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# Ultrafast carrier and phonon dynamics in GaAs and GaN quantum dots

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**Abstract**

We analyse the electronic and phononic dynamics in GaAs and GaN quantum dot structures due to their interaction with acoustic phonons. We compare results for two specific quantum dot heterostructures which have been proposed as hardware building blocks for a quantum computer in recent quantum computation/information schemes. In particular, we are interested in the loss of coherence after excitation with an ultrashort laser pulse and in the dynamics of phonons which are created as a consequence of the optical excitation process. Our results are non-perturbative with respect to both carrier–phonon and carrier–light interaction and therefore include multi-phonon processes of arbitrary order. We find that, due to different quantum dot sizes, involved electric fields and material parameters, the decoherence is stronger in the GaN dots. The interplay of these effects also strongly determines the details of the created phonon occupation, which splits into two parts: one remains in the vicinity of the dot and forms a stable polaron and another leaves the dot as a phononic wave packet travelling with the velocity of sound. Due to the dot geometry and the carrier–phonon coupling matrix elements this phonon emission is strongly anisotropic.

In this paper, we will analyse the carrier and phonon dynamics of two quantum dot (QD) structures which have been proposed for an all-optical implementation of single- and two-qubit devices where a static electric field has been used to enhance the dipole coupling between different dots [1–4]. A main issue is to compare the role of pure dephasing in these structures, which is known to induce substantial coherence losses on a short time scale after a pulsed optical excitation [5, 6]. We shall also discuss the resulting phonon dynamics which is closely related to the decoherence [6]. The structures considered are: a GaAs quantum dot with an electric field applied in the in-plane direction [1, 2] (QD A) and a GaN quantum dot which features a strong intrinsic field in the growth direction [3, 4] (QD B). Both dots are modelled by a deep potential well in the growth direction and by a harmonic potential in the in-plane direction. Only the lowest exciton state is accounted for. Electron and hole charge distributions together with the potentials both in the lateral ($x$) and the growth ($z$) directions are shown in figures 1($a$) and ($b$) for QD A and QD B. Note that QD B is smaller than QD A, whereas the intrinsic field in QD B is stronger than the one applied to QD A. However, the stronger confinement in the growth direction limits the charge separation in QD B to the width of the potential and is thus smaller than in QD A.

The Hamiltonian for a dot coupled to phonons and a light field is described by the independent boson model with an additional term that provides for the dipole coupling [5, 6]. It is well known that the corresponding linear response can be obtained analytically [12–14]. In addition, it has been shown that the exact response to an arbitrary sequence of $\delta$-pulses can be derived analytically, i.e. nonperturbative with respect to the carrier–phonon and the carrier–light coupling [5, 6]. Here, we shall employ these results for the dynamics of the optically induced polarization and for the phonon occupation after excitation with a single laser pulse. We will account

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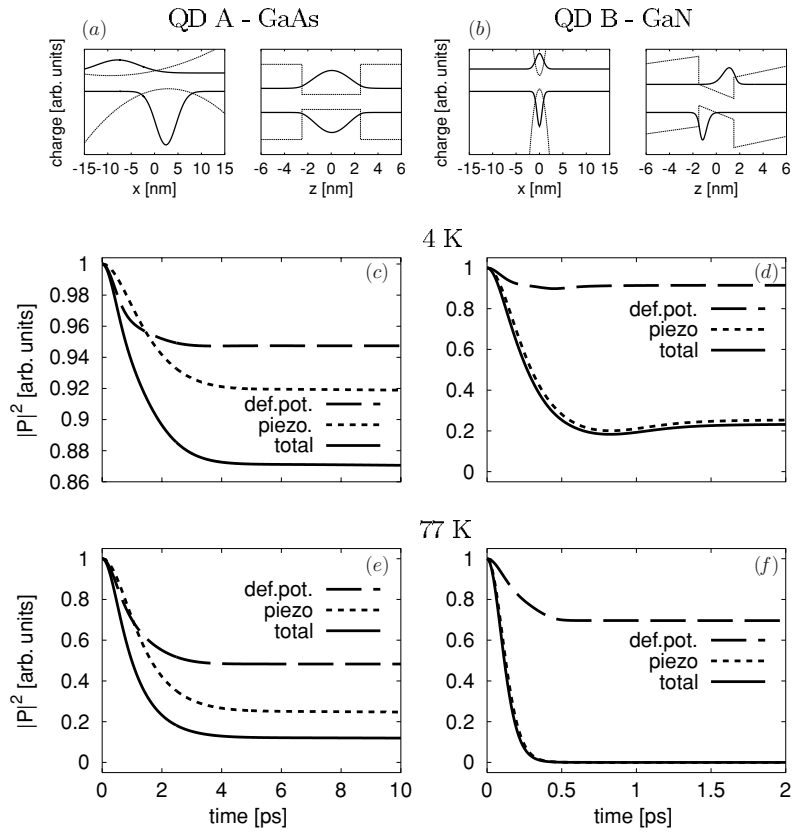


**Figure 1.** (*a*), (*b*) Electron and hole charge densities (thick lines) and corresponding confinement potentials (thin lines) of the considered QD structures; (*c*)–(*f*) optical polarizations induced by an ultrashort excitation at a temperature of 4 K ((*c*), (*d*)) and 77 K ((*e*), (*f*)). The left column refers to the GaAs dot (QD A) and the right column to the GaN dot (QD B).

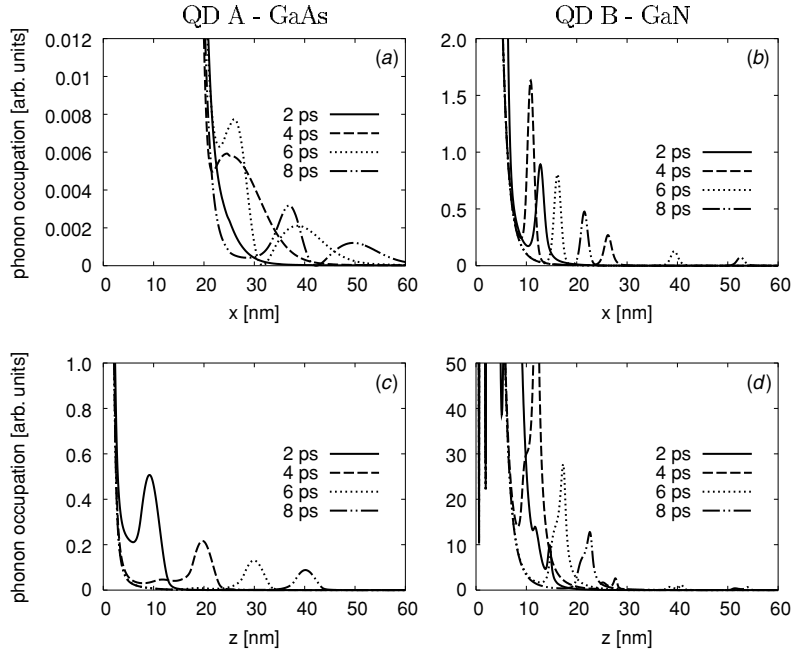


**Figure 2.** Spatially resolved nonequilibrium phonon distribution at different times along the in-plane ((*a*), (*b*)) and growth ((*c*), (*d*)) directions. The left panel refers to QD A, the right panel to QD B.

for deformation potential (DP) as well as piezo-electric (PE) carrier–phonon coupling. The deformation potentials for GaAs are given by $D^e = 7.0$ eV and $D^h = -3.5$ eV [7] for electrons and holes respectively. For GaN these values are $D^e = -4.08$ eV and $D^h = 2.1$ eV [10, 11]. For GaAs the piezoelectric constant is $e_{14} = 0.16$ C m$^{-2}$ [9],

whereas in GaN they are given by $e_{33} = 0.73$ C m$^{-2}$ and $e_{31} = e_{15} = -0.49$ C m$^{-2}$ [8]. Physically the $\delta$-pulse limit means that the pulse has to be shorter than the characteristic time scales induced by the phonon interaction. As seen below, for QD A this is well satisfied for pulses up to several hundreds of fs while for QD B the limit is about 100 fs.

An explicit formula for the optical polarization induced by a $\delta$-pulse has been given in [6]. Figures 1($c$)–($f$) show the polarization for QD A and QD B calculated for two different temperatures, $T = 4$ K (($c$), ($d$)) and $T = 77$ K (($e$), ($f$)). The left (right) column refers to QD A (QD B). In all cases the polarization exhibits a fast initial decay and a remnant polarization which does not decay in the long time limit within the present model. In real systems it decays on a much longer time scale either due to radiative recombination or transitions to higher excitonic states [15]. In QD A the decays induced by the two mechanisms are of the same order. In GaAs the intrinsic PE coupling is weak, but it has been shown to be substantially enhanced in the presence of an electric field [5]. The coupling via DP, being a non-polar mechanism, does not react as strongly to a field [5]. In QD B the PE coupling dominates. Comparing QD A with QD B reveals two main differences. First, for QD B the remnant polarization adopts lower values than for QD A, when considering both coupling mechanisms. Second, the time scales of the initial decay are different due to the different electron–hole separation in each structure. The broader $q$ extent of the coupling matrix element resulting from the smaller size of QD B permits more phonon modes to contribute to the dephasing and thus leads to a faster decay.

Due to the electron–phonon coupling an optical excitation also excites a nonequilibrium phonon population with a spatial distribution explicitly given in [6]. It consists of two parts: a phonon occupation which remains in the vicinity of the dot and forms a stable polaron and a wave packet leaving the dot. Once the packet has left the dot, the carrier–phonon system within the dot remains in a stable state. In figure 2 the phonon occupation is plotted in the in-plane ($x$) and growth ($z$) directions for QD A (left) and QD B (right). The polaronic occupation in the dot has a spatial extent roughly given by the size of the exciton wavefunction. Thus, it is much broader for QD A than for QD B. The polaron occupation increases until about 4 ps and then remains constant. The polaron formation energy is released in the form of travelling phonon wave packets emitted into the surrounding solid. For QD B, where the PE coupling dominates, one can discriminate wave packets travelling with the velocity of TA (slow) and LA (fast) phonons. In contrast, in QD A DP coupling prevails and thus only wave packets propagating with the LA velocity can be discerned. Nevertheless, QD A emits two wave packets in the $x$-direction (figure 2($a$)). The charges are well separated in this direction and thus wave packets are emitted at the electron as well as the hole position. This effect also applies to QD B in the $z$-direction, but is not so well resolved.

In conclusion, we have presented an analysis of the carrier and phonon dynamics in different dot structures after ultrafast optical excitation. The strong PE interaction in GaN in combination with the large built-in electric field leads to a strong dephasing already at low temperatures. The excitation process is accompanied by the creation of a nonequilibrium phonon distribution which can be separated into a stable polaron localized in the dot region and a highly anisotropic phonon wave packet leaving the dot with the velocity of sound.

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