In this work, we demonstrate ultra-low-threshold, optically pumped, room-temperature lasing in GaN microdisk and micro-ring cavities containing InGaN quantum dots and fragmented quantum wells, with the lowest measured threshold at a record low of 6.2 μJ/cm². When pump volume decreases, we observe a systematic decrease in the lasing threshold of micro-rings. The photon loss rate, γ, increases with increasing inner ring diameter, leading to a systematic decrease in the post-threshold slope efficiency, while the quality factor of the lasing mode remains largely unchanged. A careful analysis using finite-difference time-domain simulations attributes the increased γ to the loss of photons from lower-quality higher-order modes during amplified spontaneous emission.

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Fig. 1. (a) AFM images of uncapped InGaN epilayers on GaN. The bright spots are indium droplets that form InGaN QDs during growth of the GaN capping layer. The lighter gray area shows a network of interlinking InGaN strips, also known as QWIs, and the darker regions are bare GaN. (b) Schematic showing the active layer composition. (c) Top and side view SEM images of a microdisk and (d) a micro-ring of inner diameters \( d_i = 500 \) nm.

![Fig. 1](image)

Conductive layer to prevent charging during the subsequent e-beam lithography. Approximately 500 nm of FOX-16 negative electron-beam (e-beam) resist is then spun evenly onto the sample. We use e-beam lithography to pattern the FOX-16 into 1 μm diameter microdisks, as well as micro-rings with 1 μm outer diameter and inner diameters of \( d_i = 200 \) nm, 400 nm, and 500 nm, respectively. These structures serve as the hard masks during inductively coupled plasma etching, which operates at 500 W in a nitrogen/chlorine environment with a flow rate of 25/25 sccm. Once the pattern has been transferred into the GaN material, we evaporate a Ti/Pt metal grid onto our sample which serves as the cathode during photoelectrochemical (PEC) etching, a bandgap-selective process that selectively etches the sacrificial superlattice into a post, creating an air gap and thus providing optical isolation between the suspended microstructure and the substrate beneath. Figures 1(c) and 1(d) show some representative SEM images of the completed microdisk and micro-rings.

The devices are optically pumped using a frequency doubled, pulsed, titanium-sapphire laser emitting at 380 nm with a 76 MHz repetition rate and 200 ps pulse duration through a high (0.90) numerical aperture objective. The measurements are taken at room temperature, and the emitted light is collected through the same objective into a spectrometer. \( Q \) values of lasing modes are calculated using \( \lambda / \Delta \lambda \) where \( \lambda \) is the emission wavelength and \( \Delta \lambda \) is the full width half maximum at \( \lambda \). The typical \( Q \) values for these devices range between 2,000 and 3,000.

In Fig. 2, we plot the light-in-light-out (I-O) curves of selected microdisk and micro-rings from each geometry group. By performing linear fits on the lasing curves, we identify lasing threshold as the pump power at which the fitted line intersects the x-axis. In calculating the values of threshold power, we take into consideration the fraction of excitation beam that is intercepted by the devices, the reflection at air-GaN interfaces, the material absorption coefficient, as well as the thickness of the gain layers, similar to the calculation methods used in [11]. There are two clear correlations in laser performance with the geometry of the micro-cavity: (a) a decrease in lasing threshold as the central volume is removed and (b) a concomitant decrease in post-threshold slope efficiency.

As observed from the four devices in Fig. 2, when more of the central volume is removed the lasing threshold decreases from 12 μJ/cm² in the microdisk \( (d_i = 0 \) nm) to 9.9 μJ/cm² in a micro-ring with \( d_i = 200 \) nm, 8.2 μJ/cm² in a micro-ring with \( d_i = 400 \) nm, and 6.2 μJ/cm² in a micro-ring with \( d_i = 500 \) nm. The inset to Fig. 2 shows the consistency in decreased threshold with the removal of the central volume for a set of eight devices. The mean threshold of each micro-ring-geometry, averaged over eight data points, is marked off on the plot with a cross. Thus, the removal of the central region, where the active layer material does not spatially overlap with the WGMs, indeed results in a lowering of the lasing thresholds.

Representative power-dependent emission spectra of a microdisk and a micro-ring \( (d_i = 500 \) nm), as shown in Figs. 3(a) (microdisk) and 3(b) (micro-ring), can provide us with additional insights into the lasing mechanisms. For both structures, the spectra at low pump power reveal two dominant high-\( Q \)

![Fig. 2](image)

![Fig. 3](image)
WGMs that overlap with the emission region of our heterogeneous InGaN gain material. The shorter wavelength mode of \( \sim 440 \text{ nm} \) is attributed to emission from QDs and the longer wavelength mode of \( \sim 460 \text{ nm} \) is attributed to emission from the fQWs [1,12,13]. In both the microdisk and the micro-ring, the highest intensity mode at low pump power is at the longer wavelength, although lasing ultimately occurs at the shorter, QD wavelength.

As discussed in previous work, the blue shift in wavelength with increased power is consistent with differing carrier capture efficiencies and hence photon emission of the QDs and fQWs in our material. At low pump powers, there is a much higher probability of carrier capture into the fQWs because of the larger areal coverage of the fQWs. The percentage of fQW is high due to the higher probability of carrier capture into the fQWs because of capture efficiencies and hence photon emission of the QDs with increased power. The intensity of both WGMs is dramatically reduced and the fQWs are the dominant modes at wavelengths that do not overlap with the cavity. Higher values of \( \lambda \) result in lower slope efficiencies. If, indeed, there is an increase in \( \gamma \), or loss of photons associated with the micro-ring geometry, we expect to observe some degradation of the Q of the modes of the device, whereas the mode widths shown in Fig. 3 (related to \( \gamma \) values) show no degradation. In addition, one would imagine that greater photon loss would result in increased lasing thresholds.

To determine values of \( \gamma \) that correspond to our devices, we fit our lasing data to the characteristic “S-shape” curves of input versus output to more clearly delineate regions of sub-threshold operation, amplified spontaneous emission (ASE), and lasing. \( \gamma \) was used as the fitting parameter. The value of spontaneous emission lifetime of QDs used in our calculation is 1.9 ns, within the range of QD lifetimes from our experimental measurements, and the transparency carrier concentration is \( 1 \times 10^{26} \text{ m}^{-3} \) and \( 1.1 \times 10^{26} \text{ m}^{-3} \). Figure 5 shows an example of such a fit on a microdisk with a \( R^2 \) value of 0.97. All our fits have \( R^2 \) values ranging between 0.95 and 0.97, showing an excellent fit to the empirical data. The results are shown in Table 1, which indeed shows an increase in cavity decay rate, \( \gamma \), with increased removal of the center volume. Table 1 also shows a correlation of cavity geometry with details of the fitted ASE region. As more material is removed from the center, the total contribution of ASE is reduced, likely reflecting the loss of “incoherent photons” from the cavity. ASE arises from the amplification of spontaneously emitted photons, which copy themselves by triggering stimulated emission events. The ASE region amplifies the intensity of photons of all phases, leading to the overall photon density in the cavity.
Thus, the micro-ring geometry has given us substantial insight into the true limitations to low-threshold lasing, and how the input pump energy is allocated. These observations are important when considering which optimal nitride gain medium and cavity geometry to use to achieve lower-lasing threshold device design.

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**REFERENCES**


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**Table 1. Table of Fitted Values of the Cavity Decay Rate \( \gamma \) and ASE Height in Microdisk and Micro-Rings of Various Geometries**

<table>
<thead>
<tr>
<th>Geometries</th>
<th>Microdisk</th>
<th>400 nm Ring</th>
<th>200 nm Ring</th>
<th>500 nm Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage Volume</td>
<td>100</td>
<td>84</td>
<td>96</td>
<td>75</td>
</tr>
<tr>
<td>Fitted ( \gamma ) ( (10^{12} \text{ s}^{-1}) )</td>
<td>0.30</td>
<td>0.70</td>
<td>1.20</td>
<td>1.60</td>
</tr>
<tr>
<td>ASE Height</td>
<td>3.44</td>
<td>3.15</td>
<td>3.01</td>
<td>2.89</td>
</tr>
</tbody>
</table>

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being incoherent, although there may exist local groups of coherent photons. Excess ASE is an unwanted effect in lasers as it can limit the maximum gain that can be achieved in the gain medium. The rather distinctive effects we observe relative to lowered lasing threshold accompanied by lowered slope efficiency and reduced ASE contribution may relate to the heterogeneous nature of our gain material, with two main contributors (QD and fQW) that influence different regions of the spectrum. Thus, we believe that photon emission from the fQWs dominates the ASE, and those photons overlap the lossier higher-order modes in the micro-ring structures. The selective loss of fQW photons, together with the reduced competition from fQW emission into a mode, produce the dramatically reduced threshold for lasing that we observe.

In conclusion, we have fabricated microdisk and micro-ring cavities containing three InGaN QD layers as the gain medium. The micro-ring lasers with increasing inner diameters show systematically lower values of lasing threshold. This threshold decrease is a result of the reduction in pump volume, as much of the fQW material is removed. Although the micro-ring geometry does not compromise the \( Q \) of the WGMs, there is a reduction of \( Q \) for higher-order modes for micro-rings with larger inner diameters. This results in increased photon loss, \( \gamma \), producing a systematic decrease in the post-threshold slope efficiency with increased material removal from the center of the disk. Using \( \gamma \) as the fitting parameter, we observe an increased value of \( \gamma \) with increased micro-ring inner diameter. Our simulations indicate that the photons that are lost from the cavity are not correlated with emission from the QDs that ultimately produce lasing in our devices. Thus, our devices show both lowered lasing thresholds and lowered slope efficiencies with reduced central volume material.

The heterogeneous nature of our gain material, a combination of QDs and fQWs, together with the varying cavity geometries, gives us a detailed picture of the interactions between cavity modes and the microstructure of the gain material.