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# Resonant modes in monolithic nitride pillar microcavities

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**Abstract.** GaN-based airpost pillar microcavities are realized by focused-ion beam etching starting from an all-epitaxially grown vertical-cavity surface-emitting laser structure. Pillar diameters below 1 $\mu$m are well controllable. The sidewalls are smooth and show a damaged surface layer of a thickness less than 2 nm only. Micro-photoluminescence measurements reveal the longitudinal and transversal mode spectra of the cavities in good agreement with theoretical calculations based on a vectorial transfer-matrix method.

**PACS.** 42.55.Sa Microcavity and microdisk lasers – 78.55.Cr III-V semiconductors – 42.55.Px Semiconductor lasers; laser diodes

Semiconductor microcavities (MCs) which possess a discrete set of three-dimensionally confined optical modes are in the focus of intense research [1] driven by current and future applications such as vertical-cavity surface-emitting lasers (VCSELs) or single-photon emitters. In contrast to the well developed (Al, In, Ga)As system there are only few reports in the literature concerning the realization of high-quality and small-mode-volume cavities for the important nitride system emitting in the blue-green spectral region [2–6]. This is on the one hand due to the difficulties arising from the lattice mismatch in the Al(Ga)N/GaN system which for a long time hampered the epitaxial growth of high-quality distributed-Bragg reflectors (DBRs). AlN/GaN DBR mirrors with $R \geq 99\%$ have been reported [7,8]. Results like optically pumped lasing [9,10] and normal mode coupling with InGaN quantum wells (QWs) at room temperature [11] have been achieved using, however, at least one dielectric mirror to form a complete microcavity (MC). Recently, monolithic fully-epitaxial VCSEL structures with quality factors approaching their hybrid counterparts have been reported [12,13]. On the other hand, GaN-based structures considerably suffer from a limited applicability or even failure of methods like (selective) wet or reactive ion etching to prepare small structures with large aspect ratios. In the last years, a photoelectrochemical etching process has been developed which can be applied to slab-like structures like microdisk-resonators [5] or photonic crystal defect cavities.

In the following, we report on the successful fabrication of completely etched airpost pillar microcavities (MCs) by focused-ion beam (FIB) application starting from a monolithic nitride VCSEL structure.

## 1 Experimental details

The VCSEL structures were grown by plasma-assisted molecular-beam epitaxy at a growth temperature of 620 °C on GaN/sapphire template layers provided by metal-organic vapour-phase epitaxy. They consist of a 20.5 periods bottom distributed Bragg reflector (DBR), a $\lambda$ cavity containing three InGaN quantum wells (QWs) at the antinode position of the optical field, and an 18 periods top DBR. The high-refractive-index material of the DBRs is formed by 42 nm thick GaN layers, the low-index material by superlattices (SLs) made of 19.5 periods AlN/In$_{0.25}$Ga$_{0.75}$N layers of 1.6 nm and 0.75 nm thickness, respectively. For details see [13,14].

Cylindrically shaped pillar MCs with various diameters were prepared from the planar samples by FIB etching using an FEI NOVA NanoLab dual-beam system. A transparent aluminum oxide layer (100 nm) was evaporated on the sample for surface protection. 30 keV Ga ions with beam currents between 50 pA and 5 nA have been applied to completely remove the material around the structures so that within a radius of 10 $\mu$m around each pillar just the GaN/sapphire template was left. Transmission electron microscopy (TEM) investigations of the FIB prepared structures were carried out using a CM20 UT TEM.

A micro-photoluminescence ($\mu$-PL) set-up has been used to study the emission from the planar VCSEL structure and from individual pillar MCs at a temperature of 4 K. The InGaN QWs in the active region were excited using a continuous-wave argon-ion laser with an excitation density of about 1 kW/cm$^2$ at a wavelength of 363.8 nm providing a photon energy well above the high-energy edge of the stop band of the planar cavity and slightly below the GaN band gap. The laser was focused on the sample via a microscope objective (NA = 0.5) giving a spot diameter of about 1.5 $\mu$m which allows to subsequently excite

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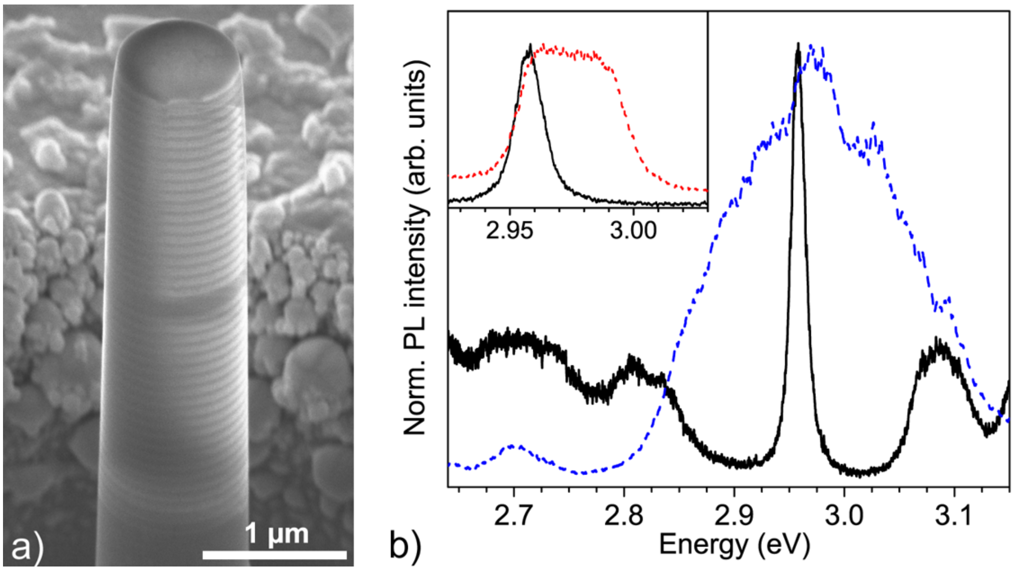

**Fig. 1.** (Color online) (a) SEM picture of a VCSEL pillar structure with a diameter of $1.0\,\mu$m. (b) PL spectra of the planar VCSEL structure (solid line) and of a reference sample without top mirror (dashed line). The inset shows the cavity resonance of the VCSEL measured with (solid line) and without (dashed line) the pinhole in the detection path.

individual pillars. The PL emission was collected by the same microscope objective within an angle of maximal 30° (in vacuum) relative to the cavity normal which could be limited to a smaller angle span via a pinhole in the detection path. The spectrally resolved signal was detected by a liquid-nitrogen cooled CCD camera.

## 2 Results and discussion

Figure 1a shows a scanning electron microscope (SEM) image of a VCSEL pillar with a diameter of 1 $\mu$m. The Bragg pairs of the top and the bottom DBR and the cavity are clearly visible. The sidewalls of the pillars are smooth, and the structures show a negligible conicity. To exclude substantial ion damage of the pillar surfaces due to lateral straggling and to a finite ion-beam diameter we performed TEM investigations of small-diameter pillars prepared by FIB out of a reference DBR sample. Figure 2a displays a bright-field TEM image of such a structure demonstrating also the impressive aspect ratios achievable for freestanding structures. The base diameter of the pillar was about 100 nm whereas at the top the diameter amounted to about 60 nm which is sufficiently thin to perform high resolution TEM (HRTEM) analysis. In HRTEM image of the sidewall near the pillar top shown in Figure 2b, undistorted lattice fringes are clearly visible together with an amorphous surface layer of 1 to 2 nm thickness only (marked by arrows). Thus, the microstructure of the pillars does not show a severe lateral damage caused by the FIB. However, to reduce the Ga ion dose during FIB processing and to minimize FIB processing time samples prestructured by chemical assisted ion-beam etching can be used which are then fine-polished by the FIB.

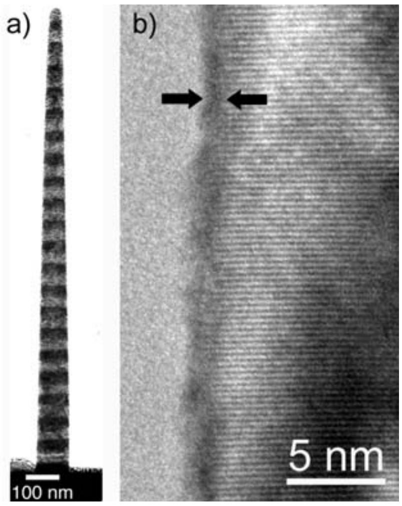

**Fig. 2.** (a) TEM image of a DBR pillar fabricated by FIB. (b) High resolution TEM image of the pillar sidewall taken near the top along the [01$\bar{1}$0] zone axis.

The spontaneous emission spectrum of the complete VCSEL structure at 4 K together with the PL spectrum of a reference sample without top mirror is depicted in Figure 1b. The latter sample consists of three InGaN QWs embedded in a GaN $\lambda$ cavity on top of a 30-fold bottom DBR and shows a broad PL band peaked at about 2.98 eV. Since the active region was grown on top of the bottom DBR which shows a significantly higher surface roughness compared to a typical GaN layer the InGaN QWs might have increased In fluctuations which leads to an FWHM of approximately 170 meV of the PL emission band of the active region. In contrast to this, the PL emission of the VCSEL exhibits a stop-band signature and a pronounced cavity resonance at 2.96 eV with an FWHM of 12 meV corresponding to a quality factor of $Q = E/\Delta E = 250$. The inset in Figure 1b shows the spectral region of the cavity resonance measured near normal incidence (pinhole closed, solid line) and by collecting within the full detection cone (pinhole open, dashed line) of the set-up. In the latter case, not only the fundamental longitudinal resonance of the cavity but also contributions at higher energy are detected. They are attributed to a continuum of modes having a non-zero in-plane momentum component thus leading to a ring-like far-field emission maximum in a tilted direction relative to the cavity normal. This behavior clearly proves the nature of the detected far-field signal as being due to the spontaneous emission from the QWs redistributed by the modes of the planar MC.

In contrast to this, for the pillar structures a set of discrete resonant modes is expected to show up in the PL spectra due to the three-dimensional optical confinement in the pillars by additional index guiding in the direction along the pillar axis [1]. PL spectra of pillars with diameters between 2.1 $\mu$m and 800 nm are shown in Figure 3 (solid lines). Compared with the flat continuum of modes observed for the planar structure (dashed line in the inset of Fig. 1b) the pillar spectra indeed reflect clear modulations becoming more pronounced for smaller pillar diameters. To clarify the observations, we calculated the transmission spectrum, i.e., the resonant modes of the three-dimensional pillars by a vectorial transfer-matrix method which consists of an expansion of modes in each layer into eigenmodes of a cylindrical optical waveguide and a matching of the electromagnetic fields at the interfaces (for details see [15]). The SL was approximated by an $Al_{0.4}Ga_{0.6}N$ layer of the same thickness and dispersion, and the pillar diameter was measured independently by SEM. The dashed lines in Figure 3 show the calculated mode spectra. The spectral position of the individual modes is indicated by arrows. The calculation yields a $Q$ factor of about 500 for the empty cavity which corresponds to an FWHM of the resonances accounting to 6 meV. The spectral positions of the calculated resonances correspond very well to the measured spectra which confirms the nature of the observed resonances as the different lowest-lying transverse modes of the pillars. For decreasing diameters $d$, a shift of the fundamental mode to higher energies (roughly proportional to $d^{-2}$) and an increase of the mode splitting can be noticed resulting from the stronger confinement of light in the smaller pillars. For the fundamental mode of the 1 $\mu$m pillar at 2.965 eV, an FWHM of 12.5 meV and, thus, a $Q$ factor of 240 can be determined which is comparable to the value measured for the planar structure. For the 800 nm pillar, a slight decrease of $Q$ can be noticed.

A more detailed analysis of the mode spectra is hampered by the huge width of the PL emission band of the QWs which prohibits a partial or complete detuning between the cavity modes and the emission of the active region, e.g., by varying the temperature. Therefore, the mode spectra of the pillars are superimposed to a PL background which is directly emitted through the sidewalls of the pillar structures and whose flat component has been subtracted in the spectra in Figure 3.

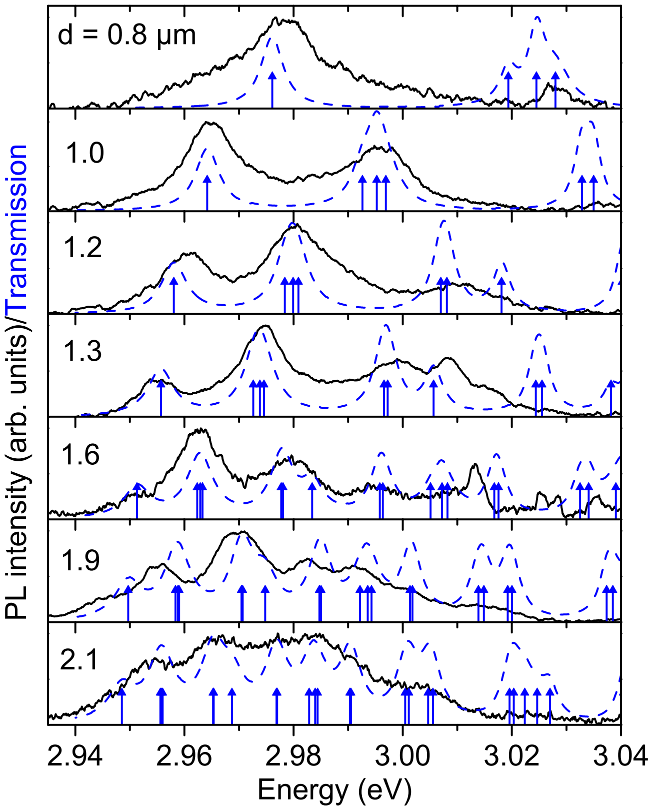

**Fig. 3.** (Color online) PL spectra of pillars with the indicated diameters (solid lines) and the calculated transmission spectra (dashed lines). Arrows mark the calculated spectral position of the individual modes.

## 3 Conclusion

Nitride based pillar microcavities were successfully realized by focused-ion beam etching starting from a monolithicly grown VCSEL structure for the blue to violet spectral region. Pillar diameters below 1 $\mu$m are well controllable, the sidewalls are smooth and show a damaged surface layer of a thickness below 2 nm only. The three-dimensional optical confinement of the structures was proven by the observation of their transversal mode structure in photoluminescence spectra in good agreement with theory. We point out again that to our knowledge for the nitride system no other method than FIB is capable to produce structures of the demonstrated quality and aspect ratios.

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