Experimental study of mode characteristics for equilateral triangle semiconductor microcavities

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Equilateral triangle semiconductor microcavities with tensile-strained InGaAsP multi-quantum-well as the active region are fabricated by the inductively coupled plasma (ICP) etching technique. The mode characteristics of the fabricated microcavities are investigated by photoluminescence, and enhanced peaks of the photoluminescence spectra corresponding to the fundamental transverse modes are observed for microcavities with side lengths of 5 and 10 μm. The mode wavelength spacings measured experimentally coincide very well with those obtained by the theoretical formulae.

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Semiconductor microcavity lasers have the potential of ultra-low threshold or even thresholdless operation because of their small volume of the active region and a large spontaneous emission factor. As typical semiconductor microcavity lasers, optical microdisk or microring lasers have achieved great success[1−7] with the lowest threshold current of 40 μA realized. To eliminate the degeneracy of the Whispering-Gallery (WG) modes, microgear lasers were fabricated by forming a grating at the perimeter of the microdisk[8]. Recently, we have numerically shown that semiconductor microlasers with an equilateral triangle resonator (ETR) are suitable for realizing directional optical output[9−13]. In this letter, we fabricate InGaAsP equilateral triangle microcavities by the ICP etching technique and study their mode characteristics by photoluminescence.

An edge-emitting-laser wafer with five-quantum-well active region was grown by metalorganic chemical vapor deposition (MOCVD) technique. The well and barrier were both 11 nm thick and the InGaAsP optical confinement layer was 80 nm thick. To enhance the emission of the TM mode that has a larger mode quality factor than the TE mode, 0.2% tensile strain was introduced into the wells. An 800-nm SiN_x layer was deposited on the grown wafer by PECVD as the mask for etching InGaAsP and InP, and then the equilateral triangle microcavity patterns were transferred onto the photoresist by the standard photolithography. After forming the cavity pattern on the photoresist, we applied the two-step ICP etching process to fabricate the equilateral triangle microcavities. We first transfered the equilateral triangle patterns onto the SiN_x layer with the reaction gas of SF_6 and then used CH_4-Cl_2-Ar mixture gases to etch InGaAsP and InP. The etched depth was about 6 μm. The scanning electron microscope (SEM) pictures of the fabricated equilateral triangle microcavities are shown in Figs. 1(a) and (b) of an equilateral triangle microcavity with side length of 5 μm and an array with side length of 20 μm. The SEM pictures show that the etched cavities are nearly vertical and the surface at the bottom is smooth. However the vertices of the cavities are round, which was mainly distorted during the photolithograph process. The vertices of the equilateral triangle microcavities are very difficult to keep in the photolithograph process and the deep ICP-etching process and the former process is crucial for the shape transferring.

The equilateral triangle microcavities were optically pumped by a frequency doubled YAG laser at wavelength of 514.53 nm at room temperature (RT) under continuous wave condition (CW). Through a 100× microscope objective, the pump beam was focused onto single equilateral triangle microcavity, and the photoluminescence spectrum was detected by an InGaAs detector array after passing a spectrometer. The measured photoluminescence (PL) spectra at the pumping intensity of P_1 and P_2 are shown in Fig. 2 for the as-grown wafer and the

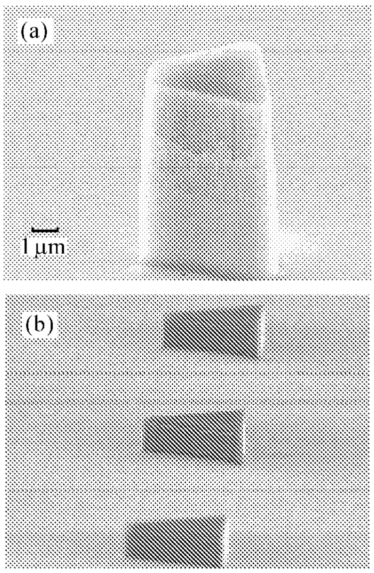

Fig. 1. SEM images of the fabricated equilateral triangle microcavities with (a) the side length $a = 5$ μm; (b) the array ETRs with the side length $a = 20$ μm.

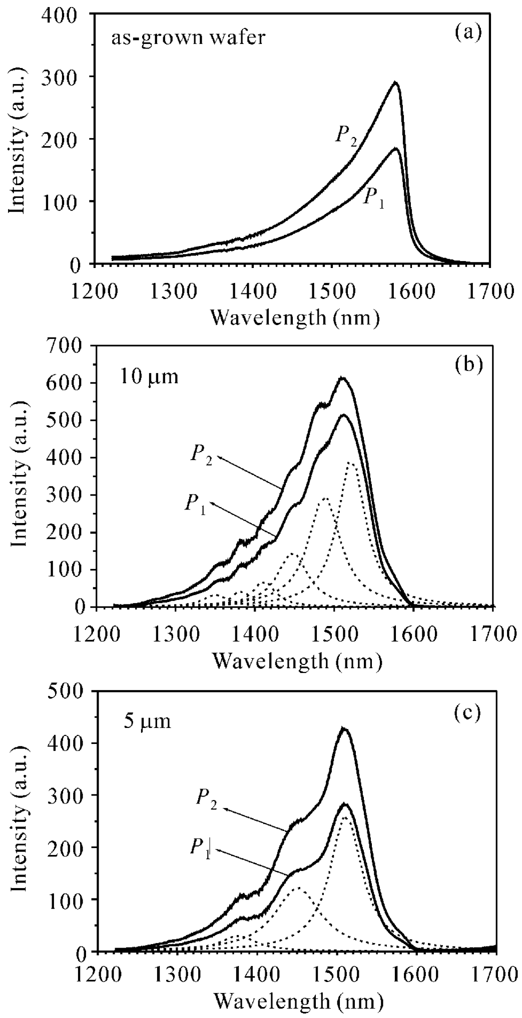

Fig. 2. Room temperature photoluminescence spectra with the pump intensity increasing from P_1 to P_2. (a) For unpatterned InGaAsP-InP epitaxial wafer with the same structure. (b) For 10 μm InGaAsP-InP equilateral triangle microcavity. (c) For 5 μm InGaAsP-InP equilateral triangle microcavity. The dashed curves represent Lorentzian fitting of peaks.

equilateral triangle microcavities with side lengths of 5 and 10 μm, respectively. We can observe six and three enhanced peaks from the photoluminescence spectra of the equilateral triangle microcavities with the side length $a = 10$ and 5μm, respectively. Fitting the photoluminescence spectra by multiple Lorentzian curves, which are shown as dashed lines in Figs. 2(b) and (c), we can obtain the peak wavelengths. The obtained peak wavelengths are 1520.7, 1482.8, 1445.1, 1412.5, 1382.0 and 1349.4 nm with the wavelength spacings of 37.9, 37.7, 32.6, 30.5 and 32.6 nm for the 10 μm equilateral triangle microcavity. For the equilateral triangle microcavity with side length of 5 μm, the peak wavelengths are 1511.1, 1451.1 and 1376.2 nm, and the corresponding wavelength spacings are 60 and 74 nm.

We calculated the mode wavelengths for the fundamental transverse TM modes based on the formula[11]

$$\lambda_{m,l} = \frac{3Na}{\sqrt{\left(l - \frac{3\theta}{\pi}\right)^2 + 3(m+1)^2}}, \tag{1}$$

where $l + m = 4, 6, 8, \cdots, N$ is the effective index and θ is the phase shift of the total internal reflection

$$\theta = \pi + 2\tan^{-1}(\sqrt{3}\beta_l/2\gamma_0). \tag{2}$$

The transverse and longitudinal propagation constants κ_m and β_l as well as the decay constant γ_0 satisfy

$$\sqrt{3}\kappa_m a = 2(m+1)\pi, \tag{3}$$

$$N^2 k_0^2 = \beta_l^2 + \kappa_m^2, \tag{4}$$

$$\gamma_0^2 = \beta_l^2/4 + 3\kappa_m^2/4 - k_0^2, \tag{5}$$

where $k_0 = 2\pi/\lambda$ is the wavenumber in vacuum. Taking the effective index N as 3.2 at the wavelength of 1550 nm and the group index N_g as 4.1 and considering the effective index varying linearly with wavelength, we obtain the dispersion of the effective index N. Substituting Eqs. (2) – (5) into Eq. (1), the confined mode wavelengths can be calculated. For the equilateral triangle microcavity with side length of 10 μm, $TM_{0,70}$, $TM_{0,72}$, $TM_{0,74}$, $TM_{0,76}$, $TM_{0,78}$, $TM_{0,80}$ mode wavelengths are 1531.2, 1493.9, 1458.5, 1424.7, 1392.4, 1361.5 nm, respectively, and the corresponding wavelength spacings are 37.2, 35.5, 33.8, 32.3, 30.8 nm. For the equilateral triangle microcavity with side length of 5 μm, $TM_{0,38}$, $TM_{0,40}$, $TM_{0,42}$ mode wavelengths are 1514.2, 1443.1, 1378.3 nm, respectively, and the corresponding spacings are 71.1 and 64.7 nm. Figure 3 shows the mode spacings versus wavelength obtained by the theoretical model and the experimental measurements.

It can be seen from Fig. 3 that the theoretical mode wavelength spacings coincide well with the experimental spacings except that a slightly larger difference exists for the 5 μm microcavity, which maybe results from the larger influence of the fabrication distortion. This verifies that the enhanced peaks of the PL spectra are associated with the fundamental transverse modes in the equilateral triangle microcavities.

In conclusion, we have fabricated equilateral triangle semiconductor microcavities by the two-step ICP etching technique. The PL spectra of fabricated microcavities were measured and compared with the unpatterned wafer of the same structure at the same pumping intensity at room temperature under continuous wave condition. Enhanced peaks of the PL spectra are observed for the equilateral triangle microcavities with side lengths of 5 and 10 μm. Compared with theoretical results, it is

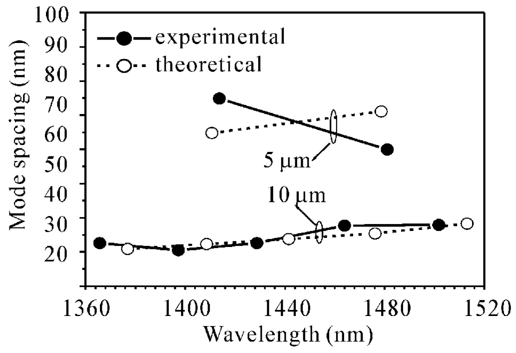

Fig. 3. Mode spacing versus wavelength obtained by the experimental measurement and the theoretical model.

found that the enhanced peaks are associated with the fundamental transverse modes in the equilateral triangle microcavities.

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