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Study of acoustic phonon interaction on single photon GaAs quantum dots

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Abstract: *The acoustic phonons make interaction with GaAs quantum dots by exchanging energy with it. Semiconductor quantum dots are most commonly coupled to the vibration modes of their host lattice. This interaction reduces the efficiency and the indistinguishability of single photons emitted from the semiconductor quantum dots. The adverse effects of phonons can be significantly reduced by embedding the quantum dot in a photonic cavity;. The phonon-induced effects in the emitted photons cannot be completely suppressed. It constitutes a fundamental limit to the ultimate performance of single-photon sources based on quantum dots. In this paper, we have presented a self-consistent theoretical description of phonon effects in such sources and we have described their influence on the figures of merit*
Keywords: *acoustic phonons, Semiconductor quantum dots, photonic cavity,*

I. Introduction

In this paper we have studied the effect of phonons on the single-photon generation from GaAs quantum dots. The acoustic phonons make interaction with GaAs quantum dots by exchanging energy with it. When the QD relaxes from its excited state to its ground state, a phonon wave packet can be simultaneously created [1 , 2]. In this way the emission of a photon with energy lower than that of the QD exciton takes place. Thus due to the loss of the energy of the phonon wave packet into the environment the photons produced through this phonon-mediated transition are inherently distinguishable. Again if the temperature of the medium is increased enough to allow for thermal population of the phonon modes, a phonon wave packet can be absorbed, due to which the emission of a blue-detuned photon takes place . [3 , 4]. In this situation In the emission spectrum of the source, these processes are observed as a broad sideband in the vicinity of a narrow zero-phonon line. Again, if the thermal occupation of phonon modes is appreciable, thermal phonons can make interaction with the QD and drive virtual transitions to higher excited states.

The influence of phonon interactions on the emission properties of QD single photon sources has been focused in this study. Also, we have analyzed the effect of a structured electromagnetic environment as a central feature. The Hamiltonian of the system may be given as

$$H = H_E + H_P + H_F + H_{EP} + H_{EF}, \quad \text{---[1]}$$

Where $H_E = \hbar\omega_{eg}$ is the free evolution of the emitter where g represents the ground state and e represents the lowest exciton state. The separation of energy level is represented by eg. Here
H_F describes the free evolution of the electromagnetic field and H_P the free evolution of the electromagnetic phonon environment. The interaction of these environments with the emitter has been represented by H_{EF} and H_{EP} .

II. Model of photonic structure

The model assumed a single quantum dot embedded in an n-i-Schottky diode structure. In the present ensemble of InGaAs/GaAs quantum dots a height of 3-4 nm and base diameters of 25-30 nm of the structure have been proposed in this model. The measurements presented are from a single dot emitting at 951 nm in the high energy tail of the dot distribution. The biexciton binding energy is 1.9 meV [5,6]. The dot is excited with a single laser pulse, and the final occupation of the exciton state is measured using photocurrent resonantly excites the neutral exciton transition. A single laser pulse with a Gaussian envelope narrow 0.2-meV FWHM spectral width are used to suppress excitation of the two-photon biexciton transition [7 ,8] .

III. Phonon–Electron Interaction in Quantum Dots:

It is well known that Quantum dots (QDs) are nanoscale semiconductor structures that confine electrons, holes, or excitons in all three spatial dimensions. This quantum confinement leads to discrete, atom-like energy levels, giving QDs the name “artificial atoms.” Because of their tunable electronic and optical properties [9,10] . The quantum dots are very important for applications such as single-photon sources, quantum computing, photodetectors, and solar cells. However, the performance of QDs in these applications is significantly influenced by the interaction between charge carriers (electrons and holes) and lattice vibrations, known as phonons.

The dual roles are played by Phonon–electron interactions . It can be detrimental by causing dephasing, line broadening, and energy relaxation. It can also enable processes such as carrier relaxation, phonon-assisted tunneling, and energy transfer. Understanding the mechanisms and consequences of phonon–electron interaction in quantum dots is essential for improving their performance in both classical and quantum technologies.

Phonons are quantized modes of lattice vibrations in a crystal. They can be broadly classified into two categories- Acoustic phonons and Optical phonons. The acoustic phonons Correspond to collective vibrations of atoms where adjacent atoms move in phase. They dominate at low energies and long wavelengths and are analogous to sound waves in solids. The Optical phonons Occur when adjacent atoms in the lattice move out of phase. They usually have higher energies and shorter wavelengths compared to acoustic phonons.Both acoustic and optical phonons interact with electrons in quantum dots in different ways. Acoustic phonons often contribute to pure de phasing and energy relaxation, while optical phonons are usually involved in inelastic scattering processes.When the charge configuration of the quantum dot changes during the formation of exciton the lattice of the host material changes its configuration. If the resulting displacement of the ion is small the interaction between the emitter and the phonon environment may be given as $H_{EP} = |e\rangle\langle e|\ (V_L+V_Q)$ this interaction consists of two parts. Here V_L gives rise to emission or absorption of phonon of phonon wave packets in the photon emission process. Vq represents the virtual transition to higher excitronic levels generated by thermal phonons .

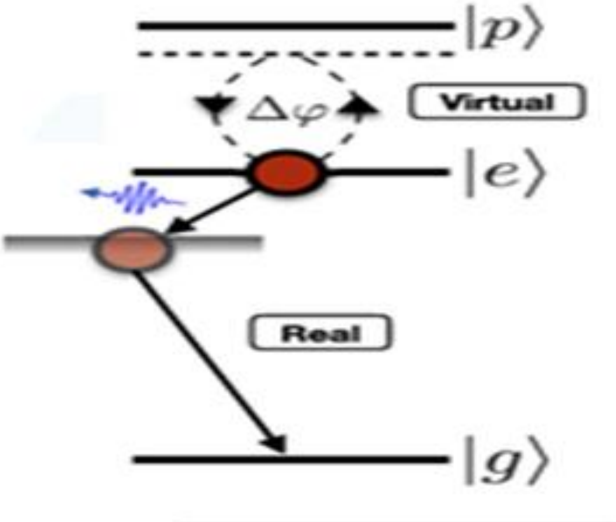

Fig. (1) The optical emission properties of QDs by two phonon-induced processes

Two phonon-induced processes affect the optical emission properties of QDs. Emission/absorption of phonon wave packet during exciton relaxation and virtual transitions to higher-lying excitonic states takes place through scattering of thermal phonons. When a wave packet is emitted or absorbed it causes a broad phonon side band in the emission spectrum. The Virtual scattering of thermal phonons leads to broadening of the zero-phonon line due to pure de phasing. When the QD is placed in an optical cavity, the electromagnetic LDOS influences the shape of the spectrum by funneling emission into the cavity resonance. In the strong coupling regime, the phonon scattering leads to an asymmetry between the polariton peaks.These transitions are virtual in nature due to significant differences of energy scales. In a typical QD the energy gap the lowest excitonic states s- shell the next state p shell. This energy is of the order of magnitude of greater than phonon energy at cryogenic temperature .Thus we can understand the quadratic interaction term as virtual scattering of a phonon from mode K into K' mediated by the excitonic state. This scattering process gives a random phase kick to the exaction .The effective coupling strength for the quadratic coupling may be written in terms of $\hbar w_j$ in the j^{th} electronic state

IV. Electron States in Quantum Dots:

In bulk semiconductors, electrons experience continuous bands of allowed energies. In contrast, in quantum dots, the confinement in all three spatial dimensions results in discrete, quantized electronic states. These levels resemble the energy levels of atoms, but they are tunable by size, shape, and material composition of the quantum dot [11,12].The strong confinement alters electron–phonon interactions compared to bulk systems. Since phonons have wavelengths comparable to or larger than the QD size, the overlap of electronic wave functions with phonon modes is modified, leading to new phenomena such as: phonon bottleneck, Polaron formation.

V. Mechanisms of Phonon–Electron Interaction:

Several mechanisms govern the interaction of electrons with phonons in quantum dots.

(a) Deformation Potential Coupling: In this mechanism, the interaction arises because lattice vibrations locally change the band gap of the material. Electrons and holes couple to these variations through the deformation potential. Acoustic phonons typically couple through this mechanism, leading to pure de phasing without necessarily changing the energy of the electron state.

(b). Piezoelectric Coupling: In certain semiconductors with non-centro symmetric crystal structures (such as GaAs or InAs), strain induced by lattice vibrations generates an electric field. Electrons interact with this field, leading to scattering events. Piezoelectric coupling is particularly relevant for long-wavelength acoustic phonons.

(c). Fröhlich Interaction This is the interaction of electrons with longitudinal optical phonons through the macroscopic electric field generated by lattice polarization. LO phonon coupling is typically stronger than acoustic phonon coupling and plays a crucial role in non-radiative energy relaxation.

(e). Polaron Formation: When electron–phonon coupling is strong, electrons can carry a “phonon cloud,” forming a quasi-particle called a polaron. This renormalizes the effective mass and modifies energy levels, influencing both relaxation and optical properties.

The experimental inferences consistently demonstrate that phonon–electron interactions strongly influence both optical coherence and relaxation dynamics in QDs.

The consequences of phonon–electron interactions are particularly important in the context of quantum information processing and quantum communication, where coherence is paramount.

The Quantum dots are leading candidates for deterministic single-photon emitters. However, electron–phonon coupling causes spectral diffusion, sidebands, and temporal jitter, degrading photon indistinguishability. Suppression or mitigation of phonon coupling is thus essential for high-performance quantum light sources.In QD-based solar cells, phonon-assisted relaxation plays a crucial role in carrier thermalization. In QDs, electron spin states are promising qubits. While spins couple weakly to phonons, spin–orbit coupling mediates spin relaxation via phonons, limiting spin lifetimes. Understanding this indirect phonon influence is essential for spin-based quantum computing.

VI. Conclusion:

The study of acoustic phonon interactions in single photon emission from GaAs quantum dots reveals both fundamental challenges and opportunities in the development of solid-state quantum light sources. Acoustic phonons, arising from lattice vibrations, strongly couple with the confined electronic states in quantum dots. This coupling leads to spectral broadening, emission line dephasing, and phonon-assisted transitions, which can limit the purity and indistinguishability of emitted photons—two parameters that are critical for applications in quantum communication and quantum information processing. At the same time, the research has also shown that a detailed understanding of phonon dynamics can be harnessed to improve device performance. By carefully engineering the quantum dot environment—through resonant excitation, Purcell enhancement via photonic cavities, or temperature control—the negative effects of phonon scattering can be mitigated. Such approaches suppress incoherent phonon sidebands, enhance zero-phonon line emission, and improve photon coherence. Importantly, the GaAs platform provides unique advantages. Its direct bandgap, high crystal quality, and compatibility with scalable semiconductor technology make it an excellent candidate for electrically driven single-photon sources. Investigations of phonon interactions in this material not only deepen our knowledge of fundamental light–matter coupling but also guide the design of robust quantum dot devices for practical use.Overall, while acoustic phonon interactions present inherent limitations to photon indistinguishability, they also provide insight into decoherence mechanisms that can be addressed by material engineering, nanophotonic structures, and optimized excitation schemes. The ongoing progress in controlling these interactions places GaAs quantum dots at the forefront of research toward highly efficient, coherent, and scalable single-photon sources, paving the way for their integration into quantum technologies.

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