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Effect of intense terahertz laser and magnetic fields on the binding energy and the transition energy of shallow impurity in a bulk semiconductor

Weiyang Wang[a,*], Lei Xu[a], Bo Wu[a], Sha Zhang[a], Xiangfei Wei[b]

[a] *School of Physics and Electronics Information, Shangrao Normal University, Shangrao, Jiangxi 334001, People's Republic of China*
[b] *West AnHui University, LuAn 237012, People's Republic of China*

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ABSTRACT

The influences of intense terahertz laser and magnetic fields on shallow-donor states in GaAs bulk semiconductors in the Faraday geometry are studied theoretically in the framework of the effective-mass approximation. The interaction between the laser field and the semiconductor is treated nonperturbatively by solving analytically the time-dependent Schrödinger equation in which the two external fields are included exactly. In the nonresonant region, we have found that the binding and transition energies decrease with increasing laser-field intensity or decreasing laser-field frequency, and the binding energy increases with magnetic field. For relatively low radiation levels, the transition energy first slowly decreases with increasing magnetic field, but after a critical value, it rapidly increases with increasing magnetic field. However, it slowly decreases with magnetic field when the laser-field intensity is strong enough. Furthermore, in the vicinity of the resonant regime, the oscillatory behaviours of the binding and transition energies with laser-field frequency and magnetic field are observed. These results obtained indicate the possibility of manipulating the shallow impurity states in semiconductor by changing the intense laser-field frequency and intensity and the magnetic field, which gives a new degree of freedom in semiconductor device application.

1. Introduction

With the advent of high-power, long-wavelength, frequency-tunable, linearly polarized laser sources such as terahertz (THz) or far-infrared free-electron lasers, studying on the interaction of intense THz laser field with electrons in semiconductors and related nanostructures has aroused great interest from physical community [1]. Many interesting THz phenomena have been already observed in semiconductor systems under intense THz laser field, such as resonant absorption [2], the photon enhanced hot-electron effect [3], THz photon-induced impact ionization [4], THz photon assisted tunneling [5], and THz cyclotron resonance (CR) [6], to mention but a few. This is mainly because the applied THz laser-field frequency is of the same order of the characteristic frequencies for the considered semiconductors and related nanostructures, which implies that the intense THz laser field can intensively interact with semiconductors and related nanostructures and modify strongly the relevant processes of momentum and energy excitation and relaxation of electrons in such structures. In particular, the physical properties of shallow impurity states and their behaviors when irradiated by a linearly polarized intense THz laser field in bulk semiconductors [7–9] and related nanostructures [10–14] have received tremendous interest of scientists to investigate such novel features of impurities in the last decades. Such attention has been motivated, in part, due to the possibility of designing new efficient optoelectronic devices [15,16] which depend on understanding of the basic physics involved in the interaction process between the intense THz laser field and electrons in extrinsic semiconductors. In such a case, the binding and transition energies associated with the shallow-donor impurities decrease monotonically (in absolute values) with increasing the laser-field intensity or decreasing the laser-field frequency [17]. More interesting, the shallow impurity in bulk semiconductors becomes stability against ionization in the high-intensity limit at a fixed laser-field frequency [18]. These interesting results show that the physical properties of shallow-donor impurity states can be modulated by the applied intense THz laser field in bulk semiconductors, which certainly shows up as modification of optical properties in such electronic systems.

Recently, the research interest of physicists around the world has focused on the nonlinear magneto-optical properties of shallow-donor impurity states in quantum wells [19–21], quantum well wires [22,23], and quantum dots [24] subjected simultaneously to an intense THz laser field and a static magnetic field, due to opening up a promising

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[*] Corresponding author.
E-mail addresses: Wang.Weiyang.CMT@foxmail.com (W. Wang), flyxfwei@gmail.com (X. Wei).

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new route to manipulate semiconductor devices by changing the external applied fields. These studies show that the binding energy as well as the other physical properties of shallow-donor impurity states in such nanostructures in the presence of intense THz laser and magnetic fields are determined not only by the laser-dressed Coulomb potential and the laser-dressed confinement potential and geometrical parameters of the considered nanostructures, but also by the polarization direction of laser field and the magnetic field, which suggests that the physical properties of shallow impurity states in semiconductor systems can be regulated by the external applied fields. It is worth to note that the previous studies by employing nonperturbative approaches [19–24] have never considered the Faraday configuration, in which the vector potential induced by the laser field couples directly to that of induced by magnetic field so that the CR effects can be observed experimentally. This is mainly because the previous theoretical approaches such as the dressed-atom approach [20–22] and the dressed-band approach [19,23,24] donot suit to investigate the properties of shallow impurity states in the semiconductor systems under intense THz laser and magnetic fields in such geometry. Furthermore, to the best of our knowledge, there are no studies on the influences of intense THz laser and magnetic fields on the binding energy, the transition energy, as well as the other physical properties of shallow-donor impurity in bulk semiconductors up to now, especially in the Faraday geometry. Thus, there is a urgent need to develop a new nonperturbative theory to study the nonlinear magneto-optical properties of shallow impurity in bulk semiconductors under the two strong external fields in this geometry.

In this study, we intend contributing theoretical work in investigating the influences of intense THz laser and magnetic fields on the binding and transition energies associated with the shallow-donor impurity in bulk semiconductors in the Faraday configuration, in which the external applied laser field is exactly included in the laser-dressed Coulomb potential. Such a novel nonperturbative approach is developed in Section 2. In conjunction with optical measurements, the numerical results for the binding and transition energies of shallow impurity affected by the external applied fields are discussed in Section 3. In Section 4, the main summarizations are presented.

2. Theoretical considerations and approaches

In this paper, we consider one electron with a shallow-donor impurity in bulk semiconductors subjected simultaneously to a static magnetic field and an intense terahertz (THz) laser field along the z-direction, where the laser field is polarized linearly in xy-plane (taken along the x-direction). Under the usual dipole approximation, the vector potential induced by the laser field is given as $A_t = \Theta(t)(F_0/\omega)\cos(\omega t)$, where $\Theta(x)$ is the unit-step function and F_0 and ω are the electric field strength and the frequency of the applied THz laser field, respectively. Within the effective mass approximation and assuming that the dielectric constant ϵ and the electron effective mass m^* are both isotropic, the time-dependent Schrödinger equation (TDSE) for describing the electron-impurity systems can be written, in the laboratory frame, as

$$i\hbar\frac{\partial}{\partial t}\Psi(t) = \left[\frac{(p_x - eBy/2 + eA_t)^2 + (p_y + eBx/2)^2 + p_z^2}{2\,m^*} - \frac{e^2}{4\pi\epsilon|\overrightarrow{R}|}\right]\Psi(t), \tag{1}$$

where $p_x = -i\hbar\partial/\partial x$ is the momentum operator along the x-direction and the last term is the Coulomb potential induced by electron-impurity interaction with $\overrightarrow{R} = (\overrightarrow{r}, z)$. Seeing from the Eq. (1), we have already entered into the Faraday geometry due to the mutual coupling between the vector potentials respectively induced by intense THz laser and magnetic fields, so that the cyclotron resonance (CR) effects can be observed experimentally. As a result, the dressed-atom approach [20–22] based on the Kramers-Henneberger (KH) unitary transformation [25,26] is no longer suitable for seeking the solution of the TDSE given in Eq. (1). Moreover, we have also entered into a regime with different competing energies, that is, the characteristic energies of the bulk semiconductors are on the order of millielectronvolts, which implies that the dressed-band approach cannot be used to study the nonlinear magneto-optical properties of shallow impurity states in bulk semiconductors for such a case, because this method is only valid far away from the resonant region [19,23,24]. Thus, so far there is no mature and effective theoretical approach to solve Eq. (1). Here we develop a nonperturbative approach to handle with this time-dependent problem, which shows that the TDSE can be solved exactly. According to the nonperturbative treatment for electron-photon interaction previously proposed by solving analytically the TDSE in a parabolical quantum dot [27], which has been successfully adopted for investigating the microwave-dressed electron-impurity interaction in a two-dimensional electron gas system under intense microwave radiation and weak magnetic fields [28], we thus define a new unitary transformation

$$\Psi(t) = U(t)\psi(t), \tag{2}$$

with the time-dependent unitary operator

$$U(t) = \exp\left[-\frac{i}{\hbar}\int_0^t d\tau f(\tau)\right]\exp\left[\frac{i}{\hbar}(u_t x + v_t y)\right]\exp\left(\frac{i}{\hbar}x_t p_x\right)\exp\left(\frac{i}{\hbar}y_t p_y\right). \tag{3}$$

Following Ref. 28 and requiring that the Schrödinger equation for the state $\psi(t)$ doesn't contain A_t term, the Eq. (1) can be rewritten, in the moving frame, as

$$i\hbar\frac{\partial}{\partial t}\psi(t) = \left[\frac{(p_x - eBy/2)^2 + (p_y + eBx/2)^2 + p_z^2}{2\,m^*} - \frac{e^2}{4\pi\epsilon|\overrightarrow{R}\,'|}\right]\psi(t), \tag{4}$$

where the last term becomes the laser-dressed Coulomb potential with $\overrightarrow{R}\,' = (\overrightarrow{r}\,', z) = (x - x_t, y - y_t, z)$ being the time-dependent coordinates shifted by the THz laser and magnetic fields. The shifts of the coordinates are obtained by

$$x_t = r_0\sin(\omega t) - r_1\sin(\omega_c t) \tag{4a}$$

and

$$y_t = r_1\cos(\omega_c t) - r_1\cos(\omega t), \tag{4b}$$

where $r_0 = (eF_0/m^*)/(\omega_c^2 - \omega^2)$, $r_1 = \eta r_0$ with $\eta = \omega_c/\omega$, and $\omega_c = eB/m^*$ is the cyclotron frequency. Obviously, the laser-dressed Coulomb potential is deeply affected both by the intense THz laser field and magnetic field, which is significant different from that of in Refs. 20–23 only influenced by radiation field. Furthermore, in the absent of the applied magnetic field (i.e., $B \to 0$), due to $\lim_{B\to 0} r_1 = 0$, the laser-dressed Coulomb potential reduces to $-e^2/[4\pi\epsilon|\overrightarrow{R} + \overrightarrow{\alpha}\sin(\omega t)|]$ with $\alpha = eF_0/m^*\omega^2$, which is completely in line with that of in semiconductor systems only subjected to radiation field and obtained by using the KH approach [7–9,11]. As well known that the physical properties of semiconductor systems remain completely unchanged after performing arbitrary unitary transformation on it, in the following section, we thus investigate the physical properties of the shallow impurity states in bulk semiconductors under the external applied fields in the accelerated frame. In addition, more detail information about the term $f(t)$ and the phase shifts u_t and v_t can be found in Ref. 27.

The coordinate shifts x_t and y_t given in Eqs. (4a) and (ab) are obviously nonperiodic in time so that the laser-dressed Coulomb potential is no longer a periodic function of time. Thus, the Floquet theory [26] cannot be used to seek for a quasiperiodic solution of the Eq. (4), which has been extensively applied to study the physical properties of shallow impurity states in semiconductor systems under intense THz laser field [7–9,11–14,17,18]. As a result, there is no simple analytical solution for the TDSE as shown in Eq. (4). Here, we thus employ the variational method to calculate the energy E of the