Coherent carrier dynamics in semiconductor superlattices

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Abstract

We investigate the coherent dynamics of carriers in semiconductor superlattices driven by ac–dc electric fields. We solve numerically the time-dependent effective-mass equation for the envelope function. We find that carriers undergo Rabi oscillations when the driving frequency is close to the separation between minibands.

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Recent advances in laser technology make it possible to drive semiconductor nanostructures with intense coherent ac–dc fields. This opens up new research fields in time-dependent transport in mesoscopic systems [1,2] and puts forward the basis for a new generation of ultra-high speed devices. Artificial two-level semiconductor nanostructures acting as switching devices based on Rabi oscillations (ROs) have been already suggested [3]. Moreover, resonant phonon-assisted tunneling through a double quantum dot could be used as an efficient electron pump from spatial ROs [4].

Zhao et al. have analytically investigated a tight-binding model of a two-band system in a time-dependent ac–dc field in the weak coupling limit [5]. They identified ROs between Bloch bands under resonant conditions, which reveal the existence of quasi-energy bands and fractional Wannier–Stark ladders. The advances achieved in molecular beam epitaxy, which allow one to fabricate semiconductor superlattices (SLs) tailored with the desired conduction-band profiles, make these systems ideal candidates to propose experiments on coherent carrier dynamics. However, the tight-binding approximation presents some limitations to describing actual semiconductor superlattices (SLs) when the coupling between neighboring quantum wells is not weak. Thus, in order to experimentally access the validity of theoretical predictions, one should use a more realistic model. In this Letter we present an effective-mass model beyond the tight-binding approximation, containing all ingredients of actual SLs, namely finite interband coupling and multiband scattering.

We consider electron states close to the conduction-band edge and use the effective-mass approximation. The electron wave packet satisfies

$$i\hbar \frac{\partial \Psi(x,t)}{\partial t} = \left(-\frac{\hbar^2}{2m^*} \frac{d^2}{dx^2} + V_{SL}(x) - eFx \sin(\omega_{ac}t) \right) \Psi(x,t), \quad (1)$$

where x is the coordinate in the growth direction, F and ω are the strength and the frequency of the ac field, respectively. The SL potential at flat band is $V_{SL}(x) = \Delta E_c$ if x lies inside the barriers and zero otherwise, ΔE_c being the conduction-band offset. We have considered a constant effective-mass m^* for simplicity.

The band structure at the flat band is computed by using a finite-element method [6]. The eigenstate j of the band i with eigenenergy $E_i^{(j)}$ is denoted as $\psi_i^{(j)}(x)$. A good choice for the initial wave packet is provided by using a linear combination of the eigenstates belonging to the first miniband. For the sake of clarity we have selected as the initial wave packet $\Psi(x,0) = \psi_i^{(j)}(x)$, although we have checked that this assumption can be dropped without changing our conclusions. The subsequent time evolution of the wave packet $\Psi(x,t)$ is calculated numerically by means of an implicit integration schema [7]. In addition to $\Psi(x,t)$ we also compute the probability of finding an electron, initially in the state $\Psi(x,0) = \psi_i^{(j)}(x)$, in the state $\psi_k^{(j)}(x)$,

$$P_{ik}^{(j)}(t) = \int_{-\infty}^{\infty} dx\, \Psi^*(x,t)\psi_k^{(j)}(x). \quad (2)$$

We present here the results for a SL with 10 periods of 100 Å GaAs and 50 Å $Ga_{0.7}Al_{0.3}As$ with band offset $\Delta E_c = 250$ meV and $m^* = 0.067m$, m being the free electron mass. We consider electric field $F = 25$ kV/cm as a typical value, although similar results are observed for other values. Fig. 1a displays $P_{01}^{(5)}(t)$ for $F = 25$ kV/cm at the resonant frequency $\omega_{ac} = (E_1^{(5)} - E_0^{(5)})/\hbar = 150$ THz. Thus, we are monitoring the transitions between the central state ($j = 5$) in the first miniband to the central state in the second miniband as a function of time. We observe the occurrence of very well defined ROs with an amplitude close to 0.3. Summing up the probabilities of the rest of states in the second miniband, the probability of finding the electron in this band is very close to unity (~ 0.99). The frequency of the ROs, obtained by performing the fast Fourier transform (FFT) of $P_{01}^{(5)}(t)$, is $\omega_{Rabi} = 19.18$ THz. The probability $P_{01}^{(5)}(t)$ is dramatically reduced when the ac driving field is out of resonance, as shown in Fig. 1b for $\omega_{ac} = 100$ THz. The FFT of those data reveals no specific features besides the peak at the driving frequency ω_{ac}.

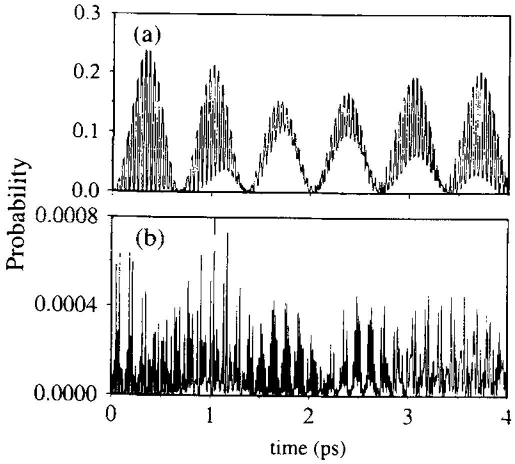

Fig. 1. The probability of finding an electron, initially situated in the state $\psi_0^{(5)}$, in the state $\psi_1^{(5)}$ as a function of time for $F = 25$ kV/cm, when the ac field (a) is tuned to the resonant frequency $\omega_{ac} = 150$ THz and (b) is out of resonance $\omega_{ac} = 100$ THz. Note the different vertical scales.

In a pure two-level system, a straightforward perturbation calculation yields $\omega_{Rabi} = |F_{01}|/\hbar$ at resonance, where F_{01} is the matrix element of the perturbation between the ground state and the first excited state. Thus, ω_{Rabi} is linear in the electric field in a pure two-level system. Although the SL is not a pure two-level system, we realize that this linear dependence still holds, as we can see in Fig. 2.

As an estimation of the leakage current that one could observe in electron pumping devices based on ROs in SLs, we have studied the integrated density in the right part of the SL, defined as

$$P_T(t) = \int_{x_r}^{\infty} |\Psi(x,t)|^2\, dx, \quad (3)$$

where x_r is the coordinate of the right edge of the SL. Fig. 3 shows the results at the resonant frequency $\omega_{ac} = 150$ THz as well as out of resonance when $\omega_{ac} = 200$ THz. Under resonant conditions the wave function is emitted by *bursts* from the SL region every time a RO has been completed. On the contrary, the tunneling across the whole SL is negligible when the

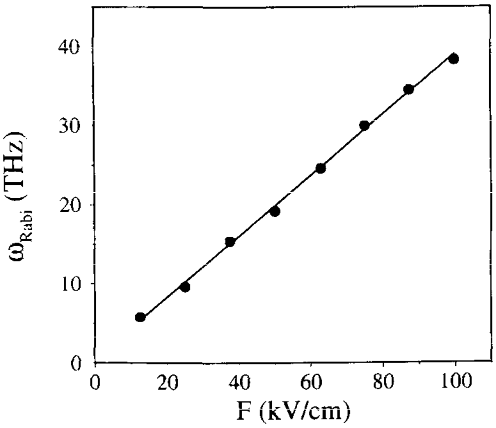

Fig. 2. Rabi frequency as a function of the dc field when the driving frequency is tuned to the resonant frequency ω_{ac} = 150 THz

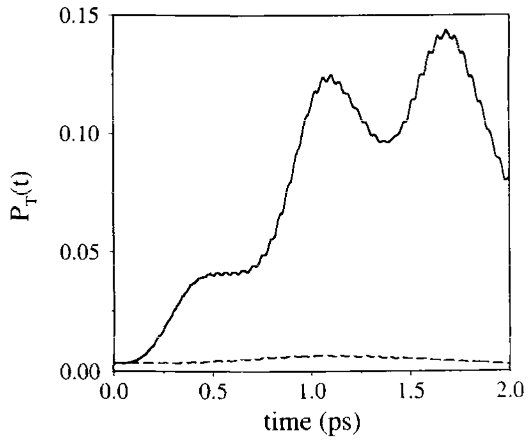

Fig. 3. $P_T(t)$ as a function of time at the resonant frequency ω_{ac} = 150 THz (solid line) and out of resonance ω_{ac} = 200 THz (dashed line).

ac driving frequency is not very close to the resonant one.

In summary, we have studied the coherent carrier dynamics in semiconductor SLs driven by an intense ac–dc field. We found that the electron can perform ROs under resonant conditions as in pure two-level systems. The Rabi frequency of the oscillations depends linearly on the strength of the electric field. We have shown that electrons are emitted by *bursts* under resonant conditions, whereas the tunneling probability is vanishingly small out of resonance. Therefore, we suggest that semiconductor SLs driven by an intense ac–dc field may be used as an efficient electron pumping device in THz science. Finally, we should mention that we have not considered the role of imperfections or any other scattering mechanism that could result in a reduction of the carrier coherence. Our preliminary results show that scattering by interface roughness does not strongly modify the above picture. Further work along these lines is currently in progress.

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References

[1] J.B. Pieper, J.C. Price, Phys. Rev. Lett. 72 (1994) 3586.
[2] S.T. Cundiff, A. Knorr, J. Feldmann, S.W. Koch, E.O. Göbel, H. Nickel, Phys. Rev. Lett. 73 (1994) 1178.
[3] T. Martin, G.P. Berman, Phys. Lett. A 196 (1994) 65.
[4] C.A. Stafford, N.S. Wingreen, Phys. Rev. Lett. 76 (1996) 1916.
[5] X.-G. Zhao, G.A. Georgakis, Q. Niu, Phys. Rev. B 54 (1996) R5235.
[6] K. Nakamura, A. Shimizu, M. Koshiba, K. Hayata, IEEE J. Quantum Electron. 25 (1989) 889.
[7] E. Diez, A. Sánchez, F. Domínguez-Adame, Phys. Rev. B 54 (1996) 14550.