

SPIN CURRENT IN (110)-ORIENTED GaAs QUANTUM WELLS

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ABSTRACT

We consider a possibility of generation of the stationary spin current in (110)-oriented GaAs-based symmetric quantum well due to the nonlinear response to external periodic electric field. The model includes the Dresselhaus spin-orbit interaction and the random Rashba spin-orbit coupling.

Key words: spin current, spin-orbit coupling, GaAs, quantum well

INTRODUCTION

Recently, symmetric GaAs (110) quantum wells (QWs) became the subject of extensive studies [1-3]. Spin orbit (SO) interaction in these systems, described by the Dresselhaus term [4], conserves the electron spin along the axis normal to the QW plane for any electron momentum \mathbf{k} . As a result, the random motion of an electron does not lead to spin relaxation. In reality, this spin component relaxes very slowly, and its analysis provides a test for the rapidly developing spin-noise spectroscopy [2]. In the case of perfect z to $-z$ symmetry (the axis z is perpendicular to the QW plane), the Rashba SO interaction is zero. But in real structures, however, the Rashba coupling still exists in the form of a spatially fluctuating SO field (though being zero on average) [5-7]. This interaction induces spin-flip processes leading to the spin relaxation [3], and can be also responsible for generation of non-equilibrium spin density due to the absorption of external electromagnetic field [7].

In this work we propose a new possibility of exciting a steady pure spin current, thus extending the abilities of spin manipulation in real situations. In

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contrast to the conventional spin Hall effect, which is linear in external electric field, the proposed spin current is quadratic in periodic field. The effect is a result of the interplay of constant Dresselhaus and spatially non-uniform Rashba interactions. The exact mechanism of this effect does not involve real spin-flip transitions of electrons between the spin-split subbands in (110)-GaAs QW, but relies on virtual spin-flip processes renormalizing the wave functions of electrons in non-equilibrium state. This makes such a nonlinear response the physically new phenomenon, which appears if one takes into account more realistic cases than those described by the conventional Rashba and Dresselhaus models.

MODEL AND GENERAL APPROACH

Hamiltonian of a two-dimensional electron gas with a constant Dresselhaus term and spatially fluctuating Rashba spin-orbit interaction, subjected to external electromagnetic field described by the vector potential $\mathbf{A}(\mathbf{r}, t)$ takes the form (we use units with $\hbar = 1$)

$$H = -\frac{1}{2m} \left(\nabla - \frac{ie\mathbf{A}}{c} \right)^2 - i\alpha\sigma_z \left(\nabla_x - \frac{ieA_x}{c} \right) - i\sigma_x \left\{ \nabla_y, \lambda(\mathbf{r}) \right\} / 2 + i\sigma_y \left\{ \nabla_x, \lambda(\mathbf{r}) \right\} / 2 + V, \quad (1)$$

Where α is the Dresselhaus coupling constant, $\{ , \}$ denoting the anticommutator and $\lambda(\mathbf{r})$ is the random Rashba SO interaction. The term V describes coupling of the electron spin to the external field $\mathbf{A}(\mathbf{r}, t)$ via the Rashba field.

Due to the assumed symmetry with respect to z -inversion, the spatially averaged Rashba interaction vanishes, $\langle \lambda(\mathbf{r}) \rangle = 0$. We assume that the random Rashba field can be described by the some correlation function related to fluctuating density of impurities near the QW [5, 7].

SPIN CURRENT

A nonzero pure spin current can be generated by an external field in the presence of random Rashba coupling. In the following we consider the z -component of spin current flowing along the x axis. The macroscopic spin current density is then given by

$$j_x^z = iT r \sum_k \int \frac{d\varepsilon}{2\pi} \hat{j}_x^z G_{k\varepsilon} \quad (2)$$

Where $\hat{j}_x^z = k_x \sigma_z / m + \alpha$ is spin current tensor component, $\mathbf{G}_{\mathbf{k}\varepsilon}$ is the Green's function of the system.

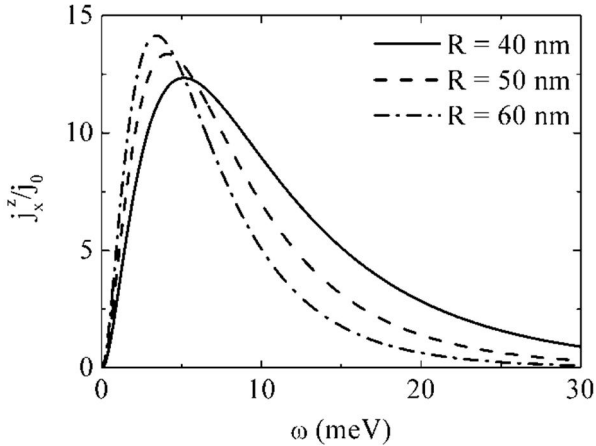


Fig. 1 – Dependence of the light-induced spin current on the frequency ω for different values of the correlation length R

The stationary spin current is excited by the external electromagnetic field described by $\mathbf{A}(t) = 2\mathbf{A}_0 \cos \omega t$. We point out that only Rashba SO interaction can generate the spin current since the field-induced perturbation in Dresselhaus term commutes with σ_z and thus does not lead to spin dynamics. After expanding Green's function up to the first order in α and second order in $\mathbf{A}(t)$ we obtain the following form of the spin current

$$j_x^z = C(\omega) \int_0^{k_F} \frac{k dk}{4\pi^2} \int_0^{q_c} \frac{q dq}{2\pi} |\lambda_q|^2 \times \left(k \frac{3q\beta_2 + 4k\beta_2^2 + 2k}{(\beta_2^2 - 1)^{5/2}} + \frac{4k^2\beta_1^2 + 2k^2 + 2q^2\beta_1^2 + q^2 + 9kq\beta_1}{(\beta_1^2 - 1)^{5/2}} \right) \quad (3)$$

Where $q_c = -k/2 + (k^2/4 + 2m\omega)^{1/2}$, $\beta_{1,2} = 2m\omega/kq \pm q/k$.

RESULTS AND DISCUSSION

Numerical results on j_x^z are shown in Fig. 1 for different values of the parameter R . We used the parameters typical for GaAs: $m = 0.067 m_0$, $k_F = 1.8 \cdot 10^6 \text{ cm}^{-1}$ and $\mu = 18.5 \text{ meV}$.

We emphasize here that the calculated spin current is a stationary nonlinear effect proportional to the intensity of incident light, in contrast to the spin

current generated by pulse excitations, where the result is proportional to the total influence in the pulse [6]. In the flux-dependent processes the pulse changes the real occupation of the spin-up and spin-down states. The calculated current is also not related to the linear response at frequency ω .

CONCLUSIONS

We have proposed a new effect which consists in the nonlinear generation of a steady pure spin currents in GaAs (110) quantum wells by electromagnetic wave. The spin current is proportional to the intensity of the external monochromatic radiation. Physical mechanism of the effect is related to the virtual spin reorientation of electrons filling the spin subband (split by Dresselhaus interaction) in the presence of a non-uniform Rashba coupling. As a result, a 'spin hole' virtually appears in the subband, leading to the light-induced spin current.

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