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0.66 μm InGaP/InGaAlP Single Quantum Well Microdisk Lasers

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Visible emitting microdisk lasers with single InGaP/InGaAlP quantum well were demonstrated for the first time. Large spontaneous emission factors β of 0.12 and 0.08 were observed for 5 and 10 μm diameter disks, respectively.

KEYWORDS: microdisk lasers

Recently, there has been much research interest in microcavity lasers made of semiconductor microdisks,$^{1)}$ microrings$^{2)}$ and of dielectric microspheres.$^{3)}$ In these wavelength scale microcavities, the density-of-state of light is greatly modified due to the strong dielectric confinement and the vacuum field fluctuation is also greatly enhanced due to small cavity volume. The quality factor is inherently high for these cavities because the whispering gallery mode$^{1)}$ is associated with total internal reflection. Thus these microcavities have large spontaneous emission factors, suitable for low threshold laser applications. The in-plane emission characteristics associated with the whispering gallery mode are also quite unique and may find potential applications in integrated optics. In 1992, McCall *et al*.$^{1)}$ proposed and demonstrated the first semiconductor microdisk lasers. They used a InGaAs/InGaAsP/InP material system in the 1.55 μm wavelength region. Since then, microdisk lasers have been realized in GaAs/GaAlAs$^{4)}$ and (ZnCd)Se/ZnS(Se)$^{5)}$ at 0.85 and 0.5 μm wavelength region, respectively. In the present paper we report the demonstration of microdisk lasers using the InGaP/InGaAlP single quantum well at a wavelength of 0.66 μm for the first time.

The metalorganic vapor phase deposition method was used to grow the InGaP/InGaAlP layers on a tilted (100) GaAs substrate (11° towards (110)). The microdisk laser wafer contains a 150-Å-thick $\mathrm{In_{0.57}Ga_{0.43}P}$ quantum well layer, sandwiched between two 300-Å-thick $\mathrm{In_{0.5}Ga_{0.3}Al_{0.7}P}$ barrier layers. The total thickness of the microdisk cavity is 750 Å, which is about quarter-wave thickness in material. This thickness was chosen for the optimization of the spontaneous emission factor β,$^{6)}$ because at this thickness the second order planar waveguide mode with respect to the direction perpendicular to the disk plane can not be excited. Also, at this thickness the radiation resulting from dipoles with polarization perpendicular to the disk plane is highly suppressed. Only dipoles with polarization parallel to the disk plane will couple to the cavity modes. A photolithographic technique and chemical wet etching were used in microdisk fabrication. First, circular mesas, about 2 μm deep, were formed by nonselective $\mathrm{HBr{:}H_2O_2{:}HCl{:}H_2O}$ etching into the GaAs substrate using a photoresist mask. Then, $\mathrm{NH_4OH{:}H_2O_2{:}H_2O}$ solution was used to selectively etch away a portion of GaAs beneath InGaP/InGaAlP. By means of this under-cutting procedure, the InGaP/InGaAlP microdisks were formed with GaAs supporting pillars. Figure 1 shows the scanning electron micrograph of 5-μm-diameter disks. Note that the pillar is tilted. This is an interesting manifestation of the crystallographic etching nature of the off-axis GaAs by $\mathrm{NH_4OH{:}H_2O_2{:}H_2O}$ solution.

In the measurement, we optically pumped the disks with a 632.8 nm HeNe laser. The pumping light was modulated by an acoustooptical modulator and was incident normal to the disk plane with a spot size of 20 μm full-width-half-maximum (FWHM). The emission from the optically pumped microdisk was collected in the direction parallel to disk plane, because of the unique in-plane far field radiation distribution. The far field pattern is centered at $\theta = \pi/2$ assuming the disk lies in the x-y plane of a spherical coordinate (r, θ, ϕ). The FWHM emission angular width is governed by a simple formula,$^{1)}$ $\Delta\theta = 2/\sqrt{m}$, where $m = \pi dn/\lambda$ is the azimuthal mode number, d is the disk diameter, n is the mode index and λ is the lasing wavelength. Using this formula, $\Delta\theta$ is as small as 15 and 10.5° for 5 and 10 μm diameter disks, respectively, at 0.66 μm wavelength assuming n=2.5. The corresponding m is 60 and 120. Figure 2 shows a typical series of visible InGaP/InGaAlP microdisk emission spectra versus pumping. The data were taken for a 10-μm-diameter disk under CW pumping condition at 20 K. The pumping levels (not the absorbed value) were 0.8, 1, 2.1 and $6P_{\mathrm{th}}$; where P_{th} is the threshold pump power of 30 μW. The pump levels were also indicated in the corresponding light output versus pumping curve shown in Fig. 3(b). A similar series of spectra was observed for 5-μm-diameter disks. Figure 2 clearly shows that, at $0.8P_{\mathrm{th}}$, the spectrum is a broad band superimposed with a small and narrow feature from the cavity mode at 662.4 nm. At increased pumpings, this narrow cavity mode emission becomes dominant, which is direct evidence of lasing ac-

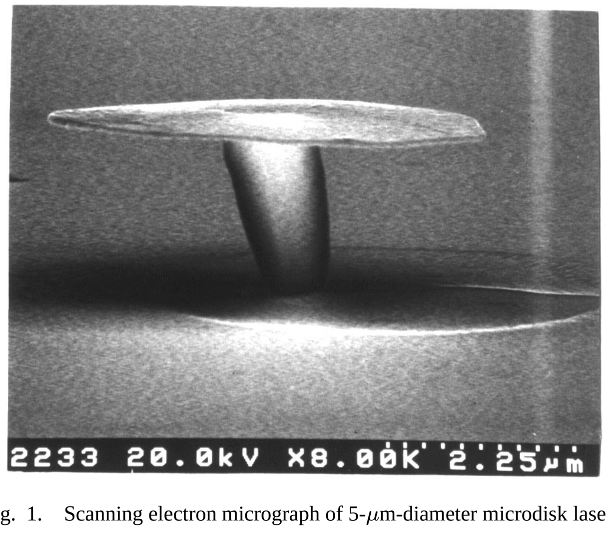

Fig. 1. Scanning electron micrograph of 5-μm-diameter microdisk laser.

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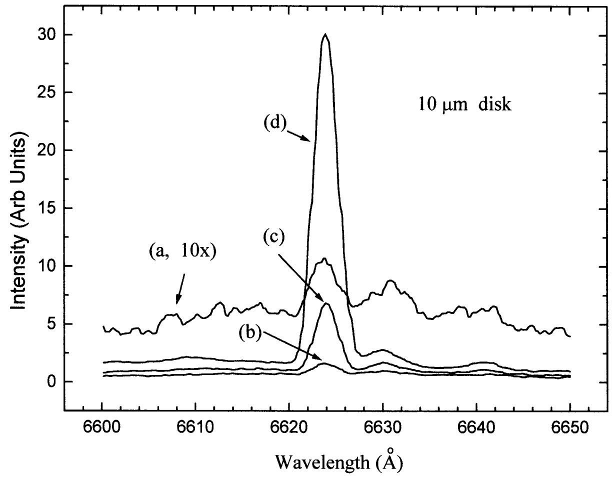


Fig. 2. Plots of emission spectrum versus pumping for a 10-μm-diameter disk. The pumping levels are 0.8 (a), 1 (b), 2.1 (c) and 6 (d) P_{th}, also indicated by arrows in Fig. 3(b). Signal for spectrum (a) is magnified 10 times.

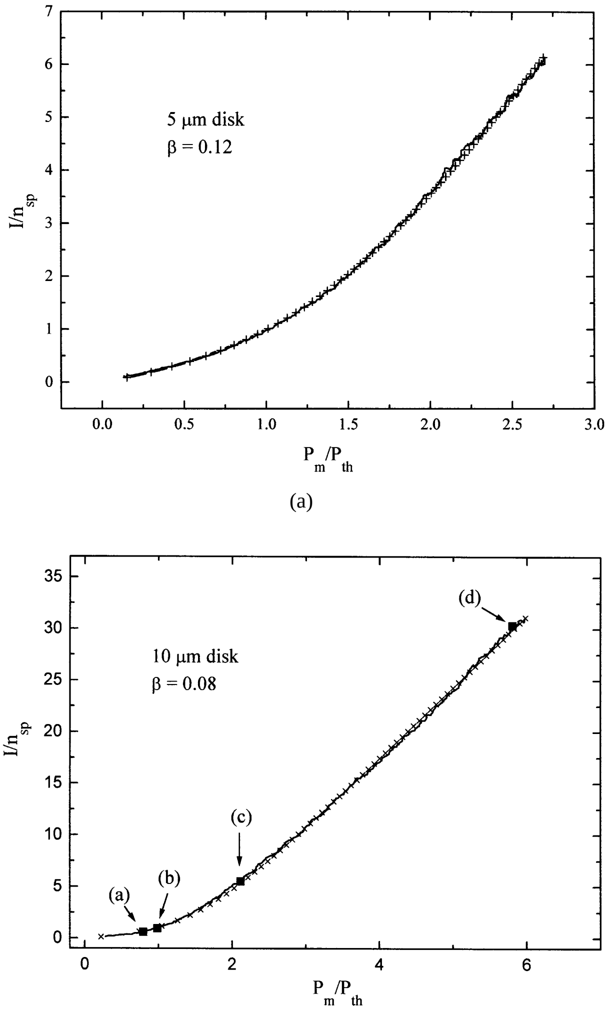
tion. The lasing linewidth is about 0.25 nm and shows no dependence on pumping within the spectrometer resolution of 0.1 nm. Similar observation was made and discussed by Mohideen *et al.*[7] in InGaAsP microdisks. The emission spectra also contain side modes about 0.6 nm (1.5 nm) from the main mode for the 10 μm (5 μm) disk. These side modes are not the adjacent $\Delta m = \pm 1$ modes, because the $m = \pi dn/\lambda$ formula predicts an adjacent mode spacing of 6 nm (12 nm) for the 10 μm (5 μm) disk. The origin of the side modes is subject to further investigation. Presumably, they are high-order transverse modes with respect to the radial direction, which are partially excited due to the roughness in the disk edge and the warping of the thin 750-Å-thick disk plane as shown in Fig. 1. CW lasing action was sustained to 50 K. The empty cavity $Q = \lambda_0/\Delta\lambda_0$ is deduced from the below threshold photoluminescence spectrum to be 2000 (800) for the 10 μm (5 μm) disks, where λ_0 is the center frequency of the cavity mode and $\Delta\lambda_0$ is the FWHM linewidth.

We now proceed to the discussion of the light output versus pumping characteristic plotted in Fig. 3 for the 5 and 10 μm disks and the determination of P_{th}. Unlike in the emission spectra, a sharp threshold transition does not appear in the two curves in Fig. 3, especially in the case of 5 μm disk. This indicates that the disks possess large spontaneous emission factors. In taking these light-output-versus-pumping data, we employed a spectral filtering arrangement by detecting the emission after it is dispersed through a spectrometer. The spectrometer is set at the laser emission wavelength and the spectral resolution is adjusted to match the cavity mode width. By doing so, only the lasing mode was measured and all the radiation modes and other cavity modes were suppressed. This is necessary in order that the single mode rate equation analysis is applicable and valid in analyzing the data. The single mode rate equations[8] are

$$\frac{\mathrm{d}I}{\mathrm{d}t} = -\gamma I + GI + R \tag{1}$$

$$\frac{\mathrm{d}N}{\mathrm{d}t} = P - N\gamma_{\text{sp}} - GI \tag{2}$$

where I denotes the total photon number of the cavity mode,



(a)

(b)

Fig. 3. Typical light output versus pump characteristic for (a) 5 μm (b) 10 μm diameter microdisk lasers. Solid lines are data and the ×-marks are from the fitting.

N is the total number of carriers, P is the pumping rate of the carrier, γ is the cavity photon decay rate, γ_{sp} is the spontaneous decay rate of carriers, $R = \beta N\gamma_{\text{sp}}$ is the spontaneous emission rate of the lasing mode, $G = R/n_{\text{sp}}$ is the stimulated emission rate, and n_{sp} is the inversion factor. The photon number I is related to the measured lasing power P_{L} by $I = f_{\text{L}}P_{\text{L}}$, where the constant factor f_{L} accounts for finite collection efficiency and cavity transmission rate. The carrier pumping rate is related to pumping power P_{m} by $P = f_{\text{m}}P_{\text{m}}$, where the constant factor f_{m} accounts for the actual absorption and other trivial conversion parameters. In the case of the steady state condition, one can show that the relation between the measured pumping power P_{m} and the measured laser power P_{L} is given by

$$P_{\text{m}} = (c_1/\beta)P_{\text{L}}(1 + \beta c_2 P_{\text{L}})/(1 + c_2 P_{\text{L}}) \tag{3}$$

where $c_1 = \gamma f_{\text{L}}/f_{\text{m}}$, $c_2 = f_{\text{L}}/n_{\text{sp}}$. It can be observed that although in general we have many unknown parameters, it is very fortunate that there are only three independent degrees of freedom in $P_{\text{L}} - P_{\text{m}}$ relation and β is one of them. Therefore we can use eq. (3) to fit the measured curve and determine the value of β unambiguously. We superimpose the numerical fitting results in Fig. 3. Excellent agreement between the experimental data and the calculations is evident for both disks. Numerical analysis yields β of 0.12 and 0.08 for the 5 and 10 μm disks, respectively. The error bar in the β values is estimated to be less than 10%. In Fig. 3, the vertical axes are expressed as cavity photon number I in the unit of the inversion factor n_{sp}. From Einstein's relation, when I/n_{sp}=1, the net stimulated emission rate of the cavity mode is equal to the spontaneous emission rate of the cavity mode. It serves as a good criterion for determining lasing threshold, when an obvious threshold characteristic is absent in the $P_{\mathrm{L}}-P_{\mathrm{m}}$ plot. By defining the corresponding power to be P_{th} when I/n_{sp}=1, we are able to express the horizontal axes in the unit of $P_{\mathrm{m}}/P_{\mathrm{th}}$ in Fig. 3.

The observed β value is inversely proportional to disk diameter. We now present an intuitive argument to explain this observation without going into complicated calculations and derivations. First, it is known that the spatial distribution of a spontaneous emission event from an excited dipole (or carrier in semiconductor) in a microcavity depends strongly on the orientation and position of the dipole and on the geometric parameters of the cavity. However, the averaged spontaneous emission rate over position and orientation is quite independent of the cavity geometry. By approximating the total spontaneous emission rate to be the bulk value γ_{sp}, β is simply the ratio between γ_{c} and γ_{sp}, where γ_{c} is the averaged rate that the dipole decays spontaneously into the lasing cavity mode. The bulk rate is obtained from the Weisskopf theory to be $\gamma_{\mathrm{sp}} = n\omega^3\mu^2/3\pi\hbar\varepsilon_0 c^2$, where ω is the angular frequency, μ is the dipole moment, ε_0 is the free space electric susceptibility, $\hbar$ is Planck's constant, and c is the velocity of light. γ_{c} is obtained directly from the Fermi golden rule as

$$\gamma_{\mathrm{c}} = \frac{2\pi\mu^2 E_0^2}{\hbar^2}\rho_{\mathrm{c}}\frac{\Delta\nu_{\mathrm{c}}}{\Delta\nu_{\mathrm{sp}}}\frac{V_{\mathrm{m}}}{V} \tag{4}$$

where $E_0 = (\hbar\omega/2\varepsilon V_{\mathrm{m}})^{1/2}$ is the vacuum field strength, V_{m} and V are the mode and cavity volumes, respectively, $\rho_{\mathrm{c}} = (\pi d/2\pi)(\mathrm{d}k/\mathrm{d}\omega)$ is the density state of the cavity mode, $\Delta\nu_{\mathrm{c}}$ and $\Delta\nu_{\mathrm{sp}}$ are the linewidths of the spontaneous emission and of the cavity mode, respectively. The spectral linewidth ratio $\Delta\nu_{\mathrm{c}}/\Delta\nu_{\mathrm{sp}}$ in eq. (4) is included to account for spectral overlap of the dipole emission to the cavity mode. $\Delta\nu_{\mathrm{c}}$ in practical devices is determined by extrinsic cavity loss and $\Delta\nu_{\mathrm{sp}}$ is a basic material parameter, therefore they are independent of disk diameter. The volume ratio V_{m}/V is equal to the fraction of carriers which overlap with light field, assuming uniform pumping and no carrier diffusion. Only carriers within the lasing mode can couple to the cavity mode. The point here is that β determined from the measured light-output-versus-pump curve is not the β for a single carrier at a particular position but the averaged value of all the carriers in the entire gain medium. After a simple algebraic step, we obtain

$$\beta = \frac{3m}{8\pi}\frac{\Delta\nu_{\mathrm{c}}}{\Delta\nu_{\mathrm{sp}}}\frac{(\lambda/n)^3}{V}$$

In the above expression, it is evident that β is inversely proportional to the microdisk diameter d, since m is proportional to d and V to d^2. This was confirmed by the experiments.

In conclusion, we have succeeded in demonstrating visible microdisk lasers using a InGaP/InGaAlP single QW material system. Large values of spontaneous emission factor β of 0.12 and 0.08 were observed for 5 and 10 μm diameter disks, respectively. This research was supported by the National Science Council of the Republic of China under Grant NSC87-2112-M-009-019.

1) S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton and R. A. Logan: Appl. Phys. Lett. **60** (1992) 289.
2) J. P. Zhang, D. Y. Chu, S. L. Wu, S. T. Ho, W. G. Bi, C. W. Tu and R. C. Tieberio: Phys. Rev. Lett. **75** (1995) 2678.
3) H. Mabuchi and H. J. Kimble: Opt. Lett. **19** (1994) 749.
4) U. Mohideen, W. S. Hobson, S, J. Pearton, F. Ren and R. E. Slusher: Appl. Phys. Lett. **64** (1994) 1911.
5) M. Hovinen, J. Ding, A. V. Nurmikko, D. C. Grillo, J. Han, L. He and R. L. Gunshor: Appl. Phys. Lett. **63** (1993) 3128.
6) S. T. Ho, S. L. McCall and R. E. Slusher: Opt. Lett. **18** (1993) 909.
7) U. Mohideen, R. E. Slusher, F. Jahnke and S. W. Koch: Phys. Rev. Lett. **73** (1994) 1785.
8) K. Petermann: *Laser Diode Noise & Modulation* (Kluwer Academic, London, 1991).