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Nonlinear dynamics in superlattices driven by high frequency ac-fields

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Abstract

We investigate the dynamical processes taking place in nanodevices driven by high-frequency electromagnetic fields. We want to elucidate the role of different mechanisms that could lead to loss of quantum coherence. Our results show how the dephasing effects of disorder that destroy after some periods coherent oscillations, such as Rabi oscillations, can be overestimated if we do not consider the electron–electron interactions that can reduce dramatically the decoherence effects of the structural imperfections. Experimental conditions for the observation of the predicted effects are discussed.

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Recent advances in laser technology make possible to drive semiconductor nanostructures with intense coherent ac-dc fields. This opens new research fields in time-dependent transport in mesoscopic systems [1] and puts forward the basis for a new generation of ultra-high speed devices. Following these results several works have been devoted to the analysis of the effects of time-dependent fields on the transport properties of resonant heterostructures [2–4] and to exploit the application in ultrafast optical technology: high-speed optical switches, coherent control of excitons, etc. [5,6].

Within this context, we are interested in the decoherence processes producing the observed fast dephasing of coherence phenomena in semiconductor superlattices (SL's) and more specifically in the interplay between the growth imperfections (disorder) and many-body effects as the electron–electron (e–e) interaction. The interplay between the effects of disorder and many-body effects on electronic properties is a long-standing problem in solid-state physics. Probably one of the most promising way to gain insight into this intricate problem is to combine the actual state-of-the-art of the Molecular Beam Epitaxy (MBE), which allow us to grew samples with monolayer perfection and consequently with well-characterized disorder, with coherent oscillations that are extremely sensitive to imperfections and nonlinear effects.

The oscillations of a two level system between the ground and excited states in the presence of a strong resonant driving field, often called transient nutation or Rabi oscillation (RO), are discussed in textbooks as a topic of time-dependent perturbation theory. Consider a two state system with ground state energy E_0 and excited state E_1 in the presence of a har-

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monic perturbation. If the frequency of the perturbation matches roughly the spacing between the two levels, the system undergoes oscillations with a frequency Ω_R which is much smaller than the excitation frequency ω_{ac}. This Rabi frequency depends on the mismatch $\delta\omega \equiv (E_1 - E_0)/\hbar - \omega_{ac}$ between the level spacing and the excitation frequency, and on the matrix element F_{10} of the perturbation $\Omega_R = \left(\delta\omega^2 + |F_{10}|^2/4\hbar^2\right)^{1/2}$. If we start with the system initially in the ground state, transitions between the ground and the excited state will occur with a period $T_R = 2\pi/\Omega_R$ as time evolves.

Semiconductor SL's present Bloch minibands with several states each one; thus it is not clear whether they can be correctly described as a a pure two state system. We should also take into account the presence of imperfections introduced during growth processes and scattering mechanism as e–e interactions. Interface roughness appearing during growth in *actual* SL's depends critically on the growth conditions. For instance, protrusions of one semiconductor into the other cause in-plane disorder and break translational invariance parallel to the layers. To describe local excess or defect of monolayers, we allow the quantum well widths to fluctuate uniformly around the nominal values; this can be seen as substituting the nominal sharp width by an *average* along the parallel plane of the interface imperfections. Our approximation is valid whenever the mean-free-path of electrons is much smaller than the in-plane average size of protrusions as electrons only see *micro*-quantum-wells with small area and uniform thickness. Therefore, in the following we will take the width of the nth quantum well to be $a(1 + W\epsilon_n)$, and the width of the nth barrier as $b(1 + W\epsilon_n)$ where W is a positive parameter measuring the maximum fluctuation, ϵ_n's are distributed according to a uniform probability distribution, $\mathscr{P}(\epsilon_n) = 1$ if $|\epsilon_n| < 1/2$ and zero otherwise, a is the nominal quantum well width and b is the nominal quantum barrier width. Even with its rather satisfactory degree of success, many-body calculations have difficulties that, in some cases, may complicate the interpretation of the underlying physical processes. Presilla et al. [7] suggested a new treatment of these interactions that, loosely speaking, could be regarded as similar to Hartree–Fock and other self-consistent techniques, which substitute many-body interactions by a nonlinear effective potential. More [...] we have proposed a new model where the [...] interaction is driven by a local field inst[...] mean-field approach used by Presilla and co[...] [7].

Here we present a new model that solve[...] sistently the Poisson and the time-dependent [...]nger equations, and we compare the results [...] local treatment based in the non-linear Sch[...] equation.

The band structure and the potential at fla[...] computed by using a finite-element meth[...] eigenstate j of the band i with eigenenergy [...] denoted as $\psi_i^{(j)}(x)$. A good choice for the [...] wave packet is provided by using a linear co[...]tion of the eigenstates belonging to the fir[...] band. For the sake of clarity we have selected [...] initial wave packet $\Psi(x,0) = \psi_i^{(j)}(x)$, althoug[...] have checked that this assumption can be [...] without changing our conclusions. The subs[...] time evolution of the wave packet $\Psi(x,t)$ is [...]lated numerically by means of an implicit integ[...] schema designed for consider time-dep[...] fields[1].

The envelope-functions for the electron [...] packet satisfies the following quantum ev[...] equation:

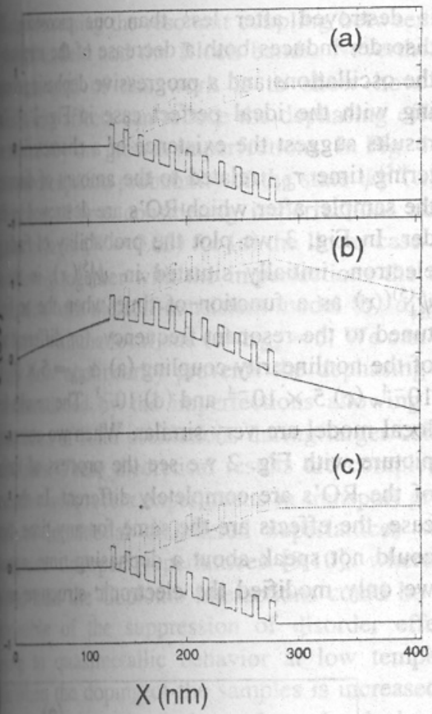
$$i\hbar\frac{\partial\Psi(x,t)}{\partial t} = \left[-\frac{\hbar^2}{2m^*}\frac{d^2}{dx^2} + V_{\mathrm{NL}}(x,t)\right]\Psi(\ldots$$

where x is the coordinate in the growth direc[...] the SL. We consider two approaches to the no[...] potential $V_{\mathrm{NL}}(x,t)$ in Eq. (1). On the one ha[...] take into account the model described, in othe[...] text, in [8] for our problem, where $V_{\mathrm{NL}}(x,t)$ is

$$V_{\mathrm{NL}}(x,t) = V(x) - eF_{\mathrm{AC}}\,x\sin(\omega_{\mathrm{AC}}t) + \alpha_{\mathrm{loc}}|\Psi(x,t)|^2 \ldots$$

and $V(x)$ is the potential at flat-band, F_{AC} an[...] are the strength and the frequency of the ac [...]

[1] Details about the numerical procedure and algorithms [...] given elsewhere.



Conduction-band profile for a perfect SL ($W = 0$) at ...(solid lines) and 1.2 ps (dashed lines) for (a) the linear case ...deling the e–e interaction with (b) the self-consistent ...($\alpha_{self} = 10^{-3}$) and with (c) the local model ($\alpha_{loc} = 10$).

...ectively, and all the nonlinear physics is con...ed in the coefficient α_{loc}, which we discuss ...w. There are several factors that configure the ...um nonlinear response to the tunneling electron. ...want to consider only the repulsive electron–...ron Coulomb interactions, which should enter ...effective potential with a positive nonlinearity, ...he energy is increased by local charge accumu...ns, leading to a positive sign for α_{loc}.

...n the other hand, we have considered a different ...ach by solving self-consistently the Schrödi...er and Poisson equations obtaining a Hartree-like ...ential. In this context, the non-linear potential is,

$$\ldots(x,t) = V(x) - eF_{AC}\, x \sin(\omega_{AC} t) + \alpha_{self} V_H(x,t), \tag{3}$$

...ere now V_H it is obtained by solving the Poisson ...ation for the density of charge $|\Psi(x,t)|^2$, and ...$_{self}$ is the coupling parameter.

We present here results for a SL with 10 periods of 100 Å GaAs and 50 Å $Ga_{0.7}Al_{0.3}As$ with conduction-band offset 300 meV and $m^* = 0.067m$, m being the free electron mass. The time and spatial mesh used in the simulations are 4×10^{-16} seconds and 10^{-8} cm; we have checked that our numerical results are not affected by these particular values. To illustrate the effects of the nonlinear coupling we show in Fig. 1 the conduction-band profile for a perfect SL ($W = 0$) at $t = 0.4$ (solid lines) and 1.2 ps (dashed lines) when the ac field is tuned to the resonant frequency $\omega_{res} = (E_1^{(5)} - E_0^{(5)})/\hbar = 24$ THz, for (a) the linear case and modeling the e–e interaction with (b) the self-consistent method ($\alpha_{self} = 10^{-3}$) and with (c) the local model ($\alpha_{loc} = 10$). To show the effects of the interface roughness we plot in Fig. 2 the probability of finding an electron, initially situated in $\psi_0^{(5)}(x)$, in the state $\psi_1^{(5)}(x)$ as a function of time when the ac field is tuned to the resonant frequency $\omega_{ac} = \omega_{res} \sim 24$ THz with (a) $W = 0$ (per-

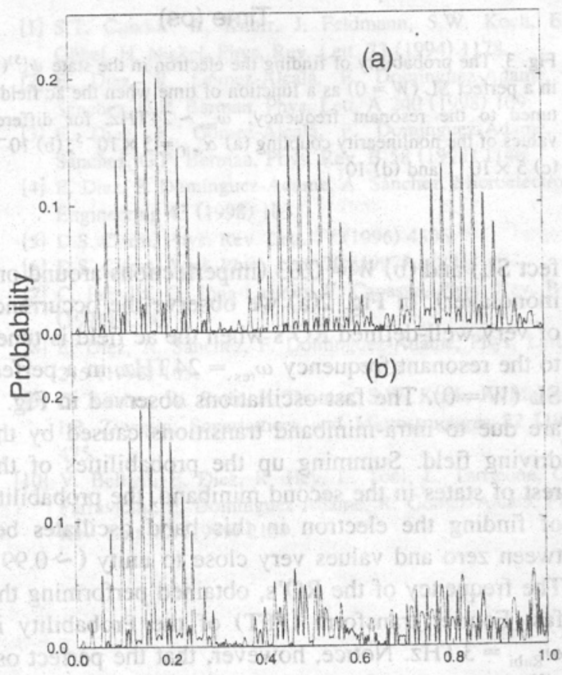


Fig. 2. The probability of finding the electron in the state $\psi_1^{(5)}(x)$ for the linear case as a function of time when the ac field is tuned to the resonant frequency $\omega_{ac} = \omega_{res} \sim 24$ THz with (a) $W = 0$ (perfect SL) and (b) $W = 0.03$ (imperfections around one monolayer).

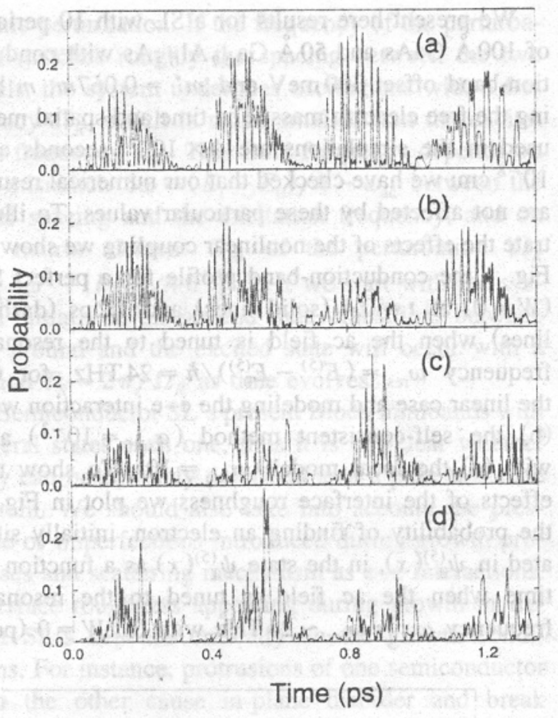


Fig. 3. The probability of finding the electron in the state $\psi_1^{(5)}(x)$ in a perfect SL ($W=0$) as a function of time when the ac field is tuned to the resonant frequency, $\omega_{res} \sim 24$ THz, for different values of the nonlinearity coupling (a) $\alpha_{self} = 5 \times 10^{-5}$, (b) 10^{-4}, (c) 5×10^{-4} and (d) 10^{-3}.

fect SL) and (b) $W = 0.03$ (imperfections around one monolayer). In Fig. 2(a) we observe the occurrence of very well-defined RO's when the ac field is tuned to the resonant frequency $\omega_{res} = 24$ THz, in a perfect SL ($W=0$). The fast oscillations observed in Fig. 2 are due to intra-miniband transitions caused by the driving field. Summing up the probabilities of the rest of states in the second miniband, the probability of finding the electron in this band oscillates between zero and values very close to unity (~ 0.99). The frequency of the RO's, obtained performing the fast Fourier transform (FFT) of the Probability is $\omega_{Rabi} = 3$ THz. Notice, however, that the perfect oscillatory pattern detected in perfect SL's is completely altered when we introduce a small amount of disorder. In Fig. 2(b) we consider a maximun excess or defect of monolayers less than one monolayer ($W = 0.03$) whereas the rest of parameters are the same. We observe that the perfect oscillatory pattern

is destroyed after less than one picos
disorder induces both a decrease of the a
the oscillations and a progressive dephasi
ing with the ideal perfect case in Fig. 2
results suggest the existence of a characte
tering time τ_{dis} related to the amount of d
the sample, after which RO's are destroye
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electron, initially situated in $\psi_0^{(5)}(x)$, i
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tuned to the resonant frequency, for differ
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10^{-4}, (c) 5×10^{-4} and (d) 10^{-3}. The resul
local model are very similar. When we com
picture with Fig. 2 we see the process of
of the RO's are completely different. In th
case, the effects are the same for any time
could not speak about a dephasing time, a
we only modified the electronic structure

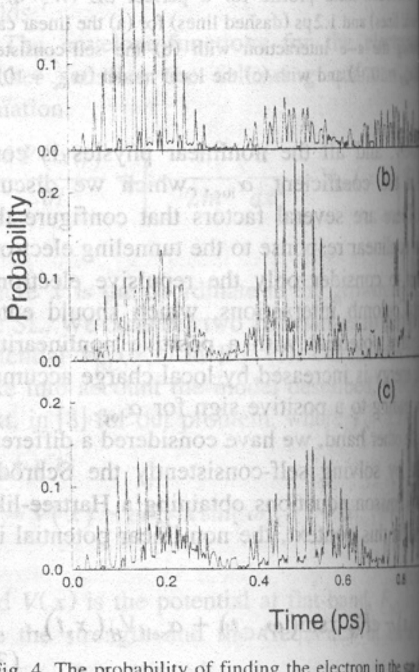

Fig. 4. The probability of finding the electron in the st
as a function of time for the resonance driving frequen
with imperfections ($W = 0.03$) for (a) the linear case, a
ing the e–e interaction with (b) the self-consistent m
$= 10^{-4}$) and with (c) the local model ($\alpha_{loc} = 5$).

we are decreasing the resonant coupling between the external ac-field and the Bloch bands. Nevertheless the main goal of this work is to show how the nonlinearity effects can reduce the dephasing effects produced by the growth imperfections. In Fig. 4 we plot the occupation probability of the state $\psi_1^{(5)}(x)$ as a function of time considering imperfections about one monolayer ($W = 0.03$) for (a) the linear case and considering together with the imperfections the e–e interaction with the self-consistent model (b) $\alpha_{\rm self} = 10^{-4}$ and with the local one (c) $\alpha_{\rm loc} = 5$. We can see clearly how nonlinearity prevents the dephasing effects introduced by the imperfections allowing the observation of Rabi oscillations during larger coherence times. These theoretical results are completely consistent with recent experiments in transport properties of intentional disordered superlattices with doped and undoped superlattices [9,10], where is showed than the Coulomb interactions could be the responsible of the suppression of disorder effects leading to quasimetallic behavior at low temperatures when the doping of the samples is increased.

In summary, we have shown how the dephasing effects of disorder are dramatically reduced when we consider the e–e interaction. We have studied two different models to introduce the non-linear interaction and the results are very similar. Our results shows that it is possible to enlarge the dephasing times and, consequently the number of periods of coherence oscillations of electrons in SL's. In semiconductor heterostructures this can be done by increasing the doping or with very intense laser excitation fields. It goes without saying that to develop new devices for THz science it is crucial to understand how to control and enlarged the coherence times. We think that the nonlinear effects could be the key to solve this problem. Further work along these lines is currently in progress.

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