Vol 18 No 12, December 2009
1674-1056/2009/18(12)/5534-05

Chinese Physics B

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Intraband dynamics and terahertz emission in biased semiconductor superlattices coupled to double far-infrared pulses*

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(Received 9 March 2009; revised manuscript received 6 July 2009)

This paper studies both the intraband polarization and terahertz emission of a semiconductor superlattice in combined dc and ac electric fields by using the superposition of two identical time delayed and phase shifted optical pulses. By adjusting the delay between these two optical pulses, our results show that the intraband polarization is sensitive to the time delay. The peak values appear again for the terahertz emission intensity due to the superposition of two optical pulses. The emission lines of terahertz blueshift and redshift in different ac electric fields and dynamic localization appears. The emission lines of THz only appear to blueshift when the biased superlattice is driven by a single optical pulse. Due to excitonic dynamic localization, the terahertz emission intensity decays with time in different dc and ac electric fields. These are features of this superlattice which distinguish it from a superlattice generated by a single optical pulse to drive it.

Keywords: density matrix theory, semiconductor superlattice, terahertz emission
PACC: 7865, 7550R

1. Introduction

The dynamic properties of electrons and holes in low dimensional systems, driven by external dc and/or ac electric fields, reveal exciting emergent phenomena in the time span around the turn of the century. The electronic and optical effects in semiconductor superlattices have been fields of continued interest after the proposal of the semiconductor superlattice by Esaki and Tsu in the early 1970s,[1−5] both because of the implications for interesting device applications and for the insight into the basic principles of solid state physics. There are many fascinating phenomena in the semiconductor superlattice when it is driven by external dc and/or ac electric fields,[6−11] such as Bloch oscillation (BO), the Wannier–Stark ladder (WSL), dynamics localization (DL) and terahertz (THz) emission.[12−20] The quantum mechanical description of a superlattice in the presence of an applied electric field shows that the miniband is split into a series of discrete levels. These levels are called the WSL and their energies are given by the WSL index. If an electron in a periodic potential is subjected to a static electric field, the electric wavepacket will oscillate spatially at the so-called Bloch oscillations. Bloch oscillations are simply the time evolution of a wave pack constructed from a linear combination of WSL states. The study of Bloch oscillations continues to be an interesting and fascinating field of research. Bloch oscillations are a source of tunable electromagnetic radiation in the THz range.[21] To date, the existence of the WSL as well as BO in semiconductor superlattices has been confirmed by a number of experiments. The BO has been detected by monitoring the interband polarization, intraband polarization, and terahertz radiation. With the development of free-electron lasers that can be continuously tuned in the THz range, the dynamics of charged particles in semiconductor superlattices in time-dependent external electric fields via an optical pulse has been a subject of intense research. More recently, much interest in the intraband dynamics of biased semiconductor superlattice excited via an optical pulse has arisen. M. M. Dignam *et al* have investigated the quasienergy spectrum and the intraband dynamics of a semiconductor (GaAs/AlGaAs) superlattice by a single optical pulse.[22−24] All these investigations focus on GaAs/AlGaAs material; there are few investigations on the properties of GaAs/InGaAs semicon-

*Project supported by the National Natural Science Foundation of China (Grant No 10647132) and the Scientific Research Fund of Hunan Provincial Education Department of China (Grant No 05B014).
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ductor superlattices via double optical pulses.

In this paper, we apply an excitonic basis to calculate the intraband polarization and terahertz emission of a semiconductor superlattice in combined static dc and ac electric fields, using a superposition of two identical, time-delayed and phase-shifted optical pulses. We find that the intraband polarization is sensitive to the time delay and the amplitude of the intraband polarization is much larger when τ_{21}=10 fs than when $\tau_{21} = 0$. The THz radiation has amplitude variation and peak values appear due to superposition of two optical pulses. We find in this case that $F_{\rm dc} = 12$ kV/cm is more beneficial to emission of the THz signal. The emission lines of THz blueshift and redshift in different dc electric fields; however, the emission lines of THz only appear to be blueshifted by a single optical pulse. On the other hand, dynamic localization can be observed.

2. Dynamic equations of the exciton

To calculate the intraband polarization and terahertz emission from a biased semiconductor superlattice system excited by two optical pulses, dynamic equations are given. In the presence of dc, ac and optical electric fields, the Hamiltonian of semiconductor superlattice excitons is given by

$$H = H_0 + H_{\rm ac}(t) + H_{\rm op}(t), \tag{1}$$

where H_0 is the single-exciton Hamiltonian for superlattice excitons in the presence of a dc electric field $F_{\rm dc}$, which is given by

$$H_0 = \sum_{\nu} E_\nu B_\nu^\dagger B_\nu, \tag{2}$$

where $B_\nu^\dagger$ and B_ν are the creation and annihilation operators for an exciton in the dc electric field with internal quantum number ν and energy E_ν, respectively. $H_{\rm ac}(t)$ is the interaction Hamiltonian between the ac electric field $F_{\rm ac}$ and the excitons, which is given by

$$H_{\rm ac}(t) = -VF_{\rm ac} * P_{\rm intra}, \tag{3}$$

where $P_{\rm intra}$ is the intraband polarization defined by

$$P_{\rm intra} = \frac{1}{V}\sum_{\nu\mu} G_{\mu\nu} B_\nu^\dagger B_\mu. \tag{4}$$

In this expression, $G_{\mu\nu}$ is the intraband dipole matrix element between two excitonic states $|\phi^\nu\rangle$ and $|\phi^\mu\rangle$, and is given by

$$G_{\mu\nu} = \langle\phi^\nu| - e(r_{\rm e} - r_{\rm h})\,|\phi^\mu\rangle\,. \tag{5}$$

The $H_{\rm op}(t)$ is the interaction Hamiltonian between the optical field $E_{\rm opt}(t)$ and the excitons, which is given by

$$H_{\rm op}(t) = -VE_{\rm opt}(t)P_{\rm inter}, \tag{6}$$

where $P_{\rm inter}$ is the interband polarization defined by

$$P_{\rm inter} = \frac{1}{V}\sum_{\nu} (M_\nu B_\nu^\dagger + M_\nu^* B_\nu), \tag{7}$$

where M_ν is the interband dipole matrix element of the ν-th excitonic state, which is defined by

$$M_\nu = M_0\sqrt{AN_z}\int \phi_\nu^*(z,z,0){\rm d}z, \tag{8}$$

where M_0 is the bulk interband dipole matrix element, A is the transverse area, ϕ^ν is the ν-th superlattice exciton eigenstate in the presence of dc electric field, and N_z is the number of superlattice sites.

The optical field is given by[25]

$$\begin{aligned} E_{\rm opt}(t) &= E_1(t) + E_2(t) \\ &= \frac{1}{2}A_0(t)\exp({\rm i}\,\omega_c t) + \frac{1}{2}A_0(t)\exp(-{\rm i}\,\omega_c t) \\ &\quad + \frac{1}{2}A_0(t-\tau)\exp[{\rm i}\,\omega_c(t-\Delta\tau) + {\rm i}\,\Delta\phi] \\ &\quad + \frac{1}{2}A_0(t-\tau)\exp[-{\rm i}\,\omega_c(t-\Delta\tau) - {\rm i}\,\Delta\phi], \end{aligned} \tag{9}$$

where $E_{\rm opt}(t)$ is the total light field, ω_c is the central frequency of the ultrashort Gaussian optical pulses and $\Delta\tau$ is the time delay, $\Delta\phi$ is the phase shift of the two optical pulses. $A_0(t)$ has a Gaussian envelope for simplicity. Using the full Hamiltonian in Eq.(1), the dynamical equations of motion for the expectation values of the interband and intraband correlation functions to the second order in the optical field are[26]

$${\rm i}\,\hbar\frac{{\rm d}\langle B_\nu^+\rangle}{{\rm d}t} = \left[E_\nu - \frac{{\rm i}\,\hbar}{T_{2\rm inter}}\right]\langle B_\nu^+\rangle + E_{\rm opt}(t) * M_\nu + E_{\rm opt}(t) * \sum_\beta G_{\nu\beta}\left\langle B_\beta^\dagger\right\rangle, \tag{10}$$

$$\mathrm{i}\hbar\frac{\mathrm{d}\left\langle B_\mu^+ B_\nu\right\rangle}{\mathrm{d}t} = -\left[E_\nu - E_\mu + \frac{\mathrm{i}\hbar}{T_{\mu\nu}}\right]\left\langle B_\mu^+ B_\nu\right\rangle + E_{\mathrm{opt}}(t) * [M_\mu^* \left\langle B_\nu\right\rangle - M_\nu \left\langle B_\mu^\dagger\right\rangle] + E_{\mathrm{opt}}(t) * \sum_\beta [G_{\mu\beta}^* \left\langle B_\beta^\dagger B_\nu\right\rangle - G_{\nu\beta} \left\langle B_\mu^\dagger B_\beta\right\rangle], \tag{11}$$

where $T_{2\mathrm{inter}}$ is the interband dephasing time, and $T_{\mu\nu}$ is defined such that $T_{\mu\nu} = T_1$ if $\mu = \nu$ and $T_{\mu\nu} = T_{2\mathrm{intra}}$ if $\mu \neq \nu$, T_1 is the excitonic population decay time, and $T_{2\mathrm{intra}}$ is the intraband dephasing time.

The linear optical absorption spectra can be calculated from the interband polarization and expressed by[27,28]

$$\chi(\omega) = \frac{4\pi\omega_c}{C\sqrt{\varepsilon_b}}\frac{\mathrm{Im}\left[P(\omega)E_{\mathrm{opt}}(\omega)^*\right]}{\left|E_{\mathrm{opt}}(\omega)\right|^2}, \tag{12}$$

where $P(\omega)$ and $E(\omega)$ are the Fourier transforms of the polarization function $P(t)$ and the laser pulse $E_{\mathrm{opt}}(t)$, respectively.

Once equations (10) and (11) are solved, the intraband polarization is obtained by Eq.(4). The emitted radiation is in the terahertz frequency range. The intensity of the emitted THz signal is given by[26]

$$I_{\mathrm{THz}}(t) \propto \left\langle \left[\frac{\mathrm{d}^2}{\mathrm{d}t^2}P_{\mathrm{intra}}(t)\right]^2\right\rangle_t. \tag{13}$$

3. Numerical results and analysis

We consider a GaAs/$In_{0.53}Ga_{0.47}As$ superlattice structure with well widths of 45 Å (1 Å=0.1 nm) and barrier widths of 45 Å. The physical parameters employed in our numerical calculation are listed in Table 1. The calculations are performed by using 25 basis states as we find that there is no change in the calculated dynamic results with an increase in the basis size beyond this.

Table 1. The effective masses and band-offset values υ_{e} and υ_{h} used in all of the calculations in Section 2. The subscript hh (lh) refers to heavy (light) hole. The remaining parameters, the static dielectric constant and the band gap of GaAs are taken to be $\varepsilon = 15.1$ and $E_{\mathrm{gap}} = 1.610$ eV.

parameter	m_{e}^*	m_{hhz}^*	$m_{\mathrm{hh}\vert\vert}^*$	m_{lhz}^*	$m_{\mathrm{lh}\vert\vert}^*$	υ_{e}/meV	υ_{h}/meV
GaAs	0.023	0.263	0.115	0.027	0.106		
$In_{0.53}Ga_{0.47}As$	0.075	0.335	0.145	0.046	0.185	326	198

In Fig.1 we present the calculated intraband polarization with a dc electric field with $F_{\mathrm{dc}} = 12$ kV/cm and ac electric field with $F_{\mathrm{ac}} = 2.0$ kV/cm for $\tau_{21} = 0$ and ± 10 fs. As can be seen, the amplitude of the intraband polarization P_{intra} is much larger when $\tau_{21} = -10$ fs than $\tau_{21} = 0$. This is because the delay of the other pulse creates a wavepacket with a different phase relationship between the different excitonic states. The intensity of intraband polarization decreases with time. The average value of P_{intra} moves steadily out beyond a time of 2 ps when $\tau_{21} = -10$ fs and $\tau_{21} = 0$. In clear contrast to this, when $\tau_{21} = +10$ fs, the oscillations decay much more slowly and relatively smoothly via double far-infrared pulses, but the intraband polarization increases or moves downwards with time via an optical pulse. This is a key result, and is due to the different time delay and phase shift.

Figure 2 shows the range of the intensity of the emitted THz signal as a function of time for dc electric fields of $F_{\mathrm{dc}} = 9$ kV/cm, 10 kV/cm and 12 kV/cm for the ac electric field frequency $\omega_{\mathrm{ac}} = \omega_{\mathrm{B}}$. As can be seen, the maximum value of THz intensity increases with the increase of the dc electric field. When the dc electric field $F_{\mathrm{dc}} = 9$ kV/cm the THz intensity decays much more rapidly to zero with time than when the dc electric field $F_{\mathrm{dc}} = 10$ kV/cm and 12 kV/cm. The dc electric field contribution to the emitted THz is due to the dipole moment of the excitonic states. We find in this case that when $F_{\mathrm{dc}} = 12$ kV/cm it is more

beneficial to emission of the THz signal. Due to the superposition of two optical pulses, the peak values appear again for the terahertz emission intensity.

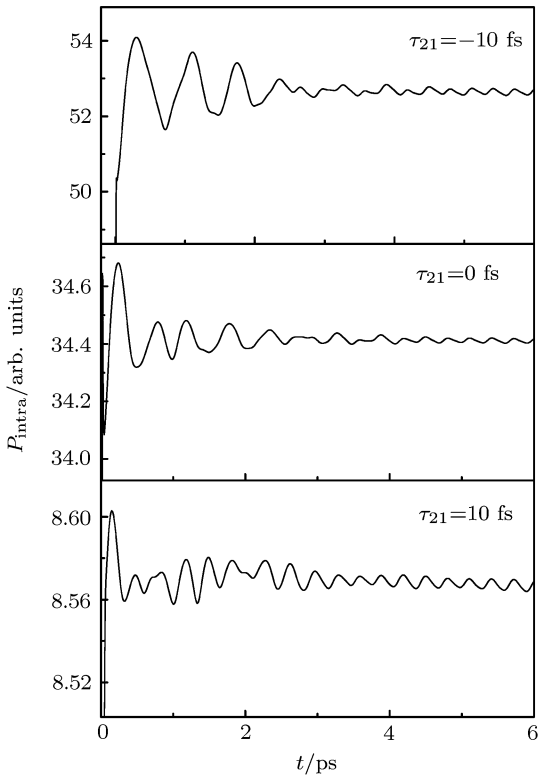


Fig.1. Intraband polarization as a function of time for a superlattice in the presence of dc electric field with $F_{\rm dc}$ = 12 kV/cm and ac electric field with $F_{\rm ac}$ = 2.0 kV/cm via double optical pulses.

In Fig.3 we show the time evolution of the THz intensity signal $I_{\rm THz}(t)$ for different ac electric fields and the dc electric field $F_{\rm dc} = 12$ kV/cm, and electric field frequency $\omega_{\rm ac} = \omega_{\rm B}$. Excitonic dynamic localization can be observed for the different ac electric fields. When the time reaches about 0.75 ps, excitonic dynamic localization will be observed and the emission lines of THz appear to blueshift. But the emission lines of THz redshift and the excitonic dynamic localization appears again when the time reaches about 1.75 ps. The emission lines of THz only appear to blueshift by a single optical pulse. Due to the superposition of two identical, time delayed and phase shifted optical pulses, the THz intensity signal is affected and the emission lines of THz appear to redshift. At the same time, as the intensity of ac electric field increases, the emission lines of THz shift due to the strong electron–hole interaction in the semiconductor superlattice, which arises from the broken symmetry induced by the external dc electric field. Excitonic dynamic localization can be affected by the ac electric field. This is due to the fact that the included excitonic effects have strongly disturbed the WSL spacing and intraband dipole matrix elements in the ac electric field.

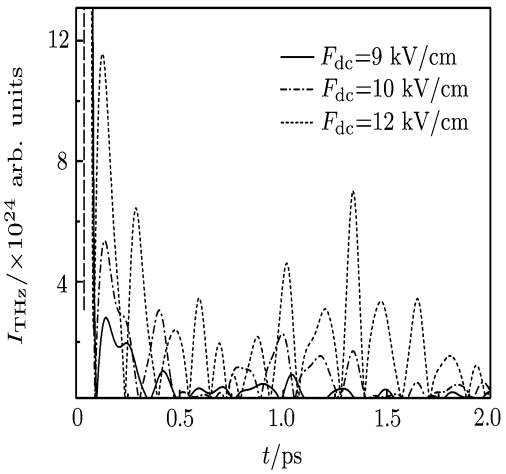


Fig.2. The calculated range of the intensity of the emitted THz signal as a function of time for different dc static electric fields $F_{\rm dc}$ for the ac electric field frequency with $\omega_{\rm ac} = \omega_{\rm B}$.

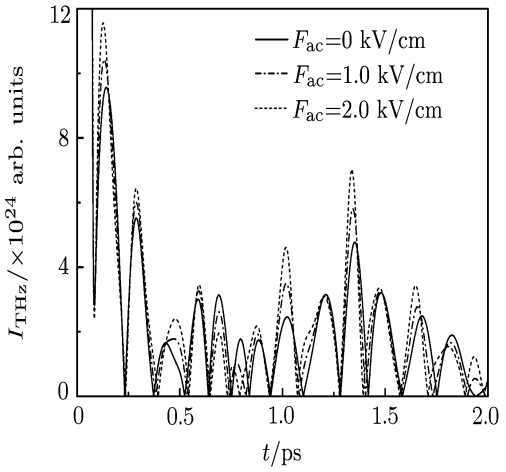


Fig.3. The time evolution of the THz intensity signal $I_{\rm THz}(t)$ for different ac electric fields $F_{\rm ac}$, for the static electric field $F_{\rm dc}$ = 12 kV/cm and ac electric field frequency with $\omega_{\rm ac} = \omega_{\rm B}$.

4. Conclusions

In summary, we have investigated the dynamics of intraband polarization, terahertz emission excited $GaAs/In_{0.53}Ga_{0.47}As$ semiconductor superlattices in

combined dc and ac electric fields. The numerical results show that the amplitude of the intraband polarization is different in different time-delayed and phase-shifted optical pulses. The THz radiation has amplitude variation and peak values appear due to superposition of two optical pulses. We find in this case that when $F_{\rm dc} = 12$ kV/cm emission of the THz signal is more beneficial. Due to dynamic localization destruction, the time evolution of the THz intensity signal decreases rapidly and the emission lines of THz redshift and blueshift with the ac electric frequency increase. These results will be useful for THz sources produced by optically pumping semiconductor superlattice structures.

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