The interaction of an exciton and several optical modes in layer of GaAs

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Abstract. Theoretically, we calculated exciton fraction in polariton modes, which correlates with the intensity of the exciton radiation associated with these modes for several microcavities. Thus, we obtained the form of the dependence of the radiation probability on the eigenfrequencies of the structure.

1. Introduction

In 1946 Purcell discovered, that the intensity of the interaction of an emitter with light can be enhanced or suppressed by engineering its electromagnetic environment [1]. From this decisive observation sprung a whole field of research, today called cavity quantum electrodynamics. In 1992 Weisbuch et al. the first observations of the vacuum-field Rabi splitting in semiconductor quantum microcavities [2]. These works have led to extensive researches in the field of strong coupling in the interaction between light and matter in semiconductor microcavities during the last three decades [3-6].

In the semiconductor microcavities, a strong field-matter interaction occurs between the optical modes and excitons, whose modes are relatively sharp, so the exciton-photon modes are often called cavity polaritons. These states emerge from coherent energy exchange between quantum well excitons and cavity mode. The reason for consideration to these quasi-particles is their low in-plane effective mass around the center of the first Brillouin zone in quantum well nanostructures. These considerations are important for understanding such effects as laser action and developing optoelectronic and photonic devices.

The strength of the interaction between exciton and optical modes is proportional to the probability of the transmission from the crystal ground state to the exciton state and is proportional to the Purcell factor. The factor Purcell, in turn, is proportional to the Q factor of the resonator. And the square root of the strength of the interaction between exciton and optical modes is proportional to the Rabi-splitting. Thus, optical modes with a high Q factor provide a strong coupling between an exciton and photons and a larger Rabi splitting than low Q factor modes.

We considered the interaction of an exciton with several optical modes with different Q-factors arising in the GaAs layer. This interaction occurs immediately in the strong and weak coupling regime, which is accompanied by multiple Rabi splitting.
2. Results and discussion

At first, we considered the layer of GaAs, more precisely the ideal square resonator. The size of these cavities corresponds to several wavelengths. And calculated the distribution of the intensity of the electromagnetic field of the modes inside of this cavity (Figure 1).

From Figure 1, we see that a strong localized mode (a) experiences a total internal reflection on the edges of the square. The intensity of weak mode (b) more uniformly distributed within the square.

Since the exciton energy in GaAs is equal to: \( E_X = 1.5554 \text{ eV} \) [6], we have found all the eigenmodes of this structure around this energy, as well as the \( Q \)-factor of these eigenmodes. From the known \( Q \)-factors of eigenmodes and structure parameters, we can find the Purcell coefficient for each eigenmode [1]:

\[
F = \frac{Q \lambda^2}{n^2 S}
\]

where \( \lambda \) is the wavelength within the cavity material, \( n \) is refractive index and \( S \) is the square of the mode.

Figure 2 (a) shows the energies and quantities \( F \) for the eigenmodes localized in the ideal square structures. Clearly, while most of the modes are characterized by moderate values of \( F \), there are still few modes with a rather high \( F \). Figure 2 (b) shows the distribution of the mode probability depending on \( F \) for ideal square structures. There is a small probability of the appearance of modes with a high value of \( F \) for ideal square structures.
As the simplified model, that could explain the interaction between exciton and several modes of ideal square GaAs structure, we have carried out an analysis of the polaritonic mode structure using the following assumption. The Hamiltonian of interaction consists of exciton and several photon modes. This Hamiltonian can be simplified by using rotating wave approximation. In the case of exciton Hamiltonian, we will exploit second quantized form and field [7]:

$$\mathcal{H} = \hbar w_0 \hat{x}^+ \hat{x} + \sum_k \hbar w_k \hat{c}_k^+ \hat{c}_k + \sum_k \hbar (g_k \hat{c}_k \hat{x}^+ + g_k^* \hat{c}_k^+ \hat{x})$$  \hspace{1cm} (2)$$

where $\hat{x}^+$, $\hat{c}_k^+$ are the operators of the creation of exciton and photons, respectively, $\hat{x}$, $\hat{c}_k$ are the operators of the annihilation of exciton and photons, respectively, $w_0$ is the exciton frequency, $w_k$ are the frequencies of cavity modes, $g_k$ are the constants, describing the strength of the interaction between exciton and optical modes. The Hamiltonian (2) of the interaction in the matrix form reads as:

$$\mathcal{H} = \hbar \begin{bmatrix} w_0 & g_1 & \cdots & g_N \\ g_1 & w_1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ g_N & 0 & \cdots & w_N \end{bmatrix} \begin{bmatrix} \hat{x} \\ \hat{c}_1 \\ \vdots \\ \hat{c}_N \end{bmatrix} = \hbar \hat{C}^+ W \hat{C}$$ \hspace{1cm} (3)$$

where $\hat{C}$ is a row, made up of operators of creation, $\hat{C}$ is a column, made up of operators of annihilation, $W$ is a square matrix, which consists of energies of the system and constant $g_k$. We can diagonalize this Hamiltonian using a unitary transformation [8]. Figure 3 shows the diagonalization scheme. After the diagonalization of the matrix, we obtain new creation and annihilation operators. These are polariton state operators. The squares of the coefficients standing next to the exciton birth operator in the polariton state birth operator are the excitonic contribution to the polaritonic state. The eigenstates of the bound system superposition’s of exciton and cavity modes are exciton-polariton modes $|i\rangle$. After diagonalization of the Hamiltonian we obtain the probability of the exciton radiation modes for each frequency.

**Figure 2 (a, b)**. (a) Energies and quantities $F$ for the modes localized in the square GaAs; (b) Histograms illustrating distribution of cavity modes depending on the quantity $F$. 

![Figure 2](image)
The strength of interaction of exciton with the specific mode $g_k$ is proportional to the Pursell factor and the probability of excitonic emission in the uniform media. The intensity of the excitonic emission associated with specific polariton mode $|i\rangle$ will correlate with its excitonic fraction described by $|a_{0i}|^2$. Figure 4 shows the energy dependence of the excitonic contribution to the polaritonic state.
3. Conclusions

We have found the eigenmodes of ideal square GaAs structure around of the exciton energy and the $Q$ factor of these eigenmodes. There is a small probability of the appearance of modes with a high value of $F$ for ideal square structures. And we have calculated energy dependence of the excitonic contribution to the polaritonic state. We have received multiple Rabi splitting due to the interaction occurs immediately in the strong and weak coupling regime. Thus, we have obtained the form of the dependence of the radiation probability on the eigenfrequencies of the ideal square GaAs structure.

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