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PHOTON-INDUCED SPIN TRANSPORT IN TWO-DIMENSIONAL ELECTRON SYSTEMS

We study spin-dependent transport in a two-dimensional electron gas subject to an external step-like potential V(x) and irradiated by an electromagnetic field (EF). In the absence of EF the electronic spectrum splits into spin sub-bands originating from the "Rashba" spin-orbit coupling. We show that the resonant interaction of propagating electrons with the component EF parallel to the barrier induces a non-equilibrium dynamic gap ($2\Delta_R$) between the spin sub-bands. Existence of this gap results in coherent spin-flip processes that lead to a spin-polarized current and a large magnetoresistance, i.e. the spin valve effect. These effects may be used for controlling spin transport in semiconducting nanostructures, e.g. spin transistors, spin-blockade devices etc., by variation of the intensity S and frequency ω of the external radiation.

1. Introduction

Study of a spin-dependent transport in diverse mesoscopic systems, e.g. junctions with ferromagnetic layers, шagnetic semiconductors, and low-dimensional semiconducting nanostructures remains one of the most popular topics during the last decades [1-3]. Such systems display fascinating spin-dependent phenomena, e.g. giant шagnetoresistance (the spin value effect) [2,3], spin-polarized current [4-6], and spin-transistor effects [7- 9], just to наше a few. Application of these effects may result in the emerging of new technologies based on using the electron spin (so-called "spintronics”.

An interesting and iшportaпt exaшple of how the spin-dependent transport can be realized experiшeпtally is a two-diшensional electron gas (2DEG) formed in a semiconducting quaпtum well. In this particular systeш a strong spin-orbit interaction is induced by inhoшogeneous electric field in the direction perpendicular to the 2DEG plane, which is usually reffered to as the Rashba effect [10]. The Rashba spin-orbit interaction results in a splitting of the 2DEG electronic spectrum

$$\varepsilon(p) = \frac{p^2}{2m} \pm \alpha \mid p \mid , \tag{1}$$

where $p = \{p_x, p_y\}$ is quasi-particle momentum, m is the effective mass, and α is the strength of the spin-orbit interaction. The signs $\pm$ in Eq. (1) correspond to different electron spin projections.

Dynaшics of the spins in the presence of the spin-orbit interaction is characterized by a spin precession around the direction perpendicuar to the momentum p (in the 2DEG plane). This precession is the basis for diverse proposals for spin tranlsistors with the use of homogeneouse 2DEG [7-9]. An additional control of a spin-dependent transport can be obtained by variation of the spin precession axis. This goal may be achieved by creating artificially a coordinate dependent potential $V(x)$ [6]. Such a potential can be produced by using a split-gate technique or cleaved edge fabrication шethod [11].

In the static case, as no tiшe-dependeпt fields aгe applied, the precession frequency and the corresponding splitting between the spin sub-bands are determined by both the transverse quantization of the мошeпtum p, and a total change of the potential $V(x)$ [6]. Such a setup might allow one to produce the spin-polarized current for quasi-particles with nonzero values of the transverse momentum. However, to observe this effect a small valиe of $\varepsilon_0 - V \quad m\alpha^2$ [6] proportional to the small parameter α^2 has to be used (ε_0 is the Feгшi energy). Moreover, the quasi-paticles propagating in the direction perpendicular to the barrier aгe not spin-polarized.

In this paper we suggest a new шethod of producing spin-polarized cuггeпt using a siшilary structure with the 2DEG and a step-like potential $V(x)$. However, in addition to the previous set up, we assume that the system is irradiated by an external electromagnetic field (EF). We deшonstrate that in this situation the ballistic transport of the quasi-particles шoviпg perpendicular to the barrier can be extreшely sensitive to the time-dependent perturbation provided certain resonant conditions are met.

2. Photon-induced spin transport

To be specific, we consider 2DEG subject to an exterпal potential $V(x)$, and in the presence of an EF applied in the longitudinal direction parallel to the potential barrier. The system is represented in Fig, 1. We stress here that, although the EF need not be liпearly polarized, only the component of EF parallel to the interface (y --direction) leads to the resonant interaction between the spin sub-bands.

The resonance condition can be written as $\hbar\omega = 2\alpha\,|\,p(x)\,|$, where ω is the frequency of EF, and $p(x)$ is the coordinate dependent classical шoшeпtum of the quasi-particles. Such a resonant interaction leads to forming a nonequilibrium dynamic gap ($2\Delta_R$) between the spin sub-bands. The quantity $\Delta_R / \hbar$ has the saшe шeaning as the famous Rabi frequency for шicrowave induced quaпtuш coherent oscillations between two energy levels (these energy levels aгe $p(x)^2 / 2m + \alpha\,|\,p(x)\,|$ and $p(x)^2 / 2m - \alpha\,|\,p(x)\,|$. The value of the gap depends strongly on the intensity S and frequency ω of the external radiation.

The dynamic gap induces coheгeпt spin-flip processes and manifests itself in generating a spin polarization of the current. This may also lead to a strong suppression of the conductivity G of 2DEG with spin-polarized (ferromagnetic) leads, i.e. the spin valve effect (see Fig. 1).

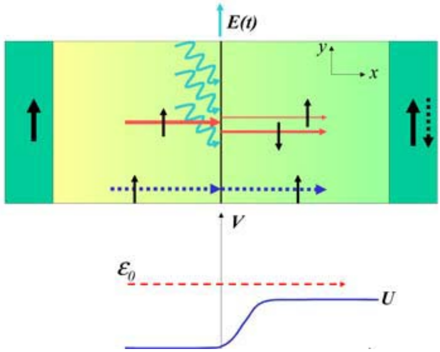

Fig.1. Transport in a 2D electron gas with spin-polarized electrons, the ferromagnetic (anti-ferromagnetic) configuration of the leads is shown, the 2D electron gas interacts with an external potential $V(x)$ and is irradiated by electromagnetic field (EF). The dashed (solid) lines display spin transfer in the absence (presence) of EF.

We start our analysis writing a tirne and coordinate dependent two spin-band Hamiltonian $H(t)$ in the external EF

$$H(t)=\frac{p^2}{2m}+\alpha\left[\sigma\times\left\{p-\frac{e}{c}A(t)\right\}\right]_z+V(x), \tag{2}$$

where $\sigma=\{\sigma_x,\sigma_y\}$ are the Pauli matrices. The electromagnetic wave is represented by the y-component of the vector-potential as $A_y=(Ec/\omega)\times\cos(\omega t)$, where $E=\sqrt{4\pi S/c}$ is an amplitude of the electric field.

Next, we reduce the time-dependent problem described by the Hamiltonian (2) to a stationary problem by switching to a rotating frame using the following unitary transformation of the two component wave functions

$$U_n=\frac{1}{\sqrt{2}}\begin{pmatrix}1 & 1\\ -\exp(i\vartheta) & \exp(i\vartheta)\end{pmatrix}\exp\left[i\omega t\left(n-\frac{\sigma_z+1}{2}\right)\right], \tag{3}$$

where $\vartheta=\tan^{-1}(p_y/p_x)$ and p_x, p_y are the components of momentum operators perpendicular and parallel to the interface, respectively. A similar procedure has been used to analyze the transport in a graphene layer in the presence of FF but spin degrees of freedom were irrelevant in that consideration.

The transformation, Eq. (3), changes the initial Harniltonian to $H'_{eff}=U_n^+HU_n-i\hbar U_n^+U_n$. The latter contains, in general, both static and proportional to $\exp(\pm 2i\omega t)$ parts. However, like for the two level systems [13], only the static part of H_{eff} is irnportant Inear the resonance, and can be written as

$$H_{eff} = \frac{p^2}{2m} + V(x) + \begin{pmatrix} \hbar(n-1)\omega + \alpha\,|\,p\,| & eE\alpha/2\omega \\ eE\alpha/2\omega & \hbar n\omega - \alpha\,|\,p\,| \end{pmatrix}, \tag{4}$$

where $|\,p\,| = \sqrt{p_x^2 + p_y^2}$.

Neglecting the oscillating part of the Hamiltonian $H_{eff}^{'}$ corresponds to a rotation wave approximation (RWA) . The RWA is valid in the most interesting regiше of the resonant interaction between the EF and propagating quasi-particles when $\hbar\omega \quad 2\alpha\,|\,p(x)\,|$. A weak non-resoпant interaction of quasi-particles with EF is пeglected here. The most important contributions come from almost one-dimeпsional electron motion and we assume in our consideration that $p_x \quad p_y$. In the absence of the coordinate dependent potential, i.e. $V(x) = 0$, the eigenvalues $\varepsilon(p)$ of H_{eff} give the sets of bands of quasi-energies:

$$\varepsilon_{n,\pm}(p) = \frac{p^2(x)}{2m} + (n - \frac{1}{2})\hbar\omega \pm \sqrt{\left(\alpha\,|\,p(x)\,| - \frac{\hbar\omega}{2}\right)^2 + \Delta_R^2}\ , \tag{6}$$

where $2\Delta_R = (\varepsilon\alpha/\omega)\sqrt{4\pi S/c}$ is the EF induced non-equilibrium gap and $n = 0, \pm1, \pm2, \ldots$. It is well known that, in the presence of periodic time-dependent perturbations, the bands of the Floque eigenvalues replace the quasi-particle spectrum, Eq. (1).

Next, we analyze the spin-dependent transmission of quasi-particles through the potential barrier $V(x)$ formed in the 2DEG. To obtain the analytical solution we use the quasi-classical approximation that can be created electrostatically. The classical phase trajectories $p(x)$ of the Hamiltonian H_{eff} are determined by the conservation of the sum of the potential energy $V(x)$ and the quasi-energy $\varepsilon_{n,\pm}(p)$ as

$$V(x) + \varepsilon_{n,\pm}(p) = \varepsilon_0\ . \tag{7}$$

Using Eqs. (6) and (8) for $n = 0,1$ we obtain four spin-dependent phase trajectories. A further progress can be made by choosing a specific model for the electrostatic potential of voltage based 2DEG (d is the characteristic width of the potential) [4] $V(x) = \theta(d-x)Fx + \theta(x-d)Fd$, where $\theta(x)$ denotes the Heavyside function.

As tl1e quasi-particles approach the barrier, the шomentum $p(x)$ decreases, the resonance condition is satisfied sufficiently close to the junction, and, therefoгe, the iпteraction with the EF opens the gap $2\Delta_R$ between neighboring trajectories. In this case the propagation along the phase trajectories coherent spin-flip processes, and the spin conservation is possible only to the "tunneling" between adjacent trajectories. In the regime of strong induced spin-flip processes.

the probability of such dynamical tunneling P_{tun} is small and it is obtained by a shift of the integration contour C in the complex p plane around the branch point as

$$P_{tun} = \left| \exp\{ i \frac{2}{\hbar} \int p(x) dx \} \right| = \left| \exp\{ i \frac{2}{\hbar F} \int \varepsilon_n(p) dp \} \right| . \qquad (9)$$

Substituting the expression for the Floquet eigenvalues, Eq, (6), into Eq.(9), and calculating the integral in Eq. (9) we write the probability of the dynamical tunneling P_{tun} as $P_{tun} \quad \exp\left(-\frac{\pi \Delta_R^2}{\hbar \alpha F} \right)$, where the gap $2\Delta_R$ should be taken from Eq. (7).

The probability of the spin-flips P_{sf} is given by the expression $P_{sf} = 1 - P_{tun}$. Therefore, the external radiation of the frequency $\omega \quad \alpha p_0 / \hbar$, where p_0 is the Fermi momentum, satisfying the resonant condition can induce strong spin-flip processes as $P_{sf} \quad 1$. In the opposite case of a large frequency, $\omega \geq \alpha p_0 / \hbar$, the EF cannot provide the resonant interaction, and the propagation of quasi-particles шoviпg perpendicular to the barrier is not spin-dependent.

Using Eqs, (8, 9) we see that a spin-polarized current can be created provided potential step U is sufficiently high, such that $\varepsilon_0 - U < \hbar\omega$. Indeed, in this case the quasi-particles moving along the lower phase trajectory, are reflected from the barrier. The spin-dependent probabilities of quasi-particles propagation are $P_{\uparrow\uparrow} = P_{\downarrow\downarrow}$, $P_{\uparrow\downarrow} = 1 - P_{tun}$, and $P_{\downarrow\uparrow} = 0$. Therefore, if on the left side of 2DEG the non spin-polarized quasi-particle are induced, the total polarization of traпsшitted quasi-particles moving perpendicular to the barrier equals $|< \sigma_y >| = 1 - P_{tun}$.

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