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Microwave-dressed electron–impurity interaction in a two-dimensional electron gas system under intense microwave radiation fields and weak magnetic fields

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ABSTRACT

Within a nonperturbative approach, the electron energy transfer rate induced by microwave-dressed electron–impurity interaction is analyzed theoretically in 2DEGs under weak perpendicular magnetic field. We find that for relatively low radiation levels cyclotron resonance (CR) is observed. However, when the radiation becomes intense, the peak of CR begins to split and the splitting increases with radiation intensity. Furthermore, we also show that multiphoton transition channels cannot be neglected in the vicinity of resonant region. The physical reasons behind these interesting finding are discussed.

1. Introduction

In the last three decades, especially since the discoveries of the quantized Hall effect [1] and fractional quantization [2], a lot of progress has been made in studying the optoelectronic and magneto-optical properties of two-dimensional electron gas systems (2DEGs), and very important and novel features of 2DEGs have been observed in the presence of external ac and dc fields, since magnetotransport in low-dimensional systems is a powerful tool to probe the nature of scattering centers and extract information about scattering-assisted electron transition between different Landau levels (LLs). In particular, transport under microwave (MW) radiation field in high mobility 2DEGs revealed many intriguing and unexpected phenomena, of which MW-radiation induced magnetoresistance oscillations (MIRO) [3–6] and associated zero-resistance states (ZRS) [7,8] are probably the most striking manifestation. Therefore, nonequilibrium transport phenomena such as MIRO, ZRS, HIRO (Hall field-induced resistance oscillations) [9] and ZdRS (Zero-differential resistance states) [10], to mention but a few, in high-purity 2DEGs subjected simultaneously to MW radiation field and perpendicular magnetic field have aroused great interest from the physical community [11]. In spite of numerous theoretical efforts, the true origin of these effects requires a great deal of further research effort in this area as well documented in Ref. [11].

In addition, when a electronic system such as 2DEG is subjected to MW radiation and quantizing magnetic fields in the Faraday geometry, both vector potentials induced by the radiation and magnetic fields couple with each other so that the cyclotron resonance (CR) effect is observable in this configuration. It is well known that scattering of electrons by ionized impurities is most important in 2DEGs at low temperature, where phonon effects are small. Such scattering events at low temperature can lead to electronic resonant transitions between different LLs, more specially, the effects of impurity CR (ICR) can be observed experimentally [12–15]. These effects of ICR in various electronic systems are already extensively investigated theoretically in the linea (in radiation field) approximation [16–20]. More interesting, when the radiation field is strong enough, apart from single-photon processes, multiphoton processes (nonlinear ICR) are possible. Such multiphoton ICR effects are also investigated in electronic systems both experimentally [21,22] and theoretically [23]. However, in the previous theoretical approaches, the radiation field has been often taken as a perturbation either or ICR effects occur at high magnetic field

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region. Note that for the case of intense radiation field, such an approach may not be held any more. Therefore, there is a need to investigate both theoretically and experimentally into the effects of ICR in 2DEGs subjected to intense MW radiation fields and weak perpendicular magnetic fields.

We now possess greatly interesting in investigating how electrons in a 2DEG (does not require high quality) response to intense MW radiation and weak static magnetic fields at low temperature. For this purpose we thus employ a nonperturbative approach [24] to evaluate electron interactions with intense MW radiation field for 2DEGs. In the present study, we intend contributing a theoretical work in handling microwave-dressed electron–impurity interaction in a 2DEG, in which the radiation field is included in a more exact way. Such a novel approach is presented in Section 2. In conjunction with magneto-optical measurement, in Section 3 the numerical results for magneto-optical properties of 2DEGs are calculated and the reasonable physical mechanisms are revealed. Finally, the main theoretical findings from this study are summarized in Section 4.

2. Theoretical considerations and approaches

In this paper, we are concerned with the microwave (MW) radiation effects on the magneto-optical properties of a typical heterojunction whose grown-direction is taken along the z-axis with a confining potential $V(z)$ in the presence of quantizing magnetic field B along that direction. Here, we consider the situation where: (i) the MW radiation field $A(t)$ is polarized linearly in the xy-plane (take along the x-direction); and (ii) the Landau gauge and the Coulomb gauge are adopted to describe the vector and scalar potentials respectively induced by the static magnetic field and by the MW radiation field. In such a configuration and known as the Faraday geometry, the cyclotron resonance (CR) effect can be observed experimentally as a result of the mutual coupling between the vector potentials induced by magnetic field and MW radiation field, respectively. In this case, due to those couplings in time-dependent electronic Hamiltonian of two-dimensional electron gas systems (2DEGs) under the external fields, the Kramers–Heneberger unitary transformation [25,26] is unsuitable for seeking the solution of the corresponding time-dependent Schrödinger equation (TDSE). In this work, we thus employ a nonperturbative approach to seek the solution of TDSE for 2DEGs, which is proposed in Ref. [24] by solving analytically the TDSE for a parabolically confined quantum dot (QD) in which the magnetic and radiation fields are included exactly.

Within the framework of the effective mass approximation and assuming that the electron effective mass m^* is isotropic, the time-dependent Hamiltonian for 2DEGs under external fields in the laboratory frame can be written, in the presence of scattering center, as

$$H(t) = H_0(t) + H_i(\mathbf{R}), \tag{1}$$

where the unperturbed electron Hamiltonian for 2DEGs is given by

$$H_0(t) = \frac{[p_x - eA(t)]^2 + (p_y + eBx)^2 + p_z^2}{2m^*} + V(z), \tag{2}$$

and $H_i(\mathbf{R})$ in Eq. (1) represents an external potential with an explicit dependence on the spatial coordinates and known as perturbation. Here, $p_x = -i\hbar\partial/\partial x$ is the momentum operator along the x direction, $A(t) = \Theta(t)(F_0/\omega)\sin(\omega t)$ is the vector potential induced by the radiation field with $\Theta(x)$ being the unit-step function, and F_0 and ω are respectively the radiation intensity and the radiation frequency of the applied MW radiation field. In Ref. [24], the corresponding TDSE has been solved analytically. As a result, the electron wave function is directly deduced, in the moving frame, by

$$|n,\nu,t\rangle = \Psi_{n\nu}(\mathbf{R},t) = \psi_{n\nu}(\mathbf{r},t)\phi_n(z), \tag{3}$$

where

$$\psi_{n\nu}(\mathbf{r},t) = e^{ik_y y}\chi_N(x-X)e^{-i(\epsilon_N+\varepsilon_n+\Lambda)t/\hbar},$$

and the corresponding energy spectrum of 2DEGs given as

$$E_{n\nu} = \mathbb{E}_N + \varepsilon_n. \tag{4}$$

Here, $\nu = (Nk_y)$ refers to quantum numbers for sates in the xy plane, $\mathbf{R} = (\mathbf{r}, z) = (x, y, z)$, k_y is the electron wavevector along the y-direction, $X = -l^2 k_y$ with $l = (\hbar/eB)^{1/2}$ being the radius of the ground cyclotron orbit and with $\omega_c = eB/m^*$ being the cyclotron frequency respectively, and $\mathbb{E}_N = (N + 1/2)\hbar\omega_c$ is the Nth Landau level (LL) with $N = 0, 1, 2, \ldots$. The wave function $\phi_n(z)$ and the corresponding electronic subband energy ε_n are determined by time-independent Schrödinger equation along the growth-direction, which are not directly affected by the external fields. In Eq. (3), $\chi_N(x) = \left(2^N N!\pi^{1/2}l\right)^{-1/2} e^{-\varsigma^2/2}H_N(\varsigma)$ with $H_N(x)$ denoting the Hermite polynomials and with $\varsigma = x/l$. In contrast to the electron wave function in Eq. (3) in that frame, the one in the laboratory frame takes as a form

$$\Psi'_{n\nu}(\mathbf{R},t) = e^{ik_y y}\chi_N(x - X - x_t)\, e^{-i(\mathbb{E}_{n\nu}t + \int_0^t d\tau f(\tau))/\hbar} \times e^{i(u_t x - y_t\hbar y)/\hbar}\phi_n(z), \tag{5}$$

where the coordinate shifts are

$$x_t = r_0\cos(\omega t) - r_0\cos(\omega_c t)$$

and

$$y_t = r_1\sin(\omega t) - r_0\sin(\omega_c t),$$

with $r_0 = (eF_0/m^*)/(\omega^2 - \omega_c^2)$ and $r_1 = (eF_0\omega_c/m^*\omega)/(\omega^2 - \omega_c^2)$. The shifts of phase is

$$u_t = r_2\sin(\omega t) - r_3\cos(\omega_c t),$$

with $r_2 = (eF_0\omega_c^2/\omega)/(\omega^2 - \omega_c^2)$ and $r_3 = eF_0\omega_c/(\omega^2 - \omega_c^2)$. Furthermore,

$$f(t) = \frac{1}{2m^*}\left[(u_t + eA(t))^2 + (eBx_t)^2\right] - \dot{u}_t x_t.$$

Notice that $u_t = x_t = y_t = 0$ has been taken as initial conditions when $t = 0$. Most importantly, the wave function in Eq. (5) is completely in line with that in Ref. [27]. At the same time, the potential $H_i(\mathbf{R})$ becomes time-dependent MW-dressed $H_i(\mathbf{R}')$ and regarded as a perturbation in such moving frame with $\mathbf{R}' = (\mathbf{r}', z) = (x - x_t, y - y_t, z)$ being the time-dependent coordinates shifted by the magnetic and MW radiation fields. In the following section we investigate the magneto-optical properties of 2DEGs in the accelerated frame, because as we known that the properties of semiconductors remain completely unchanged after performing arbitrary unitary transformation on it.

With the time-dependent electron wave function in Eq. (3) and the corresponding energy spectrum in Eq. (4), the electron d–d correlation function can be derived analytically. In order to study the magneto-optical properties of 2DEGs in the presence of MW radiation and magnetic fields, it is convenient to derive the electron density–density (d–d) correlation function (or pair bubble) in $(\mathbf{q}, t)$-representation. Here $\mathbf{q} = (q_x, q_y)$ is the factor of Fourier transform in the xy-plane, which corresponds to the change of the electron wave-vector during a scattering event. In such a case, the electron d–d correlation function is defined as

$$\Pi(\mathbf{q},t) = \frac{\Theta(t)}{i\hbar}\frac{g_s}{2\pi l^2}\sum_{\lambda',\lambda}\langle[\rho_{\lambda'\lambda}(\mathbf{q},t), \rho_{\lambda\lambda'}(-\mathbf{q},0)]\rangle, \tag{6}$$