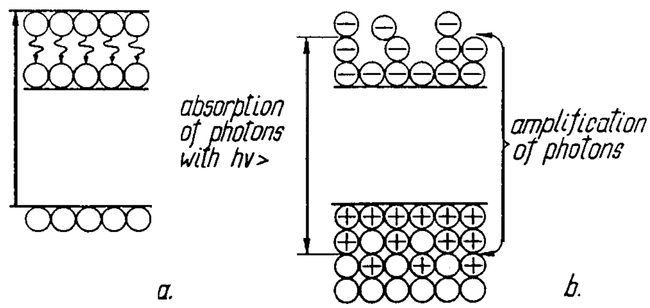

Fig. 6. Optical pumping. (a) Three levels diagram for atoms; (b) for semiconductors.

near the surface of the sample. As a source of radiation one may use the light from other types of lasers: gas lasers, lasers based on luminescent crystals or lasers based on *p-n* junctions[11].

(b) The excitation of semiconductors by a beam of fast electrons

If a beam of fast electrons is directed into the surface of a semiconductor, the electrons easily penetrate into the semiconductor. On their way the electrons collide with the atoms of the crystal and create electron-hole pairs. Calculations and experiments[12,13] have shown that an amount of energy approximately three times greater than the minimum energy difference between the bands is spent on the production of one electron-hole pair (Fig. 7a). The electrons and holes obtained give their excess energy to the atoms of the lattice and accumulate in the levels near the edges of the corresponding bands. In this case a state with negative temperature may be created[14,15]. The higher the electron energy, the deeper they will penetrate. However, there exists a

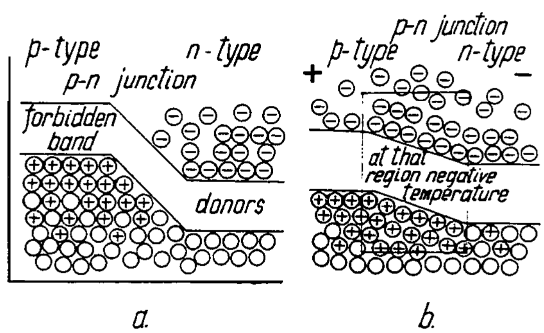

Fig. 7. (a) *p-n* junctional equilibrium; (b) *p-n* junction in the external electrical field.

certain threshold energy, beginning with which the electrons will produce defects in the crystal; that is, will destroy the crystalline lattice. This threshold energy depends upon the binding energy of the atoms in the crystals and is usually equal to about several hundred KeV. Experiments have shown that electrons with energy in the range of 200-500 KeV are not yet capable of noticeably harming the lattice.

The current density of fast electrons at which negative temperature is produced strongly depends upon the lifetime of electrons and holes. For semiconductors with a lifetime of 10^{-7} sec at the temperature of liquid nitrogen, the threshold of the current density has the order of one Ampere per cm^2. Since in the presence of such large currents it is difficult to remove the energy released in the semiconductor, the impulse method of excitation with a short impulse duration is usually employed.

(c) The injection of electrons and holes through p-n junctions

As it was noted above, a specific characteristic of semiconductors is that their energy levels may be filled with electrons or holes by introducing into the crystals special types of impurity atoms. However, the simultaneous introduction of donor and acceptor impurities does not result in the production of states with negative temperature. Therefore, in order to obtain an inverse population one does as follows: take two pieces of a semiconductor, inject donor impurities into one of them, and inject acceptor impurities into the other. If one then connects one piece to the other, a *p-n* junction will be created. On the boundary between the semiconductors there arises a potential difference which does not allow electrons to penetrate into the crystal having holes and likewise does not allow holes to penetrate into the crystal having electrons (Fig. 7a). As it was pointed out above, a large concentration of electrons and holes is necessary for the production of an inverse population (more than half of the levels in a certain energy band should be occupied), that is the semiconductor must have a large number of impurities.

If one applies an external voltage to a *p-n* junction, removing the potential difference between the two pieces of the semiconductor, the equilibrium of the distribution of electrons will be disturbed, and current will flow through the semiconductor. In this case electrons appear to flow into the region with a large concentration of holes, and holes - into the region with a large concentration of electrons. An inverse population arises in a narrow region near the *p-n* junction at a distance of several microns. Thus, there is obtained a layer of the semiconductor which is able to amplify electromagnetic waves by means of the stimulated emission of quanta during the transition of electrons from the conduction band to the valent band[16] (Fig. 7b).

Many methods for the production of *p-n* junctions were worked out during research on semiconductors. At the present time two methods of making *p-n* junctions are used for the creation of lasers: the diffusion method[17,18] and the method of dopping with different impurities during the process of growing a crystal[19].

III. Semiconductor Lasers

In order to carry out generation on the basis of systems with negative temperature, one must introduce feedback coupling into the system. This feedback coupling is carried out with the aid of cavities. The simpliest type of cavity in the optical range is a cavity with plane-parallel mirrors[20,21]. Light quanta reflecting from the mirrors will pass many times through the amplifying medium. If a light quantum, before its absorption by the mirrors or inside the sample, has time to cause stimulated emission of more than one quantum (that is, if the condition of self-excitation is fulfilled in the system), that system will operate as a laser (Fig. 8). If one maintains a certain negative

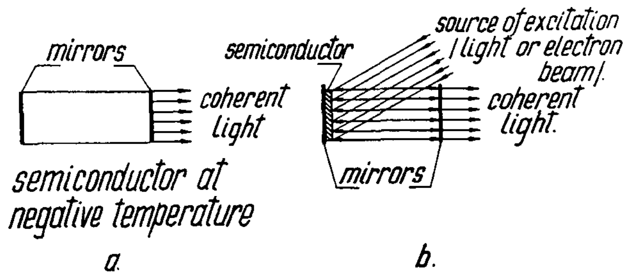

Fig. 8. Diagram of semiconductor lasers. (a) Usual; (b) with radiative mirrors.

temperature in the sample with the help of an external energy source, the number of quanta in the cavity will increase until the quantity of electrons excited per time unit becomes equal to the number of emitted quanta.

It should be especially noted, that when a quantum system with feed-back coupling operates as a laser, its emission has a very narrow frequency band. This characteristic makes laser emission different from all other light sources:

filament lamps, luminescent lamps and light sources with very narrow atomic and molecular spectral lines.

The monochromatic emission of lasers is a result of the properties of stimulated radiation: the quantum frequency of the stimulated radiation equals the frequency of the quantum which produced the radiation. The initial line width in semiconductors is usually about several hundred ångstroms. At the present time it has been shown that the line width in lasers which use a *p-n* junction in GaAs is less than fifty megacycles[22,24]. The minimum value of the line width in lasers is connected with the phenomenon of spontaneous emission.

Spatial directivity of the emission arises together with change in the spectral composition of the oscillation regime. It is connected also with the nature of stimulated radiation: during stimulated radiation, a light quantum has the same direction of propagation as the quantum which produced it.

Usually in semiconductor lasers, the sample itself serves as a cavity; since semiconductor crystals have a large dielectric constant, and, since the polished boundary of the division between the air and the dielectric is able of reflecting about 30% of the radiation.

The first semiconductor lasers were made utilizing *p-n* junctions in crystals of GaAs[17,18]. Some time later, lasers were made under excitation by an electron beam[15], and, recently, under excitation by a light beam[23]. In Table 1 different semiconducting materials are shown with which lasers have been made, and the methods of excitation are given.

With the help of semiconductors it has already become possible to cover a large frequency range from 0.5 to 8.5 . In a number of cases it is possible to continuously overlap a very large frequency range, since the variation of the concentration of components in three-component semiconductors units results in changes in the distances between the bands, that is, allows one to continuously change the emission frequency. For instance, variation of composition in the system In As-In P results[25] in frequency changes from 0.9 to 3.2 .

At present, the highest degree of development has been obtained with lasers utilizing *p-n* junctions in GaAs. Impulse and continuous regimes were obtained with an average power of several Watts, and peak power of up to 100 Watts, with an efficiency[24] of about 30%.

The most interesting characteristic of semiconductor lasers is their high efficiency.

Since a direct transformation of electric current into coherent emission takes place in lasers utilizing *p-n* junctions, their efficiency may approach uni-

Table I
Semiconductor lasers

The semi-conductor 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 efficiency[26] of 70-80%.

Lasers with monochromatic optical pumping should also have a very high efficiency, since the pumping frequency may be made close to the emission frequency[11].

The efficiency of lasers with electron excitation cannot be higher[12] 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 produced[28].

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 semiconductor 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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