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Heterosemiconductors

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Professor Alferov speaking at the General Meeting in York after the presentation of the 1978 Hewlett-Packard Europhysics Prize for his outstanding contributions to our understanding and to the practical realization of heterojunctions. In this article he summarizes the essential characteristics of these devices and reviews the impact they have already made on the field of semiconductors.

The creation of pure and doped Ge- and Si- monocrystals, and the development of methods of obtaining p-n junctions in them, have stimulated the growth of a number of investigations on semiconductor physics and technology. This has resulted in a revolution in radio-techniques, electronics, and electrical engineering.

Improvements to the properties of the devices implied, in most cases, perfecting the methods of p-n junction creation, and the application of new materials. The replacement of Ge by Si has allowed the working temperature of the devices to be increased and high-voltage diodes and thyristors to be produced. Progress made in the manufacturing technology of GaAs and other semiconductor $A^{(3)}B^{(5)}$ compounds, has led to the creation of semiconductor lasers, light emitting diodes and various photocells. The wide application of semiconductors, especially in optoelectronics, has called for the development of new methods of obtaining materials with various sets of properties, and there was an incentive to combine different semiconductors in one device.

The development of methods of epitaxial semiconductor crystal growth allowed, in the 60's a systematic study of monocrystalline heterojunctions in semiconductors to be started. These concerned graded and abrupt contacts of semiconductors with different chemical composition, realized in a single monocrystal. Such structures generally undergo not only a change in the forbidden gap width, but in other fundamental properties as well, notably, bandstructure, effective masses of current carriers, their mobility, etc. The possibility of controlling these properties, as well as the forbidden gap width, has opened new prospects for physical investigations and practical applications of semiconductors in devices and crystals.

The experimental realization of graded and abrupt AlAs-GaAs heterostructures with properties close to ideal models and the discovery of effective injection and of the superinjection effect in these structures have served as a basis for the creation of a large number of devices with a heterostructure as the main element. Of greatest interest has been the application of heterojunctions for optoelectronics semiconductor devices, such as injection lasers, light emitting diodes, solar-cell batteries and all kinds of photocells, modulators, amplifiers, and light converters. Although the use of heterojunctions for conventional injection devices has not yet given sufficiently effective results, there is no doubt that heterostructures will become a main element for such widely used devices as rectifying diodes, transistors, dynistors, and thyristors.

A most interesting and promising feature of the research is the development of complex monolithic integrated systems, based on heterostructures, which could determine the future course of integrated optics.

In this paper a short review is given of the physical investigation of heterojunctions and their application in electronics, obtained mainly in the Laboratory of Contact Phenomena in Semiconductors of the A.F. Ioffe Physico-Technical Institute of the USSR Academy of Sciences.

Peculiarities of Electrical and Optical Phenomena in Heterostructures

In p-n heterostructures with properties close to the ideal, i.e. in heterostructures containing sufficiently small amounts of interface states in regions of changing chemical composition and forbidden band-width (in which phenomena take place simultaneously), mainly one-sided effective injection occurs from the wide gap into the narrow gap region, inde-

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pendently of the doping levels of the "p" and "n" regions. An extremely valuable property of p-n heterostructures is the possibility of injecting practically any concentration of non-equilibrium carriers from the wide gap material into the narrow gap material, thus considerably exceeding their equilibrium concentration in the emitter. In graded p-n heterojunctions (p-n structures with a variable forbidden gap), owing to the influence of built-in quasi-electric fields, a marked increase or decrease in the effective diffusion length of the injected carriers also occurs.

Thus heterostructures appear to have a powerful means of controlling the carrier flow, i.e. the carrier concentration, diffusion rate and recombination region dimensions. Moreover, heterostructures also permit effective control over the light flow in crystals, both introduced from outside, and generated due to radiative recombination inside.

The so-called wide gap window effect, whose possible use in solar batteries has long been recognized, permits light radiation of appropriate spectral composition to be introduced into the required structural region without losses. A multilayer heterostructure is a dielectric thin film waveguide with effective light wave guiding in a narrow gap material. This waveguide effect permits the controlled propagation of light flow in crystals; its application in heterolasers was pointed out in the beginning of the 60's. The above peculiarities of injection and optical heterojunction properties were first experimentally discovered and studied in AlAs-GaAs heterostructures.

Preparation of Heterosemiconductors

A heterojunction is a "pair" and the choice of an "ideal pair" is naturally a complicated problem. It requires that numerous compatibility conditions as regards the mechanical, crystallochemical and thermal properties as well as the crystalline and energy structure of the materials in contact, be fulfilled. Gallium arsenide has been widely used in different semiconductor devices owing to a successful combination of a small effective mass and a large forbidden gap, effective radiative recombination and a sharp optical absorption edge due to a "direct" band structure, high mobility in the absolute minimum of the conduction band and its abrupt decrease in the nearest minimum in point $< 100 >$. Taking into account the fact that the use of a heterojunction between a semiconductor, which serves as an active material, and a material with a wider forbidden gap, results in a maximum effect, AlAs-GaAs, GaP-GaAs and AlP-GaAs heterojunctions on the basis of GaAs may be expected to be promising. As the coincidence of lattice parameters is the first and the most important criterion of compatibility of the materials of a pair, AlAs-GaAs heterojunctions are preferable.

Among the numerous methods of epitaxial semiconductor crystal growth, the following are the most widely employed :

1. Growth of crystals from the gas phase, involving chemical reactions, i.e. vapour-phase epitaxy (VPE).
2. Growth of epitaxial layers by means of evaporation in superhigh vacuum, i.e. molecular-beam epitaxy (MBE).
3. Growth of crystals from a liquid melt, i.e. liquid phase epitaxy (LPE).

The first monocrystalline heterojunctions were obtained by VPE. Recently, VPE has been widely used for obtaining heterostructures of large area by means of precise control over the epitaxial layer thicknesses. MBE has not yet gained application because of its comparatively complex experimental technology. LPE appears as the simplest and most efficient method and has been used for the preparation of AlAs-GaAs multilayer heterostructures with layer thicknesses from hundreds Å up to tens µm. It has also been used to obtain multilayer heterostructures of four-component $A^{(3)}B^{(5)}$ solid solutions. On the basis of the latter it appeared possible to create close to "ideal" heterojunctions within a wide range of forbidden gap widths such as - InGaAsP, GaAlAsSb, GaAlAsP etc.

Heterostructures in Discrete Optoelectronic Devices

The above peculiarities of the electrical and optical properties of heterostructures have been successfully applied to the fundamental improvement of the parameters of a large number of semiconductor devices and in the development of new devices which are impossible to create on the basis of homostructures.

Heterostructure Lasers

In double heterostructure lasers (DHL) the regions of recombination, light radiation and population inversion coincide completely and are confined to the middle layer. Owing to the heterojunction potential barriers, recombination losses in passive regions are negligible and the electron-hole plasma is confined to a potential box in the middle layer. Due also to the marked difference in refractive indices, the middle layer serves as a high-quality waveguide and light radiation losses in passive regions are negligible. Population inversion is obtained by double injection and neither a high doping level nor even degeneracy is needed. All this leads to a considerable reduction in losses and in the threshold current density. In such a structure both external and internal quantum efficiences almost coincide and there seems to be a strong possibility that a quantum efficiency close to 100 % will be obtained.

It was in 1970 that injection heterolasers with threshold current density less than 1000 A/cm^2 were created; external differential quantum efficiency and full efficiency reached 70 % and 25 % respectively. The low threshold current density allowed the realization of CW operation at room temperature, which is impossible with p-n homojunctions. For AlAs-GaAs heterostructures, the energy of coherent radiation is determined by the composition of the $Al_xGa_{1-x}As$ solid solution in the middle layer and may be found for wavelengths within the range 6900-9000 Å.

During the past 8 to 9 years, since the creation of low threshold heterolasers and the realization of CW operation at room temperature, scientists in laboratories the world over have achieved great success in the optimization of heterostructure technology and parameters, with the record-breaking results seen in 1969-1970. In a number of papers, certain double-structure modifications were suggested and studied, but they resulted in little improvement of the parameters. Of considerable interest has been the physicotechnological study of defects occuring in heterostructures after long operation. As a result, DHLs with a 10 000 h life of continuous operation were created and in some authors' opinion, the operational life will reach 100 000 h. This work has made the construction of optical communication systems based on lightguides with low losses and on DHLs, a real possibility.

Important and fruitful lines of study appear to be the creation of DHSs based on other semiconductor materials and also the operation of DHLs in a wide spectral region.

Whereas an attempt to enter the IR region, using heterostructures containing a solid solution of Pb chalcogenide, has been quite successful - mastering the visible range has proved more difficult. Heterostructures, based on quaternary $A^{(3)}B^{(5)}$ compounds may be considered the most promising for creating injection DHLs for the yellow and green spectral regions. After the first AlGaAsP DHSs were grown — of theoretical rather than practical importance — attention was concentrated on the system InGaAsP, in which DHSs and red DHLs operating at room temperature have recently been obtained. This is the system most appropriate for the yellow spectral region. For the creation of green DHLs, a knowledge of the technology of obtaining an AlGaInP system will be necessary; the metallurgy of the system is extremely complex. The development of multichannel optical communication systems increases the importance of injection coherent radiation sources within the range 1-1.5 μm. Encouraging results have recently been obtained with double heterostructures in the systems InGaAsP and AlGaAsSb.

Heterostructure Light-Emitting Diodes

Development of injection spontaneous radiation sources, i.e. light-emitting diodes (LED), coincided with the creation of semiconductor lasers. Initially these devices were fabricated only on the base of homo p-n structures. However, heterostructures have a number of indisputable advantages for LEDs as well. These advantages arise from the possibility of coupling out the radiation from the recombination region to the crystal surface without self-absorption and also from the use of the super-injection effect to choose the optimum doping levels, and either to restrict or expand recombination regions, since both abrupt and graded heterojunctions have built-in potential barriers.

Because their fabrication is rather simple, LEDs with graded heterojunctions have been developed primarily (i.e. p-n-structures in crystals with a variable band gap). In the most efficacious constructions, LEDs were obtained by sequential growth of two layers with different gaps when the p-n junction position either coincided with or was slightly removed from the metallurgical interface. The recombination region is "pressed" to the wide gap window and recombinative radiation is coupled out without absorption. LEDs obtained on the basis of such structures in AlAs-GaAs systems have yielded an external quantum efficiency of 1.0 to 1.5 % at 300 K in the near infrared and red (up to $\lambda = 0.65$ μm) spectral region for a flat construction without anti-reflection coverings. However, DHSs without absorbing layers are more promising for LEDs; the external efficiency obtainable at present for flat LEDs is 30-40 % at 100 % internal quantum efficiency, and further development will undoubtedly produce an efficiency of up to 50-80 %. Such high efficiences of LEDs have guaranteed the possibility of their application as powerful light sources and for pumping of solid state lasers on the basis of YAG : Nd^{3+}, in particular.

Extension of the spectral range, as with lasers, is connected with the use of new materials for the heterostructures.

Photoelectric Cells and Light Converters

The main advantage of the use of heterojunctions for photoelectric devices springs from the possibility of using the wide gap part of a heterojunction as a transparent "window" for light absorbed in its narrow part. Electron-hole generation takes place immediately in the space charge region of a p-n junction which, in principle, allows high response to be obtained, eliminating recombination losses in the illuminated surface and making recombination losses in the narrow gap material negligible.

For the creation of high efficiency solar cell batteries, the doping conditions of a wide gap material for providing minimum spread resistance, were determined. The full efficiency of solar cell batteries at room temperature is at present about 20-25 %. The advantage of heterophotoconverters lies in the possibility of using them at high temperatures; at 200° C their efficiency decreases by only 15-20 %. These results show that solar converters based on heterostructures are promising as terrestrial energy sources. The use of concentrators can make the construction of solar electric power plants an economic proposition.

Poor agreement between the radiation spectra of gas-discharge pumping sources and that of the active medium absorption spectra is known to be the main reason for the low efficiency of solid state lasers. This has suggested the idea that semiconductor LEDs with a comparatively narrow radiation band, the maximum of which may coincide with one of the active medium absorption bands of a laser, be used as pumping source. However, the creation of large square LEDs for laser pumping is technically difficult. as is also the assembly in one pumping system of a great number of LEDs.

In this connection a hybrid type of pumping has been developed which implies that semiconductor, similar to heteroLED structures, convert the wide discharge lamp radiation spectrum into a narrow radiation band coinciding with one of the absorption bands YAG:Nd^{3+} ($\lambda = 0.805$ μm).

Luminescent light, after multiple reflections and re-radiation, leaves the converter through the layers of wide gap materials. External quantum efficiency of such conversion is now 40-50 % which has allowed the pumping system efficiency to be doubled and the pumping threshold power to be reduced by the same factor. Fabrication of converters with a unitary square of several cm^2 does not cause any technological difficulties. With the combination of such converters with a p-n junction in a GaAs substrate, high-efficiency photocells can be made for operation at solar light concentrations of 2000 suns and even more (with an efficiency of about 20 %).

Powerful Diodes, Transistors, and Thyristors

Further progress in powerful semiconductor technology is associated with the application of $A^{(3)}B^{(5)}$ wide gap materials, and in the first place, of GaAs and GaAs-AlAs solid solutions. For a long time the use of these materials was thought to be impossible because of the difficulties of obtaining pure crystals, and achieving large diffusion lengths of non-equilibrium carriers, needed for the base region conductivity modulation of a diode or thyristor with a thickness of 100 μ m, which is necessary for obtaining high reverse voltages. These difficulties may be overcome by an increase in the diffusion length of injection current carriers caused by internal electric fields in graded AlAs GaAs heterostructures and by the re-radiation mechanism at 100 % internal efficiency.

Based on GaAs, it has proved possible to create powerful diodes with a working current density of 10^3 A/cm^2 and reverse voltage of 1000 V, thyristors with a voltage of 100-200 V and working current density of 200 A/cm˙. The fact that these devices can operate at increased frequences (several MHz) and high limit temperatures (300°-400° C), makes them advantageous. The possibility of controlling light fluxes in heterostructures plays an important role in powerful devices as well as the conversion of a certain amount of power into light.

Although it was first suggested that a wide gap emitter be used in a transistor, and the attempts to create such a transistor were carried out rather a long time ago, the first high efficiency transistors based on heterostructures have been obtained only recently. At present, a transistor with heterojunctions on the basis of GaAs-AlAs solid solution is the best kind of bipolar transistor for high frequences and increased working temperatures. It enables the amplification coefficient to be independent of current within practically the whole available range of current densities.

Heterostructures in Integrated Optics

The science of integrated optics is based on the possibility of generating and controlling light waves located in a thin film dielectric waveguide. The main purpose of the investigations is the application of thin film technology and integrated techniques for the creation of new optical and optoelectronic systems. The parallel problem of creating discrete thin film optical devices is being solved.

Although investigations of optical waveguide structures based on various organic and inorganic materials are being carried out at present, it is quite evident that multifunctional integrated optical schemes will be based on single-crystal heterojunctions. This may be said, not only because the optical properties of semiconductor crystals can be effectively controlled, but also because heteroepitaxial structures permit immediate and highly effective conversion of electric signals into optical effects and vice versa.

Since the final aim of integrated optics is to fabricate all optoelectronic elements on a single semiconductor heterojunction platelet (an integrated scheme being made of a silicon platelet) it is necessary to choose from a number of heterostructures the one which combines all the necessary passive and active elements of an integrated scheme. Just as in microelectronics the transistor is an essential element, so in integrated optics, lasers are of paramount importance.

Of known heterostructures, DHLs meet the requirements best of all. It should be emphasized that this structure permits planar combination in a single platelet of all the necessary active and passive elements for integrated optics such as lasers, LEDs, photocells, modulators, deflectors and light-beam input and output systems.

Distributed-Feedback DHLs

The possibility of replacing the Fabry-Perot or similar types of resonator in lasers with a periodic structure, has been shown by the Bell Laboratories of the USA. The authors described a laser with an active medium in which the refractive index changes periodically from layer to layer. If an inhomogeneity period equals an integral number of half wave - lengths, then owing to the optical inhomogeneity, the wave is Bragg reflected in a similar way to the reflection of light from Fabry-Perot resonator mirrors. As the reflection originates in the active medium itself, the lasers were named distributed-feedback lasers (DFLs). The same authors later developed the theory of these lasers.

At the same time a new type of semiconductor laser with light output through a diffraction grating on the surface of a heterostructure active layer was proposed in the A.F. Ioffe Physico-Technical Institute of the USSR Academy of Sciences, with a view to reducing the radiation divergence and replacing the Fabry-Perot resonator with a distributed-feedback structure formed by the interaction between the waveguide modes and the surface diffraction grating; a detailed theoretical analysis of diffraction grating laser operation was developed.

The possibility of creating low divergence semiconductor lasers, with radiation output through a plane parallel to the active layer due to the interaction between a waveguide mode and the diffraction grating on the waveguide surface, was also first demonstrated experimentally in the A.F. Ioffe Physico-Technical Institute.

An important peculiarity of lasers with radiation output through the diffraction grating, is the almost 100 % polarization of the coupled out radiation with vector **E** parallel to the grating lines. In the case of distributed feedback, radiation divergence in a plane perpendicular to the active layer and the grating grooves, is considerably less than in the case when radiation generated in a Fabry-Perot resonator is coupled out by the grating. Near the generation threshold the divergence does not exceed 0.1° and is close to the aperture divergence.

A valuable property of DFB lasers is a rather weak temperature dependence of the generation line position within a small range of working temperature changes (several dozens of degrees). This dependence is determined not by the $\mathbf{E}_g$ temperature dependence, but by the temperature changes of the grating period.

Recently, a continuous operation regime at room temperature has been realized for both DFB lasers (the grating being in the active layer region, which is injection pumped), and DBR lasers (in which, with a view to improving the degradation characteristics, the grating is separated from the active region).

The first operating monolithic integrated optical scheme was obtained in Japan. It was an AlAs-GaAs heterostructure with six DFB lasers, the generation wavelength of each laser being shifted by 20 Å. The lasers' radiation was coupled out into a common waveguide.

Further development of DFB lasers will, probably, result in the creation of better long life injection semiconductor lasers with such advantages as - coherence, small radiation divergence, frequency stability with temperature changes, the possibility to obtain single-mode and single-frequency regimes. Spectral range broadening is connected with the development of multicomponent semiconductor solid solution technology.

Conclusion

The development of methods of obtaining "ideal" heterostructures and the discovery of a number of new phenomena in them which allow electron and light fluxes in crystals to be effectively controlled, has considerably broadened the possibilities of semiconductor electronics. Results first obtained with heterostructures on the basis of $A^{(3)}B^{(5)}$ semiconductor compounds, have been extended to other classes of materials - $A^{(2)}B^{(6)}$, $A^{(4)}B^{(6)}$, etc., and, recently, to heterostructures on the basis of amorphous semiconductor compounds.

One may, at present, distinguish a new type of material - the heterosemiconductor - the properties of which may be chosen in accordance with the particular functional aims in mind.