Semiconductor lasers

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Recent advances in the field of semiconductor lasers are treated—injection lasers and lasers excited with fast electrons. Considerable attention is paid to new, four-component heterostructures and ultrathin active layers for injection lasers. Data are given on the fundamental fields of applications of semiconductor lasers.

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1. INTRODUCTION

Semiconductor lasers have entered a period of mass practical application. The direct supply from low-voltage current sources, high efficiency, simplicity, and compactness of design of injeciton lasers, and high speed of action have predetermined the advantage of using them in such fields as fiber-optic communications, optical memory systems (in particular, video disk apparatus), character-printing automation, spectroscopic diagnostics of various media and materials (hygrometry, environmental monitoring, etc.), and also in scientific studies and industrial testing (high-resolution spectroscopy, certification of photoreceivers, intensity standards for radiation sources, various types of metrologic calibration, etc.).

Approaches have been developed recently toward specialization of laser designs and materials for particular applications; for example, one can speak of the most promising "communication" laser based on a strip design of diode with a fiber-optic radiation output that operates in a continuous or pulsed regime at wavelengths matching the optimal range of the transmission power of fiber light guides (1.3 or 1.55 μm). Spectroscopic problems are solved by tunable single-frequency lasers, mainly based on chalcogenide crystals (A^4B^6). For obtaining high power for photographic exposure, optical pumping, or remote ranging, non-strip, ("broad") diodes or composite emitters (one- and two-dimensional of laser diodes) have the advantage.

The industry of technologically advanced countries has mastered the production of an entire series of varieties of semiconductor lasers, as well as more complicated specialized modules including these lasers. They function in numerous laser communication lines whose total extent has exceeded many thousands of kilometers. The greatest fraction of the mass production involves injection lasers based on two types of laser heterostructures: GaAlAs/GaAs and InGaAsP/InP, which cover the wavelength ranges 0.67–0.91 and 1.06–1.67 μm, respectively. Semiconductor lasers can be characterized as being both the most miniaturized and the most reliable and long-lived products of quantum electronics, having remarkable dynamic and spectral properties.

Among the first-ranking problems are the achievement of mass production and application of long-wavelength infrared lasers for environmental monitoring in cities, in factories, in mines, and other worksites. We shall return again to the problems of practical application. Here we should note that up until recently the rates and scales of physical studies of semiconductor lasers continued to increase, including studies of fundamental nature. This indicates the existence of great potentialities of this field of quantum electronics and laser technology.

Different types of semiconductor lasers are classified according to the methods of creating an inverted population:

—injection lasers, in which inversion is created by counter-diffusion of electrons and holes in 9 diode upon applying a dc voltage to it;

—electron- or optically-pumped lasers, in which the inversion is created by fast electrons or photons, respectively;

—streamer lasers, in which a strong electric field arising from an avalanche creates an inverted population in a narrow channel (streamer).

One can also employ other forms of ionizing radiation (gamma-rays, ions), which give rise physically to the same laws as does electron excitation.

The history of the invention of all types of semiconductor lasers is indissolubly connected to the studies of Soviet scientists, who began studies specifically with these lasers to master laser action in the optical range,[1] proposed and developed different types of semiconductor lasers (injection,[2] electron-pumped,[3,4] and optically pumped[5]), and who were the first to obtain indications of stimulated scattering from a gallium-arsenide diode.[6] And in the subsequent development of semiconductor lasers Soviet scientists have taken the

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decisive steps—they have invented semiconductor lasers based on heterojunctions and multicomponent solid solutions, were the first to obtain laser action upon "longitudinal" pumping of a semiconductor with an electron beam and invented a laser electron-beam tube, studied theoretically and experimentally the dynamics of emission of semiconductor lasers, and designed optical logic elements using them, etc. Below in the appropriate sections of this article, we shall speak in greater detail about these studies.

The first well-grounded proposal for the invention of the device later called the injection laser appeared in the scientific literature in 1961.[2] The topic was a semiconductor diode biased in the forward (transmission) direction. Owing to the well known phenomenon of injection of excess carriers through the p-n junction, an unusual, so-called inverted state of filling of the energy levels at the edges of the conduction bands and the valence band was created. This state is necessary for obtaining amplification in stimulated interband radiative transitions, on which the principle of action of all known semiconductor lasers is based. The idea of Ref. 2 consists in employing degenerate semiconductors to facilitate obtaining the necessary level of injection, which has served as a reliable orientation for experimenters. Soon thereafter, lasers based on a "degenerate" p-n junction in gallium arsenide (GaAs) were invented.[7–10] The convenience was also mentioned[2] of applying heterojunctions to lower the threshold of laser action of the injection laser. As is known, subsequently this idea was embodied in the so-called "heterolasers".

The first report on the practical realization of a semiconductor laser came from the General Electric laboratory group[7] and somewhat later from a set of other groups.[8–10] The creation of a laser based on heterojunctions required a considerably greater time—the first successful experiments were performed by the associates in the A. F. Ioffe Leningrad Physicotechnical Institute of the Academy of Sciences of the USSR in 1970.[11] The point is that first it was necessary to find suitable materials and develop a technology of preparation of perfect (defect-free) semiconductor heterojunctions between single crystals of differing chemical composition. The solution of this problem was aided in the first stage by the circumstance that two known semiconductors, gallium and aluminum arsenides, have very closely coincident lattice periods. Preparation of the mixed crystal GaAlAs made possible a reduction of the difference in periods to values (less than 10^{-3} in relative terms) at which mismatch dislocations and other accompanying defects are not formed. A more general solution of the problem of defect-free joining of crystal boundaries in heterojunctions was found later, based on using quaternary and other multicomponent systems of solid solutions of semiconductor compounds.[12] Continuous "isoperiodic" sequences of compositions exist in these systems. That is, they correspond to the same lattice period as the composition and electrophysical properties are varied. In principle any pair of compositions within the scope of a single isoperiodic system is suitable for creating a defect-free heterojunction. A problem remains in the method of preparation of such a heterojunction and heterostructures (structures including one or more heterojunctions). The development was required of delicate technological methods based on epitaxial methods of crystallization, so as to obtain completely new semiconductor materials, multicomponent mixed crystals, which exist even now only in the form of epitaxial films. This has not hindered some of them from becoming among the most important and most studied semiconductor materials. Here we must point out in first place the quaternary system InGaAsP. A semiconductor laser based on it was invented in 1974[12] in a joint study by the Institute of Physics of the Academy of Sciences of the USSR and the State Rare Metals Research Institute. Now this is the most widespread injection laser for long-distance and ultralong-distance optical communication lines.

Not only injection but also other means of pumping of semiconductors have proved effective for obtaining laser emission. The optical method first carried out in Ref. 5 offers a rather simple and universal method of testing the "laser capability" of materials.

Its restricted, laboratory application is explained by the need of using some other laser as the pumping source. Promising schemes using a semiconductor laser with optical pumping imply variants of practical interest of converting one laser radiation into another, e.g., in order to obtain coherent summation of the radiation of different lasers, broad spectral tuning, shortening of optical pulses, etc.

Although semiconductor lasers pumped with fast electrons are not yet used as widely as injection lasers, they possess an entire set of important properties that injection lasers cannot have at all, or else their attainment for injection lasers is yet highly problematic. These are the possibility of fast scanning of the laser radiation, including two-dimensional scanning, in the case of fast-electron pumping, the possibility of obtaining laser action with a broad area (i.e., high power), and also laser action throughout the visible spectrum, including the infrared and ultraviolet ranges.

Another method of pumping a semiconductor laser, which was historically the first proposed,[1] is based on reversible electric breakdown in a solid accompanied by an avalanche increase in the carrier concentration. Although the rapid growth of energy of the carriers in the strong electric field is a hindering factor against obtaining an inverted population of bands, the abrupt removal of the strong field does make it possible to obtain the conditions necessary for laser action. They are realized in Gunn diodes,[13] and also is the so-called streamer breakdown of high-resistivity crystals.[14,15]

2. ADVANCES AND PROBLEMS IN THE PHYSICS OF INJECTION LASERS

The publications on injection semiconductor lasers are mainly divided into three groups. First are the studies of fundamental character that contribute to the theory of lasers of this type and open up new fields of their functional possibilities. Second, a large fraction of the reports consists of studies on new varieties of structures and materials for lasers on which a certain standard of requirements on characteristics has already been developed (the possibility and the

threshold of continuous generation, single-mode character, limiting power, linear range of the power-current relationship, lifetime characteristics, modulation, and spectrum). Third, and finally many publications have pertained to applied developments. This is mainly the achievement of new schemes of practical application or substantial improvement of known variants.

We can consider the most important fundamental results of the recent period to be the following:

1) The elucidation of the causes of fast degradation and their successful elimination. This has allowed us to exceed the boundary of working lifetime of 10^4 hours for mass-production wares and to approach the solution of the problem of obtaining a lifetime of 10^5–10^6 hours.

2) The invention of new heterolaser systems for a broad range of wavelengths, mainly using various mixed crystals (solid solutions). A solution in principle has been proposed and successfully carried out for the problem of defect-free heterojunctions based on using multicomponent solid solutions of semiconductor compounds. The most striking example of new "isoperiodic" heterosystems is the quaternary system gallium-indium-phosphorus-arsenic, which covers the optimal wavelengths of fiber-optic communications.

3) The development of laser optics as applied to semiconductor media with account taken of their "giant" nonlinear refraction; the manifestation of a number of new effects, such as refractive bistability, nonlinear mode competition, and phase conjugation of modes of satellites, self-focusing, etc. In this same regard, we must mention the development of a theory and technology of mode selection of semiconductor lasers (obtaining a single-mode regime, optical heterodyning with semiconductor lasers, autostabilization of single-frequency laser action).

4) The creation of ultrathin quantum-dimensional structures and supergratings for laser applications, further improvement of the threshold and power characteristics based on new precision technology.

These fields are still in the stage of establishment and expansion of the front of studies. The more problematic fields are:

—increasing the working temperature of injection lasers, especially those of long wavelengths ($\lambda > 1\ \mu$m), decreasing the role of radiationless transitions (Auger recombination, leakage through heterobarriers, etc.);

—creating "integrated-optics circuits" with semiconductor lasers; carrying out effective coupling and uncoupling of them; miniaturization of circuits, etc.;

—mastering the short-wavelength range ($\lambda < 0.6\ \mu$m) and improving the lifetime characteristics of lasers in the range $0.6 < \lambda < 0.8\ \mu$m;

—developing methods of stabilization of wavelengths, which are generally subject to the effect of many external factors; the achievement of coherent methods of signal reception.

We must consider the traditional requirements of compactness, simplicity, and reliability that injection lasers have always satisfied. The new developments prove the more valuable, the fewer deviations that they compel one to make from these principles. Therefore, unwieldy control systems (stabilization, modulation, etc.) seem unattractive. Though justified as applied to other lasers, they are not suitable for semiconductor lasers. One of the frequently necessary refinements of the design of a semiconductor laser consists in thermal stabilization of the housing. Coherent optical communications require a temperature stability of ± 0.001 °C or better. In order that a device with this level of stabilization should not lose in compactness, semiconductor thermoelectric devices have been developed that are compatible with the laser housing or can be placed inside the housing.

2.1. New heterostructures

The advantages of heterostructures in injection lasers are well proved by the example of GaAlAs/GaAs heterosystems ($\lambda = 0.64$–$0.90\ \mu$m) and reduce to two characteristic phenomena—electron "confinment" (confinement of the injected carriers in the active region, which forms a potential well for them) and optical "confinement" (confinement of photons within the same region owing to waveguide properties).

To answer the need for lasers of a broader range (in particular, for the wavelengths 1.06, 1.27, and 1.55 μm applied in optical technology) the quaternary heterosystem InGaAsP[12] appeared about 10 years ago, and then other multicomponent systems. The decisive fact in the choice of quaternary and other multicomponent systems is the rigid requirement of isoperiodicity of heterostructures with the substrate (i.e., adherence to equality of lattice periods). This restricts the choice of suitable materials. Within the framework of multicomponent systems having a sufficient number of degrees of freedom of chemical composition, this problem has a general solution: any pair along the isoperiodic curve is suitable for forming a defect-free heterojunction.

The preparation of layers and isoperiodic heterostructures based on quaternary systems has been mastered by using liquid-phase epitaxy, and also is being mastered by other epitaxial methods. This pertains to the chosen quaternary systems formed by neighboring elements in the Mendeleev periodic table. They include GaAlAsP, InGaAsP, GaAlSbAs, and InGaSbAs. The mixing of compounds containing more remote neighbors, e.g., the preparation of the mixed crystal InAlSbP and an entire series of others, cannot be done by methods close to equilibrium ("chemical" methods of epitaxy). Perhaps the "physical" methods of epitaxy from a molecular beam and atomic epitaxy can be successfully applied to them. In any case, the first results of application of molecular-beam epitaxy have been obtained with heterosystems such as AlGaInP, etc.[16]

Greatest attention has been attracted to the heterostructures InGaAsP/InP for lasers at the wavelengths 1.3 μm (active medium $In_{0.72}Ga_{0.28}As_{0.6}P_{0.4}$) and 1.55 μm ($In_{0.60}Ga_{0.40}As_{0.88}P_{0.12}$). Among these, 1.3-$\mu$m lasers are already in mass industrial production (e.g., the device ILPN-202).

Study of laser heterostructures based on InGaAsP/InP has shown that, apart from the common principles of action

in these and in the more traditional GaAlAs/GaAs heterostructures, an entire set of features exists, especially regarding the sensitivity of the emissive properties to temperature and degradative processes. Even the first studies[12] on InGaAsP/InP heterolasers noted that the temperature-dependence of the threshold current in the temperature range near room temperature and above is steeper than is typical for lasers based on GaAlAs/GaAs. Usually these dependences are described approximately by the exponential function $\exp(T/T_0)$. Here the parameter T_0 in GaAlAs/GaAs amounts to about 150 K. In contrast, e.g., in InGaAsP lasers T_0 lies in the range 40–60 K (at $T \geqslant 250$ K), which corresponds to a very rapid increase in the threshold and an upper bound on the region of working temperatures. The highest temperature for continuous generation in lasers at the wavelength 1.3 μm is about 100 °C, whereas in 0.83-μm lasers it exceeds 200 °C. This elevated temperature sensitivity in the new heterostructures is combined with a feature such as a tendency of the intensity of spontaneous emission to saturate at high current density. This tendency is also heightened with increasing temperature. Mechanisms of radiationless losses have been adduced to explain it. First, these losses are accelerated with increasing temperature. Second, the rate of losses increases with increasing pump current faster than the rate of radiative recombination does. Consequently the emissive characteristics of this type of heterostructures is impaired with increasing temperature above room temperature far faster than in heterostructures for the shorter-wavelength range. This gives rise to technical problems in applied developments, where one generally requires a high working capability of the apparatus over a broad temperature range. For example, one must equip the emitter with a temperature-stabilizing system to prevent overheating of the diode.

On the other hand, the new systems often display favorable physicochemical features as compared with the more traditional systems. It is worth mentioning some of these features of the system InGaAsP/InP as compared with GaAlAs/GaAs. They include:

—a higher chemical, photochemical, and electrochemical stability of the surface of the crystal;

—a higher optical durability;

—absence of fast degradative processes, e.g., the so-called "dark-line disease", which involves the presence of initial dislocations;

—good wettability in liquid-phase epitaxy (which is due to the absence of a chemically active element such as aluminum, which easily forms refractory oxides).

Owing to this, some of the problems such as increase of lifetime, avoidance of optical breakdown, application of multistage epitaxial processes, etc., prove not so severe as in the case, e.g., of GaAlAs/GaAs.

Recently lasers based on the new system GaAlAsSb/GaSb with a wavelength about 1.8 μm,[17] which were first built in 1976,[18] have been added to the list of lasers operating in a continuous regime (at 300 K). The attainment of laser action at a wavelength of 40–45 μm is an advance in the field of infrared emisison.[19]

2.2. Laser heterostructures having an ultrathin active layer

The most impressive advances of recent time have involved the mastery of a methodology of preparing heterostructures with ultrathin layers by using new epitaxial processes. In particular, a metal-organic variant of gas-phase epitaxy (the MOS-hydride method) has enabled preparation of layers uniform in thickness and sufficiently planar in the system GaAlAs/GaAs, in which quantum-dimensional effects are reproduced. Previously gas-phase epitaxy was hardly applied, owing to difficulties with controlling thicknesses and an imperfect morphology of the heterojunctions. High-quality structures have also been obtained by using molecular-beam epitaxy.

The expedience of diminishing the thickness of the active layer in laser heterostructures to 200–500 Å had been indicated earlier[20] in connection with a computational optimization to a minimum threshold current density. Within the framework of the model of an ideally plane two-sided heterostructure (with a single-layer waveguide), a decrease in the thickness, even without taking account of "quantum-dimensional effects", is expedient only when the increase in amplification with increasing pump current is faster than the square of the current density. In the contrary case, the thinning of the active layer either does not lower the threshold or it increases it, owing to diffraction of the radiation. The laser mode is characterized by the optical confinement parameter Γ, which corresponds to the relative fraction of the optical flux incident on the active layer. The amplification for the mode is proportional to Γ, since amplification does not occur outside the active layer. When the thickness d of the active layer is less than the wavelength of the radiation, Γ rapidly declines (in proportion to d^2). First, this arises from the spread of the radiation beam owing to weakening of the waveguide effect, and second, from the decrease in d. This implies that a decrease in Γ must be compensated by a rather rapid growth in the amplification coefficient (for a plane wave) in the active layer. Here the threshold current density generally passes through a minimum and increases with decreasing d as soon as the increase in amplification with increasing pumping weakens. In the general case the curve of the dependence of the amplification index $g(j)$ on the current has a "superquadratic" region, as shown in Fig. 1. Here the optimum corresponds to the upper bound of this region (point A). One can determine Γ and the proposed optimal thickness d_0 from the magnitude of the bulk amplification g at the point A and from the necessary mode amplification g_m at the threshold. Such a calculation was presented as early as Ref. 20, where the small values of d_0 (~ 200 Å) for room-temperature lasers based on GaAlAs/GaAs were pointed out (with a threshold of ~ 500 A/cm^2 or less).

Two-sided heterostructures with a more complex waveguide—gradient or multilayer—allow one to reduce the laser-action threshold to values of 100–200 A/cm^2 in GaAlAs/GaAs[21,22] and 400–500 A/cm^2 in InGaAsP/InP.[23,24] A calculation of Γ for a three-layer waveguide (an active layer between two passive layers of intermediate com-

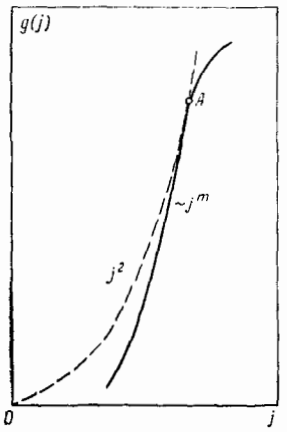

FIG. 1. Dependence of the local optical amplification index g on the current density j (solid curve and the quadratic dependence j^2 (dotted curve). The point A marks the upper bound of the range of superquadratic increase in g.

position surrounded by following materials of more wide-band character) has shown that the $\Gamma(d)$ relationship is modified (Fig. 2), and Γ is appreciably increased at small d for the same total magnitude of the heterobarrier.[25] This happens because the additional steps in the profile of the refractive index in the three-layer waveguide partially halt the expansion of the optical beam with decreasing d. Hence it becomes possible to increase the amplification of a mode with the same pump current or to decrease the threshold current.

Thus the optimization with respect to thickness further decreases d_0 to values of 40–50 Å. Here one can simultaneously improve the second parameter to be optimized—the overall thickness w of the three-layer waveguide. Figure 3 shows the dependence of Γ on w for certain values of d. Figures 1–3 explain the fundamental pattern of optimization from the standpoint of the optical (waveguide) structure.

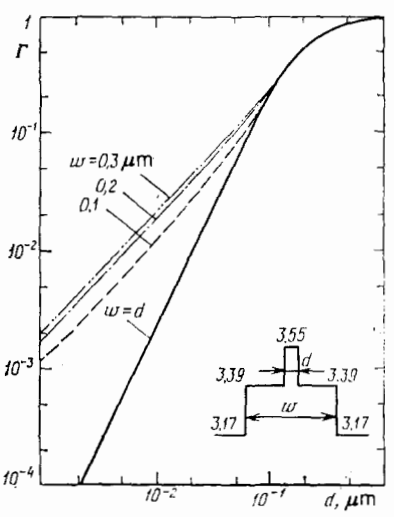

FIG. 2. Magnitude of the optical-confinement parameter Γ as a function of the thickness d of the active layer in an ordinary two-sided heterostructure (solid curve, $w = d$) and in heterostructures with a three-layer waveguide (dotted and dot-dash curves) for different values of total thickness w (in μm). Inset: profile of the refractive index of the calculated three-layer waveguide for a laser at the wavelength 1.55 μm.

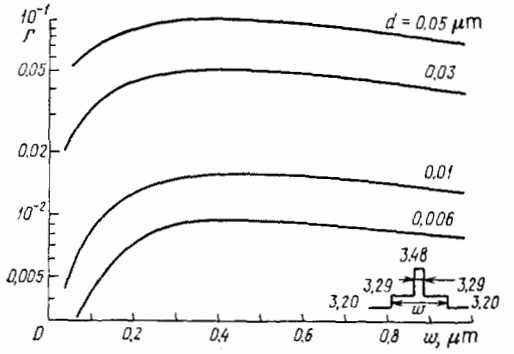

FIG. 3. Magnitude of the optical-confinement parameter Γ as a function of the thickness w of a three-layer waveguide for several values of the thickness d of the active layer (in μm). Inset: profile of the refractive index of the calculated three-layer waveguide for a laser at the wavelength 1.3 μm.

2.3. Quantum-dimensional effects

The one-dimensional potential well created by the narrow-band layer with a sufficiently small thickness redistributes (quantizes) the energy levels and ultimately modifies the density-of-states function and the matrix elements for the different quantum transitions. In this layer the density of states in the case of one-dimensional quantization has a stepped form, in quantum-dimensional filaments—series of peaks, as shown in Fig. 4. The lower level is raised above the nominal bottom of the band by the amount of the "kinetic energy of localization" $h^2/2md^2$, where m is the effective mass, and d is the thickness of the potential well. The quantum-dimensional effect in the energy spectrum acquires meaning under the condition that the characteristic energy of quantization (which is of the order of the cited kinetic energy of localization) exceeds the spread of the energy levels caused by the decay of the corresponding quantum states (of the order of h/τ, where τ is the intraband relaxation time). In the series of studies of ultrathin structures performed in Ref. 26 it was shown that spectral signs of the quantum-dimensional effect in the heterostructures GaAlAs/GaAs and GaInPAs/InP begin to be manifest at thicknesses below 300 Å. It was also found that in single-layer structures the trapping of carriers by the lower quan-

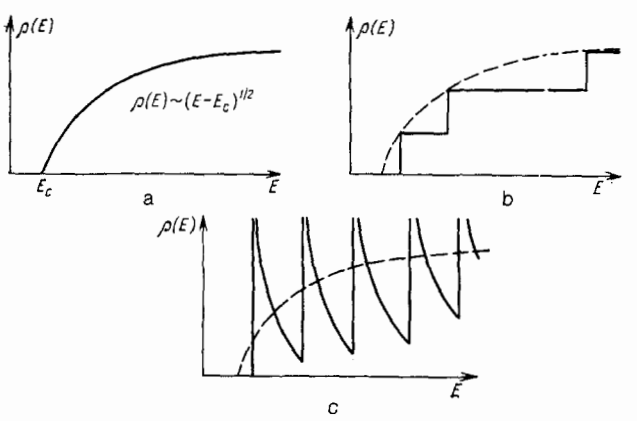

FIG. 4. The density-of-states function $\rho(E)$ in the electron band of a semiconductor: in the bulk (a), in a thin layer (solid lines) (b), and in a filamentous structure (solid lines) (c).[25]

tum levels is retarded with decreasing thickness. Thus at small thicknesses (below ~ 150 Å) the intensity of luminescence from the lower levels is greatly weakened). Correspondingly, one can suggest a weakening of the effect of electron confinement, since most of the trapped carriers stay in levels considerably above the bottom of the potential well.

Certain hopes of improving the temperature-dependence of the threshold current (i.e., reducing the threshold at elevated temperature) arise from the favorable change in the form of the density of states $\rho(E)$ in quantum-dimensional layers. In principle, the use of a discrete spectrum of the type shown in Fig. 4 can eliminate the influence of a very important factor of the temperature-dependence of the threshold such as the "thermal" filling of the bands in the semiconductor. Thus it enables one to eliminate the difficulties involving the fast (exponential) temperature increase in the laser-action threshold in injection lasers. In the case of a stepped form of the spectrum $\rho(E)$, one also expects a weakening of the temperature effect. However, one can directly point out the limits of possible improvement. It is qualitatively evident that filling of the "nonworking" levels above the region of working levels is undesirable. If thermal filling of the next step (or peak of $\rho(E)$) begins, then this corresponds to acceleration of the increase in the threshold, even as compared with a laser with a thick active layer. Thus the possibility of decreasing the threshold current by modifying $\rho(E)$ is bounded above by the temperature at which the characteristic quantization energy ceases to be large enough with respect to the thermal energy kT.

As regards the trapping of carriers in an ultrathin, narrow-band layer, many-layer quantum-dimensional structures of the "supergrating" type have been proposed[27] to avoid difficulty with delayed trapping. The tunneling exchange of carriers in them suffices. It has been shown that the lower quantum levels operate effectively in these structures and a laser regime is attained relatively easily. In regard to optical structure, these lasers can be designed by analogy with the ordinary two-sided heterostructures (THS's) having a certain effective (total) thickness of the waveguide layer. Upon turning to optimization with respect to the threshold current, one must also use the total thickness of the active layers in this case. Hence one can expect that the threshold current will be increased by a factor equal to the number of active layers being pumped as compared with a single-layer structure, (other conditions being the same). This means that, without employing any of the features of the quantum-dimensional effects, in the minimal threshold current in a multilayer structure can hardly be lower that in a single-layer structure (apart from high temperatures, where the electron confinement breaks down more quickly in a single-layer structure). Apparently another pathway is realized in structures having a three-layer (stepped or gradient) waveguide, where the potential well has a stepped or funnel-shaped form. Perhaps two-stage trapping of carriers is more effective. In any case, in studies on low-threshold ultrathin laser structures,[21–23] the problem of carrier trapping has not been mentioned, even at a thickness of a single active layer of 60–80 Å.

We must view the pressing problems in these studies and developments as being the extension of the technology of ultrathin and quantum-dimensional structures to the practically important range of wavelengths 1.3 and 1.55 μm, the elucidation of the influence of the quantum-dimensional effect on the various radiative and radiationless mechanisms and also on other processes that play a role in the physics of the injection laser, and the further optimization of laser structure (while taking account of lateral boundedness, integrated-optics elements, technique of isolation, etc.).

2.4. Increase in emission power of injection lasers

Increase in emission power is necessary for extension of the fields of applications (printing and other methods of optical recording, nonlinear spectroscopy, long-distance communications, intensity gating, etc.). However, the point is to intensify while maintaining high quality (coherence) of the radiation. For example, for "digital" recording on videodisks, we are considering the focusing of 20–40 mW into a spot of diameter of the order of 10^{-4} cm. This requires coherent radiation with small distortions of the wavefront, i.e., single-mode radiation. The technology of coherent communications requires modulated radiation having a spectrum corresponding to the modulation (rather than to the noise, when the width of the generator band exceeds the frequency of modulation).

The phenomenon of stimulated scattering by "waves" of inverted population occurs in semiconductors,[28] and leads to an "anomalous" interaction of the spectral modes, as was first shown in 1975.[29] Space-time beating of modes in the inverted medium gives rise to oscillations of the electron density at the difference frequencies. The interaction of the "strong" mode with the corresponding dynamic permittivity grating of the medium deforms the spectral contour of the amplification, mainly in favor of the long-wavelength modes. Here a spectral gap arises in the vicinity of the "strong" mode, i.e., the weak modes are suppressed. While the resonator suppresses the remote modes, the close-lying modes are suppressed by an internal nonlinear mechanism in the frequency interval $\Delta\omega \leqslant \tau^{-1}$, where τ is the lifetime of the minority carriers. In other words, conditions can be created for autostabilization of a single-frequency regime, as was shown in Ref. 30. The mechanism of this effect reduces to a response to a possible amplification of the intensity of a neighboring "weak" mode. Here, according to the equations of stability of the stationary regime, its interaction with the "strong" mode quenches this amplification. Thus, in a certain range the increase in power of single-frequency generation in a semiconductor laser is accompanied by stabilization against jumpwise switching to other frequencies. This substantially facilitates a higher degree of coherence of the high-power emission.

Let us examine several ways of increasing the power of coherent radiation of injection lasers.

2.4.1. Cascade amplification

Optical amplifiers based on laser diodes have not yet become widespread. Interest in them has heightened in recent years in connection with their possible use as receiving preamplifiers and in a cascade transmitter. The fundamental hindrance consists in the small efficiency of input of the external radiation into the active region of the amplifier. To compensate the input losses requires an amplification of 10–20 dB. Hence the only amplifiers promising here are those with a very large amplification coefficient. This can be attained in a traveling-wave amplifier (TWA) by substantially reducing the reflection from the end faces or in a regenerative amplifier (RA) at the cost of a great narrowing of the signal band (and impairment of stability of operation) and increased lag.

In a recent study on ring-laser regimes, we have developed and studied a laser active element with mirrors inclined (to the active strip) to enable laser action in a ring resonator (i.e., one known to give an "external" amplification greater than unity). The analysis showed that the residual reflection at the ends was reduced to 10^{-4} (for a 10° angle). This allowed an "internal" amplification in a TWA regime up to 40 dB. A TWA operating in a continuous regime was included in the double-cascade scheme of a laser transmitter (Fig. 5) that enabled obtaining narrow-band emission (with a 10-MHz band) while conserving coherence upon modulating the TWA (and maintaining a stable single-frequency regime in the master oscillator). A distinct pattern or side lines at the corresponding distance from the carrier was obtained upon modulating the TWA at frequencies of 0.1–1 GHz. We note that two effects are superposed upon modulating the generator—broadening of the line owing to "chirping" of the frequency and excitation of new longitudinal modes. In this case an increase in the attainable power of radiation of "radiotechnical" quality was obtained with a moderate "external" amplification ($\sim$5–10 dB).

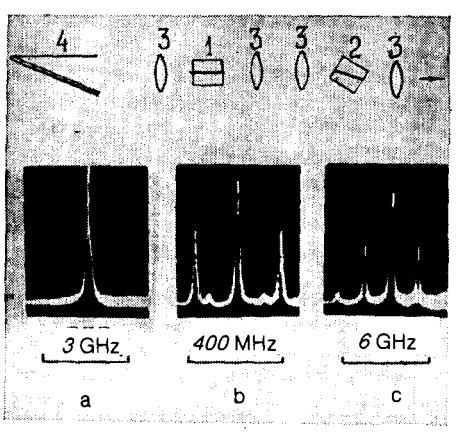

FIG. 5. Diagram of a two-cascade transmitter based on injection lasers with modulator-amplifier power (above) and the emission spectra in a stationary regime (a), and with modulation of the amplifier current at the frequency 190 MHz (b) and 2 GHz (c).[43] 1—active element (laser diode) of the single-frequency generator of the optical carrier; 2—traveling-wave amplifier (laser diode with inclined strip structure); 3—collimator of the external resonator of the generator; 4—spectral holographic selector.

2.4.2 Synchronization in a multistrip structure

The phenomenon of mutual trapping of oscillations in injection lasers in the presence of optical coupling among them was studied theoretically[31] and experimentally[32] rather long ago. Insufficient stimulus existed for expansion of the studies in this field, since the needed optical coupling could be created only by unwieldy external optics. Diffraction coupling via close positioning of the elements could not be effectively used, owing to the mutual thermal effect of the diodes. A decisive revolution occurred quite recently, after it became possible to decrease the threshold currents by optimizing (thinning) the active layer. In the multistrip structure (period 10 μm, active-strip width 3–4 μm) described in Ref. 33, it was possible to obtain a continuous regime upon considerably exceeding the threshold and effectively synchronizing the optical oscillations (in an in-phase or counterphase regime of adjacent strips). As is known, the maximum power was increased to 2.6 W in these diodes. A high degree of mutual coherence of the oscillations was maintained up to 0.8 W, i.e., practically single-mode type of generation. An objective estimate of the quality of the radiation is the possibility of concentrating it into a spot of small dimensions. Such measurements[34] revealed the possibility of focusing up to 90 mW into a spot 2.5 μm in diameter (at a wavelength of 770 nm).

2.4.3. Difference of materials. Promising pulsed structures

Experiment shows that the restrictions on the peak power in semiconductor lasers substantially depend on the materials. In GaAs the limiting fluxes, which depend on the pulse duration, amounted to 1–2 MW/cm^2.[35] For 1.3-μm lasers these limits have not yet been finally established. It has been reported that catastrophic degradation is not observed at flux densities 3–5 times larger than the stated values. Thus one can choose the optimal semiconductor for increasing the pulse power. From the standpoint of the mechanism of optical breakdown (the thermal "microexplosion" model[35]), the reason for the difference can consist in the states of the surface (surface recombination), which predetermine the initial "seed" source of heat release.

From the standpoint of the technology of pulsed lasers with improved collimation of the output beam, we assume the "nonwaveguide" resonators[36] to be of interest. In these the active surface is inclined to the mirrors by an angle of 10–12°. This precludes the usual output of the radiation along the waveguide layer. Injection lasers of this type have been obtained[37] with laser action at 300 K in a pulsed regime with a threshold current density of 18 kA/cm^2 (at a wavelength of 1.3 μm). The improvement in the divergence amounted to a factor of 5–8 in a plane perpendicular to the active layer (5–7° instead of 40–50°). "Longitudinal" generation in an injection laser was reported (i.e., at an angle of 90°, at which the active layer is parallel to the resonator mirrors[38]).

We note that, among the quaternary systems, GaInAsSb/GaSb alone is most favorable for such applications at present, since the active layer possesses antiwaveguide properties. Hence it is easier to prevent undesirable laser action along it. In addition to these variants, laser

structures have been studied with the so-called "leaky modes",[39] which show strong discrimination of the high-order transverse modes.

Owing to the brevity of this review, we could not examine an entire set of pressing problems involved with injection lasers. Space has not been taken for the dynamics and modulation of radiation, the production of ultrashort pulses,[40] the suppression of relaxation pulsations,[41,42] bistable regimes,[43] heterodyning,[44] lifetime characteristics,[45] etc. Injection lasers have been substantially enriched recently, both from the standpoint of understanding the physics of the processes occurring in them, and to an even greater degree, from the standpoint of the technology of preparing them. Yet the practical utilization of injection lasers was preceded by very bold prognoses.

3. ELECTRON-PUMPED SEMICONDUCTOR LASERS (EPSL's)

The formation of minority current carriers in an EPSL arises from multistep ionization caused by fast electrons entering the semiconductor. In this case "hot" electrons and holes are produced. That is, their kinetic energy in the corresponding bands exceeds many-fold the energy of the carriers in equilibrium with the lattice. The interaction of the hot carriers with the lattice of the semiconductor cools them to temperatures close to that of the lattice. That is, the minority carriers, which were initially spread over a broad temperature range of the appropriate bands, occupy a narrow energy interval of the order of kT near the edges of the bands (the electrons at the bottom of the conduction band and the holes near the top of the valence band). The pumping must be of the type such that the "cooled" carriers are degenerate in the corresponding bands. That is, the spacing between the Fermi quasilevels would become greater than the width of the forbidden band. The energy transferred to the lattice in the cooling of the hot carriers constitutes the unavoidable energy losses in the method of pumping with fast electrons (just as in pumping with other ionizing radiations). This requires an additional cooling of the active region as compared with injection lasers. The theoretical calculations and experimental data indicate that these energy losses cannot be less than 64%. That is, the maximum possible efficiency of an EPSL is of the order of 30%.

Pumping with fast electrons is a rather universal method of obtaining laser action in semiconductors that is suitable for materials with any width of the forbidden band and with any initial electric resistance. For this reason, pumping of this type has been applied up to now to a large number of semiconductor materials. It has proved especially important to obtain laser radiation in the visible range with a wavelength shorter than 0.6 μm, where injection lasers do not work.

The EPSL exists in two geometric varieties: with transverse and longitudinal pumping (Fig. 6). In the former case the axis of the optical resonator as well as the direction of the laser radiation are perpendicular to the direction of incidence of the fast electrons. In this variant a great length of the active region between the mirrors is made possible, and it facilitates the lowering of the threshold pumping level. In

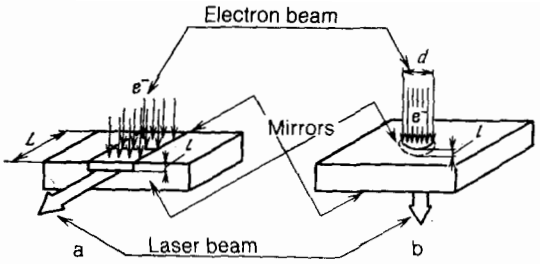

FIG. 6. Semiconductor lasers with transverse (a) and longitudinal (b) electron pumping.

the longitudinal geometry the resonator axis coincides with the direction of incidence of the electrons, so that the length of the active region is limited to the depth of penetration of the fast electrons. This depth depends on the energy E_0 of the fast electrons, which lies in the range from 10 to 300 keV. The lower bound of the energy involves the possibility of penetration of the electrons through the surface layer, and the upper bound involves the formation of defects, which degrade the laser. The depth of penetration varies from several μm ($E_0 = 10$ keV) to 100 μm ($E_0 = 300$ keV). On the one hand, in the case of longitudinal pumping, two-dimensional scanning of the sharply focused electron spot is possible, and hence, that of the laser beam. On the other hand, one can expand the excitation area to increase the total power and decrease the diffractional divergence of the radiation. In order to prevent spread of the inversion over a large excited area, one must create a light-absorbing grid, and for mutual synchronization of the individual elements of a mosaic laser of this type one must employ a second external mirror, which substantially improves the directionality of the radiation.

At present the laser electron-beam tube (LEBT), which was proposed and built by Soviet scientists,[46] has found a number of important technical applications.

In the LEBT longitudinal pumping is carried out (Fig. 7) with fast electrons on a plane-parallel semiconductor target—a plate several centimeters in diameter and several tens of micrometers in thickness. A metallic mirror coating is deposited on the side of incidence of the electrons that is easily penetrable by the fast electrons. The laser-radiation spot has a diameter of 10–50 μm, and can be shifted continuously or discretely over the plate. In a scanning regime the spot passes through the entire raster line by line; in a random-access regime the electron beam is deflected according

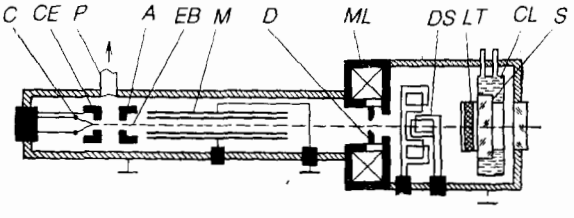

FIG. 7. Diagram of an LEBT for projection television.[46] *C*—cathode, *CE*—control electrode; *P*—outlet for pumping; *A*—anode; *EB*—electron beam; *M*—modulating plates; *D*—diaphragm; *ML*—magnetic lens; *DS*—deflecting system; *LT*—laser target; *S*—sapphire substrate; *CL*—cooling liquid.

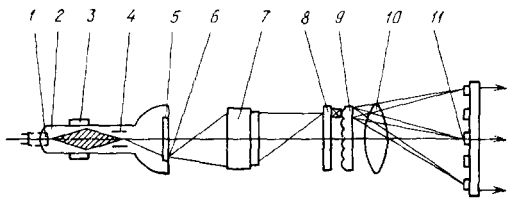

FIG. 8. Diagram of the construction of an optical memory with an LEBT.[49] 1—electron gun with with modulator; 2—anode; 3—focusing coil; 4—deflecting plates; 5—laser screen; 6—generating point; 7—objective; 8—photocarrier; 9—lens raster; 10—lens; 11—array of photodetectors; right—output to measuring apparatus.

to the address to a given position and brightens the corresponding spot. Random access enables one to build various memory devices based on the LEBT. For example, in the variant shown in Fig. 8 the corresponding microframe written on the photocarrier was illuminated under command of the control block with the laser beam and the image was recorded with an array of photoreceivers. A microhologram can also play the role of the microframe. In the performed experiments the number of bits of information in one microframe (hologram) amounted to 10^2 and could be increased. The most direct and highly promising application of the LEBT is projection television on a large screen.[47] The high radiation densities with a considerable efficiency, and mainly, the directionality of the laser beam (with an angle in the range of 20°) are equivalent to an increase in brightness of the screen of an ordinary television set by a factor of 10,000. That is, the image from a 1-cm^2 target of a LEBT projected on a 1-m^2 remote screen has the brightness of a standard television image (Fig. 9). As we have already mentioned above, with a spot diameter on the target of 15–40 μm with a line dimension of 3–4 cm, one can obtain up to 2500 elements per line. That is, the highest television standard is achieved (cinema frame), which is unattainable for all other means of displaying television information on a large screen. The characteristic parameters of a working LEBT are: target dimensions 3×2.25 cm^2, maximum power 10 W, screen dimensions 15–20 m^2.

To obtain a color image, one requires three colors with a ratio of intensities 0.4:1:0.5 for the red, green, and blue colors. Up to now LEBT's have been developed with working materials based on cadmium sulfide (496–510 nm) for the blue-green region, and a cadmium sulfide-selenide solid solution (620–630 nm) for the red region. For the blue component one requires a more broad-band semiconductor, e.g., zinc selenide (460 nm). The wavelengths are cited for conditions of liquid-nitrogen cooling of the target. At room temperature the emission wavelengths are greater by 30–40 nm. At present the preparation of targets of the necessary quality has been mastered for the green and red regions of the spectrum. In principle laser action has been obtained in individual crystals of zinc selenide. However for devices one requires growth of crystals 5 cm in diameter and greater with a high perfection (absence of twinning, defects, etc.). This still involves considerable technical difficulties.

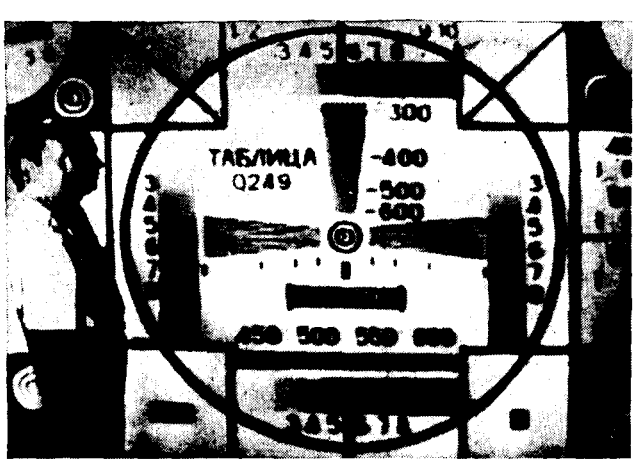

FIG. 9. Television image on a 6-m^2 screen obtained with an LEBT.[47]

Laser projection television sets will considerably surpass all other systems of information display on a large screen in real time in image quality—number of resolvable elements per line, color purity, absence of halos and afterglow, and small energy requirement (the efficiency exceeds 10%).

In comparison with injection lasers, a large part of the pumping energy in an EPSL goes into heating the lattice and the conditions for heat removal are considerably poorer (cooling in a injection laser from two sides of a layer a fraction of a micrometer thick versus cooling in an EPSL from only one side of a layer up to ten micrometers thick). Therefore, for a long time it was not possible to obtain continuous laser action in pumping with an electron beam of one particular region of the semiconductor. However, when the plate is pumped with a sharply focused electron beam with increase in the characteristic dimension of the excitation region $2r_0$ (r_0 is the radius of the beam), the temperature remains constant upon increasing the specific pump power as r_0^{-2}. This situation has enabled obtaining a continuous-generation regime[48] under sharp focusing of an electron beam ($r_0 = 2.5$, 5, and 8 μm at $E_0 = 50$, 75, and 100 keV, respectively).

Figure 10 shows the emission spectra for three different pump currents. Up to the laser-action threshold ($I = 0.7\ I_{thr}$), the width of the spontaneous-emission spectrum amounts to 20 nm. The spectrum clearly manifests the structure of the longitudinal modes of the resonator. When the threshold current is moderately exceeded ($I = 1.3 I_{thr}$), the intensity of a single longitudinal mode is increased by a factor of more than 100. This case corresponds to beam pattern with an angle of divergence close to the diffraction limit (5°). The laser-action spectrum when the threshold pump level is exceeded threefold consists of several longitudinal modes, while the angle of divergence of the radiation is increased to 10° owing to excitation of several transverse types of oscillation of the resonator. The observed shift in the maximum toward the long-wavelength part of the spectrum with increasing electron-beam current is explained by the increase in temperature of the active region. No appreciable changes in the laser-action characteristics were observed upon continuous pumping of a single point of the plate for an hour. When scanning in an ordinary television regime, the laser screens can operate up to 2000 hours.[29]

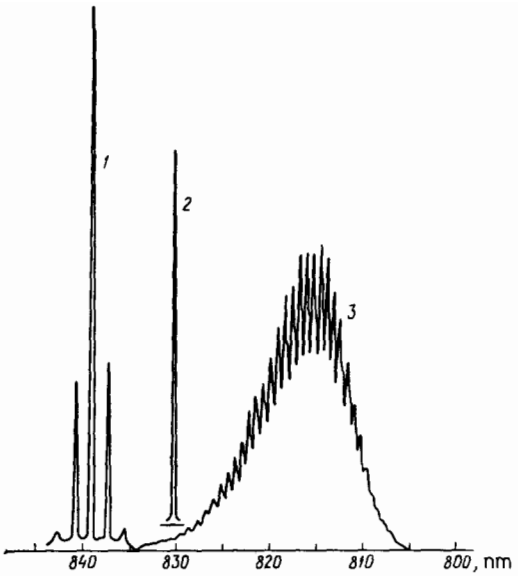

FIG. 10. Emission spectra of a continuous EPSL as a function of the pump power.[48] 1—$I = 0.7I_{thr}$; 2—$I = 1.3I_{thr}$; 3—$I = 3I_{thr}$.

In addition to the injection lasers and fast-electron-pumped lasers described above, as we have already mentioned earlier, streamer semiconductor lasers have been invented and studied in the Institute of Physics of the Academy of Sciences of the USSR. In these the excitation is carried out by forming an avalanche of nonequilibrium current carriers in the strong electric field at the front of a running "streamer". The phenomenon of streamer breakdown in semiconductors is analogous in many ways to a lightning discharge. As the potential rises rapidly at a point contact brought up to the specimen (usually made from the group A_2B_6 and A_3B_5), which is placed in a dielectric medium, an electron-hole avalanche arises in the specimen. The streamer proceeds in a certain direction and creates a vast concentration of nonequilibrium electrons and holes on its path in the relatively small high-field region. The velocity of progress of the high-field region (the "streamer") is close to the velocity of light in the semiconductor, so that the ionizing field acts at a given site of the low-resistance channel and transports the high field to its leading front. The carriers themselves are decelerated and form an inverted population, which leads to generation of light.

For streamer semiconductor lasers and lasers with high-power optical pumping, many features have been elucidated of the behavior of semiconductors under conditions of a very high concentration of minority current carriers (about 10^{20} cm^{-3}). In particular, the laws of multiquantum absorption were established, in which the energy of the exciting photon is smaller than the width of the forbidden band.

However, an entire set of experimentally observed phenomena, e.g., the direction of development of a streamer and its vast velocity of motion, have not yet been theoretically explained.

4. CONCLUSION

At present semiconductor lasers have become a mass-produced device with varied practical applications. Their

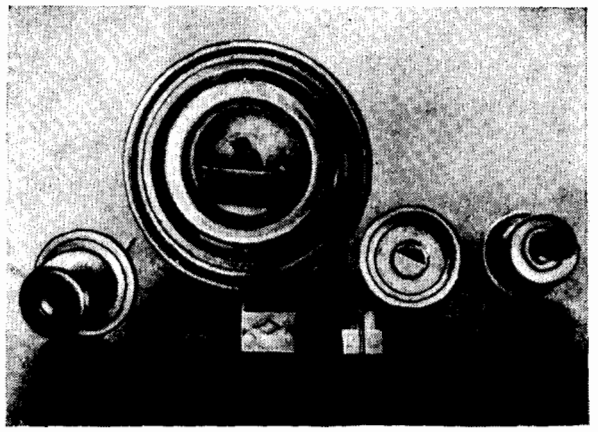

FIG. 11. Different types of injection lasers.[50]

world production is apparently approaching one million per year (Fig. 11) and shows a trend toward further growth. The most important fields of application (optical communications, audio- and videodisk technology, character-printing instruments, and other devices for information display) consume a large fraction of the semiconductor lasers. However, fields exist also of effective applications where the consumption of these devices is not so large at present, but undoubtedly will expand substantially in the future. These are fields such as scientific research, primarily high-resolution spectroscopy and nonlinear spectroscopy, certification of photoreceivers, spectral analysis and monitoring of air pollution, optical automatization, long-distance ranging, etc. Apparently semiconductor lasers can gradually supplant helium-neon lasers in applications such as alignment in construction and mining, holography, precision machine tools and testing apparatus, adjustment equipment and testing of optical elements, laser Doppler and other velocimetry, etc. This is facilitated by the rapid progress in improvement of the emissive characteristics of the lasers, cheapening of the technology, and increase of the output of suitable lasers in production.

At the same time, we must note that semiconductor lasers continue to be a highly fruitful area as a scientific field, which has given rise to new ideas and paths of development. These ideas and achievements exert a stimulating influence on related fields, such as integrated optics, which is now switching to semiconductor media, light-emitting diodes and photodiodes employing ternary and quaternary heterostructures of laser type, and the physics of reliability of semiconductor devices, which has been enriched by the long lifetime of injection lasers. We can relate to this important sections of solid-state physics and technology, in particular quantum-dimensional structures and supergratings, coherent interaction of light with the medium, properties of heterojunctions, nonlinear optics of semiconductors, etc.

Active studies continue in the fields involving the newest technological methods, in particular molecular-beam and metal-organic technologies of preparing heterostructures. We have also noted the topical fields concerning lasers with electron pumping and streamer lasers.

There is every ground for thinking that very soon semiconductor lasers with fast-electron pumping and streamer

lasers will be widely applied for high-quality information display, including television in real time on a broad screen.

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