High quality factor of AlN microdisks embedding GaN quantum dots

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We report the observation of high quality (Q) factor whispering gallery modes for GaN/AlN quantum dot based microdisks. Room temperature photoluminescence measurements show a large number of high Q modes on the whole PL spectral range. For the first time we report Q values up to 6000 for nitride based cavities. We attribute this improvement of the Q factor to the etching quality and to the relatively low cavity loss by inserting dots into the microdisks. The uniformity of the resonant modes with respect to a wide range of energies allows us to identify the different radial mode families.

1 Introduction III-N materials have become the dominant materials for UV to blue-green semiconductor light sources. Due to the increasing demand for lower-threshold and higher efficient laser devices at room temperature there is an interest on fabricating low-dimensional laser devices in order to reduce the non-radiative mechanisms taking place in bulk material especially at high temperature. Moreover by strongly coupling the emission with resonant modes of a micro-cavity strong Purcell effects can be observed increasing further the efficiency of the emitters.
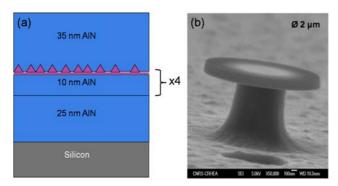
Recent results have shown that GaN/AlN Quantum Dots (QDs) with a high radiative efficiency can be grown on Si substrate [1]. The incorporation of dots to photonic resonators such as microdisks [2] can reduce the optical losses of the cavity due to lower absorption of dots compare to wells [3] with aim to fabricate novel type of low-threshold laser devices without the requirement of systems with high optical gain [4, 5].

In this work we report considerable improvement of the optical quality of microdisks with embedded GaN/AlN QDs. By performing micro-photoluminescence (μ-PL) measurements we observe high quality whispering gallery modes (WGMs) with high Q factors ($Q = \lambda/\delta\lambda$), i.e. up to 6000 for the 5 μm in diameter microdisk, which is to our knowledge the best reported value for nitride based photonic cavities. Also, we present PL spectra for microdisks of various diameters at room temperature, showing a large number of spectrally uniform modes appearing within the whole spectrum. This allows identifying different families of resonant modes particularly in the case of 2 μm microdisk.

2 Experimental The QD structure shown in Fig. 1(a) is grown by (ammonia based) molecular beam epitaxy. The GaN dots are grown on the top of AlN barrier and the sample consists 4 periods of 7 ML/10 nm GaN/AlN layers which are grown on a thin 35 nm AlN buffer layer. The whole optically active area is very thin, i.e. 100 nm and is grown on the top of a Silicon substrate. This area will act as a single mode waveguide in the microdisk plane. The Si is selectively removed from the area below the waveguide in order to form the microdisk on the top of Si post as it is shown by the Scanning Electron Microscope (SEM) image (Fig. 1b). The optimization of the etching conditions lead to smooth sidewalls of the microdisk, and is further confirmed by the high measured Q factors. Further details
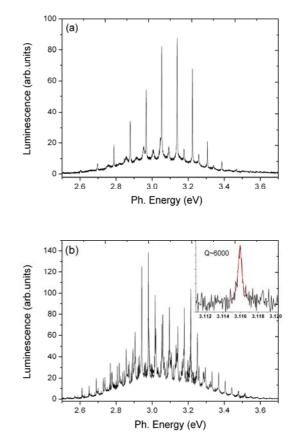
about the structure growth and the microdisk processing steps can be found elsewhere [1].

Figure 1 a) Epitaxial structure: the optically active area above the Silicon substrate contains 4 periods of GaN/AlN QD layers. b) Scanning Electron Microscopy image of a 2μm in diameter microdisk.

For the characterisation of the microdisks we performed μ-PL spectroscopy measurements by photo-exciting a single microdisk with a 266 nm CW laser beam and by collecting the PL emission from the edge at the microdisk plane at room temperature. The PL signal was detected by a cooled CCD camera after being dispersed by a spectrometer having a high resolution up to ~ 0.16 meV.

3 Results and discussion Figure 2 shows the PL spectrum of a 2 μm and 5 μm in diameter microdisks. The sharp peaks uniformly and periodically appearing across the spectrum correspond to WGMs which are distinguishable within a wide spectral range covering from 2.6 eV to 3.5 eV. This interesting feature is due to the inhomogeneous broadening of dots PL emission, underlined by the broad background level peak of the PL spectra in Fig. 2, which can probe the microdisk resonant modes over a wide spectral range [3]. Such a uniformity of the WGMs across the whole spectrum as well as the fact that these modes are clearly distinguishable for a wide spectral range has not been observed in previous works on nitride based microdisk due to re-absorption of photons in the active area incorporating Quantum Wells (QWs) [3, 7].
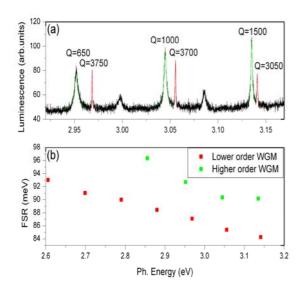

Figure 2 Photoluminescence spectra of a (a) 2 μm and (b) 5 μm in diameter microdisk. Inset : High resolution spectrum of a WGM of high Q value, i.e. Q ~ 6000; the peak is fitted by a Lorentzian lineshape (red line).

In the case of a 5 μm microdisk (Fig. 2b) a high number of spectrally very close WGMs appears on the PL spectrum. By increasing the radius of the microdisk then the number of radial modes (given by n) and of azimuthal order modes (given by m) are both increasing. Theoretically, lower radial and higher azimuthal order modes show higher Q values [8]. Thus, here for the 5 μm we obtained record Q values up to 6000 (see an example of high Q mode in the inset of Fig. 2(b)) compare to Q reaching a value up to 5000 for the 2 μm microdisk. However the increase of the Q factor, as well as the fact that there is a greater number of modes propagating far from the highly absorbing Silicon post for a wider in diameter microdisk, is at the expense of coupling a single dot emitter with several very spectrally close modes. This is not desirable as it limits the coupling efficiency of the QD emitter with a single mode which is the requirement for observing strong Purcell effect [3].

Within the microdisk micro-cavities studied here the limitations of the WGM Q values are described by the equation [6]

$$Q = Q_{rad}^{-1} + Q_{scat}^{-1} + Q_{abs}^{-1}. \qquad (1)$$

The two first factors Q_{rad}^{-1} and Q_{scat}^{-1} are related with photons which radiate outside the cavity due to tunneling (Q_{rad}^{-1}) or to scattering by imperfections of the microdisk sidewall (Q_{scat}^{-1}). The last factor depends on the absorption coefficient of materials in the waveguide [6]. For the sample described here the first two factors of equation (1) Q_{rad}^{-1} and Q_{scat}^{-1}, are estimated by the waveguide geometry and the roughness of the micro-disk sidewalls [8] respectively. Due to high quality of the etching and the strong confinement of the modes inside the microdisk, absorption is considered as the main mechanism responsible for optical losses. Absorption can take place either in the silicon post or in the nitride layers (barrier, wetting layer and QDs).

Figure 3 Different radial order families of WGMs for a 2 μm microdisk as these are indicated (a) by the color of the Lorentzian fit of the modes profile, i.e. red and green corresponding to lower and higher order modes respectively, and (b) by their Free Spectral Range (FSR) with respect to their energy.

In order to explore the different radial mode families appearing on the PL spectra we analyze the spectral spacing of the modes of the 2 μm microdisk (Fig. 3), named the Free Spectral range (FSR). Figure 3(a) presents two different families of the sharpest modes appearing in a clear periodic way across the whole PL spectrum, with an estimated Q value and a fitted Lorentzian curve. The FSR of these modes is plotted in (Fig. 3(b)). We can identify two different radial mode families from the spectral dependence of the FSR. Lower order modes (appearing with red color in Fig. 3) exhibit a smaller mode spacing and higher

Q value than higher order modes (appearing with green color in Fig. 3) [8]. Physically higher order modes are propagating closer to the center of the microdisk where absorption from the Si post limits their Q factor values. For the 1st radial mode (i.e. the lowest-order mode) the FSR can be approximated as

$$\Delta\lambda_{n=1} = \lambda_0^2/\pi R n_{eff}, \qquad (2)$$

where λ_0 is the wavelength in vacuum, R the microdisk radius and n_{eff} the effective refractive index of the 1D slab waveguide. At 3 eV, this worth $\Delta\lambda_{n=1(theor)} \sim 85$ meV, in a very close agreement with the $\Delta\lambda_{n=1(exp)} \sim 86$ meV. Thus, we associated the highest Q factor family of modes (red in Fig. 3) with the first radial order modes; the next family of modes (green) is attributed to the second radial order modes.

4 Conclusions

We have demonstrated high Q values up to 6000 of resonant modes of microdisks embedding GaN/AlN. The wide spectral PL emission of QDs at room temperature allowed us to observe a high number of whispering gallery modes within a wide range of energy, i.e. from 2.5 eV to 3 eV. Concerning the 2 μm microdisk, the FSR between modes allows identifying the two first families of radial modes.

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