Squeezing of phonoritons in semiconductors

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Abstract. If a semiconductor sample is illuminated by high-intensity electro-magnetic radiation near the resonance, the occupation number of polaritons in the same mode is large and the interaction between polaritons and phonons become very important. This interaction leads to the formation of a new kind of elementary excitation called phonoriton, which actually is a coherent superposition of excitons, photons, and longitudinal acoustic phonons under Brillouin scattering of an intense polariton. The phonoritons have been studied theoretically and experimentally and have been found in Cu2O. In this work we discuss the squeezing of phonoritons inside semiconductors from a theoretical point of view. We found the squeezed states, or so called 'low-noise' states- the states of reduced quantum noise with reducing effect of vacuum fluctuation, for phonoritons. It shows that the phonoritons are intrinsically squeezed. From our results we also have the possibility to tune the squeeze amplitude, what is important both theoretically and experimentally.

1. Introduction

The problem of interaction between electromagnetic radiations with excitons has been studied for a very long time and attracted many theoretical and experimental studies [1-12]. It is well known nowadays that in direct band gap semiconductor when the semiconductor is illuminated by electromagnetic radiation near the exciton resonance, the excitons and photons will couple strongly to form a mixing state of exciton and photon (i.e. when the energy of photons of the field are equal or close to the exciton energy). This state is called polariton. It is said that there is a reconstruction of the dispersion near the exciton-photon resonance with the existence of the exciton-polariton, very important quasi-particle in semiconductors.

When a bulk semiconductor with direct band gap is illuminated by high-intensity electromagnetic radiation near the resonance, the occupation number for the polariton mode with frequency close to that of the incident field is very high. One can imagine that at some wave vector $k_o$ there are many photons and excitons with the same wave vector $k_o$ propagating in the crystal. In other words, the mode $k_o$ is macroscopically filled. In these conditions, the interaction between polaritons and phonons, or we can say between excitons, photons and phonons become very important. It was predicted theoretically in 1982 by L.V. Keldysh and A.L. Ivanov [1-3] that a new kind of elementary excitations

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called phonoritons will be formed. J. L. Birman and B.S. Wang [4-5] proposed a new simple two-level model to explain the origin of phonoritons. Other authors also have studied other properties of phonoritons [6].

The realization in 1995 of Bose condensation of atoms where very large number of atoms can be put together at their ground state of a quantum system within a small volume opens a door for a realization of polariton condensation. If the Bose-condensation of polaritons can be achieved, then the observation of phonoritons would not be very far away. In 1999, authors [7] have reported the first time the observation of longitudinal acoustic phonoritons eigenstates in Cu2O crystal. Also, the condensation of exciton-polaritons is observed in semiconductor microcavity [8] is a big step in the research of optical properties of semiconductor. At this step we believe that a deep research on the properties of phonoriton is very important both theoretically and experimentally.

In this paper we investigate some properties of phonoritons. We will discuss squeezing in phonoritons inside semiconductors from a theoretical point of view and we show that phonoritons are intrinsically squeezed quasi-particles. Squeezed states, the states of reduced quantum noise with reducing effect of vacuum fluctuation, have attracted a lot of attention because not only they allow improving the precision of optical measurements but also they exhibit typical non-classical features.

2. Phonoritons

When the resonant semiconductor is excited by an intense laser, the interaction of intense photons, exciton and phonons is very strong and qualitatively new phenomena arise [1-3]. At high intensity, a reconstruction of polariton dispersion happens and a new gap appears. This indicates the existence of a new quasi-particle-phonoriton.

To illustrate the formation of phonoritons, as Birman et al [4], the Hamiltonian of a system of excitons, photons and phonons is written as the following:

\[ H = \sum_p \{ \omega^{ex}(p) a_p^+ a_p + \omega^\gamma(p) b_p^+ b_p + \Gamma_p (a_p^+ b_p + b_p^+ a_p) + \Omega^c(p) C_p^+ C_p + \sum_q S(p-q) a_q^+ a_q (C_{(p-q)} + C_{-(p-q)}^+) + c.c. \} \]  \hspace{1cm} (1)

where \( a_p^+ , a_p \) are creation (annihilation) operators for exciton with momentum \( p \); \( b_p^+ , C_p^+ (b_p , C_p) \) are creation(annihilation) operators for photons and phonons with momentum \( p \), respectively. \( \omega^{ex}(p), \omega^\gamma(p), \Omega^c(p) \) are energies of excitons, photons and phonons. \( \Gamma_p \) is the coefficient of exciton-photon interaction and \( S(p-q) \) is the exciton-phonon interaction coefficient. From experiments, we have the photon-exciton interaction much larger than the phonon-exciton interaction.

The first line of (2.1) can be diagonalized to form a two-branch polariton, and the whole Hamiltonian can be written as [4]:

\[ H = \sum_p \{ \omega^{pol}(p) B_p^+ B_p + \Omega^\chi(p) C_p^+ C_p + \sum_q S'(p-q) B_{pq}^+ <B_{pq}> (C_{(p-q)} + C_{-(p-q)}^+) + c.c. \} \]  \hspace{1cm} (2)

where \( B_p^+ \) is the creation operator of the \( i \)-branch of polariton. \( S'(p-q) \) are renormalized polariton-phonon interaction matrix elements. The polariton is macroscopically filled at \( q \), so at \( q \) the operator \( B_{pq} \) can be replaced by the average value \( <B_{pq}> \) [5].

The Hamiltonian (2) again can be diagonalized to obtain the Hamiltonian of phonoritons by introducing the phonoriton operator [4]:

\[ D_{\pm p} = u B_{\pm p}^+ + v C_{\pm p}^+ + w B_{\pm (p-q)}^+ + y C_{\pm (p-q)}^+ \]  \hspace{1cm} (3)
where \( i = 1, 2 \). In order to have “free “phonoritons, the following condition must be satisfied:

\[
[D_p, H] = \varepsilon_p D_p
\]  
(4)

This condition determines the phonoriton energy \( \varepsilon_p \) and the weigh factors of the polariton and the phonon in the phonoriton operator \( u_i, v_i, w_i, y_i \). Then the Hamiltonian becomes the Hamiltonian of the phonoritons [4]:

\[
H = \sum_p \varepsilon_p D_p^+ D_p
\]  
(6)

3. Phonoriton squeezing

3.1 Squeezed states

In a quantum system, all amplitudes and phases of a physical state have fluctuation. Even if all influence of surrounding is removed, the system still has its intrinsic indeterminacy. This indeterminacy is related to Heisenberg principle. For example, if \( \Delta F, \Delta G \) are variances of operators \( F, G \) with the commutator \([F, G] = iM\), the variances of these operators are limited by uncertainty condition \(< (\Delta F)^2 > < (\Delta G)^2 > \geq M >^2 / 4\).

It is known [5] that if there are two operators \( a_1 \) and \( a_2 \), the state with minimum uncertainty is the two-mode coherent state obtained by applying the two-mode displacement operator on the vacuum:

\[
|a_{12} > = \exp[-\frac{1}{2} (|a_1|^2 + |a_2|^2) e^{a_1a_1^+} e^{a_2a_2^+}] |0> = D(a_{12}) |0>
\]  
(7)

Our particular interest in this work is the squeezed state, or the “low noise” state. The squeezed state has been discussed in literature [5]. Here we only recall [5] the definition of a two-mode squeezed state \( |a_{12} > > z \) as the state obtained by displacing the squeezed vacuum

\[
|a_{12} > > z = D(a_{12}) S_{12}^z (z) |0>
\]  
(8)

where

\[
S_{12}^z (z) = S_{12}^z (r, \varphi) = \exp(r [a_1 a_2 e^{-2i\varphi} - a_1^+ a_2^+ e^{2i\varphi}])
\]  
(9)

is the two-mode squeeze operator, \( r \) is the squeeze factor and \( \varphi \) is the phase.

An operator \( a_i \) is transformed into a squeeze operator by applying the two-mode squeeze operator as following:

\[
S_{12}^z (z) a_i S_{12}^z (z)^+ = a_1 \cosh r + a_2^+ e^{i\varphi} \sinh r
\]  
(10)

3.2 Phonoritons and squeezing

In this part we will prove the intrinsic squeezing of phonoritons. We will follow the method Birman et al. [5] for the squeezing of polariton and apply for the phonoriton system.

Now return to the Hamiltonian (2). The Hamiltonian (2) can be diagonalized by the operator (3) to obtain the phonoriton Hamiltonian (6). Follow Birman et al. [5], in this part in order to show the squeezing of phonoriton we will try to achieve (6) by a different path: we will diagonalize the operator (2) by two steps. In analogy to [5], as the first step we introduce the new polariton-phonon mixed mode:

\[
A_z = \alpha_p B_{p+} + e^{2i\varphi} B_p C_{p-q}
\]  
(11)
Then the Hamiltonian (2) becomes:

\[ H = \sum_p \Omega_p [A_+^+ A_+ - A_-^+ A_-] + 2i \xi_p [A_+ A_- - A_-^+ A_+] \]  

(12)

Here \( \Omega_p, \xi_p \) are functions of \( \omega^{pol}(p), \omega^{p}(p), \Omega^{p}(p), S(p-q) \). We note here that the Hamiltonian (6) is not diagonalized, so operator \( A_\pm \) is not the phonoriton operator. In order to obtain the phonoriton state, we still need to diagonalize (12). It will be our second step.

For the two operators \( A_+^+ (A_+) \), \( A_-^+ (A_-) \) we define the two-mode squeeze operator:

\[ S_\pm^2(r, \phi) = \exp(r[A_\pm A_\pm^* e^{-2i\phi} - A_\pm^* A_\pm e^{2i\phi}]) \]  

(13)

Now we apply this two-mode squeeze operator (13) to transform operator \( A_\pm^+ \) into the squeeze operator \( \mu_\pm^+ \):

\[ S_\pm^2(z) A_\pm S_\pm^2(z) = \mu_\pm \]

\[ = B_p \cos \theta_p \cosh r + C_{p-q} e^{2ix} \sin \theta_p \cosh r + B_p^e e^{2i\phi} \sinh r + C_{p-q}^e e^{2i(\phi-x)} \sin \theta_p \sinh r \]  

(14)

Then the Hamiltonian has the following form:

\[ H = \sum_p \varepsilon_p (\mu_+^+ \mu_+^* + \mu_-^+ \mu_-^*) \]  

(15)

Compare (15) with (6) we see the two forms are identical.

We see that the introduction of the intermediate state \( A_\pm \) reveal the squeezed structure of the phonoriton. The intermediate states are transformed into the phonoriton state by a squeezing transformation. So we come to the conclusion that the intermediate states are squeezed.

So we found that the phonoritons are intrinsically squeezed. And from our result we have the possibility to tune the frequency and the squeeze amplitude. This very new result is very important matter both theoretically and experimentally.

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