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Farsane Tabataba-Vakili , Christelle Brimont, Blandine Alloing, Benjamin Damilano , Laetitia Doyennette, Thierry Guillet , Moustafa El Kurdi, Sébastien Chenot, Virginie Brändli, Eric Frayssinet, Jean-Yves Duboz , Fabrice Semond, Bruno Gayral, and Philippe Boucaud 



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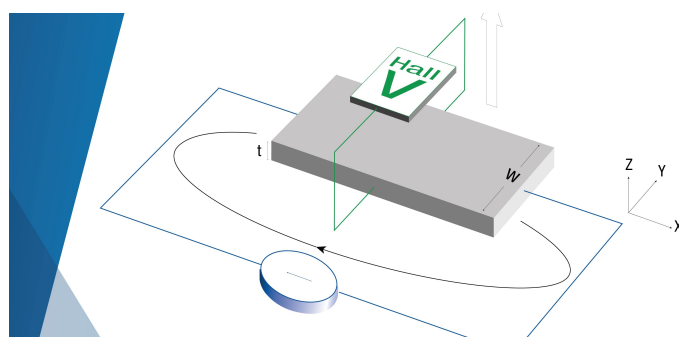
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Farsane Tabataba-Vakili,<sup>1,2</sup>  Christelle Brimont,<sup>3</sup> Blandine Alloing,<sup>4</sup> Benjamin Damilano,<sup>4</sup>  Laetitia Doyennette,<sup>3</sup> Thierry Guillet,<sup>3</sup>  Moustafa El Kurdi,<sup>1</sup> Sébastien Chenot,<sup>4</sup> Virginie Brändli,<sup>4</sup> Eric Frayssinet,<sup>4</sup> Jean-Yves Duboz,<sup>4</sup>  Fabrice Semond,<sup>4</sup> Bruno Gayral,<sup>2</sup> and Philippe Boucaud<sup>4,a)</sup> 

## AFFILIATIONS

<sup>1</sup>Université Paris-Saclay, CNRS, C2N, 91120 Palaiseau, France

<sup>2</sup>University Grenoble Alpes, CEA, IRIG-Pheliqs, 38000 Grenoble, France

<sup>3</sup>L2C, Université de Montpellier, CNRS, 34095 Montpellier, France

<sup>4</sup>Université Côte d'Azur, CNRS, CRHEA, 06560 Valbonne, France

<sup>a)</sup> Author to whom correspondence should be addressed: [Philippe.Boucaud@crhea.cnrs.fr](mailto:Philippe.Boucaud@crhea.cnrs.fr)

## ABSTRACT

Low-threshold lasing under pulsed optical pumping is demonstrated at room temperature for III-nitride microdisks with InGaN/GaN quantum wells on Si in the blue spectral range. Thresholds in the range of  $18 \text{ kW/cm}^2$  have been achieved along with narrow linewidths of  $0.07 \text{ nm}$  and a large peak-to-background dynamic of 300. We compare this threshold range with the one that can be calculated using a rate equation model. We show that thresholds in the few  $\text{kW/cm}^2$  range constitute the best that can be achieved with III-nitride quantum wells at room temperature. The sensitivity of lasing on the fabrication process is also discussed.

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Small foot-print microresonators such as microdisks are an important building block for integrated photonic circuits. The first microdisk laser was reported in 1991 by McCall *et al.* using the InP platform in the near-infrared (NIR).<sup>1</sup> To go towards the visible (VIS) and ultraviolet (UV) spectral ranges requires large bandgap semiconductors and is very interesting for visible light communication<sup>2</sup> or biosensing.<sup>3</sup> III-nitrides are the optimal candidates as they provide a large transparency window from the UVC to the NIR and allow for the monolithic integration of active emitters in the UV-VIS spectral range. III-nitride photonic cavities have been studied for the past 15 years.<sup>4</sup> Individual microdisk lasers have been demonstrated from the UVC to the green spectral range, mainly under pulsed optical pumping at room temperature.<sup>5–11</sup> A few reports have also been made on continuous-wave (CW) lasing in III-nitride microdisks.<sup>12–14</sup> Large quality (Q) factors in the range of 7000–10 000 have been reported.<sup>15,16</sup> Electrically injected microdisk lasers have been demonstrated in the blue and UVA under pulsed and CW pumping.<sup>17–20</sup> Microdisk lasers have been monolithically integrated into photonic circuits in the blue<sup>21,22</sup> and UVA<sup>23</sup> spectral range, and a scheme to combine photonic circuits and electrical injection has been proposed.<sup>24</sup>

In this Letter, we will discuss our recent advances in III-nitride optically pumped microdisk lasers. We demonstrate a significantly low

threshold down to  $P_{th} = 18 \text{ kW/cm}^2$  at room temperature under pulsed optical pumping. This low threshold comes along with a narrow linewidth and a large peak-to-background ratio. We discuss the parameters governing the threshold in III-nitride microdisks following a rate equation analysis. This includes the transparency carrier density, the cavity quality factor, the modal overlap of the active region with the confined mode, the material gain, and the carrier lifetime. We find excellent agreement between experimental values and the calculated ones using appropriate values for these III-nitride microresonators. We will show that in order to attain the transparency carrier density  $n_{tr}$  in blue InGaN quantum wells (QWs), a minimum pump power of a few  $\text{kW/cm}^2$  is required. The thresholds reported in this work are, thus, close to the optimum for room temperature lasing with III-nitride microdisks. The rate equation analysis allows us to discuss previous values reported in the literature.

The investigated sample was grown by metal organic chemical vapor deposition (MOCVD) on Si (111). In a first growth run, a template was grown consisting of 220 nm AlN and 320 nm GaN. Then, in a second growth run, another 200 nm of GaN was grown followed by the active region consisting of  $5 \times 3 \text{ nm In}_{0.1}\text{Ga}_{0.9}\text{N}/7 \text{ nm GaN}$  QWs and a 20 nm GaN cap layer. The total thickness is 810 nm. A schematic of the heterostructure is depicted in Fig. 1(a). The threading

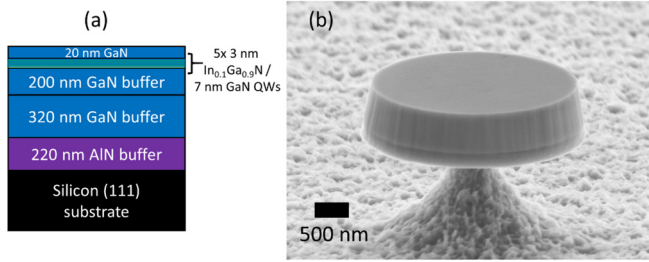


FIG. 1. (a) Schematic of the heterostructure of the investigated sample and (b) SEM image of a  $3 \mu\text{m}$  diameter disk.

dislocation density is estimated to be  $1.2 \times 10^{10} \text{ cm}^{-2}$  from a  $2 \times 2 \mu\text{m}^2$  atomic force microscopy image (see Fig. S1 in the [supplementary material](#)), a standard value for thin III-nitride layers grown on Si. A photoluminescence (PL) measurement of the as-grown sample is shown in Fig. S2 of the [supplementary material](#), showing QW emission centered around 428 nm. We fabricated microdisks using standard cleanroom processing. We used a plasma-enhanced chemical vapor deposition (PECVD)  $\text{SiO}_2$  hard mask, e-beam lithography using UV5 positive resist, and inductively coupled plasma (ICP) etching using  $\text{CH}_2\text{F}_2$  and  $\text{CF}_4$  gases for the  $\text{SiO}_2$  and  $\text{Cl}_2$  and  $\text{BCl}_3$  gases for the III-nitride. The Si was underetched using  $\text{XeF}_2$  gas. A scanning electron microscope (SEM) image of a  $3 \mu\text{m}$  diameter disk is depicted in Fig. 1(b), showing smooth slightly inclined side-walls.

We use a standard  $\mu\text{-PL}$  setup with a 355 nm pulsed laser (4 ns pulse width; 7 kHz repetition rate) and a  $50\times$  microscope objective to both pump the microdisk and collect its emission from the top. A spectrometer and a Peltier-cooled charge coupled device (CCD) are used as the detector.

Figure 2 shows pump power dependent spectra of a  $3 \mu\text{m}$  diameter disk. Several modes are lasing and we can see clamping of the spontaneous emission at low energy (see Fig. S3 in the [supplementary material](#)). The two strongest modes at 419 and 423 nm have very similar thresholds and are in strong competition. Figures 3(a) and 3(b) show the integrated intensity and linewidth over peak pump power for the modes at 419 and 423 nm, respectively. We point out the limited

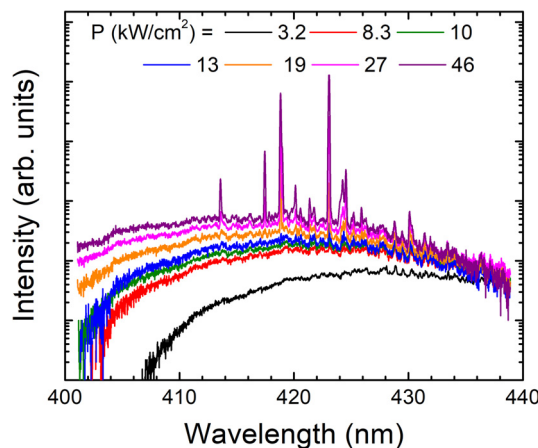


FIG. 2. Pump power dependent spectra of a  $3 \mu\text{m}$  diameter disk.

visibility of whispering-gallery modes (WGMs) below threshold in a top-collection setup as WGMs radiate preferentially in-plane. For the mode at 419 nm [Fig. 3(a)], the narrowest linewidth of 0.07 nm is observed at  $15 \text{ kW/cm}^2$  peak power and the threshold is around  $18 \text{ kW/cm}^2$  (or threshold energy per pulse of  $0.07 \text{ mJ/cm}^2$ ). At higher power densities, a second mode appears at nearly the same wavelength (see Fig. S4 in the [supplementary material](#)), thus making the linewidth analysis complex. For the mode at 423 nm [Fig. 3(b)], the linewidth starts narrowing at  $8 \text{ kW/cm}^2$ . A zoom of the low power range of  $3\text{--}17 \text{ kW/cm}^2$ , given in Fig. 3(c), shows the onset of the mode dynamics and indicates a threshold at  $10 \text{ kW/cm}^2$  consistent with the linewidth narrowing. There is, nonetheless, mode competition with the 419 nm mode, which is discussed in more detail in the [supplementary material](#) (Fig. S5). Consequently, Fig. 3(b) indicates an overall threshold to be around  $25 \text{ kW/cm}^2$ . A close-up of the mode at 423 nm at low pump powers below threshold is shown in Fig. 3(c). A large dynamic between the peak intensity and the background spontaneous emission of  $> 300$  can be discerned for the 423 nm mode in Fig. 3(d), where we plot the peak and background intensities over pump power in a double logarithmic plot. At the last point of  $45 \text{ kW/cm}^2$ , the CCD is saturated.

Using the rate equation model introduced by Baba and Sano, we get the following formula for the threshold power:<sup>25</sup>

$$P_{th} = \frac{E_{phot}d}{U\eta_{inj}(1-R)} \left( \frac{1-C_{sp}}{\tau_{sp}} + \frac{1}{\tau_{nr}} \right) n_{th}, \quad (1)$$

with  $E_{phot}$  being the photon energy of the pump laser,  $d$  the total thickness of the active medium,  $U$  the ratio between the homogeneous broadening of the laser mode and the spectral broadening of the spontaneous emission,<sup>25</sup>  $\eta_{inj}$  the injection efficiency of the carriers into the QWs,  $R$  the surface reflectivity,  $C_{sp}$  the spontaneous emission factor,  $\tau_{sp}$  the spontaneous emission lifetime,  $\tau_{nr}$  the non-radiative lifetime, and  $n_{th}$  the threshold carrier density, which is given by

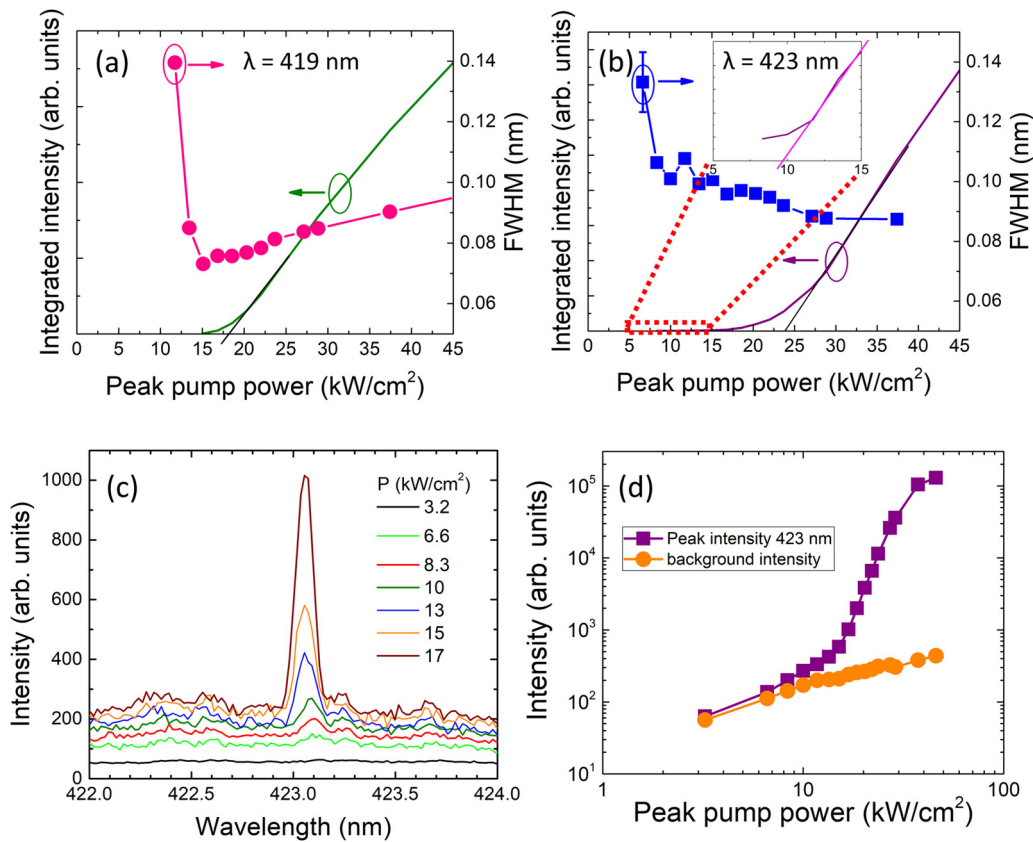
$$n_{th} = n_{tr} + \frac{n_g}{c\Gamma g\tau_c}, \quad (2)$$

where  $n_{tr}$  is the transparency carrier density,  $n_g$  the group index,  $c$  the speed of light,  $\Gamma$  the overlap of the optical mode with the QWs,  $g$  the dynamic gain, and  $\tau_c$  the photon lifetime. Equation (2) indicates that the first requirement to obtain a net positive gain is to reach transparency. Once transparency is attained, another important factor to reach threshold is  $\Gamma$ . For the  $\text{TE}_0$  mode, we calculate  $\Gamma = 0.44\%$  for our 5 QWs (see Fig. S6 in the [supplementary material](#)), which is very small and could be improved in future work. We calculate  $n_g = 3.44$  and  $g$  is given by  $g = g_0/n_{tr}$ , where  $g_0$  is an empirical gain coefficient, which we estimate to be  $35000 \text{ cm}^{-1}$ , based on Ref. 26, where they study a fairly similar QW (3 nm, 15% In) and which constitutes a typical value. For more information on the threshold gain, refer to the [supplementary material](#).

The photon lifetime is given by

$$\tau_c = \frac{Q\lambda}{2\pi c}, \quad (3)$$

with  $Q$  being the quality factor and  $\lambda$  the peak wavelength. We calculate  $Q = 6000$  using the below threshold linewidth, which is in good agreement with our previous samples,<sup>10,22</sup> and  $\lambda = 420 \text{ nm}$ . We get  $\tau_c = 1.3 \text{ ps}$ .



**FIG. 3.** Integrated intensity and full-width at half maximum (FWHM) of the modes (a) at 419 nm and (b) at 423 nm. The inset in (b) shows a zoom-in at low power density. (c) Close-up of the spectra at low power density for the 423 nm mode. (d) Peak and background intensities over pump power for the mode at 423 nm.

The sheet transparency carrier density is around  $3 \times 10^{12} \text{ cm}^{-2}$  for InGaN QWs, which gives us  $n_{tr} = 1 \times 10^{19} \text{ cm}^{-3}$  for our 3 nm QWs.<sup>26–28</sup> Using Eq. (2), we thus get  $n_{th} = 1.57 \times 10^{19} \text{ cm}^{-3} = 1.57n_{tr}$ .

We can calculate  $C_{sp}$  using<sup>25</sup>

$$C_{sp} = \frac{p\Gamma_r\lambda^3}{4\pi^2 n_{eff}^3 V_m \Delta\lambda}, \quad (4)$$

where  $p$  is the polarization anisotropy of the spontaneous emission,  $\Gamma_r$  is the relative confinement factor,  $n_{eff}$  is the effective refractive index,  $V_m$  is the mode volume, and  $\Delta\lambda$  is the homogeneous broadening of the QW emission. We calculate the mode volume using the finite-difference time-domain (FDTD) method with  $V_m = \int_V \epsilon |\mathbf{E}|^2 dV / [\epsilon |\mathbf{E}|^2]_{max}$  and obtain  $0.22 \mu\text{m}^3$  for a first order radial TE<sub>0</sub> mode. Note that this weak mode volume is linked to the short wavelength investigated. Using  $p = 1$  (consistent with the formula for  $\beta$ , the spontaneous emission factor, in Ref. 29, p. 562),  $\Gamma_r = 1$  (for a cavity with many modes<sup>30</sup>)  $n_{eff} = 2.49$ , and  $\Delta\lambda = 15 \text{ nm}$ , we get  $C_{sp} = 2 \times 10^{-2}$ . This value is still fairly small and can, thus, be neglected in Eq. (1).

Note that  $C_{sp}$ , the spontaneous emission factor, is in first approximation inversely proportional to the number of allowed cavity modes in the spectral broadening. This spontaneous emission factor is in the literature often presented as  $\beta$ .<sup>10,13,26</sup> By accounting for the homogeneous broadening in the calculation of  $C_{sp}$ , we assume to be in the so-called

bad emitter regime, i.e., emitter linewidth larger than the cavity linewidth.<sup>29,31</sup> Note that Eq. (1) is the same as in Ref. 29 (p. 252) except for the pre-factor  $U$  that accounts for homogeneous broadening.

Using the standard rate equations given in Ref. 29 (p. 249), we can fit the L–L curve of Fig. 3(b) in the range up to  $25 \text{ kW/cm}^2$ . We obtain a value of  $6 \times 10^{-3}$  for the spontaneous emission factor, which is within a factor of 3 of the calculated value of  $C_{sp}$ . For the here presented range of microdisk parameters, the equations for the laser threshold are equivalent to those for ridge waveguide lasers<sup>29,32</sup> where the spontaneous emission factor is weak.

$E_{phot} = 3.49 \text{ eV}$  for our pump laser and  $d = 15 \text{ nm}$  for our 5 QWs. The reflectivity of GaN at  $355 \text{ nm}$  is 19%.<sup>33</sup> We can estimate  $\tau_{sp}$  and  $\tau_{nr}$  using the ABC model<sup>34</sup> with

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{sp}} + \frac{1}{\tau_{nr}} = A + Bn + Cn^2, \quad (5)$$

where the first term describes Shockley–Read–Hall recombination, the second term describes radiative recombination, and the third term describes Auger-type recombination. We use  $A = 4.2 \times 10^7 \text{ s}^{-1}$ ,  $B = 3 \times 10^{-12} \text{ cm}^3 \text{ s}^{-1}$ , and  $C = 4.5 \times 10^{-31} \text{ cm}^6 \text{ s}^{-1}$  (see Refs. 26 and 34). As discussed below, there is a large spread on these values in the literature. We use the aforementioned values because they have been measured for InGaN laser diodes emitting in the same spectral

range as our sample and at high carrier densities. However, the laser diodes studied by Scheibenzuber *et al.*<sup>34</sup> were grown on bulk GaN, thus having a much smaller dislocation density than our material, which has an influence on the non-radiative lifetime. Assuming a 5 times larger  $A$  would increase  $P_{th}$  by a factor of 2, a 10 times larger  $A$  would result in a factor 3 increase in  $P_{th}$ . Given that our measured thresholds are quite low, the non-radiative lifetime cannot be extremely short. At threshold, we calculate  $\tau_{tot} = 5.1$  ns,  $\tau_{sp} = 21$  ns, and  $\tau_{nr} = 6.6$  ns using the ABC values of Scheibenzuber *et al.*<sup>34</sup> It corresponds to an internal quantum efficiency of 24% at threshold. This  $\tau_{tot}$  is very close to and a bit larger than the pulse width of 4 ns, which can influence the carrier dynamics and increase the threshold. Meanwhile, a 5 times larger  $A$  would result in a  $\tau_{tot}$  of 2.7 ns, which is significantly shorter than the pulse width, and a factor 2 larger  $P_{th}$ , which would still fit well with our experimental values. Our threshold calculation assumes a pseudo-continuous modeling. In the [supplementary material](#), we compare the carrier lifetimes and thresholds obtained for the ABC values of Scheibenzuber *et al.*<sup>34</sup> and Espenlaub *et al.*<sup>35</sup> for our sample as well as the samples of Refs. 12 and 26.

The parameters  $U$  and  $\eta_{inj}$  in Eq. (1) are not well-known.  $U$  is the ratio between the homogeneous broadening and the spectral broadening. It is unlikely that all the spontaneous emission participates homogeneously to the laser mode, and  $U$  is certainly less than one. Under non-resonant optical pumping, the carriers are photo-induced in the barriers and subsequently captured in the QWs. Moreover, at room temperature, a fraction of the carriers can thermally escape from the QWs. There are 5 QWs in our active structure. Considering a  $U$  value of 0.4 (for a spectral broadening of 35 nm and a homogeneous broadening of 15 nm) and a large range of  $\eta_{inj}$  between 0.3 and 0.7, their product is likely in the 0.1–0.3 range.

In Fig. 4(a), we plot  $n$  over  $P$  below threshold for different values of  $U\eta_{inj}$  between 0.1 and 1 using Eq. (1) (which is valid below and at threshold) and (5). The values of  $n_{tr}$  and  $n_{th}$  of our sample are indicated. For  $U\eta_{inj} = 0.18$ , we get  $P_{th} = 18$  kW/cm<sup>2</sup>, which is the value we observed experimentally, indicating that the parameters considered for the III-nitride microresonators on silicon are relevant. We cannot be sure which vertical mode order is lasing. For the TE<sub>1</sub> mode, we would have a larger value of  $\Gamma$ , 1.6%, and the same  $P_{th}$  value would be attained for a smaller value of  $U\eta_{inj}$  of 0.1. A different vertical order would also imply a different mode volume. A  $P_{th} = 10$  kW/cm<sup>2</sup> would correspond to a  $U\eta_{inj} = 0.3$ .

In Fig. 4(b), we plot  $P_{th}$  as a function of  $g\Gamma Q$  using Eqs. (1), (2), (3), and (5). High gain, high Q, and strong overlap are parameters governing the threshold. For large values of  $g\Gamma Q$  (i.e., for a very high-Q

cavity),  $P_{th}$  goes towards  $P_{tr}$ , the power needed to reach transparency. We can see that even for an unrealistic  $U\eta_{inj} = 1$  at room temperature,  $P_{tr}$  is still 1.2 kW/cm<sup>2</sup>. Using a single QW, as opposed to 5, can reduce the minimum power needed to reach transparency to 0.24 kW/cm<sup>2</sup>. We recall that for III-nitrides, the relatively large threshold values as compared to other compound semiconductors are directly associated with the large density of states due to the heavy electron and holes effective masses characteristic of III-nitrides.

In Fig. S7 in the [supplementary material](#), we show  $P_{th}$  as a function of the number of QWs.

While low-threshold lasing has been demonstrated under electrical injection,<sup>36</sup> we note that care needs to be taken when comparing such lasing thresholds with those measured under optical pumping. Martens<sup>37</sup> (p. 32–33) reported for virtually identical structures a threshold of 100 kW/cm<sup>2</sup> under optical pumping at 266 nm and 2 kA/cm<sup>2</sup> under electrical injection. We can estimate the expected threshold current density of an equivalent structure to ours using<sup>38</sup> (p. 635)

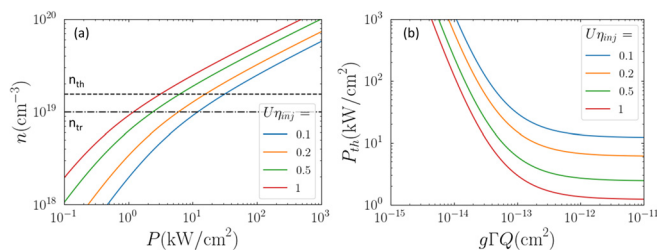
$$J_{th} = ed \frac{n_{th}}{\tau_{tot}}, \quad (6)$$

where  $e$  is the elementary charge, and using  $d = 5 \times 3$  nm,  $n_{th} = 1.57 \times 10^{19}$  cm<sup>-3</sup>, and  $\tau_{tot} = 5.1$  ns, and obtain 700 A/cm<sup>2</sup> for an ideal electrical injection, whereas we have measured 18 kW/cm<sup>2</sup> under optical pumping.

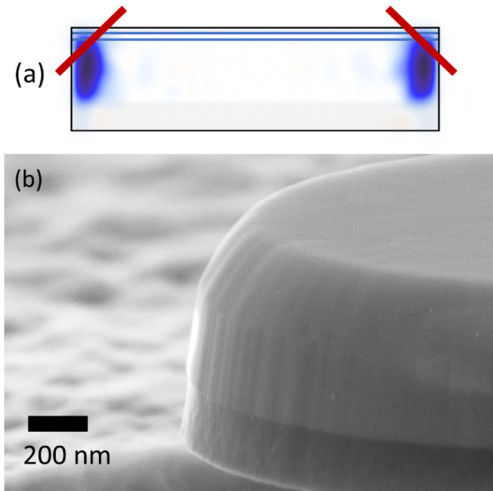
Achieving a threshold below 1 kW/cm<sup>2</sup> for a multi-QW (MQW) at room temperature is, thus, highly challenging. In the literature, a claim of lasing at threshold powers as low as 0.3 kW/cm<sup>2</sup> at a similar wavelength and for a comparable active region (also 5 QWs) was reported in Ref. 12. They demonstrate a dynamic between peak and background of only a factor of around 8 at  $9P_{th}$ , which is 40 times smaller than in our case. We need to consider the large variability of ABC parameters in the literature.<sup>35,39–41</sup> In order to achieve  $P_{th} = 0.3$  kW/cm<sup>2</sup> with the parameters of the sample reported by Tamboli *et al.*,<sup>12</sup> a  $\tau_{tot}$  of 110 ns would be required at  $U\eta_{inj} = 0.35$ , which would require  $C$  to be around one order of magnitude smaller as compared to the values of Scheibenzuber *et al.*,<sup>34</sup> along with a smaller  $B$  value and a much smaller  $A$  value, i.e., very long radiative lifetimes and high material quality leading to very long non-radiative lifetimes. We discuss different ABC parameters and the resulting calculated thresholds in the [supplementary material](#). This radiative lifetime improvement could be combined with an increase in the  $C_{sp}$  factor by decreasing the cavity size. If a different gain medium was studied, i.e., quantum dots instead of QWs, or generally more localized emitters, the density of states would be different,<sup>42</sup> and the threshold could possibly be reduced since  $n_{tr}$  would be lower. Localized states are expected in InGaN QWs, but for the pump powers reported by Tamboli *et al.*<sup>12</sup> or in this work, it is expected that they are saturated and that a 2D density of states is recovered, thus justifying the QW rate equation analysis.

The here-discussed linewidth of 0.07 nm at threshold is one of the narrowest values reported for III-nitride microdisks. The only smaller value we found, 0.033 nm, was reported by Simeonov *et al.*<sup>6,7</sup> for III-nitride microdisks on sapphire with a higher threshold of 166 kW/cm<sup>2</sup>. As for III-nitride microdisk lasers on silicon, we have not found any narrower values.

While even a perfect resonator cannot infinitely reduce the threshold, a badly processed microdisk can easily result in no lasing



**FIG. 4.** (a) Calculation of  $n$  over  $P$  for different values of  $U\eta_{inj}$  using Eqs. (1) and (5) and indicating the values of  $n_{tr}$  and  $n_{th}$ . (b) Calculation of  $P_{th}$  over  $g\Gamma Q$  for different values of  $U\eta_{inj}$  using Eqs. (1), (2), (3), and (5).



**FIG. 5.** (a) Schematic of a  $3\ \mu\text{m}$  diameter disk with truncated edges and depicting the  $H_z$  field of a first order radial mode. (b) SEM image of a truncated microdisk.

being observed at all. Figure 5(a) shows a schematic of the cross section of a  $3\ \mu\text{m}$  diameter disk depicting the  $H_z$  field of a first order radial mode (for a perfect microdisk) and indicating truncated edges that strongly reduce the overlap of the mode with the QWs, which are at the top of the structure, not taking into account that the truncated edges would also change the mode profile a bit. In Fig. 5(b), we show an SEM image of such a disk, which does not lase under pulsed optical pumping. We have also observed an order of magnitude difference in threshold for microdisks on two samples separately processed from the same wafer, highlighting the need for a high quality cavity.

We did not observe CW lasing for our sample, which is likely due to the fact that our microdisks are fairly large ( $3\ \mu\text{m}$  diameter) and our CW laser is not sufficiently powerful. Meanwhile, CW lasing is always challenging for microdisk structures due to thermal management and pedestal size. A weak dependence of threshold vs temperature is also mandatory and will be the subject of future work.

In conclusion, we have demonstrated low threshold ( $18\ \text{kW}/\text{cm}^2$  peak power) pulsed optically pumped lasing in III-nitride microdisks grown by MOCVD on Si with a narrow linewidth and a large peak-to-background dynamic of 300. We calculated the threshold power using a rate equation model and obtained values that are in good agreement with our measurements, which highlights the fact that InGaN MQWs require minimum power on the order of  $\text{kW}/\text{cm}^2$  to reach the transparency carrier density. The presented microresonators fabricated on Si are thus close to the best that can be achieved with III-nitride QWs.

See the [supplementary material](#) for material characterization, additional lasing spectra, a 1D simulation of the mode overlap; a discussion of the threshold gain; a discussion of the dependence of the threshold on the number of QWs; and a discussion of the calculated lasing thresholds using different ABC values.

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#### DATA AVAILABILITY

The data that support the findings of this study are available within the article and its [supplementary material](#).

#### REFERENCES

- <sup>1</sup>S. L. McCall, A. F. J. Levi, R. E. Slusher, S. J. Pearton, and R. A. Logan, “Whispering-gallery mode microdisk lasers,” *Appl. Phys. Lett.* **60**, 289–291 (1992).
- <sup>2</sup>M. S. Islim, R. X. Ferreira, X. He, E. Xie, S. Videv, S. Viola, S. Watson, N. Bamiedakis, R. V. Penty, I. H. White, A. E. Kelly, E. Gu, H. Haas, and M. D. Dawson, “Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED,” *Photonics Res.* **5**, A35–A43 (2017).
- <sup>3</sup>M. C. Estevez, M. Alvarez, and L. M. Lechuga, “Integrated optical devices for lab-on-a-chip biosensing applications,” *Laser Photonics Rev.* **6**, 463–487 (2012).
- <sup>4</sup>R. Butté and N. Grandjean, “III-nitride photonic cavities,” *Nanophotonics* **9**, 569–598 (2020).
- <sup>5</sup>E. D. Haberer, R. Sharma, C. Meier, A. R. Stonas, S. Nakamura, S. P. DenBaars, and E. L. Hu, “Free-standing, optically pumped, GaN/InGaN microdisk lasers fabricated by photoelectrochemical etching,” *Appl. Phys. Lett.* **85**, 5179–5181 (2004).
- <sup>6</sup>D. Simeonov, E. Feltin, H.-J. Bühlmann, T. Zhu, A. Castiglia, M. Mosca, J.-F. Carlin, R. Butté, and N. Grandjean, “Blue lasing at room temperature in high quality factor GaN/AlInN microdisks with InGaN quantum wells,” *Appl. Phys. Lett.* **90**, 061106 (2007).
- <sup>7</sup>D. Simeonov, E. Feltin, A. Altoukhov, A. Castiglia, J.-F. Carlin, R. Butté, and N. Grandjean, “High quality nitride based microdisks obtained via selective wet etching of AlInN sacrificial layers,” *Appl. Phys. Lett.* **92**, 171102 (2008).
- <sup>8</sup>I. Aharonovich, A. Woolf, K. J. Russell, T. Zhu, N. Niu, M. J. Kappers, R. A. Oliver, and E. L. Hu, “Low threshold, room-temperature microdisk lasers in the blue spectral range,” *Appl. Phys. Lett.* **103**, 021112 (2013).
- <sup>9</sup>J. Sellés, C. Brimont, G. Cassabois, P. Valvin, T. Guillet, I. Roland, Y. Zeng, X. Checoury, P. Boucaud, M. Mexis, F. Semon, and B. Gayral, “Deep-UV nitride-on-silicon microdisk lasers,” *Sci. Rep.* **6**, 21650 (2016).
- <sup>10</sup>J. Sellés, V. Crepel, I. Roland, M. Elkurdi, X. Checoury, P. Boucaud, M. Mexis, M. Leroux, B. Damilano, S. Rennesson, F. Semon, B. Gayral, C. Brimont, and T. Guillet, “III-nitride-on-silicon microdisk lasers from the blue to the deep ultra-violet,” *Appl. Phys. Lett.* **109**, 231101 (2016).
- <sup>11</sup>G. Zhu, J. Li, N. Zhang, X. Li, J. Dai, Q. Cui, Q. Song, C. Xu, and Y. Wang, “Whispering-gallery mode lasing in a floating GaN microdisk with a vertical slit,” *Sci. Rep.* **10**, 253 (2020).
- <sup>12</sup>A. C. Tamboli, E. D. Haberer, R. Sharma, K. H. Lee, S. Nakamura, and E. L. Hu, “Room-temperature continuous-wave lasing in GaN/InGaN microdisks,” *Nat. Photonics* **1**, 61–64 (2007).
- <sup>13</sup>M. Athanasiou, R. Smith, B. Liu, and T. Wang, “Room temperature continuous-wave green lasing from an InGaN microdisk on silicon,” *Sci. Rep.* **4**, 7250 (2014).
- <sup>14</sup>M. Athanasiou, R. M. Smith, J. Pugh, Y. Gong, M. J. Cryan, and T. Wang, “Monolithically multi-color lasing from an InGaN microdisk on a Si substrate,” *Sci. Rep.* **7**, 10086 (2017).
- <sup>15</sup>M. Mexis, S. Sergent, T. Guillet, C. Brimont, T. Bretagnon, B. Gil, F. Semon, M. Leroux, D. Néel, S. David, X. Checoury, and P. Boucaud, “High quality factor nitride-based optical cavities: Microdisks with embedded GaN/Al(GaN) quantum dots,” *Opt. Lett.* **36**, 2203–2205 (2011).
- <sup>16</sup>I. Rousseau, G. Callsen, G. Jacopin, J.-F. Carlin, R. Butté, and N. Grandjean, “Optical absorption and oxygen passivation of surface states in III-nitride photonic devices,” *J. Appl. Phys.* **123**, 113103 (2018).

- <sup>17</sup>M. Kneissl, M. Teepe, N. Miyashita, N. M. Johnson, G. D. Chern, and R. K. Chang, "Current-injection spiral-shaped microcavity disk laser diodes with unidirectional emission," *Appl. Phys. Lett.* **84**, 2485–2487 (2004).
- <sup>18</sup>M. Feng, J. He, Q. Sun, H. Gao, Z. Li, Y. Zhou, J. Liu, S. Zhang, D. Li, L. Zhang, X. Sun, D. Li, H. Wang, M. Ikeda, R. Wang, and H. Yang, "Room-temperature electrically pumped InGaN based microdisk laser grown on Si," *Opt. Express* **26**, 5043–5051 (2018).
- <sup>19</sup>J. Wang, M. Feng, R. Zhou, Q. Sun, J. Liu, Y. Huang, Y. Zhou, H. Gao, X. Zheng, M. Ikeda, and H. Yang, "GaN-based ultraviolet microdisk laser diode grown on Si," *Photonics Res.* **7**, B32–B35 (2019).
- <sup>20</sup>J. Wang, M. Feng, R. Zhou, Q. Sun, J. Liu, X. Sun, X. Zheng, M. Ikeda, X. Sheng, and H. Yang, "Continuous-wave electrically injected GaN-on-Si microdisk laser diodes," *Opt. Express* **28**, 12201–12208 (2020).
- <sup>21</sup>F. Tabataba-Vakili, L. Doyennette, C. Brimont, T. Guillet, S. Rennesson, E. Frayssinet, B. Damilano, J.-Y. Duboz, F. Semond, I. Roland, M. ElKurdi, X. Checoury, S. Sauvage, B. Gayral, and P. Boucaud, "Blue microlasers integrated on a photonic platform on silicon," *ACS Photonics* **5**, 3643–3648 (2018).
- <sup>22</sup>F. Tabataba-Vakili, L. Doyennette, C. Brimont, T. Guillet, S. Rennesson, B. Damilano, E. Frayssinet, J.-Y. Duboz, X. Checoury, S. Sauvage, M. ElKurdi, F. Semond, B. Gayral, and P. Boucaud, "Demonstration of critical coupling in an active III-nitride microdisk photonic circuit on silicon," *Sci. Rep.* **9**, 18095 (2019).
- <sup>23</sup>F. Tabataba-Vakili, B. Alloing, B. Damilano, H. Souissi, C. Brimont, L. Doyennette, T. Guillet, X. Checoury, M. E. Kurdi, S. Chenot, E. Frayssinet, J.-Y. Duboz, F. Semond, B. Gayral, and P. Boucaud, "Monolithic integration of ultraviolet microdisk lasers into photonic circuits in a III-nitride-on-silicon platform," *Opt. Lett.* **45**, 4276–4279 (2020).
- <sup>24</sup>F. Tabataba-Vakili, S. Rennesson, B. Damilano, E. Frayssinet, J.-Y. Duboz, F. Semond, I. Roland, B. Paulillo, R. Colombelli, M. ElKurdi, X. Checoury, S. Sauvage, L. Doyennette, C. Brimont, T. Guillet, B. Gayral, and P. Boucaud, "III-nitride on silicon electrically injected microrings for nanophotonic circuits," *Opt. Express* **27**, 11800–11808 (2019).
- <sup>25</sup>T. Baba and D. Sano, "Low-threshold lasing and Purcell effect in microdisk lasers at room temperature," *IEEE J. Sel. Top. Quantum Electron.* **9**, 1340–1346 (2003).
- <sup>26</sup>N. Vico Triviño, R. Butté, J.-F. Carlin, and N. Grandjean, "Continuous wave blue lasing in III-nitride nanobeam cavity on silicon," *Nano Lett.* **15**, 1259–1263 (2015).
- <sup>27</sup>W. Chow, A. Wright, and J. Nelson, "Theoretical study of room temperature optical gain in GaN strained quantum wells," *Appl. Phys. Lett.* **68**, 296–298 (1996).
- <sup>28</sup>A. Hangleiter, G. Frankowsky, V. Härle, and F. Scholz, "Optical gain in the nitrides: Are there differences to other III–V semiconductors?," *Mater. Sci. Eng., B* **43**, 201–206 (1997).
- <sup>29</sup>L. A. Coldren, S. W. Corzine, and M. L. Masanovic, *Diode Lasers and Photonic Integrated Circuits* (John Wiley & Sons, Hoboken, New Jersey, 2012), Vol. 218.
- <sup>30</sup>T. Baba, "Photonic crystals and microdisk cavities based on GaInAsP-InP system," *IEEE J. Sel. Top. Quantum Electron.* **3**, 808–830 (1997).
- <sup>31</sup>M. Van Exter, G. Nienhuis, and J. Woerdman, "Two simple expressions for the spontaneous emission factor  $\beta$ ," *Phys. Rev. A* **54**, 3553–3558 (1996).
- <sup>32</sup>H. Morkoç, *Handbook of Nitride Semiconductors and Devices: GaN-Based Optical and Electronic Devices* (Wiley-VCH, Weinheim, 2009).
- <sup>33</sup>T. Kawashima, H. Yoshikawa, S. Adachi, S. Fuke, and K. Ohtsuka, "Optical properties of hexagonal GaN," *J. Appl. Phys.* **82**, 3528–3535 (1997).
- <sup>34</sup>W. Scheibenzuber, U. Schwarz, L. Sulmoni, J. Dorsaz, J.-F. Carlin, and N. Grandjean, "Recombination coefficients of GaN-based laser diodes," *J. Appl. Phys.* **109**, 093106 (2011).
- <sup>35</sup>A. C. Espenlaub, D. J. Myers, E. C. Young, S. Marcinkevičius, C. Weisbuch, and J. S. Speck, "Evidence of trap-assisted Auger recombination in low radiative efficiency MBE-grown III-nitride LEDs," *J. Appl. Phys.* **126**, 184502 (2019).
- <sup>36</sup>T. Kozaki, H. Matsumura, Y. Sugimoto, S.-I. Nagahama, and T. Mukai, "High-power and wide wavelength range GaN-based laser diodes," *Proc. SPIE* **6133**, 613306 (2006).
- <sup>37</sup>M. Martens, "Optical gain and modal loss in AlGaIn based deep UV lasers," Ph.D. thesis (Technische Universität Berlin, 2018).
- <sup>38</sup>E. Rosencher and B. Vinter, *Optoelectronics* (Cambridge University Press, Cambridge, 2004).
- <sup>39</sup>J. Piprek, "Efficiency droop in nitride-based light-emitting diodes," *Phys. Status Solidi A* **207**, 2217–2225 (2010).
- <sup>40</sup>S. Karpov, "ABC-model for interpretation of internal quantum efficiency and its droop in III-nitride LEDs: A review," *Opt. Quantum Electron.* **47**, 1293–1303 (2015).
- <sup>41</sup>A. David, N. G. Young, C. Lund, and M. D. Craven, "The physics of recombinations in III-nitride emitters," *ECS J. Solid State Sci. Technol.* **9**, 016021 (2020).
- <sup>42</sup>Y. Arakawa and H. Sakaki, "Multidimensional quantum well laser and temperature dependence of its threshold current," *Appl. Phys. Lett.* **40**, 939–941 (1982).