Optical properties of a laterally confined semiconductor microcavity containing a single quantum well

E.S. Leea,*, H.M. Gibbst, G. Khitrova b

aDepartment of Optical Engineering, Inje University, Kimhae, Kyungnam 621-749, South Korea
bOptical Sciences Center, University of Arizona, Tucson, AZ 85721, USA

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Abstract

The semiconductor microcavity with a thin oxide-aperture layer is fabricated, and linear optical transmission spectrum measured for various aperture diameters. First, the observation of bare cavity modes is demonstrated in this microstructure which is capable of confining light field three-dimensionally. Several transverse modes are observed as transmission peaks, which manifests the lateral field confinement achieved well down to 2 μm aperture diameter. And the transmission spectrum of cavity modes coupled to the excitonic resonance is measured for the same microcavity system containing a single quantum well. The result shows that each transverse mode couples to an exciton independently as it approaches the excitonic resonance frequency, giving rise to an anti-crossing behavior between coupled modes.

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1. Introduction

Semiconductor Fabry-Perot planar microcavities have been attracting one’s attentions not only for many photonics applications of enhancing the device performance, but also for fundamental studies. An example is the vertical-cavity surface-emitting laser, where a thin layer of semiconductor material inside a high-finesse microcavity acts as a very efficient miniature laser system. The same system also shows interesting light-matter coupling effect far below lasing threshold [1]. In the latter case, a thin layer of semiconductor quantum well with a sharp excitonic resonance line acts as dielectric substance of linear optical absorption and dispersion inside the microcavity. This results in very pronounced index changes in the vicinity of the excitonic absorption so that the Fabry-Perot resonance condition, requiring an integral number of wavelengths between the two mirrors, can be satisfied at some wavelengths different from the resonance wavelength of bare cavity. Therefore, we might say that the light-exciton coupling in semiconductor microcavity occurs in such a way that the space inside the cavity gets modified by excitonic absorption to change the optical path length as a function of wavelength. This effect is called normal mode coupling (NMC) [2–4], which manifests itself in two separated peaks observed in optical transmission measurement. And an anti-crossing curve is obtained when we plot the positions of two peaks as the bare cavity resonance is tuned through the excitonic one, where the minimum separation depends on the absorption coefficient of exciton and the volume of optical field confined inside cavity.

Recent progress in microfabrication techniques involving electron beam lithography and reactive ion etching has allowed a three-dimensional engineering of microstructures starting from Fabry-Perot planar microcavities grown by molecular beam epitaxy (MBE) [5–7]. So it is now possible to have optical field confinement in all three directions and very small volume of optical mode inside the microcavity. As in planar microcavity system, if a quantum well is incorporated into the spacer layer of the three-dimensional microcavity, then we expect to see the NMC between the optical mode of cavity and the excitonic one of quantum well in a very similar way. So it is now interesting to see how the NMC behaves for this three-dimensionally confined optical field of small volume.

* Corresponding author. Fax: +82-55-320-3631.
E-mail address: eslee@ijnc.inje.ac.kr (E.S. Lee).
In this work, oxide-aperture three-dimensional microcavity is fabricated from semiconductor Fabry-Perot planar microcavity containing a single In$_{0.04}$Ga$_{0.96}$As quantum well, and the optical response of the sample is investigated by optical transmission measurement.

2. Experimental method

Most three-dimensional microcavities from MBE-grown planar ones have been made pillar shaped; large parts of the top mirror layers and the spacer are etched away all the way down to the bottom distributed Bragg reflector (DBR). The three-dimensional field confinement in this type of microcavity is due to a large change of the refractive index in the lateral direction, thus the cavity quality factor is very sensitive to the roughness of the side walls, and becomes worse as the lateral size of cavity decreases [6]. So, in our case, we choose a different approach demonstrated earlier by Deppe et al. [8]. A thin dielectric layer of oxide aperture is placed on top of the spacer layer of planar microcavity. The physics of lateral field confinement in this type of microstructure has been explained by the cut-off frequencies of a planar waveguide induced by the big difference in the refractive indices of the AlAs and the oxide [9]. Therefore, the boundary effect is less serious. The sample under investigation is shown in Fig. 1, and it was prepared as follows. The MBE-grown bottom mirror of the sample consists of 16 periods of GaAs/AlAs and a $\lambda/4$ layer of Al$_{0.2}$Ga$_{0.8}$As. The $\lambda$ spacer of GaAs and a 25 nm wide Al$_{0.2}$Ga$_{0.8}$As top layer contains one 8.5 nm thick high-quality In$_{0.04}$Ga$_{0.96}$As quantum well located at the intracavity field antinode. On top a $\lambda/4$ layer of 50 nm AlAs and GaAs/Al$_{0.2}$Ga$_{0.8}$As and a $\lambda/4$ layer of GaAs were grown. Photolithography and etching down to just above the spacer produced several arrays of posts with various diameters. The thin AlAs layer of these posts is then gradually oxidized in hot steam conditions resulting in various sizes of unoxidized AlAs apertures ranging from 2 to 7 $\mu$m. As a final step, the entire sample was coated with five periods of ZnSe/MgF$_2$ acting as the top mirror. Since the lateral spacing between the adjacent apertures is 100 $\mu$m, coupling between apertures can be excluded.

Transmission experiments were performed using a spectrally broad 100 fs pulse probe from a Ti:sapphire laser pumped by a 6 W Ar-ion laser. The sample was mounted in an optical cryostat equipped with an x–y–z stage. To make the probe spot size small enough to be comparable with an aperture size, a microscope objective with a numerical aperture of 0.3 was used as a focusing lens. The transmitted light was dispersed and detected by a monochromator and a charge coupled device (CCD) camera with a spectral resolution better than 0.06 nm.

3. Results and discussion

3.1. Bare cavity modes

First, we investigated the behavior of bare cavity modes for various aperture sizes. The layer thickness changes of our sample across the wafer allow us to measure at a wavelength of about 876 nm, far off-resonance from the excitonic absorption at 833 nm; this avoids the coupling of the optical mode to the quantum well exciton. Fig. 2 shows the transmission spectra of the modes for various aperture diameters. The data were

![Fig. 1. Schematic of an oxide-aperture microcavity.](image1)

![Fig. 2. Transmission spectra of oxide-aperture microcavities with varying aperture size.](image2)
taken at a solid angle of 30°. As expected for the laterally confined cavity system, one clearly sees a number of discrete transverse modes excited by an external probe light. Since the angles of excitation and collection of the probe were not so big in our measurement setup, we could not observe the higher modes than the third one. The first quantized mode shifts to shorter wavelength with respect to the two-dimensional (2D) reference. As 2D reference we use a large aperture size of 25 μm, where we do not expect any significant lateral confinement effects. The smaller the aperture size, the stronger is the confinement of the cavity mode, the larger is the shift of the ground state cavity mode, and the larger is the splitting of the higher transverse modes. To verify the three-dimensional confinement further, angular transmission measurements have been performed by tilting the sample about 10° from normal incidence; see Fig. 3. For the 2D reference, a blue shift of the cavity peak of about 0.6 nm was observed. In contrast, the spectral position of each transverse mode in the confining aperture did not change, verifying the lack of lateral dispersion of the quantized modes. However, with increased angle of observation, the intensities of the individual modes redistribute toward the shorter wavelength side.

Next, we measured the linewidth of cavity mode with high resolution and estimated cavity quality factor for each aperture size. We found that the factor is as high as 2500 for the aperture sizes larger than 3 μm and a little less for 2 μm diameter due to increase scattering loss at the edge of oxide-aperture.

3.2. Cavity modes coupled to exciton in QW

To obtain the condition of strong coupling between the exciton and the cavity modes for NMC, we used two possibilities. One is to take advantage of the varying sample thickness in growth direction and scan the probe spot keeping the same aperture size. In this way, we could shift the cavity mode wavelength toward excitonic resonance because the excitonic resonance is not sensitive to thickness variation. The other is to use the stronger temperature dependence of the excitonic resonance wavelength to tune the exciton through the cavity resonances. We could see well-resolved NMC transmission peaks and anti-crossing behaviors by both approaches. Fig. 4 shows the NMC behavior of a 4 μm oxide-aperture microcavity measured in transmission for various thickness of the sample. Since the second transverse mode for this small aperture is also noticeably excited by an external probe in our experimental setup as can be seen in Fig. 2, we see coupling of the exciton to two transverse modes that has not been observed in planar microcavity system. As the two transverse cavity modes approach to the excitonic resonance, the other two peaks show up in the opposite side of the exciton around 833 nm which result from light-exciton coupling. Due to the increased absorption near excitonic transition, the transmission intensity decreases as the cavity modes approach to the exciton. And we also notice that

Fig. 3. Angular transmission spectra measured by tilting the sample 10° from normal for 3.5 μm aperture size.

Fig. 4. Transmission spectra of oxide-aperture microcavities of 4 μm diameter for various positions on the wafer.
the linewidth of transmission peaks gets broader as the cavity mode goes further away from excitonic resonance because of the increased absorption in shorter wavelength side of exciton [10]. Fig. 5(a) is the plot of spectral positions of transmission peaks as a function of aperture position on the wafer, which shows double anti-crossing curves due to the coupling of the quantum well exciton to the first transverse mode (filled symbols) and to the second mode (open symbols). The spectral separations of two peaks at each anti-crossing curve are shown in Fig. 5(b). The results clearly indicate that each transverse mode gives its own NMC independently as expected by the rigorous quantum theory [11]. The restricted range of detuning on the sample did not allow us to go through the minimum separation for the second transverse mode. But, using the temperature tuning method of NMC, we found the same minimum separation value for the second mode as for the first one. A minimum separation value of 2.25 nm and a separation-to-linewidth ratio of 4.9 are obtained for each NMC. The ratio has not been reached in previous approaches because of broader excitonic resonances. In addition, we found that the value 2.25 nm is not much different from the 2D reference value of 2.3 nm, whereas, in pillar shaped microcavities reported by Gutbrod et al. [12], a relatively larger reduction of about 10% of the minimum separation was observed due to the lateral extension of the field in the bottom mirror beyond the etched region. Their physical argument given to the reduction suggests that the oxide-aperture microcavity may be a more effective way to confine the optical field laterally. There is also one notable effect of the dielectric top mirror on our sample. Due to the higher refractive index contrast of the ZnSe and MgF2 layers of the top mirror, we observe stronger field confinement in the normal direction leading to a 16% larger minimum separation value for the 2D reference compared to microcavities made with a GaAs/AlAs top DBR mirror.

4. Conclusions

We demonstrated the optical properties of oxide-aperture microcavity fabricated from MBE-grown semiconductor planar microcavity. The transmission measurements of bare cavities show several transverse modes manifesting the lateral field confinement achieved well down to 2 μm aperture diameter. The same microcavity system containing a single quantum well shows the coupling between exciton and cavity modes as the detuning of cavity mode from exciton decreases. It is found that two transverse modes give two independent anti-crossing behaviors of exciton and cavity modes.

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