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Effective polarized electron emitters based on semiconductor nanostructures

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High-energy beams of spin-polarized electrons have proven to be exceptionally useful in many experiments of elementary particle physics. By studying the scattering of polarized electrons by polarized and unpolarized targets it is possible to restore what is known as the nucleon spin structure functions and to investigate problems associated with the relative contribution of quarks and gluons to the observed value of nucleon spin, problems whose solutions are important for the development of quantum chromodynamics [1].

The second direction of research in this field is the study of CP symmetry violation in the electroweak interaction. The main result here is the exceptional accuracy (the relative error is about 0.1%) in measuring the electroweak mixing angle [2]. These measurements allowed the making of the most stringent (for the present) estimate of the maximum possible value of the Higgs boson mass. The value of 147 GeV c^{-2} obtained in this estimation was found to be within the range of energy attainable for modern accelerators, which makes the hope of discovering this particle in the near future quite realistic.

Less intensive is the expansion of polarized electron beam applications in materials science and, in particular, when investigating spin-dependent scattering, inverse photoemission, and spin-dependent absorption in thin films and surface layers of magnetic and semimagnetic materials [3].

The main achievements in the development and use of sources of highly polarized electrons have been made in the last decade, beginning with the experimental research in photoemission from highly strained semiconducting InGaAs and GaAs layers [4, 5], in which the possibility of creating a 75–85% electron polarization was demonstrated for the first time. Since that time semiconductor photocathodes with strained layers became the standard sources of electron beams in accelerators. Their main merit is the possibility of rapidly and precisely changing the orientation of the electron spin to the opposite, which makes it possible to specify the spin-dependent part of cross sections with ease.

The degree of the electron polarization of a beam determines the accuracy of measuring the spin-dependent effects, especially in the cases where there are limitations on the electron beam current, which are related to the properties of the target. The polarization of nearly 80% in the region of the targets is sufficiently high for the majority of experiments. A further increase in polarization and current density in the beam would make it possible to shorten the measurement times and would therefore reduce the cost of such experiments.

The development of research that uses the beams of polarized electrons has stimulated the study of polarized photoemission and the fabrication of new semiconducting materials with optimal photoemissive properties. In this report I will discuss the results and prospects of such research.

The operation of semiconductor photoemitters of polarized electrons leans upon two phenomena well-known in physics of semiconducting III–V compounds: optical orientation of electron spins as a result of excitation by circularly polarized light [6], and reduction of the work function of a p-doped semiconductor to negative electron affinity (when the vacuum level is below the edge of the conduction band in the crystal) in the process of activation of an atomically clean surface by a Cs(O) [or Cs(F)] deposition [7]. Here photoemission appears to be a consequence of the following processes: interband light absorption, trapping of electrons to the region of band bending at the surface (this region emerges because of the pinning of the Fermi level at the surface states within the forbidden band), and emission proper, i.e. the tunneling from the near-surface well into the vacuum through the residual surface barrier.

Such a pattern has been corroborated by experiments and calculations of the photoemission excitation spectra, the spectra of the energy distribution of the emitted electrons, and the dependence of these spectra on the photoemitter parameters (such as the doping level, layer thickness, temperature, and so forth) [3, 7].

Optical orientation is caused by the spin–orbit splitting of the valence band states, as a result of which the upper split-off states of the heavy and light holes have a total angular momentum $J = 3/2$ and are characterized by strong mixing of the orbital and spin movements. The difference between the probabilities for optical transitions to the conduction band from states of the multiplet with angular momentum projections $J_z = \pm 3/2$ and $J_z = \pm 1/2$, which are accompanied by the electron angular momentum change equal to unity (when the absorbed light is circularly polarized), results in unequal population of the two spin states of the conduction band: $|\uparrow\rangle$ and $|\downarrow\rangle$. The emerging optical orientation of the spins is characterized by the polarization $P = (n_\uparrow - n_\downarrow)/(n_\uparrow + n_\downarrow)$, where $n_\uparrow$, $n_\downarrow$ are, respectively, the concentrations of electrons with spins parallel and antiparallel to the direction of light propagation in the crystal [6].

Additional splitting of the multiplet with $J = 3/2$ into the subbands of heavy ($J_z = \pm 3/2$) and light ($J_z = \pm 1/2$) holes, when the crystal is under uniaxial strain, is used to make only one electron state populated. A fairly high strain is achieved by growing a $Ga_xIn_{1-x}As$ layer with a large lattice constant on a GaAs substrate. The best results have been achieved by growing GaAs (or $GaAs_{0.95}P_{0.05}$) layers on a $GaAs_xP_{1-x}$ (with $x = 0.28-0.32$) pseudosubstrate obtained, for instance, by growing a sequence of $GaAs_{1-y}P_y$ layers on a GaAs substrate with increasing concentration y. To reach the necessary photoemission current, the thickness of the photocathode's active layer must be no less than 0.1 μm, which is ten times the critical thickness for such strained layers and corresponds to dislocation-free growth. For this reason strained films prove to be partially relaxed and have a highly imperfect block crystalline structure. This in turn leads to a smearing of the absorption edge, hole scattering from defects in the process of absorption, and the filling of the second electron spin state, which reduces the initial polarization.

The above mechanism of polarization loss can be distinguished by calculating the dependence of the photoemission quantum yield Y and the polarization P of photoemission and photoluminescence radiations on the excitation energy and by

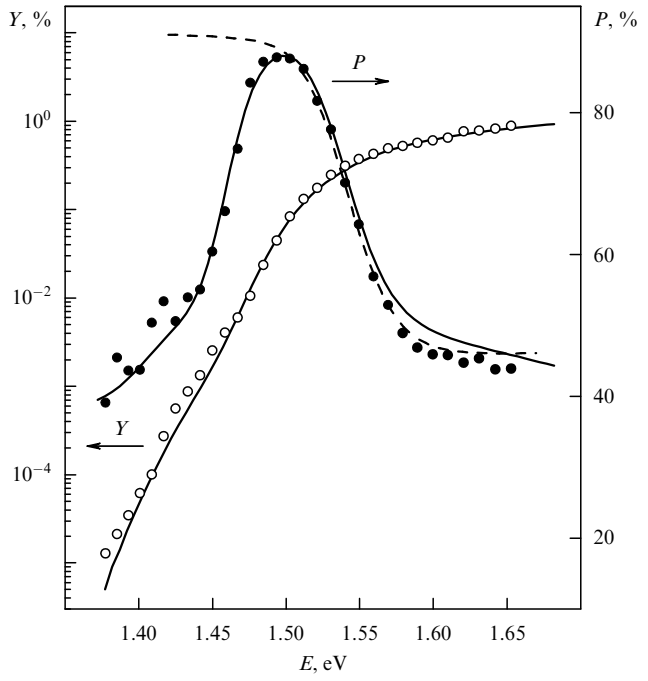

Figure 1. Degree of spin polarization P of photoelectrons and the photoemission quantum yield Y as functions of the excitation energy E for a strained GaAs film on a $GaAs_{0.72}P_{0.28}$ pseudosubstrate at $T = 300$ K; the experimental results and the results of calculations without allowance for smearing of the absorption edge (dashed curve) and with allowance for that smearing (solid curves) are depicted.

comparing the results to the experimental data (see Fig. 1) [8]. Calculations made it possible to determine the parameters of strained films (experimentally examined and calculated polarized luminescence excitation spectra were compared simultaneously to exclude any ambiguity in such a procedure). It was found that the initial polarization primarily depends on the ratio between the strain-induced valence-band splitting Δ_{str} and the parameters characterizing the smearing of the interband absorption edge due to indirect transitions in which optical phonons and tails of the density of states belonging to the valence band participate. The peak value of the electron polarization at the momentum of excitation is roughly 94% (for the given sample).

Additional depolarization occurs when electrons are extracted to the space charge region near the surface, which manifests itself in time-resolved experiments involving excitation by short pulses and also in experiments with films of different thicknesses. In thin films of thickness $d \ll L$, $1/\alpha$ (where L is the diffusion length, and α is the light absorption coefficient), the time of carrier trapping into the space charge region is $\tau_{esc} = d/S$, where S is the surface recombination rate. Here the decrease in the carrier polarization $\delta P = -d/(S\tau_s)$, where τ_s is the electron spin relaxation time in the active layer. For typical values of the layer parameters these losses amount to about 7% for $d = 100$ nm and decrease in lightly doped samples with lowering temperature.

Experimental studies of the dependences of polarized distribution functions on the energy of the escaped electrons indicate that there is a weak depolarization of electrons in the band bending region near the surface for energies below the bottom of the conduction band. In view of the spatial separation of carriers in this region, the main mechanism of spin relaxation is the precession of electron spins in the effective crystal field, whose magnitude and direction are determined by the magnitude and direction of the electron momentum (the D'yakonov–Perel' mechanism [6]). In the potential well of the band bending region there is a strong fluctuative Coulomb potential generated by ionized acceptors and donors, with states below the percolation level being localized in the surface plane. Electrons rapidly relax in energy, emitting optical phonons up to the percolation level, after which the D'yakonov–Perel' mechanism proves to be suppressed due to the averaging of the effective field over the directions of electron movements.

For this reason heavy doping of the band bending region does not lead to additional depolarization of the emitted electrons. This conclusion is especially important for emitters designed for generating high-density emission currents (≈ 1 A cm^{-2}), when due to intensive optical excitation there may be a buildup of electrons at the surface states and partial straightening of the surface band bending, which leads to a decrease in quantum yield. Heavy doping of the near-surface region suppresses these effects [9].

Analysis of the various mechanisms of spin polarization losses at the different stages of photoemission shows that these losses in strained films are close in magnitude, while the range of accessible variations of the layer parameters is quite narrow.

Semiconducting strained short-period superlattices constitute alternative materials for photocathodes. In such structures the splitting of the states in the valence band may be made much greater due to the difference in masses of heavy and light holes and their size quantization in layers corresponding to the quantum wells, and the initial polarization may be made much higher. Furthermore, one can use superlattices with a reduced average strain in the active area (when the wells are highly deformed), and therefore with a more perfect crystal structure. Finally, profile doping may easily be introduced into the technology of superlattice growth, which makes it possible to retain a high acceptor level only within a narrow layer near the surface and to increase the spin relaxation time in the active area.

An important advantage of superlattices is the large number of variable parameters, which allows the optimization of the structure in such a way so as to minimize polarization losses at each stage in photoemission without degradation of the emission properties, for instance, by reducing the average spin–orbit splitting while retaining a high spin–orbit splitting in the well materials.

So far the $In_xGa_{1-x}As/Al_yGa_{1-y}As$ and $GaAs/GaAs_yP_{1-y}$ superlattices with strained wells [3, 10] and $GaAs/Al_xIn_yGa_{1-x-y}As$ superlattices with strained barriers [11] have been studied. In the latter structure, the use of the quaternary composition in the barrier makes it possible to reduce the conduction band offset at heterointerfaces to a minimum. This ensures a high mobility of the electrons along the superlattice axis and reduces the polarization losses during extraction.

The employment of modulation doping in the $Al_xIn_yGa_{1-x-y}As/GaAs$ superlattice, in addition to high deformation of the layers, makes is possible to reliably achieve an 86% polarization (P) with a high quantum yield Y in the vicinity of the polarization peak. In less strained lattices, the polarization at a photoemission maximum proves to be smaller.

The problem of optimizing the photoemitter's structure is rather complicated, and its solution is only at the initial stage.

First we must know the band structure of the material and the spectrum of initial electron polarization and their dependences on the parameters of the materials of the layers and the structure as a whole. Calculations of the band structure, the absorption coefficient, and the degree of initial orientation of the electrons for superlattice-based photoemitters were first done in Ref. [12] in the multiband Kane model within the enveloping function approximation. The results of these calculations for a superlattice with strained barriers and the basic optical transitions corresponding to the strongest van Hove singularities in the interband absorption spectrum are depicted in Fig. 2.

The results of calculations of the polarization spectrum [12] for an energy separation of 37 meV between the hole subbands and a parameter γ that characterizes the smearing of the absorption edge and equals 10 meV are depicted in Fig. 3 (without corrections for spin relaxation under thermalization). The fairly good agreement with the experimental data indicates that it is possible to employ such calculations in optimizing photoemissive structures and in restoring the parameters of strained superlattices, in particular, the conduction band offset at heterointerfaces. The advantages of using polarized electrons are in many ways similar to those of harnessing polarized light in optics, for example, in Raman spectroscopy: the gain in information is worth the effort in developing the appropriate technology, which has been fully realized in high-energy physics. Undoubtedly, spectroscopy (including tunneling spectroscopy) and microscopy that use polarized electrons will develop rapidly in the near future.

The main obstacle to the wide harnessing of the existing photoemitters of polarized electrons in materials science is the high sensitivity of the Cs(O) [or Cs(F)] activation layer to the vacuum conditions (a fairly long lifetime of the activated surface is achieved at a residual pressure of $10^{-11}-10^{-12}$ Torr) and the relatively low sensitivity of the most common Mott polarimeters (combined with the low accuracy of such polarimeters). The progress in developing more stable activation layers, protective coatings, and membranes and in manufacturing new compact and sensitive polarimeters based on multilayer magnetic structures is sure to solve these problems.

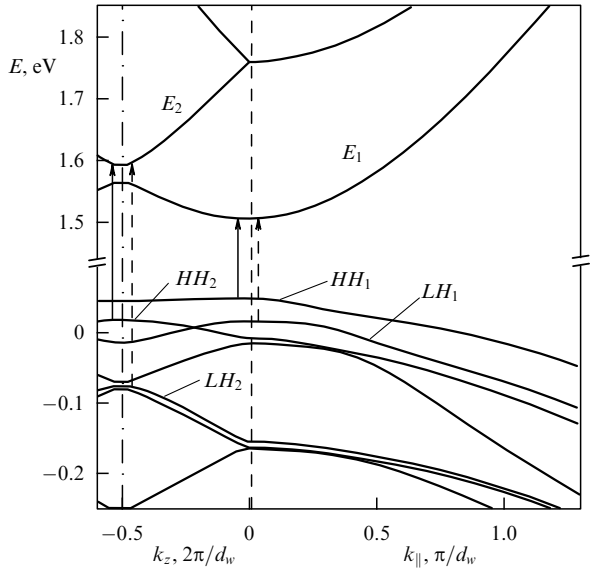

Figure 2. The band structure of the short-period strained GaAs/$Al_{0.18}In_{0.16}Ga_{0.66}As$ superlattice with equal barrier and well widths: $d_B = d_w = 4$ nm. The arrows indicate transitions that produce the principal singularities in the initial polarization spectrum.

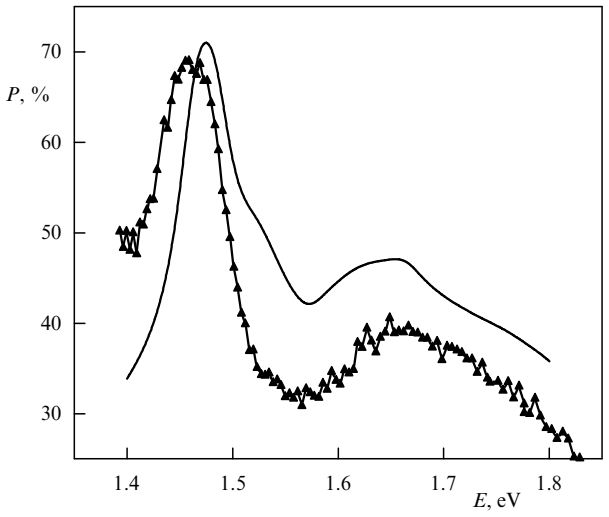

Figure 3. Spectral dependence of the photoemission spectra for a superlattice with the parameters specified in Fig. 2; the experimental results (triangles) and the results of calculating polarization at the moment of excitation (solid curve) are depicted.

A detailed investigation into the kinetics of polarized electrons in semiconductor nanostructures, the effects related to heterointerfaces, doping, and near-surface layers as well as the properties of these entities will be useful not only in developing new photoemissive materials but also in developing the elements of spin electronics.

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