Spin-split two-dimensional electron gas perturbed by intense terahertz laser fields

W. Xu*

Department of Theoretical Physics, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia

(Received 8 March 2004; revised manuscript received 18 June 2004; published 3 November 2004)

A time-dependent theoretical approach is developed to investigate the effects of intense terahertz (THz) laser radiation on optoelectronic properties of a two-dimensional electron gas (2DEG) in which the spin-orbit interaction is induced by the Rashba effect. It is found that for InGaAs-based spintronic systems, the electron density of states, the Fermi energy and the spin polarization are sensitive to THz laser fields. The results demonstrate that intense THz radiation can be used to enhance spin polarization and to achieve optical perturbation of the spintronic properties of a 2DEG and the Rashba spin splitting can be identified optically.

DOI: 10.1103/PhysRevB.70.193301 PACS number(s): 71.70.Ej, 78.67.De, 73.21.Fg

At present, one important aspect in the field of spin electronics (or spintronics) is to investigate spin polarized electronic systems realized from semiconductor nanostructures in the absence of an external magnetic field. The realization of these novel material systems has led to recent proposals dealing with advanced electronic devices such as spin transistors,[1] spin waveguides,[2] spin filters,[3] etc. It is known that in narrow-gap semiconductor nanostructures such as quantum wells, the zero-magnetic-field spin splitting (or spontaneous spin splitting) of the carriers can be achieved by the inversion asymmetry of the microscopic confining potential due to the presence of the heterojuction.[4] This corresponds to an inhomogeneous surface electric field and, hence, is electrically equivalent to the Rashba spin splitting or Rashba effect.[5] The state-of-the-art material engineering and micro and nanofabrication techniques have made it possible to achieve experimentally observable Rashba effect in, e.g., InAs- and $In_{1-x}Ga_xAs$-based two-dimensional electron gas (2DEG) systems. The value of the Rashba parameter in these spintronic systems has reached up to $\alpha \sim (3-4) \times 10^{-11}$ eV m.[6] The published experimental results[6,7] have indicated that in InAs-and $In_{1-x}Ga_xAs$-based 2DEG systems, the spontaneous spin splitting is mainly induced by the Rashba effect [with a SU(2) symmetry] which can be enhanced with increasing the gate voltage applied. Other contributions such as the Dresselhaus term [with a SU(1,1) symmetry] is relatively weak, because it comes mainly from the bulk-inversion asymmetry of the material.[8] Currently, the Rashba effect in a 2DEG is mainly identified via magnetotransport measurements[6,7] and most of the published work in the field of spintronics has been focused on electronic and transport properties of 2DEG's in the presence of the spin-orbit interaction (SOI), due to important applications as novel electronic devices.

In this paper, we study optoelectronic properties of spintronic systems in the presence of intense terahertz (10^{12} Hz or THz) electromagnetic (em) radiation. The prime motivation of this work is to examine how electrons in a spin-split 2DEG interact with intense laser field and to explore the possibility to achieve optical control of the spintronic devices. Here we focus our attention on single-particle aspects of the system. We consider an $In_{1-x}Ga_xAs$-based 2DEG in which SOI is induced by the Rashba effect. The growth direction of the 2DEG is taken along the z-axis. An em field with a vector potential $A(t)$ is applied along the z direction and is polarized linearly in the two-dimensional (2D)-plane (taken along the x direction). In this configuration, the em field couples to the potential induced by SOI and, as a result, the electronic subband structure can be perturbed optically. By including the lowest order of SOI induced by the Rashba effect,[4,5] the electron Hamiltonian can be written as

$$H(t) = \frac{p_x^2(t) + p_y^2}{2m^*} - \frac{\alpha}{\hbar}[\sigma_y p_x(t) - \sigma_x p_y] + U(z). \qquad (1)$$

Here, m^* is the electron effective mass, $p_y = -i\hbar\,\partial/\partial y$ is the momentum operator, when an em field is present $p_x \to p_x(t) = p_x - eA(t)$, σ_x and σ_y are the components of the Pauli spin matrix, α is the Rashba parameter, which measures the strength of the SOI, and $U(z)$ is the confining potential of the 2DEG along the growth direction. This Hamiltonian is a 2×2 matrix and the corresponding time-dependent Schrödinger equation can be solved analytically. Here we take $A(t) = (F_0/\omega)\sin(\omega t)$ under the usual dipole approximation, where ω and F_0 are, respectively, the frequency and electric field strength of the radiation field. The time-dependent electron wave function is then obtained as

$$\Psi_{n\mathbf{k}\sigma}(\mathbf{R},t) = \Psi_{n\mathbf{k}\sigma}(\mathbf{R},0)e^{-i[E_{n\sigma}(k)+E_{\rm em}]t/\hbar} \times e^{i\gamma\,\sin(2\omega t)}e^{ir_o(k_x+\sigma k_\alpha)[1-\cos(\omega t)]} \qquad (2a)$$

with

$$\Psi_{n\mathrm{k}\sigma}(\mathbf{R},0) = 2^{-1/2}(1,\sigma(k_y - ik_x)/k)e^{i\mathbf{k}\cdot\mathbf{r}}\psi_n(z) \qquad (2b)$$

being in the form of a row vector. Here, $\mathbf{R} = (\mathbf{r}, z) = (x, y, z)$, n is the index for the nth electronic subband along the z direction, $\mathbf{k} = (k_x, k_y)$ is the electron wave vector in the 2D plane, $k = (k_x^2 + k_y^2)^{1/2}$, $\sigma = \pm 1$ refers to different spin branches, and

$$E_{n\sigma}(k) = \hbar^2 k^2/2m^* + \sigma\alpha k + \varepsilon_n \qquad (3)$$

is the energy spectrum of the 2DEG. The electron wave function $\psi_n(z)$ and subband energy ε_n are determined by a

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spin-independent Schrödinger equation along the z direction. Furthermore, $E_{\rm em}=(eF_0)^2/4m^*\omega^2$ is an energy induced by the radiation field due to dynamical Franz-Keldysh effect,[9,10] $\gamma=E_{\rm em}/2\hbar\omega, r_0=eF_0/m^*\omega^2$, and $k_\alpha=\alpha m^*/\hbar^2$. It can be seen that because the radiation field couples to the spin orbits, the presence of the em field shifts the center of the electron wave function [so that $x\rightarrow x-r_0(1+\sigma k_\alpha/k_x)\cos(\omega t)$] and the shift depends on the SOI via $\sigma=\pm 1$.

With the time-dependent electron wave function, one can derive the retarded propagator or Green's function for electrons in time representation. For a spin-split 2DEG subjected to a radiation field, we have

$$G_{n\mathbf{k}\sigma,n'\mathbf{k}'\sigma'}(t,t') = \delta_{n',n}\delta_{\mathbf{k},\mathbf{k}'}\delta_{\sigma',\sigma}G_{n\mathbf{k}\sigma}(t,t'), \tag{4a}$$

where

$$G_{n\mathbf{k}\sigma}(t,t') = -\frac{i}{\hbar}\Theta(t-t')e^{i[E_{n\sigma}(k)+E_{\rm em}](t-t')/\hbar} \times e^{i\gamma[\sin(2\omega t)-\sin(2\omega t')]}e^{-ir_0(k_x+\sigma k_\alpha)[\cos(\omega t)-\cos(\omega t')]} \tag{4b}$$

is a two-time Green's function due to the time-dependent nature of the radiation field, with $\Theta(x)$ being the unit step function. Thus, the steady-state Green's function in spectrum representation can be obtained by Fourier analyzing $G_{n\mathbf{k}\sigma}(t,t')$ along the $t-t'$ direction and by averaging the initial time t' over a period of the em field,[10] which reads

$$G_{n\mathbf{k}\sigma}(E) = \sum_{M=-\infty}^{\infty}\frac{F_M^2[r_o(k_x+\sigma k_\alpha)]}{E-E_{\rm em}-E_{n\sigma}(k)-M\hbar\omega+i\delta}. \tag{5}$$

Here, E is the electron energy, an infinitesimal quantity $i\delta$ is introduced to make the integral coverage, $M>0$ ($M<0$) corresponds to channel for M-photon absorption (emission) and $M=0$ to a channel for elastic photon scattering, and $F_M(x)=\sum_{l=-\infty}^{\infty}J_l(\gamma)J_{2l-M}(x)$ with $J_N(x)$ being a Bessel function.

From the imaginary part of the retarded electron Green's function in spectrum representation, we can immediately obtain the electron density-of-states (DOS). From now on, we limit ourselves to the situation of a narrow-width quantum well in which only the lowest electronic subband is present (i.e., $n=0$). Measuring the energy from $\varepsilon_0=0$, the steady-state DOS for a 2DEG in the $\pm$ spin branch is given by

$$D_+(E) = \frac{D_0}{8\pi^2}\sum_{M=-\infty}^{\infty}\Theta(E_M^*-E_\alpha) \times \int_{-\pi}^{\pi}d\phi\int_{-\pi}^{\pi}d\phi'(1-\sqrt{E_\alpha/E_M^*})I_{M+}(\phi,\phi') \times C_{M+}(\phi,\phi') \tag{6a}$$

and

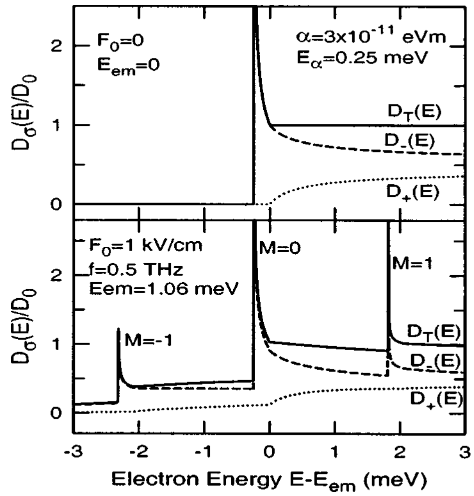

FIG. 1. Density of states for a 2DEG in the $\pm$ spin branches in the absence (upper panel) and presence (lower panel) of an em field at a fixed Rashba parameter α. Here, the electron energy E is measured from $E_{\rm em}=(eF_0)^2/4m^*\omega^2$, $D_0=m^*/\pi\hbar$, $D_T(E)=D_+(E)+D_-(E)$ is total DOS, $f=\omega/2\pi$, and in the lower panel $M=-1$, 0, and 1 are the contributions from, respectively, one-photon emission, elastic-photon scattering, and one-photon absorption. $E_\alpha=\alpha^2m^*/2\hbar^2$.

$$D_-(E) = \frac{D_0}{8\pi^2}\sum_{M=-\infty}^{\infty}\Theta(E_M^*)\int_{-\pi}^{\pi}d\phi\int_{-\pi}^{\pi}d\phi' C_{M-}(\phi,\phi') \times[(1+\sqrt{E_\alpha/E_M^*})I_{M-}(\phi,\phi')+\Theta(E_\alpha-E_M^*) \times(\sqrt{E_\alpha/E_M^*}-1)I_{M+}(-\phi,-\phi')]. \tag{6b}$$

Here, $D_0=m^*/\pi\hbar^2$, $E_\alpha=\alpha^2m^*/2\hbar^2$, $E_M^*=E-E_{\rm em}-M\hbar\omega+E_\alpha$, $A_0=r_0\sqrt{2m^*}/\hbar$, $C_{M\sigma}(\phi,\phi')=\cos\{M(\phi+\phi')+\sigma A_0\sqrt{E_\alpha}(\sin\phi+\sin\phi')-\gamma[\sin(2\phi)-\sin(2\phi')]\}$, and $I_{M\sigma}(\phi,\phi')=J_0[A_0(\sqrt{E_M^*}-\sigma\sqrt{E_\alpha})(\sin\phi+\sin\phi')]$. For the case of high-frequency and/or low-intensity radiation so that $A_0\sim F_0/\omega^2\rightarrow 0$, Eqs. (6a) and (6b) become the DOS of a spin-split 2DEG in the absence of the em radiation,

$$D_+(E) = (D_0/2)\Theta(E)[1-\sqrt{E_\alpha/(E+E_\alpha)}] \tag{7a}$$

and

$$D_-(E) = (D_0/2)[\Theta(E)(1+\sqrt{E_\alpha/(E+E_\alpha)}) + 2\Theta(-E)\Theta(E+E_\alpha)\sqrt{E_\alpha/(E+E_\alpha)}]. \tag{7b}$$

In this paper, the numerical results are presented for $In_{1-x}Ga_xAs$-based 2DEG systems in which the Rashba effect dominates the spintoronic properties. Here the electron effective mass is taken as $m^*=0.042m_e$ with m_e being the electron rest mass. In Fig. 1, the DOS for a 2DEG in the $\pm$ spin branches is shown in the absence and presence of a radiation field. We see that in contrast to a spin-degenerate 2DEG whose DOS is given simply by $D(E)=D_0\Theta(E)$, the DOS for a spin-split 2DEG depends strongly on the SOI. As a result, (i) electrons in different spin branches have different DOS; (ii) the DOS depends not only on those step functions but also on $E_\alpha\sim\alpha^2$ via E_α/E_M^*, because of a nonparabolic energy spectrum given by Eq. (3); (iii) the DOS in the − branch is always larger than that in the + branch, which implies that the electron density in the spin-down states is always larger than that in the spin-up states; and (iv) more importantly, the presence of the SOI leads to a redshift of the DOS by an energy $E_\alpha = \alpha^2 m^*/2\hbar^2$ and the maximum DOS can be observed at $E - E_{\rm em} = -E_\alpha$ in the spin-down branch. Moreover, when the radiation field is present, (1) the electron DOS is blueshifted by an energy $E_{\rm em} = (eF_0)^2/4m^*\omega^2$ because of dynamical Franz-Keldysh effect;[9,10] (2) the peaks of the DOS can be observed when $E - E_{\rm em} + E_\alpha = M\hbar\omega$ is satisfied, due to opening up of channels for optical transition including multiphoton emission and absorption. These peaks are mainly induced in the − spin branch; and (3) the DOS can exist even when $E - E_{\rm em} + E_\alpha < 0$ because of channels for optical emission, whereas there is no DOS when $E + E_\alpha < 0$ in the absence of the radiation (see upper panel of Fig. 1).

The electron DOS is one of the central quantities to determine and to understand almost all physically measurable properties. A direct and important application of the DOS for a 2DEG with SOI is to determine the Fermi energy of the spintronic system and the electron density in different spin orbits. The electron density in the spin branch σ is defined by $n_\sigma = \int_{-\infty}^{\infty} dE\, f(E) D_\sigma(E)$, with $f(E)$ being the Fermi-Dirac function. At a low-temperature limit (i.e., $T \to 0$), the electron density in the $\pm$ spin branches is obtained as

$$n_+ = \frac{D_0}{4\pi^2 A_0} \sum_{M=-\infty}^{\infty} \Theta(E_F^M - E_\alpha) \int_{-\pi}^{\pi} d\phi \int_{-\pi}^{\pi} d\phi' (\sqrt{E_F^M} - \sqrt{E_\alpha})\, \Pi_{M+}(\phi,\phi') C_M(\phi,\phi') \tag{8a}$$

and

$$n_- = \frac{D_0}{4\pi^2 A_0} \sum_{M=-\infty}^{\infty} \Theta(E_F^M) \int_{-\pi}^{\pi} d\phi \int_{-\pi}^{\pi} d\phi' C_{M-}(\phi,\phi') [(\sqrt{E_F^M} + \sqrt{E_\alpha}) \Pi_{M-}(\phi,\phi') + \Theta(E_\alpha - E_F^M)(\sqrt{E_\alpha} - \sqrt{E_F^M}) \Pi_{M+}(\phi,\phi')], \tag{8b}$$

where $E_F^M = E_M^*|_{E=E_F}$ with E_F being the Fermi energy and $\Pi_{M\sigma}(\phi,\phi') = (\sin\phi + \sin\phi')^{-1} J_1[A_0(\sqrt{E_F^M} - \sigma\sqrt{E_\alpha}) \times (\sin\phi + \sin\phi')]$. For the case of high-frequency and/or low-intensity radiation so that $A_0 \sim F_0/\omega^2 \to 0$, the electron density in the $\pm$ spin branch is given by Ref. 11; $n_\pm = (n_e/2) \mp (k_\alpha/2\pi)\sqrt{2\pi n_e - k_\alpha^2}$. With the condition of electron number conservation $n_e = n_+ + n_-$, where n_e is the total electron density of the 2DEG, the Fermi energy can be determined.

The dependence of the Fermi level and of the electron distribution in different spin orbits on frequency and intensity of the radiation field is shown in Figs. 2 and 3. From Fig. 2, we see that high- and low-frequency radiation affects rather weakly both the Fermi energy and the electron distribution, and a strong effect of the radiation on these quantities can be observed when $f = \omega/2\pi$ is at 0.1–1 THz for $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}$-based 2DEG systems. The main physical reasons behind this interesting phenomenon are as follows: (i) For high-frequency radiation so that $A_0 \sim \omega^{-2} \ll 1$, the effect of the radiation can be neglected. As a result, E_F and $n_\pm$ are close to those obtained at $F_0 = 0$. (ii) For low-frequency radiation so that $\hbar\omega \ll 1$, the energy exchange during an electron-photon scattering event is relatively small and the radiation therefore affects rather weakly the spintronic properties. (iii) However, when $f \sim 0.1$–1 THz, the photon energy $\hbar\omega$ is comparable to the spin energy E_α for $\mathrm{In}_{1-x}\mathrm{Ga}_x\mathrm{As}$-based systems. The radiation field couples strongly to the potential induced by the SOI and, hence, a strong effect of the radiation on spintronic properties can be expected. With increasing radiation frequency, the spin polarization [i.e., $p = (n_- - n_+)/n_e$] first decreases and then increases. With further increasing f, p decreases and becomes that in the absence of an em field when $A_0 \ll 1$.

From Fig. 3, we see that when the radiation frequency is at $f \sim 0.1$–1 THz, the strongest effect of the radiation on

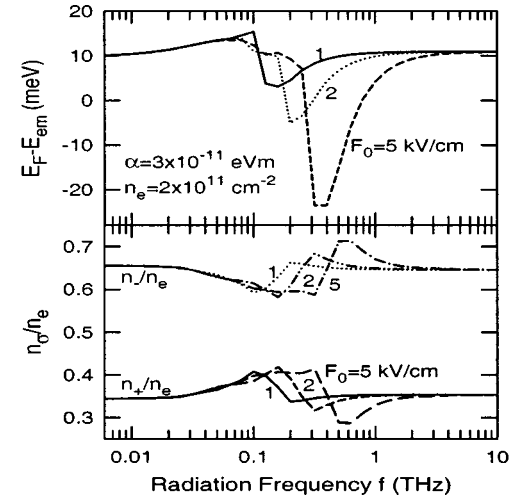

FIG. 2. Fermi energy E_F measured from $E_{\rm em}$ (upper panel) and electron density in different spin branches $n_\pm$ (lower panel) as a function of radiation frequency $f = \omega/2\pi$ at a fixed total electron density n_e and a fixed Rashba parameter α for different radiation intensities F_0 as indicated.

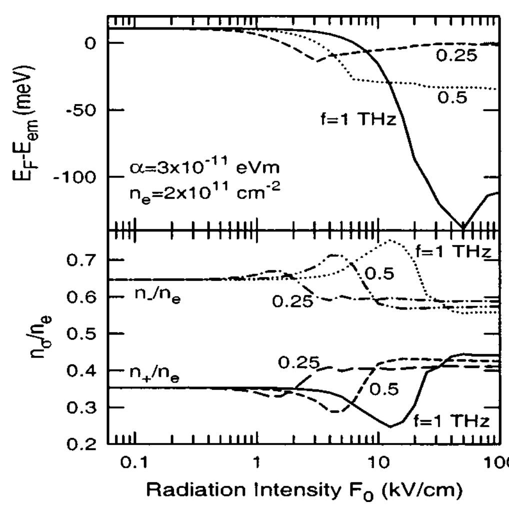

FIG. 3. Fermi energy $E_F - E_{\rm em}$ and electron distribution $n_\pm/n_e$ in the $\pm$ spin branches as a function of radiation intensity F_0 at a fixed total electron density n_e and a fixed Rashba parameter α for different radiation frequencies f as indicated.

spintronic properties can be observed when the radiation intensity F_0 is at about 10 kV/cm. For low-intensity radiation such that $A_0 \sim F_0 \ll 1$, the effect of the radiation field can be neglected and E_F and $n_\pm$ are close to those obtained at $F_0 = 0$. When F_0 is at about 10 kV/cm, the condition $A_0 E_\alpha^{1/2} \sim 1$ and $\hbar\omega \sim E_\alpha$ can be satisfied and, consequently, a strong radiation effect on spintronic properties can be observed. At very high excitation levels so that $A_0 E_\alpha^{1/2} \gg 1$, the radiation affects the Fermi energy strongly but the spin polarization weakly. In this case, the system cannot absorb fully the energy from the radiation field via the SOI and $E_F - E_{\rm em}$ therefore can become negative, which implies that photon emissions are principle channels for the determination of the Fermi level and the spin polarization. With increasing radiation intensity, the spin polarization first increases and then decreases. With further increasing F_0, p depends weakly on F_0.

The results shown above have demonstrated that when an intense THz em field is applied to an $In_{1-x}Ga_xAs$-based 2DEG with the SOI induced by the Rashba effect, the radiation field can couple strongly to the spin orbits and perturb significantly the spintronic properties of the device system. In such a case, the spin polarization, $p = (n_- - n_+)/n_e$, can be altered and enhanced optically from about 0.3 to 0.5 (more than 60%) through varying the radiation intensity or frequency. The most important conclusion drawn from these theoretical results is that intense laser radiation can be used to enhance spin polarization and to achieve optical control of the spintronic systems. At present, the best laser sources to provide intense THz radiation are far-infrared free-electron laser (FEL's).[9,12] In fact, using FEL's as intense THz radiation sources the dynamical Franz-Keldysh effect (DFKE) has been observed in spin-degenerate 2DEG systems via measuring the optical-absorption-edge (OPE).[9] It should be noted that the OPE connects directly to the electron DOS. Thus, the redshift of the DOS by a spin energy $E_\alpha = \alpha^2 m^* / 2\hbar^2$ (see Fig. 1) can also be measured via optical experiments and, hence, the Rashba parameter can be determined optically. Currently, the most popularly used experimental technique to identify the Rashba spin splitting is magnetotransport measurements that require Ohmic contacts and quantizing magnetic fields; in this case the Rashba effect is mixed with the Zeeman spin splitting. Therefore the optical examination of the Rashba spin splitting is more favorable. Finally, we hope that the important and interesting theoretical predictions merit attempts at experimental verification.

ACKNOWLEDGMENTS

The author received financial support from the Australian Research Council. Discussion with P. Vasilopoulos (Concordia University, Canada) are gratefully acknowledged.

*Electronic address: wen105@rsphysse.anu.edu.au

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