LOSS OF PHASE COHERENCE IN SEMICONDUCTOR HETEROSTRUCTURES DUE TO THE COULOMB INTERACTION

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ABSTRACT

We present a theoretical study of the dynamics of free photo-generated carriers in asymmetric GaAs-AlGaAs double wells. Photo-generation occurs on a sub-picosecond time scale and produces a coherent ensemble of electron-hole pairs in the wider well. The simultaneous thermalization and tunneling of electrons between the two wells is analyzed within the density matrix approach. The interplay between tunneling and Coulomb scattering is analyzed at several levels of approximation regarding free carrier screening. We find that the Coulomb interaction represents an effective agent to destroy phase coherence and to damp out charge oscillations. Nevertheless, our calculations predict that, if the free carrier Coulomb interaction represents the dominant dephasing mechanism, charge density oscillations associated with *free* carriers should be observable up to carrier sheet densities of about 10^{10} cm^{-2} .

I. INTRODUCTION

Various optical techniques have been used to monitor transport (tunneling) and thermalization of hot photo-generated carriers in quantum-well structures and superlattices. Recently, measurement of dipole radiation signals has been used to demonstrate both the existence of Bloch oscillations in superlattices and charge oscillations due to tunneling in semiconductor double wells.[1-4] To our knowledge, all charge oscillations which have been observed up to now have been attributed to excitons. No evidence for charge oscillations associated with free carriers has been presented so far. There are several reasons why excitons are more likely to exhibit charge oscillations than free carriers. Excitons are less exposed to structural imperfections in the double well. Moreover, any imperfections tend to detune the exciton levels and their optical excitation is inhibited. Excitons are neutral quasiparticles and thus interact with each other and free carriers more weakly than free carriers among each other, leading to longer phase coherence times. Finally, excitons are known to dominate the four-wave mixing signal, even when vastly outnumbered by free carriers.[5]

In this work we investigate the possibility of inducing charge oscillations of free carriers in double well structures. In particular, the role of free-carrier screening is investigated.

II. THEORY

We apply the density matrix approach to a situation in which a sub-picosecond laser pulse generates free electron-hole pairs of low to moderate densities in asymmetric GaAs-AlGaAs double-wells.[6,7] We consider an experimental situation identical to the one under which excitons have been created resonantly in double wells, except that here the laser energy of maximum intensity exceeds the energy gap by typically 10 to 20 meV.[2,4] As the hole bands involved in the excitation process are far off resonance, hole dynamics is neglected. Due to the low excess photon energy, optical phonon emission is unimportant. Here, the formation of excitons via LO phonon emission is neglected.

The problem reduces to a study of the time-evolution of an electronic one-particle density matrix

$$\begin{pmatrix} f_{LL}(k,t) = \langle b^\dagger_{Lk} b_{Lk}\rangle(t) & f_{LR}(k,t) = \langle b^\dagger_{Lk} b_{Rk}\rangle(t) \\ f_{RL}(k,t) = \langle b^\dagger_{Rk} b_{Lk}\rangle(t) & f_{RR}(k,t) = \langle b^\dagger_{Rk} b_{Rk}\rangle(t) \end{pmatrix}$$

with

$$\langle A\rangle = Tr\{\rho A\}(t)$$

for an electron observable A and density operator ρ. $f_{LL}(k,t)$ and $f_{RR}(k,t)$ are the electron distribution functions associated with left and right well, respectively. k denotes the magnitude of the k–vector associated with in–plane motion. The off–diagonal element $f_{RL}(k,t)$ denotes the "polarization".

The time evolution of the density matrix originates from several sources:

• Firstly, laser generation of electron–hole pairs is incorporated as a generation term of the form

$$\frac{d}{dt} f_{LL}(k,t)|_{laser}.$$

As we are not concerned with ultra–short pulses this term should be adequate for the present purpose.

• Secondly, elastic tunneling between left and right well is taken into account within a two–subband approximation and the Hamiltonian

$$H_o = \sum_k \{\epsilon_{Lk} b^\dagger_{Lk} b_{Lk} + \epsilon_{Rk} b^\dagger_{Rk} b_{Rk} + V[b^\dagger_{Lk} b_{Rk} + b^\dagger_{Rk} b_{Lk}]\}$$

The basis states $|Lk\rangle$ and $|Rk\rangle$ are linear combinations of the two lowest eigenstates of the double well, $|+,k\rangle$ and $|-,k\rangle$ with eigenvalues $\epsilon_{+,k}$ and $\epsilon_{-,k}$, respectively. Here, $\epsilon_{\alpha,k} = \epsilon_\alpha + \frac{(\hbar k)^2}{2m^*}, \alpha = \pm, L, R$. Perfect interfaces are assumed. This provides a major reduction in complexity of the problem, but may be somewhat unrealistic in real structures.

• Thirdly, the Coulomb interaction between free carriers,

$$v = \frac{1}{2} \sum_{\alpha,\beta,\gamma,\delta,q,k,k'} v_{\alpha\beta\gamma\delta}(q) b^\dagger_{\alpha k+q} b^\dagger_{\beta k'-q} b_{\delta k'} b_{\gamma k},$$

$\alpha, \beta, \gamma, \delta = L, R$, leads to nonlinear terms in the equations of motion which tend to destroy phase coherence in the system.[8]

We apply a decomposition procedure of the structure $\langle \tilde{b}^4 \rangle(t) \approx \langle \tilde{b}^2 \rangle(t) \langle \tilde{b}^2 \rangle(t)$ to truncate the BBGKY hierarchy in the many–particle density matrix elements and arrive at a self–consistent and closed Markovian set of non–linear differential equations of first–order in time.[8]

The Coulomb matrix elements $v_{\alpha\beta\gamma\delta}$ are evaluated approximately for wave functions associated with infinitely deep wells. In particular we consider only matrix elements of the form $v_{\alpha\beta\alpha\beta}$. Termination of the BBGKY hierarchy at second order in v requires implementation of free–carrier screening by hand. Here, we adopt a commonly used short–cut and treat screening within the random–phase approximation (RPA). The retarded density fluctuation correlation function is evaluated within the plasmon–pole approximation (PPA)

$$D^o_\alpha(q,\omega) \approx D^o_{PPA\alpha}(q,\omega) = \frac{1}{v_c(q)} \frac{\omega^2_{pl\alpha}(q)}{(\omega + i\eta)^2 - \frac{q}{\kappa_\alpha} \omega^2_{pl\alpha}(q)}.$$

$\omega^2_{pl\alpha}(q) = (2\pi e^2 n_\alpha)/(\varepsilon_o m^*) q$ is the square of the plasmon frequency at sheet charge density n_α.[7] $\kappa_\alpha = \frac{2}{a^*_B} f_{\alpha\alpha}(0)$ is the $q = 0$ screening wave vector in two dimensions and a^*_B is the effective Bohr radius.

III. NUMERICAL RESULTS AND DISCUSSION

For a discussion of our numerical results we choose the left well L to be a 170Å GaAs well and the right well R to be a 120Å GaAs well, separated by a 17Å AlGaAs barrier. Here, we consider an electric field which provides resonance between the lowest electronic subband associated with each of the (isolated) quantum wells. The duration of the excitation pulse was varied between "0" and 0.5 ps with an average carrier excess energy of up to $20 meV$. The latter is to ensure validity of the two–subband approximation, as well as the neglect of optic phonon effects. The pulse width used was $4.2 meV$. Particle densities between 10^9 and 10^{11} cm^{-2} have been considered.

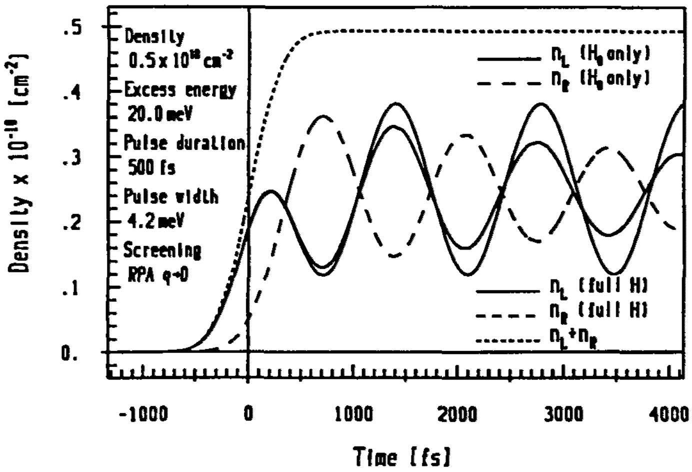

Fig. 1. Charge density in left and right well as a function of time.

A typical set of data is given in Figs. 1 to 3. Fig. 1 shows the time–evolution of the total number of electrons in the left well, solid line, and in the right well, dashed line. The undamped solid line gives the carrier density in the left well in the absence of the free carrier interaction, while the dotted line gives the total number of carriers in the double well. At 5×10^9 carriers per cm^2, we observe charge oscillations, however, the Coulomb interaction provides strong damping of the latter. The polarization is plotted as a function of time in Fig. 2. It also displays a damped oscillatory behavior. Its second time derivative is proportional to the radiated electric field. In case of resonant exciton excitation, up to about 15 such oscillations have been observed in a similar structure.[2]

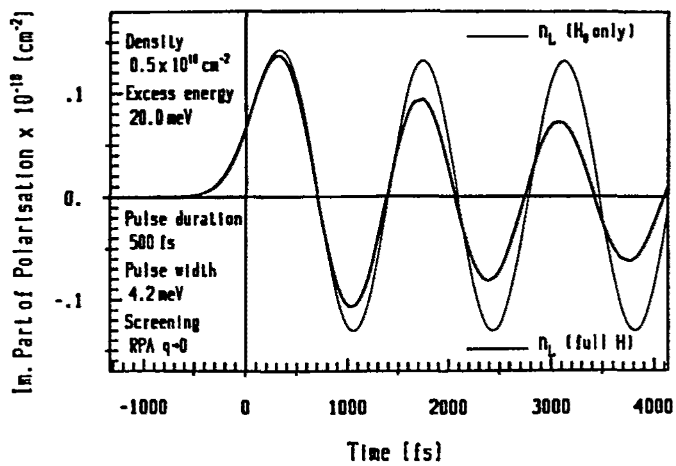

Fig. 2. Electron polarization $f_{LR}(t)$ as a function of time.

Simultaneous to the damping of the charge oscillations, thermalization among the electrons takes place on the time–scale of a few picoseconds. Fig. 3 (lhs) and Fig. 3 (rhs), respectively, give $f_{LL}(k,t)$ and $f_{RR}(k,t)$ as a function of k at selected times.

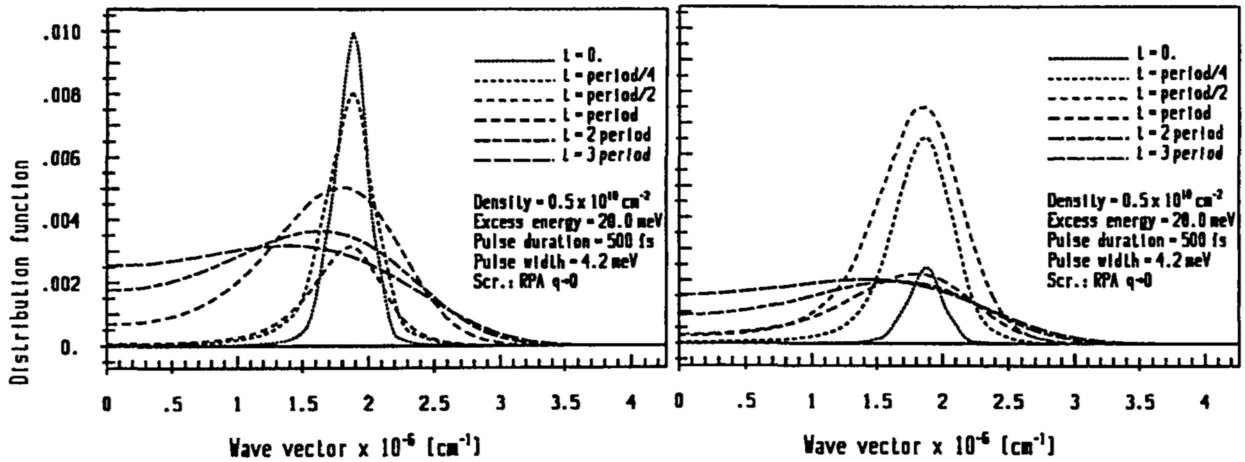

Fig. 3. lhs: distribution function $f_{LL}(k)$; rhs: distribution function $f_{RR}(k)$ at selected times.

IV. SUMMARY AND OUTLOOK

Our results can be summarized as follows. Charge oscillations due to *free* photo–generated carriers should be observable in asymmetric semiconductor double wells of high structural quality, provided that the inter–carrier Coulomb interaction provides the dominant dephasing mechanism. They should be observable up to about 10^{10} carriers per cm^2. Above this value the Coulomb interaction becomes so effective that it suppresses the onset of charge oscillations. Simultaneous to the destruction of phase coherence, the Coulomb interaction provides rapid thermalization of the photo–excited electrons.

It is remarkable that our results are rather insensitive to the screening model which is employed. The (dynamical) PPA, static RPA, Debye–Hückel, and Thomas–Fermi approximation produce practically identical results. This is largely due to the long–range nature of the Coulomb interaction and competing terms in the balance equations.

Further improvements, such as inclusion of electron–hole scattering, carrier–phonon interactions, and excitons, are desirable to clarify their role in the dephasing process.

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