Ring resonator optical modes in InGaN/GaN structures grown on micro-cone-patterned sapphire substrates

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Abstract. Molecular beam epitaxy (MBE) of III-nitride compounds on specially prepared cone-shaped patterned substrates is being actively developed nowadays, especially for nanophotonic applications. This type of substrates enables the successful growth of hexagonal nanorods (NRs). The insertion of an active quantum-sized region of InGaN inside a GaN NR allows us to enhance the rate of optical transitions by coupling them with resonant optical modes in the NR. However, we have observed the enhancement of emission not only from the NR but also around the circumference region of the cone-shaped base. We have studied this specific feature and demonstrated its impact on the output signal.

1. Introduction
Microresonators are frequently used for amplification of the radiative transitions inside of them. The coupling of optical transitions with resonator modes results in a significant enhancement of emission. This effect is proportional to the Purcell factor $F_P$ which mainly depends on the quality ($Q$) factor, the transition energy, and the volume of the mode [1]. Therefore, the creation

\begin{figure}[h]
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\includegraphics[width=\textwidth]{figure1.png}
\caption{Side view sketch of the cone with a formed ring-like microresonator in the dip of its circumference (left); SEM image illustrating the top view of a cone with the ring-like resonator situated in the darkest region (red lines are shown here for clarity) (right).}
\end{figure}
of the high quality structures is one of the ways to obtain a larger $Q$. This can be achieved by using the MBE growth technology. Recently, we have demonstrated that there is an approach to fabricate InN and GaN single-crystal microresonators on patterned cone-shaped substrates [2, 3]. This approach also makes it possible to obtain standardized NR microresonators with a quantum-sized active region inside [4]. However, the special form of a substrate causes the simultaneous appearance of another type of microresonator - the ring one. In this paper, we show how an InGaN/GaN quantum well (QW) fabricated on a cone-shaped substrate couples with a ring microresonator and how it influences the output radiation in this area. We also observed cathodoluminescence of the ring microresonator, which confirms the enhancement of the optical transitions particularly in the circumference of the cones.

![Figure 2](image.png)

**Figure 2.** $\mu$-CL from the surface near the circumference of the cone (blue line) and far (black line) from it; the inset shows a SEM image illustrating inhomogeneous surface growth on and around the cone.

2. MBE growth and experimental characterization

Here, we present the formation of ring-like resonators in a single growing process of GaN NRs on a cone-shaped patterned c-sapphire substrate with regularly located cones with a diameter and a height of 3.2 and 1.7 $\mu$m, respectively. The structures were grown by using a two-stage process. In the first stage, a nucleation layer of GaN was grown by migration enhanced epitaxy. In the second stage, strongly N-rich conditions were used to stimulate the growth of NRs. Finally, a 3-nm-thick InGaN/GaN single QW was formed by standard plasma-assisted MBE at a reduced growth temperature. The details of the MBE growth details demonstrating the successful formation of the NRs on the cone tops are described in [5]. An interesting feature we observed by using scanning electron microscopy (SEM) and micro-cathodoluminescence ($\mu$-CL) in the circumference region around the cones was a slight dip next to them (figure 1, right part). It is the hole visible in the darkest region in a SEM top view image of a single cone and highlighted here by two red circles for clarity. The existence of such a hole makes it possible for
the formation of the ring-like microresonators to form. The scheme of a side view of the cone where a ring is formed in a dip is shown in figure 1 (left part).

It is clear that an InGaN QW is located in different parts of the sample: inside GaN NRs, on the circumference of the cones and on the conventional 3D unperturbed layer between the cones. The formation of the microresonator would reveal itself by the enhancement of the output signal in the near-cone area. Therefore, we have performed the \( \mu \)-CL experiments to validate that. Figure 2 shows two different CL spectra for two different spots: on the circumference (blue line) and far from it (black line). As we see, the CL intensity is much higher for the near-cone region. It is presumably due to the coupling of the QW emission to the mode of a ring-like resonator.

3. Theoretical modelling

In order to understand the \( \mu \)-CL signal enhancement, we have calculated eigenfrequencies of the formed 3 nm QW in GaN/InGaN for electrons and heavy holes. We have used the effective-mass approximation taking into account a large internal electric field, which is a common thing for piezoelectric materials such as III-nitride with \( C_{6v} \) point group symmetry. Moreover, both GaN and InGaN materials are known for their internal spontaneous polarization [6]. The left part of figure 3 shows the scheme of a band profile for electrons and heavy holes (hh). The horizontal lines show the confined energies for both electrons and hh in In\(_{0.2}\)Ga\(_{0.8}\)N QW of 3 nm width. Radiative optical transitions are reduced due to the spatial separation. However, narrow QWs allow to have long tails of wave functions inside the barriers and, hence, a higher probability of optical transitions. The calculated wavelength of such an optical transition is at \( \lambda_{opt} = 525 \) nm which is in close agreement with the maximum peak intensity of the measured \( \mu \)-CL spectra.

To model the real ring-like resonator and its eigenmodes on frequencies close to optical transitions, we have taken the real size and shape of a ring microresonator, assuming \( r_1 = 1.65 \) \( \mu \)m and external one \( r_2 = 1.8 \) \( \mu \)m for the internal and external radii, respectively, and solved the Maxwell’s equations using the perfectly-matched-layer approximation [7] at the boundaries. Such an approach is useful for modelling the electric field which can leak into nearby layers depending on the imaginary part of the refractive index. Figure 3 demonstrates the modulus of the electric field distribution in the ring-like resonator at a wavelength of 523 nm, which corresponds to the eigenmode of such a system. It turns out that this mode is a whispering gallery mode (WGM) with the mode order \( m \sim 50 \). A simple approximation shows that the
wavelengths inside the ring should satisfy the expression $\lambda \sim \pi n (r_1 + r_2)/m$, where $n \sim 2.5$ is the refractive index. This estimation shows reasonable consistency between the experiment and modelling. The WGMs are known for their high quality factor and coupling with light [8]. Considering the imaginary part of the refractive index, we find the quality factor of $Q \sim 200$. Consequently, the coupling of the existing WGM in a ring-like resonator with a QW mode explains more intensive $\mu$-CL on the circumference of the cones in contrast to a weaker intensity of the unperturbed layer emission far from the cone.

4. Summary
In this paper, we have discovered a specific feature of the MBE growth on the cone-shaped substrates. The unique ring-like resonators were self-formed on the c-substrates, supporting high-order optical modes. To prove that, we have calculated the optical transitions in QWs of InGaN/GaN taking into account the internal electric fields, and we have also simulated the eigenmodes of the ring-like microresonators. It turns out that the modes that are close to the optical transitions frequencies were WGMs of a high order. They cause the enhancement of emission. $\mu$-CL experiments showed significant enhancement of the signal in the near-cone region, which proves the formation of the ring-like microresonators. Two microresonators fabricated simultaneously in a single growth process (the nanorod resonator and the ring one that are in close proximity to each other) is a unique feature that may be used for different applications, e.g., as an alternative way of indirect pumping by the energy transfer from one microresonator to another.

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