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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.

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 efficient 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 = λ/δλ), 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 2µm microdisk.

Experimental

The QD structure shown in figure 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 7ML/10nm 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 serve as a single-mode waveguide in the microdisk plane. The Si is selectively removed in the area below the waveguide in order to form the microdisk on the top of a Silicon substrate. This area will serve as a single-mode waveguide in the microdisk plane. The Si is selectively removed in the area below the waveguide in order to form the microdisk on the top of a Silicon substrate. Further details about the structure growth and the microdisk processing steps can be found elsewhere [1].

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.
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.

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 figure 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 (figure 2.b) 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 figure 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]

\[ Q = Q_{\text{rad}}^{-1} + Q_{\text{scat}}^{-1} + Q_{\text{abs}}^{-1}. \]  

(1)

The two first factors \(Q_{\text{rad}}^{-1}\) and \(Q_{\text{scat}}^{-1}\) are related with photons which radiate outside the cavity due to tunneling (\(Q_{\text{rad}}^{-1}\)) or to scattering by imperfections of the microdisk sidewall (\(Q_{\text{scat}}^{-1}\)). 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)\(Q_{\text{rad}}^{-1}\) and \(Q_{\text{scat}}^{-1}\), 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).

\[ Q = Q_{\text{rad}}^{-1} + Q_{\text{scat}}^{-1} + Q_{\text{abs}}^{-1}. \]

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 (figure 3), named the Free Spectral range (FSR) with respect to the whole PL spectrum.

Within the microdisk the FSR between modes allows 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.

**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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