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Terahertz field-induced modulations of intersubband absorptions in quantum wells*

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Nonlinear optical properties of intersubband electrons in a 3-level quantum well under intense terahertz field are investigated by using a density matrix approach. The results show that the terahertz fields with different frequencies cause the distinct modulations of the intersubband absorptions. The terahertz-induced sideband and Autler–Towns splitting in the absorption spectrum are obtained, respectively for the terahertz-photon energy below and close to the transition energy between the ground and first excited state.

Keywords: terahertz field, intersubband transition, sideband absorption, AC-stark splitting
PACC: 7800, 7320D

1. Introduction

The modulations of optical properties in semiconductor quantum well (QW) induced by an intense laser field have been investigated by several groups.[1−7] The effects can be applied to the modern optical telecommunications, such as efficient optical modulators,[8] all optical switches,[9] and wavelength division multiplexing.[10] The characteristic energies of electrons in low-dimensional semiconductors are often in a range of milli-electron volts, which correspond to terahertz (THz) frequencies. Therefore the THz fields can strongly modify the quantum states of low-dimensional semiconductors and influence their electronic and optical properties. When the subband energy difference is close to the THz-photon energy, the intense THz field can couple with the quantum states to form dressed states. Quantum interferences in the intersubband transitions of semiconductor QW can lead to many interesting phenomena, for example, electromagnetically induced transparency,[1,2] coherent control of electron transitions,[3] coherent population trapping,[4] and intersubband gain via multiphoton processes.[5] The coherent control based on quantum interferences can be successfully applied in semiconductor physics, which has been shown experimentally.[6,7]

Recently there has been a rapid development of THz sources, such as the negative-effective-mass oscillator,[11,12] the inflection-point THz oscillator,[13,14] and THz quantum cascade lasers,[15−17] which provide a new experimental capability for studying the transport and optical properties of electrons in semiconductor QW. Many distinctive THz-induced phenomena have been well investigated,[17−25] such as THz photon-induced impact ionization,[18,19] dynamical Franz–Keldysh effect,[20] AC-Stark effect,[6] and THz optical sideband and mixing.[21−23] Most of them are devoted to the interband optical responses and the modifications of both electron and hole states under THz fields where as, the influences of an intense THz radiation on intersubband transitions are scarcely investigated to the best of our knowledge. Compared with the interband transitions, the intersubband resonances in semiconductor QW have a closely spaced quantum confined levels with transition energies in a THz range, and have unique properties including a large dipole moment, an ultrafast dynamic response and a large tunability of transition wavelength. Intersubband reso-

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nances are also the physical basis for the sources and detectors of THz radiation.[26] In this paper we study theoretically the effect of the intense THz field on intersubband absorptions. The distinct nonlinear modulations of optical properties by THz fields in the cases of resonance and nonresonance are discussed in detail. Such a strong THz field can be achieved by using free-electron or gas lasers experimentally.

The paper is organized as follows. In Section 2 we give the theoretical model used to describe the dynamics of subband populations and intersubband polarizations based on the density matrix theory, and then we obtain the intersubband optical properties of a double QW structure under the THz pump. The results for the numerical description are discussed in Section 3. Concluding remarks are given in Section 4.

2. Microscopic theoretical model

We consider one-electron states in each subband μ of the conduction band having a certain momentum k in a plane of QW. In the second quantization, the Hamilton of this system for subbands interacting with electromagnetic field $E(t)$ in a rotating frame can be written as[27]

$$\begin{aligned} H =& H_0 + H_{\rm I} + H_{\rm C} = \sum_{\mu,k} \varepsilon_{\mu,k} a^{\dagger}_{\mu,k} a_{\mu,k} \\ & - \sum_{\{\mu,\nu\}k} (d_{\mu\nu,k} E(t) a^{\dagger}_{\mu,k} a_{\nu,k} \\ & + d^{*}_{\mu\nu,k} E^{*}(t) a^{\dagger}_{\nu,k} a_{\mu,k}) \\ & + \frac{1}{2} \sum_{\mu\nu\mu'\nu'kk',q} V_q^{\mu\nu\nu'\mu'} a^{\dagger}_{\mu,k+q} a^{\dagger}_{\nu,k'-q} a_{\nu',k'} a_{\mu',k}, \quad (1) \end{aligned}$$

where H_0 is the kinetic term, $H_{\rm I}$ and $H_{\rm C}$ represent the interaction with electromagnetic field and the Coulomb interaction, ε_μ, $a^{\dagger}_\mu$ and a_μ are the electron energy, electron creation and electron annihilation operators of the μth subband, and $d_{\mu\nu,k} = e\int F^{*}_{\mu k}(z) z F_{\nu k}(z) {\rm d}z$ is the dipole matrix element, and $F_{\mu k}$ is the envelope wavefunction.

We propose probing the THz-field-induced modulations in the quantum-well energy spectrum by intersubband-absorption measurements with a weak ultrafast mid-infrared probing beam. The ultrafast probing beam is assumed to be a Gaussian pulse $E_{\rm pro}(t) = E_0 \exp[-t^2/\Delta^2] \exp[-{\rm i}\omega_{\rm pro} t]$, in which Δ is the duration of the pulse, $\omega_{\rm pro}$ is the central frequency of the probing beam. For a three-subband system driven by a growth-direction-polarized THz electric field $E(t) = E_{\rm THz}\cos(\omega_{\rm THz} t)$, the electron distribution function $f_{\mu k}$ of the μth subband and the intersubband polarization $p^{\mu\nu}_k$ $(\mu, \nu = 1, 2, 3)$ in the Hartree–Fock approximation satisfy the intersubband semiconductor Bloch equations (ISBEs):[27,28]

$$\begin{aligned} \frac{{\rm d}f_{\nu k}}{{\rm d}t} =& (-1)^{\nu} \sum_{\mu\neq\nu} \Im[2(\Omega_{\mu\nu,k} - \varepsilon_{\mu\nu k}/\hbar) p^{\mu\nu}_k] \\ & + \frac{{\rm d}f_{\nu k}}{{\rm d}t}|_{\rm coll}, \quad (2) \end{aligned}$$

$$\begin{aligned} \frac{{\rm d}p^{\mu\nu}_k}{{\rm d}t} =& \frac{1}{{\rm i}\hbar}(\varepsilon_{\mu k} - \varepsilon_{\nu k}) p^{\mu\nu}_k \\ & + {\rm i}(\Omega_{\mu\nu,k} - \varepsilon_{\mu\nu k}/\hbar)(f_{\mu k} - f_{\nu k}) \\ & + \frac{{\rm d}p^{\mu\nu}_k}{{\rm d}t}|_{\rm coll}, \quad (3) \end{aligned}$$

where $\Omega_{\mu\nu,k} = d_{\mu\nu,k} E(t)/\hbar$ is the Rabi frequency. The collision terms in the above equations describe electron–phonon and electron–impurity scattering, and possibly other dephasing mechanisms. In the dephasing rate approximation, we assume

$$\frac{{\rm d}p^{\mu\nu}_k}{{\rm d}t}|_{\rm coll} = -\gamma_{\mu\nu} p^{\mu\nu}_k$$

and

$$\frac{{\rm d}f_{\nu k}}{{\rm d}t}|_{\rm coll} = -\gamma_{\nu}(f_{\nu k} - f^{\rm FD}_{\nu k}),$$

where $\gamma_{\mu\nu}$ denotes the total transition dephasing time and γ_ν is the population decay of subband ν, $f^{\rm FD}_{\nu k}$ is the equilibrium distribution function. The renormalized single particle energy $\varepsilon_{\mu k}$ with Coulomb self-energy correction and the local field correction $\varepsilon_{\mu\nu k}$ are, respectively, given by

$$\varepsilon_{\mu k} = E^{(0)}_{\mu k} - \sum_{\nu,q} V_q^{\mu\nu\mu\nu} f_{\nu,k+q}, \quad (4)$$

$$\varepsilon_{\mu\nu k} = -\sum_{m\neq n,q} V_q^{\nu m\mu n} p^{mn}_{k+q} + \sum_{m\neq n,q} V_0^{\nu mn\mu} p^{mn}_q. \quad (5)$$

The Coulomb matrix element $V_q^{\nu m\mu n}$ is defined as what it is defined as in Ref.[29], and the subband dispersion $E^{(0)}_{\mu k}$ and the envelope function $F_{\mu k}$ can be obtained by solving the Schrődinger–Poisson equations self-consistently.[30] The local field correction consists of two Coulomb interactions: the vertex term with $q \neq 0$ (first) and the depolarization term with $q = 0$ (second), these two collective excitations are responsible for the FES and ISP.[28]

The ISBEs are solved numerically by using the fourth-order Runge–Kutta method. The subband population can be obtained by summing different k parts. The total intersubband polarization function P can be computed as follows:

$$P = \frac{2S}{(2\pi)^2 V} \sum_{\mu\neq\nu} \int {\rm d}k (d^{\mu\nu}_k)^{*} p^{\mu\nu}_k, \quad (6)$$

where $V = WS$ is the QW volume, W and S are the width and normalization area of the QW. For linear response problem, the intersubband absorption coefficient $\alpha(\omega)$ is related to the imaginary part of the optical susceptibility $\chi(\omega)$ by the following expression:

$$\alpha(\omega) = \frac{\omega}{n(\omega)c}\Im(\chi(\omega)) = \frac{\omega}{n(\omega)c}\Im(\frac{P(\omega)}{\varepsilon_0 E(\omega)}), \qquad (7)$$

where $P(\omega)$ and $E(\omega)$ are the Fourier transforms of the polarization and the electric field, and c is the speed of light in vacuum.

3. The THz-induced intersubband absorption

We study here the symmetric double QW structure, which consists of two 7.0 nm GaAs coupled QW separated by a 1.13 nm $Al_{0.3}Ga_{0.7}As$ barrier. Each double QW structure is separated by a modulation-doped 30 nm wide $Al_{0.3}Ga_{0.7}As$ barrier. The doping density is $1 \times 10^{11}cm^{-2}$. The symmetric design causes the transition from the ground subband to the second excited subband to be prohibited. The eigen energies and the wave functions of confined electrons in the conduction band can be obtained from self-consistently solving Schrödinger–Poisson equations in an effective mass approximation.[30] The inset in Fig.1 shows the calculated wave functions and the structure scheme. The lowest three conduction subbands are taken into consideration in our model. The energy separation between the ground subband and the first excited subband is $E_{12} = 12.4$ meV, and the energy separation between the upper two excited subbands is $E_{23} = 118.0$ meV. In our calculation, the subband population decay $\gamma_1 = \gamma_2 = \gamma_3 = 0.01$ meV. The transition dephasing times γ_{12} and γ_{23} are set to be 0.03 meV, while $\gamma_{13} = 0.01$ meV as a result of the dipole forbidden transition between the subband 1 and 3. A strong THz laser will couple the E_{12}, and a weak probe light with a frequency around the energy difference between the upper two levels will be used to detect the absorption spectrum.

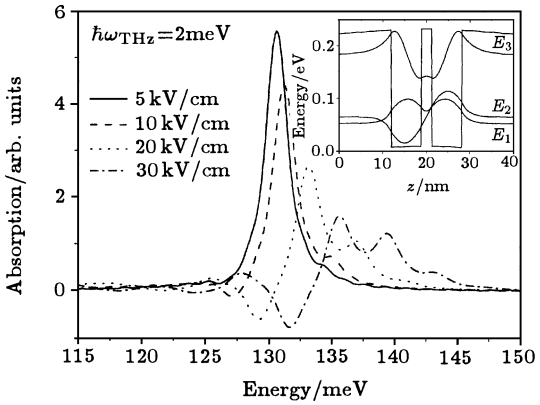


Fig.1. Optical absorption of the double QW in the presence of a low-frequency THz field ($\hbar\omega_{THz} = 2$ meV). The THz strengths are respectively 5, 10, 20, and 30 kV/cm. The inset shows the QW structure sketch and the confinement wavefunctions calculated self-consistently.

Firstly, we study the optical properties of the double QW structure in the presence of a THz field with $\hbar\omega_{THz} = 2$ meV, which is much lower than the energy separation E_{12}. The results are shown in Fig.1, in which the THz intensities are E_{THz} =5, 10, 20, and 30 kV/cm respectively. It can be seen that the THz field shifts the absorption peaks towards the higher energy values and reduces the magnitude of the absorption with the strength of THz field increasing. These effects are also called AC-Stark effects, which are due to the lowering of the energy-level of the first subband by the THz field. More importantly, we also see that the intense THz field causes the THz sidebands in the absorption spectrum. The frequencies of the THz sideband absorptions are $\omega_{sideband} = \omega_{pro} + 2n\omega_{THz}$, n is an integer. Due to the symmetry of our QW structure, only the even sidebands can be obtained and they are separated by twice the THz frequency, corresponding to the energy separation $2\hbar\omega_{THz}$=4 meV. As the strength of THz field increases, more replicas corresponding to the high-order THz sidebands are obtained. In addition, the negative absorption in the spectrum is usually called intersubband Raman gain, which is caused by the multi-photon dressed effects and Raman scattering.[4,5] This feature can be used to implement the intersubband lasers without population inversion(LWI). The studies of LWI in semiconductor QW has also attracted great attention recently.[1,5]

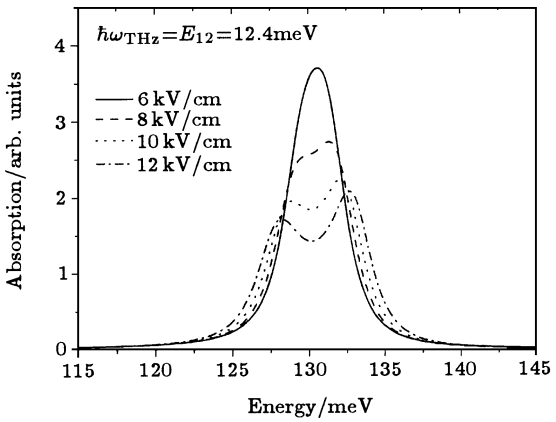


Fig.2. Absorption spectrum induced by the resonant ($\hbar\omega_{\rm THz} = 12.4\,$meV) THz field. The THz amplitudes are, respectively, $E_{\rm THz} = 6, 8, 10,$ and $12\,$kV/cm.

If the THz frequency is close to the energy separation E_{12} ($\hbar\omega_{\rm THz} = 12.4\,$meV), the transition between the subband 1 and 2 is resonantly coupled with the THz field. Figure 2 shows the optical absorption spectra in this case at different THz intensities. The lowest THz intensity produces a weak Lorentzian absorption peak centred at $E_{13} = 130.4\,$meV with 4 meV full width at half maximum (FWHM). As $E_{\rm THz}$ increases to 8 kV/cm the FWHM of the absorption peak broadens to about 6 meV [dashed line]. At higher $E_{\rm THz}$ an increasingly well-resolved doublet structure appears [dotted line and dot-dashed line], and it is also called Autler–Townes splitting. This phenomenon can be explained by the quantum interference between the THz photon state and the intersubband transition state, and the double peaks correspond to the new photon-electron coupled states. Meanwhile we can see that the splitting energy is proportional to the strength of the THz field. For weaker fields a clear splitting at the resonance is not observed, both peaks are merged with each other into one broadened peak. As the THz strength augments, the splitting energy increases to about 5.2 meV at $E_{\rm THz} = 12\,$kV/cm. In the time domain, we show in Fig.3 the time evolution of the electron populations for subbands 1 and 2 in the presence of a resonant THz field with $E_{\rm THz} = 12\,$kV/cm. We can see that the electron populations of the subbands 1 and 2 experience rapid Rabi oscillations at a period of 0.75ps, then reach a steady state after 3 ps. The small fluctuations result from the intrinsic oscillations of THz field. By quantum interference theory, for $E_{\rm THz} = 12\,$kV/cm the energy separation between the new coupled electron–photon eigenstates is $\hbar\Omega_{12} = d_{12}E_{\rm THz} \approx 5.4\,$meV, where the dipole matrix element $d_{12} = 45e\cdot$Å(Here e is the electron charge). The electron population is expected to cycle coherently between the ground and first excited state at a period $\tau = 2\pi/\Omega_{12} \approx 0.76\,$ps. So our simulated results based on Bloch equation are in good agreement with the evaluation from quantum interference theory.

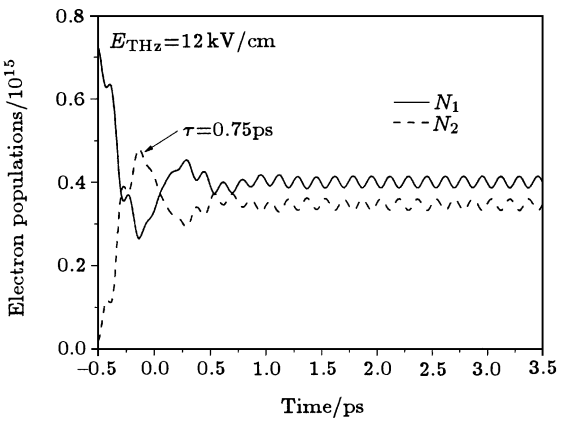


Fig.3. Time evolution of the electron populations for two lower subbands 1 and 2 in the presence of a resonant THz field. The THz field have the frequency $\hbar\omega_{\rm THz} = 12.4\,$meV and amplitude $E_{\rm THz} = 12\,$kV/cm.

In Fig.4 we show the optical absorption spectra for $E_{\rm THz} = 9\,$kV/cm when changing the THz frequency. As the THz frequency increases from 1.5 THz to 3.0 THz, the absorption peak shifts slightly to the blue and decreases in strength. When the THz frequency comes close to the resonance between the subband 1 and 2 at about 3 THz, a double-peak structure emerges in the absorption spectrum. Each of the peaks has a smaller magnitude, and the separation between the peaks depends on the THz strength. The positions of the double peaks are not corresponding to the subband transition states, but the new coupled states resulting from the quantum interference effects. When the THz frequency exceeds the resonant one, the absorption peaks also move slightly to the blue, and the lower-energy peak increases in magnitude while the higher-energy peak decreases in magnitude. From Fig.4 we also clearly see that the anticrossing of the coupled levels occurs when the THz frequency passes through the resonance.

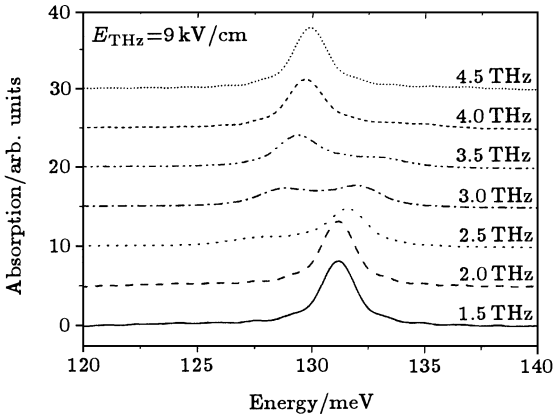


Fig.4. Optical absorption spectra for a E_{THz} = 9 kV/cm THz field when changing the frequency from 1.5 to 4.5 THz. The spectra are shifted vertically for clarity.

4. Conclusion

In conclusion, we have studied the nonlinear optical properties of intersubband transitions in a double QW structure irradiated by an intense THz field. The absorption spectrum is obtained by numerical integration of ISBE in a 3-level model; the results show strong modulations of absorption caused by the THz field. For the THz field below the energy separation between the lowest two subbands (non-resonance), its application causes a blueshift of the main peak and a reduction in its magnitude. Except for the above AC-Stark effects by the THz field, we obtain some replicas separated by even numbers of the THz frequency as a result of the THz sideband absorptions. When the THz field approaches the energy separation between the lowest two subbands (resonance), we can observe a double peak absorption spectra—the well known Autler–Towns splitting—due to the resonant coupling between the intersubband transition state and the THz photon state. The energy splitting of the doublet structure is enhanced with the increase of the THz field strength, and this phenomenon has been explained by the quantum interference theory. In addition, an observable anticrossing of the levels in the absorption spectra can be obtained as the frequency of the THz field swept through the resonance.

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