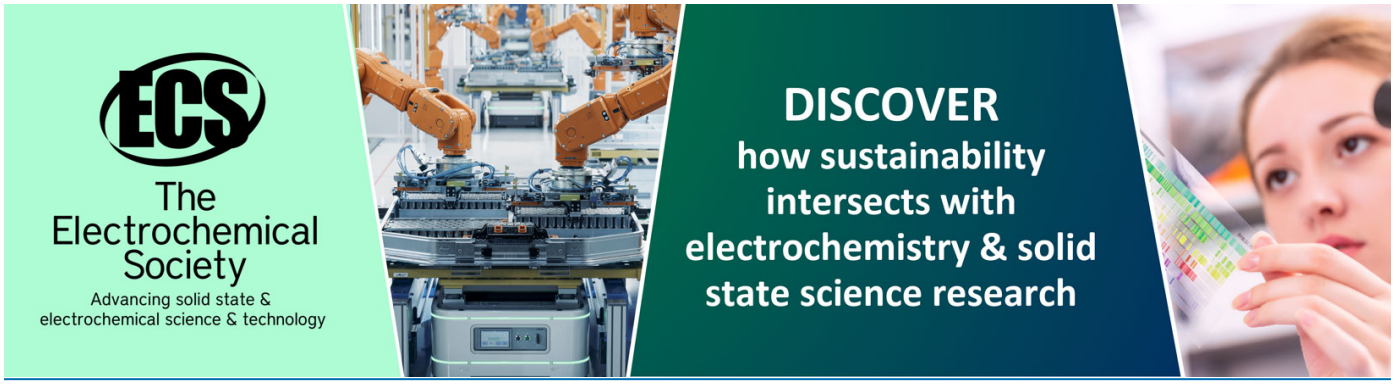
# Mode adjustment in hexagonal microresonators with an active region





# Mode adjustment in hexagonal microresonators with an active region

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**Abstract.** We present original types of III-nitride monocrystal microresonators with an inserted active quantum-sized region. Modelling of microresonator's modes allows us to select right parameters of a polarized quantum well (width, composition) in the way that excitation of its optical transitions would be selectively amplified by interaction with the resonator modes. Adjustment of a GaN nanocolumn resonator to an InGaN quantum well is performed.

## 1. Introduction

Tunable microresonators, which can be fabricated by molecular-beam epitaxy (MBE) in a single-growth-run process, attract attention as promising elements for nanophotonics [1]. Especially an active region can be inserted inside of them immediately during growth without any additional cleanroom processing. Such active structures allow to amplify radiation of active layers selectively using the Purcell effect [2]. These structures can be used as a source of quantum or coherent light [3]. In this paper, we demonstrate III-nitride microresonators with inserted InGaN quantum wells (QWs), which can exhibit bright photoluminescence [4], and show how to adjust the resonator modes energy to the transition energy of such active region.

## 2. Samples and characterization

In our experiments GaN nanocolumns were grown on cone-shaped patterned c-sapphire substrates by plasma-assisted (PA) MBE. The PAMBE process has been developed to control the monocrystals shape [5]. The variation of substrate temperature, flux ratios $F_{Ga,In}/F_N$, and polarity, N or Ga(In), can change its shape from nanocolumn with cups on the top to tapered nanocolumns (Figure.1). The fabrication process includes the consecutive growth of GaN nucleation layer (Ga flux 5.6 nm/min) with flux ratio $F_{III}/F_N$=0.86 at $T_s$=760ºC. Then the temperature of Ga source was decreased to maintain flux ratio $F_{III}/F_N$=0.2 (Ga flux 1.32 nm/min) to grow GaN nanocolumns while keeping always constant the active N flux and the growth temperature at 760ºC. InGaN QWs of varying thicknesses of 3-10 nm were grown at the substrate temperature $T_s$=600ºC and flux ratio $F_{III}/F_N$=0.22. High-spatial-resolution technique such as micro-photoluminescence (μPL) is widely used to determine experimentally the spectral characteristics of GaN nanocolumn and InGaN active layer inside of it. The μPL measurements were done with cw excitation by a 325nm laser line at room temperature. We exploited the objective Mitutoyo 40x NUV and liquid nitrogen-cooled charge-coupled detector (CCD). The beam impinging normally to the surface was focused by the objective into a spot with FWHM of 1 μm that is enough to measure separately the monocrystals. The same objective collected the PL signal from sample surface.

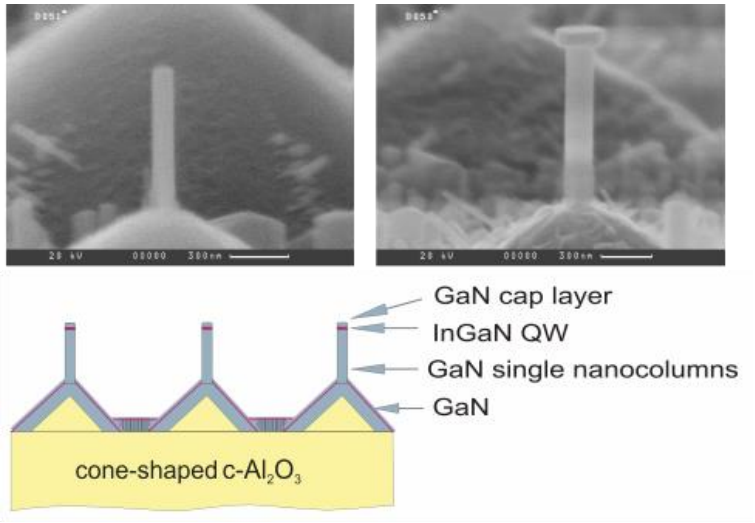


**Figure 1.** Different shapes of GaN nanocolumns grown by PA MBE (top) and design of GaN nanocolumn (bottom).

### 3. Modelling of InGaN quantum well in GaN barriers

Optical transitions of InGaN QWs depend not only on the band gap values, but also on the large internal electric fields arising due to piezoelectric and spontaneous polarizations. The former depends on the lattice mismatch between the InGaN well and the GaN barriers, whereas the latter one is a material constant due to dipole moment of ions of wurtzite crystal [5]. Figure 2 shows an example of the band profile and electron and hole ground state energies in $In_{0.1}Ga_{0.9}N$/GaN QW of 3 nm in width.

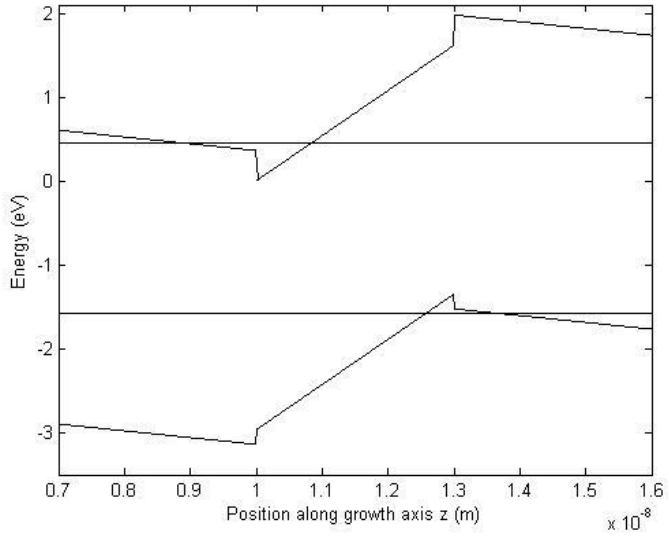


**Figure 2**. Example of band profile, electron and hole ground state energies in an $In_{0.1}Ga_{0.9}N$/GaN with a well width of 3 nm.

In this paper, optical transition energy is calculated using an effective-mass approximation. The single-particle ground-state electron and hole energies were found numerically by solving Harrison's finite difference version of the one-dimensional Schrödinger equation that reads as

$$\frac{\psi(z+h)}{m^*(z+h/2)} \simeq \left\{ \frac{2h^2}{\hbar^2}[V(z)-E] + \frac{1}{m^*\left(z+h/2\right)} + \frac{1}{m^*\left(z-h/2\right)} \right\} \psi(z) - \frac{\psi(z-h)}{m^*\left(z-h/2\right)},$$

where $\psi$ is the wave function, $m^*$ is the effective mass, $z$ is the distance in the growth direction, $V$ is the band potential, and $E$ is the energy. The results of calculations are presented in Figure. 3 for two different temperatures of 300 K and 77 K as dependence on the In content in the $In_xGa_{1-x}N$ QW.

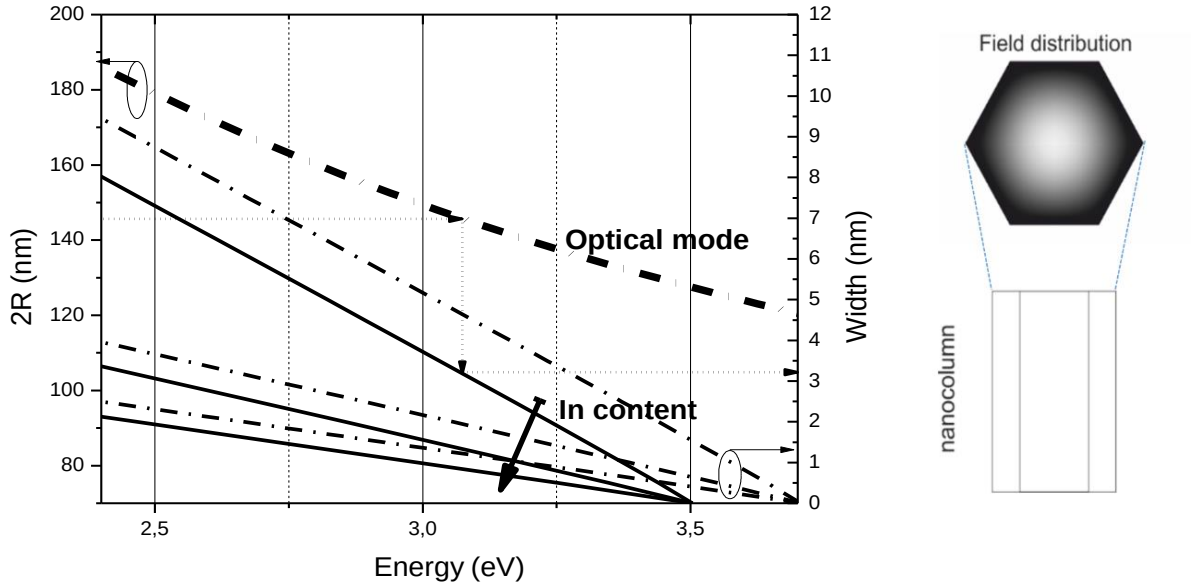


**Figure 3**. (left) Ground state transition energies in an $In_xGa_{1-x}N/GaN$ QW as a function of a well width for various In content (x equals to 0.1, 0.2 and 0.3) at temperatures of 300 K (solid lines) and 77 K (dot-dashed lines). The mode energy of the first order is shown as a function of nanocolumn diameter 2R (bold dot-dashed line). Fine dashed lines with arrows show how to choose the diameter of nanocolumn and the width of QW to fit the energy of optical mode to the energy of optical transition. (right) Typical field distribution of the low order optical mode in a nanocolumn (shown from its top).

In Figure. 3, there is an example of how we can adjust the InGaN QW to GaN nanocolumn mode of the first order, while keeping the diameter of nanocolumn. We should consider its mode energy and then adjust QW emission to be in resonance with a microresonator mode by varying its width and In content. The energies of optical transitions in the InGaN/GaN QWs are calculated taking into account internal electric fields. The nanocolumn optical modes energy depends only on the geometry of resonator and its refractive index. Regarding to all the aforesaid we are able to resonantly adjust the transitions in the active layer with the microresonator mode. This approach can be used to analyse emission spectra.

## 4. Experimental results

The InGaN QW layer is not homogeneous because it is grown in three possible places: inside GaN nanocolumn, on an unperturbed layer and on cone-shaped patterned substrate. Therefore, to prove that the Purcell effect in resonator and respective amplification exist, we perform μPL measurements. In Figure. 4, we present μPL spectra of 150-nmwide GaN nanocolumns with the 8-nm InGaN QW inside. Measurements were done in two different points between nanocolumns and on a nanocolumn. The spectra measured at different excitation power densities are normalized to the intensity of GaN emission to control the relative enhancement of InGaN QW emission from its different parts. The analysis shows that the enhancement really exists with increasing laser power density from 1.1 kW/cm$^2$ to 11 kW/cm$^2$ on the nanocolumns (3.1 eV energy), while between them the increase of signal intensity has not been detected (Figure. 4).

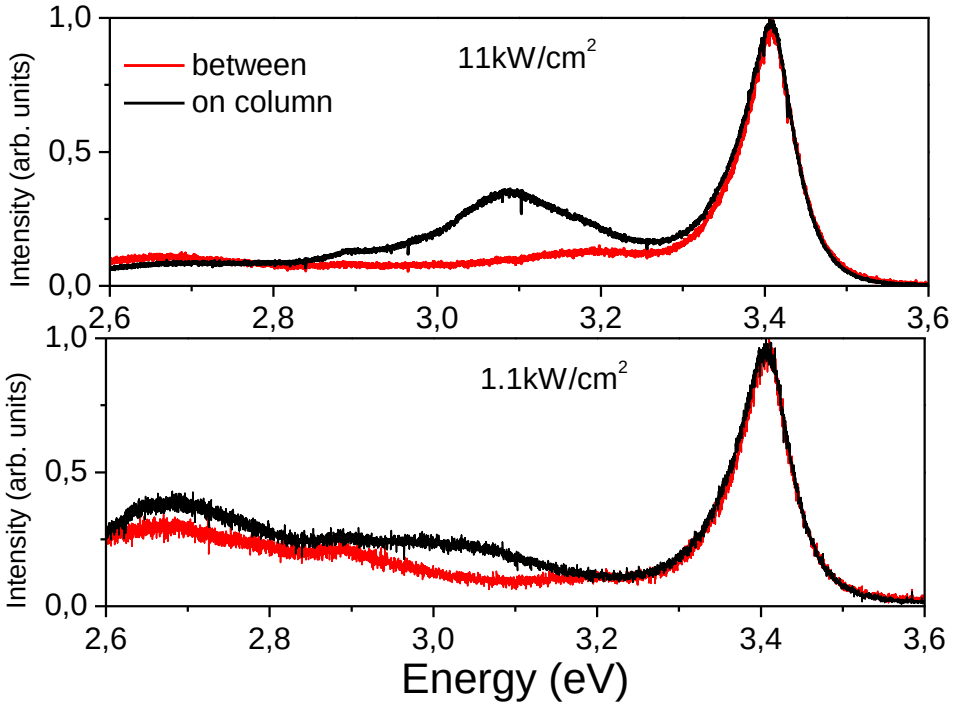


**Figure 4.** Room temperature μPL spectra of a measured nanocolumn (black solid line) and signal between nanocolumns (red solid line) with varying laser power.

## 5. Summary

We have presented monocrystal GaN nanocolumns on cone-shaped patterned c-sapphire substrates grown by PA MBE. These nanocolumn cavities contain InGaN QW inside. We have shown that it is possible to adjust the quantum level energies in the QW to optical mode in nanocolumn by solving one-dimensional Schrödinger equation and calculating numerically optical mode energy of nanocolumn. Analyzing the μPL spectra in different points of our structures, we have proved approaching the enhancement of QW emission. Therefore, this method could be used to make precise adjustment of the resonances of different types in microcavities with QW active regions.

## Acknowledgments

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