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Current-induced spin orientation in semiconductors and low-dimensional structures

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ABSTRACT

We present here a brief overview of current-induced spin polarization in bulk semiconductors and semiconductor structures of various dimension. The role of band structure and spin relaxation processes is discussed. The related phenomena, such as spin Hall effect, inverse spin Hall effect and other are discussed. Our recent results in this field are presented as well.

Spin-orbit coupling (SOC) is a relativistic effect that provides a link between spin and electric field (including the field of light wave). The SOC is the basis of modern concept of semiconductor spintronics. One can distinguish two main type of the spin orientation at current carrying through the sample: (i) spin Hall effect (SHE), which is the spatial separation of carriers with opposite spins and (ii) homogeneous in the sample polarization. This paper is focused mainly on effect of homogeneous current-induced spin polarization (CISP), however, the related phenomena such as SHE, inverse SHE and other are discussed as well. We will conduct presentation adhering to the chronology of events, which coincides with the transition from bulk semiconductors to low-dimensional ones.

SHE is due to so-called Mott-scattering [1], known in atomic physics, that is the asymmetry of the scattering relative to the plane determined by momentum and spin that in turn is due to SOC. In semiconductors the role of SOC increases and such an effect is several order of magnitude stronger. In 1971 Dyakonov and Perel predicted this phenomenon in semiconductors [2,3]. The name SHE was introduced later by Hirsch in 1999 [4] and the fist experimental observation of SHE was in Awschalom group [5] through more than 30 years after the prediction. The qualitative picture of SHE is depicted in Fig. 1a, where one can see, that the electrons with opposite spin orientation experience the scattering predominantly in opposite directions. This leads to accumulation of carriers with opposite spin projection at opposite sides of the sample at the length scales about spin diffusion length l_s.

The inverse SHE, i.e. the appearance of the dc current due to the nonhomogeneous spin polarization, was predicted by Averkiev and Dyakonov in 1983 [6] and detected by Bakun et al. [7] in the case, when inhomogeneous spin polarization appears due to spin diffusion after interband excitation under condition of optical orientation.

There are two main differences between CISP and SHE: (i) homogeneous vs non-homogeneous spin polarization; (ii) CISP takes place only in gyrotropic semiconductors, while SHE can be realized even in structure with inversion center.

Phenomenologically CISP is described by second rank pseudotensor $\hat{Q}$ linking the current density vector $\mathbf{j}$ and average spin pseudovector $\mathbf{S}$

$$S_i = \sum_k Q_{ik} j_k, \quad i, k = x, y, z. \tag{1}$$

From the symmetry point of view the gyrotropy means that the polar vector (current density) and axial vector (spin) transform under the same irreducible representation. Phenomenological description (1) shows that pseudotensor $\hat{Q}$ has non-zero component Q_{ik} only if S_i and j_k equally transform under all symmetry operations of the point group of structure. Thus, the relative orientation of spin $\mathbf{S}$ and current $\mathbf{j}$ is completely determined by the point group symmetry of the structure. The details of symmetry analysis for frequent two-dimensional (2D) structures one can find e.g. in Ref. [8].

In gyrotropic point symmetry groups there is no difference between components of polar vector (e.g. electric field or current) and axial vector (e.g. magnetic field or spin). The necessary requirement for gyrotropy is the lack of inversion center. However, there is misleading statement, that the gyrotropic crystals have no reflection planes. Nevertheless, this is too strict requirement, and among 21 classes without spatial inversion only 3 (T_d, C_{3h} and D_{3h}) are non-gyrotropic, and among the remaining 18 ones only 11 are chiral (have no reflection planes or rotation-reflection axes). The III-V-semiconductors with

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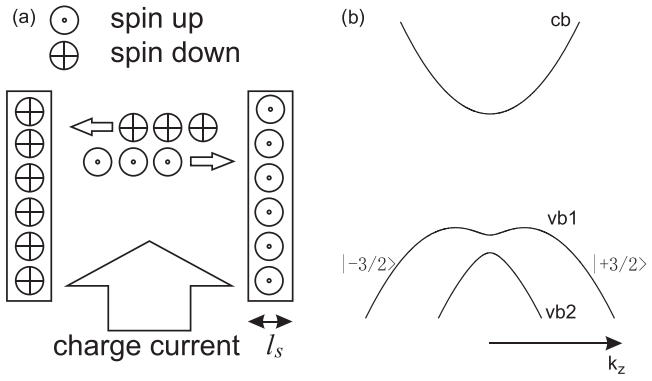

Fig. 1. (a) Schematic description of SHE (top view). The spins are accumulated in layers of width l_s close to sample edges. (b) The band structure of tellurium (schematically) near the H-point of Brillouin zone. The valence bands are non-degenerate in spin.

zinc-blende lattice possess T_d-symmetry and hence are non-gyrotropic, but any symmetry reduction such as strain or dimension lowering leads to CISP. The wurtzite semiconductors (point group C_{6v}) are initially gyrotropic.

For the first time, the possibility of CISP was proposed for bulk semiconductor tellurium [9]. In this case due to specific band structure (see Fig. 1b), caused by strong SOC, the electric current along trigonal axis leads to non-zero spin oriented in that direction. The effect was detected by means of additional rotation of polarization plane of the light [10].

The carriers acquire the energy in electric field and this process is counterbalanced by scattering, thus, electron distribution is shifted to the following magnitude of quasi-momentum

$$\hbar \mathbf{k}_{dr} = e\mathbf{E}\tau. \tag{2}$$

This anisotropy of carrier distribution leads to uncompensated average spin in non-degenerate in spin band such as tellurium valence band. Here $\mathbf{E}$ is the electric field and τ is the momentum relaxation time.

In 2D electron structures the CISP mechanism is sufficiently different from that in tellurium. The conduction band spin-splitting is determined in 2D-structures by the Hamiltonian

$$H = \frac{\hbar^2 k^2}{2\,m^*} + \sum_{ij} \beta_{ij}\sigma_i k_j, \tag{3}$$

where m^* is the effective mass, σ_i ($i = x, y, z$) are Pauli matrices, k_j ($j = x, y$) are the components of in-plane wave vector, and components of pseudotensor $\widehat{\beta}$ depend on structure symmetry. From the symmetry point of view the tensors $\widehat{\beta}$ and $\widehat{Q}$ in Eq. (1) are equivalent.

The first mention on possibility of CISP in 2D-structure due to Rashba spin-splitting [11] was in Ref. [12]. The consistent theory of CISP in 2D-structures was almost simultaneously proposed in Refs. [13,14]. In this connection CISP frequently referred in literature as the Edelstein effect. More complete theory for strained $A^{III}B^{V}$ semiconductors and 2D systems was developed in Ref. [15]. The microscopical calculation of CISP is usually based on the solution of quantum kinetic equation

$$\frac{\partial \rho}{\partial t} + \frac{i}{\hbar}[H_k^{so}, \rho] + \frac{e\mathbf{E}}{\hbar}\frac{\partial \rho}{\partial \mathbf{k}} = \mathrm{St}\rho, \tag{4}$$

where ρ is the density matrix, that is diagonal in subband or momentum index, $[A, B]$ stands for commutator, H_k^{so} is the Hamiltonian describing spin-orbit splitting of conduction band (subband), $\mathrm{St}\rho$ is the collision integral taking into account the processes of elastic scattering. This equation usually can be solved by iterations taking into account the weakness of spin-orbit splitting and electric field. It should be noted, that SOC has to be taken into account in collision integral in contrast to consideration of spin relaxation.

After [13–15] theoretical works extensively reported about CISP in 2D-structures with different symmetry and different types of SOC [16–20], such as structure inversion asymmetry (SIA) [11] due to asymmetry of quantum well (QW) and bulk inversion asymmetry (BIA) [21] that is due to lack of inversion center in semiconductor material [22].

The average spin per particle can be estimated as

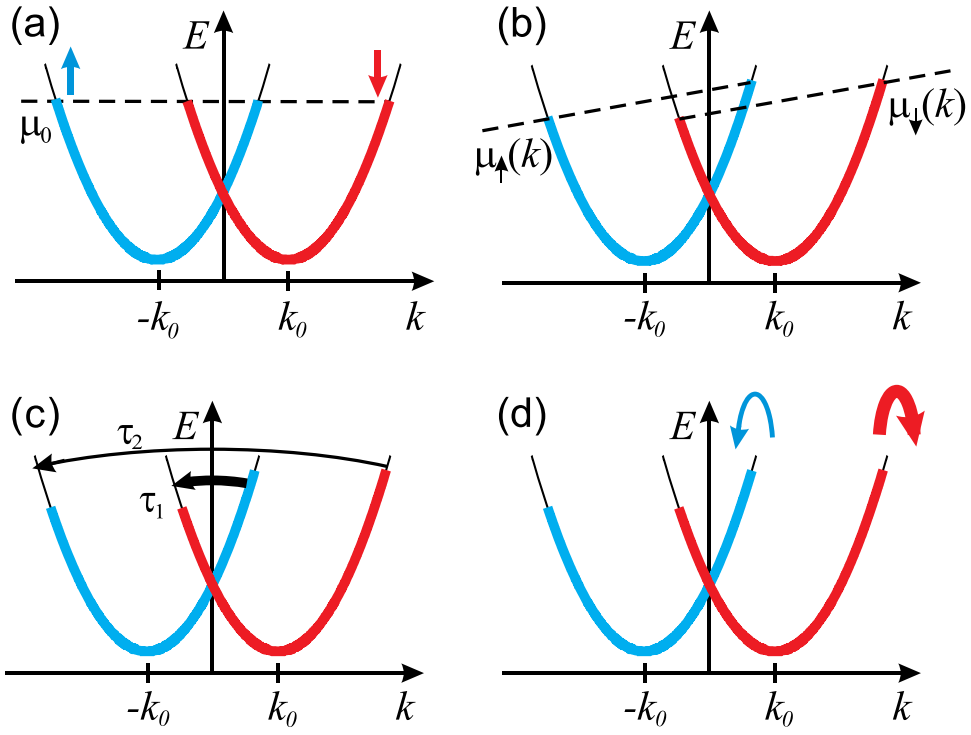

Fig. 2. Qualitative explanation of CISP emergence in 2D structures. Three ingredients are required for CISP in 2D: spin-orbit splitting (a); electric field, that alter quasi-equilibrium carrier distribution (b); spin relaxation, that can be both due to k-dependent relaxation time (c) and due to k-dependence of precession frequency in DP-mechanism of spin relaxation (d).