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Blue lasing at room temperature in high quality factor GaN/AlInN microdisks with InGaN quantum wells

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The authors report on the achievement of optically pumped III-V nitride blue microdisk lasers operating at room temperature. Controlled wet chemical etching of an AlInN interlayer lattice matched to GaN allows forming inverted cone pedestals. Whispering gallery modes are observed in the photoluminescence spectra of InGaN/GaN quantum wells embedded in the GaN microdisks. Typical quality factors of several thousands are found ($Q > 4000$). Laser action at ~ 420 nm is achieved under pulsed excitation at room temperature for a peak power density of 400 kW/cm^2. The lasing emission linewidth is down to 0.033 nm. © *2007 American Institute of Physics*.
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High quality factor ($Q = \lambda/\Delta\lambda$) three-dimensional semiconductor microcavities (MCs) and microdisks (μdisks) attract much attention because of their potential use for fabricating low-threshold lasers.[1,2] They are equally interesting for studying cavity quantum electrodynamics (CQED) phenomena in the solid state such as strong light-matter coupling[3,4] or the Purcell effect.[5,6] Furthermore embedding quantum dots (QDs) in such structures opens the way to the realization of single photon emitters.[7] In this respect, III-V nitride semiconductors are particularly attractive for observing CQED phenomena at room temperature (RT) due to their large oscillator strength and exciton binding energies.[8]

Recent progress in the fabrication of planar nitride-based MCs has led to the successful demonstration of high Q (~ 2800) MCs,[9] as well as laser emission under optical pumping in vertical cavity surface emitting laser structures.[10] The interest on semiconductor μdisks resides in their high Q whispering gallery modes (WGMs) and their small modal volume.[2] Furthermore, while the fabrication of high quality nitride distributed Bragg reflectors and MCs usually requires strain engineering solutions,[11] μdisks remain rather simple photonic structures in comparison. In addition, the latter possess the same advantages of compactness and ability to be integrated in two-dimensional arrays. However, the fabrication of μdisks has proven to be challenging in III-V nitrides mainly due to the lack of efficient underetching techniques. Indeed a convenient wet etching process suitable for the formation of thin disks ($d < \lambda/2n_{\text{eff}}$) optically isolated from any surrounding higher index materials, as it is the case, e.g., for the III-V arsenide system,[6] does not exist for standard AlGaN and InGaN alloys. Furthermore at short wavelengths, the emitted light is more sensitive to processing defects leading to scattering losses.

WGMs in nitrides were first observed in circular mesas.[12] The mode structure was studied but neither lasing action nor high Q factors were demonstrated. Recently the fabrication of nitride μdisks using photoelectrochemical band gap selective etching was successfully achieved leading to disks optically isolated from the underneath template.[13] Low temperature ($T = 10$ K) lasing in these structures was reported under pulsed optical pumping with a peak power density threshold of 27 MW/cm^2.

In this letter we report the fabrication of μdisk structures, containing InGaN quantum wells (QWs), in the lattice-matched GaN/AlInN system. Typical WGM Q factors in the spontaneous emission regime of about 4000 are found. These μdisks exhibit a RT lasing in the blue wavelength range with a threshold at a peak power density of about 400 kW/cm^2.

The growth was carried out by metal organic vapor phase epitaxy (MOVPE) on 2 in. *c*-plane sapphire substrates. After deposition of a standard GaN template, a 200 nm thick GaN:Si doped layer is grown. It is followed by a 400 nm thick nonintentionally doped (nid) GaN layer to reduce the current flowing out of the mesas during the oxidation process. A 400 nm thick Si doped AlInN layer ($x_{\text{In}} \sim 18\%$) nearly lattice matched to GaN is then deposited for subsequent lateral oxidation. The cavity and the active region are formed by a 100 nm thick GaN layer with three In$_{0.15}$Ga$_{0.85}$N QWs about 3 nm thick separated by 12 nm thick GaN barriers.

After the MOVPE growth step, 200 nm thick circular SiO$_2$ masks are formed and 550 nm high circular mesas 3–10 μm in diameter are etched by Cl$_2$/Ar reactive ion etching to give access to the GaN:nid layer and the AlInN layer sidewall. Then the bottom part of the AlInN layer is laterally etched using high current densities during a lateral oxidation process similar to that described in Ref. 14. This procedure gives access to the N polarity face of the AlInN layer. The mesas are then wet etched in a HCl:H$_2$O$= 1:1$ solution. Here etching occurs both laterally and in the vertical direction through the previously revealed N polarity face. This process seems to be isotropic as no specific crystallographic planes appear (Fig. 1). After the etching step, the remaining protective SiO$_2$ layer is dissolved in a BHF solution.

A typical μdisk structure is presented in the scanning electron microscope images in Fig. 1. The sidewall is smooth and inclined at $\sim 45°$. In such μdisk structures, part of the emitted light is waveguided in the GaN layer. While the top

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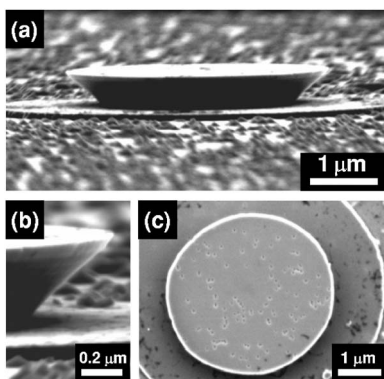
FIG. 1. Scanning electron micrograph of a 4 μm diameter disk: (a) perspective view, (b) edge close-up view, and (c) top view.

confinement is only ensured by air, the bottom one is ensured by air at the edge of the disk and AlInN (refractive index $n \sim 2.28$ at $\lambda = 420–440$ nm)[15] in the central part. As a consequence, the effective refractive index n_{eff} in the GaN waveguide varies between 2.10 and 2.28 when going from the edge to the central part of the disk. The guided light will be laterally confined by total internal reflections and thus will form a disk cavity.

The modal structure of the μdisks was investigated by photoluminescence (PL) using the 244 nm line of a cw Ar$^+$ laser frequency doubling unit. Laser action was achieved using a pulsed 266 nm neodymium-doped yttrium aluminum garnet laser with an average output power of 2 mW, a repetition rate of 8 kHz, and a pulse length of 500 ps. Measurements were performed in backscattering geometry using an UV microscope objective ($\times$80) with a numerical aperture of 0.55. Samples were fixed normally to the optical axis. While recording spectra the laser is intentionally defocused in order to excite a whole μdisks ($\sim$4 μm in diameter). The spectra are recorded with a spectrometer offering a maximum spectral resolution of 0.019 nm. All measurements were carried out at RT.

The 300 K PL spectrum of InGaN/GaN QWs before processing, measured under cw excitation, is presented in Fig. 2(a). The broad PL linewidth ($\sim$20 nm) is a usual feature of InGaN QWs. No degradation of their optical properties due to the growth on AlInN instead of a GaN buffer is observed. Note that the multiple peak line shape originates from the interference occurring in the GaN template. For comparison, a PL spectrum of a single μdisk is presented in Fig. 2(b). It is worth emphasizing that such a broad luminescence allows probing simultaneously several optical modes, as it is the case with InAs QD ensemble (see below).[16] The excitation power density of the cw laser was kept intentionally low, namely, $\sim$200 W/cm^2. Multiple modes are observed but narrow ones can be found only in the low energy part of the spectra. The modal picture suggests that they correspond to both TE and TM WGMs.[12] The existence of higher order radial modes is also possible. However, their exact assignment requires complex simulations and will be the subject of future work. The narrowest linewidths are of the order of 0.07 nm but they are likely reduced by the short range interference due to internal reflections occurring in the sapphire substrate. After fitting the envelope of these oscillations we obtain typical linewidths of $\sim$0.1 nm corresponding to Q factors of $\sim$4000. These relatively high Q factors
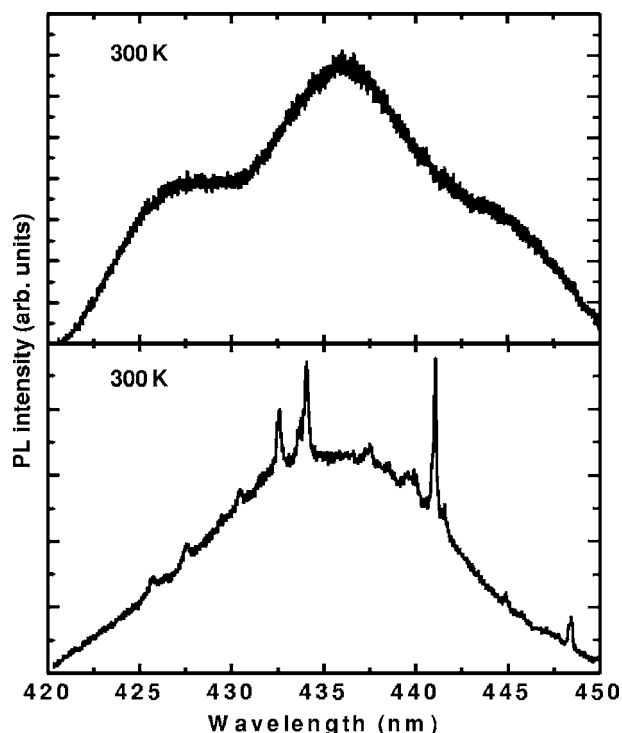

FIG. 2. (a) RT photoluminescence spectrum of bare InGaN/GaN QWs. (b) Multimode structure of a single 4 μm μdisk. The typical mode linewidth is $\sim$0.1 nm which corresponds to a quality factor $\sim$4000.

are promising for both CQED studies and the achievement of low-threshold nitride-based lasers.

It is worth discussing the origin of the parameters limiting the Q factor. The latter can be decomposed as[17]

$$Q^{-1} = Q_{rad}^{-1} + Q_{abs}^{-1} + Q_{scat}^{-1}. \tag{1}$$

The value of Q_{rad} is directly linked to the ratio of the disk diameter to the mode wavelength. For μdisks with a diameter of 4 μm at $\lambda \sim 440$ nm, this value exceeds 10^{25} and consequently does not limit the performance of our system.[2,17] The value of Q_{abs} is intrinsic to the grown materials and is defined as $Q_{abs}^{-1} = \alpha \lambda / 2\pi n_{eff}$, where α is the mean absorption coefficient in the cavity. Absorption usually occurs both in the guiding layer and in the QWs. If QW absorption was the dominant factor, we should observe a narrowing of the optical modes when increasing the pumping power until QWs reach the transparency regime.[16] Since we do not observe such a behavior for over four decades of excitation power change we can conclude that the impact of QW absorption on α is marginal for these narrow modes. This is in agreement with the large Stokes shift usually reported for InGaN QWs arising mainly from the quantum confined Stark effect.[18] Furthermore, it reminds the weak modal absorption observed in microdisks using QDs as an active region,[16] a picture consistent with the QD-like behavior seen in InGaN/GaN QWs.[19] Consequently in this case the average absorption coefficient in the cavity does match closely that of GaN. For the studied wavelengths, the typical value for the GaN sub-band-gap absorption ranges between 20 and 40 cm^{-1},[20] leading to values for Q_{abs} comprising between 16 000 and 8000, respectively. However, a stronger absorption is expected in the QWs at higher energy due to the reduced Stokes shift between their absorption and emission. This could explain why high quality factors are only
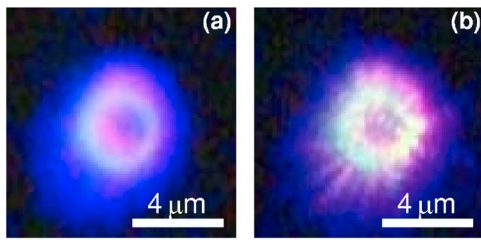
FIG. 3. (Color online) Optical microscope images of a 4 μm μdisk under homogeneous (Gaussian beam) excitation: (a) below and (b) above lasing threshold.

measured on the low energy part of the PL spectra [Fig. 2(b)]. For the low energy modes we can estimate Q_{scat}, which represents the combined influence of surface scattering, external coupling (template) and light extraction. Using Eq. (1), the obtained value is in the range of 4000-8000. This means that the influence of absorption and that of leaky modes are comparable and cannot be easily discriminated. The values found for Q_{scat} can, however, be tentatively ascribed to an increased light extraction in the vertical direction due to the inclined sidewall. Indeed, under homogeneous laser excitation an increased extraction of the luminescence near the disk edge is observed in optical microscope images [Fig. 3(a)]. The width of this bright ring, about half a micron, corresponds to that of the in plane projection of the sidewall [Fig. 1(b)].

Lasing action was investigated under pulsed excitation. The power dependence of the integrated intensity of the lasing mode as well as its line shape are presented in Figs. 4(a) and 4(b), respectively. It should be noted that laser action has been only achieved for modes in the high energy part of the QW PL spectra which is consistent with the larger absorption in this spectral region, i.e., a larger oscillator strength. A superlinear power dependence, corresponding to single mode lasing operation at 422.5 nm, is observed for an average power density $P_{av} > 1.5$ W/cm^2 at RT. The threshold is found at a peak power density of 400 kW/cm^2. For densities superior to 2 MW/cm^2, a degradation and even a complete collapse of the lasing mode are observed. Such behavior is attributed to overheating of the μdisk samples causing their mechanical failure. However a stable lasing action at room
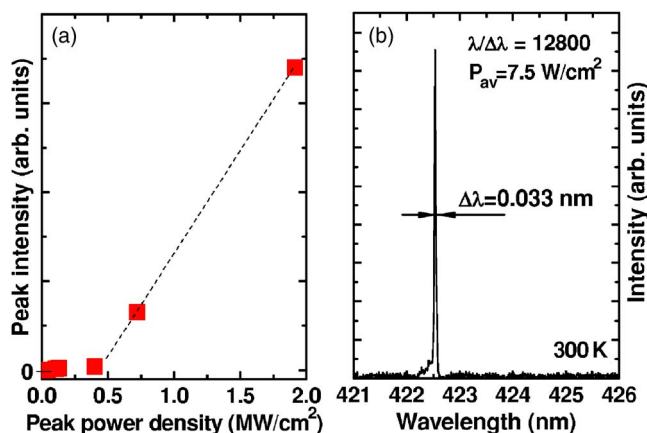
temperature is observed for a range of powers up to four to five times the threshold power which is a significant improvement over what has been previously reported for nitride μdisks.[13] This improvement is assigned to increased heat sink capabilities of the present μdisks due to their large pedestal. The measured linewidth of the laser mode under strong excitation (~ 1.8 MW/cm^2 peak power density) in the stable lasing regime goes down to 0.033 nm, i.e., $\lambda/\Delta\lambda \sim 12\,800$ [Fig. 4(b)]. Finally the light emission pattern above lasing threshold in the normal direction is presented in Fig. 3(b). The structured pattern demonstrates well coherent light emission.

In conclusion, we have demonstrated the fabrication of III-V nitride μdisk resonators in the blue wavelength range. Narrow WGMs with a typical quality factor of ~ 4000 are observed. RT lasing action was achieved under pulsed optical excitation for a peak power density at threshold as low as 400 kW/cm^2. In the stable lasing regime, the linewidth is less than 0.033 nm. Such system seems to be promising with regard to its light extraction and thermal properties.

FIG. 4. (Color online) (a) Mode intensity plotted as a function of the peak power density demonstrating a laser threshold at 400 kW/cm^2. (b) μdisk emission line above threshold.

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