Optical orientation

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Optical Orientation. Eds. F. Meier and B. P. Zakharchenya. North-Holland, Amsterdam; Oxford; New York; Tokyo, 1984, pp 523 (Modern Problems in Condensed Matter Sciences. V.8. Series Eds. V.M. Agranovich and A.A. Maradudin)

The brevity and expressiveness of title of the current volume of the series "Modern Problems in Condensed Matter Sciences" published by an international editorial board in Holland balances its evident incompleteness: the question begs itself—what is being oriented? When this subject first appeared in the scientific literature at the very beginning of the 1950s the words "optical orientation" were used exclusively with the addition of the words "of atoms" (OOA). From the point of view of the physics side of the phenomenon the discovery of OOA could have been made a quarter of a century earlier—in the 1930s. Essentially, the effect of the polarization of resonance fluorescence of atoms discovered at the beginning of the century could have been interpreted as the orientation by light of excited atoms, while the Hanle effect discovered in 1924 (depolarization of fluorescence in a magnetic field) represented a particular case of magnetic resonance—in the zero-frequency field initiating the resonance—and simultaneously, a particular case of the phenomenon of level crossing! However, this became clear only much later, in the 1960s, when the coherence of atomic states began to be investigated in parallel with work on OOA, and both these directions on merging formed a most extensive research "Klondike". Opened up by the work of A. Kastler and J. Brossel it rapidly went beyond the boundaries of France and in the course of a decade gave rise to hundreds of publications from many countries of the world. The popularity of these investigations was due to the ultimate simplicity of the experiments deriving from the technique of R. Wood, and the transparency of the results which gave a magnificent illustration of the foundations of quantum mechanics.

Speaking of the principal achievement of the first discoverer of OOA A. Kastler, it probably consists in the implantation in the consciousness of physicists of the idea of the exchange of angular momentum between atoms and circularily polarized light. The evident breadth of this idea impelled the investigators to seek ways of transferring the techniques of OOA to solids. However this was not achieved immediately. The first successes in this direction were obtained in the early 1960s by utilizing as objects of investigation doped dielectric crystals, but the most significant burst of activity was initiated by the work of G. Lampel who realized in 1968 orientation of silicon nuclei by lengthy irradiation of the crystal with circularily polarized light. After several years of a latent period a new stage of the "Gold Rush Fever" began, the fruits of which have been published in concentrated form for the first time in the monograph "Optical Orientation" edited by B. P. Zakharchenya (Leningrad) and F. Meier (Zurich).

What is it that is being oriented by light interacting with a solid? The conduction electrons of a semiconductor, the holes in the valence band, the local paramagnetic centers, the nuclei of the lattice and the impurities, excitons, electrons, photoemitted from a semiconductor. The breadth of this list explains the brevity of the title of the book.

In concluding this digression we note that in contrast to OOA optical orientation in solids could hardly have been formed into any kind of a full-bodied direction before the 1960s, since it needed a developed theory of solids, superpure materials and the entire modern research arsenal including laser technology.

In accordance with the traditions of the series the eighth volume has been prepared by a multinational collective of authors, leading specialists in this field of solid-state physics. The composition of the collective of authors reflects the considerable contribution to this problem made by Soviet physics—half of the materials were presented by members of the A.F. Ioffe Physico-technical Institute of the Academy of Sciences of the USSR, LFTI (a State Prize of the USSR was awarded for this work in 1977). The second half of the book is made up of articles written by physicists from France, FRG, Switzerland and the USA.

The collection of articles contains eleven review articles, of which seven present the results of investigations of optical orientation of electrons, nuclei and excitons in semiconductors, and three others are devoted to the effect of orientation of the photoemitted electrons and the creation on its basis of sources of polarized electrons.

The opening article of the collection (B. P. Zakharchenya and V. I. Perel') plays the role of an extended introduction to the first group of articles. The authors give a brief review of the principal ideas and phenomena of optical orientation of electrons and nuclei in semiconductors. The principal concept of the Kastler optical pumping is presented—production of a difference in the population between quasidegenerate energy states as a result of anisotropic optical excitation with subsequent recording of the anisotropy of the optical properties of the material arising as a result of it. After a brief review of the history of OOA the authors proceed to a presentation of the special features of the processes of optical orientation in semiconductors which do not have analogs in OOA, basing themselves primarily on research carried out at the LFTI.

The similarity of the processes of orientation of atoms and of semiconductors is rapidly exhausted in the transition to the orientation of the nuclear subsystem of a semiconductor interacting with oriented electrons. In view of the high density of nuclei and the large dimensions of the region of delocalization of an electron (both of a free one, and one bound to an impurity) the nuclear magnetic field turns out to be strong, and its interaction with the electron very effective. As a result a characteristically unique feedback arises: the orientation of electrons leads to the dynamic orientation of nuclei which by their magnetic field act on the electrons. The behavior of the system as a whole turns out to be extremely sensitive to the value of the external magnetic field and to its direction with respect to the polarization vector of the light and the crystallographic axes of the sample. Three chapters of the collection of articles are devoted to a detailed theoretical and experimental investigation of the orientation of the spins of electrons and a nuclei and to their interaction. One of them is a review of the theory of optical orientation in semiconductors. It contains a discussion of the connection of the band structure of a semiconductor with the spectrum of action of the orienting radiation, problems of relaxation of electrons in the conduction band and of holes in the valence band are discussed, as well as the effect of the deformation of the crystal on the processes of orientation. The Hanle effect in semiconductors is described, as well as its application to the investigation of the relaxation of nonequilibrium carriers and of its special features associated with the dynamic polarization of nuclei. Considerable attention is devoted to the optical manifestations of nuclear orientation, in particular, the recording of nuclear magnetic resonance by using the degree of polarization of the recombination radiation.

A separate chapter is devoted to the nonlinear processes of interaction of the electron and the nuclear subsystems of a semiconductor. It describes a large number of new surprising effects discovered and interpreted by the authors (Fleischer and Merkulov), the complex structure of the Hanle effect in CaAs crystals and of its special features in inclined fields, the effects of the anisotropy of optical orientation in cubic crystals, the effects of bistability and randomization of the cooperative motion of spins in a coupled electron-nuclear system.

A number of the chapters of the collection is devoted to a description of the investigations of oriented electrons in the conduction band. The optical methodology has not only permitted to orient the electrons in the kinematic sense of the word, but also provides unique possibility of measuring the rate of relaxation of the spin and the momentum of an electron right down to times of the picosecond scale. An extension of the methodological possibilities brought about the increase of attention paid to relaxation processes, and this led to the discovery of several new relaxation mechanisms. In the course of the investigations, along with the circularily-polarized luminescence which brings out the "polar" orientation of electron spins linear polarization was also discovered, which was successfully interpreted within the framework of the model of lining up of electron moments. Individual chapters of the collection are devoted to the problem of optical recording of paramagnetic resonance of conduction electrons, and also to the phenomenon of optical orientation of excitons which was for the first time discovered in the work by the group from LFTI headed by the "father of the exciton" E. F. Gross.

Work on optical orientation of carriers of charge and of excitations in semiconductors is closely related to work with a different specific methodology and different problems—investigation of the photoemission of optically oriented electrons from the surface of solids. The pioneering work in this field was carried out by D. T. Pierce and F. Meier in 1976 using a CaAs crystal doped with cesium. The discovered phenomenon was doubly valuable—as an additional means of investigating band structure of solids and as a new effective method of obtaining polarized electrons.

In the book under review there is a thorough discussion of the physics of the process of polarizing photoelectrons and its connection with band structure and with crystal symmetry. One of the articles is devoted to a review of papers on sources of polarized electrons and on their application. A description is given of sources based on CaAs with a degree of electron polarization up to 50% and a discussion is given of the application of polarized electrons in experiments on investigating spin-dependent interactions in the physics of electron-atom collisions, for studying the properties of the surfaces of ferromagnetic substances, and in high energy physics. In particular, the source based on CaAs was utilized in the historical experiment on discovering parity violating weak interactions of neutral currents in the case of inelastic scattering of ultrarelativistic polarized electrons by liquid deuterium. As is well known, this experiment confirmed the unified theory of the electroweak interaction (as was done, by the way, in another experiment completed two months earlier in Novosibirsk in which the natural optical activity of bismuth vapor was measured).

Thus, in the current eighth volume of the series a new division of the physics of semiconductors undergoing exceedingly fruitful and dynamic development is presented. The book represents not so much a summary of work in the mainstream of the direction indicated above, as a report from the front lines by direct participants in the campaign. Such a style of the book also determines some of its defects. The absence of monographic unity of the volume manifests itself in numerous intersections of the articles and repetitions, while many important facets of the investigations in this field are not included in the collection of articles. Thus, an interesting cycle of investigations carried out at the LFTI to study static and dynamic characteristics of the process of optical orientation of silicon nuclei as a function of concentration and type of impurities in the crystal is barely mentioned (although in three different places). These investigations opened up a new method of studying spin diffusion and the impurity content of semiconductors. Nevertheless as of today the collection of articles represents a monograph that is unique in the degree of detail and breadth of content concerning the physics of the processes of optical orientation of particles and quasiparticles in semiconductor crystals and, doubtlessly, could serve as a reference book for many specialists in the physics of semiconductors and optics of solids.

Translated by G. M. Volkoff