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N.G. Basov and early works on semiconductor lasers at P.N. Lebedev Physics Institute

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Abstract. **A survey is presented of works on creation and investigation of semiconductor lasers during 1957 – 1977 at the P.N. Lebedev Physics Institute. Many of these works were initiated by N.G. Basov, starting from pre-laser time, when N.G. Basov and his coworkers formulated principal conditions of creation of lasers on interband transitions in semiconductors. Main directions of further works were diode lasers based on various materials and structures, their characteristics of output power, high-speed operation and reliability.**

Keywords: *N.G. Basov, semiconductor lasers, heterostructures, laser power, radiation dynamics.*

1. Introduction

Among outstanding scientific achievements of N.G. Basov, semiconductor lasers occupy a significant place. After a series of priority works in co-authorship with A.M. Prokhorov on molecular oscillators in the 1950s, N.G. Basov turned to a problem of applying the principles of quantum electronics to an optical range. As is well known, the first laser on the basis of a ruby crystal was demonstrated in 1960. But in pre-laser times in 1958 N.G. Basov developed an idea to obtain oscillation by stimulated transitions in the optical range. Particularly, in paper [1] a possibility of laser use of semiconductors was discussed. At the beginning, the case in question was pumping by reversible electronic breakdown using the impact ionisation which produces the excess density of carriers. This method of pumping was realised later as well as the optical pumping and the pumping by a beam of fast electrons. But the most attractive idea was to use the pumping by injection at direct bias of the p – n junction, which made it possible to expect here not only simplicity and compactness of the device but also high efficiency and high-speed operation.

In 1961, N.G. Basov, O.N. Krokhin, and Yu.M. Popov published a short paper [2] containing actually a project of the injection (diode) laser and an explanation of the inversion conditions for the interband transitions in terms of the quasi-Fermi levels. Below we shall consider that paper in more detail. First-generation diode lasers (DLs) corresponding to this project were created in 1962.

N.G. Basov was an enthusiast in this sphere of laser physics. He told his ideas to his disciples and colleagues. His Nobel lecture (1964) was devoted to semiconductor lasers and their applications. He considered attractive properties of these lasers to be high overall efficiency of conversion of electric energy to coherent emission, high-speed operation, compatibility to microelectronic circuits and, definitely, their compactness and simplicity of the pumping design.

For the development of the scientific and technological base in the field of semiconductor lasers, N.G. Basov proposed and organised the Department of Semiconductor Lasers at the P.N. Lebedev Physics Institute and also initiated and headed several R&D projects, nameky 'PKG' (semiconductor quantum oscillators). For this project a governmental directive was issued making the P.N. Lebedev Physics Institute a leading organisation in scientific investigations. In the course of this project under supervision of N.G. Basov, technological developments on the first-generation DLs were carried out as well as studies of lasers with electron-beam and optical pumping, of the high speed operation and of the generation of ultrashort pulses. Thanks to epitaxial technology at the P.N. Lebedev Physics Institute, high-power DLs were developed. They had scientific application as sources of intense illumination (particularly, in studies of electron – hole droplets). The pulse power of DLs under liquid nitrogen cooling was recorded at a level of 50 – 100 W (overall efficiency 25%) and cw power at ~5 W. As to room temperature regime, a decrease in the pulse threshold current density from 100 kA cm^{-2} to ~20 kA cm^{-2} was obtained. Actually, by the PKG program the limiting parameters of the first-generation DLs were achieved (based on homojunctions in contrast to the next generation of heterostructure lasers).

2. 50th anniversary of semiconductor lasers

In 2012, the scientific community celebrated the fiftieth jubilee of semiconductor lasers. First demonstrations of the laser effect were performed in 1962 in several laboratories working with heavily-doped GaAs diodes [3 – 6]. In the USSR first lasers of that type were realised at the P.N. Lebedev Physics Institute [7] and in the Semiconductor Chair at the Department of Physics of the M.V. Lomonosov Moscow State University at about the same time (publications appeared in 1963 and subsequent years [7, 8]).

Accounting for importance of the semiconductor lasers, especially of diode lasers (DLs), in modern science and technology, it is possible to say that 50 years ago a breakthrough occurred into a new field of practical application of semiconductors and in the understanding of optical properties of semiconductors. Before that, photoreceiving was acknowl-

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edged as an advantage of semiconductors, but then semiconductors appeared to be the most effective sources of the coherent radiation! Besides the high overall efficiency of DLs, their other technical merits attracted enhanced interest. Particularly, researchers noticed the high-speed performance of DLs, and also their exclusive compactness and suitability for miniaturisation or micro-miniaturisation of the optical device, the low-voltage electrical feeding, and compatibility to integrated microcircuits. These and other properties played a role in wide spreading of DLs that became the most popular laser devices, actually to be ‘the lasers in every home’. They are exploited in the disk memory, including commercial audio players, in printers, various systems of communication and signal transmission, the range-finding, the automatic technology, systems of illumination, target-indication, and optical pumping.

3. Early theoretical investigations

Among early but approved ideas, one has to mention the proposition to use the semiconductor chip with mirror-like facets as the optical resonator of the laser [9]. This approach is used in billions of DLs fabricated in industry. Paper [1] was registered as the invention application in 1958. In that work, a possibility of usage of a reversible avalanche breakdown or other means of electrical discharge that do not damage the semiconductor crystal was considered theoretically. Lasers based on the electrical discharge have been realised later.

The most important contribution appeared in the paper by N.G. Basov, O.N. Krokhin, and Yu.M. Popov [2] which considered a possibility of electrical pumping using the injection through the p–n junction. It was actually the recipe to make an injection DL. It is expedient to pay attention to this work in more detail.

(i) For the first time the condition to obtain the inverted population for interband transitions was formulated in terms of the quasi-Fermi levels. It is quite applicable to systems close to a state of quasi-equilibrium. Such a state appears if the intraband relaxation occurs sufficiently faster as compared with interband transitions, and the population inside bands corresponds practically to the Fermi–Dirac distribution. In this case one can introduce quasi-Fermi levels to describe and to calculate the population in both bands. In contemporary terminology, the energy difference between the electron quasi-Fermi level and the hole should exceed the energy bandgap E_g. This inequality is the condition of the inverted population for interband transitions, or, as it was formulated in the 1960s, the condition for the ‘negative temperature’.

The inversion condition was written in the form

$$\mu_e + \mu_h > E_g, \tag{1}$$

where μ_e and μ_h are the quasi-Fermi levels of electrons and holes respectively measured in opposite directions in the energy diagram from a common reference point, for example, from the middle of the forbidden band.

(ii) The injection through a p–n junction is an effective method to obtain high density of excess carriers. However, these densities are limited because of restricted built-in voltage V_c. On the other hand, V_c is larger along with higher doping. In order to obtain the inverted population it was proposed to use degenerate semiconductors (at least on one side of the p–n junction). If the value of eV_c exceeds the band gap energy E_g, this gives a possibility of creating the inverted population when the applied voltage approaches V_c. (In principle at very high direct voltage it is possible to get the bias higher than V_c, but this theoretical possibility has no practical importance.) In contrast to this another situation takes place in the degenerate p–n junction. This is the main sense of the theoretical proposition. As the applied voltage approaches V_c, it exceeds E_g/e. In paper [2] the desirable state was called ‘negative temperature’ in terminology used in the maser technique. This term means inverted population when the upper level is occupied higher than the lower level. To apply the Gibbs statistics, the description of such a state requires assigning the negative value to temperature. Obviously the subject is a substantially non-equilibrium population. The inversion (or negative temperature) state relates to a limited amount of working levels providing desirable transitions. It is possible to speak about the inversion in respect to definite spectral lines (bands).

(iii) Another important proposition in work [2] was to use the p–n junction between semiconductors having different energy band gaps, i.e., heterojunction in contemporary terminology, in order to lower the laser threshold. In such a junction it is also possible to obtain the inversion by the injection (presumably one-direction, from wider bandgap emitter semiconductor to narrow-bandgap one). The discontinuity of the bandgap in the heterojunction plays the same role as the energy of degeneracy in a heavily-doped semiconductor junction. In other words it allows one to increase the built-in voltage. Therefore the condition of inversion becomes easier. To the present time in the majority of commercial DLs the heterojunctions are used, to be more precise, heterostructures are used (multilayer structures including several heterojunctions). Of principal importance was the invention of double heterostructures (DHSs) patented by Zh.I. Alferov and R.F. Kazarinov [10]. In the simplest version the DHS contains a narrow-bandgap active layer sandwiched between two wide-bandgap emitter layers of n- and p- types. More advanced heterostructures, widely used in production, contain several heterojunctions. Particularly the separate-confinement heterostructures (SCHs) contain a waveguide which provides the optical confinement and a more narrow active layer (or several layers) for example of a quantum well which provides the electron confinement.

(iv) As the laser regime is a regime of intense stimulated recombination, it influences the electrical current through the diode. It was proposed [2] to use simple electrical measurements in order to find and investigate the laser oscillations. It is the idea of the electrical diagnostics of lasers and of laser amplifiers. The laser threshold and other changes of the oscillation regime are detectable actually by I–V characteristics. At the laser threshold the growth of optical amplification is stopped because the steady-state gain should compensate losses but not more. As a consequence, the voltage applied to p–n junction is also stopped. This behaviour is observable as a kink at the I–V curve [11]. More information is obtained by studying differential characteristics. Besides this, it is possible to observe an electrical response of the laser diode to the passing optical signal in DL-based optical amplifiers. This effect (called sometimes the optoelectronic signal) as described in work [12] appears as a result of stimulated emission (with no loss of optical signal). Therefore it is an effect opposite to the usual internal photoeffect based on the light absorption (and with disappearance of the optical signal). Correspondingly the optoelectronic signal has an opposite sign. Particularly, a passage of amplified pulse through the amplifier is accompanied with lowering of the junction voltage but not with its increase.

Thus in paper [2], apart from the recipe to make the laser, important physical factors influencing the laser operation were predicted. However a whole year was required to realise the DL in practice.

Here it is relevant to mention some aspects of priority in formulation of laser conditions in semiconductors. The subject is that, in parallel to works at the P.N. Lebedev Physics Institute an excellent work was performed by M. Bernard and G. Duraffourg [13] in the Ecole Polytechnique in Paris. This work gets more citations on the West than [2] due to easier access to the English version and also because there the condition of inversion was derived in the following form

$$F_n - F_p > h\nu, \qquad (2)$$

where F_n and F_p are the quasi-Fermi levels of electrons and holes respectively, as measured into one direction; and $h\nu$ is the photon energy of the working transition. As it is applied to interband transitions, this condition is identical to condition (1). However the paper of M. Bernard and G. Duraffourg was submitted to Physica Status Solidi in September of 1961, and published in the last issue of the journal in December of 1961. The comparison with the data of paper [2] leads to the priority of Basov et al.'s paper as it was received in the editorial desk of the JETF journal on 18 April 1961 and it was published in the June issue, 1961.

In recent paper by M. Bernard [14] devoted to the history of laser conditions in semiconductors it was mentioned that M. Bernard and G. Duraffourg lost two months in 1961 because of rejection from Physical Review Letters (the date of receiving by editorial office is July 1961). It is seen that Basov et al.'s paper was submitted three months earlier and published before M. Bernard and G. Duraffourg applied to editorial office of PRL and also published for three months before they submitted to Physica Status Solidi. Unfortunately the paper of M. Bernard [14] presented incomplete history of 'laser condition in semiconductors' as the paper of Basov et al. [2] is not mentioned at all.

4. Early experimental works at the P.N. Lebedev Physics Institute

First, initiative research in pre-laser times will be considered. These works were successfully completed by demonstration of a DL in 1962–1963 [7, 8] after pioneering works in the USA [3–6]. Earlier works were focused on indium antimonide (DLs based on InSb were realised later [15]). In these DLs a phenomenon of pinching was observed which was an obstacle to get uniform pumping of the active region.

In the following years, works on investigation and further improvement of DLs were carried out according to the governmental project 'PKG'. Throughout this Project, the P.N. Lebedev Physics Institute was directed to perform both theoretical and experimental physical investigations, whereas development of semiconductor materials was a task for the State Research Institute of Rare Metals (GIREDMET) and for plants connected to it. The task was the delivery of not only initial ultra-pure materials like Ga, In, As. etc. into the electronic industry and to academic institutes, but also of single crystal laser materials (arsenides and antimonides of gallium and indium, etc.). Later the GIREDMET elaborated epitaxial technologies of fabrication of laser materials of mixed content (solid solutions including multi-component compositions). The cooperation with the GIREDMET had an exclusive importance for the whole cycle of works at the P.N. Lebedev Physics Institute on lasers based on various materials, primarily based on compounds and solid solutions of III–V type. It was necessary to establish validity of natively-produced materials for using them in new devices of quantum electronics (in lasers and laser amplifiers), and also to study limits of performance of lasers (output power, overall efficiency, high-speed operation and so on).

In the PKG Project, works on other pumping techniques are also included. Among them, the electron-beam and optical pumping attracted the interest. A corresponding theory was developed by Yu.M. Popov, and these results made up his doctoral dissertation. One of the subjects was the kinetics of fast electrons in semiconductors and their avalanche multiplication. The electron-beam pumping required an arrangement of some compact equipment including electron guns and electron accelerators to some moderate energy range (100–150 keV). The limit of accelerating voltage is imposed by the nature of interaction between fast electrons and semiconductor crystals. The fast electron bombardment leads to an appearance of secondary electrons. By multiple acts of internal ionisation, high-energy electrons undergo thermalisation and produce non-equilibrium electron–hole plasma. This process serves as the mechanism of pumping in lasers. However if the incident electron energy is increased, the probability of lattice damage grows, particularly of formation of vacancy–interstitial atom pairs. As lattice defects are usually the centres of nonradiative recombination or of traps for electrons or holes, their formation is undesirable. Rules of energy transfer from light particles (electrons) to lattice atoms establish the threshold energy of defect formation. Thus, there is an optimal range of energy at which the pumping produces excess electron–hole pairs but does not damage the crystal. The upper limit in GaAs is about 200 keV. Problems and achievements in the field of electron-beam pumping were presented in the book by O.V. Bogdankevich et al. 'Semiconductor lasers' (Moscow: Nauka, 1976).

For optical pumping of semiconductors a rather high intensity is required and actually another laser should be used as a source. By the way, one of the mass applications of DLs is so called diode pumping of other lasers, solid-state and gaseous ones. DLs are more effective sources of pumping (compared to discharge lamps) thanks to their high overall efficiency and to narrow spectral range. The expediency of usage of diode pumping is based not only on an increase in efficiency but also on a possibility to improve the coherence or increase the peak power by energy accumulation in more inertial active element. On this basis the industry of diode-pumped solid-state, fibre and gaseous lasers grows. Besides this, the optical pumping of semiconductors served as a useful noncontact method of testing the materials and structures for determination of their luminescent and laser properties. One of the first examples of DL-pumping was demonstrated at the P.N. Lebedev Physics Institute in 1967. It was the InP-laser pumped by a GaAs DL [16]. In the majority of cases, the regime of high power and high efficiency occurs with multimode content of emission from DLs. The diode pumping allowed coherent properties of output emission to be improved if the pumped active element permits obtaining a single-mode or single-frequency regime. In this case, the goal is summation of optical power of low coherence for obtaining highly-coherent emission. Diode pumping of solid-state lasers including active fibre lightguides allows an increase in the peak power by accumulation of pumping energy at excited ions. This progress started the successful application of DLs in laser technology.

5. New materials and structures

The main milestones in the development of semiconductor materials for lasers consisted of the following: first, in fabrication of DLs operating at different wavelength (in frames of elaboration of first generation of laser structures – homojunctions, 1963–1968); second, in transition to heterojunctions based on a AlGaAs/GaAs system (1969–1973); and then, third, in transition to a wider class of new heterostructures based on multinary solid solutions (1973–1988). The evolution of the threshold current density was as follows. In first-generation DLs laser oscillation was reached in a pulse regime under current density over 100 kA cm^{-2} (diffusion homostructures). However, by use of epitaxial technology and doping optimisation the threshold was lowered to about 20 kA cm^{-2} in homostructures. In pAlGaAs-pGaAs-nGaAs single-heterostructures the threshold was reduced to 7–9 kA cm^{-2}. These results were obtained at the P.N. Lebedev Physics Institute in cooperation with the GIREDMET in 1969. The next step was a fabrication of AlGaAs-GaAs-AlGaAs double heterostructures where the threshold was lowered to about 1 kA cm^{-2}. This was sufficient for obtaining the continuous-wave operation at 300 K [17, 18]. The cw laser action was demonstrated at the P.N. Lebedev Physics Institute in 1970 [19], after similar works at the Ioffe Physical-Technical Institute [20] and at the Bell Lab in the US [21]. An explosive-like raise of interest followed these works in practical applications of DLs. Actually the first detailed study of the cw DLs operating in the wavelength range 850–880 nm was carried out at the P.N. Lebedev Physics Institute [18, 19].

However, a serious difficulty appeared for practical use – relatively rapid aging (degradation) of DLs which limited the service life of cw lasers. The first samples of these DLs degraded in view during measurements of usual characteristics. A work was necessary on study and exclusion of the previously unknown degradation processes. It was clear that in an industry, where DLs were in series production (at least experimental samples) it would be easier to perform life testing of a large number of DLs and to reveal decisive factors. In spite of this, it was desirable to maintain our participation in these studies. Most works were performed in cooperation with the electronic industry in Moscow and Saratov. The results of these works were theoretical modelling of rapid degradation, revealing factors of mechanical stress, surface processes of optical self-damage and of slow degradation. For the first time systematic data were obtained on a critical intensity of catastrophic optical damage (COD) of end facets. The intensity decreases along with an increase in the reverse square root of the pulsewidth [22]. This observation indicated a thermal nature of damage mechanism in agreement with the model of the thermal micro-explosion (or thermal runaway) presented in the same work. Only in 1979 could we achieve the operation lifetime of cw DLs at the level of 10^4 hours [23]. This meant that there was a possibility of practical mass application of DLs in telecommunication, in disk systems, in automatics, in optical pumping, in printers, and in other devices.

Another aspect of the development was the creation of DLs based on new materials and on new heterostructures. In the first stage at the P.N. Lebedev Physics Institute cooled DLs were realised based on following materials: GaAsP, InP, InAsP [24, 25], InAsSb, InSb [15]. These DLs covered the wavelength range from 640 to 5200 nm. The next step was the successful development of iso-lattice-parameter multinary systems of solid solutions, valid for creation of defect-free laser heterostructures. The need for these materials was provided by the necessity to have laser devices for new spectral ranges outside the segment covered by AlGaAs-GaAs heterostructures (700–880 nm). There were no binary compounds with equal or close lattice parameters in other heterosystems. A principle of iso-lattice-parameter substitution of components was as follows. To use quaternary and other multinary systems, one can compose pairs with equal lattice parameters by dosed substitution of components (where the influence of the components on the parameter is mutually compensated). For example, if the initial material is indium phosphide (InP), the partial substitution of In atoms by Ga atoms leads to a decrease in the lattice parameter because Ga has smaller covalent radius than In. Simultaneously it is necessary to make partial substitution of phosphorus atoms by arsenic atoms, that corresponds to an increase in the parameter as As has larger covalent radius than P. In order to compensate for influences of both components, the content of As should be 2.2 times larger than content of Ga. Watching this rule allows one to obtain iso-lattice-parameter family of InGaAsP compositions so each of them can be defect-free jointed to InP and also to each other. In this case, the energy bandgap of the quaternary solution changes in the range from 1.32 to 0.74 eV. The realisation of such iso-lattice-parameter systems suggests a possibility to obtain solid solutions in the whole range of compositions. It can be impeded by the known phenomenon of immiscibility or of instability of solution. The technological elaboration can also be influenced by volatility and by chemical aggressiveness of components. Beside this, the type of the energy band should be established. The direct bandgap type is needed for lasers whereas many semiconductors (like Ge, Si, GaP) and some solid solutions belong to indirect bandgap types. Hence in addition to calculation of iso-lattice-parameter families, one should elaborate the corresponding technology of fabrication and investigate basic properties.

The system of InGaAsP/InP was developed in the cooperative work of the P.N. Lebedev Physics Institute and the GIREDMET. In 1974 first DLs based on double heterostructures were demonstrated [26]. This result opened the way to DLs covering practically important wavelengths in the range 950–1680 nm including optimal ranges of optical fibre communication at 1300 and 1550 nm. Thus, the communication DLs that supply the long cable connections up to now were created.

The same principle of iso-lattice-parameter substitution was applied in further time to other heterosystems, such as InGaAsSb-GaSb [27] and PbSnTeSe/PbSe [28]. Lasers based on InGaAsSb-GaSb covered the wavelength range 1750–2300 nm. There are ranges that are eye-safe because of strong absorption in water.

In connection with wide usage of DLs in optical communications it is relevant to pay attention to work [29] performed by proposition and by cooperation with the Institute of Long-Distance Communication of the radio-industry. The spectral multiplexing is a routine means for modern multichannel systems. But in 1969 when the work was presented at the

International CLEA (Washington, D.C., USA) the demonstration of an example of optical frequency multiplexing was an innovation, in spite of relative simplicity of the approach and a small number of channels (four). In that work DLs were used based on various semiconductor materials and emitting at different wavelengths in the range 750–950 nm. Laser beams were joint in one beam directed to the lens system of distant communication at the testing ground of the Institute of Long-Distance Communication. Thus, the optical multichannel transmission based on semiconductor lasers had been demonstrated in 'before-fibre' times when low-loss fibre cables were not yet available. In subsequent years, works on 'communication' DLs and modules with DLs were carried out systematically at the P.N. Lebedev Physics Institute. The transmitter module at 1300 nm with a fibre pigtail for application in communication systems was elaborated in cooperation with the Institute of Optics and Spectroscopy (Academy of Science of the German Democratic Republic) and it was awarded the Gold Medal of the International Leipzig Fair in 1986.

6. Investigation of high-speed operation and of ultrashort pulse generation

An important motivation of interest in miniature semiconductor lasers was associated with high-speed operation (in particular, in comparison with micro-electronic devices of that time). N.G. Basov foresaw the development of the photonics based on DLs and on integrated circuits with DLs as active elements. First, he reasonably considered that if photons propagate faster than electrons, the limits of high-speed operation in the photonic devices should be higher than in the microelectronic ones. Naturally for reducing the inertia in DL-based schemes both the diode size and distance between diodes should be minimised. Second, DLs and amplifiers based on DLs can be used as switching devices controlling flows of photons. N.G. Basov set a task of creation of laser logic elements valid for the base of an all-optical computer. Also works on the generation of ultrashort pulses were started. The availability of electronic-optical registrators – devices converting IR image into a visible one and supplying high-speed scanning (time resolution about 10^{-11} s) was quite favourable for these works. Usage of the registrator (known also as streak-camera) made studies of fast processes in DLs easier and quicker. One of the first important observations of GaAs DLs was the self-sustained pulsing of laser oscillation in DLs of first generation. Periodic pulsing was characterised by the repetition rate in the nanosecond range. The control of pulsing oscillation was demonstrated in two-section diodes [30].

The theory of laser emission dynamic in such DLs was presented in work [31]. The usual approach for obtaining a passive *Q*-switching is a combination of two media with different optical parameters at the frequency of operating transition, namely active medium (for example, a rod of neodymium glass) and a dye solution with saturable absorption (in the inter-cavity cell). In the two-section DL a condition for nonuniform pumping is fulfilled and a role of a saturable absorber is played by the same medium as in the active section but supplied by lower pumping. As a result, by choosing the regime in both sections one can obtain the *Q*-switching regime corresponding to a generation of periodic optical pulses of sub-nanosecond duration. By adding an external mirror the mode-locking regime is achievable when the period of ultrashort pulsing is determined by the round-trip time in the external cavity [32]. In work [33] regimes were investigated of amplification and quenching of the emission in a system of two optically connected DLs via a microscopic gap between them produced by a cleavage.

Here it is expedient to mention an investigation associated with the activity of N.G. Basov. It was a study of the nonlinear amplification of light pulses [34]. A phenomenon now called superluminal propagation was observed and theoretically interpreted. An optical pulse in amplifying medium consumes inversion with an increase in pulse energy but also with depletion of energy in the medium. Due to this the front of the pulse gets more energy than the last part, and the 'gravity' centre of pulse shifts ahead. Later similar observations in different media (amplifying or absorbing) led to studies of fast and slow light. The abovementioned work appeared to be pioneering in this direction. In its experimental part the ruby laser and amplifier have been used. The passage time was measured by the top of a 16-ns long laser pulse through the amplifying 24-cm-long rod to determine the group velocity of light. At a sufficiently high density pulse energy (about 4 J cm^{-2}) the result has been registered paradoxical for that time: the velocity of pulse propagation happened to be 6–9 times higher than velocity c of light in vacuum! Forty years after these studies the superluminal phenomenon became observable in semiconductor optical amplifiers.

7. New cavity configurations of semiconductor lasers

An idea to use the semiconductor chip as the laser resonator was stated in 1960 [9]. Now it is used in millions of laser devices all over the world. Thanks to high refractive index the semiconductor–air interface is characterised by high reflectivity (in GaAs it is 32%). The optical gain on interband transitions is huge ($\sim 10^4$ cm^{-1}), and accounting for this, the condition of self-excitation of oscillator is fulfilled easily with reflection from natural surfaces. The Fabry–Perot cavity is obtainable easily by crystalline cleavage [35]. A modification of reflection by deposition of dielectric coatings is required sometimes for reduction of optical feedback, particularly to obtain a regime of the travelling wave. Also optimisation of reflectivity coefficients is widely applied in order to increase the overall efficiency and to obtain unidirectional output (full rear mirror and reduced reflection of front mirror).

N.G. Basov initiated studies of new cavity configurations soon after the realisation of DLs. The task was to improve the mode selection under enlarged output power. In work [36] results were reported on semiconductor lasers with the so-called 'emitting mirror'. It was the new version of an increased active volume laser, which is now known as a surface-emitting cavity. Such a version corresponded to longitudinal pumping (by electron or optical beam) and it included a possibility to use an external mirror for enhancement of angular selection. At present time the VECSELs (vertical external cavity surface-emitting laser) correspond to this version. Such cavities are optimised for high-power operation. In studies of emitting-mirror lasers the lateral losses of inversion were found and methods were developed to eliminate these losses.

Composite-cavity DLs were proposed and realised [37–40] to improve mode selection, as well as dispersion external cavity lasers (with diffraction grating and of holographic reflectors). The spectral tuning by external cavity has been reported for the first time in work [41]. By usage of two diffraction gratings a regime of two spectral modes has been obtained and an investigation of this regime allowed us to reveal the nonlinear asymmetric interaction of modes in DLs [42, 43]. After the appearance of the distributed feedback (DFB) structures, experiments were made with first DFB lasers based on the quaternary InGaAsP structures [44].

Studies with different cavities for DLs were continued in subsequent years, and various methods were tested to control the mode content and to make a spectral tuning with usage of external cavities of the following types: the Fabry–Perot type [45], the Michelson interferometer [46], the unstable resonator [47], and the ring cavity [29]. Also experiments were carried out on spectral-consisted modulation of a DL and on heterodyning in a system of two DLs [48]. These experiments appeared to be useful in studies on the nonlinear optics of DLs.

When the waveguide theory of DLs was developed [49], an issue appeared about optimisation of active region thickness. It was shown that ultrathin structures have some advantages in lowering the threshold and in increasing the overall efficiency. Depending on gain characteristics, the optimal thickness of active layer can be formally close to zero, but it is sufficient to reduce the thickness to about 10–20 nm (in the case of double heterostructures). Actually this result was obtained many years before the transition to ultrathin and to quantum-well structures.

8. Nonlinear phenomena in semiconductor lasers

A saturation of gain is one of first phenomena revealed in DLs and it was relatively easy to investigate since the appearance of cw lasers (at cryogenic temperature in the beginning and then since 1970 – at room temperature). It is mentioned above about an observation of a pinning of the applied voltage in the p–n junction above the laser threshold [50]. In cw lasers measurements are performed at dc pumping, and this provides higher accuracy of measurements.

As the multimode oscillation easily appeared in DLs, an opinion existed that the spectral band of edge emission (interband and one close to it) is inhomogeneously broadened. The saturation of voltage appeared to be a fact confirming the prevalence of homogeneous broadening. As to multimode emission, it is associated with factors of spatial non-uniformity (at least at low exceeding of the threshold) and with the self-sustained pulsing in the sub-nanosecond range. As it was mentioned above, the refractive index of a semiconductor is sensitive to the carrier density (and also to a redistribution of carriers over energy, so-called spectral hole burning). In the oscillation regime, the density is rather high ($10^{17}-10^{19}$ cm^{-3}). The variation of the density leads to index variation; therefore, it leads to various phenomena including the optical nonlinearity of the medium. Among these phenomena are the self-focusing instability, the anti-guiding effect, the frequency self-modulation (so-called 'chirping'), the bistable regimes, the mode interaction, and phenomena of slow an of fast (superluminal) light propagation.

The most important work in this direction was the finding and the theoretical interpretation of nonlinear mode interaction [42] to which following effects are associated: the spectral asymmetric component of nonlinear gain, the multi-wave mixing, the acceleration or slowing of the light, and the frequency splitting in the spectrum of intermode beating. By the way, in this work the factor of amplitude–phase coupling was introduced. It plays an important role in calculation of the linewidth of laser emission of DLs. A substantial consequence of nonlinear interaction is self-stabilisation of the single-frequency regime in the semiconductor laser. A review of investigated nonlinear phenomena provided by the influence of carriers on the refraction was given in paper [51].

9. New types of semiconductor lasers

At present time both solitary DLs and devices based on them are well-developed goods. The production scale of DLs is amazing. The record growth rate was achieved in best times of high-technology industry. Modern systems of diode pumping can include millions of similar DLs densely packed into water-cooled blocks. This is a development of N.G. Basov's projects to apply diode pumping in the laser assisted ignition of controlled thermonuclear synthesis.

At the same time scientific works were continued, and this resulted in widening of semiconductor laser types in addition to classical injection DLs. Known types are shown in Table 1 with proposed classification by methods of pumping and by working transitions.

Obviously, injection lasers, after a half-century history of improvement, are of predominate type by production and practical application scale, and by a degree of technological development (mainly, on the base of gallium arsenide and indium phosphide platforms). A special interest was attracted to quantum-cascade DLs [53], in which optical transitions are used between levels in quantum-well structures belonging to different sub-bands, mainly, to electron sub-bands. Multicascade approach is favoured by the unipolar nature of these

Table 1. Types of semiconductor lasers (after 50 years of R&D) [52].

Pumping method	Working optical transitions	Types of lasers	Comments
Electrical:			
injection	Interband	Injection Lasers (DLs)	
carrier heating	Intersubband, cyclotron, etc.	Hot-holes lasers	Low temperatures
tunneling	Intersubband	Quantum-cascade lasers	IR and THz ranges
discharge	Interband	Streamer lasers and lasers on high-field domains	High resistivity crystals
Optical	Interband, impurity–band	Photopumped lasers, including VECSELs	
	Combination	Raman lasers Frequency converters	
	Magnetic-combination	Spin-flip lasers	Low temperatures
Fast particle irradiation	Interband	Electron-beam pumped lasers	

DLs. This provides an achievement of a sufficient optical gain. In other words, several cascades with active layers in each are placed in the modal volume. An electron passing through the cascade structure can participate in emitting transition many times.

A valuable property of quantum-cascade lasers is the room-temperature covering of IR, where interband DLs require cryogenic condition. If the cooling is used, the quantum-cascade lasers can supply the terahertz laser oscillations. As to other new types of semiconductor lasers, they have not yet come from laboratory stage.

Lasers based on combination transitions (i.e. on stimulated Raman emission) attract an interest because, first, one can use numerous indirect-band materials and, second, one can move laser elements into well-developed silicon circuitry. These elements operate in wide transparency bands of the semiconductors. The photon energy at the output differs from the photon energy of pumping (usually into Stokes side) by energy of an elementary excitation in given crystal. The excitation in Raman lasers is an optical phonon, and in spin-flip lasers the excitation is oscillation, associated with reorientation of electron spin in a magnetic field. Due to the fact that the magnetic field influences the frequency of the oscillations, the spin-flip lasers allow magnetic tuning of the emission frequency. As to lasers on hot holes, the detailed investigation showed that in the emission spectrum one can observe transitions between bands of light and heavy holes, transitions inside the light–hole band (the cyclotron lines), and also lines of transitions in shallow impurity acceptors centres. Unfortunately, the laser lines are observed exclusively at low temperatures.

10. Conclusions

The 1960s were breakthrough years in semiconductor physics and in optics when both the objects of studies and physical instruments of investigation underwent substantial updating. This was a legendary time of an arrival of the laser physics. New types of lasers were created, and approaches were significantly revised. All of us who worked with N.G. Basov at that time are thankful to him for his supervision, for his amazing intuition and for the generation of many ideas in new projects and directions.

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