Telegraph to Gaussian Stochastic Noises:

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Abstract

We present a general theoretical description of the extrinsic dephasing mechanism of spectral diffusion that dominates the decoherence dynamics in semiconductor quantum dots at low temperature. We discuss the limits of random telegraph and Gaussian stochastic noises and show that the combination of both approaches in the framework of the pre-Gaussian noise theory allows a quantitative interpretation of high-resolution experiments in single semiconductor quantum dots. We emphasize the generality and the versatility of our model where the inclusion of asymmetric jump processes appears as an essential extension for the understanding of semiconductor quantum dot physics.

1. Introduction

Decoherence is one of the fundamental limitations in quantum information science, and the understanding and the control of its dynamics appears as a crucial issue for the development of quantum information devices. Various systems are being investigated in condensed matter physics because of their potential in terms of integrability and scalability, such as superconducting circuits [1], edge states in the Fractional Quantum Hall effect [2], and semiconductor quantum dots (QDs) [3]. In the latter case, the development of spatially-resolved optical spectroscopy has allowed the implementation of quantum information schemes in single QDs. Single photon emission [4], photon coalescence [5], and quantum gate implementation [6] have successfully been demonstrated with an efficiency intrinsically limited by the decoherence due to the coupling of the QD with its environment. In this review, we discuss the extrinsic dephasing mechanism of spectral diffusion that dominates the QD decoherence at low temperature. We present a theoretical model in the framework of the pre-Gaussian noise theory where random telegraphs and Gaussian stochastic noises are combined. We illustrate the generality of our model with quantitative interpretations of the different signatures of spectral diffusion in single QDs.

2. Theory

2.1. Spectral Diffusion in Semiconductor Quantum Dots

At low temperature, the decoherence in QDs is mainly determined by the phenomenon of spectral diffusion. In fact, photoluminescence experiments in single QDs have revealed the extrinsic influence of the solid matrix that generates fluctuating electric fields and shifts the QD line through the quantum confined Stark effect. This so-called spectral diffusion phenomenon was interpreted as due to carriers randomly trapped in defects, impurities in the QD vicinity [7]. Given the time-resolution imposed by the detector integration time, the emission spectrum can be analyzed by considering two different classes of random events. The first one is associated to rare and strongly-shifting processes that result in abrupt jumps of the QD emission energy, that is, spectral discontinuities in the time-evolution of the photoluminescence spectrum. In the case of colloidal QDs or nanocrystals, these events may also inhibit the emission and the corresponding blinking effect [7] is a severe restriction to the realization of efficient single QD-devices based on this type of nanostructures. The second type of events is related to frequent and weakly-shifting processes that lead, within the detector integration time, to a single line with a width that is larger than the radiative limit and that is determined by the statistical distribution of the small energy shifts. However, these different phenomenologies are usually separately and partially addressed in the theoretical descriptions developed in colloidal and epitaxial QDs. We present in this review a general model that reaches a full comprehensive description of spectral diffusion in semiconductor QDs and that provides a flexible framework for the quantitative interpretation of experimental data in semiconductor QDs. In particular, we emphasize that our theoretical model takes into account a specific and original point, namely the dynamical asymmetry of the spectral jump processes that is not discussed in previous theoretical work while being of fundamental importance in the physics of semiconductor nanostructures .

Our model is based on a Markov chain composed of an arbitrary number of N independent random telegraphs. A random telegraph is a two-state jump process that corresponds to a discrete spectral shift $\delta\omega=\pm\Omega/2$ of the optical line. The transition from the upper (lower) state to the lower (upper) one occurs with a probability $dt/\tau\downarrow$ ($dt/\tau\uparrow$) in the time interval dt and induces a spectral jump $-\Omega/2(+\Omega/2)$, as sketched in Figure 1. In the context of spectral diffusion in QDs, the upper (lower) state corresponds to an empty (occupied) defect, $\tau\downarrow$ ($\tau\uparrow$) to the capture (escape) time of one carrier in the defect, and Ω to the Stark shift of the QD line due to the electric field created by the charge carrier in the defect located in the QD vicinity.

2.2. Random Telegraph Noise

The intensity spectrum in the presence of frequency fluctuation due to Markovian processes was addressed by Kubo in his seminal paper on the stochastic theory of lineshape where the general resolution of the Chapman-Kolmogorov equation was presented The stochastic theory of lineshape was further completed by Wódkiewicz and coworkers in their pre-Gaussian noise theory They made the link between random telegraphs and Gaussian stochastic processes by calculating the relaxation function $\phi N(t)=[\phi 1(t)]N$ for a given number of N identical, uncorrelated random telegraphs, and by then expanding their treatment to the limit $N\to\infty$. However, this model is limited to the case of symmetric jump processes ($\tau\downarrow=\tau\uparrow$; see Figure 1).

In the prospect of a more general theory that would catch the specific physics of semiconductor nanostructures, we have extended the former model to the case of asymmetric two-state jump processes and derived the expression of the relaxation function $\phi 1(t)$ when $\tau\uparrow\neq\tau\downarrow$. Following the guidelines of the Kubo theory, we find for the generalized analytical expression of the relaxation function $\phi 1(t)$:

3. Conclusion

In this review, we have presented a general theoretical description of the extrinsic dephasing mechanism of spectral diffusion that dominates the QD decoherence at low temperature. We have discussed the limits of random telegraph and Gaussian stochastic noises and shown that the combination of both approaches in the framework of the pre-Gaussian noise theory allows a quantitative interpretation of high-resolution experiments in single semiconductor QDs. We emphasize the generality and the versatility of our model where the inclusion of asymmetric jump processes appears as an essential extension for the understanding of semiconductor QD physics, and hopefully, more generally, for quantum information devices based on solid-state nanostructures.

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