Polaritonic analogue of Datta and Das spin transistor

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We propose the scheme of a novel spin-optronic device, optical analog of Datta and Das spin transistor for the electrons. The role of the ferromagnetic–nonmagnetic contact is played by a spatially confined cavity polariton BEC. The condensate is responsible for the appearance of effective magnetic field which rotates the spin state of a propagating pulse of polaritons allowing to tune the transmittivity of the device.

Spintronics is one of the trends in modern mesoscopic physics [1]. It was born in 1990, when S. Datta and B. Das in their pioneer work proposed a theoretical scheme of the first spintronic device [2], which afterwards was named Datta and Das spin transistor. It consists of two ferromagnetic 1D or 2D electrodes, usually with collinear magnetizations, separated by a non-magnetic semiconductor region in which a Spin-Orbit Interaction (SOI) of the Rashba type is induced by a top gate electrode,

\[ \hat{H}_{SOI} = \alpha \left( \mathbf{k} \times \sigma \right) \cdot \mathbf{e}_z, \quad (1) \]

where \( \mathbf{e}_z \) is a unity vector in the direction of the structure growth axis \( z \), \( \sigma \) denotes a set of Pauli matrices, \( \mathbf{k} = -i \nabla \). \( \alpha \) is a characteristic Rashba parameter, which depends on the degree of asymmetry of a quantum well (QW) in the \( z \) direction. It can be efficiently tuned by varying the top gate voltage \( V_g \). The Hamiltonian can be interpreted in terms of an effective magnetic field lying in the plane of a QW and being perpendicular to the carriers’ kinetic momentum. This effective field provokes the rotation of the spin of the carriers in the semiconductor region and results in the oscillations of the transmitted current \( I_{tr} \) as a function of Rashba coupling controlled by the gate voltage \( V_g \) : \( I_{tr} \sim \cos^2 \left( 2m_{eff} \alpha L / \hbar^2 \right) \), where \( m_{eff} \) is the carrier effective mass in the semiconductor.

On the other hand, it was recently proposed that in the domain of mesoscopic optics the controllable manipulation of the (pseudo)spin of excitons and exciton-polaritons (polaritons) can provide a basis for the construction of optoelectronic devices of the new generation, called spin-optronic devices, that would be the optical analogs of spintronic devices. The first element of this type, namely polarisation-controlled optical gate, was recently realised experimentally [9], and the principal schemes of other devices such as Berry phase interferometer [10], have been proposed theoretically. It has also been demonstrated by several experimental groups that equilibrium polariton Bose Einstein condensation (BEC) can be achieved [11, 12, 13, 14, 15]. Also the spatial modulation of the polariton wavefunction and polariton condensates is now well controlled experimentally [10], offering extremely wide perspectives for the implementation of polaritons circuits.

Polaritons are the elementary excitations of semiconductor microcavities in the strong coupling regime. An important peculiarity of the polariton system is its spin structure: being formed by bright heavy-hole excitons, the lowest energy polariton state has two allowed spin projections on the structure growth axis (±1), corresponding to the right and left circular polarisations of the counterpart photons. The states having other spin projections are split-off in energy and normally can be neglected while considering polariton dynamics. Thus, from the formal point of view, the spin structure of cavity polaritons is similar to the spin structure of electrons (both are two-level systems), and their theoretical description can be carried out along similar lines. The possibility to control the spin of cavity polaritons opens a way to control the polarisation of the light emitted by a cavity, which can be of importance in various technological implementations including optical information transfer.

It should be noted, however, that the fundamental nature of elementary excitations is different in two kinds of systems: electrons and holes (i.e. fermions) in the case of spintronics, polaritons (i.e. bosons) in the case of spin-optronics. Also, it appears that the account of
many-body interactions is of far greater importance for spinoptonic devices with respect to the spintronic ones. The polariton-polariton interactions in microcavities are strongly spin-anisotropic: the interaction of polaritons in the triplet configuration (parallel spin projections on the structure growth axis) is much stronger than that of polaritons in the singlet configuration (antiparallel spin projections) [20]. This leads to a mixing of linearly polarised polariton states which manifests itself in remarkable nonlinear effects, which are of great importance for the functioning of spinoptonic devices in nonlinear regime.

As shown in [10], the analogue of Rashba SOI in microcavities can be provided by the longitudinal-transverse splitting (TE-TM splitting) of the polariton mode. However, the TE-TM splitting cannot be easily tuned by the simple application of a voltage, unlike the Rashba SOI. In ring interferometers the control of the polariton Berry phase which governs the interference pattern therefore requires to modulate an external magnetic field, which is expected to be relatively slow. In the present paper we propose a completely new and tunable way to realise an optical ferromagnetic-nonmagnetic contact, which will finally allow to design a nano-device, optical analogue of the Datta and Das spin transistor.

We propose to use the change of the polarisation eigenstates induced by the formation of polariton BEC in the presence of magnetic field as the analogue of the Rashba field. In that case the modulation of the signal will be driven not by the modulation of the magnetic field, but by the modulation of the condensate density, which can be achieved either by the modulation of a pumping laser intensity, or by the modulation of a voltage in case of electrically pumped condensate [21, 22, 23]. The device is constituted by a planar microcavity showing a confining potential having the shape of a stripe of width L as shown on the upper panel of the Fig. (1).

We divide the system into three regions: (1) \( x < 0 \), (2) \( 0 < x < L \) and (3) \( x > L \). We assume that critical conditions for the formation of a quasi-equilibrium BEC of polaritons are fulfilled as demonstrated experimentally by several independent groups [11, 12, 14, 15]. We also assume that the chemical potential \( \mu \) stands below the edge of the barriers, so that the condensate is confined in the central region and absent in the flanking regions. We consider the effect of an external magnetic field \( B \) applied perpendicularly to the structure interface. In the lateral regions 1 and 3, the normal Zeeman splitting \( E_z \) between the polariton modes occurs as shown in the lower panel of the Fig. 1. This opens an energy gap \( E < E_z = \mu g B \) where only one of the two circularly polarised component can propagate. We assume here and in the following that the Zeeman splitting is much larger than the TE-TM splitting which can therefore be neglected. In the central region, however, the presence of the condensate leads to the full paramagnetic screening, also known as spin-Meissner effect [24]. For a given field \( B \), the critical density \( n_c \) in the polariton condensate can be defined as \( n_c = \mu g B / \alpha_1 - \alpha_2 \), where \( \alpha_1(2) \) are the interaction constants for particles with the same (perpendicular) spin projection, \( g \) is the exciton g-factor and \( \mu_b \) is the Bohr magneton. Below this critical density \( n_c \), the spin anisotropy of the polariton-polariton interactions leads to a full paramagnetic screening of the Zeeman splitting \( E_Z \) resulting in a quenching of the Zeeman gap, as shown in the lower part of the Fig. 1. The polariton condensate is elliptically polarised, which is also the case for the propagative modes in the central region. The polarisation degree of these modes depends on the condensate density. Therefore a circularly polarised \( \sigma_+ \) pulse with an energy located within the Zeeman gap of the lateral regions can enter into the central region. During its propagation in this region its polarisation vector will be rotated by an effective magnetic field whose direction is associated with the polarisation of the eigenstates in this region. This effective "spin-Meissner field" has some in-plane component and plays the role of the Rashba SOI effective field. The intensity of the outgoing current depends on the angle \( \Delta \phi \) between the pseudospin vector of the polaritons reaching the outgoing lead. If the precession is such that the pulse becomes fully \( \sigma_- \) polarised on the interface between 2 and 3, the pulse will be fully reflected. If the pulse is fully \( \sigma_+ \) polarised, it will be fully transmitted. Working in this energy range means that for polaritons we create a situation analogous to ferromagnetic-nonmagnetic-ferromagnetic interface, which one needs for a creation of the Datta and Das device.
Such a configuration has a number of possible advantages with respect to classical spintronics: the dramatic impact of carrier spin relaxation or decoherence, which has severely limited the achievement or the functionality of any semiconductor-based spintronic devices, is strongly reduced [23]. Besides, the solution of the spin injection problem is now trivial: it is performed simply by choosing an appropriate polarisation of the exciting laser.

Quantitatively, the outgoing amplitude can be calculated by solving a system of linear equations. The wavefunction of a propagating mode in the three regions can be written in the following way:

\[
\Psi_1 = (e^{ikx} + re^{ikx}) \begin{pmatrix} 1 \\ 0 \end{pmatrix} + Ae^{\gamma x} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad (2)
\]

\[
\Psi_2 = (C_1^+ e^{ik_1x} + C_1^- e^{-ik_1x}) \begin{pmatrix} \cos \beta \\ \sin \beta \end{pmatrix} + C_2^+ e^{ik_2x} + C_2^- e^{-ik_2x} \begin{pmatrix} -\sin \beta \\ \cos \beta \end{pmatrix}, \quad (3)
\]

\[
\Psi_3 = (te^{ikx}) \begin{pmatrix} 1 \\ 0 \end{pmatrix} + De^{-\gamma x} \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \quad (4)
\]

where \( r \) is the amplitude of reflectivity, \( t \) is transmission amplitude, \( C_{1,2}^{+(-)} \) are the complex amplitudes of forward (backward) running waves in the trap with different polarisations and wavevectors \( k_1 \) and \( k_2 \). The wavevectors are determined by the dispersion relations for each region Ref.[24], which read:

\[
k = \sqrt{\frac{2m}{\hbar^2} E, \gamma = \sqrt{\frac{2m}{\hbar^2} (E_z - E)}}
\]

\[
k_{1,2} = \sqrt{\frac{n_2}{m} (\frac{\hbar^2}{n_2} U_{1,2} + 4(E - \mu)^2 + n_2^2 U_{1,2})}
\]

\[
U_{1,2} = \alpha_1 \pm \sqrt{\alpha_1^2 + (\alpha_2^2 - \alpha_2^2) (B/BC)^2}
\]

The polarisation of the excitations in the regions 1 and 3 is \( \sigma_+ \) and \( \sigma_- \). The polarisation of the elementary excitations of the condensate in the spin-Meissner phase (region 2) has never been calculated. It can be found by the standard method of linearisation with respect to the amplitude of the elementary excitations of the condensate, which gives the following result:

\[
\tan \beta = \frac{-\alpha_1 \cos 2\Theta + \sqrt{\alpha_1^2 \cos^2 2\Theta + \alpha_2^2 \sin^2 2\Theta}}{\alpha_2 \sin 2\Theta}, \quad (5)
\]

where \( \Theta = \frac{1}{2} \arcsin \sqrt{1 - (B/BC)^2} \).

Interestingly, the polarisation of the excitations, associated with the angle \( \Theta \), is different from the one of the condensate, associated with the angle \( \beta \). The precession frequency in the spin-Meissner effective field directed along \( (\cos \beta, \sin \beta) \), can be estimated as

\[
\Omega_t = \frac{E k_1^2 - k_2^2}{2\hbar k_1 k_2}. \quad (6)
\]

To find the amplitude of the outgoing fringe one has different possibilities. Using an analytical approach similar to the transfer matrix method, one obtains for the reflected \( r \) and transmitted \( t \) amplitudes:

\[
t = e^{ik_1 L} \cos^2 \beta + e^{ik_2 L} \sin^2 \beta + \frac{[\cos \beta \sin \beta (e^{ik_1 L} - e^{ik_2 L})]^2 [\sin^2 \beta e^{ik_1 L} + \cos^2 \beta e^{ik_2 L}]}{1 - [\sin^2 \beta e^{ik_1 L} + \cos^2 \beta e^{ik_2 L}]^2}
\]

\[
r = \frac{[e^{ik_1 L} - e^{ik_2 L}] \cos \beta \sin \beta}{1 - [\sin^2 \beta e^{ik_1 L} + \cos^2 \beta e^{ik_2 L}]^2}.
\]

In this analytical approach, the \( \sigma_- \) polarised part is assumed to be fully reflected and does not have decaying tails outside the central region. A more exact approach is to use the wavefunctions (Eqs. (2)-(4)) without this approximation, applying corresponding boundary conditions, which ensure the continuity of the wavefunction and current conservation at the interfaces. Fig 2 shows the dependence of the transmission coefficient \( T = |t|^2 \) and reflection coefficient \( R = |r|^2 \) on the excitation energy \( E \) (a) and on the chemichal potential of the condensate \( \mu \) (b). The polarisation of the particles is rotated during the propagation in region 2 with elliptically polarised excited states. The calculation is performed taking into account realistic parameters of a GaAs microcavity (listed in the figure caption). Varying the energy of the injected particles, which can be done by changing the excitation angle of the resonant laser, increases or decreases the value of the spin-Meissner effective field affecting the particle propagation in the central region. Another way to modulate the outgoing beam keeping the particle energy constant (close to the resonances on Fig 2(a)), is to change the particle concentration (and thus the chemical potential \( \mu \) ) in region 2. This can be
simply realised by the modulation of the optical or electrical pumping of the condensate. The impact of the particle concentration is shown in Fig. 2(b). Close to the resonances, the outgoing beam drops from full transmission to zero transmission for a very weak change of particle concentration almost without reflection.

FIG. 3: Calculated propagation of a wavepacket through the spin transistor: (a) wavepacket created by a laser pulse; (b) wavepacket reflected by the condensate; (c) wavepacket transmitted through the trap with the condensate. Panels (b,c) show the system after the wavepacket has interacted with the condensate: in (b) the packet is mostly reflected, whereas in (c) a larger part passes through. The two latter panels correspond to two different regimes of the spin transistor operation depending on the condensate density: closed (b) and open (c). The broadening of the wavepacket is due to the interaction with the condensate; however this relatively small broadening should not be detrimental for the device.

In conclusion, we proposed a scheme of a polaritonic analogue of Datta and Das spin transistor. The proposed geometry allows to solve the problems of decoherence and inefficient spin injection which were blocking the experimental implementation of Datta and Das spin transistor for electrons. The requirement of abrupt interfaces seems also easier to achieve for polaritons which are more extended particles than electrons. The role of the non-magnetic region is played by a confined spinor polariton BEC. The polariton BEC provokes the appearance of an effective "spin-Meissner" magnetic field which is acting along the pseudospin of the propagating polaritons. This field and therefore the device transmissivity is easily and quickly controlled tuning the condensate density which in an ideal case can be done changing an applied voltage.

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[26] See EPAPS Document No. for movies of the pulse propagation through the transistor in reflection and transmission mode.