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Optical modes within III-nitride multiple quantum well microdisk cavities

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Optical resonance modes have been observed in optically pumped microdisk cavities fabricated from 50 Å/50 Å GaN/$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$($x\sim 0.07$) and 45 Å/45 Å $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$/GaN($x\sim 0.15$) multiple quantum well structures. Microdisks, approximately 9 μm in diameter and regularly spaced every 50 μm, were formed by an ion beam etch process. Individual disks were pumped at 300 and 10 K with 290 nm laser pulses focused to a spot size much smaller than the disk diameter. Optical modes corresponding to (i) the radial mode type with a spacing of 49–51 meV (both TE and TM) and (ii) the Whispering Gallery mode with a spacing of 15–16 meV were observed in the GaN microdisk cavities. The spacings of these modes are consistent with those expected for modes within a resonant cavity of cylindrical symmetry, refractive index, and dimensions of the microdisks under investigation. The GaN-based microdisk cavity is compared with its GaAs counterpart and implications regarding future GaN-based microdisk lasers are discussed. *© 1998 American Institute of Physics.* [S0003-6951(98)00513-0]

Recently, great successes toward stable and robust III-nitride lasers have been reported, and the realization of commercially available III-nitride laser devices operating in the ultraviolet and blue regime appears to be imminent.[1,2] The anticipated success of these edge-emission lasers is encouraging for the study of alternative laser geometries, which offer several benefits over the edge emitter. For instance, the microdisk cavity laser offers benefits over edge emitters including the ability to create arrays of individually controllable lasers on a single chip, laser production without cleaving or edge polishing, enhanced quantum efficiency, and a greatly reduced lasing threshold.[3] Successful microdisk cavity lasers have already been fabricated within the InGaAsP quaternary system[4,5] suggesting that the geometry may also be feasible for the III-nitride system. Previously, a large enhancement of the intrinsic transition lifetime and quantum efficiency relative to the as-grown multiple quantum wells (MQWs) structure was observed for the GaN/AlGaN MQW microdisks.[6] In this letter, we report the observation of optical mode behavior in GaN/AlGaN and InGaN/GaN MQW microdisk cavities. The resonance modes are observed in the photoluminescence (PL) spectra under the condition of high intensity optical excitation of a single disk, and the mode spacing is found to be consistent with the calculated spacings of the expected mode types for the microdisk cavity.

The description of optical resonance modes in a thin dielectric disk involves the satisfaction of Maxwell's equations across a boundary of cylindrical symmetry.[5,7,8] The fields within the disk are described by Bessel functions while the evanescent wave outside of the disk is described by Hankel functions. It has been pointed out that the microdisk cavity may support two distinctly different resonant mode types.[8] One mode type is described by Bessel functions $J_m(\chi)$ with $m=-1,0,1$ within the cavity. These modes are dominated by photon wave motion along the radial direction of the disks. The equivalent cavity is formed between the edge and the center of the disk giving an effective round-trip cavity length of $2R$ where R is the radius of the microdisk. This mode consists of radial oscillations of field intensity much like the wavelets formed by a pebble dropped in still water. Another type, known as the Whispering Gallery (WG) mode,[9] is described by Bessel functions $J_m(\chi)$ for large m. The WG mode may be thought of as in-plane propagation around the inside perimeter of the disk, which is facilitated by total-internal reflection. An effective cavity length of $2\pi R$ is given by the periodic boundary condition imposed on the circulating wave.

The two MQW structures used for this study were grown on (0001) sapphire substrates. The GaN/AlGaN MQW was grown by molecular beam epitaxy and consists of a 50 nm AlN buffer layer followed by a 10 period 50 Å/50 Å GaN/$\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$($x\sim 0.07$) MQW and a 200 Å AlN cap layer. The InGaN/GaN MQW was grown by metal organic chemical vapor deposition and consists of a 50 nm GaN buffer layer followed by a 20 period 45 Å/45 Å $\mathrm{In}_x\mathrm{Ga}_{1-x}\mathrm{N}$/GaN($x\sim 0.15$) MQW. All layers were grown nominally undoped. Dry etching was used to pattern arrays of microdisks of approximate 9 μm diam and 50 μm spacing. The samples were etched to an approximate depth of 250 nm and thus into the sapphire substrate so that no III-nitride material is present between microdisks. The micro-

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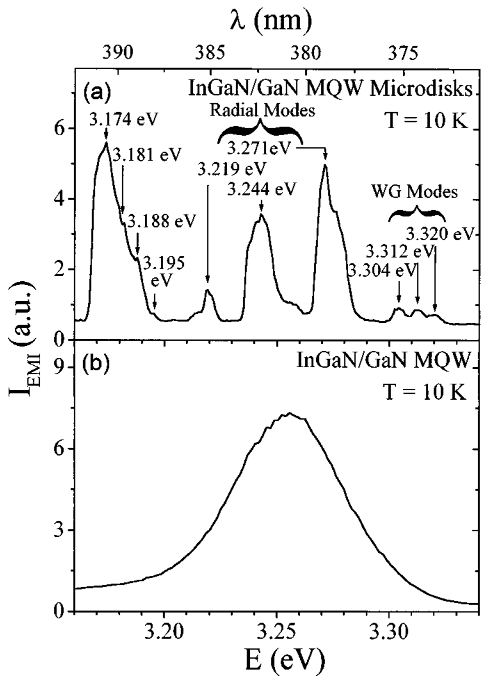

FIG. 1. Room-temperature PL spectrum from (a) InGaN/GaN MQW microdisk and (b) the InGaN/GaN MQW without microdisks. Optical modes of the WG and radial type are observed in (a), and the indicated spacings are consistent with those expected from Eqs. (4) and (6).

disk structure was verified by atomic force microscopy which yielded a measured diameter of 9.3 μm. An UV transmitting objective was used in a confocal geometry to optically pump a single microdisk normal to the sample surface and to collect the PL emitted in the direction of the surface normal. The excitation laser and PL detection system have been described elsewhere.[10] Focused beam spot diameters as small as 2 μm could be achieved with the objective lens.

Strong optical-mode behavior was observed in the 10 K PL emission spectra of individually pumped InGaN/GaN MQW microdisks as shown in Fig. 1(a). These mode peaks may be compared with the emission spectrum shown in Fig. 1(b) from the InGaN/GaN MQWs without microdisks obtained under equivalent conditions. The three small peaks (3.304, 3.312, and 3.320 eV) seen at the high-energy side of Fig. 1(a) exhibit spacing of 8 meV and are attributed to alternating TE and TM WG modes. The labeled peaks on the low-energy side of the spectrum (3.174, 3.181, 3.188, and 3.195 eV) are separated by 7 meV and also attributed to the WG mode. The three large peaks (3.219, 3.244, and 3.271 eV), on the other hand, are spaced by approximately 26 meV and due to alternating TE and TM radial ($m=0$) modes. The spacing and assignment of the two mode types are discussed in more detail in the following.

Precise determination of mode spacing for the resonances within a microdisk is a complicated calculation involving consideration of the field within and outside the cylinder when satisfying the boundary conditions. However, some of the features of the modes may be understood with simplified calculations. In the following, we assume the disk walls are perfectly conducting so that the field outside of the disk vanishes. In this way, approximate mode positions and spacings are readily derivable. For the radial mode type ($m=0$), the fields within the disk are described by zeroth order Bessel functions and the boundary condition for a TM (TE) mode requires that $J_0(kR)=0$ [or $J_0'(kR)=0$]. Here, k is the photon wave number in the disk and $k=2\pi/(\lambda/n)$ with λ and n being the wavelength of the mode and index of refraction of the microdisk, respectively. Differentiation is performed with respect to the radial variable. The optical modes can be found by noting that in the limit of $kR \gg 1$ (as in this case),

$$J_0(kR) \approx (2/\pi kR)^{1/2} \cos(kR-\pi/4). \tag{1}$$

We can, thus, obtain the eigenmodes for the case of $m=0$ as $J_0(kR)=0$ [$J_0'(kR)=0$], or equivalently,

$$\text{TM modes:} \quad 2nR=(p+3/4)\lambda, \quad p=1,2,3,..., \tag{2}$$

$$\text{TE modes:} \quad 2nR=(p+1/4)\lambda, \quad p=1,2,3,... . \tag{3}$$

From Eqs. (2) and (3), we find both the TE and TM radial modes exhibit a mode spacing of

$$\Delta\lambda_{\text{rad}}^{\text{TE}}=\Delta\lambda_{\text{rad}}^{\text{TM}}=\lambda^2/2Rn. \tag{4}$$

Furthermore, the $\lambda/2$ offset between Eqs. (2) and (3) indicates the equally spaced modes alternative between TE and TM.

The second type of microdisk cavity mode, the WG mode, has a low loss due to the total-internal reflection, and thus, low threshold for lasing. The effective cavity length of $2\pi R$ imposed by the periodic boundary condition results in a WG eigenmode condition of

$$2\pi Rn=m\lambda, \quad \text{for large (integer) } m, \tag{5}$$

and the mode spacing is given by

$$\Delta\lambda_{\text{WG}}=\lambda^2/2\pi Rn=\Delta\lambda_{\text{rad}}/\pi. \tag{6}$$

It is shown in Eq. (6) that the radial mode spacing is expected to be larger than the WG mode spacing by a factor of π. For the InGaN/GaN MQW microdisk emission spectrum shown in Fig. 1(a), mode spacings of 16 and 52 meV are observed (TE to TE or TM to TM). Calculation of the expected spacings with Eq. (6) and representative values of $R=4.65$ μm and $n=2.6$ reveals that the observed spacings correspond well to the WG and radial-mode types, respectively. From the observed mode spacings of 16 and 52 meV for the WG and the radial modes, we indeed obtain the ratio of $\Delta\lambda_{\text{rad}}/\Delta\lambda_{\text{WG}}=3.25\approx\pi$ as expected from Eq. (6).

Figure 2 shows a PL emission spectrum obtained from an individually pumped GaN/AlGaN MQW microdisk at 300 K and mode fringes are clearly seen. The indicated mode spacing of 51 meV is due to alternating TE and TM modes of the radial ($m=0$) type. The approximate fringe positions have been denoted by equally spaced lines and the radial modes calculated and labeled using Eqs. (2) and (3). No WG modes are observed in this 300 K spectrum. The observed mode spacing of 51 meV agrees well with a calculated spacing obtained from Eq. (4) using values of 2.61 for the refractive index and 4.65 μm for the disk radius.

Figure 3 shows a PL emission spectrum obtained from an individually pumped GaN/AlGaN microdisk at 10 K, which also clearly shows mode fringes. This spectrum shows two mode spacings similar to the spectrum of Fig. 1. Here, the spacing of the stronger mode peaks is found to be approximately 15 meV as indicated by the solid lines and is

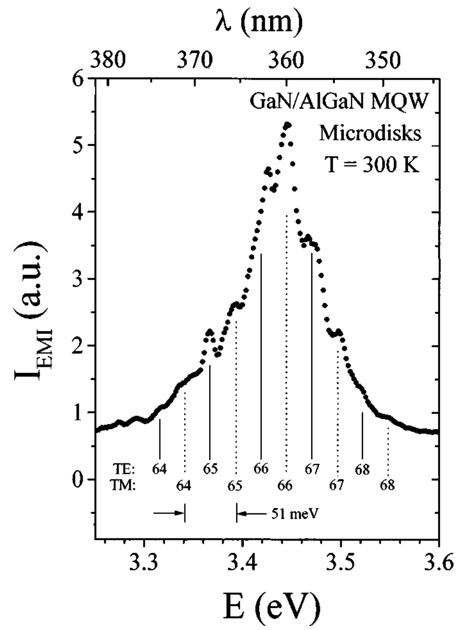

FIG. 2. Room-temperature PL spectrum from a single GaN/AlGaN MQW microdisk showing radial ($m=0$) optical resonance modes. Equally spaced lines show the approximate spacing of TE and TM modes (51 meV). The radial mode number and type (TE or TM) are also indicated.

attributed to WG modes in the microdisk. However, only TE (or TM) WG modes are observed here while both TE and TM WG modes are seen in Fig. 1. A secondary weak fringe of spacing 48.5 meV is also observed as indicated by the dotted lines. This spacing represents the radial mode type (alternating TE and TM) just as observed in Fig. 2. The spacings of 15 and 48.5 meV for the GaN/AlGaN MQW microdisks in Fig. 3 agree well with calculated spacings using Eq. (6) and values of $n=2.8$ and $R=4.65\ \mu\text{m}$ and also give a ratio of $\Delta\lambda_{\text{rad}}/\Delta\lambda_{\text{WG}}=3.2\approx\pi$.

With the effects of the microdisk cavity being observed in GaN, a comparison between GaN microdisks with other conventional III–V semiconductors, say GaAs, can be made in order to provide a guideline for future GaN microdisk lasers. The obvious and attractive distinction of the GaN-based microdisk is the working wavelength range in the blue and ultraviolet. There are also other differences between the conventional and III–N microdisk systems. The GaAs-based system benefits from a larger index of refraction, which aids in optical confinement. However, the refractive index difference between GaN and the substrate material (sapphire) is much larger than the index differences found between GaAs-based microdisks and their substrate materials (typically, GaAs or InP). This lack of sufficient index difference requires that conventional GaAs microdisks be specially etched to be isolated from the substrate[4] resulting in a less mechanically stable structure. Perhaps such procedures will not be necessary for the III-nitride/sapphire system. Finally, we note that the cavity quality (Q) for the WG mode is expected to increase with the mode number (m).[4,7] By increasing the microdisk radius, one can increase m and thus Q, but the mode density within the spontaneous emission spectrum will also be increased. For a fixed disk radius, the GaN system will have a much greater mode number (m) than the GaAs system because the GaN emission spectrum occurs at a much shorter wavelength.

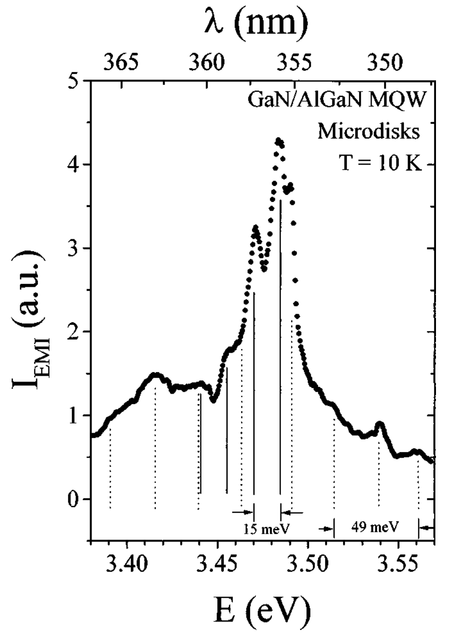

FIG. 3. PL spectrum from a single GaN/AlGaN MQW microdisk at 10 K showing WG and radial-mode behavior. The indicated mode spacing is approximately 15 meV for the WG mode and 48 meV for the radial mode.

In summary, we have observed both radial and WG optical modes within the PL spectra of individually pumped GaN/$Al_{0.07}Ga_{0.93}N$ and $In_{0.2}Ga_{0.8}N$/GaN MQW microdisks. The GaN-based and GaAs-based microdisk systems were compared and possible advantages of the GaN-based microdisk system were discussed. The presence of cavity modes in these MQW microdisks is a promising indication that at least optically pumped III-nitride microdisk cavity lasers may soon be achievable.

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