resonance levels in the metallic layers do not coincide and the tunnel current has no resonant features. However, for a device of this type to become realizable, the interface between the ferromagnet and the insulator must be nearly ideal, which is practically impossible to achieve with the modern level of technology.

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Circular photogalvanic effect in nanostructures

E L Ivchenko

1. Introduction. Phenomenological description

During recent years spin-related phenomena in the physics of heterostructures have aroused heightened interest among researchers (e.g., see the review article [1]). The advances in studies of optical orientation in semiconductors [2–4] and spin phenomena in metallic heterostructures [5] form a base for developing such solid-state electronic devices as a spin transistor [6] and a quantum computer [7–9], which both utilize the additional degree of freedom of the electron, viz. its spin. The fabrication of spintronic devices relies on the effects of injection and detection of spin-polarized carriers, on the fact that the spin relaxation times of these carriers in electron transport are long, and on the possibility of controlling the spin polarization by an external electric field [10–13].

One of the most investigated and widespread methods of spin injection consists of using circularly polarized light whose absorption in semiconductors gives rise to spin orientation of the charge carriers [2]. Recently Ganichev et al. [14, 15] discovered that optical orientation in semiconductor heterostructures is accompanied by generation of an electric current. The emergence of such a constant electromotive force, which is induced by light, depends on the sign of circular polarization of the light, is not related to the spatial inhomogeneity of the irradiation or the inhomogeneity of the medium, and has been studied earlier in bulk crystals (see Refs [16–18]), became known as the circular photogalvanic effect (CPGE). Physically this effect consists of transforming the angular momentum of photons into the translational motion of free charge carriers and is described phenomenologically by the following relation

$$j_\lambda = \gamma_{\lambda\mu}\, \mathrm{i}(\mathbf{E} \times \mathbf{E}^*)_\mu \,. \tag{1}$$

Here, $\mathbf{j}$ is the induced photocurrent density, and $\mathbf{E}$ is the complex-valued amplitude of the electric field of the light wave; for a transverse wave we have the identity $\mathrm{i}(\mathbf{E} \times \mathbf{E}^*) = E_0^2\, P_{\mathrm{circ}}\, \hat{\mathbf{e}}$, where E_0 is the amplitude of $|\mathbf{E}|$, P_{circ} is the degree of circular polarization, and $\hat{\mathbf{e}}$ is the unit vector pointing in the direction of light propagation. According to equation (1), CPGE is allowed in systems without an inversion center, whose point symmetry does not distinguish between the components of polar and axial vectors. It is precisely gyrotropic crystals that possess this property. CPGE was predicted independently in Refs [19, 20] and was first discovered in tellurium [18]. This effect can also manifest itself in two-dimensional (2D) nanostructures [21], which was demonstrated in experiments involving semiconducting quantum wells [14, 15, 22]. Studies of CPGE and its dynamics make it possible to extract information about spin relaxation times in semiconductor nanostructures [23] and the width of the spin splitting which plays an important role in controlling spin processes; they also provide a new instrument for investigating the symmetry of heterostructures and spin injection processes.

More than that, in low-symmetry heterostructures, the nonequilibrium spin orientation leads to appearance of a current irrespective of the way in which such orientation was achieved [21, 24]. Since the operation of the elements of spintronics assumes the presence of strong polarization, it is obvious that this new class of spin-galvanic phenomena must be taken into account in developing electronic devices. The present report discusses the results of a combined theoretical and experimental investigation into the CPGE in quantum wells and the mechanism of this effect in one-dimensional systems, namely, in chiral carbon nanotubes.

2. CPGE in 2D structures with a zinc blende lattice

Bulk semiconductors with a zinc blende lattice are nongyrotropic (the crystal class T_d), so that CPGE is forbidden in them. In heterostructures with quantum wells grown from such semiconductors, the point symmetry is lowered to D_{2d} in a symmetric quantum well with a growth axis [001], to C_{2v} in an asymmetric quantum well or a single heterojunction with a growth axis [001], and to C_s in a 2D structure grown along a low-symmetry axis $[hhl] \neq [001], [111]$. In all three cases the tensor γ in equation (1) comprises nonzero components. In what follows we use Cartesian coordinate axes x, y, and z that are parallel to the crystallographic directions $[1\bar{1}0]$, $[ll(\overline{2h})]$, and $[hhl]$, respectively. Since barriers obstruct the motion of charge carriers along the growth axis, in quantum wells the index λ entering into Eqn (1) runs through the values of only two coordinates, x and y. Notice that, by definition, CPGE is not related to the spatial inhomogeneity of a quantum well in the interface plane (neither it is related to the aperiodicity of a quantum wire in the case of a one-dimensional structure).

CPGE in quantum wells of the C_{2v} symmetry is characterized by two linearly independent components γ_{xy} and γ_{yx} and shows itself only under the oblique incidence of the circularly polarized light. In this case, the vector relation (1), when written down in terms of projections, takes the form

$$j_x = \gamma_{xy} \hat{e}_y P_{\text{circ}} E_0^2 \,, \quad j_y = \gamma_{yx} \hat{e}_x P_{\text{circ}} E_0^2 \,. \tag{2}$$

In a quantum well of the D_{2d} symmetry, the components γ_{xy} and γ_{yx} coincide. In the structures of the low symmetry C_s with the reflection plane $(1\bar{1}0)$, the relations in Eqn (2) must be augmented with

$$j_x = \gamma_{xz} \hat{e}_z P_{\text{circ}} E_0^2 \tag{3}$$

and the circular photocurrent is generated even when the light incidence is normal.

2.1 CPGE microscopic mechanisms

Transformation of the angular momentum of photons into translational motion of the free carriers becomes possible because of spin – orbit coupling. It is described by spin-dependent terms in the effective electronic Hamiltonian, which are responsible for the splitting of the spin branches in the dispersion curve (this splitting is linear in the wave vector $\mathbf{k}$). These terms have the form $\sum_{\lambda\mu} \beta_{\lambda\mu} k_\lambda \sigma_\mu$, where σ_λ are the spin Pauli matrices, and the tensor β is similar to the tensor γ in its symmetry properties. The origin of CPGE can be explained qualitatively in the following manner: the absorption of circularly polarized light results in optical orientation of the electron spins, and the spin – $\mathbf{k}$-vector relationship described by the tensor β leads to a directed motion of charge carriers (electrons and/or holes) i.e., to an electric current.

The CPGE microscopic current density, or simply the circular photocurrent, is related to the nonequilibrium distribution function of free charge carriers through the formula $\mathbf{j} = e \sum_{n\mathbf{k}} \mathbf{v}_{n\mathbf{k}} f_{n\mathbf{k}}$, where e is the electron charge, $\mathbf{v}_{n\mathbf{k}}$ is the group velocity in the $|n, \mathbf{k}\rangle$ state, and the subscript n numbers both bands and spin states. The necessary condition for current generation is the asymmetry of the distribution function or, more precisely, the presence of a component $f_{n\mathbf{k}}^-$ antisymmetric under reversal of the wave vector and the electron spin. Generally, there are two different mechanisms that contribute to CPGE: the asymmetry of optical excitation [19, 25], and the asymmetry of the spin relaxation of the optically oriented carriers [21, 24]. The first contribution j_1 is caused by the asymmetry in the carrier-quasi-momentum distribution at the moment of photoexcitation of the carriers by circularly polarized light. The second contribution j_2 emerges in the process of spin relaxation of the optically oriented thermalized carriers. Estimates to an order of magnitude of both j_1 and j_2 currents yield $eWs_0(\beta/\hbar)\tau_{\text{p}}$, where W is the photon absorption probability per unit time and per unit d-dimensional volume ($d = 3, 2$, and 1 in a bulk crystal, quantum well, and quantum wire, respectively), s_0 is the average spin of photoexcited carriers, β is one of the components of the tensor β, and τ_{p} is the momentum relaxation time of the free carriers. Although j_1 and j_2 may be of the same order of magnitude, the physical difference between these two contributions becomes obvious when photoexcitation is suddenly switched off: the current j_1 decays in time τ_{p}, while the decay of the current j_2 is determined by the spin relaxation time τ_{s} which is usually much longer than τ_{p}.

It is worthwhile to mention that CPGE is the electron analog of mechanical systems that convert rotational motion into translational motion. There are two different ways in which such a conversion may be implemented: one is realized in systems with a screw (e.g., an airplane with a propeller), while the other is realized in systems in which there is contact between a round surface and a flat surface (e.g., the wheel on a car and the surface of a road). The electron analog of the propeller effect is described by the diagonal components of the tensor β, in particular, by the terms $\beta_{\lambda\lambda} k_\lambda \sigma_\lambda$. In this case, when the light propagates along the λ-axis, the generated circular photocurrent flows in the same direction. CPGE has been observed in such a geometry in the bulk crystals of tellurium, of the sillenites $Bi_{12}RO_{20}$ (R = Ge, Si, and Ti), and lead germanate $Pb_5Ge_3O_{11}$ (see Ref. [17]). The analog of the wheel effect is described by the off-diagonal components of the tensor β. According to equation (3), precisely this effect is realized in a quantum well of symmetry C_s, when the light incidence is normal: the electron spins become aligned parallel to the z-axis and, due to the spin – orbit coupling $\beta_{xz} k_x \sigma_z$, the generated current flows in the transverse direction x perpendicular to the reflection plane $(1\bar{1}0)$. In a quantum well with a growth axis [001], and in the particular case of $\gamma_{xy} = -\gamma_{yx}$, the circular photocurrent flows in the direction that is perpendicular to the light incidence plane irrespective of the plane's orientation in relation to the crystallographic axes. If $\gamma_{xy} \neq -\gamma_{yx}$, then the angle between the direction in which the photocurrent flows and the incidence plane is not fixed and changes as the light incidence plane rotates. A theory of the CPGE accounting for band-to-band optical transitions in quantum wells has been developed by Golub [26].

2.2 Experiment

Figure 1 presents the experimental data illustrating the CPGE in structures with p-type GaAs/AlGaAs quantum wells and n-type InAs/AlGaSb quantum wells, grown along the [113]- and [001]-axes, respectively. The source of light was a high-power pulsed submillimeter NH_3 laser with optical pumping. Linearly polarized light was sent through a $\lambda/4$-plate, and the sample was illuminated by elliptically polarized light with a degree of circular polarization $P_{\text{circ}} = \sin 2\varphi$, where φ is the angle between the polarization plane of the laser radiation and the optical axis of the $\lambda/4$-plate. The measurements that resulted in the curves in Fig. 1 were taken at room temperature and a light wavelength $\lambda = 76$ μm. Note that no external voltage was applied to the samples.

In accordance with the phenomenological formulae (2) and (3), the photocurrent is proportional to $\sin 2\varphi$, i.e., it reaches the extreme point when the light is circularly polarized and changes its polarity as the sign of circular polarization changes. In the first sample, the circular photocurrent was also observed when the light incidence was normal, while in the second sample the current was generated only when the exciting light beam was deflected from the normal to the external surface.

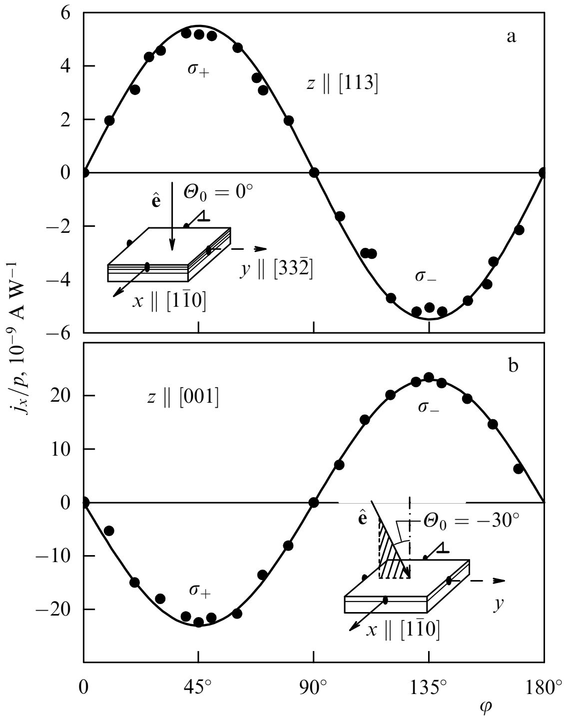

Figure 1. Ratio of the photocurrent in a heterostructure to the optical pump power as a function of the angle φ determining the helicity of the photons: (a) normal incidence of the light on a structure with p-GaAs/AlGaAs[113]A quantum wells (point symmetry C_s), and (b) oblique incidence of the light at an angle $\Theta = 30°$ on a structure with n-InAs/AlGaSb[001] quantum wells (point group C_{2v}). The solid curves have been calculated by formulae (2) and (3). The insets depict the geometries of the experiment.

3. Saturation of circular and linear photogalvanic effects in p-type structures

In media with a point symmetry which allows for piezoelectricity, a linear photogalvanic effect (LPGE) is also observed in addition to CPGE. This effect is described by a tensor $\mathcal{X}_{\lambda\mu\nu}$ of rank 3 symmetric in relation to the permutation of the last two indices: $j_\lambda = \mathcal{X}_{\lambda\mu\nu}(E_\mu E_\nu^* + E_\nu E_\mu^*)/2$ (see Refs [14, 16–18]). For a normal incidence of elliptically polarized light on a heterostructure with a growth axis [113] in the direction of axis $x \parallel [1\bar{1}0]$, the total current generated in the sample is given by

$$j_x = \left(\gamma_{xz}\,\hat{e}_z P_{\rm circ} + \mathcal{X}_{xxy}\,P_{\rm lin}\sin 2\alpha\right)E_0^2\,, \qquad (4)$$

where $P_{\rm lin}$ is the degree of linear polarization, $P_{\rm lin}^2 + P_{\rm circ}^2 = 1$, and α is the angle between the major axis of the polarization ellipse and the x-axis. In the geometry of the experiment depicted in the inset to Fig. 1a, the angle α is zero and only a circular photocurrent flowing in direction x is generated. The linear photocurrent is at its maximum upon excitation by light that is linearly polarized along the [100]-axis, when $\alpha = \pi/4$.

Ganichev et al. [22, 23] discovered that LPGE and CPGE become saturated with the increase in excitation intensity I, with the corresponding photocurrents described satisfactorily by the following sublinear relations

$$j_{\rm L} \propto \frac{I}{1 + I/I_{\rm L}}\,, \quad j_{\rm C} \propto \frac{I}{1 + I/I_{\rm C}}\,,$$

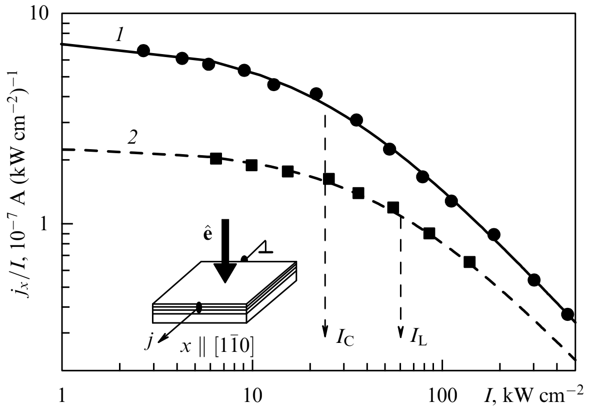

Figure 2. Ratio of the photocurrent in p-GaAs/AlGaAs[113]A quantum wells to the pump intensity I as a function of I for circular (*1*) and linear (*2*) polarizations of the exciting light. The inset shows the geometry of the experiment. The black circles and squares represent the experimental data, and the curves *1* and *2* have been calculated by formula (5) for values of $I_{\rm L}$ and $I_{\rm C}$ indicated by vertical arrows. LPGE was measured for light whose plane of linear polarization was oriented at an angle of 45° to the x-axis.

where $I_{\rm L}$ and $I_{\rm C}$ are the characteristic intensities of saturation of the photocurrent j_x for linearly and circularly polarized light. Figure 2 shows the dependences of the ratios

$$\frac{j_{\rm L}}{I} = \frac{A_{\rm L}}{1 + I/I_L}\,, \quad \frac{j_{\rm C}}{I} = \frac{A_{\rm C}}{1 + I/I_C} \qquad (5)$$

on the intensity I, measured in the samples with GaAs/AlGaAs quantum wells, grown along the [113]-axis ($A_{\rm L,C}$ are the constant coefficients).

Since the LPGE current is proportional to the probability W of optical absorption in direct intersubband transitions, the saturation parameter $I_{\rm L}$ is related to the light-induced effective heating of 2D holes and to a decrease in the population of the initial states of the holes participating in the optical transitions. The difference between $I_{\rm L}$ and $I_{\rm C}$ can be explained only by the orientation of the hole spins in the direct intersubband absorption of circularly polarized light. The equilibrium holes occupy the lower subband of dimensional quantization of heavy holes *hh*1 with an angular momentum (spin) $m = \pm 3/2$. When the light is circularly polarized, for example, σ_+-polarized, the photoexcitation rates of holes from the states $(hh1, 3/2)$ and $(hh1, -3/2)$ to the upper subbands differ: $W_{3/2} \neq W_{-3/2}$. In the process of energy relaxation back to the *hh*1 subband, the photoexcited holes lose their directed spin. Hence, in the absence of spin relaxation, there is light-induced transfer of holes from one spin state into another in the lower subband until the probabilities $W_{+3/2}$ and $W_{-3/2}$ become equal. Because the circular photocurrent is proportional to the difference $W_{+3/2} - W_{-3/2}$, the ratio $j_{\rm C}/I$ will decrease to zero with the passage of time. For a finite time ($\tau_{\rm s}$) of spin relaxation between the branches $(hh1, 3/2)$ and $(hh1, -3/2)$, this ratio is time independent and remains finite in the event of steady-state excitation, but it decreases as I grows in accordance with formula (5), where $I_{\rm C} = (p_{\rm s}/\tau_{\rm s})(I/W^{(0)})$, with $p_{\rm s}$ being the 2D concentration of holes (2×10^{11} cm^{-2}), and $W^{(0)}$ the rate of optical transitions in an approximation that is linear in light intensity. A comparison between the theoretical results and the experimental data made it possible to estimate the time $\tau_{\rm s}$

for heavy holes, which is of the order of 10 ps in the 5 – 50 K temperature range and varies according to the law $\tau_s \propto T^{-1/2}$.

4. Spin-galvanic effect

The CPGE caused by the asymmetry of spin relaxation processes (see Section 2.1) can be described by the more general relationship

$$j_\lambda = Q_{\lambda\mu} S_\mu \,, \tag{6}$$

which links the extraneous current $\mathbf{j}$ to the nonequilibrium total spin $\mathbf{S}$ of the thermalized carriers. In heterostructures grown along the [001]-axis, only two components, Q_{xy} and Q_{yx}, of the tensor $\mathbf{Q}$ are nonzero. The spin $\mathbf{S}$ can be oriented by optical pumping, by injection from the ferromagnetic layer built into the structure, or by any other technique. Hence, formula (6) describes an effect that may be called spin-galvanic by analogy with the galvanomagnetic and photogalvanic effects.

To observe the spin-galvanic effect, Ganichev et al. [24] used the optical method of orienting the electrons in a single n-GaAs/AlGaAs heterojunction along the growth axis [001] in an external magnetic field $\mathbf{B}$ (see the inset to Fig. 3). When the field is zero and the incidence of the circularly polarized light is normal, the electron spins are optically oriented along the z-axis, but no photocurrent is generated, since in such a geometry there can be no CPGE effect. A magnetic field $\mathbf{B} \parallel x$ turns the spins about the x-axis and they acquire a y-component (the transverse Hanle effect):

$$S_y = -\frac{\omega_L T_s^2}{1 + (\omega_L T_s)^2} \, \dot{S}_z \,, \tag{7}$$

where ω_L is the Larmor precession frequency, $\dot{S}_z$ is the rate of optical spin generation, and $T_s = \sqrt{T_{s,\parallel} T_{s,\perp}}$, with $T_{s,\parallel}$ and $T_{s,\perp}$ being the longitudinal and transverse spin lifetimes. Substituting (7) in (6), we find that the transverse Hanle effect has to manifest itself directly in the dependence of the photocurrent on the magnetic field B_x, namely, when the field is weak, the photocurrent is proportional to B_x, but as the field becomes stronger the photocurrent reaches its maximum value and then drops to zero. The nonmonotonic behavior of the photocurrent, predicted by the theory, has been truly observed in experiments (see Fig. 3). Observations of the spin-galvanic effect have made it possible to determine the time T_s for electrons in the heterostructures studied. In connection with the given investigation, the necessity arose to calculate the optical orientation of the electron spins in participating intraband absorption. The theory of monopolar intrasubband optical orientation has been developed recently in Ref. [27].

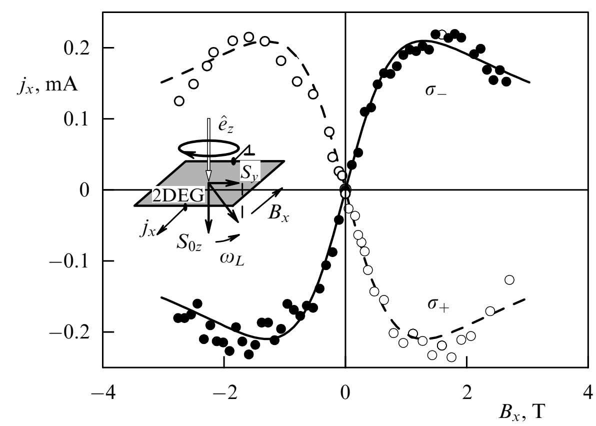

Figure 3. The photocurrent j_x plotted as a function of the magnetic field induction for normal excitation of a structure with n-GaAs/AlGaAs[001] quantum wells by σ_+- and σ_--light polarized circularly ($\lambda = 148$ μm, power 20 kW, $T = 4.2$ K). The inset depicts the optical orientation of electron spins and their rotation in the magnetic field.

5. CPGE in structures with SiGe quantum wells

Crystals with a diamond type lattice, in particular the semiconductors Ge and Si, have an inversion center, with the result that both CPGE and LPGE are forbidden in them. This, however, does not constitute an obstacle for growing noncentrosymmetric heterostructures from such semiconductors. The outcomes of the experimental work that led to the discovery of CPGE in the structures with double-layer $Si_{0.75}Ge_{0.25}$(4 nm)/$Si_{0.55}$ $Ge_{0.45}$ (2.4 nm) quantum wells bounded by Si barriers and in asymmetrically doped structures with $Si_{0.75}Ge_{0.25}$ quantum wells, grown along the [001]- and [113]-axes, are presented in Ref. [28]. To verify the results, measurements were also made in a compositely symmetric and symmetrically doped structure with 60 $Si_{0.7}Ge_{0.3}$ quantum wells. No photocurrent was discovered in this sample, despite the fact that the structure had many more wells compared to the respective number in the other, asymmetric, structures.

The same researchers analyzed the possible mechanisms of the appearance of spin-dependent terms that are linear in $\mathbf{k}$ in p-type $Si_{1-x}Ge_x$/Si heterostructures: (a) the Rashba terms induced by the built-in electric field; (b) the mixing of the states of heavy and light holes on nonequivalent interfaces, and (c) terms of the $\sigma_z k_x$ type that appear in asymmetric structures with the growth axis [113] as a result of dimensional quantization of the Luttinger Hamiltonian.

6. CPGE in carbon nanotubes

CPGE may serve as a convenient instrument for studying one-dimensional structures, such as carbon nanotubes. With the exception of 'zigzag' and 'armchair' nanotubes, all other nanotubes are chiral, i.e., they possess chiral symmetry and allow for a photocurrent $j_z = \gamma\, \mathrm{i} (\mathbf{E} \times \mathbf{E}^*)_z$, where z is the principal axis of the structure. The theory of CPGE in such systems has been developed in Ref. [29]. In contrast to the mechanisms discussed above, CPGE in carbon nanotubes is not related to spin, since spin – orbit coupling in carbon appears to be very weak. The appearance of a photocurrent j_z can be explained by the relation that exists between the wave vector k_z and the electron orbital angular momentum m which characterizes the symmetry of the electron wave function in respect to the screw rotation about the z-axis. It is this relation that leads to corrections to the electron energy that are proportional to the product mk_z and describe the electron analog of the propeller effect.

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