Polaritonic analogue of Datta and Das spin transistor

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We propose the scheme of a 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 Bose-Einstein condensate. The condensate is responsible for the appearance of effective magnetic field which rotates the spin state of a propagating pulse of polaritons, allowing tuning the transmittivity of the device.

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I. INTRODUCTION

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 one-dimensional or two-dimensional electrodes, usually with collinear magnetizations, separated by a nonmagnetic semiconductor region in which a spin-orbit interaction (SOI) of the Rashba type is induced by a top gate electrode,

$$\hat{H}_{SOI} = \alpha[\hat{\mathbf{k}} \times \sigma] \cdot \mathbf{e}_z, \tag{1}$$

where $\mathbf{e}_z$ is a unity vector in the direction of the structure growth axis z, σ denotes a set of Pauli matrices, $\hat{\mathbf{k}} = -i\nabla$, and α 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.[3–5] 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: $I_{tr} \sim \cos^2(2m_{\rm eff}\alpha L/\hbar^2)$, where $m_{\rm eff}$ is the carrier effective mass in the semiconductor. The above formula has a very clear physical meaning: only the spin component parallel to the magnetization can propagate in the outgoing ferromagnetic lead. The outgoing current should be thus dependent on the rotation angle accumulated over a distance L between the two leads, $\Delta\phi = 2m_{\rm eff}\alpha L/\hbar^2$.

Although the scheme of the Datta and Das spin transistor seems very simple from a theoretical point of view, its practical implementation appears to be extremely complicated due to the problems of spin injection, decoherence, and realization of an abrupt enough ferromagnetic-nonmagnetic junction. These difficulties led to alternative propositions of spintronic devices which do not need spin injection.[6,7] More than 15 years of intensive experimental work in this direction did not result in any breakthrough and the Datta and Das device still remains a theoretical concept.[8]

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 polarization-controlled optical gate, was recently realized 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.[11–15] In Ref. 15 polariton lifetimes about 30 ps have been reported. This lifetime is long enough to allow the realization of extended condensates close to thermal equilibrium. Also the spatial modulation of the polariton wave function and polariton condensates is now well controlled experimentally,[16–19] 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 polarizations 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 polarization 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 spinoptronic 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 polarized polariton states which manifests itself in remarkable nonlinear effects, which are of great importance for the functioning of spinoptronic devices in nonlinear regime.

As shown in Ref. 10, the analog 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 tunable way to realize an optical ferromagnetic-nonmagnetic contact, which will finally allow designing a nanodevice, optical analog of the Datta and Das spin transistor.

In the following section we describe the principle working scheme of the proposed device. Section III presents an analytical and a numerical calculation of the reflection and transmission coefficients and Sec. IV presents the results of a realistic Gross-Pitaevskii simulation. A summary and conclusions are given in the last section.

II. WORKING SCHEME

We propose to use the change of the polarization eigenstates induced by the formation of polariton BEC in the presence of magnetic field as the analog 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.[21–23] 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 quasiequilibrium BEC of polaritons are fulfilled as demonstrated experimentally by several independent groups.[11,12,14,15] We also assume that the chemical potential μ 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 Fig. 1. This opens an energy gap $E<E_z=\mu_b g B$ where only one of the two circularly polarized components 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

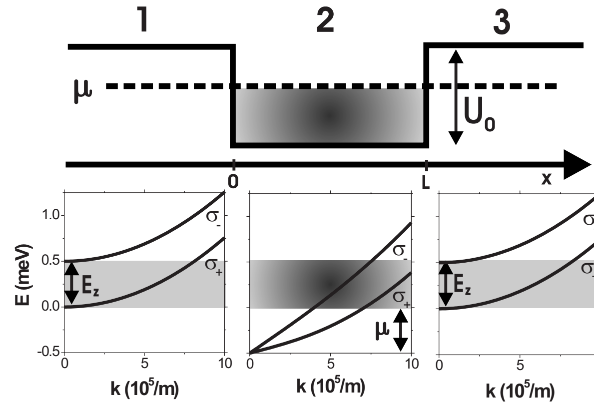

FIG. 1. Schematic illustration of a polariton spin transistor (upper panel) with the corresponding renormalized polariton dispersions for the two circular polarizations (lower panel). The regions are indicated with 1 ($x<0$), 2 ($0<x<L$), and 3 ($x>L$). Dark gray corresponds to σ_- and light gray for σ_+ polarization. In region 2 the mixing of both circular polarizations results in an elliptical polarized condensate, while in flanking regions only the σ_+ component can propagate.

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 $n_c=\mu_b g B/(\alpha_1-\alpha_2)$, where $\alpha_{1(2)}$ are the interaction constants for particles with the same (opposite) spin projection, g is the exciton g-factor, and μ_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 Fig. 1. The polariton condensate is elliptically polarized, which is also the case for the propagative modes in the central region. The polarization degree of these modes depends on the condensate density. Therefore a circularly polarized σ_+ 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 polarization vector will be rotated by an effective magnetic field whose direction is associated with the polarization 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 $\Delta\phi$ characterizing the pseudospin vector of the polaritons reaching the outgoing lead. If the precession is such that the pulse becomes fully σ_- polarized on the interface between 2 and 3, the pulse will be fully reflected. If the pulse is fully σ_+ polarized, it will be fully transmitted. Working in this energy range means that for polaritons we create a situation analogical 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.[25] Besides, the solution of the spin injection problem is now trivial: it is performed simply by choosing an appropriate polarization of the exciting laser.

III. TRANSMISSION AND REFLECTION COEFFICIENT

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

$$\Psi_1 = (e^{ikx} + re^{-ikx})\begin{pmatrix}1\\0\end{pmatrix} + Ae^{\gamma x}\begin{pmatrix}0\\1\end{pmatrix}, \tag{2}$$

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

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

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

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

$$k_{1,2} = \sqrt{\frac{m}{\hbar^2}\left(-n_2U_{1,2} + \sqrt{4(E-\mu)^2 + n_2^2U_{1,2}^2}\right)},$$

$$U_{1,2} = \alpha_1 \pm \sqrt{\alpha_2^2 + (\alpha_1^2 - \alpha_2^2)(B/B_C)^2}.$$

The polarizations of the excitations in the regions 1 and 3 are σ_+ and σ_-. The polarization 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 linearization with respect to the amplitude of the elementary excitations of the condensate, which gives the following result:

$$\tan\beta = \frac{-\alpha_1\cos 2\Theta + \sqrt{\alpha_1^2\cos^2 2\Theta + \alpha_2^2\sin^2 2\Theta}}{\alpha_2\sin 2\Theta}, \tag{5}$$

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

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

$$\Omega_t = \frac{E}{2\hbar}\frac{k_1^2 - k_2^2}{k_1k_2}. \tag{6}$$

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

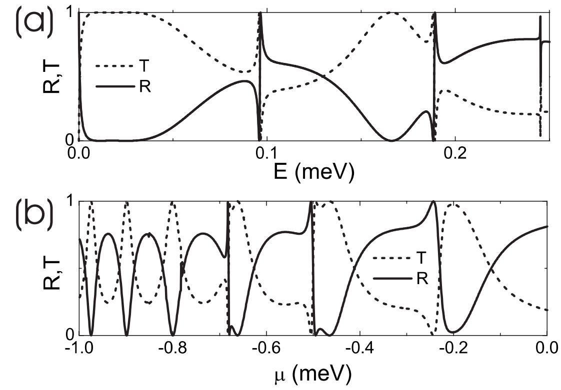

FIG. 2. Reflection and transmission coefficient versus energy of the probe pulse excitation energy: (a) Dependence of T (dashed line) and reflection coefficient R (solid line) on the excitation energy E (μ=−0.7 meV) and (b) T and R versus chemical potential μ (E=0.2 meV). The used parameters are: B=5 T, E_Z=0.25 meV, L=20 μm, and U_0=−1 meV.

$$t = e^{ik_1L}\cos^2\beta + e^{ik_2L}\sin^2\beta + \frac{[\cos\beta\sin\beta(e^{ik_1L} - e^{ik_2L})]^2[\sin^2\beta e^{ik_1L} + \cos^2\beta e^{ik_2L}]}{1 - [\sin^2\beta e^{ik_1L} + \cos^2\beta e^{ik_2L}]^2},$$

$$r = \frac{([e^{ik_1L} - e^{ik_2L}]\cos\beta\sin\beta)^2}{1 - [\sin^2\beta e^{ik_1L} + \cos^2\beta e^{ik_2L}]^2}. \tag{7}$$

In this analytical approach, the σ_- polarized 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 wave functions [Eqs. (2)–(4)] without this approximation, applying corresponding boundary conditions, which ensure the continuity of the wave function and current conservation at the interfaces.

Figure 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 chemical potential of the condensate μ (b). The polarization of the particles is rotated during the propagation in region 2 with elliptically polarized 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 μ) in region 2. This can be simply realized 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 μ. This gives a possibility to tune rapidly the outgoing current of the proposed device simply by changing one external parameter.

Of course the outgoing intensity can also be modulated by the magnetic field, but the change of the magnetic field intensity is rather slow in comparison to intensity modulation of a pumping laser or to modulation of the applied voltage (in case of electrical pumping). From the point of view of experimental realization, increasing the magnetic field enlarges the Zeeman splitting and the energy range where only one polarization component can propagate outside the condensate. Thus, on one hand, it should be preferable to apply a huge magnetic field in order to increase the operating energy range. On the other hand, high magnetic fields complicate the practical applications.

IV. GROSS-PITAEVSKII SIMULATION

We have also performed a realistic numerical simulation of the device operation. We have first calculated the wave function of the condensate in the trap region by minimizing the free energy of the system on a grid, taking into account the two polarization components and the interactions between them. All the parameters are taken the same as in Fig. 2.

We have then simulated the propagation of a circularly polarized pulse through the system with the spinor Gross-Pitaevskii equation for polaritons using the wave function of the condensate found previously. The main difference with the analytical model presented above is the spatial profile of the wave function of the condensate; this difference becomes negligible at larger densities, when the interaction energy is much higher than the kinetic one and the wave function achieves the Thomas-Fermi profile. Another difference is that we study the propagation of a pulse, more important from the practical point of view, instead of solving a steady-state problem.

Figure 3 shows the snapshots of the pulse propagation through the device. Full movies are available in the auxiliary material.[26] Only the wave function of the pulse is shown, without the condensate located in the trap shown by the rectangle. Panel (a) shows the initial state: a Gaussian wave packet is created by a short laser pulse to the left of the trap with the condensate. Panels (b) and (c) show the system after the wave packet 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 wave packet is due to the interaction with the condensate; however this relatively small broadening should not be detrimental for the device.

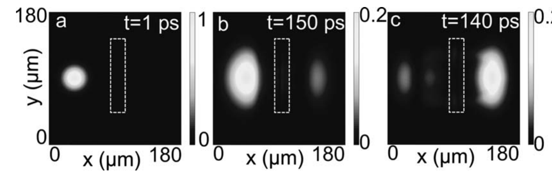

FIG. 3. Calculated propagation of a wave packet through the spin transistor: (a) wave packet created by a laser pulse; (b) wave packet reflected by the condensate; (c) wave packet transmitted almost without reflection.

V. CONCLUSIONS

In conclusion, we proposed a scheme of a polaritonic analog 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 role of the nonmagnetic 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 on the pseudospin of the propagating polaritons. This field and therefore the device transmissivity are easily and quickly controlled, tuning the condensate density.

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[26] See supplementary material at http://link.aps.org/supplemental/10.1103/PhysRevB.81.125327 for movies of the pulse propagation through the transistor in reflection and transmission mode.