Photo-induced pure spin currents in quantum wells

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As is well known the absorption of circularly polarized light in semiconductors results in optical orientation of electron spins and helicity-dependent electric photocurrent, and the absorption of linearly polarized light is accompanied by optical alignment of electron momenta. Here we show that the absorption of unpolarized light in a quantum well (QW) leads to generation of a pure spin current, although both the average electron spin and electric current are vanishing.

I. INTRODUCTION

Spin and charge are among the basic properties of elementary particles such as an electron, positron and proton. The perturbation of a system of electrons by an electric field or light may lead to a flow of the particles. The typical example is an electric current that represents the directed flow of charge carriers. Usually the electric currents do not entail a considerable spin transfer because of the random orientation of electron spins. However, the charge current can be accompanied by a spin current as it happens, e.g., under injection of spin-polarized carriers from magnetic materials or in the optical-orientation-induced circular photogalvanic effect. Furthermore, there exists a possibility to create a pure spin current which is not accompanied by a net charge transfer. This state represents a non-equilibrium distribution when electrons with the spin “up” propagate mainly in one direction and those with the spin “down” propagate in the opposite direction. In terms of the kinetic theory, it can be illustrated by a spin density matrix with two nonzero components, \( \rho(s, k; \bar{s}, k) = \rho(\bar{s}, -k; s, -k) \), where \( s \) and \( k \) are the electron spin index and the wave vector, respectively, and \( \bar{s} \) means the spin opposite to \( s \). Spin currents in semiconductors can be driven by an electric field acting on unpolarized free carriers which undergo a spin-dependent scattering. This is the so-called spin Hall effect where a pure spin current appears in the direction perpendicular to the propagation of the random orientation of electron spins. However, the spin components along the QW normal are equal. In the presence of spin splitting, the optical appearance of a pure spin current under optical pumping is linked with two fundamental properties of semiconductor QWs, namely, the spin splitting of energy spectrum linear in the wave vector and the spin-sensitive selection rules for optical transitions.

II. INTERBAND OPTICAL TRANSITIONS

The effect is most easily conceivable for direct transitions between the heavy-hole valence subband \( hh1 \) and conduction subband \( e1 \) in QWs of the \( C_s \) point symmetry, e.g. in (113)- or (110)-grown QWs. In such structures the spin component along the QW normal \( z \) is coupled with the in-plane electron wave vector. This leads to \( k \)-linear spin-orbit splitting of the energy spectrum as sketched in Fig. 1, where heavy hole subband \( hh1 \) is split into two spin branches \( \pm 3/2 \). As a result they are shifted relative to each other in the \( k \) space. In the reduced-symmetry structures, the spin splitting of the conduction subband is usually smaller than that of the valence band and not shown in Fig. 1 for simplicity. Due to the selection rules the direct optical transitions from the valence subband \( hh1 \) to the conduction subband \( e1 \) can occur only if the electron angular momentum changes by \( \pm 1 \). It follows then that the allowed transitions are \( |+3/2\rangle \rightarrow |+1/2\rangle \) and \( |-3/2\rangle \rightarrow |-1/2\rangle \), as illustrated in Fig. 1 by vertical lines. Under excitation with linearly polarized or unpolarized light the rates of both transitions are equal. In the presence of spin splitting, the optical transitions

\[ F_{\alpha\beta} = \sigma_\alpha k_\beta \]

represent components of a pseudo-tensor \( F \) with two nonzero components describing the flow of the spin current. The spin current is contributed by a non-equilibrium correction \( \propto \sigma_\alpha k_\beta \) to the electron spin density matrix, where \( \sigma_\alpha \) is the Pauli matrix. We demonstrate that the appearance of a pure spin current under optical pumping is linked with two fundamental properties of semiconductor QWs, namely, the spin splitting of energy spectrum linear in the wave vector and the spin-sensitive selection rules for optical transitions.

FIG. 1: Microscopic origin of pure spin current induced by interband photoexcitation.
transitions induced by photons of the fixed energy $\hbar \omega$ occur in the opposite points of the $k$-space for the spin branches $\pm 1/2$. The asymmetry of photoexcitation results in a flow of electrons within each spin branch. The corresponding fluxes $j_{1/2}$ and $j_{-1/2}$ are of equal strengths but directed in the opposite directions. Thus, this non-equilibrium electron distribution is characterized by the nonzero spin current $j_{\text{spin}} = (1/2)(j_{1/2} - j_{-1/2})$ but a vanishing charge current, $e(j_{1/2} + j_{-1/2}) = 0$.

The direction $\beta$ of the photo-induced spin current and the orientation $\alpha$ of transmitted spins are determined by the form of spin-orbit interaction. The latter is governed by the QW symmetry and can be varied. For QWs based on zinc-blende-lattice semiconductors and grown along the crystallographic direction $[110] \parallel z$, the light absorption leads to a flow along $x \parallel [110]$ of spins oriented along $z$. This component of the electron spin flow can be estimated as

$$F^x_{\beta} = \gamma^{(h1)}_{xx}(\hbar \omega) \frac{\tau_e}{2m_e + m_h} \frac{m_h}{m_e + m_h} \eta_{e\alpha} I,$$

where $\gamma^{(h1)}_{xx}$ is a constant describing the $k$-linear spin-orbit splitting of the $hh1$ subband, $\tau_e$ is the relaxation time of the spin current, $m_e$ and $m_h$ are the electron and hole effective masses in the QW plane, respectively, $\eta_{e\alpha}$ is the light absorbance, and $I$ is the light intensity. Note that the time $\tau_e$ can differ from the conventional momentum relaxation time that governs the electron mobility.

In (001)-grown QWs the absorption of linearly- or unpolarized light results in a flow of electron spins oriented in the QW plane. In contrast to the low-symmetry QWs considered above, in (001)-QWs the $k$-linear spin splitting of the valence subband $hh1$ is small and here, for the sake of simplicity, we assume the parabolic spin-independent dispersion in the $hh1$ valence subband and take into account the spin-dependent contribution $\gamma^{(e1)}_{\alpha\beta} \sigma_{\alpha} k_\beta$ to the electron effective Hamiltonian. Then, to the first order in the spin-orbit coupling, the components of the pure spin current generated in the subband $e1$ are derived to be

$$F^x_{\beta} = \gamma^{(e1)}_{\alpha\beta}(\hbar \omega) \frac{\tau_e}{2m_e + m_h} \frac{m_h}{m_e + m_h} \eta_{e\alpha} I,$$

where $\gamma^{(e1)}_{\alpha\beta}$ is a constant describing the $k$-linear spin splitting of the $eh1$ subband.

**III. FREE-CARRIER ABSORPTION**

Light absorption by free carriers, or the Drude-like absorption, occurs in doped semiconductor structures when the photon energy $\hbar \omega$ is smaller than the band gap as well as the intersubband spacing. Because of the energy and momentum conservation the free-carrier optical transitions become possible if they are accompanied by electron scattering by acoustic or optical phonons, static defects etc. Scattering-assisted photoexcitation with unpolarized light also gives rise to a pure spin current. However, in contrast to the direct transitions considered above, the spin splitting of the energy spectrum leads to no essential contribution to the spin current induced by free-carrier absorption. The more important contribution comes from asymmetry of the electron spin-conserving scattering. In semiconductor QWs the matrix element $V$ of electron scattering by static defects or phonons has, in addition to the main contribution $V_0$, an asymmetric spin-dependent term [2]

$$V = V_0 + \sum_{\alpha\beta} V_{\alpha\beta} \sigma_\alpha (k_\beta + k'_\beta),$$

where $k$ and $k'$ are the electron initial and scattered wave vectors, respectively. Microscopically this contribution is caused by the structural and bulk inversion asymmetry similar to the Rashba/Dresselhaus spin splitting of the electron subbands. The asymmetry of the electron-phonon interaction results in non-equal rates of indirect optical transitions for opposite wave vectors in each spin subband. This is illustrated in Fig. 2, where the free-carrier absorption is shown as a combined two-stage process involving electron-photon interaction (vertical solid lines) and electron scattering (dashed horizontal lines).

The scattering asymmetry is shown by thick and thin dashed lines: electrons with the spin $+1/2$ are preferably scattered into the states with $k_x > 0$, while particles with the spin $-1/2$ are scattered predominantly into the states with $k_x < 0$. The asymmetry causes an imbalance in the distribution of photoexcited carriers in each subband $s = \pm 1/2$ over the positive and negative $k_x$ states and yields oppositely directed electron flows $j_{S}^{\pm 1/2}$ shown by horizontal arrows. Similarly to the interband excitation considered in the previous section, this non-equilibrium distribution is characterized by a pure spin current without charge transfer.

Let us assume the photon energy $\hbar \omega$ to exceed the typical electron kinetic energy, $E_F$ for degenerate and $k_B T$ for non-degenerate electron gas. Then the pure spin current induced by free-carrier light absorption is given by

$$F^x_{\beta} = \frac{\tau_e}{\hbar} \left[ \frac{V_{xx}}{V_0} \left( 1 + \frac{|e_x|^2 - |e_y|^2}{2} \right) + \frac{V_{xy}}{V_0} e_x e_y \right] \eta_{e1} I,$$

where $e = (e_x, e_y)$ is the light polarization unit vector, and $\eta_{e1}$ is the light absorbance in this spectral range.
In addition to the free-carrier absorption, the spin-dependent asymmetry of electron-phonon interaction can also give rise to a pure spin current in the process of photoelectron energy relaxation. In this relaxational mechanism the spin current is generated in a system of hot carriers, independently of heating means.

Besides the spin, free charge carriers can be characterized by another internal property, e.g., by the valley index in multi-valley semiconductors. Thus, one can consider pure orbit-valley currents in which case the net electric current vanishes but the partial currents contributed by carriers in the particular valleys are nonzero.

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