Effect of inter-dot distance on excitonic dephasing in quantum dot chains

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Abstract. We present a study of the dephasing of an excitonic qubit trapped within a chain of two semiconductor quantum dots immersed in a bulk material. We consider a specific excitonic wave-function which spreads across the chain. The source of the dephasing is the phonon field of the bulk material interacting with the single exciton within the structure. We show that an excitonic wave function which extends over more than one quantum dot is remarkably more robust against the dephasing. The details of dephasing depends on the distance which separates the two quantum dots. In particular, as this distance increases, the residual coherence increases up to a maximum value. However, the short-time dephasing is shown to be characterised by the appearance of a transient behavior. The actual duration of this transient is determined by the separation between the dots.

1. Introduction

The capability and computational power of traditional devices have been growing very fast over the last few decades. However we will not be able to sustain this continuous improvement, as, for example, device miniaturization will inevitably lead to the appearance of unwanted quantum effects which may alter their functionalities. Moreover, any traditional device can implement only algorithms based on classical bits. It has been though demonstrated that algorithms based on ‘quantum bits’ or ‘qubits’ outperform some of the best ‘classical’ algorithms and may even provide an exponential speed-up with respect to their classical counterparts[1]. For these reasons practical implementations of Quantum Information Processing (QIP) devices are attracting special interest worldwide.

Unfortunately, the realization of these devices is extremely challenging. In fact, in QIP devices the computation should be carried out through an externally-controlled evolution of a set of quantum systems (the qubits) and it is necessary to preserve the quantum properties of such objects throughout the computation. Unfortunately the unavoidable interaction with the environment reduces (and eventually destroys) the quantum coherence of the qubits, degrading them to the status of classical ones. This phenomena is known as decoherence. Only a system robust enough against the coupling to the environment (or made robust thanks to active strategies such as dynamical decoupling [2], for example) can be used as QIP hardware.

Quantum Dots (QDs) have many features that makes them one of the best candidate as physical realization of qubits [3, 4, 5, 6, 7]. It is possible to exploit the presence or absence of a ground state exciton to encode a qubit in each QD[3], and manipulation of excitons (in order to implement logic gates) could be done using all-optical schemes[8]. In addition the hardware is in principle scalable. Furthermore their discrete energy levels make QDs relatively robust against the coupling with the environmental
degrees of freedom, and there are studies to reduce the related decoherence, for example using dynamical
decoupling techniques[9].

2. The system
In this article, we are studying a system made by two identical semiconductor QDs, forming a chain
along the in-plane x-axis. We consider oblate quantum dot, located at a distance d from each other. We
are interested in a system in which at most one exciton is present overall. This configuration is interesting
because similar chains of QDs can be used to realize a quantum bus[10, 11]. In particular, we are focusing
on self-assembled GaAs/AlAs QDs, at low temperature (T = 4K). Under these circumstances it was
demonstrated that the exciton-acoustic phonon interaction is the relevant cause of decoherence[12].
This type of interaction leads to pure dephasing: only the off-diagonal elements of the excitonic density matrix
are affected, while the excitonic population remains constant. This dephasing is very rapid (picosecond
time-scale), but, at low temperature, the system coherence is not completely destroyed and saturates to a
finite value[12], until excitonic recombination occurs. Decoherence studies of systems similar to our (but
considering different exciton states) have been recently performed[13, 14]. Our aim here is to understand
how coupling to phonons would affect a ground state exciton equally spread between the two QDs and
how the distance between the dots modifies this dephasing.

The Hamiltonian of the system is
\[
H = E_{exc} c^\dagger c + \hbar \sum_{j,k} \omega_j(k) b^\dagger_{j,k} b_{j,k} + \hbar c \sum_{j,k} (g_{j,k} b^\dagger_{j,k} + g^*_{j,k} b_{j,k}),
\]
with \( E_{exc} \) the energy of the ground state exciton relative to the crystal ground state, \( c^\dagger (c) \) is the creation
(annihilation) operator for the exciton in the system, and \( b^\dagger_{j,k} (b_{j,k}) \) the bosonic creation (annihilation)
operators for a phonon of mode \( j \), wave vector \( k \) and angular frequency \( \omega_j(k) \). The matrix element \( g_{j,k} \)
represents the coupling between the exciton and the phonon field,
\[
g_{j,k} = \int dr_e dr_h |\Psi(r_e, r_h)|^2 (G^e_{j,k} e^{i k \cdot r_e} - G^h_{j,k} e^{i k \cdot r_h}).
\]
Here \( e \) and \( h \) stand for electron and hole, respectively. \( j \) indicates the phonon mode and \( k \) is the phonon
wave-vector. The bulk coupling matrix element \( G^e/h_{j,k} \) depends on the type of phonon-carrier interaction:
piezoelectric interaction (caused by longitudinal and transverse acoustic phonons) and deformation
potential (due to longitudinal acoustic phonons only). The latter is the most important in the material we
are considering, when no electric field is applied[15]. The geometrical details of the QD chain will affect
our calculations through the exciton wave-function. We will consider the ground state of an exciton
spread over the chain and approximate its wave-function as
\[
\Psi_+(r_e, r_h) = \frac{1}{\sqrt{2[1 + \Theta_{1:2}(d)]}} \sum_{l=1}^2 \varphi_l(r_e, r_h),
\]
where \( \varphi_l(r_e, r_h) \) is the single-dot ground-state excitonic wave-function located in the \( l \)-th dot, and
\( \Theta_{1:2}(d) \) represents the overlap between single-dot wave-functions located at different dots. The wave
function \( \varphi_l(r_e, r_h) \) is modelled as products of single-particle Gaussian wave-packets, with \( \lambda_{x/y_e} = 6.16 \)
nm, \( \lambda_{x/y_h} = 3.05 \) nm and \( \lambda_{z/e/h} = 1.5 \) nm, as we consider dots in the strong confinement regime.

The phonon interaction may couple the state \( \Psi_+ \) to its antisymmetric counterpart with an Hamiltonian
\[
H_{\pm} = \sum_{j,k} g^\pm_{j,k} \langle \Psi_+ | b_{j,k} + h.c. \rangle. \]
This coupling would lead to a leakage from the computational into non-computational states. In this contribution though we wish to concentrate on the effects of the chain geometry on the dephasing of the ground (computational) state, so we will defer the study of this
leakage mechanism to further work.

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3. Pure Dephasing

In order to calculate the dephasing, we assume that the chain of QDs is in thermal equilibrium with the phononic bath, and that at the initial time $t = 0$ the qubit and the phonon bath are uncorrelated. The time evolution of the off-diagonal exciton density matrix element $\rho_{01}$, calculated in the interaction picture in respect to $H_0 = E_{\text{exc}} c + h \sum_{j,k} \omega_j(k) b_{j,k}^\dagger b_{j,k}$ is given by

$$\rho_{01}(t) = \rho_{01}(0)e^{-\Gamma(t)}$$  \hspace{1cm} (4)

where the exponent $\Gamma(t)$ is given by [2, 12]

$$\Gamma(t) = \int_0^\infty d\omega \frac{I(\omega)}{\omega^2} \coth \left( \frac{\hbar \omega}{k_B T} \right) (1 - \cos(\omega t)).$$  \hspace{1cm} (5)

$I(\omega)$ is the spectral function

$$I(\omega) = \sum_{j,k} \delta(\omega - \omega_j(k)) |g_{j,k}|^2,$$  \hspace{1cm} (6)

where $\omega = \omega_j(k)$ is the dispersion relation for the phonons. The fact that $\rho_{01}(t) < \rho_{01}(0)$ for $t > 0$ signals a loss in quantum coherence. This quantity is related to the optical polarization $P(t)$, and hence it is directly measurable.

The key difference between the function $\Gamma(t)$ for the case of an exciton in a single QD and our case (one exciton spread over a chain of quantum dots) is the appearance of an interference between the wave-functions $\varphi_j(r_e, r_\text{h})$ located on different QDs. The exponential in Eq. (4) could be rewritten for $d > \lambda_{se}$, i.e. $\Theta_{1,2}(d) \approx 0$,

$$e^{-\Gamma(t)} \left. \right|_{d>\lambda_{se}} \approx e^{-\frac{1}{2} \Gamma_{\text{QD}}(t)} e^{-\frac{1}{2} \Gamma_I(t)},$$  \hspace{1cm} (7)

where $\Gamma_{\text{QD}}(t)$ is the single-QD dephasing function and $\Gamma_I$ contains the effects of the interference (and overlap) between the different $\varphi_j(r_e, r_\text{h})$.

4. Numerical results

In order to study the dephasing, we calculated $|e^{-\Gamma(t)}|^2 = |P(t)|^2 / |P(t = 0)|^2$ for different values of $d$. Let us first focus on the spectral density Eq. (6). This determines the energy range of the phonons that interact with the exciton and its spread and shape are related to the geometry of the system, which comprise the geometrical features of each QD, and the distance $d$ between the QDs. This new characteristic length is encoded in the interference term. The contribution from the deformation potential is about one order of magnitude larger than the one arising from the piezoelectric interaction. We present the plots for these contributions, $I_{\text{piez}}$ and $I_{\text{def}}$, in Fig. 1.

Their behaviour is marked by two common features. The first one is the decreasing of their value as $d$ passes from 0 (i.e. single dot case) to $d = 10$ nm. This behaviour will correspond to a decreasing of the dephasing as $d$ increases. The second one is the appearance of an oscillating behaviour as the QDs are separated from each other. This further structure arises from the part of $I(\omega)$ which depends on the interference term. In particular as $d$ increases this part becomes smaller and starts to oscillate.

Finally in Fig. 2 we present the plots of the dephasing (right panel) and of its saturation value for $t \to \infty$ (left panel). From this we notice that the saturation value of the dephasing increases as the distance between the dots increases, until it reaches a nearly constant value for $d \simeq 20$ nm. The plot of the dephasing shows the gain in the quantum coherence of the two-dots chain in respect to the single dot case, $d = 0$. A marked characteristic of these plots is the appearance of a transient (step) behaviour when the two-dots are clearly separated. The position of this step is related to the time necessary to the phonon modes to travel between the dots.
5. Conclusions

We have presented a study of pure dephasing for one exciton spread across a chain of two identical quantum dots. Our results show that the time evolution of the exciton dephasing is affected by the internal structure of the chain and that this can substantially increase the exciton long term coherence.

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