Impact of disorder on high quality factor III-V nitride microcavities

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The authors report on the micron scale characterization of a monolithic GaN microcavity (MC) with lattice matched AlInN/GaN distributed Bragg reflectors by means of a microtransmission setup. This technique allows extracting very high quality factors (Q up to 2800), in accordance with theoretical predictions, contrary to what was previously reported for nitride based MCs. Furthermore, two-dimensional mappings of the MC transmission spectrum allow probing the disorder in this MC. The direct relationship between an increased disorder and a reduction in the Q factor is clearly observed. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2420788]

During the past few years, high quality planar nitride-based microcavities (MCs) have received an increasing interest owing to their potential as light emitters but also for investigating light-matter interaction phenomena.[1] Indeed, despite the maturity of devices such as light-emitting diodes[2] and laser diodes,[3] there is still room for novel nitride-based photonic light sources such as vertical cavity surface emitting lasers (VCSELs). On the other hand, high quality MCs processed in micropillars with embedded quantum dots (QDs) could also have important application as quantum light sources.[4–6] Furthermore, the recent improvement of planar nitride MC structures allows performing strong light-matter interaction studies at room temperature.[7–9]

Although lasing action of optically pumped nitride VCSEL structures has been reported several years ago,[10] few progress have been accomplished toward the realization of an electrically pumped device.[11] However, there are still several issues to tackle before achieving this goal. Besides high p-type layer resistivity and contact resistance, the optical quality of nitride MCs remains systematically below theoretical expectations.[12,13] Indeed, despite the successful growth of high reflectivity ($R>99\%$) nitride-based distributed Bragg reflectors (DBRs),[1] nitride MCs with quality factors ($Q=\lambda/\Delta\lambda$) in accordance with these DBR reflectivities have not been reported to date.[12,13] Thus in Ref. 13, the measured Q factor ($Q\sim800$) would correspond to a cavity with $\sim94\%$ reflectivity mirrors. This value has to be compared with the calculated 97% and 96% reflectivity values for the bottom and top DBRs, respectively. The presence of crystal imperfections such as dislocations in nitride layers is known to strongly affect their structural and optical properties. As a result, the quality of such a sample is expected to fluctuate depending on these defects. In this context, probing these various properties at a small scale could give a better understanding of the disorder present in such MCs. In addition to standard structural characterization tools (e.g., atomic force microscopy, scanning and transmission electron microscopies), an optical characterization tool operating at the cavity mode scale would provide complementary information to understand the mechanisms leading to the degradation of optical properties.

In this letter, we report an in depth study of the optical properties of an empty monolithic AlInN/GaN based microcavity by means of microtransmission (μT) spectroscopy experiments. Q factors as high as 2800 are measured using this technique.

The sample, grown by metal organic vapor phase epitaxy on c-plane sapphire, consists in a $3\lambda/2$ GaN cavity centered at $\lambda=420$ nm surrounded by two nearly lattice-matched $Al_{0.80}In_{0.20}N/GaN$ DBRs, a 35 pair bottom one and a 30 pair top one. The use of AlInN lattice matched to GaN as the low refractive index material instead of Al(Ga)N prevents the formation of new dislocations and/or cracks. Detailed growth parameters regarding this structure have been reported elsewhere.[14] Single DBRs have been characterized and exhibit reflectivities close to theoretical expectations ($R\sim99\%$).[15] The μT experiments, described in Fig. 1(a), are carried out at room temperature, using the continuous spectrum of a xenon lamp as the incident light source. The light is focused on the sample using a long working distance near UV microscope objective ($\times100$) with a numerical aperture of 0.5. The transmitted light is then collected by a 400 μm core UV fiber in far field configuration, ensuring an angular selection of 0.6° ($\Delta k\sim1600$ cm^{-1}). The signal is then measured with a UV-enhanced charge-coupled device

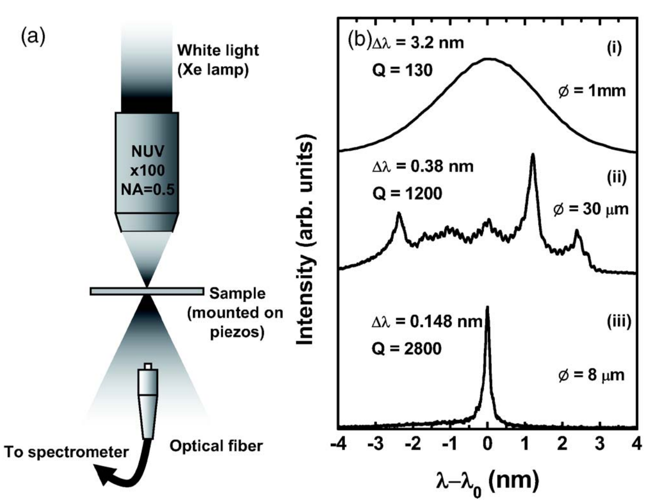

FIG. 1. (a) Experimental setup. (b) Transmission spectra acquired with different spot sizes: (i) 1 mm, (ii) 30 μm, and (iii) 8 μm. Each spectrum is plotted relative to λ_0, the cavity mode position: (i) $\lambda_0=419.9$ nm, (ii) $\lambda_0=416.1$ nm, and (iii) $\lambda_0=418.4$ nm.

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monochromator combination offering a 0.012 nm spectral resolution. The sample is mounted on a two-dimensional piezoelectric translation stage allowing up to $100\times 100\ \mu m^2$ scans to be performed. By carrying out an intensity mapping of a nanoapertured metallic mask (500 nm holes) deposited on a sapphire substrate, an 8 μm spot size was determined for this experimental setup.

When measuring transmission spectra with a commercial UV-visible spectrophotometer, a cavity mode linewidth about 3.2 nm corresponding to a Q factor of 130 is obtained [Fig. 1(b)(i)]. Considering the high reflectivity of the DBRs ($R\sim 99\%$), such a Q factor appears surprisingly low. This is further confirmed by transfer matrix simulations.[16] The initially calculated cavity mode linewidth, using the optical refractive indices from Brunner *et al.*[17] for GaN and Carlin and Ilegems[18] for the AlInN alloy, is 0.104 nm at 420 nm, which corresponds to a Q factor of 4040. The model can be refined by taking into account the residual absorption in the DBRs ($60\pm 20\ cm^{-1}$ at 420 nm).[15] The resulting cavity mode linewidth is now 0.152 ± 0.015 nm and the corresponding Q factor is 2800 ± 270. This modeling which considers a perfect planar MC with absorption cannot account for the experimentally observed spectrum.

Nitride layers usually exhibit a relatively important structural disorder compared to their III-V arsenide counterparts. Therefore an averaging process similar to that observed for standard photoluminescence spectra measured on a QD ensemble could occur.[19] In this context, the large diameter of the probed area ($\sim$1 mm) could explain the extraction of a low Q factor. This is further confirmed by measurements performed at a smaller scale. A transmission spectrum taken with a custom-made experimental setup giving a spot diameter about 30 μm is also shown in Fig. 1(b)(ii). Several peaks can be observed at this scale with a typical linewidth about one order of magnitude lower than that measured when using the spectrophotometer. The most intense peak has a width of 0.38 nm, which corresponds to a Q factor of 1200. This value is relatively high when compared to previous reports for nitride MCs.[12,13] However, it remains far below theoretical expectations. Note that the small oscillations observed in the spectrum come from interference in the sapphire substrate. When decreasing the spot size down to 8 μm, a single linewidth as small as 0.148 nm can be measured [Fig. 1(b)(iii)]. The associated Q factor exceeds slightly 2800, a value which well agrees with the theoretical one. This very high Q factor indicates that the cavity mode linewidth in this spectrum is only limited by the reflectivity and absorption values of the DBRs. In other words, in some places at a local scale ($\sim$8 μm), there are no more thickness fluctuations affecting the cavity mode and the MC can be considered as almost perfect.

Two-dimensional mappings have been obtained by recording a transmission spectrum every micrometer over $50\times 50\ \mu m^2$ areas. The MC mode wavelength has been extracted and reported in an image plot [Fig. 2(a)]. This measure gives a good indication of the in plane cavity disorder. Indeed, a variation of the MC mode position will result either from a change in the cavity layer optical thickness or from a change in the electromagnetic wave phase shift at the reflection on the Bragg mirrors due to optical thickness fluctuations of the DBR layers. Careful simulations demonstrate that for similar relative optical thickness changes, the cavity and DBR layers have both a significant contribution to cavity

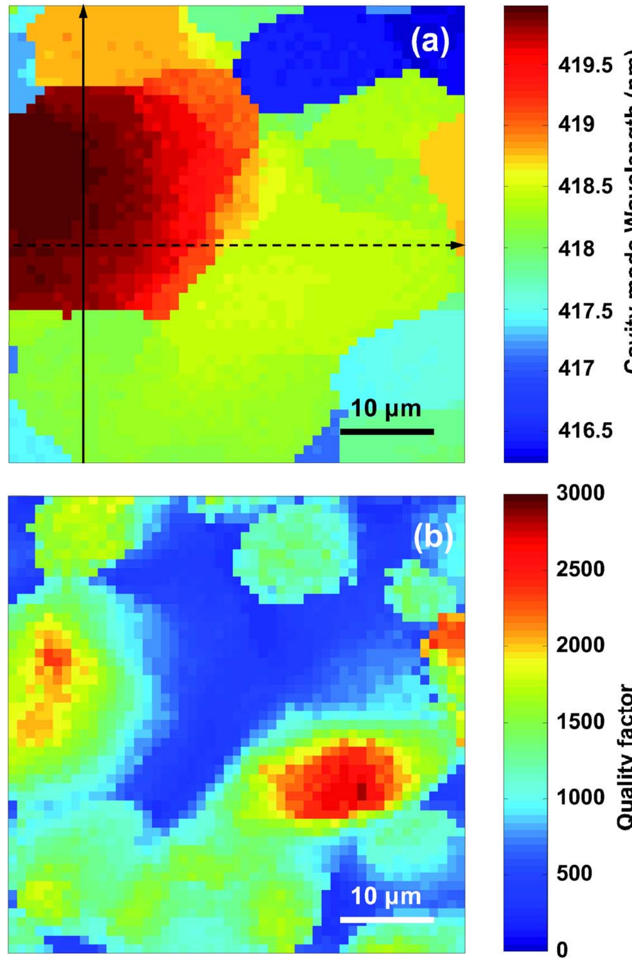

FIG. 2. (Color online) (a) $50\times 50\ \mu m^2$ mapping of the cavity mode wavelength. (b) $50\times 50\ \mu m^2$ mapping of the cavity quality factor [same area as that shown in (a)].

mode fluctuations (typically 2 nm for the cavity layer and 1.1 nm for the DBR layers). In Fig. 2(a), fairly extended homogeneous areas ($>10\times 10\ \mu m^2$) can be observed. In addition, areas exhibiting strong fluctuations in the cavity mode position are also present. These measurements demonstrate that areas with highly uniform structural properties can be found in such a MC sample. In these regions, the observation of a single high Q factor MC mode is therefore expected, whereas in disordered areas we would rather expect a broader mode or several cavity modes.

To check the influence of the cavity mode wavelength homogeneity on its linewidth, an image plot of the MC Q factor has been performed and is reported in Fig. 2(b). The good agreement between the flat extended areas seen in Fig. 2(a) and the areas with a high Q factor in Fig. 2(b) appears clearly. These high Q factor areas ($Q>1500$) correspond to relatively flat areas in the mapping of the MC mode wavelength. Furthermore, the area located in the central part of the Q factor image plot with lower Q (<1000) corresponds precisely to the area exhibiting many thickness fluctuations in the mapping of the MC wavelength. This latter result thus confirms the strong link between the cavity thickness homogeneity and the value of the Q factor.

Finally, the behavior of the cavity mode along given directions in the sample is reported in Figs. 3(a) and 3(b). Transmission spectra taken every 2 μm when moving along the continuous arrow shown in Fig. 2(a) are reported in

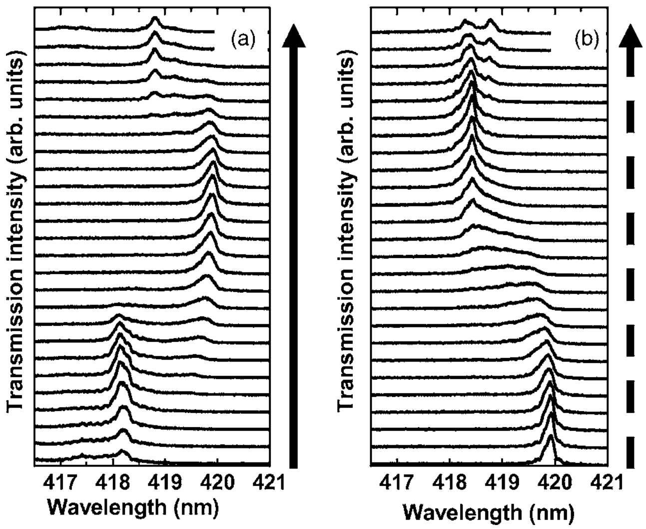

FIG. 3. Transmission spectra recorded every 2 μm (a) along the continuous arrow and (b) along the dashed arrow of Fig. 2(a).

Fig. 3(a). In this case, spectra are issued from homogeneous areas. This is clearly observed when looking at the spectra: narrow linewidth modes observed along distances longer than 10 μm shift suddenly by a change in wavelength $\delta\lambda$ much larger than their linewidth ($\delta\lambda > 1$ nm). These results indicate that along this linescan the homogeneous areas are separated by fluctuations occurring on a short distance scale. Such a transition is so abrupt that the cavity mode is not sensitive to it. Indeed, the mode wavelength jumps directly from one value to the other. Note that when there is a change in the cavity mode position, two modes are observed on a short distance. This is due to the spot size, which is then large enough to probe two modes simultaneously. In Fig. 3(b), the spectra are taken along the dashed arrow shown in Fig. 2(a). This linescan passes through an extended disordered area. In this case, narrow linewidth modes are still observed in extended homogeneous areas, but due to the disordered area, the transition occurs over a much longer distance (>10 μm). We can notice that the cavity mode is highly sensitive to these fluctuations as it is dramatically broadened.

These results show that this type of MCs exhibits regions suitable for the demonstration of a VCSEL. Indeed, areas with a high Q factor are large enough with respect to a typical mesa size (~ 10 μm). Understanding the precise origin of the roughness should help the development of realistic processes for the production of short wavelength VCSELs. Thus the impact of dislocations could be explored using other types of substrates such as low dislocation freestanding GaN templates.

In summary we have shown that the measurements usually performed on nitride-based MCs to determine their Q factor do not reproduce the calculated homogeneous linewidth of the cavity mode. Local transmission measurements using a spot size of about 8 μm allowed the extraction of a narrow cavity mode linewidth, and consequently a high Q factor ($\sim$2800), close to theoretical values. μT mappings have given valuable information on the cavity layer structure and have emphasized the close relations existing between structural and optical properties. Extended areas ($>10\times 10$ μm^2) exhibiting a homogeneous cavity mode wavelength together with a high Q factor are also observed. All these results reveal to be highly informative in view of realizing nitride-based VCSELs or for fundamental studies where cavity disorder is expected to play a key role.

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