pure injection method without the necessity of using high-level doping and degenerate p-n junctions. Owing to the potential barriers and the wave guide symmetry of the structure ($n_2 > n_1$ and n_3), there are practically no recombination and light losses, as a result of which the threshold generation currents are drastically reduced and the efficiency increased (at 300° K, $j_{thr} \approx 10^3$ A/cm^2, the differential quantum yield $\eta_d \approx 70\%$, the efficiency $\eta = 25\%$ instead of $j_{thr} \approx 50 \times 10^3$ A/cm^2, $\eta_d \approx 10-15\%$, and $\eta = 1-2\%$ for lasers with p-n junctions). The performance parameters of a number of other devices (solar converters, photodiodes, phototransistors, switching diodes) have also been considerably improved and completely new devices, which could not be realized on the basis of homo-p-n junctions, have been constructed: converters of infrared radiation to visible radiation, selective picture receivers, etc. The spectral band of emitting and photoelectric devices can be considerably broadened into both the visible and the infrared regions, since the possibility of producing ideal heterojunctions based on other $A^{III}B^V$ compounds (AlSb – GaSb, AlP – GaP, and some others) has now been demonstrated.

Zh. I. Alfërov, Inzhektsionnye geterolazery (Injection Heterojunction Lasers), in: Poluprovodnikovye pribory i ikh primenenie (Solid-State Instruments and Their Application), No. 25, Sov. Radio, M., 1971; Zh. Alfërov, Proc. of the Intern. Conference on Heterojunctions, (Budapest, October 1970), Vol. 2, Académiai Kiadó, Budapest, 1971; Sov. Sci. Rev. 2, 147 (1971).

V. S. Vavilov and E. A. Konorova. Semiconductor Diamonds. Diamond is structurally one of the simplest and, with respect to physical properties, one of the most interesting nonmetallic crystals. The high thermal conductivity and the chemical and thermal stability of diamond, as well as the high mobility of the charge carriers—electrons and holes[1]—make the production, study, and practical application of semiconducting diamonds a pressing problem. Advances in the synthesis of insulating and semiconducting diamonds under laboratory conditions[2,3] and the increase in the output of natural diamonds suggest that in the next decade, besides the traditional industrial applications, diamonds will also become a valuable material in electronics. The investigation into the possibility of an ionic implantation of electrically active donor (lithium, phosphorus, antimony) and acceptor (boron) impurities in plates of natural diamond carried out at the P. N. Lebedev Physics Institute of the USSR Academy of Sciences in collaboration with the I. V. Kurchatov Institute of Atomic Energy[4,5] has led to the production of n- and p-type semiconducting layers which are stable right up to 1400°C and have highly mobile carriers.

It was established in the course of the indicated investigations that for implanted-ion doses not exceeding certain critical values, annealing leads to the restoration of the diamond lattice structure. It has been demonstrated that we can, using the ion-implantation method, fabricate p-n junctions which possess diode volt-ampere characteristics and exhibit the barrier-layer photoeffect in the spectral range corresponding to the interband electron transitions in diamond ($h\nu > 5.4$ eV)[6]. It has been established that upon increase in the concentration of the implanted impurity (in particular, boron and antimony), the conductivity realized in the conduction or valence band is changed into conductivity of the "hopping" type. Using the ion-implantation method, we can realize not only structures consisting of n- and p-type semiconducting layers on the surface of or inside an insulating diamond plate, but also heterogeneous structures—in particular, layers of silicon carbide SiC implanted in diamond[7].

Further investigations should be directed towards the production of low-resistance contacts based on n-type semiconducting diamonds and the investigation of the electron processes near the surface of semiconducting diamonds, after which we can, in principle, realize electronic devices characterized by the ability to operate at high temperatures and by stability. As an example of a diamond-based electronic device which has already found practical application, we can cite the nuclear-particle and photon detectors constructed at FIAN[8].

[1] R. Berman (ed.), The Physical Properties of Diamonds, Oxford Univ. Press, 1965.
[2] C. Luggins and P. Cannon, Nature **194**, 829 (1962).
[3] L. F. Vereshchagin et al., Dokl. Akad. Nauk SSSR **192**, 1015 (1970) [Sov. Phys.-Doklady **15**, 566 (1970)].
[4] V. S. Vavilov, M. A. Gukasyan, M. I. Guseva, and E. A. Konorova, Fiz. Tekh. Poluprov. **6**, 858 (1972) [Sov. Phys.-Semicond. **6**, No. 5 (1972)].
[5] V. S. Vavilov, M. I. Guseva, E. A. Konorova, and V. F. Sergienko, ibid. **4**, 17 (1970) [Sov. Phys.-Semicond. **4**, 12 (1970)].
[6] V. S. Vavilov, M. A. Gukasyan, E. A. Konorova, and V. F. Sergienko, Dokl. Akad. Nauk SSSR **200**, 821 (1971) [Sov. Phys.-Doklady **16**, 856 (1972)].
[7] I. P. Akimchenko et al., Fiz. Tekh. Poluprov. **6**, 1182 (1972) [Sov. Phys.-Semicond. **6**, No. 6 (1972)] (A brief communication).
[8] S. F. Kozlov and E. A. Konorova, Fiz. Tekh. Poluprov. **4**, 1865 (1970) [Sov. Phys.-Semicond. **4**, 1600 (1971)].

L. N. Kurbatov. Photoelectric Solid-State Receivers and New Methods of Optical-Radiation Reception. The development of instrument manufacture and the working out of optico-electronic systems have led in the last decade to a rapid growth of interest in the reception of radiation in the optical band. A considerable impetus to the investigations and the development of receivers was given by quantum electronics, the attainment of which allowed the production of high-power radiation fluxes with a high degree of coherence. The characteristics of coherent radiation made it possible to carry over to the optical band certain principles of reception which had been known for a long time in radio engineering—in particular, heterodyne reception.

Still another circumstance, connected with the appearance of lasers, is the necessity for the broadening of the frequency band, i.e., for the construction of receivers with a high speed of response.

Radiation receivers have been the subject of an extensive literature, including review articles. However, the rate of development of this field is so high that the presentation of a special report at a session of the Division of General Physics and Astronomy of the USSR Academy of Sciences is justified. Not being in a position to consider all types of receivers in the report, we limit ourselves to only the range of questions named in the title.

It will be 100 years in 1973 since the discovery of photoconductivity by Smith. The last 30 years have been especially productive. During this time the main semiconductor photoelectric devices—photoresistors and photodiodes—have passed through fundamental investigations to mass production and application in important equipment.

A great contribution to the development of the investigations and the construction of the devices was made by the scientists of the institutes of the Academy of Sciences (the Physico-Technical Institute, the Physics Institute, the Institute of Radio Engineering and Electronics, the Institute of Semiconductors of the Ukrainian Academy of Sciences). The investigations and device construction encompassed the entire optical band, including the submillimeter region. The overlap of the optical and the microwave bands in the submillimeter region facilitated the interpenetration of the ideas and methods characteristic of each of the bands.

As the main trends of the development of photoelectric semiconductor receivers (PSR) in recent years, we can cite the following:

1) The mastering of the great variety of semiconducting materials which guarantee reception in the entire optical band (germanium and silicon with diverse impurities; $A^{III}B^{V}$, $A^{II}B^{VI}$, $A^{IV}B^{VI}$ compounds; ternary systems) continued. Some of these materials have been brought to a high degree of perfection. Numerous types of PSR—types which are not cooled, as well as those requiring cooling to low temperatures, including liquid-helium temperatures—have been constructed on their basis. The most important development in the last 5 years has been the construction on the basis of ternary systems of PSR for the region near 10 μ. Besides good photoelectric properties, these PSR surpass the earlier ones by the fact that it is not necessary to cool them to temperatures below the boiling point of liquid nitrogen.

2) The existence of good materials and technological advances have enabled us to reduce in a number of cases the minimum registrable power to values close to the limiting values which are determined by radiation fluctuations (radiation threshold).

3) From the constructional point of view the PSR become complex devices which include, besides the sensors, optical elements (windows, lenses, filters, screens, light conductors) made of a number of unusual materials, microcoolers, and highly miniaturized preamplifiers. This, of course, does not imply that the simplest PSR are no longer of any value. On the contrary, they fully preserve their value in certain fields of application.

4) Progress in the field of materials and microelectronic techniques has made it possible to construct multielement PSR with tens and hundreds of minute elements. This trend will subsequently result in a change of function for the PSR: from their present function as radiation detectors and radiation-power meters they will become image converters, converting images from one spectral region to another.

The appearance of multielement PSR structures gives us grounds to speak of a new direction for semiconductor electronics, to wit, of microphotoelectronics.

5) Still greater interest is being shown in high-speed PSR with time constants in the region of the nanosecond and subnanosecond bands. The most interesting in this connection are the photodiodes—in particular, the avalanche ones.

(Several diapositives and a small exhibit give us some idea about the outside diameter and construction of certain models of the PSR, the microrefrigerators, and the preamplifiers.)

The usual use of PSR, when the electrical signal is taken off from the load resistance in the circuit of the irradiated sensing element, may, in radio-engineering terminology, be called direct detection. In the least favorable region near 10 μ, direct detection allows the registration of a minimum power of about 10^{-11} W/Hz$^{1/2}$ when the area of the sensing element is 1 mm^2. New methods, which are considered below, allow us to obtain considerably better results. This pertains primarily to heterodyne reception and optical amplification based on stimulated emission.

1. Heterodyne (Homodyne) Reception. The optical shift in a PSR of the coherent radiation of a signal and the local oscillator allows us to obtain an intermediate-frequency signal of power higher than in the case of direct detection by a factor proportional to the ratio of the powers of the local oscillator and the signal. This enables us to increase the signal/noise ratio by several orders of magnitude and to lower the minimum registrable power.

The main conclusion from the elementary analysis of the performance of the PSR in a heterodyne receiving device consists in the possibility in principle of registering 1—2 quanta per unit frequency band if the quantum efficiency is equal to 1. In contrast to the case of direct detection, conversion to an arbitrary frequency band is effected according to a linear law.

In a number of investigations, including ours (N. Sh. Khaĭkin, B. V. Yurist), thresholds of around 10^{-19} W/Hz (a photon energy of about 10^{-20} J) have actually been attained.

From the constructional point of view a heterodyne photosemiconductor device (PSD) is an analog of the Michelson interferometer. The PSR with a cadmium telluride-mercury telluride sensing element is used in the PSD. Cooling is accomplished by a miniature gas cooling machine.

2. The Optical Quantum Amplifier (OQA). The phenomenon of stimulated emission enables us to considerably amplify a signal at wavelengths of 3.39, 3.51, and 3.57 μ. By transmitting a weak optical signal through a gas discharge tube with an active medium, we can achieve amplifications to tens of decibels at the indicated wavelengths. In an actual amplifier of length 50 cm investigated by I. P. Mazan'ko and E. P. Kuznetsov, a 50-dB amplification can be achieved in the 100-MHz-frequency band. The noise introduced by the amplifier is negligible. Therefore, the OQA allows us to considerably lower the minimum registrable power

of a well-collimated beam (by a factor roughly equal to the amplification factor). The situation turns out to be less favorable when amplifying a diverging beam owing to the loading of the receiver by the spontaneous radiation of the OQA.

3. Receiver with a Microantenna. A. Javan has shown that infrared radiation can be detected with the aid of a microantenna and a metal oxide-metal point contact. Such a receiver turns out to be the direct analog of the UHF detector. The merits of the receiver are the exceptionally high speed of response (of the order of 10^{-13} sec) and the fact that there is no need for cooling. The volt-ampere characteristics of the contact were computed in a joint paper by G. D. Lobov and some American co-workers. The threshold power was found by A. A. Drugova using a numerical method. In the heterodyne regime, it is 10^{-14} W/Hz, in agreement with R. Abrams's experimental results. The disadvantages of the receiver with the microantenna are the extreme instability of the contact and the small value of the sensitive area (of the order of a wavelength). These circumstances have so far allowed the application of the receiver with the microantenna in only unique physical experiments.

4. Noncontact Converter of Modulated Optical Signals into UHF Signals (''UHF Shift''). The idea of the method of ''UHF shift'' was proposed and realized by us in 1957. It consists in measuring the additional microwave-power absorption during the interaction in the semiconductor between the wave and the nonequilibrium carriers induced by radiation of the optical band or by some other method. The semiconductor is in this case considered as a dielectric with losses which can be modulated by an optical radiation. Several types of UHF devices were used in P. V. Zarubin and F. I. Bakun's investigations and in a large number of American investigations. For the widest-band reception, a circuit with a serrated waveguide is preferable. In the presence of low-noise amplifiers a UHF circuit (of the cooled parametric type) can realize a response time of 5×10^{-11} sec.

The experience of the use of the UHF-shift method has shown that its advantages over the usual direct-current circuit manifest themselves only for very wide frequency bands (of the order of 1 GHz).

The possibility of using materials of arbitrarily high resistivity (e.g., germanium with impurities at liquid-helium temperatures) should also be acknowledged as some merit. An obvious disadvantage is connected with the complexity of the apparatus and the unwieldiness of the construction. Nevertheless, the use of the modern techniques of microcavity lines and Gunn diodes as UHF sources eases this disadvantage.

S. M. Ryvkin. Solid-State Nuclear-Radiation Counters. Semiconductors, which have made a big contribution to the development of a number of important fields of technology, are for the past decade being successfully introduced into the field of experimental nuclear physics, where they function as high-performance precision counter-spectrometers for nuclear particles and photons.

In solid-state ionization chambers based on semiconductors of the n-i-p structures, it is possible to realize the main advantages of the solid body: high efficiency (connected with the high matter density), a relatively large charge that can be released during ionization (at the expense of the small energy of formation of the electron-hole pair), and a very high energy resolution, determined only by the unavoidable fluctuations of the ionization process (owing to the practically complete collection of the charge produced by the ionizing particle, i.e., the exclusion of the structure-sensitive recombination processes).

In the report we analyze in detail, on the basis of the investigation of the principal mechanisms underlying the action of semiconductor detectors (SCD), specific semiconductor problems of the realization of solid-state ionization chambers with a high resolving power. The causes of the insufficient resolving power of dielectric and semiconductor ''homogeneous'' crystal counters are explained.

Analysis shows that in order to eliminate the effects of polarization of the counter and charge losses connected with capture and recombination of the current carriers, it is necessary to use a material of very high degree of purity (not greater than 10^{11}—10^{12} impurity centers in 1 cm^3) and homogeneity. Thus, the level of requirements which materials for SCD must satisfy is considerably higher than that obtaining for the other applications of semiconductors.

In the Soviet Union we have extracted from our own raw materials, material (germanium and silicon) of the requisite quality, and we have organized the mass production of some of the most important SCD models, including large-capacity SCD based on lithium-doped germanium, and germanium SCD which are stable at room temperature (i.e., do not require to be kept at a liquid-nitrogen temperature), and which are prepared by the ''cold-doping'' method (the creation of the operating band of the counter on account of the compensation of the material by radiation defects).

In Figs. 1 and 2 we present examples of spectra obtained with the aid of these detectors. These spectra demonstrate the high resolving power of the detectors.

The use of the SCD already allows us to solve important scientific and technological problems including the problem of the synthesis of a number of transuranic elements, the investigation of the structure of nuclei by the methods of Coulomb excitation of the nuclei, the study on board satellites of the earth's radiation belts and of the solar wind, neutron activation analysis of ores, the use of SCD to construct crystalless x-ray spectrometers, etc.

The subsequent development of this new class of solid-state instruments should, besides the improvement

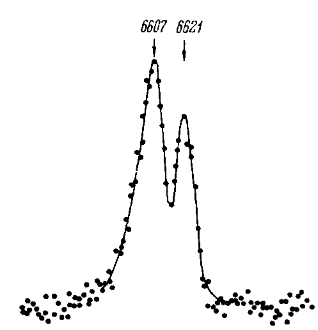

FIG. 1. The spectrum of the γ-radiation of the 7.640-MeV level of the isotope Fe^{57}, taken with the aid of a coaxial germanium-lithium detector of volume 25 cm^3 (the "double runaway" peaks were detected).