Dynamic localization in finite quantum-dot superlattices: A pure ac field effect

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We propose that dynamic localization can be unambiguously observed through the linear optical absorption coefficient of a finite quantum dot superlattice. It is shown that the miniband collapse is almost exact in a pure ac field driven system. In the presence of Coulomb interaction, the dynamic localization is partially preserved, showing clear fingerprints in the modulation of the excitonic spectra. The spectra are obtained within an extended semiconductor Bloch equation framework, taking into account the center-of-mass motion for a finite system.

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The dynamic properties of electrons and holes in low dimensional systems, driven by ac fields, reveal exciting emergent phenomena in the time span around the turn of the century. Such a rich scenario has been established by the concurrent development of powerful theoretical analysis tools, design and realization of high quality nanostructured devices, as well as of tunable microwave and THz ac field sources. These striking developments made possible the exploration of the interaction of THz fields with condensed matter, leading even to biological tissue imaging. Therefore a microscopic understanding of the THz field effects on designed nanostructures constitutes an important framework for further developments.

A very interesting example in this context is the prediction of dynamic localization, which has been a subject of intense research in the past few years, from both theoretical and experimental point of views. The initial prediction states that, within a single band tight-binding approximation, an initially localized particle will return to its initial state following the periodical evolution of a driving pure sinusoidal field. This phenomenon can be simply visualized by the related collapse of the quasienergy minibands, i.e., the localization of electronic states of a periodic unidimensional structure in real space driven by a field periodic in time. Such collapses occur whenever the field intensity/frequency ratio, \( eaF/\hbar\omega \), is a root of the zero-order Bessel function of the first kind.

The quest for experimental signatures of dynamic localization is an involved task, since a variety of perturbations to an ideal situation is always present in real systems. The question that has to be answered is how the dynamic localization, related to the quasienergy miniband collapses, may be identified in a context where concurring effects also tend to modify the quasienergy spectra. For semiconductor superlattices, dynamic localization has been suggested as the mechanism for an absolute negative conductance observed in photon assisted tunneling effects. A definitive evidence, however, is still lacking.

A far more difficult problem concerns the dynamic localization in the presence of Coulomb interactions, unavoidable in optically excited semiconductor superlattices. The existence of dynamic localization in the presence of Coulomb interaction has been suggested for semiconductor quantum well superlattices, within the framework of the semiconductor Bloch equations (SBE). It has been done in \( k \)-space, considering the same energy dispersion relations for electron and hole, for a unidimensional and infinite superlattice, and neglecting the carrier center-of-mass motion.

Recently Zhang et al. have suggested that dynamic localization may not be observed in a pure ac field. Their results have been obtained using an excitonic basis, in \( k \)-space with zero center-of-mass momentum, to treat the dynamics. They have said, however, that for the pure ac field case, the unbound excitons (not included in their excitonic basis) play a much larger role and may dominate the dynamics.

The aim of this paper is to show that a signature of dynamic localization can be seen unambiguously in the linear optical absorption spectra in an applied ac field, even in the presence of Coulomb interactions. We propose that such effect would be observable in a novel, realistic, and promising nanostructure, namely semiconductor finite quantum dot superlattice in a nanowire, as sketched in Fig. 1. Important steps towards the realization of such unidimensional heterostructures have been the focus of recent experimental investigations. It is worth noting that the system we are dealing with is very close to a heuristic 1D chain of atomic sites, in which excitonic spectrum reflects the miniband structure. It also has the essences of large, but finite, molecular nature.

FIG. 1. Quantum rod 3.5 \( \mu m \) long of InP and a superlattice of 20 In\(_{0.53}\)Ga\(_{0.47}\)As dots (InP barriers) in its central part.
lar systems. The optical absorption coefficient is obtained from the SBE considering the electron and hole degrees of freedom. It takes into account the translational invariance breaking down of the system, which is in contrast to the usual approach of solving only the electron-hole relative motion. The SBE is extended to include the finite number of quantum dot potentials for electron \( \Phi_e(z_e) \) and hole \( \Phi_h(z_h) \). Although we consider here all dots with the same thickness and confining potentials, our scheme can treat equally well a finite superlattice with quantum dots of different forms and arrangements in the superlattice.

The system is handled as a finite quantum wire with infinity potential on the lateral and ending walls (see Fig. 1). Along the wire there is a potential modulation, due to alloy alternation, as in a usual superlattice. The system is under the action of a short optical pulse and an oscillating homogeneous electric field along the wire in terahertz frequency scale.

The optical absorption coefficient that gives us the signature of the dynamic localization is obtained from the interband polarization. Its dynamic takes place on the coherent time- and space-localization. \(^1\) The dephasing time is \( T_{\text{d}} = 40 \text{ fs} \) and frequency \( \omega = 2 \times 10^{16} \text{ Hz} \) for the conduction electron and \( \omega_{\text{eh}} = 3.8 \times 10^{16} \text{ Hz} \) for the valence heavy hole. The electron (hole) potential \( \Phi_e(z_e) = 0 \) inside the dots and \( \Phi_h(z_h) = 0 \) in the InP barriers. The background dielectric constant is \( \varepsilon_{\text{bg}} = 13.9 \), and the interband dipole moment is \( d_0 = 0.3 \text{ nm} \). The width of the Gaussian optical pumping pulse is \( \sigma = 40 \text{ fs} \) and frequency centered at the effective material band gap, i.e., \( \omega_0 = \tilde{E}_g = 1259 \text{ meV} \). The dephasing time is \( T_{\text{d}}^{-1} = 500 \text{ fs} \). \(^{12} \)

We initially consider the absorption spectra in the absence of Coulomb interaction, i.e., for band-to-band absorption. The absorption spectrum reveals the underlying unidimensional-like density of states of the minibands, as it is shown by the solid line in Fig. 2 for the field-free case. A finite system with 20 quantum dots already has the main features of an infinite periodic superlattice. This absorption spectrum also indicates that the minibands are highly symmetric, a condition for an exact dynamic localization.\(^{10} \)

Figure 2 also presents the ac field effects on the absorption spectra in the absence of Coulomb interaction. The absorption coefficient is shown for different ratios \( x = \epsilon J_{\text{ac}} / \hbar \), with fixed THz field frequency \( \Omega = 20 \text{ meV} \). The cusps at the edges of the absorption profile reflect the
higher electron-hole joint density of states at the center and border of the Brillouin zone. Increasing $x$, up to $x=2.4$, we can see a progressive shrinking of the optical absorption spectrum. The distance between the cusps at the edges of the absorption spectrum (signature of the conduction and valence miniband widths) reaches a minimum at $x=2.4$. The optical absorption coefficient becomes single peaked at the same peak position, and with the same intensity, of the optical absorption coefficient for a single quantum dot, with the same radius $R=5$ nm and 6 nm thick, in the absence of Coulomb interaction and ac field (see inset on the left). For $x>2.4$, the miniband width first increases and subsequently decreases. This behavior can be clearly seen in the inset on the right of Fig. 2, where the distance between the cusps of the edges of the spectrum $\Delta E$ is shown as a function of $x$. The inset on the right shows also the analytical prediction for the evolution of dressed minibands given by $\Delta E = J_0(\kappa)\Delta E_0$, where $J_0$ denotes the zero-order Bessel function, and $\Delta E_0$ denotes the miniband width for the case without Coulomb interaction and ac field. The striking agreement indicates that the finite 1D quantum dot superlattice is a suitable system for analyzing the effect of Coulomb interaction on the dynamic localization through optical absorption experiments.

The absorption spectra as a function of the THz field intensity is drastically modified in the presence of Coumb interaction. The oscillator strength is almost completely transferred from the minibands to the exciton and shifts (redshift) the optical spectrum (exciton binding energy). Therefore a direct evidence for photon dressed minibands could be hindered in optical measurements. Nevertheless, for a quasi-one-dimensional system, the excitonic dispersion relation follows the dispersion relation of the minibands.$^{11}$ In Fig. 3 we show the excitonic absorption spectra for a finite quantum dot superlattice under the influence of Coulomb interaction and of THz field. The excitonic spectra for different $x=edF_0/\hbar\Omega$ with fixed THz field frequency $\hbar\Omega=20$ meV are shown. In the absence of the THz field (solid line in Fig. 3), a characteristic asymmetric line shape for excitons in 1D periodic systems can clearly be seen. Turning on the THz field, several interesting features appear, as the changing of the linewidth of the excitonic peak (signature of the dynamic localization) and the appearance of satellite peaks on the absorption spectra. Those peaks, on the left at $E-E_{g,0}^{\text{d}}=75$ meV and on the right at $E-E_{g,0}^{\text{d}}=95$ meV (see Fig. 3), are replicas of the excitonic states dressed by terahertz photons.$^{13}$

The linewidth of the excitonic peak is a function of the THz field strength. It decreases when we increase the THz field amplitude for a fixed frequency $\Omega$. The linewidth reaches a minimum at $x=2.4$ but its modulation cannot be related directly to $J_0(\kappa)$, since there is a finite minimum due to the finite lifetime of the exciton. A more reliable measurement of the dynamic localization is given by $\eta=(\Delta E - \Delta E_{1d})/\Delta E_{1d}$, where $\Delta E$ is the width of the excitonic spectrum (full width at half maximum) of the excitonic spectrum and $\Delta E_{1d}$ the excitonic linewidth of a single dot for ac field free (inset on the left).

In conclusion, we have investigated the dynamic localiza-
tion in a linear and finite quantum dot superlattice with a longitudinal and homogeneous ac field in terahertz scale. We have found that the signature of the dynamic localization can be seen through the linear optical absorption spectra. The latter was obtained from the SBE, which has been extended to consider the nonrelative coordinates of the carriers in direct space, taken also into account a realistic and finite superlattice potential. Switching off the Coulomb interaction, we have found that the dynamic localization occurs and indeed follows the rule \( \Delta E = J_0 \left( \frac{edF_0}{\hbar \omega} \right) \Delta E_0 \) for the miniband collapse. Switching on the Coulomb interaction, the dynamic localization still leads to the spectrum collapses at the zeros of the zero-order Bessel function, however it occurs partially (\( \approx 80\% \)). We propose that the observation of this effect can be realized in unidimensional superlattices that are currently being developed.

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