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# Investigation Of Exciton–Phonon Coupling In Electrically Pumped Gallium Arsenide Quantum Dot Based Single Photon Emitters

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***Abstract***
*Single photon emitters (SPEs) based on semiconductor quantum dots have emerged as promising candidates for applications in quantum communication, quantum cryptography, and photonic quantum information processing. Among various material systems, Gallium Arsenide (GaAs) quantum dots exhibit superior optical quality, high emission efficiency, and compatibility with established semiconductor fabrication technologies. In electrically pumped quantum dot devices, excitons are generated through carrier injection, and their interaction with the surrounding lattice vibrations, particularly acoustic phonons, plays a critical role in determining emission linewidth, coherence, and photon indistinguishability. This study presents a detailed investigation of exciton–phonon coupling in electrically driven GaAs quantum dot single photon emitters. The interaction between confined excitons and acoustic phonons is analyzed to understand its influence on radiative recombination dynamics and spectral stability. Special emphasis is placed on deformation potential coupling and its temperature-dependent effects on excitonic coherence. The study highlights how phonon- induced scattering mechanisms limit the performance of single photon sources and discusses strategies for minimizing decoherence through optimized device design. The results contribute to improving electrically driven solid-state single photon emitters suitable for scalable quantum photonic applications.*

***Keywords:*** *Gallium arsenide quantum dots; Acoustic phonons; Quantum coherence; Semiconductor nanostructures; Solid-state quantum optics*

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## I. Introduction

Single photon sources form the backbone of emerging quantum technologies, enabling secure communication protocols and advanced quantum computation architectures. Semiconductor quantum dots act as artificial atoms, providing discrete energy levels and enabling the controlled generation of single photons on demand. GaAs-based quantum dots are particularly attractive due to their low defect density, high oscillator strength, and compatibility with electrical injection schemes.

In an electrically pumped GaAs quantum dot device, electrons and holes are injected from opposite contacts and confined within the quantum dot potential. Their Coulomb interaction leads to the formation of bound electron–hole pairs known as excitons. The radiative recombination of an exciton produces a single photon, provided multi-exciton generation is suppressed. However, the solid-state environment introduces interactions between excitons and lattice vibrations (phonons), which significantly influence emission properties.

Among phonons, **acoustic phonons** dominate exciton scattering at low energies and temperatures. These phonons interact with excitons via deformation potential and piezoelectric coupling, leading to spectral broadening, energy shifts, and loss of coherence. Understanding exciton–phonon coupling is therefore essential for realizing high-quality electrically driven single photon emitters.

### Exciton Formation Reaction

The fundamental exciton formation process under electrical pumping can be represented as:

$$e^- + h^+ \rightarrow X^0 + h\nu$$

Where

$e^-$ = injected electron,

$h^+$ = injected hole,

$X^0$ = neutral exciton,

$h\nu$ = emitted single photon.

This process is strongly influenced by phonon interactions, which modify the recombination dynamics.

## II. Exciton–Phonon Coupling Mechanism In Gaas Quantum Dots

In GaAs quantum dots, excitons interact with lattice vibrations through deformation potential coupling. Acoustic phonons modulate the band edges, altering the excitonic energy levels. This interaction becomes particularly significant in electrically driven devices, where injected carriers introduce local heating and non-equilibrium phonon populations.

**Exciton–Phonon Interaction Hamiltonian**

$$H_{ep} = \sum_{\mathbf{q}} M_{\mathbf{q}}(b_{\mathbf{q}} + b^{\dagger}_{-\mathbf{q}})|X\rangle\langle X|$$

where

$M_{\mathbf{q}}$ represents the exciton–phonon coupling strength,

$b^{\dagger}_{\mathbf{q}}$ and $b_{\mathbf{q}}$ are phonon creation and annihilation operators.

This coupling leads to phonon sidebands in the emission spectrum and causes pure dephasing of excitonic states.

## III. Temperature-Dependent Phonon Scattering Effects

Acoustic phonon scattering is strongly temperature dependent. At low temperatures, phonon absorption is minimal, and exciton coherence is preserved. However, as temperature increases, phonon occupation rises, enhancing scattering rates.

**Scattering Rate Relation**

$$\Gamma_{ph}(T) \propto \alpha T$$

where

$\Gamma_{ph}$ = phonon-induced dephasing rate,

$\alpha$ = material-dependent coupling constant,

$T$ = temperature.

This linear dependence results in linewidth broadening and reduced photon indistinguishability in GaAs quantum dot single photon emitters.

## IV. Impact On Single Photon Emission Coherence

Exciton–phonon coupling directly affects the temporal coherence of emitted photons. Phonon-induced phase fluctuations cause spectral diffusion, reducing the coherence time (T2T_2T2).

**Coherence Time Relation**

$$\frac{1}{T_2} = \frac{1}{2T_1} + \Gamma_{ph}$$

where

$T_1$ = exciton radiative lifetime.

Minimizing $\Gamma_{ph}$ is crucial for achieving near-transform-limited single photon emission required for quantum interference experiments.

## V. Electrical Pumping and Phonon-Induced Decoherence

Electrical injection introduces additional challenges compared to optical pumping. Carrier tunneling and Joule heating generate excess acoustic phonons, enhancing exciton– phonon coupling. Device geometry, contact resistance, and current density play critical roles in determining phonon population.

**Energy Relaxation via Phonons**

$$X^* \rightarrow X + \hbar\omega_{ph}$$

where

$X^*$ = excited exciton state,

$\hbar\omega_{ph}$ = emitted acoustic phonon energy.

This relaxation pathway contributes to energy loss and spectral instability.

## VI. Representative Figures

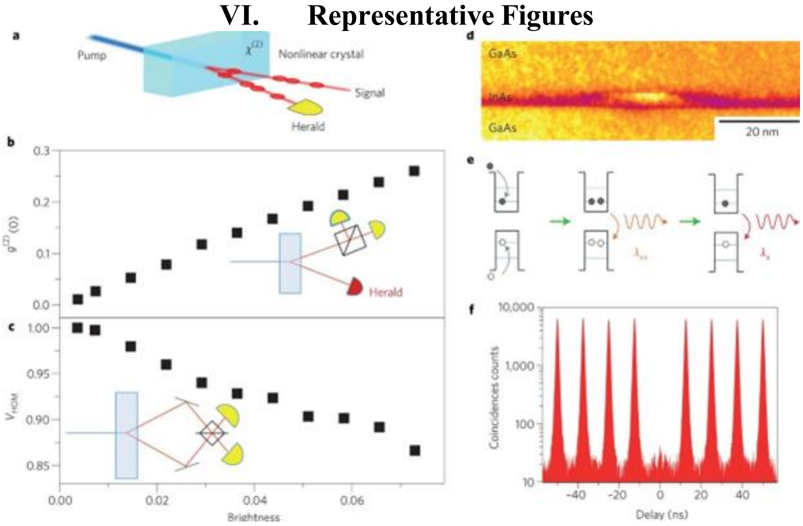


***Figure 1:*** *Schematic of electrically pumped GaAs quantum dot single photon emitter*

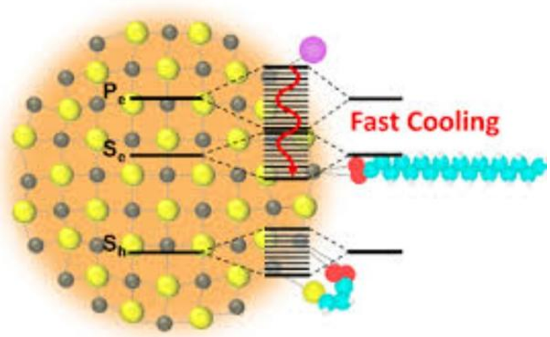


***Figure 2:*** *Exciton–acoustic phonon coupling mechanism*

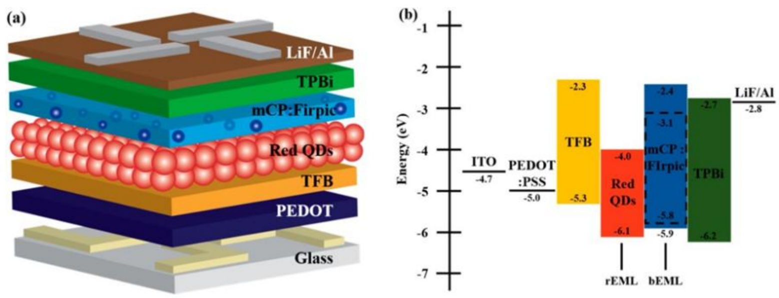


***Figure 3:*** *Energy level diagram showing phonon-assisted transitions*

## VII. Conclusion

The investigation of exciton–phonon coupling in electrically pumped GaAs quantum dot single photon emitters reveals the critical role of acoustic phonons in limiting emission coherence and spectral purity. Deformation potential coupling between confined excitons and lattice vibrations leads to temperature-dependent dephasing and linewidth broadening, which adversely affect photon indistinguishability. Electrical injection further enhances phonon interactions due to non-radiative heating and carrier relaxation processes.

Despite these challenges, careful optimization of device architecture, operating temperature, and injection conditions can significantly suppress phonon-induced decoherence. Understanding exciton–phonon dynamics provides a pathway for engineering high- performance electrically driven single photon sources suitable for scalable quantum photonic technologies. Future advancements in material growth and phonon engineering are expected to further enhance coherence and efficiency in GaAs quantum dot based single photon emitters.

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