Physica B 434 (2014) 74–77

Contents lists available at ScienceDirect

Physica B

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

Multiple kinds of emission modes in semiconductor microcavity coupled with plasmon

Ling Du [a], Huibing Mao [a,*], Xuqiang Luo [a], Jiqing Wang [a], Zdenek Remes [b]

[a] Key Laboratory of Polar Materials and Devices, East China Normal University, Shanghai 200241, PR China
[b] Institute of Physics, Academy of Sciences of the Czech Republic, Cukrovarnicka 10, 16200 Prague 6, Czech Republic

ARTICLE INFO

Article history:
Received 9 September 2013
Received in revised form
28 October 2013
Accepted 29 October 2013
Available online 5 November 2013

Keywords:
Plasmon
Exciton polariton
Microcavity
ZnO
Effective refractive index

ABSTRACT

The photoluminescence emission of the ZnO microcavity coupled with the plasmon has three kinds of modes: the emission modes in the band-edge emission band, the wide emission modes and the thin emission modes in the defect-related emission band. The emission modes in the band-edge emission band are the plasmon coupled exciton polariton with the effective refractive index of 2.04. The exciton coupling equation with the effective refractive index can describe the coupling between the exciton, plasmon and microcavity very well. The wide emission modes in the visible band are the plasmon coupled transverse Fabry–Perot modes with the effective refractive index of 1.84 at the wavelength of 580 nm (2.14 eV). The thin emission modes in the visible band are the plasmon coupled WGM with the effective refractive index of 1.87 at the wavelength of 566.1 nm (2.190 eV). Because of the phase difference of the two polarizations in the total internal reflections, doubled modes are observed for the WGM, which leads to the thin modes in the visible band.

1. Introduction

Solid-state cavity quantum electrodynamics offers a robust and scalable platform for the quantum optics experiments and the development of quantum information processing devices [1–5]. The microcavity induces an increase of the spontaneous emission rate and a preferential funneling of the emitted photons into the microcavity mode opening the possibility of a high collection efficiency of the emitted photons. Surface plasmon polaritons are the key to break down the diffraction limit of the converntional optics, which open a new area of subwavelength optics [6]. It is believed that the couple between the surface plasmon and the microcavity will change the fundamental property of the microcavity [2,7–9]. For example, the above coupling will introduce an effective optical index for the microcavity [2]. The photoluminescence is an important method to investigate the semiconductor microcavity, in which many eigen modes have been observed in its luminescence spectrum.

In the semiconductor microcavity coupled with plasmon, the interaction among exciton, plasmon and microcavity is very important to determine the microcavity property. ZnO microcavity is an important semiconductor microcavity in this research area, because ZnO is a wide band gap semiconductor having large exciton oscillator strength and binding energy (~60 meV). Besides, ZnO is itself a promising materials for ultra-violet or visible photonic nanodevices [10,11]. However, there is no intensive research into the above interaction. In the mcrocavity there are two kinds of modes: the Fabry–Perot modes and the whispering gallery modes (WGM), which have been intensively investigated separately. However, to the best of our knowledge, there is no any report about the two kinds of modes simultaneously in the microcavity.

This paper will investigate the coupling effect on the eigen modes among the plasmon, the exciton and the microcavity in the ZnO microstructure. Meanwhile, the luminescence property of the microcavity, in which the Fabry–Perot modes and WGM appear simultaneously, will be studied in depth.

2. Experimental details

All chemicals were of analytical grade and used without further purification. The microrod sample was prepared through hydrothermal method. Briefly, zinc acetate dehydrate [$Zn(Ac)_2 \cdot 2H_2O$] and hexamethylenetetramine ($C_6H_{12}N_4$) were added in a deionized water and stirred at 60 °C for 10 min. Then the solution was suspended in the thermostat water bath at 95 °C for 12 h. The resulting solution were washed with deionized water and ethanol respectively, after which the solution which contains precipitates was dropped on a silicon substrate electroplating with the metal Ag layer and dried at room temperature.

The scanning electron microscopy (SEM) (Hitachi S-4800) was used to investigate the structure of the ZnO microrod. The

* Corresponding author. Tel./fax: +86 21 54345152.
E-mail address: hbmao@ee.ecnu.edu.cn (H. Mao).

0921-4526/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.physb.2013.10.046

spectroscopic experiments were carried out in a confocal micro-photoluminescence system. The single microrod lying on the substrate was homogeneously excited with a cw He–Cd laser at a wavelength of 325 nm. The luminescence was analyzed with a Horiba Jobin Yvon spectrophotometer and a semiconductor refrigerator cooled (down to −70 °C) CCD. The size of the microrod was determined by the optical microscope of the micro-photoluminescence system.

3. Results and discussion

3.1. Experimental results

As shown in Fig. 1, the SEM image presents that the ZnO microstructure has a hexagonal cross section. Although the microrod is not an ideal cylinder structure, the smooth microrod was selected for the optical measurement. The investigated sample has a width of 6.7 μm and a length of 16.6 μm. As the ZnO microrod has a hexagonal cross section, the radius of the cross section is 3.35 μm.

Fig. 2 shows the photoluminescence spectra of the ZnO microcavity with the normalized excitation power 1, 0.5, 0.25, 0.1 and 0.01. As presented in Fig. 2(a), all the 5 spectra include 2 emission bands: the band-edge emission at the waveband of about 3.2 eV and the defect-related emission at the visible band. As shown in Fig. 2, the most peculiar property of the luminescence spectra is that for both emission bands there are series of luminescence modes. For the band-edge emission band, there are 7 modes in the waveband from 3.07 to 3.27 eV, which are located at 3.242, 3.222, 3.200, 3.177, 3.153, 3.122 and 3.094 eV as shown in Fig. 2(b). For the defect-related emission more than 17 wide modes can be observed form 1.4 to 2.8 eV. The mode spacing of the wide modes is about 58 meV at the wavelength of about 580 nm (2.138 eV), which is in the peak emission band of the defect-related emission. For the defect-related emission band, a more noticeable phenomenon is that there are many thin luminescence modes in the range of 2.0–2.3 eV besides the wide luminescence modes as indicated by the solid and dash lines in the inset of Fig. 2(a). The mode spacing of the thin modes is about 9.5 meV at the wavelength of about 580 nm (2.14 eV). These thin luminescence modes can be observed for the normalized excitation power 1, 0.5, 0.25 and 0.1. For the normalized excitation power 0.01, only the wide luminescence modes can be observed, which are identically consistent with the wide luminescence modes for the normalized excitation power 1. As shown in Fig. 2(a), the wide modes appear as the

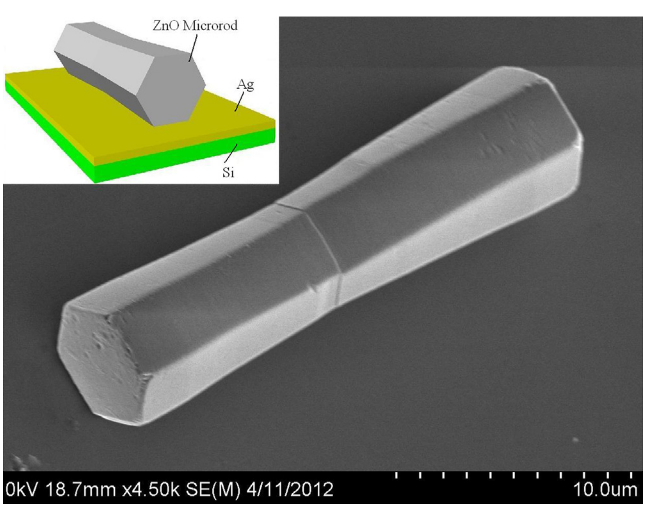

Fig. 1. SEM image of the ZnO microrod and sketch of the microrod lying on the Ag/silicon substrate.

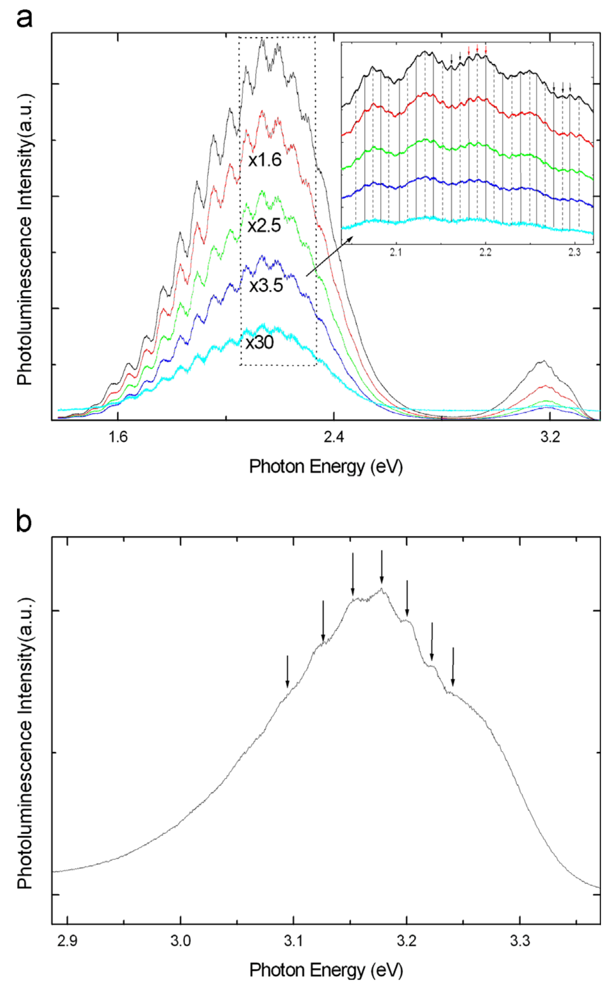

Fig. 2. (a) Photoluminescence spectra of the ZnO microcavity with the normalized excitation power 1, 0.5 0.25 0.1 and 0.01, in which the inset shows the thin modes between 2.04 and 2.32 eV. (b) Photoluminescence spectrum of the ZnO microcavity at the band-edge emission region with the noamalized excitation 1.

envelop of the thin modes in the range of 2.0–2.3 eV. These phenomena imply that for the ZnO microcavity, there are two different kinds of eigen modes in the waveband 2.0–2.3 eV.

3.2. Discussion

The determination of the luminescence mode origin is the key problem of this paper. According to the luminescence spectra of the microrod, three kinds of mode origin will be discussed in this paper: the band-edge emission modes, the wide modes and the thin modes in the visible band.

3.2.1. Analysis of the band-edge polariton emission

It is reported that the background dielectric constant ε_∞ is 6.2 [12], which corresponds to the refractive index (RI) $n=\sqrt{\varepsilon_\infty \mu_r}=2.49$ (the dielectric permeability $\mu_r=1$ in semiconductor). For the band-edge emission, there are three possible mode origins. The first is the longitudinal Fabry–Perot mode between the two facets of the microrod. As the length of the microrod is 16.6 μm, the corresponding mode spacing is 1.75 nm at the wavelength of 380 nm (3.26 eV) with the RI of 2.49, which is far less than the experimental mode spacing. The second is the WGM in the cross section of the hexagonal microrod. As the radius of the hexagonal microrod is 3.35 μm, the corresponding mode spacing is 3.33 nm at the wavelength of 380 nm with the RI of 2.49, which is also less than the experimental mode