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Control of spin dynamics in a two-dimensional electron gas by electromagnetic dressing

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We solved the Schrödinger problem for a two-dimensional electron gas (2DEG) with the Rashba spin-orbit interaction in the presence of a strong high-frequency electromagnetic field (dressing field). The found eigenfunctions and eigenenergies of the problem are used to describe the spin dynamics of the dressed 2DEG within the formalism of the density matrix response function. Solving the equations of spin dynamics, we show that the dressing field can switch the spin relaxation in the 2DEG between the cases corresponding to the known Elliott-Yafet and D’yakonov-Perel’ regimes. As a result, the spin properties of the 2DEG can be tuned by a high-frequency electromagnetic field. The present effect opens an unexplored way for controlling the spin with light and, therefore, forms the physical prerequisites for creating light-tuned spintronics devices.

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I. INTRODUCTION

One of the most exciting trends in modern condensed matter physics is using the electron spin of freedom to store and transfer information. This field of research—which is known as spintronics—opened a way for various high-performance devices which have a number of important advantages as compared to conventional electronics, including growth in data processing speed, reduction in power consumption, etc. [1–6]. Besides successful spintronic experiments based on various ferromagnetic structures [7–9], an alternative approach to use nonmagnetic semiconductor nanostructures with spin-orbit interaction is actively investigated in recent years [10–12]. Therefore the study of spin transport in a two-dimensional electron gas (2DEG) with spin-orbit interaction is currently in the focus of attention. One of the most important characteristics of spintronics devices is the spin relaxation time which describes the spin evolution. Since it is responsible for the spin transfer of information, the search of ways to control this time is interesting from both fundamental and applied viewpoints. In the present paper, we report a novel method to control the spin relaxation time of 2DEG with a strong high-frequency electromagnetic field.

It is well-known that the interaction between electrons and a strong high-frequency electromagnetic field cannot be described as a weak perturbation. In this case, the system “electron + electromagnetic field” should be considered as a whole. Such a bound electron-field system, which was called “electron dressed by field” (dressed electron), became a commonly used model in modern physics [13,14]. Recently, we demonstrated that a strong interaction between 2DEG and a high-frequency electromagnetic field drastically suppresses the scattering of dressed electrons [15,16]. Since the spin relaxation depends on both the mechanism of spin-orbit interaction and scattering processes, one can expect that the spin relaxation time is strongly affected by the dressing electromagnetic field. Although various mechanisms of spin evolution in 2DEG have been studied in details, both theoretically and experimentally (see, e.g., Refs. [17–20]), the spin dynamics of electromagnetically dressed 2DEG escaped the attention before. The present study is aimed to fill partially this gap at the border between spintronics and quantum optics.

II. THE SPIN HAMILTONIAN OF DRESSED 2DEG

For definiteness, we will restrict our consideration to a 2DEG with the Rashba spin-orbit interaction, which is subjected to a plane monochromatic linearly polarized electromagnetic wave propagating perpendicularly to the 2DEG plane (see the insert in Fig. 1). In what follows, we will assume that the wave frequency \( \omega_0 \) meets two conditions. Firstly, the wave frequency is far from the resonant electron frequencies corresponding to interband electron transitions and, therefore, the interband absorption of the wave by the 2DEG is absent. Secondly, the wave frequency is high enough in order to satisfy the inequality \( \omega_0 \tau_0 \gg 1 \), where \( \tau_0 \) is the electron scattering time in an unirradiated 2DEG. It is well-known that the intraband (collisional) absorption of wave energy by conduction electrons is negligibly small under this condition (see, e.g., Refs. [21,22]). Thus the considered electromagnetic wave can be treated as a purely dressing (nonabsorbable) field. In the absence of scatterers, the wave function of a dressed electron satisfies the nonstationary Schrödinger equation with the Hamiltonian

\[
\hat{H} = \frac{1}{2m} (\hbar \mathbf{k} - e \mathbf{A})^2 + \alpha [\mathbf{\sigma} \times (\hbar \mathbf{k} - e \mathbf{A})], \tag{1}
\]

where \( \mathbf{k} = (k_x, k_y) \) is the wave vector of the electron in the 2DEG, \( m \) is the effective electron mass in the 2DEG, \( e \) is the electron charge, \( \mathbf{A} = (E_0/\omega_0) \cos \omega_0 t \) is the vector potential of the electromagnetic wave, \( E_0 = (0, E_0, 0) \) is the electric field amplitude of the wave which is assumed to be linearly polarized along the y axis, \( \mathbf{\sigma} = (\sigma_x, \sigma_y, \sigma_z) \) is the Pauli matrix vector, and \( \alpha \) is the Rashba spin-orbit coupling constant. To simplify the calculations, let us subject the Hamiltonian (1) to...
The figure shows the sketch of the system under consideration.

The 2DEG is assumed to fill electronic states under the Fermi energy $E_F = \varepsilon_F / 2m$. Then Eq. (5) takes a form that is mathematically equal to the equations of quantum dynamics of a two-level quantum system under periodical pumping, which is analyzed in details in conventional textbooks on quantum mechanics. If the photon energy $\hbar \omega_0$ is much larger than both the Fermi energy $\varepsilon_F$ and the spin-orbit interaction energy $\alpha \hbar k$, the high-frequency harmonics $e^{i \hbar n \omega_0 t}$ with $n \neq 0$ in the Jacobi-Anger expansion (“nonresonant terms”) make a negligibly small contribution to the solutions of the quantum dynamics equations (5) and can be omitted (see, e.g., the similar analysis for a two-level quantum system under a periodic pumping in Ref. [24]). Therefore Eq. (5) can be rewritten for the considered high-frequency dressing field as

$$i \dot{a}_\pm = \left( \frac{\hbar k^2}{2m} \pm \alpha k_x \right) a_\pm \mp i \alpha k_x a_\mp J_0 \left( \frac{2 \alpha e E_0}{\hbar \omega_0} \right),$$

where $J_0(\omega_0)$ is the zero-order Bessel function of the first kind. The equations (6) can be solved trivially and we arrive at the two sought wave functions (4),

$$\psi_\pm(k) = \left( \begin{array}{c} \sqrt{2} i \left( k_x^2 + \frac{2 \alpha e E_0}{\hbar \omega_0} \right)^{1/2} \alpha k_y \left( k_x^2 + \frac{2 \alpha e E_0}{\hbar \omega_0} \right)^{-1/2} \hbar^2 k_y^2 / 2m - \alpha \hbar k_y \end{array} \right) e^{\mp i \alpha k_y},$$

which correspond to the two spin-split branches of energy spectrum of dressed 2DEG,

$$\epsilon_\pm(k) = \frac{\hbar^2 k^2}{2m} \pm \alpha \hbar \sqrt{k_x^2 + J_0^2 \left( \frac{2 \alpha e E_0}{\hbar \omega_0} \right)^2} k_y^2.$$
where \( \nu_F \) is the density of states of 2DEG at the Fermi level, \( \tau \) is the scattering time of 2DEG at the Fermi level, and \( i,j = x,y,z \). Correspondingly, \( G^{(A)}(k, \varepsilon_F) \) in Eq. (9) is the disorder-averaged single-particle retarded (advanced) Green’s function,

\[
G^{(R)}(k, \varepsilon_F) = \sum_{n= \pm} \frac{\psi_n(k) \psi_n^*(k)}{\varepsilon_F - \varepsilon_n(k) \pm i\hbar/2\tau},
\]

which is written in the representation of wave vector \( k \) and frequency \( \omega \). Formally, the key expressions (10) and (9) have the same form for both unirradiated 2DEG and 2DEG subjected to a dressing field. However, for the considered case of dressed 2DEG, we have to use the wave function of dressed 2DEG (7) and the energy spectrum of dressed 2DEG (8) in order to calculate the Green’s function (10). We have also to take into account that the dressing field renormalize the scattering time \( \tau \), which takes place both in Eqs. (10) and (9).

Generally, the scattering time is given by the expression

\[
\frac{1}{\tau} = \sum_{k} w_{kk} k',
\]

where \( w_{kk} \) is the electron scattering probability per unit time between electron states with wave vectors \( k \) and \( k' \). For the dressed 2DEG, the scattering probability has the form [15]

\[
w_{kk} = J_2^0 \left( \frac{\epsilon E_0 (k - k')}{m_0^2 \omega_0^2} \right) w_{kk}^{(0)},
\]

where \( w_{kk}^{(0)} \) is the scattering probability for the 2DEG in the absence of the dressing field.

To simplify the calculation of the spin dynamics, let us assume that the scattering disorder is weak (\( \hbar/\tau \varepsilon_F \ll 1 \)) and the energy of spin-orbit coupling is low (\( \alpha \hbar \omega_F / \varepsilon_F \ll 1 \)). Performing the integration in Eq. (9) over the Fermi level, we get the matrix elements of the diffuson. As a result, the spin relaxation time in the 2DEG plane can be neglected and we arrive at the expression \( \tau_{x,y} = \tau/2 \equiv \tau_s \), where \( \tau_s \) is the characteristic spin relaxation time in the 2DEG plane, which is caused by the spin-orbit interaction.

**IV. DISCUSSION AND CONCLUSIONS**

It follows from Eq. (13) that the spin relaxation time \( \tau_s \) strongly depends on the ratio of the scattering time and the spin precession time, \( \zeta = \tau/\tau_{so} \). Namely, for the case of \( \zeta \gg 1 \), the spin relaxation time is \( \tau_s \sim \tau \). On the contrary, for the case of \( \zeta \ll 1 \), the spin relaxation time is \( \tau_s \sim \tau_{so} \).

This strong dependence of the spin relaxation time (13) on the ratio \( \zeta = \tau/\tau_{so} \) arises from different mechanisms of spin relaxation, which are dominant for the cases of \( \zeta \gg 1 \) and \( \zeta \ll 1 \) (see, e.g., Refs. [33–35]). If the scattering time \( \tau \) is much larger than the spin precession time \( \tau_{so} \), the spin relaxation is defined substantially by the scattering processes (the Elliott-Yafet (EY) spin relaxation mechanism [36,37]). The EY spin relaxation alone results in \( \tau_s \sim \tau \) for the case of \( \zeta \gg 1 \). If the scattering time \( \tau \) is much less than the spin precession time \( \tau_{so} \), the spin relaxation is defined substantially by the spin-orbit interaction (the D’yakonov-Perel’ (DP) spin relaxation mechanism [38]). The DP spin relaxation alone results in \( \tau_s \sim \tau_{so} \) for the case of \( \zeta \ll 1 \). As a consequence, the nonmonotonic dependence of the spin relaxation time \( \tau_s \) on the ratio \( \tau/\tau_{so} \) appears (see Fig. 2). For an unirradiated 2DEG, the scattering time \( \tau = \tau_{so} \) depends only on the properties of the given nanostructure and cannot be easily changed in experiments (experimentally measured values of the scattering time \( \tau_{so} \) in various two-dimensional systems can be found, e.g., in Ref. [39]). On the contrary, in the considered case of dressed 2DEG, the scattering time \( \tau \) depends on both the dressing field amplitude \( E_0 \) and the dressing field frequency \( \omega_0 \) [see Eqs. (11) and (12)] and can strongly differ from the initial scattering time in unirradiated 2DEG, \( \tau_{so} \). Therefore changing the parameters of dressing field, we can change the value of the scattering time \( \tau \). As a result, the attractive possibility to switch the spin relaxation process between EY and DP regimes with a high-frequency electromagnetic field appears.

To clarify the results of numerical calculations of the spin relaxation time \( \tau_s \) [see Figs. 1 and 2], let us discuss the dependence of the scattering time (11) on the intensity...
of the dressing field $I = \epsilon_0 E_0^2 c^2 / 2$. It follows from the scattering probability (12) that the dependence arises from the Bessel function which decreases with increasing the intensity, $I$. Therefore the scattering time in 2DEG $\tau$ increases with increasing intensity of the dressing field [15,16]. If the initial scattering time in unirradiated 2DEG $\tau_0$ is large enough (the dashed line in Fig. 1), the EY spin relaxation is dominant in the absence of the dressing field. In this case, the field-induced increase of scattering time $\tau$ does not change qualitatively the EY spin relaxation mechanism. As a result, the relaxation time marked by the dashed line in Fig. 1 increases monotonically with increasing the dressing field intensity. On the contrary, if the scattering time in unirradiated 2DEG $\tau_0$ is small enough (the solid and dot-dashed lines in Fig. 1), the DP spin relaxation is dominant in the absence of the dressing field. In this case, the field-induced increasing of scattering time $\tau$ switches the DP spin relaxation mechanism to the EY one. As a consequence, the relaxation times marked by the solid and dot-dashed lines in Fig. 1 demonstrate nonmonotonical behavior with increasing the dressing field intensity. Therefore the dressing field can switch the spin relaxation between DP and EY regimes in a 2DEG with strong scattering (see the insert in Fig. 2). As to the weak oscillating behavior of the curves in Fig. 1, it is caused formally by the oscillating behavior of the Bessel function in the scattering probability (12).

Summarizing the aforesaid, we can conclude that the dressing field can switch the spin relaxation mechanism in the 2DEG between the cases corresponding to the well-known Elliott-Yafet and D’yakonov-Perel’ regimes. As a result, the spin properties of the 2DEG can be tuned by a high-frequency electromagnetic field. Particularly, we showed that the irradiation of 2DEG by the dressing field results in increasing the spin relaxation time. Currently, only low-frequency (particularly, stationary) magnetic and electric fields were considered as a tool to control the spin properties of solids. Therefore the present effect opens an alternative way for the spin control with light and, therefore, forms physical prerequisites for creating light-tuned spintronics devices.

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