

Can an electric current orient spins in quantum wells?

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A longstanding theoretical prediction is the orientation of spins by an electrical current flowing through low-dimensional carrier systems of sufficiently low crystallographic symmetry. Here we show by means of terahertz transmission experiments through two-dimensional hole systems a growing spin orientation with an increasing current at room temperature.

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The manipulation of the spin degree of freedom in electrically conducting systems by electric and/or magnetic fields is at the heart of semiconductor spintronics [1]. Spin control in low-dimensional systems is particularly important for combining magnetic properties with the versatile electronic characteristics of semiconductor heterojunctions. The feasibility to orient the spin of charge carriers in GaAs based quantum wells by driving an electric current through the device was theoretically predicted more than two decades ago [2, 3, 4]. A direct experimental proof of this effect is missing so far.

In this Letter we demonstrate by means of terahertz transmission experiments that an electric current which flows through a low-dimensional electron or hole system leads to a stationary spin polarization of free charge carriers. Microscopically the effect is a consequence of spin-orbit coupling which lifts the spin-degeneracy in \mathbf{k} -space of charge carriers together with spin dependent relaxation.

In the simplest case the electron's (or hole's) kinetic energy in a quantum well oriented perpendicularly to the z -direction depends quadratically on the in-plane wave

vector components k_x and k_y . In equilibrium, the spin degenerated k_x and k_y states are symmetrically occupied up to the Fermi energy E_F . If an external electric field is applied, the charge carriers drift in the direction of the resulting force. The carriers are accelerated by the electric field and gain kinetic energy until they are scattered. A stationary state forms where the energy gain and the relaxation are balanced resulting in a non-symmetric distribution of carriers in \mathbf{k} -space. This situation is sketched in Fig. 1a for holes, a situation relevant for the experiments presented here. The holes acquire the average quasi-momentum

$$\langle \mathbf{k} \rangle = \frac{e\tau_p}{\hbar} \mathbf{E} = \frac{m^*}{e\hbar p} \mathbf{j}, \quad (1)$$

where \mathbf{E} is the electric field strength, τ_p the momentum relaxation time, \mathbf{j} the electric current density, m^* the effective mass, p the hole concentration and e the elementary charge. As long as spin-up and spin-down states are degenerated in \mathbf{k} -space the energy bands remain equally populated and a current is not accompanied by spin orientation. In QWs made of zinc-blende structure material like GaAs, however, the spin degeneracy is lifted due to lack of inversion symmetry and low-dimensional quantization [5, 6] and the resulting dispersion reads

$$\varepsilon = \frac{\hbar^2 \mathbf{k}^2}{2m^*} \pm \beta |\mathbf{k}| \quad (2)$$

with the spin-orbit coupling strength β . The corresponding dispersion is sketched in Fig. 1b. The parabolic energy band splits into two subbands of opposite spin direction shifted in \mathbf{k} -space symmetrically around $\mathbf{k} = 0$ with minima at $\pm k_0$. In the presence of an in-plane electric field the \mathbf{k} -space distribution of carriers gets shifted yielding an electric current. Due to the band splitting carrier relaxation becomes spin dependent. Relaxation processes including spin flips are different for the two subbands because the quasi-momentum transfer from initial to final states is different [7]. In Fig. 1b the \mathbf{k} -dependent spin-flip scattering processes are indicated by arrows of different lengths and thickness. As a consequence different num-

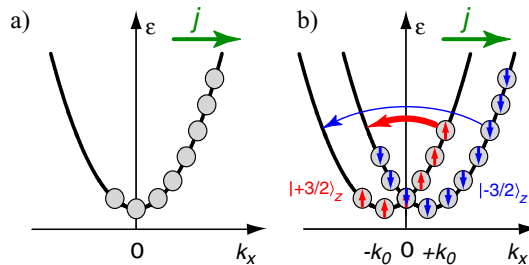


FIG. 1: Comparison of current flow in (a) spin-degenerate and (b) spin-split subbands. (a) Electron distribution at a stationary current flow due to acceleration in an electric field and momentum relaxation. (b) Spin polarization due to spin-flip scattering. Here only $\sigma_z k_x$ term are taken into account in the Hamiltonian which splits a valence subband into two parabolas with spin-up $(+3/2)_z$ and spin-down $(-3/2)_z$ in z -direction. Biasing along x -direction causes an asymmetric in \mathbf{k} -space occupation of both parabolas.

bers of spin-up and spin-down carriers contribute to the current causing a stationary spin orientation.

For the coupling constant β and the mechanism depicted in Fig. 1b we consider solely spin orbit coupling due to a Hamiltonian of the form $H_{SO} = \beta\sigma_z k_x$ with the Pauli matrix σ_z . This corresponds to a subband splitting for eigenstates with spins pointing in z -direction, normal to the quantum well plane and detectable in experiment. In our QWs of C_s symmetry the x -direction lies along $[1\bar{1}0]$ in the QW plane. For the moment we assume that the origin of the current induced spin orientation is, as sketched in Fig. 1b, exclusively due to scattering and hence dominated by the Elliot-Yafet spin relaxation time [7].

In order to observe current induced spin polarization we study transmission of terahertz radiation through devices containing multiple hole QWs. A spin polarization in z -direction affects, in principle, incoming linearly polarized radiation by two mechanisms: i) dichroic absorption and ii) Faraday rotation. The first mechanism is based on different absorption coefficients for left and right circularly polarized light while the Faraday rotation is due to different coefficients of refraction for left and right circularly polarized radiation. In experiment we used direct inter-subband transitions between the lowest heavy-hole and light-hole subbands of the valence band excited by linearly polarized terahertz radiation of a far-infrared laser. The linearly polarized light can be thought of being composed of two circularly polarized components of opposite helicity.

The resulting different absorption coefficients for left and right circularly polarized light changes the light's state of polarization. In particular, linearly polarized radiation gets elliptically polarized. The Faraday rotation, in contrast, becomes important for weak absorption and is proportional to the difference of the indices of refraction for left and right circularly polarized radiation. In this case only the phases of left and right circularly polarized light are shifted resulting in a rotation of the polarization axis of the incoming linearly polarized light. Without spin orientation in the lower subband, the absorption strength as well as the index of refraction for right- and left-handed polarized light are equal and transmitted light does not change its state of polarization. However, Faraday effect and dichroic absorption proof current induced spin polarization.

As material we have chosen p -type GaAs QWs of low symmetry having only - in addition to identity - one plane of mirror reflection (i.e. C_s point group according to Schönflies's notation). This was achieved by growing modulation doped QWs on (113)A- or miscut (001)-oriented GaAs substrates (tilt angle: 5° towards the $[110]$ direction) by molecular-beam-epitaxy (MBE) or metal-organic-chemical-vapor-deposition (MOCVD), respectively. Two types of samples were prepared. Sample A: (113)A with QW of width $L_W = 10$ nm, and a free

carrier density of $p \approx 2 \cdot 10^{11}$ cm $^{-2}$ and sample B: miscut (001) with $L_W = 20$ nm and $p \approx 2 \cdot 10^{11}$ cm $^{-2}$. To cope with the small absorption signal and/or rotation angle of an individual quantum well we fabricated multiple QW structures. Sample A contained $N = 100$ and sample B $N = 400$ QWs, respectively. The sample edges were oriented along $[1\bar{1}0]$ in the QW plane (x -direction) and perpendicular to this direction (y -direction). Two pairs of ohmic contacts were centered along opposite sample edges of 5 mm width. In addition samples containing 100 QWs and having very thin barriers were taken as quasi-bulk reference samples.

A spin polarization is not expected for all current directions. For materials of low symmetry, used here, only an electric current along $x \parallel [1\bar{1}0]$ -direction is expected to align spins; in contrast, current flowing in y -direction does not yield a spin orientation. By symmetry arguments it is straightforward to show that a current j_x , in the plane of the QW yields an average spin polarization S_z normal to the QW according to

$$S_z = R_{zx}j_x \quad (3)$$

where \mathbf{R} is a second rank pseudo-tensor [11]. However, for a current flowing along y -direction, $S_z=0$ holds since, due to symmetry, $R_{zy}=0$. Thus we expect to observe a spin polarization for current flow in one but not in the other (perpendicular) direction. Below we denote these directions as active and passive, respectively.

The transmission measurements using linearly polarized 118 μm radiation of an optically pumped cw far-infrared laser were carried out at room temperature. The electric current (0 to 180 mA) was applied as 10 μs long pulses with a repetition rate of 20 kHz. The schematic experimental set up is shown in Fig. 2a: the sample was placed between two metallic grid polarizers and the cw terahertz radiation was passed through this optical arrangement (see Fig. 2a). The transmitted radiation was detected using a highly sensitive Ge:Ga extrinsic photodetector operated at 4.2 K.

In order to detect a current dependent change of the polarization of the transmitted light we used a crossed polarizer set-up. The crossed polarizers are expected to let pass only light whose state of polarization was changed by the current through the sample. The experimental result of the transmission, which is proportional to the photodetector signal, is shown in Fig. 2b as function of the current strength, I , for both passive and active directions. Although the signal in the active direction is by a factor 2-3 higher than for the passive one, the transmission signal increases in both cases with I . As will be pointed out below the observed transmission for the 'passive' case is a polarization independent background signal while the difference of transmission between the 'active' and the 'passive' traces is the sought-after polarization dependent transmission signal proofing current induced spin polarization in QWs.

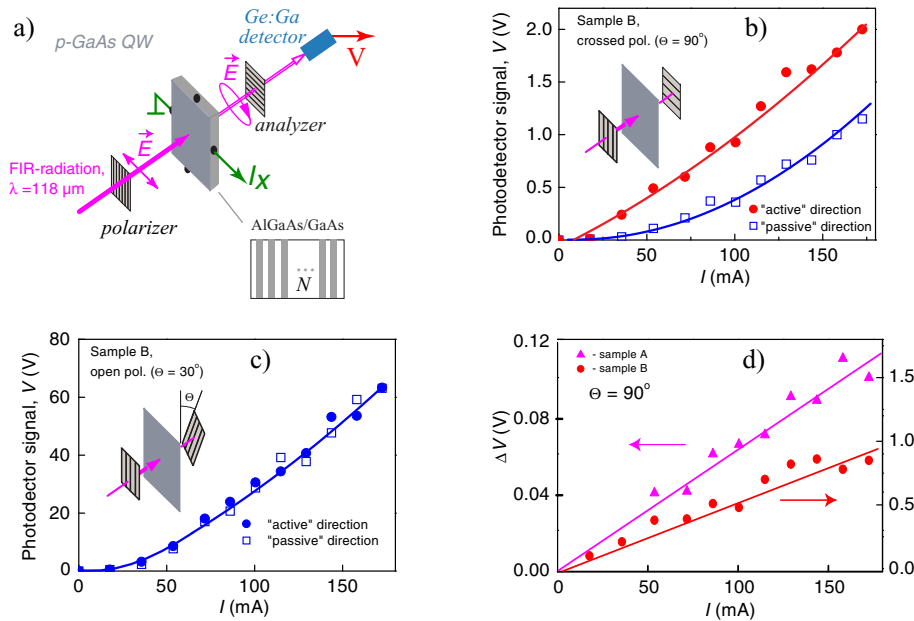


FIG. 2: (a) Experimental set-up. The sample is placed between crossed polarizer and analyzer blocking optical transmission at zero current through the sample. Injecting a modulated current in the sample yields a signal at the detector which is recorded by box-car technique. (b) and (c) Detector signal as a function of the current in the active (full symbols) and the passive (open symbols) directions for sample B and two states of the analyzer: (b) crossed polarizers ($\Theta = 90^\circ$) and (c) partially open polarizers ($\Theta = 30^\circ$). (d) Differences ΔV between the signal at current in active and passive direction as a function of current for two samples, A (triangles, left axis) and B (circles, right axis) for crossed polarizers.

To ensure that the signal for current flow in the active direction is indeed due to spin orientation we carried out two additional experiments. First we tested the quality of our polarizers. As result we obtained even for crossed polarizers ($\Theta = 90^\circ$) that a small fraction $\alpha_{90^\circ} = 5.4 \cdot 10^{-3}$ of the radiation is still transmitted though we used far-infrared polarizers of highest available quality. The signal increasing with increasing current along the passive direction is ascribed to carrier heating by the current. By this process the subband hole distribution is changed and the transmission increases with increasing current [9]. The heating induced enhanced transmission with increasing current together with the finite transmission through crossed polarizers explains the nonlinear increase of the transmission signal for current in the passive direction (see Fig. 2b). The signal for the active direction, also displayed in Fig. 2b, is markedly higher for crossed polarizers. In a second experiment the analyzer is rotated away from 90° and the signals for passive and active direction become equal, documented in Fig. 2c. This is due to the fact that the heating induced signal increases drastically for open polarizers whereas the signal induced by the polarization change varies only slightly. The heating induced signal dominates for open polarizers, whereas the polarization and the heating induced signals, are comparable for crossed polarizers. The purely spin polarization induced signal can be consequently extracted from the transmission difference of active and passive directions

for crossed polarizers.

The difference signals for sample A and B are shown in Fig. 2d. The difference signal, reflecting the build up of spin polarization with increasing current, increases almost linearly. Control experiments on the quasi-bulk sample give – in accordance with theory which forbids current induced spin orientation for T_d point group symmetry – the same signal for passive and active directions.

While the experiment displays clear spin polarization due to the driving current, it is not straightforward to determine the value of spin polarization. Due to lack of compensators for the far infrared regime it is difficult to judge whether the transmitted signal is linearly (Faraday effect) or elliptically polarized (dichroic absorption). In case of dominating dichroic absorption the average spin polarization of a quantum well is given by [10]

$$\langle S \rangle = \Delta p/p = 8\sqrt{\alpha_{90^\circ} \Delta V/V^{(p)}/K_0} . \quad (4)$$

Here, Δp is the difference of spin-up and spin-down hole densities, ΔV is the spin induced photosignal plotted in Fig. 2d, and $V^{(p)}$ is the photodetector signal obtained for a current in the passive current direction, plotted for sample B in Fig. 2b. The absorption K_0 , which determines the ratio of incoming (I_0) and transmitted (I_T) intensity through the multi-QW structure, $I_0/I_T = \exp(-K_0)$, is obtained from an independent transmission experiment, carried out on unbiased devices. For sample A we obtained $K_0 = 2.7$, for sample B, $K_0 = 3.4$. The would re-

sult in spin polarization of 0.12 for sample A and 0.15 for sample B at current densities 3 mA/cm and 0.75 mA/cm per QW, respectively. If the increased signal, however, is due to Faraday rotation a different analysis has to be applied. The angle of Faraday rotation can be determined by rotating the analyzer for current along the passive direction until the signal becomes equal to the signal obtained for the current in active direction for crossed polarizers. We obtain a rotation angle φ of 0.4 mrad per quantum well for sample A and 0.15 mrad for sample B. In case of dominating Faraday effect, however, no straightforward way to extract the value of the spin polarization from the Faraday rotation angle is at hand.

According to the theory of Aronov et al. [2] current should yield a spin polarization on the order of $\langle S \rangle \approx \beta \cdot \langle k \rangle / k_B T$. Using Eq. 1 we estimate this value as

$$\langle S \rangle = \frac{Q\beta}{k_B T} \cdot \frac{m^*}{e\hbar p} j, \quad (5)$$

where $Q \simeq 1$ is a constant determined by momentum scattering and the spin relaxation mechanism [11]. For a situation where Fermi statistic applies the factor $k_B T$ needs to be replaced by $2E_F/3$. Calculating $\langle S \rangle$ from Eq. 5 with the experimental parameters $p = 2 \cdot 10^{11} \text{ cm}^{-2}$, $m^* = 0.2m_0$ and spin splitting constant $\beta = 5 \text{ meV}\cdot\text{nm}$ [12, 13], we obtain an average spin polarization of $3.2 \cdot 10^{-4}$ and $0.8 \cdot 10^{-4}$ for the experimentally relevant current densities. Since the values obtained from an analysis of our data under the assumption of dominating dichroic absorption is by a factor of more than 1000 higher than expected we assume that Faraday rotation and not dichroic absorption dominates the change of polarization of the transmitted light. Also the fact that the spin orientation induced signal increases linearly with current (see Fig. 2d) and not quadratically, as expected from dichroic mechanism (see Eqs. (??)), points to the Faraday rotation as the dominating mechanism proofing current induced spin orientation.

So far we assumed that the subband spin splitting occurs for spin eigenstates pointing normal to the QW. However, if the hole subbands are also split due to a spin-orbit coupling $\propto \sigma_x k_y$ in the Hamiltonian an additional mechanism of spin orientation, the precessional mechanism [2, 11], needs to be taken into account. The difference in the spin relaxation rates for spin-up and spin-down subbands are now determined by the D'yakonov-Perel spin relaxation process. In this case the relaxation rate depends on the average \mathbf{k} -vector [6], equal to $\bar{k}_{3/2} = -k_0 + \langle k \rangle$ for the spin-up and $\bar{k}_{-3/2} = k_0 + \langle k \rangle$ for the spin-down subband. Hence also for the D'yakonov-Perel spin relaxation mechanism a current through the hole gas causes spin orientation. If this type of spin-orbit interaction is present, the magnitude of spin orientation is also given by Eq. 5, only the constant Q is different but also of order 1 [11].

Finally, we discuss our results in the light of related

experiments. Based on theoretical predictions made by Ivchenko and Pikus [14], Vorob'ev et al. observed a current induced spin polarization in bulk tellurium [15]. This is a consequence of the unique band structure of tellurium with hybridized spin-up and spin-down bands and is, other than in our experiment, not related to spin relaxation. More recently for spin injection from a ferromagnetic film into a two-dimensional electron gas Hammar et al. used the above concept of a spin orientation by current in a 2DEG [16] (see also [17, 18]) to interpret their results. Though a larger degree of spin polarization was extracted the experiment's interpretation is complicated by other effects [19, 20]. We would also like to note that Kalevich and Korenev [21] reported an influence of an electric current on the spin polarization achieved by optical orientation. The current does not align spins, but the effective magnetic field due to the current causes a spin depolarization like the Hanle effect in an external magnetic field. While preparing the manuscript we became aware of experimental results obtained on strained InGaAs bulk material [22]. Analyzing Faraday rotation the authors of this preprint also report on the build up of a spin polarization under current bias, however, in three dimensional system.

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