DAMPED COHERENT CHARGE OSCILLATIONS IN SEMICONDUCTOR QUANTUM WELLS(*)

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ABSTRACT

A recently developed mean–field approximation to high–field transport in coupled electron–phonon systems is used to investigate charge oscillations in AlGaAs/GaAs. We find that acoustic phonons effectively damp the ensuing charge oscillations provided that the phonon correlation frequency and the Rabi frequency of the double well are of the same order of magnitude.

I. Introduction

Inelastic processes, such as phonon emission and absorption processes, are commonly believed to destroy phase coherence in mesoscopic systems.[1] This conclusion is mainly based on experimental evidence, as well as general considerations which are closely related to the quantum measurement problem. One of the most elementary coherent processes are oscillations in double wells which have been recently seen in semiconductor double wells.[2] Explicit theoretical demonstrations of the loss of phase coherence in mesoscopic systems have remained small in number. Next to purely phenomenological approaches,[2,3] Feynman path integrals have been a very successful tool to study simple fermionic systems coupled to a phonon "bath ".[4–6] Here we use a mean–field approximation which has recently been developed via a coherent–state functional integral approach to investigate the damping of charge oscillations in quantum wells due to acoustic phonons.

II. The Model

The time–evolution of a coupled electron–phonon system which is driven out of thermal equilibrium by an external field can be written as an expansion about mean–field solutions.[7,8] Within lowest order, the system is approximated by an independent fermion system which propagates in a self–consistent mean field which accounts for the electron–electron and electron–phonon interaction. In absence of electron–phonon interaction, the effective Schrödinger equation simply reduces to a (time–dependent) Hartree equation. The phonon term has the form of a convolution which contains an electronic part and a phonon part. It makes the equations non–Markovian. Although the time–evolution preserves the norm of the wave–function, the electron–phonon coupling causes that the system is not invariant under time reversal and thus displays features of a "dissipative" quantum system. The present approach includes the full quantum–mechanical nature of the independent particle system, in particular tunneling processes and the external field. Approximations merely concern the treatment of the particle–particle interactions. This renders the present approach suitable for application to a variety of mesoscopic systems.

From a computational point of view, the investigation of the system in thermal equilibrium is a many–particle Hartree–type equation which must be solved self–consistently. The time–evolution presents itself in form of a time–dependent mean–field equation which is of Hartree–type also, except that the past of the system ($t' < t$) must be recorded to compute the effective potential $x^{\circ}(t,0)$. Standard techniques are used to obtain the time–evolution of the system.[9]

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III. Application to Double Wells

Here we apply this approach to electron tunneling in a symmetric double well. Originally, an external bias ensures that the lowest subband of the left well lies sufficiently below the lowest subband of the right well so that, in thermal equilibrium, practically all electrons reside in the left well. Then the bias is changed to align the two lowest subbands. The resulting charge oscillations are studied. In this preliminary study we make a variety of simplifying assumptions. Next to single subband occupation and the usual effective-mass approximation, we assume perfectly uniform well and *barrier* thicknesses, as well as a uniform (initial) charge distribution. In this study, the electron–electron interaction is neglected. In the present situation only coupling to acoustic phonons needs to be considered. Simple bulk phonon modes with linear dispersion relation are used. We consider only intra–well coupling processes. Phonon–mediated inter–well coupling is not considered here. Finally, the effect of phonon–scattering in the right well is neglected in the calculation of the effective potential for the left well, and *vice versa*. The latter is only a 10% effect for barriers as thin as 1nm. Intra–well phonon matrix elements are calculated for eigenfunctions of an infinitely deep well.

Due to the translational invariance in plane, the problem reduces to a two–level system coupled to a phonon–bath via the mean field x^o. The effective potential takes the form

$$x_i^o(0,0) = -N_i \sum_j \frac{L_z}{2\pi} \int_{-\pi/a_L}^{+\pi/a_L} dq_z \frac{2|M_j(q_z)|^2}{\hbar\omega_q}$$

and

$$x_i^o(t,0) = x_i^o(0,0) + \Delta x_i^o(t,0),$$

with

$$\Delta x_i^o(t,0) = -\frac{L_z}{\hbar\pi} \sum_j \int_0^t dt' \int_{-\pi/a_L}^{+\pi/a_L} dq_z |M_j(q_z)|^2 \sin[cq_z(t-t')]\Delta N_i(t').$$

Here, $M_j(q_z)$ is the screened matrix element for coupling mode j (=adp, piezo). N_i is the number of electrons in well i (=L, R). a_L is the lattice constant and c is the sound velocity. ω_q and q are phonon frequency and wave number, respectively.

We present results for the following parameters. For thermal equilibrium, the carrier concentration is $0.5 \times 10^{12} cm^{-2}$, temperature $T = 15K$, and, due to an applied electric field, the right subband is 10meV above the left subband. Standard material parameters are used for GaAs.[10] Well widths are 7.5nm. Instead of specific barrier thicknesses, we use various values for the overlap V. At time zero, the applied bias is turned off.

Fig. 1 shows the normalized probability for finding an electron in the left well for various values of V. If the overlap $|V|$ is large, rapid tunneling occurs and virtually undamped charge oscillations are obtained. As $|V|$ is reduced one enters a regime of (strongly) damped oscillations. When $|V|$ is made even smaller, slow weakly damped and, finally, undamped oscillations are obtained.

Technically, this behavior can be understood from the structure of the electron–phonon term. The convolution of two oscillating time–dependent functions can only be large, if the oscillations occur on the same time scale. The phonon correlation function for the acoustic deformation potential and piezo–electric coupling are shown in Fig. 2. Oscillations occur on a time scale of about 1 ps which we loosly characterize by a correlation frequency ω_c. Thus, V needs to be in the range of 1meV. From a physical standpoint, if the two wells are strongly coupled Rabi oscillations of frequency $\omega_o = |V|/\hbar$ are fast compared to "phonon emissions". Only if phonon emission processes occur on the same (or a smaller) time scale as (than) Rabi oscillations can the former effectively damp the oscillations. The failure of the model to give the physically intuitive result in the limit $\omega_o << \omega_c$ is not clear at present. One possibility is that the mean–field approximation is too simple.

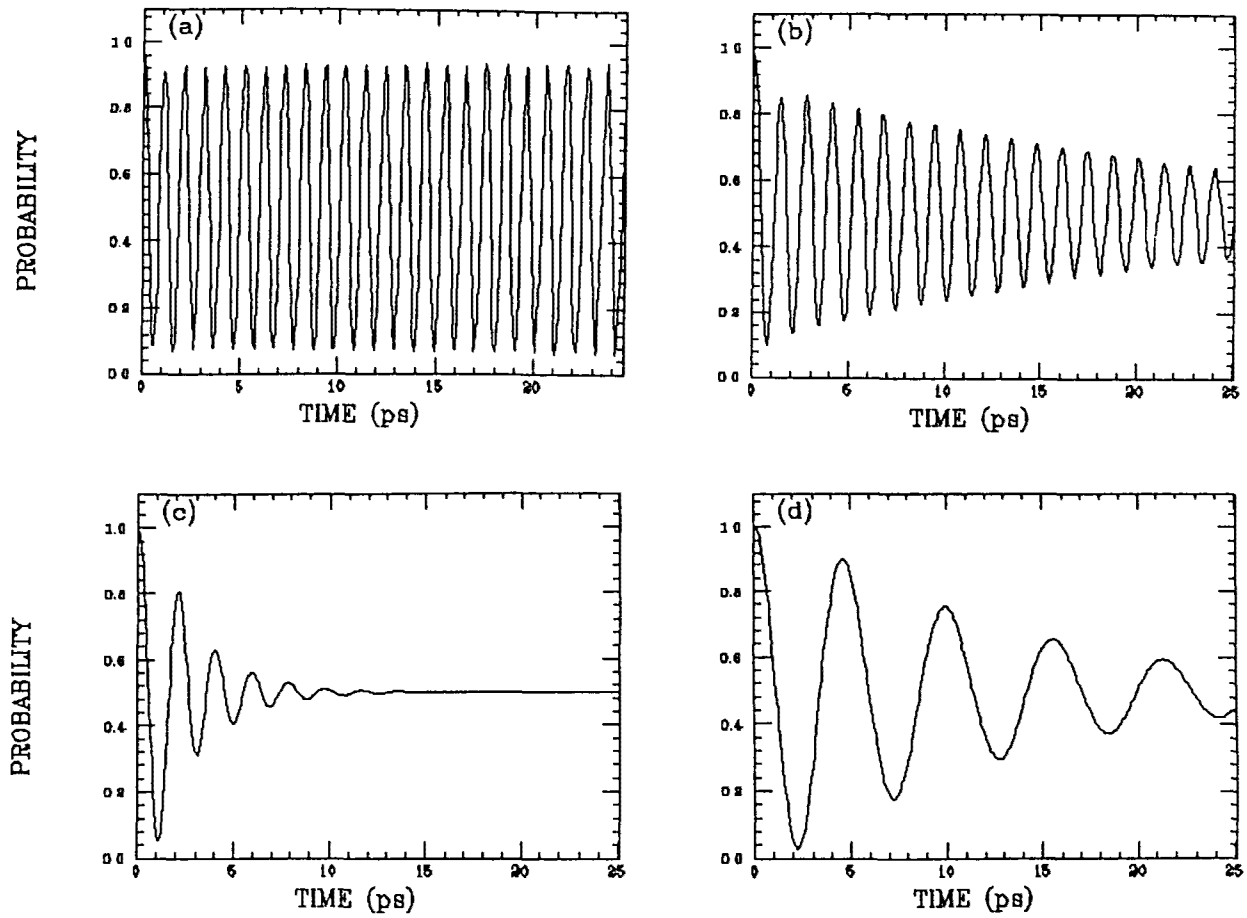

Fig. 1. Normalized occupation probability of the left well as a function of time: $V = -2meV$ (a), $V = -1.5meV$ (b), $V = -1meV$ (c), $V = -0.5meV$ (d).

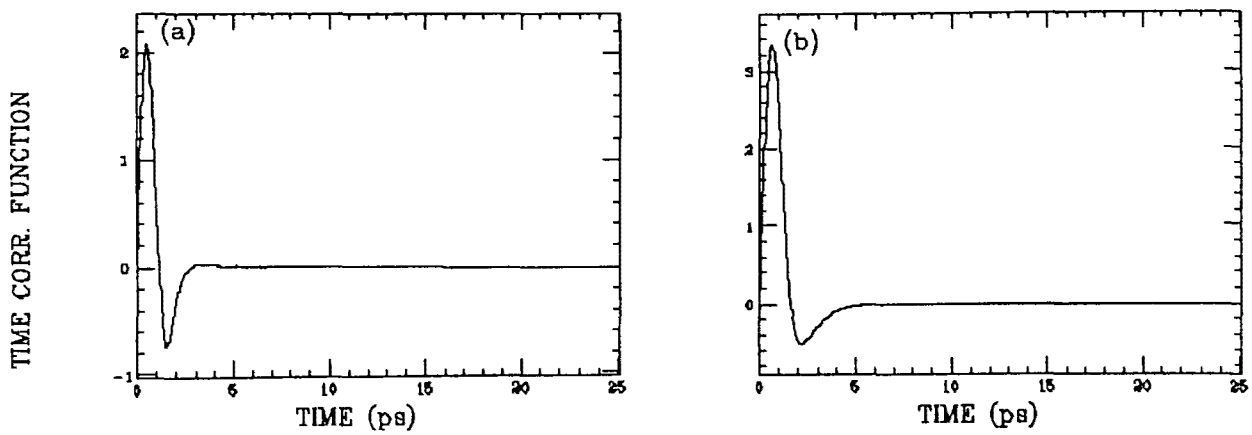

Fig. 2. The phonon time-correlation function: acoustic deformation potential coupling (a), piezoelectric coupling (b).

Alternatively, the phonon model may be too simple. For instance, the translation invariance in

plane causes that x^o does not couple different electronic states $|\vec{k}_{||}\rangle$. In a simple semiclassical picture for this situation, electrons would tunnel from the left well into the right well, scatter down the subband and, most likely, never return to the left well. We found that an increase of the electron phonon coupling strength leads to a "self-trapping" of electrons in the left well in this frequency regime. However, for realistic coupling strengths for GaAs this does not seem to occur via the coupling to acoustic phonons. This effect, similar to the small polaron, may be possible via the polar-optical coupling and will be investigated. However, due to their nearly dispersionless ω-q relation, optical phonons do not serve as a "bath", as we verified explicitly for the present situation. Moreover in the present case, optical phonon emission is energetically not allowed. In the present model, this is expressed by $\omega_{LO} >> \omega_o$. It should also be noted that a study of the Fröhlich polaron within the present approach has shown that this approximation works better in the strong coupling regime, as expected.[11]
Real structures contain additional sources for dephasing. Particularly for narrow barriers, 1.5 nm were reported in [2], layer width fluctuations by one monolayer dramatically affect the inter-well coupling. Similarly, inhomogeneities in the initial carrier distribution, as well as diffusion, may have a strong influence on the time-evolution of the system. Within our approach, loss of in-plane translational invariance dramatically increases the complexity of the problem. In particular, intra-subband transitions are now allowed within the mean-field approximation.

IV. Summary and Conclusions

We have used a simple, but largely non-phenomenological, model to study the damping of charge oscillations in GaAs/AlGaAs double wells. We find that for a regime where the acoustic phonon correlation frequency ω_c is of the same order of magnitude as the Rabi frequency ω_o of the double well, acoustic phonons efficiently damp the charge oscillations. The deeper reasons for the failure of the present model to provide damping in the regime $\omega_o << \omega_c$ are presently not understood and are under current investigation. For realistic coupling strengths we find no evidence of self trapping of electrons in one well due to coupling to acoustic phonons.

V. References

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