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Micropillar resonator in a magnetic field: Zero and finite temperature cases

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Abstract

In this work, we present a theoretical study of a quantum dot–microcavity system which includes a constant magnetic field in the growth direction of the micropillar. First, we study the zero temperature case by means of a self-consistent procedure with a trial function composed of a coherent photon field and a BCS function for the electron–hole pairs. The dependence of the ground state energy on the magnetic field and the number of polaritons is found. We show that the magnetic field can be used as a control parameter for the photon number, and we make explicit the scaling of the total energy with the number of polaritons. Next, we study this problem at finite temperatures and obtain the scaling of the critical temperature with the number of polaritons.

Keywords: Quantum dot; Microcavity; Polaritons; BEC

1. Introduction

In the last few years, the study of many microsystems that confine light and provide the interaction with an active medium has made possible the observation of interesting phenomena such as the control of spontaneous emission (the Purcell effect) [1–3], and the enhancement of ground state occupation for exciton–polaritons at low temperatures [4,5] (in the search for the BEC of polaritons). Many interesting applications to quantum computation [6] and other areas are envisaged.

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An exciton–polariton is a quasi-particle composed of an exciton and a photon in the strong coupling regime. These quasi-particles have less reduced effective mass than atoms or excitons and, consequently, a relatively high condensation temperature is expected.

In this work, we study the effects of a homogeneous magnetic field, applied in the growth direction of a quantum dot–micropillar system on the energy, the mean number of photons in the microcavity, and the critical temperature for BE condensation of polaritons. Our calculations assume a conserved number of polaritons. Due to the fact that polaritons do indeed decay, such an assumption means that their lifetime is much longer than the time required to achieve thermal equilibrium at a fixed number of polaritons [7].

The paper has been written as follows. In Section 2, we describe the system and the theoretical model to be used below. In Section 3, we describe the self-consistent method used to obtain the ground state energy. In the next section, we explain the extension of the method to finite temperatures and, finally, in the last section we present numerical results for the ground state energy, mean number of photons and the critical temperature.

2. Theoretical model

The heterostructure that we are interested in is a circular pillar grown by periodic deposition of layers of GaAs and AlGaAs (Bragg mirrors). In the center of this pillar a λ-cavity defect of GaAs is placed. It contains in the middle a set of quantum dots of GaInAs. When the radius of this micropillar resonator is about 0.5 μm, one can assume that the microcavity operates with a single electromagnetic mode coupled to the quantum dot excitations (the next cavity mode is separated ∼20 meV) [8]. Furthermore, we consider a homogeneous magnetic field along the z direction (the pillar growth direction) [9].

In our calculations, we take the lateral confinement in the quantum dot as a parabolic potential. A Landau basis of single particle states for electrons (holes) is used. The parameters have been taken as follows. Effective in-plane masses $m_e = 0.05\ m_0$, $m_h = 0.07\ m_0$, where m_0 is the free electron mass, are used. $\hbar\omega_0 = 1$ meV is the confinement energy. $\hbar\omega = 1$ meV is the photon energy, measured with respect to the nominal band gap. The photon–matter coupling strength is given by $g = 0.5$ meV. We take the Coulomb interaction constant $\beta = 2.73\sqrt{B}$ meV, and the cyclotronic frequencies for electrons and holes as $\hbar\omega_c^{e(h)} = 1.15 * 10^{-1} B/m_{e(h)}$ meV, where B is given in teslas. The Hamiltonian for this problem is

$$\begin{aligned}\hat{H} &= \sum_n (E_n^{(e)} e_n^\dagger e_n + E_{\bar{n}}^{(h)} h_{\bar{n}}^\dagger h_{\bar{n}}) + \sum_n (t_{kn}^{(e)} e_k^\dagger e_n + t_{\bar{k}\bar{n}}^{(h)} h_{\bar{k}} h_{\bar{n}}) \\ &+ \frac{\beta}{2} \sum_{r,s,u,v} \langle r, s | \frac{1}{r} | u, v \rangle\, e_r^\dagger e_s^\dagger e_v e_u + \frac{\beta}{2} \sum_{r,s,u,v} \langle r, s | \frac{1}{r} | u, v \rangle\, h_{\bar{r}}^\dagger h_{\bar{s}}^\dagger h_{\bar{v}} h_{\bar{u}} \\ &- \beta \sum_{r,s,u,v} \langle r, s | \frac{1}{r} | u, v \rangle\, e_r^\dagger h_{\bar{s}}^\dagger h_{\bar{v}} e_u + \hbar\omega a^\dagger a + g \sum_n (a^\dagger e_n h_{\bar{n}} + a h_{\bar{n}}^\dagger e_n^\dagger). \qquad (1)\end{aligned}$$

3. $T = 0$

We use a BCS variational method with a trial function given by

$$|u_n, v_n, \sigma\rangle = |\sigma\rangle \otimes \prod_n^{\text{N states}} (u_n + v_n e_n^\dagger h_n^\dagger)\, |0\rangle\,, \qquad (2)$$