Datta-and-Das spin transistor controlled by a high-frequency electromagnetic field

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We developed the theory of spin dependent transport through a spin-modulator device (so-called Datta-and-Das spin transistor) in the presence of a high-frequency electromagnetic field (dressing field). Solving the Schrödinger problem for dressed electrons, we demonstrated that the field drastically modifies the spin transport. In particular, the dressing field leads to renormalization of spin-orbit coupling constants that varies conductivity of the spin transistor. The present effect paves the way for controlling the spin-polarized electron transport with light in prospective spin-optronic devices.

I. INTRODUCTION

One of most excited fields of modern condensed-matter physics is the physics of spin-based electronic devices (spintronics), which is expected to play a crucial role in the realization of high-performance information processing [1–4]. There are various kinds of logic devices based on spin-polarized electron transport in ferromagnets and semiconductors [5–7]. In ferromagnetic materials, the spin transfer can be manipulated by an external magnetic field. As to semiconductor structures, their spin properties are effectively controlled with the spin-orbit interaction. Namely, the Rashba mechanism of spin-orbit coupling (based on the structure inversion asymmetry) and the Dresselhaus mechanism of spin-orbit coupling (originating from the bulk inversion asymmetry) allow tuning the spin states of electrons in semiconductors without external magnetic fields [8–10].

The concept of semiconductor spin-transfer device (spin transistor) was put forward by Datta and Das in their pioneering work [11]. Constructively, Datta-and-Das spin transistor consists of two magnetized ferromagnetic electrodes and a semiconductor channel between them (see Fig. 1). In this design, the ferromagnetic electrodes 1 and 3 are used to inject and collect spin-polarized electrons, whereas the semiconductor area 2 serves to rotate electron spin via the spin-orbit coupling. As a result, the transmissivity of the spin transistor depends on the strength of the spin-orbit coupling in the semiconductor channel [11–14]. Originally, the spin-orbit coupling was proposed to be controlled with a gate voltage applied to the semiconductor channel [11]. In the present study, we propose the alternative method of optical control.

It is well known that light is an effective tool to manipulate electronic properties of various quantum systems in the regime of strong light-matter coupling. Since the strongly coupled system "electron + electromagnetic field" should be considered as a whole, the bound electron-field object—"electron dressed by electromagnetic field" (dressed electron)—became a commonly used model in modern physics [15,16]. It has been demonstrated that a dressing field crucially changes physical properties of conduction electrons in various condensed-matter structures, including bulk semiconductors [17–19], quantum wells [20–25], quantum rings [26–28], graphene [29–38], etc. Therefore, one can expect that spintronic devices are strongly affected by a dressing field as well. However, a consistent theory describing spin transport in electronic devices subjected to electromagnetic radiation was not, to the best of our knowledge, elaborated on up to now.

II. MODEL

Let us consider a semiconductor channel of the spin transistor irradiated by a linearly polarized electromagnetic wave (dressing field) propagating perpendicularly to the channel (see Fig. 1). In what follows, temperature T is assumed to be close to zero. As a consequence, only electrons situated in the close vicinity of the Fermi energy ε_F contribute to conductivity of the channel.

The Hamiltonian of the electrons reads

$$\hat{\mathcal{H}}_e = \frac{1}{2m_s}(\hbar\mathbf{k} - e\mathbf{A})^2 + \alpha[\boldsymbol{\sigma} \times (\hbar\mathbf{k} - e\mathbf{A})]_z$$
$$+ \beta[\sigma_x \cdot (\hbar\mathbf{k} - e\mathbf{A})_x - \sigma_y \cdot (\hbar\mathbf{k} - e\mathbf{A})_y], \quad (1)$$

where m_s is the effective electron mass in the semiconductor, $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ is the Pauli matrix vector, $\mathbf{k} = (k_x, k_y)$ is the electron wave vector, $\mathbf{A} = (0, [E/\omega]\cos\omega t)$ is the vector potential of the wave, ω is the wave frequency, E is the amplitude of electric field of the wave, and α and β are the Rashba and Dresselhaus spin-orbit coupling constants, respectively. In order to describe the spin transistor, we specifically consider electrons propagating in the one-dimensional channel along the x axis. Therefore, the Hamiltonian (1) can be rewritten as
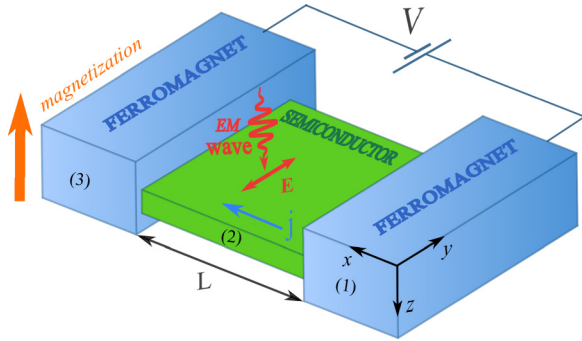
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FIG. 1. Sketch of the spin transistor irradiated with an electromagnetic (EM) wave. Under the applied voltage V the source ferromagnetic contact 1 injects the spin-polarized current j into the semiconductor channel 2 along the x axis. The drain ferromagnetic contact 3 collects the current. The linearly polarized EM wave propagates perpendicularly to the channel and its electric field E is directed along the y axis.

$\hat{\mathcal{H}}_e = \hat{\mathcal{H}}_0 + \hat{\mathcal{H}}_k$, where

$$\hat{\mathcal{H}}_0 = \frac{e^2 E^2}{2m_s \omega^2} \cos^2 \omega t + (\beta \sigma_y - \alpha \sigma_x) \frac{eE}{\omega} \cos \omega t \quad (2)$$

is the Hamiltonian describing the dressed electron state at $\mathbf{k} = 0$ and

$$\hat{\mathcal{H}}_k = \frac{\hbar^2 k_x^2}{2m_s} + (\beta \sigma_x - \alpha \sigma_y) \hbar k_x \quad (3)$$

is the Hamiltonian of "bare" electron in the channel. Solving the nonstationary Schrödinger equation, $i\hbar \partial \Psi_0 / \partial t = \hat{\mathcal{H}}_0 \Psi_0$, one can easily obtain the exact eigenspinors of the Hamiltonian (2),

$$\Psi_0^{\pm} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ \pm \frac{\alpha - i\beta}{\gamma} \end{pmatrix} e^{-i \frac{e^2 E^2}{4m_s \hbar \omega^2} \left(t + \frac{\sin 2\omega t}{2\omega} \right)} e^{\pm i \frac{eE\gamma}{\hbar \omega^2} \sin \omega t}, \quad (4)$$

where $\gamma = \sqrt{\alpha^2 + \beta^2}$ is the effective spin-orbit coupling constant which takes into account both the Rashba spin-orbit interaction mechanism and the Dresselhaus one. Since the eigenspinors (4) form the complete basis of the considered electron system, we can seek eigenspinors of the full Hamiltonian $\hat{\mathcal{H}}_e = \hat{\mathcal{H}}_0 + \hat{\mathcal{H}}_k$ as

$$\Psi_k(t) = a^+(t)\Psi_0^+ + a^-(t)\Psi_0^-. \quad (5)$$

Substituting the expansion (5) into the Schrödinger equation with the full Hamiltonian $\hat{\mathcal{H}}_e = \hat{\mathcal{H}}_0 + \hat{\mathcal{H}}_k$, we arrive at the two differential equations describing the quantum dynamics of the considered system:

$$i\hbar \dot{a}^{\pm}(t) = \left[\frac{\hbar^2 k_x^2}{2m_s} \pm \frac{2\alpha\beta}{\gamma} \hbar k_x \right] a^{\pm}(t)$$
$$\mp i \frac{\alpha^2 - \beta^2}{\gamma} \hbar k_x e^{\mp i \frac{2eE\gamma}{\hbar \omega^2} \sin \omega t} a^{\mp}(t). \quad (6)$$

It follows from the Floquet theory of periodically driven quantum systems [39–41] that the wave function (5) can be written in the form $\Psi_k(t) = e^{-i\tilde{\varepsilon}t/\hbar} \Phi(t)$, where the function $\Phi(t) = \Phi(t + 2\pi/\omega)$ periodically depends on time and $\tilde{\varepsilon}$ is the quasienergy (energy of dressed electron). Since the

quasienergy plays the same role in periodically driven quantum systems as the usual energy in stationary ones, the present analysis is aimed at finding the energy spectrum $\tilde{\varepsilon}(k_x)$ for electrons propagating through the irradiated semiconductor channel. The periodicity of the function $\Phi(t)$ allows seeking the coefficients $a^{\pm}(t)$ in Eqs. (6) as the Fourier expansion,

$$a^{\pm}(t) = e^{-i\tilde{\varepsilon}t/\hbar} \sum_{n=-\infty}^{\infty} a_n^{\pm} e^{in\omega t}. \quad (7)$$

As to the exponents on the right sides of Eqs. (6), they can be transformed with the use of the Jacobi-Anger expansion, $e^{iz \sin \phi} = \sum_{-\infty}^{\infty} J_n(z) e^{in\phi}$, where $J_n(z)$ is the Bessel function of the first kind. If the dressing field is both high-frequency and nonresonant, the rapidly oscillating terms, $e^{in\omega t}$, make a negligibly small contribution into the quantum dynamics equations (6). Physically, this is a general rule for periodically driven quantum systems (see, e.g., the qualitatively similar analysis for various dressed nanostructures in Refs. [23–25,30,34]). Therefore, the high-frequency harmonics $e^{in\omega t}$ with $n \neq 0$ can be omitted in Eqs. (6). As a consequence, Eqs. (6) can be reduced to the expression

$$\left(\frac{\hbar^2 k_x^2}{2m_s} \pm \frac{2\alpha\beta}{\gamma} \hbar k_x - \tilde{\varepsilon} \right) a_0^{\pm} \mp i\hbar k_x \frac{\alpha^2 - \beta^2}{\gamma}$$
$$\times J_0 \left(\frac{2eE\gamma}{\hbar \omega^2} \right) a_0^{\mp} = 0. \quad (8)$$

Solving Eqs. (8), we obtain the energy spectrum of dressed electrons,

$$\tilde{\varepsilon}(k_x) = \frac{\hbar^2 k_x^2}{2m_s} \pm \tilde{\gamma} \hbar k_x, \quad (9)$$

where $\tilde{\gamma} = \sqrt{\tilde{\alpha}^2 + \tilde{\beta}^2}$, $\tilde{\alpha}$ and $\tilde{\beta}$ are the spin-orbit coupling constants renormalized by a dressing field:

$$\tilde{\alpha} = \alpha \left[J_0 \left(\frac{2eE\gamma}{\hbar \omega^2} \right) + \frac{2\beta^2}{\gamma^2} \left(1 - J_0 \left(\frac{2eE\gamma}{\hbar \omega^2} \right) \right) \right],$$
$$\tilde{\beta} = \beta \left[J_0 \left(\frac{2eE\gamma}{\hbar \omega^2} \right) + \frac{2\alpha^2}{\gamma^2} \left(1 - J_0 \left(\frac{2eE\gamma}{\hbar \omega^2} \right) \right) \right]. \quad (10)$$

Physically, the quantum dynamics equations (8) exactly correspond to the stationary Schrödinger equation with the effective Hamiltonian of dressed electrons in the irradiated semiconductor channel,

$$\hat{\mathcal{H}}_s = \frac{\hbar^2 k_x^2}{2m} + (\tilde{\beta} \sigma_x - \tilde{\alpha} \sigma_y) \hbar k_x, \quad (11)$$

which results in the same energy spectrum (9). It should be noted that the Hamiltonian of dressed electrons (11) exactly coincides with the well-known Hamiltonian for "bare" electrons (3) with the formal replacement $\alpha, \beta \rightarrow \tilde{\alpha}, \tilde{\beta}$. Consequently, all physical quantities describing dressed electrons can be easily derived from the "bare" ones with the same replacement. The energy spectrum of dressed electrons (9) turns into the well-known spin-split energy spectrum of "bare" electrons in the absence of the dressing field ($E = 0$). It should be stressed that the spin-orbit constants of dressed electrons differ from the same constants for "bare" electrons by the Bessel-function factor depending on the dressing field

amplitude E and the frequency ω [see Eqs. (10)]. In turn, the influence of the dressing field on the renormalized constants $\tilde{\alpha}$ and $\tilde{\beta}$ depends on the "bare" constants α and β. Particularly, the influence vanishes in the case of $|\alpha| = |\beta|$.

III. SPIN TRANSPORT

In the original proposal for the Datta-and-Das spin transistor [11], the semiclassical model was used. Within this approach, the spin-orbit interaction was treated as an effective magnetic field which depends on the electron wave vector along the semiconductor channel, k_x, and is perpendicular to the magnetization of ferromagnetic contacts. The spin-polarized electrons injected to the semiconductor channel from the source ferromagnetic contact are affected by the effective field. As a consequence, the spin of the electrons undergoes the rotation, whose angle at the drain ferromagnetic contact is $\theta = 2m_s \gamma L/\hbar$, where L is the length of the channel. Assuming the semiconductor channel to be in the ballistic regime, the amplitude of their probability to enter into the drain is equal to $\cos\theta/2$. Controlling the spin-orbit constant $\gamma = \sqrt{\alpha^2 + \beta^2}$ with external actions, one can control the conductance of the spin transistor. Particularly, it follows from Eq. (10) that the spin-orbit coupling can be controlled with an irradiation. Performing the formal replacement, $\gamma \rightarrow \tilde{\gamma}$, in the known expressions describing the spin transistor [11], we obtain the semiclassical conductance of the irradiated transistor,

$$G = \left(\frac{e^2}{2h}\right)\left[1 + \cos\left(\frac{2m_s \tilde{\gamma} L}{\hbar}\right)\right]. \tag{12}$$

To carry out the full quantum treatment of the spin transport, let us divide the model structure into the regions 1, 2, and 3, where the regions 1 and 3 correspond to the ferromagnetic contacts and the region 2 corresponds to the semiconductor channel (see Fig. 1). The electronic properties of the irradiated semiconductor region 2 are described by the Hamiltonian (11), whereas the Hamiltonian of ferromagnetic regions 1 and 3 can be written as $\hat{\mathcal{H}}_f = \hat{p}_x^2/2m_f - \sigma_z \Delta/2$, where $\hat{p}_x$ is the operator of electron momentum along the x axis, m_f is the electron effective mass in the ferromagnetic, and Δ is the Zeeman spin splitting of electron states in the ferromagnetic. Then the spinors describing the spin transistor in the three regions, $\psi_{1,2,3}(x)$, are given by

$$\psi_1(x)|_{x<0} = \left(e^{iq_+x} + C_1 e^{-iq_+x}\right)\begin{pmatrix}1\\0\end{pmatrix} + C_2 e^{q_-x}\begin{pmatrix}0\\1\end{pmatrix},$$

$$\psi_2(x)|_{0<x<L} = \left(C_3 e^{ik_+^{(1)}x} + C_4 e^{ik_-^{(1)}x}\right)\begin{pmatrix}1\\\frac{\tilde{\beta}-i\tilde{\alpha}}{\tilde{\gamma}}\end{pmatrix}$$

$$+ \left(C_5 e^{ik_+^{(2)}x} + C_6 e^{ik_-^{(2)}x}\right)\begin{pmatrix}1\\\frac{\tilde{\beta}+i\tilde{\alpha}}{\tilde{\gamma}}\end{pmatrix}$$

$$\psi_3(x)|_{x>L} = C_T e^{iq_+x}\begin{pmatrix}1\\0\end{pmatrix} + C_7 e^{-q_-x}\begin{pmatrix}0\\1\end{pmatrix}, \tag{13}$$

where $\hbar k_\pm^{(1)} = \pm\sqrt{2m_s\varepsilon + m_s^2\tilde{\gamma}^2} - m_s\tilde{\gamma}$ and $\hbar k_\pm^{(2)} = \pm\sqrt{2m_s\varepsilon + m_s^2\tilde{\gamma}^2} + m_s\tilde{\gamma}$ are the electron momenta in the semiconductor channel at the energy ε, $\hbar q_\pm = \sqrt{2m_f(\Delta/2 \pm \varepsilon)}$ are the electron momenta in

the ferromagnetic contacts at the same energy, and electrons in the contacts are assumed to be fully spin polarized ($\varepsilon < \Delta/2$). In order to find the transmissivity of the spin transistor, C_T, we have to use the conventional continuity conditions at the borders of the regions [42],

$$\psi_1(0) = \psi_2(0), \quad \psi_2(L) = \psi_3(L),$$

$$\hat{v}_1\psi_1(0) = \hat{v}_2\psi_2(0), \quad \hat{v}_2\psi_2(L) = \hat{v}_3\psi_3(L), \tag{14}$$

where $\hat{v} = i[\hat{\mathcal{H}},x]/\hbar$ is the velocity operator in the different regions: $\hat{v}_{1,3} = \hat{p}_x/m_f$ and $\hat{v}_2 = \hat{p}_x/m_s + (\tilde{\beta}\sigma_x - \tilde{\alpha}\sigma_y)$. Substituting the transmission amplitude C_T found from Eqs. (13)–(14) into the Landauer formula,

$$G = \frac{e^2}{h}|C_T|^2, \tag{15}$$

we can calculate the quantum conductance of the spin transistor G.

IV. DISCUSSION AND CONCLUSIONS

Discussing the limits of applicability of the developed theory, we have to underline that the considered dressing field must not be absorbable by electrons. This is important since the absorption of radiation could be detrimental when it generates intraband excitations (heating the Fermi sea). It is well known that the intraband absorption of radiation by free conduction electrons is forbidden by the energy conservation low and the momentum conservation low. Therefore, the intraband absorption of THz radiation can only take place due to the electron scattering (collisional absorption). However, the semiconductor channel of the Datta-Das spin transistor is assumed to be in the ballistic regime. Since scatterers are absent in the ballistic channel, the radiation-induced intraband excitations can be neglected. As to the optical absorption of the field by electrons, it can be neglected if the field frequency ω lies far from resonant electron frequencies corresponding to interband (intersubband) electron transitions. Therefore, the frequency ω should be low compared to the characteristic optical frequencies. On the other hand, the frequency ω should be high enough to satisfy the condition $\omega\tau \gg 1$, where $\tau \sim L/\sqrt{2\varepsilon/m_s}$ is the characteristic transit time of electron in the channel. Physically, this condition means that the dressing field experiences multiple oscillations while an electron flies ballistically from the source contact 1 to the drain contact 3 (see Fig. 1). Moreover, the photon energy $\hbar\omega$ must be larger than the characteristic spin-orbit coupling energy, $\varepsilon_{so} \sim \gamma\sqrt{2m_s\varepsilon}$, in which case it is safe to neglect the rapidly oscillating terms in the quantum dynamics equations (6). Therefore, the dressing field must be both high frequency and nonresonant.

At low temperatures, the electrons contributing to the spin transport in the channel are situated at the Fermi level. Therefore, the energy ε in all expressions above coincides with the Fermi energy in the semiconductor channel ε_F. The temperature T should be low compared to both the Fermi energy ε_F and the spin-orbit coupling energy, $\varepsilon_{so} \sim \gamma\sqrt{2m_s\varepsilon_F}$. It should be noted also that employing the concept of dressing field we assume that $\hbar/\tau_\varphi < g_0$, where τ_φ is the characteristic dephasing time, and $g_0 = eE\gamma/\omega$ is the characteristic constant of light-matter coupling in the semiconductor channel. In the
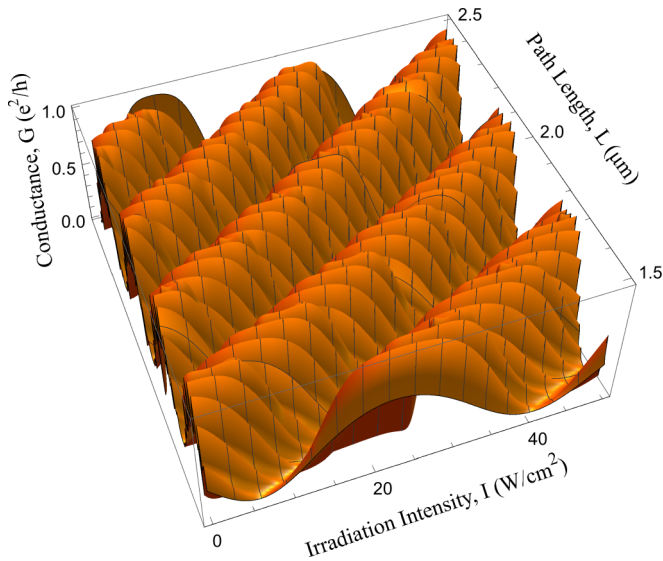
FIG. 2. The quantum conductance of the irradiated spin transistor G as a function of the irradiation intensity I and the length of the semiconductor channel (path length) L for the Rashba and Dresselhaus spin-orbit coupling constants $\alpha = \beta/4 = 5 \times 10^3$ m/s.

FIG. 3. The conductance of spin transistor G as a function of the irradiation intensity I for the length of the semiconductor channel $L = 2.3 \, \mu$m: (a) semiclassical conductance (dashed line) and quantum conductance (solid line) for the Dresselhaus constant $\beta = 2 \times 10^4$ m/s and the Rashba constant $\alpha = 0$; (b) quantum conductance for the Dresselhaus constant $\beta = 2 \times 10^4$ m/s and the different Rashba constants α.

considered case of ballistic channel, the dephasing time can be estimated as $\tau_\varphi \sim \tau \sim L/\sqrt{2\varepsilon/m_s}$. Therefore, the field amplitude E should be large enough to satisfy the condition $E > \hbar\omega\sqrt{2\varepsilon/m_s}/(e\gamma L)$.

Numerical calculations of the conductance of the irradiated spin transistor G with use of the semiclassical Datta-and-Das formula (12) and the quantum Landauer formula (15) are presented in Figs. 2 and 3 for the field frequency $\omega = 1$ THz, the Fermi energy $\varepsilon_F = 10$ meV, the Zeeman splitting in ferromagnetic contacts $\Delta = 40$ meV, the electron effective masses $m_f = m_e$ (in the ferromagnetic contacts) and $m_s = 0.067 m_e$ (in the GaAs semiconductor channel), where m_e is the mass of free electron. The difference between the quantum and semiclassical results is due to the multiple electron scattering between the source and drain contacts, which is not accounted for within the semiclassical approach. The multiple scattering leads to formation of the standing electron waves between the contacts, which have the same physical nature as eigenmodes of the Fabry-Perot resonator. As a consequence, the amplitude of quantum conductance experiences additional modulation (see Fig. 3).

The plotted dependence of the conductance G on the irradiation intensity I originates from the field-induced modification of the spin-orbit coupling constants (10). Conventionally, only the gate voltage was used before to tune the constants [14,43–45]. In particular, the gate-controlled scheme of the spin transistor was proposed by Datta and Das [11]. The present theory indicates that the spin-orbit coupling can be effectively controlled with an external optical field as well.

To summarize, the strong coupling between electron spins and a high-frequency electromagnetic field is an efficient control tool for the spin precession rate in spin transistors.
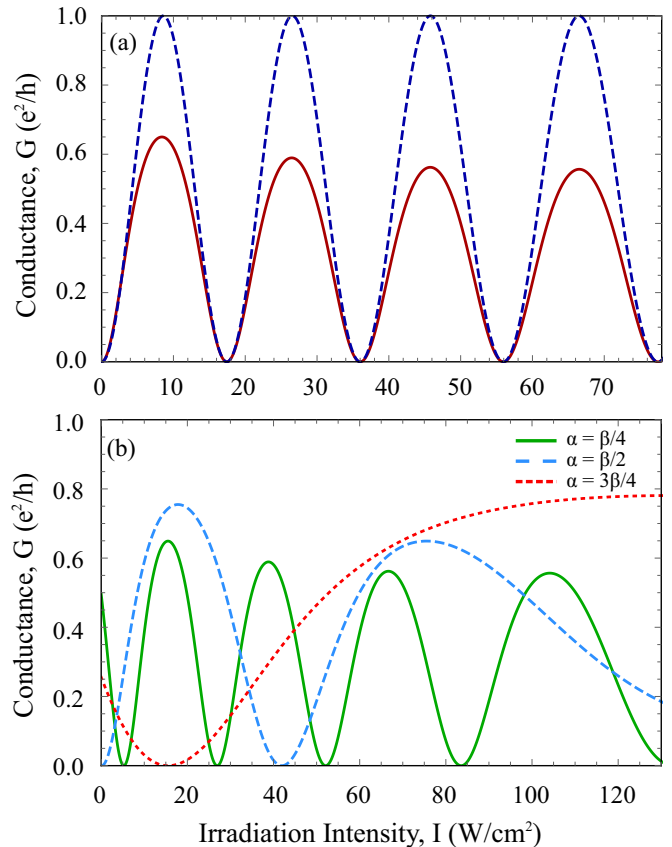
Since the dressing field renormalizes spin-orbit coupling constants, the variation of the dressing field intensity drastically modifies the spin transport properties of the transistors. Thus, the predicted effect opens the way to realization of new spin-optronic devices. Since light-controlled electronic devices are typically much faster than those of electrically controlled, the optically-controlled Datta-and-Das spin transistor is expected to be faster than the gate-controlled one.

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