GaN Quantum Dots in (Al,Ga)N-based Microdisks

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Abstract. We report on the fabrication and study of (Al,Ga)N microdisks with embedded GaN quantum dots. In order to facilitate the microdisk fabrication, very thin (h < 120 nm) nitride epilayers containing optically efficient GaN quantum dots are grown directly on silicon substrates. The microdisks defined by optical lithography exhibit whispering-gallery modes with a short 1.2 nm mode spacing and quality factors as high as 2000. We show that the quality factor is limited by scattering losses due to the microdisk sidewall roughness. Finally, using e-beam lithography, we obtain microdisks with enhanced features.

1. Introduction

Because of their strong exciton binding energy and large band-offsets, GaN quantum dots (QDs) are seen as promising UV emitters for the fabrication of new photonic devices operating at room temperature (RT). This has been illustrated in a recent work reporting short-wavelength single-photon emission at 200 K [1]. Embedding such efficient QDs in microdisks (µdisks) is of major interest since it should enable the observation of the Purcell effect or even strong photon-exciton coupling up to RT.

Due to the chemical inertness of III-N materials, the fabrication of nitride-based µdisks has been mainly demonstrated through techniques that remain difficult to master, such as removal of an (Al,In)N sacrificial layer [2], or bandgap selective photoelectrochemical etching [3]. Instead, we here choose to fabricate µdisks through a much simpler approach: by growing the µdisk slab directly on a silicon substrate, we benefit from the strong etching selectivity between silicon and nitrides, so that the undercut and the post fabrication are straightforward. This approach has been first proposed by Choi et al. [4] for thick GaN-based µdisk slabs and led to lasing devices despite low quality factors. However, because we are targeting single mode propagation in the UV range, the thickness h of the µdisk slab cannot exceed 120 nm (h ≤ λ/2n_eff), so that our approach brings up one important difficulty: would it be possible to grow optically active GaN QDs in the close vicinity of the substrate interface?

We here show that despite the growth of a thin epilayer on a highly mismatched silicon substrate, it is possible to form GaN QDs exhibiting strong photoluminescence up to 300 K, which confirms their potential for RT operation. Then, we detail the fabrication of µdisks containing such QDs and discuss their microphotoluminescence (µPL) spectra as well as the origin of losses in such resonators.
2. Optical properties of GaN quantum dots in thin (Al,Ga)N epilayers

In order to study the optical properties of thin (Al,Ga)N epilayers containing GaN QDs and grown directly on silicon, we have fabricated a 120-nm-thick sample containing 3 planes of GaN/Al_{0.55}Ga_{0.45}N QDs. Fabrication aspects and optical properties of the sample are detailed in Ref. [5]. Due to the high mismatch between silicon and nitride materials, the sample presents a very high threading dislocation density (TDD) of $2 \times 10^{11}$ cm$^{-2}$. However, when compared to state-of-the-art GaN/(Al,Ga)N QDs grown far from the substrate interface of a commonly used sapphire substrate [6], i.e. with a TDD lower by one order of magnitude, the RT integrated PL intensity of QDs grown close to the silicon substrate is only 5 times weaker (Figure 1). This behaviour, despite the presence of a high density of non-radiative recombination centres, underlines the good carrier confinement properties of such GaN QDs and confirms their potential for RT operation.

![Figure 1. Comparison of the RT PL spectra (linear scale) of two QD samples: one grown on a thin (Al,Ga)N layer on Si (solid line) and another one grown on a 1µm-thick (Al,Ga)N layer on sapphire (dashed line, details about the sample in ref. [6], Fig. 2). Figure extracted from Ref [5].](image)

3. Embedment of GaN quantum dots in (Al,Ga)N microdisks

With the purpose of enhancing light-matter coupling, one would then want to embed those efficient GaN QDs into a microcavity such as a µdisk resonator.

After the MBE growth of a 72-nm-thin (Al,Ga)N epilayer containing a single QD-plane, the top surface is covered with photoresist prior to UV photolithography. The epilayer is then etched by Cl$_2$ / CH$_4$ / H$_2$ reactive ion etching (RIE): the transfer of the photoresist profile to the epilayer led to 30° sidewall angles. The µdisk post is finally obtained by a HF : HNO$_3$ : CH$_3$COOH (HNA) wet undercut of silicon, resulting in a free-standing µdisk (Figure 2). According to AFM measurements, both µdisk sides exhibit a very smooth surface ($rms \sim 3$ Å). This indicates that HNA wet etching does not affect the (Al,Ga)N epilayer, even on its N-polarity face. As depicted in Figure 2, the technique is not only simple but highly reproducible.

Preliminary µPL results on 6-µm-diameter µdisks show evidence of whispering-gallery modes (WGM) around 380 nm with quality factors up to $Q_{max} = 2000$ and a $\Delta \lambda_{exp} = 1.2$ nm mode spacing (Figure 3). Considering only the lowest-order radial mode ($n = 1$), theory expects a mode spacing of about 8 nm:

$$\Delta \lambda_{n=1} = \frac{\lambda_0}{R.n_{eff}}$$  \hspace{1cm} (1)
where $R$ is the µdisk radius, $\lambda_0$ the wavelength in vacuum and $n_{\text{eff}}$ the effective index of the µdisk slab. The discrepancy between $\Delta \lambda_{\text{exp}}$ and $\Delta \lambda_{\text{n=1}}$ indicates the propagation of higher radial modes into the µdisks, up to $n = 4$ according to calculations. In order to increase the spacing, one can either reduce the µdisk diameter according to equation (1), or increase the silicon post diameter to prevent higher radial modes to propagate. Our UV photolithography setup limiting the µdisk diameter to 4 µm, one would want to use e-beam lithography to widen the mode spacing.

**Figure 3.** 4 K µPL spectra of a 6-µm-diameter µdisk. (a) WGMs with quality factors up to 2000 superimposed onto the QD ensemble spectrum. (b) Zoom of (a) exhibiting a 1.2 nm mode spacing, which is shorter than $\Delta \lambda_{\text{n=1}} = 8 \text{ nm}$, the spacing one expects for the lowest order radial modes.

Despite promising preliminary results, the maximum quality factor value is much lower than one would expect if losses were only related to tunneling of light from the µdisk to free space. Moreover, as compared to higher dimensionality emitters, the choice of QDs as the active layer minimizes the absorption $\alpha$ and its induced losses: $Q_{\text{abs}}^{-1} = \alpha \lambda / 2\pi n_{\text{eff}}$. Thus, while quantum wells absorption prevent any mode to propagate on the high energy side of their emission band [2, 3], our QD-embedding µdisks exhibit good quality WGMs on the whole spectral range of their PL band. Therefore, the main loss mechanism is driven by light scattering, mostly at the sidewalls of the µdisk since top and bottom surfaces are very smooth. Borselli et al. [7] detailed the mechanism and showed that the losses $Q_{\text{scatt}}^{-1}$ could be estimated from the statistical parameters of the µdisk edges roughness, its correlation length $L_c$ and its standard deviation $\sigma_r$. The electric dipole of those GaN QDs is parallel to the µdisk plane so we only consider the propagation of TE modes. In that case, we can write:

$$Q_{\text{scatt}}^{-1} = \frac{4\pi^{7/2} n_d n_{\text{eff}} (n_d^2 - n_0^2)^2}{3\lambda^3 n_d (n_{\text{eff}}^2 - n_0^2)} \left( \frac{L_c h\sigma_r^2}{\pi R} \right)$$  \hspace{1cm} (2)

where $n_d$ is the refractive index of the disk material i.e. 2.4 for Al$_{0.5}$Ga$_{0.5}$N, $n_0$ is the air index and $h$ the slab thickness. $\sigma_r$ is calculated from the sidewalls profile derived from the top-view SEM image of a µdisk (Figure 2 insets). $L_c$ is obtained from the Gaussian fit of the roughness autocorrelation. According to the sidewalls roughness measurements of a 6-µm-diameter µdisk (Figure 4 (a)), $\sigma_r$ and $L_c$ are respectively estimated to 10 ± 2 nm and 70 nm. Thus, light scattering limits the quality factor to a few $10^3$ in the near UV range, in good agreement with the µPL spectra (Figure 3). The sidewalls roughness being limited by our UV photolithography setup, we then used e-beam lithography and kept the same dry and wet etching processes to fabricate µdisks with enhanced features: we could obtain µdisks with diameters as small as 500 nm and much smoother sidewalls, as seen on Figure 2 inset (b). From the estimation of the standard deviation $\sigma_r = 2 \pm 1 \text{ nm}$ and autocorrelation length $L_c = 50 \text{ nm}$ (Figure 4 (b)) of a 2-µm-diameter µdisk roughness profile, we can evaluate the quality factor related to light scattering losses $Q_{\text{scatt}}$ to be larger than $10^4$. Such a value is yet to be confirmed by µPL but already demonstrates that, despite the chemical inertness of group-III nitride materials, a very good quality etching is possible by Cl$_2$ RIE.
Figure 4. Roughness profile and roughness autocorrelation of a μdisk sidewall defined by (a) UV photolithography and (b) e-beam lithography. They are derived from SEM images of Figure 2 insets. Dashed lines are Gaussian fits to the roughness autocorrelation.

4. Conclusion

We have demonstrated the good potential of GaN QDs embedded in very thin (Al,Ga)N epilayers directly grown on silicon substrates. Despite the vicinity of the silicon substrate interface and a large defect density, GaN QDs exhibit strong PL up to RT. Taking advantage of the good etching selectivity between silicon and nitrides, those efficient emitters can be easily inserted in μdisks resonators. Preliminary μPL measurements of such resonators exhibit whispering-gallery modes with quality factors up to 2000. This value is limited by the sidewalls roughness of the μdisks obtained by UV lithography. The use of e-beam lithography enabling much smoother sidewalls, it should lead to higher quality factors. This work shows good prospects for the observation of attractive phenomena such as the Purcell effect, strong light–matter coupling, or low-threshold lasing at RT.

This work is supported by French National Research Agency (ANR) through Nanoscience and Nanotechnology Program SINPHONI ANR-08-NANO-021-01.

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