Physica E 53 (2013) 55–58

Contents lists available at SciVerse ScienceDirect

Physica E

journal homepage: www.elsevier.com/locate/physe

Polariton–polariton collinear interaction in semiconductor microcavities

M.V. Lebedev *

Institute of Solid State Physics RAS, Chernogolovka, Russia

HIGHLIGHTS

- Collinear polariton–polariton scattering is found having no analogs in bulk polariton scattering.
- The $k=0$ state plays a key role, being involved in a great number of different scattering processes.
- Direct population of the $k=0$ state excludes the explanation in terms of BEC of microcavity polaritons.

ARTICLE INFO

Article history:
Received 15 February 2013
Received in revised form
15 April 2013
Accepted 22 April 2013
Available online 2 May 2013

Keywords:
Polariton scattering
Microcavity
Bose–Einstein condensation

ABSTRACT

It is shown that the existence of a small polariton mass near $k=0$ and a large exciton mass leads to a special type of polariton–polariton interaction: a collinear scattering, which has no analogs in bulk polariton scattering. This scattering process governed with energy and momentum conservation laws is very sensitive to the population of the $k=0$ state, which plays a main role in nonlinear relaxation of polaritons.

1. Introduction

While it is more or less clear that polariton–polariton scattering should be governed with energy and momentum conservation laws experimental evidence for this remains uncertain [1–4]. It is usually understood that the $k=0$ state cannot be populated directly through polariton–polariton interaction and macrooccupation of this state is the consequence of Bose condensation of the interacting polariton gas. The impossibility to explain some emission properties of microcavities in terms of energy and momentum conservation leads to explanations with strong renormalization of polariton dispersion and multistability. The analysis undertaken in this paper shows that many basic things may nevertheless be explained with peculiarities of energy and momentum conservation in the polariton–polariton scattering process leading to efficient collinear scattering of polaritons. It will be shown in what follows that the $k=0$ state plays a key role in nonlinear polariton relaxation being directly and effectively occupied and involved in a great number of nonlinear scattering processes.

2. Polariton–polariton scattering

Polariton–polariton scattering is a very efficient nonlinear process of population redistribution on the lower polariton branch. It is governed by energy and momentum conservation laws which have some peculiarities arising from light polariton mass near $k=0$and heavy exciton mass. If we rewrite the ordinary conservation laws for polariton–polariton interaction

$$\vec{k}_1+\vec{k}_2=\vec{k}_3+\vec{k}_4$$
$$\hbar\omega_1+\hbar\omega_2=\hbar\omega_3+\hbar\omega_4 \tag{1}$$

where $\vec{k}_i$are the wavevector components parallel to the crystal plane surface, in the form

$$\vec{k}_1+\vec{k}_2=\vec{k}_3+\vec{k}_4$$
$$\hbar\omega_0+\varepsilon_1+\hbar\omega_0+\varepsilon_2=\hbar\omega_0+\varepsilon_3+\hbar\omega_0+\varepsilon_4 \tag{2}$$

We can see that these resemble in some sense the conservation laws of relativistic particles with the rest energy $\hbar\omega_0$. We can consider interaction processes neglecting the rest energy but have to keep in mind that the number of quantum should be conserved.

$$\vec{k}_1+\vec{k}_2=\vec{k}_3+\vec{k}_4$$

* Tel.: +7 903 539 3097; fax: +7 496 522 8160.
E-mail address: lebedev@issp.ac.ru

1386-9477/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physe.2013.04.015

$$\varepsilon_1+\varepsilon_2=\varepsilon_3+\varepsilon_4 \tag{3}$$

This last remark is important because among possible states we have in this picture is now also a state with $\vec{k}=0$ and$\varepsilon=0$ which could be formally added or removed from Eq. (3) without changing equations.

3. Dispersion curves algebra and collinear polariton–polariton scattering

It is convenient to consider graphical representation of Eq. (3) in a form of a dispersion curves algebra (see Fig. 1). If we take the (k_1,ε_1) state as a first initial state (point A in Fig.1) and put at this point the origin of the dispersion curve of the second initial state (k_2,ε_2), the coordinates of their sum (point C in Fig. 1) in the first coordinate system will be $(k_1+k_2,\varepsilon_1+\varepsilon_2)$ representing thus the left part of Eq. (3). The existence of polariton mass due to the quadratic dispersion near $k=0$makes that the (k_2,ε_2) dispersion curve will always go to the right of the (k_1,ε_1) dispersion curve. If we suppose that the exciton mass is infinitely large we get that

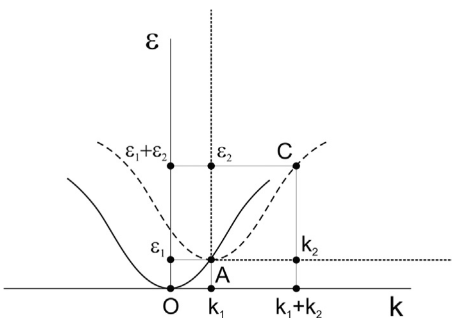

Fig. 1. The dispersion curves algebra.

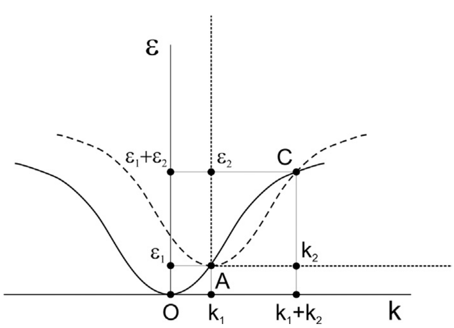

Fig. 2. Collinear intersection of dispersion curves.

polariton dispersion is tending to a finite energy $\varepsilon_{ex}$with the increase of momentum. While $\varepsilon_1$is tending to ε_{ex} with the increase of k_1, the energy of the intermediate state$\varepsilon_1+\varepsilon_2$ is tending to $\varepsilon_{ex}+\varepsilon_2\rangle\varepsilon_{ex}$. This means that there exist such a finite momentum k_2 that the dispersion curve of the second initial state intersects with that one of the first (see Fig. 2). In other words conservation laws (Eq. (3)) may be satisfied with $\vec{k}_4=0$ and $\varepsilon_4=0$. This fact of the dispersion curves intersection enables nontrivial collinear in $k$solutions of the conservation laws which find no analogs in bulk polariton interactions.

The dispersion of the low energy polariton branch depends critically on detuning $\delta=E_c–E_{ex}$ (where E_{ex} is the exciton energy and E_c the cavity mode energy for$k=0$) and can be represented with a class of monotonic curves having a minimum at $\vec{k}=0$ and tending asymptotically to E_{ex} at large $\vec{k}$ (see Fig. 3). These curves have obviously an inflection point and we suppose that they have a single inflection point only, because the existence of more than one inflection point demands very specific properties of exciton–photon interaction. Let us analyze possible collinear solutions for this class of dispersion curves.

Collinear intersection of dispersion curves considered above means that for every state $\varepsilon(k_1)$ one can find such a wavevector $k_2$that

$$\varepsilon(k_1)+\varepsilon(k_2)=\varepsilon(k_1+k_2) \tag{4}$$

Let us analyze the behavior of the intersection point C: $(k_1+k_2,\ \varepsilon_1+\varepsilon_2)$ with the increase of ε_1. The sum k_1+k_2obviously tends to infinity when $k_1\to\infty$ and $\varepsilon_1+\varepsilon_2\to\varepsilon_{ex}$. Eq. (4) is permutation symmetric against the initial polariton states $\varepsilon(k_1)$ and $\varepsilon(k_2)$: one can reach the same final state C on the dispersion curve starting from point A:(k_1,ε_1) or point B:(k_2,ε_2) of the initial dispersion curve—this changes only the order of terms in the left hand side of Eq. (4). This permutation symmetry leads to the symmetry of possible solutions of Eqs. (3) or (4). To show this let us consider all possible final states of the polariton–polariton interaction process with the intermediate state C (Fig. 2).

We can rewrite Eq. (3) in the following form:

$$\vec{k}_1+\vec{k}_2-\vec{k}_3=\vec{k}_4$$
$$\varepsilon_1+\varepsilon_2-\varepsilon_3=\varepsilon_4 \tag{5}$$

This means that we can subtract from the sum $(k_1+k_2,\varepsilon_1+\varepsilon_2)$ the state (k_3,ε_3) plotting its dispersion curve in the inversed coordinate system $(-k,-\varepsilon)$ with the origin at the point $(k_1+k_2,\ \varepsilon_1+\varepsilon_2)$ and finding the intersections of this curve with the dispersion curve of the first initial state (see Fig. 4). The intersection points of the inversed dispersion curve (shown with dash) with the initial dispersion curve (solid line) will be the points A and B (for steep dispersion curves in addition D and F, see

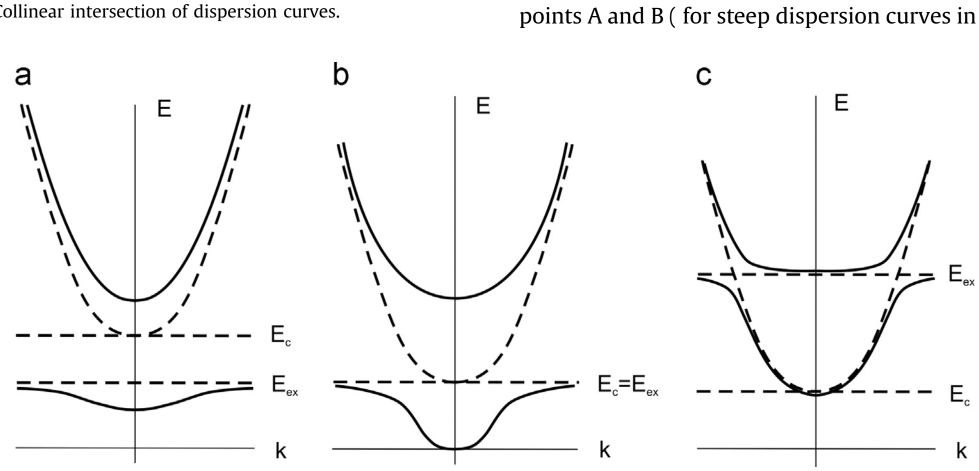

Fig. 3. Polariton dispersion curves for different detunings.