PHYSICAL REVIEW B **68**, 081302(R) (2003)

Spin-galvanic effect due to optical spin orientation in *n*-type GaAs quantum well structures

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(Received 6 March 2003; revised manuscript received 24 March 2003; published 29 August 2003)

Under oblique incidence of circularly polarized infrared radiation the spin-galvanic effect (SGE) has been unambiguously observed in (001)-grown *n*-type GaAs quantum well structures in the absence of any external magnetic field. Resonant intersubband transitions have been obtained making use of the tunability of the free-electron laser FELIX. A microscopic theory of the SGE for intersubband transitions has been developed, which is in good agreement with experimental findings.

DOI: 10.1103/PhysRevB.68.081302 PACS number(s): 72.40.+w, 72.25.Fe, 78.67.−n

The spin of electrons and holes in solid-state systems is an intensively studied quantum-mechanical property showing a large variety of interesting physical phenomena. Lately there is much interest in the use of the spin of carriers in semiconductor heterostructures together with their charge for novel applications such as spintronics.[1] The necessary conditions to realize spintronic devices are high spin polarizations in quantum well (QW) structures and large spinsplitting of subbands in $\boldsymbol{k}$ space. The latter is important for the ability to control spins with an external electric field by the Rashba effect.[2] Significant progress has been achieved recently in generating large spin polarizations, in demonstrating the Rashba splitting, and also in using the splitting for manipulating the spins.[1] At the same time, as these conditions are fulfilled, it has been shown that the spin polarization itself drives a current if the spins are oriented in the plane of the QW.[3] This spin-galvanic effect (SGE) was previously demonstrated with optical excitation and the assistance of an external magnetic field to achieve an in-plane polarization. As a step towards the long-term aim of showing its existence with only electric injection we report here the demonstration of the optically induced SGE in zero magnetic field. We also present the microscopic theory of this effect.

The spin-galvanic effect has been observed at room temperature by studying transitions between size quantized subbands $e1$ and $e2$ in *n*-type GaAs QW's. Samples, grown along $z \parallel [001]$ by mulecular beam epitaxy, consisting of 30 QW's with a well width of 7.6 nm, 8.2 nm, and 8.8 nm, and free-carrier density in a single well n_e of about $2 \times 10^{12}\ \mathrm{cm}^{-2}$ were investigated at room temperature. Samples were quadratic in shape, with edges oriented along the $x \parallel [1\bar{1}0]$ and $y \parallel [110]$ crystallographic directions. Two pairs of ohmic contacts were attached in the center of opposite sample edges (see Fig. 1). In order to excite resonantly and to obtain a measurable photocurrent it was necessary to have a tunable high-power radiation source for which we used the free-electron laser ''FELIX'' at FOM-Rijnhuizen in The Netherlands.[4] The output pulses of light from FELIX were chosen to be 3 ps long, separated by 40 ns, in a train (or ''macropulse'') of duration 5 μs. The macropulses had a repetition rate of 5 Hz.

On illumination of the QW structures by circularly polarized radiation at oblique incidence in the (xz) or (yz) plane a current signal perpendicular to the plane of incidence was measured, e.g., in the y direction for the configuration depicted in Fig. 1. Left-handed (σ_-) and right-handed (σ_+) circularly polarized radiation was achieved making use of a Fresnel rhomb. The photocurrent signals generated in the unbiased devices were measured via an amplifier with a response time of the order of 1 μs, i.e., averaged over the macropulse.

The observed current is proportional to the helicity P_{circ} of the radiation. The current was measured for incidence in two different planes with the in-plane component of propagation along the x and y directions. In Fig. 2 the observed current for both directions is plotted as a function of photon energy $\hbar\omega$ for σ_+ polarized radiation together with the absorption spectrum. It can be seen that for current along $x \parallel [1\bar{1}0]$ the shape is similar to the derivative of the absorption spectrum, and in particular there is a change of sign which occurs at the line center of the absorption. When the sample was rotated by 90° about z, so that light propagates now along x and the current flows along $y \parallel [110]$, the sign rever-

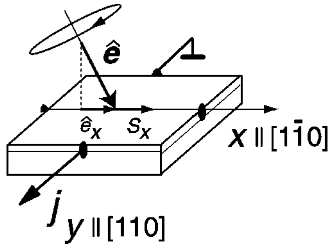

FIG. 1. Geometry of the experiment. At oblique incidence of radiation we obtained projections on the x or y directions of the unit vector $\hat{\boldsymbol{e}}$ and the averaged spin $\boldsymbol{S}$. The current $\boldsymbol{j}$ is recorded perpendicular to the direction of light propagation.

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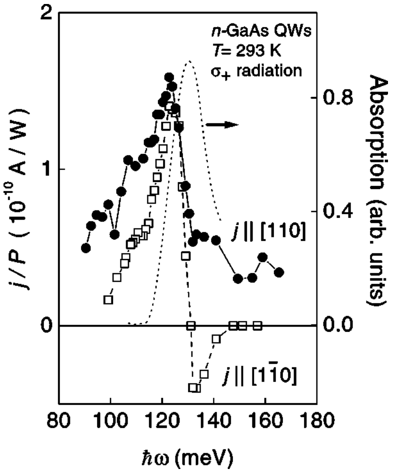

FIG. 2. Photocurrent in GaAs QW's of 8.2 nm width normalized by the light power P as a function of the photon energy. Circles: current in [110] direction in response to irradiation parallel $[1\bar{1}0]$. Squares: current in $[1\bar{1}0]$ direction in response to irradiation parallel [110]. The dotted line shows the absorption measured using a Fourier-transform spectrometer.

sal in the current disappears and its shape follows more closely the absorption spectrum.

It has been shown in Refs. 3,5 that in QW's belonging to one of the gyrotropic crystal classes a nonequilibrium spin polarization of electrons uniformly distributed in space causes a directed motion of electrons in the plane of the QW. On a microscopic level spin photocurrents are the result of spin orientation in systems with **k**-linear terms in the electron effective Hamiltonian. In general, two mechanisms contribute to spin photocurrents: photoexcitation and scattering of photoexcited carriers. The first effect is the circular photogalvanic effect (CPGE) which is caused by an asymmetry of the momentum distribution of carriers excited in optical transitions.[5,6] The second effect is the spin-galvanic effect which in general does not need optical excitation but is a result of an asymmetric spin relaxation.[3] The current due to CPGE decays with the momentum-relaxation time τ_p of photoexcited free carriers whereas the SGE induced current decays with the spin-relaxation time τ_s. Both effects are illustrated in Fig. 3.

The change of sign of the photocurrent with photon energy is characteristic for CPGE at resonant transitions in *n*-type QW's and has been described previously.[6] As illustrated in Fig. 3(a) for σ_+ radiation and at a small photon energy less than the energy separation between $e1$ and $e2$ at $k_x = 0$, excitations occur preferentially at positive k_x. We note that for C_{2v} symmetry the optical transitions are spin conserving but spin dependent.[6] This causes a stronger reduction in the electron population at positive k_x in the lower $|-1/2\rangle_y$-subband and therefore a spin-polarized current in the positive *x* direction. We note that there is a corresponding increase of the electron population in the $e2$ $|-1/2\rangle_y$-subband, also asymmetrical, but in our case this randomizes quickly via optical-phonon scattering and therefore does not contribute significantly to the current.[6] Increase of the photon energy shifts the dominating transition towards negative k_x and reverses the current. In fact it has been shown that the CPGE at intersubband absorption in *n*-type QW's is proportional to the derivative of the absorption spectrum.[6] This behavior is observed for the current in the $x \parallel [1\bar{1}0]$ direction. In particular, the position of the sign inversion of the current coincides with the maximum of the absorption spectrum which shows that the spin-galvanic effect for this direction is vanishingly small and the current is caused by the CPGE.

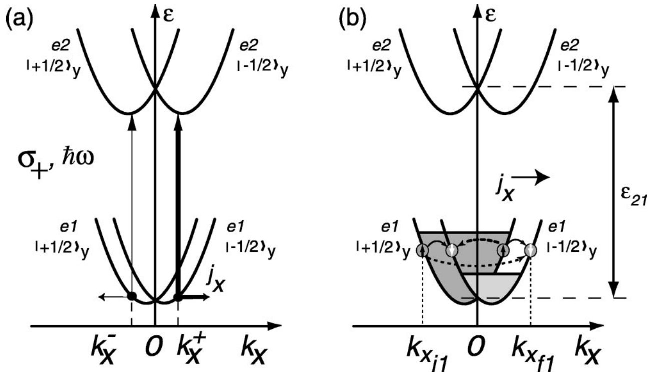

FIG. 3. Microscopic picture of the current mechanisms at intersubband excitation in C_{2v} symmetry QW's. In (a) the CPGE current j_x is caused by the imbalance of optical transition probabilities at k_x^- and k_x^+ decaying with the momentum-relaxation time τ_p. In (b) the SGE current occurs after spin-nonspecific thermalization in $e1$ which results in the spin orientation. This current is caused by asymmetric spin-flip scattering and decays with the spin-relaxation time τ_s (Ref. 3).

In contrast to the CPGE the sign of the spin-galvanic current is independent of the wavelength.[7] This can be seen from Fig. 3(b) that illustrates the origin of the spin-galvanic effect. All that is required is a spin orientation of the lower subband, and asymmetrical spin relaxation then drives a current.[3] In our case the spin orientation is generated by resonant spin-selective optical excitation followed by spin-nonspecific thermalization. The magnitude of the spin polarization and hence the current depends on the initial absorption strength but not on the momentum **k** of transition. Therefore there is no sign change and the shape of the spectrum follows the absorption.[7] The lack of a sign change for current along $y \parallel [110]$ in the experiment shows that the spin-galvanic effect dominates for this orientation.

In order to understand the difference between the two orientations we now introduce a phenomenological picture for the C_{2v} symmetry representing samples investigated here. Phenomenologically the SGE and the CPGE in *x* and *y* directions are given by

$$j_{SGE,x} = Q_{xy} S_y, \qquad j_{SGE,y} = Q_{yx} S_x \tag{1}$$

$$j_{CPGE,x} = \gamma_{xy} \hat{e}_y E_0^2 P_{circ}, \qquad j_{CPGE,y} = \gamma_{yx} \hat{e}_x E_0^2 P_{circ}. \tag{2}$$

where $\boldsymbol{j}$ is the photocurrent density, $\boldsymbol{Q}$ and $\boldsymbol{\gamma}$ are second rank pseudotensors, $\boldsymbol{S}$ is the average spin of electrons in QW's, E_0 and $\hat{\boldsymbol{e}}$ are the amplitude of the electromagnetic wave and the

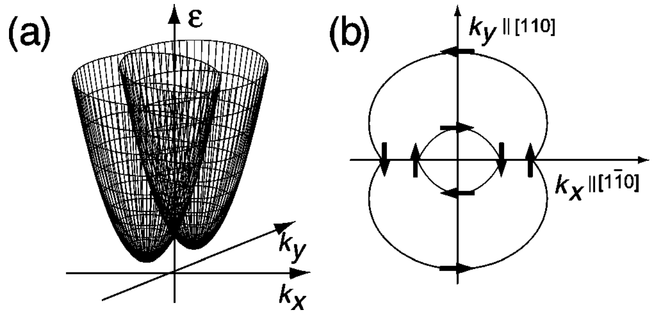

FIG. 4. Schematic two dimensional (2D) band structure with $\boldsymbol{k}$-linear terms for C_{2v} symmetry and the distribution of spin orientations at the 2D Fermi energy. Arrows indicate the orientation of spins.

unit vector pointing in the direction of light propagation, respectively. In the present case $\boldsymbol{S}$ is obtained by optical orientation, its sign and magnitude are proportional to P_{circ}, and it is oriented along the in-plane component of $\hat{\boldsymbol{e}}$ (see Fig. 1). Because of tensor equivalence of $\boldsymbol{Q}$ and $\boldsymbol{\gamma}$ the spin-galvanic current induced by circularly polarized light always occurs simultaneously with the CPGE. If the in-plane component of $\hat{\boldsymbol{e}}$ is oriented along $[1\bar{1}0]$ or [110], i.e., x or y, then both currents flow normal to the light propagation direction. The strength of the current is different for the radiation propagating along x or y. This is due to the nonequivalence of the crystallographic axes $[1\bar{1}0]$ and $[110]$ because of the twofold rotation axis in C_{2v} symmetry.

Both currents are caused by spin splitting of subbands in the $\boldsymbol{k}$ space.[3,5] This splitting is due to $\boldsymbol{k}$-linear terms in the Hamiltonian of the form $\hat{H}' = \Sigma_{lm}\beta_{lm}\sigma_l k_m$, where β_{lm} is a second-rank pseudotensor and σ_l are the Pauli matrices. The tensors $\boldsymbol{\gamma}$ and $\boldsymbol{Q}$ determining the current are related to the transposed pseudotensor $\boldsymbol{\beta}$. They are subjected to the same symmetry restrictions so that their irreducible components differ only by scalar factors. For (001)-grown QW's of C_{2v} symmetry there are two nonzero tensor elements $\beta_{xy} \neq \beta_{yx}$ which may also be different for $e1$ and $e2$ subbands. It is reasonable to introduce symmetric and antisymmetric tensor components $\beta_{BIA}^{(\nu)} = (\beta_{xy}^{(\nu)} + \beta_{yx}^{(\nu)})/2$ and $\beta_{SIA}^{(\nu)} = (\beta_{xy}^{(\nu)} - \beta_{yx}^{(\nu)})/2$, where $\nu = 1,2$ indicates the $e1$ and $e2$ subbands, respectively. Here $\beta_{BIA}^{(\nu)}$ and $\beta_{SIA}^{(\nu)}$ result from bulk inversion asymmetry (BIA) also called the Dresselhaus term[8] (including a possible interface inversion asymmetry[9]) and from structural inversion asymmetry (SIA) usually called the Rashba term,[2] respectively. In order to illustrate band structures with a $\boldsymbol{k}$-linear term, in Fig. 4 we plotted the energy ε as a function of k_x and k_y. The nonequivalence of x and y directions is clearly seen from Fig. 4(b).

As discussed above and sketched in Fig. 3 both CPGE and SGE currents, say in the x direction, are caused by the band splitting in the k_x direction and therefore are proportional to β_{yx} (for current in the y direction one should interchange the indices x and y). Then the currents in the x and y directions read

$$j_x = A_{CPGE}[(\beta_{BIA}^{(1)} - \beta_{SIA}^{(1)}) - (\beta_{BIA}^{(2)} - \beta_{SIA}^{(2)})]P_{circ}\hat{e}_y + A_{SGE}(\beta_{BIA}^{(1)} - \beta_{SIA}^{(1)})S_y \tag{3}$$

$$j_y = A_{CPGE}[(\beta_{BIA}^{(1)} + \beta_{SIA}^{(1)}) - (\beta_{BIA}^{(2)} + \beta_{SIA}^{(2)})]P_{circ}\hat{e}_x + A_{SGE}(\beta_{BIA}^{(1)} + \beta_{SIA}^{(1)})S_x, \tag{4}$$

where A_{CPGE} and A_{SGE} are factors related to $\boldsymbol{\gamma}$ and $\boldsymbol{Q}$, respectively. The magnitude of the CPGE is determined by the value of $\boldsymbol{k}$ in the initial and final states, and hence on the spin splitting (β_{BIA} and β_{SIA}) of both $e1$ and $e2$ subbands. In contrast, the spin-galvanic effect is due to relaxation between the spin states of the lowest subband $e1$ and hence only on $\beta_{BIA}^{(1)}$ and $\beta_{SIA}^{(1)}$. Equations (3) and (4) show that in directions x and y the spin-galvanic effect and the CPGE are proportional to terms containing the difference and the sum, respectively, of BIA and SIA terms. When they add [see Eq. (4)] it appears in our samples that the spin-galvanic effect dominates over the CPGE, which is proved by the lack of sign change for currents along the y direction in Fig. 2. Conversely when BIA and SIA terms subtract [see Eq. (3)] the spin-galvanic effect is suppressed and the CPGE dominates. We would like to emphasize at this point that at the frequency where CPGE is equal to zero for both directions, the current obtained in the y direction is caused by the spin-galvanic effect only.

The occurrence of a spin-galvanic current is due to the spin dependence of the electron-scattering matrix elements $M_{\boldsymbol{k}'\boldsymbol{k}}$. The 2×2 matrix $\hat{M}_{\boldsymbol{k}'\boldsymbol{k}}$ can be written as a linear combination of the unit matrix $\hat{I}$ and Pauli matrices as follows:

$$\hat{M}_{\boldsymbol{k}'\boldsymbol{k}} = A_{\boldsymbol{k}'\boldsymbol{k}}\hat{I} + \boldsymbol{\sigma}\cdot\boldsymbol{B}_{\boldsymbol{k}'\boldsymbol{k}}, \tag{5}$$

where $A_{\boldsymbol{k}'\boldsymbol{k}}^* = A_{\boldsymbol{k}\boldsymbol{k}'}$, $B_{\boldsymbol{k}'\boldsymbol{k}}^* = B_{\boldsymbol{k}\boldsymbol{k}'}$ due to Hermiticity of the interaction and $A_{-\boldsymbol{k}',-\boldsymbol{k}} = A_{\boldsymbol{k}\boldsymbol{k}'}$, $B_{-\boldsymbol{k}',-\boldsymbol{k}} = -B_{\boldsymbol{k}\boldsymbol{k}'}$ due to the symmetry under time inversion. The spin-dependent part of the scattering amplitude in (001)-grown QW structures is given by[10]

$$\boldsymbol{\sigma}\cdot\boldsymbol{B}_{\boldsymbol{k}'\boldsymbol{k}} = v(\boldsymbol{k}-\boldsymbol{k}')[\sigma_x(k_y'+k_y) - \sigma_y(k_x'+k_x)], \tag{6}$$

where $v(\boldsymbol{k}\text{–}\boldsymbol{k}')$ is a function defined in Ref. 10. We note that Eq. (6) determines the spin-relaxation time τ_s' due to the Elliot-Yafet mechanism. Then, for instance, for the spin component S_x assuming a Boltzmann distribution, the spin-galvanic current in the y direction has the form

$$j_{SGE,y} = \frac{4\pi e}{m^*} S_x \sum_{\tilde{\boldsymbol{k}}\tilde{\boldsymbol{k}}'} (\tilde{k}_y' - \tilde{k}_y)(\tilde{k}_x' + \tilde{k}_x)^2 |v(\tilde{\boldsymbol{k}} - \tilde{\boldsymbol{k}}' - 2\boldsymbol{k}_0)|^2 \tau_p \times f\left(\frac{\hbar^2\tilde{\boldsymbol{k}}^2}{2m^*}\right) \delta\left(\frac{\hbar^2\tilde{\boldsymbol{k}}'^2}{2m^*} - \frac{\hbar^2\tilde{\boldsymbol{k}}^2}{2m^*}\right) \tag{7}$$

where e is the electron charge, τ_p is the momentum scattering time, f is the distribution function, δ is the delta function,

m^* is the electron effective mass, $\tilde{\boldsymbol{k}} = \boldsymbol{k} + \boldsymbol{k}_0$, $\tilde{\boldsymbol{k}}' = \boldsymbol{k}' - \boldsymbol{k}_0$, and $\boldsymbol{k}_0 = (m^* \beta_{xy}/\hbar^2, 0, 0)$. By using Eq. (7) we can estimate the spin-galvanic current as

$$j_{SGE,x} = Q_{xy} S_y \sim e\, n_e \frac{\beta_{yx}^{(1)}}{\hbar} \frac{\tau_p}{\tau_s'} S_y, \quad j_{SGE,y} = Q_{yx} S_x \sim e\, n_e \frac{\beta_{xy}^{(1)}}{\hbar} \frac{\tau_p}{\tau_s'} S_x. \tag{8}$$

Since scattering is the origin of the spin-galvanic effect, the current j_{SGE} is determined by the Elliot-Yafet spin-relaxation process even if other spin-relaxation mechanisms dominate. The Elliot-Yafet spin-relaxation time τ_s' is proportional to the momentum-relaxation time τ_p. Therefore the ratio τ_p/τ_s' in Eqs. (8) does not depend on the momentum-relaxation time. The in-plane average spin, e.g., S_x, in Eqs. (8) decays with the total spin-relaxation time τ_s. Thus the time decay of the spin-galvanic current following pulsed photoexcitation is determined by τ_s. This time may have contributions from any spin-relaxing process and in the present case of GaAs QW's is determined by the D'yakonov-Perel' mechanism.

For the present case, where spin relaxation is obtained as a result of intersubband absorption of circularly polarized radiation, the current is given by

$$j_{SGE,x} \sim e \frac{\beta_{yx}^{(1)}}{\hbar} \frac{\tau_p \tau_s}{\tau_s'} \frac{\eta_{21} I}{\hbar\omega} P_{circ} \xi \hat{e}_y, \quad j_{SGE,y} \sim e \frac{\beta_{xy}^{(1)}}{\hbar} \frac{\tau_p \tau_s}{\tau_s'} \frac{\eta_{21} I}{\hbar\omega} P_{circ} \xi \hat{e}_x. \tag{9}$$

η_{21} is the absorbance at the transitions between $e1$ and $e2$ subbands, I is the radiation intensity. The parameter ξ varying between 0 and 1 is the ratio of photoexcited electrons relaxing to the $e1$ subband with and without spin flip. It determines the degree of spin polarization in the lowest subband [see Fig. 3(b)] and depends on the details of the relaxation mechanism. Optical orientation requires $\xi \neq 0$.[11–13] Equations (9) show that the SGE current is proportional to the absorbance and is determined by the spin splitting in the first subband, $\beta_{yx}^{(1)}$ or $\beta_{xy}^{(1)}$.

In conclusion we observed the spin-galvanic effect under all-optical excitation and without applying external magnetic fields by making use of the interplay of the Rashba and Dresselhaus splitting of the conduction band. Our results demonstrate the nonequivalence of the $[110]$ and $[1\bar{1}0]$ directions in zinc-blende structure QW's. The results also clearly show the difference between the microscopic pictures for SGE and CPGE which have the same phenomenological description.

We thank L. E. Golub for many helpful discussions. Financial support from the DFG, the RFBR, INTAS, the EPSRC (UK) and FOM (NL) is gratefully acknowledged. The authors are grateful to the FELIX facility team and especially for the skillful assistance of Dr. A. F. G. van der Meer.

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