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# Influence of surface roughness on the lasing characteristics of optically-pumped thin-film GaN microdisks

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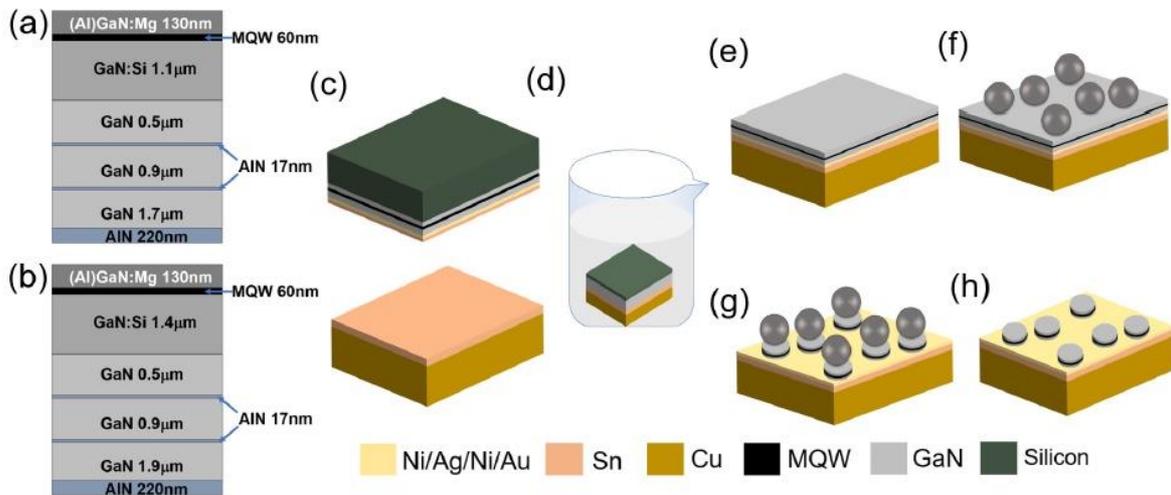
Optically-pumped whispering-gallery mode (WGM) lasing is observed from thin-film GaN microdisk processed from GaN-on-Si InGaN/GaN multi-quantum well wafers by selective wet etch removal of the substrate. Compared to thinfilm microdisks processed from GaN-on-sapphire wafers through laser lift-off of the sapphire substrate, the exposed surface is significantly smoother as laser-induced damage is avoided, with root-mean-square roughness of 1.3 nm compared to 5.8 nm of the latter wafer. The 8  $\mu\text{m}$  diameter microdisks, fabricated by pattern transfer from a silica microsphere and dry etching, benefit from the surface smoothness to offer superior optical confinement within the cavity. WGM lasing thresholds of 2.9  $\text{mJ}/\text{cm}^2$  and 3.5  $\text{mJ}/\text{cm}^2$  with quality factors (Q) of 3100 and 1700 are observed at the peak lasing wavelengths of 453 nm and 532 nm respectively, which are significantly better than thin-film microdisks processed from GaN-on-sapphire wafers despite lower internal quantum efficiency, highlighting the importance of surface smoothness in such optical cavities.

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## INTRODUCTION

With growing interest in integrated photonic systems, there has been rapid advancement in the development of small-dimension active and passive photonic components that can be integrated on a chipscale level, especially micro- and nano-lasers which are integral parts of such integrated systems [1]. Among the common laser diodes such as edge emitting lasers and vertical-cavity surface-emitting lasers (VSELs) that adopt the Fabry-Perot resonator configuration, the whispering gallery mode (WGM) microdisks hold its own owing to its small modal volume, simple fabrication process and excellent optical confinement [2–4]. Extensive studies on GaN-based WGM microdisks on various substrates including sapphire, Si and GaN have been reported recently [5–8]. Three main factors affect the performance, including lasing threshold and quality factor (Q), of a microdisk cavity: (1) the efficiency of the gain medium, (2) the refractive index contrast between the microdisk and the ambient [9], and (3) surface and sidewall smoothness. GaN microdisks benefit from the high internal quantum efficiency (IQE) of InGaN/GaN multi-quantum wells (MQWs) and high refractive index. In order to achieve high-performance GaN microdisk laser, light confinement within the cavity must be optimized [10–12]. Compared to conventional microdisks with undercut structures for partial optical isolation from the substrate, thin-film GaN microdisks achieved with wafer bonding and laser lift-off (LLO) of the sapphire substrate have been demonstrated as an alternative solution that offers a route towards electrical-injection microdisk lasers. The metallic layers used for wafer bonding double as mirrors after substrate removal [13–17]. Moreover, the thickness of the microdisk cavity can readily be tailored by dry-etch thinning of the GaN film for optimization of modal gain. Nevertheless, the harsh laser ablation during LLO

will lead to inevitable roughening and physical damage on the exposed surface, leaving behind undulations and residues [16]. This is exacerbated by the non-uniformity of the large laser beam commonly used for LLO, as well as the laser scanning process. Such imperfections are partially removed by polishing, although the smoothness of the surface is incomparable to the as-grown. Since the smoothness of a GaN microdisk surface and sidewall play a critical role in optical confinement and leakage [9], improvements to the method of substrate removal is desired. In a previous report of optically-pumped lasing from a thin-film microdisk fabricated by LLO, the measured threshold of  $9 \text{ mJ/cm}^2$  and Q-factor of 770 [13] is inferior to those of undercut microdisks. In this work, thin-film microdisks are fabricated from GaN-on-Si wafers instead of GaN-on-sapphire so that the LLO process can be avoided. Instead, the Si substrate can be removed by the milder approach of wet etching which is also more efficient and uniform compared to LLO that involves serial scanning of the beam. Removing the Si substrate in this way can potentially reduce damage and roughness on the exposed surface, thereby reducing light leakage and thus promote light confinement within the disk cavity. In this study, optically-pumped green and blue lasing from In-GaN/GaN MQW thin-film microdisk is demonstrated. The microdisks are formed on substrate-removed GaN-on-Si wafers by microsphere lithography and dry etching. The morphological and optical properties of the microdisks are comprehensively studied, and compared to its counterparts on sapphire substrates.



**Fig. 1.** Epitaxial structure of (a) blue-light and (b) green-light emitting wafers. Schematic diagrams depicting the process flow: (c) InGaN/GaN MQW wafer grown on Si substrate wafer bonded to copper substrate; (d) removal of Si by wet etching in  $\text{HF}/\text{HNO}_3$ ; (e) thin down to  $\sim 450 \text{ nm}$  by ICP etching; (f) microspheres spin-coated onto the GaN thin-film; (g) ICP dry etch for disk pattern transfer; (h) removal of residual microspheres by sonification.

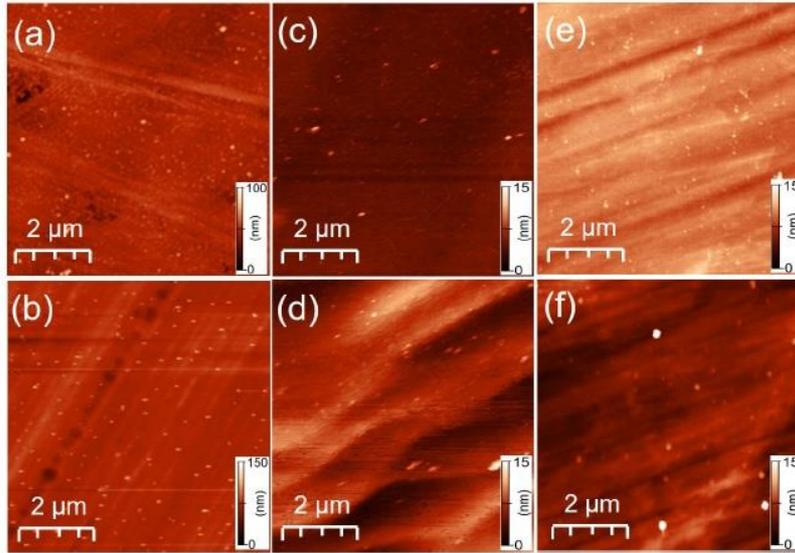
## 2. EXPERIMENTAL DETAILS

The microdisks are fabricated on a blue- and green-light emitting wafer with epitaxial structures shown in the schematic diagrams of Fig. 1(a) and (b) respectively. The wafers are grown by metal-organic chemical vapor deposition (MOCVD) on silicon substrates, details of which can be found in Ref [17]. The IQEs of the MQWs are estimated by comparing the photoluminescence (PL) intensities between 300K and 18K, while the etch-pit density (EPD) of the samples characterized by atomic force microscopy (AFM) following surface plasma

treatments [18] as listed in Table 1. The p-type surface of the wafers are bonded to Cu substrates to achieve good heat dissipation. Ni/Ag/Ni/Au (5nm/100nm/25nm/50nm) multilayers are deposited on the p-GaN surface by electron-beam (ebeam) evaporation, followed by rapid thermal annealing (RTA) at 450 °C in O<sub>2</sub> ambient. Ti/Au (30nm/100nm) is then coated on the annealed metal layers by e-beam evaporation as seeding layer for subsequent electroplating of Cu-Sn for wafer bonding as demonstrated in Fig. 1(c). After wafer bonding by an EVG501 wafer bonder, the silicon substrate is removed by wet etch using HF:HNO<sub>3</sub>(1:1) solution for 30mins as Fig. 1(d) illustrates. After removal of Si, the exposed AlN surface is smooth with root-mean-square roughness of 1.3 nm as shown in the AFM image of Fig. 2(c). The film is then thinned down to 450 nm by etching away the AlN, u-GaN and parts of the n-GaN layers using inductively-coupled plasma (ICP) etching using BCl<sub>3</sub> as shown in Fig. 1(e). Incidentally the non-electrically-conducting AlN layers embedded throughout the epitaxial structure are removed during the thin-down process, enabling electrical-injection to the microdisk. Silica spheres with mean diameters of 8 μm are dispersed in de-ionized (DI) water followed by dispensing onto the wafers using a micro-pipette. The spheres are randomly dispersed onto the wafer by spin-coating as shown in Fig. 1(f). The microsphere-coated wafer is ICP etched for 2mins using a Cl<sub>2</sub> based recipe as depicted in Fig. 1(g), resulting in pattern transfer from the spheres as etch masks to the GaN film. After removal of the residual microspheres by sonification in DI water, the microdisks are formed as illustrated in Fig. 1(h). For comparison, thin film microdisks are fabricated from GaN-on-sapphire wafers based on the LLO process for substrate removal. Details of the wafer and process can be found in a previous report [13].

### 3. RESULTS AND DISCUSSION

The surface morphology of the exposed surfaces after LLO of sapphire and wet etch removal of Si is characterized by AFM. The root-mean square (r.m.s.) roughness of the GaN surfaces after LLO of sapphire, evaluated from the AFM scans shown in Fig. 2(a) and (b), are 5.8 nm and 10.4 nm before and after thin-down respectively. The r.m.s. roughness of the exposed AlN surfaces on the blue-and green-light emitting wafer after wet etch removal of Si substrate are 1.3 nm and 1.6 nm; after thin-down the roughness of the exposed GaN surfaces are 1.1 nm and 1.9 nm, as determined from the respective AFM scans in Fig. 2(c)-(f). The AlN surface after Si removal is significantly smoother than the GaN surface that has undergone LLO which induces laser damage. The findings provide robust evidence that thin-films processed from GaN-on-Si wafers through wet etch removal of Si (111) substrate are optically smoother than their GaN-on-sapphire counterparts, and that microdisks processed from such wafers can potentially confine light to a greater extent and thus more suitable for fabricating microdisk cavities.



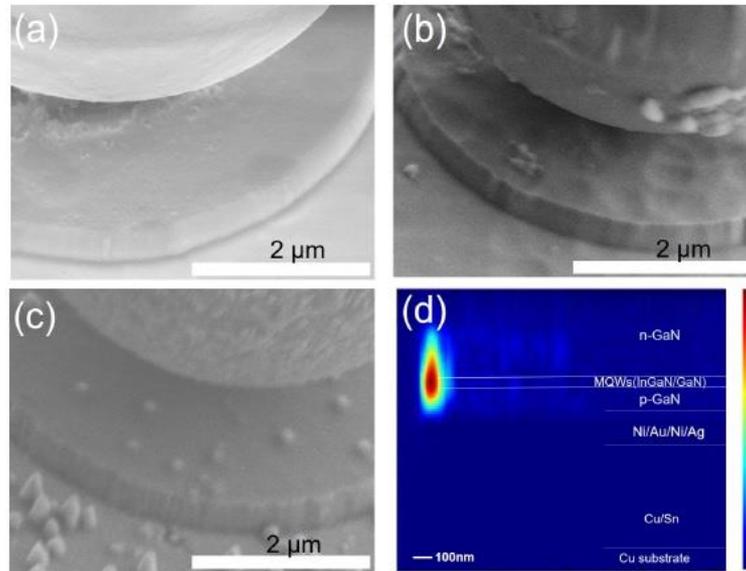
**Fig. 2.** AFM images of (a) GaN surface after LLO removal of sapphire substrate and (b) n-GaN surface after thin down; (c) AlN surface after wet etch removal of Si substrate from blue-light wafer and (d) n-GaN surface after thin down; (e) AlN surface after wet etch removal of Si substrate from green-light wafer and (f) n-GaN surface after thin down.

**Table 1.** Comparison of thin-film GaN microdisks processed from on GaN-on-Si and GaN-on-sapphire substrates.

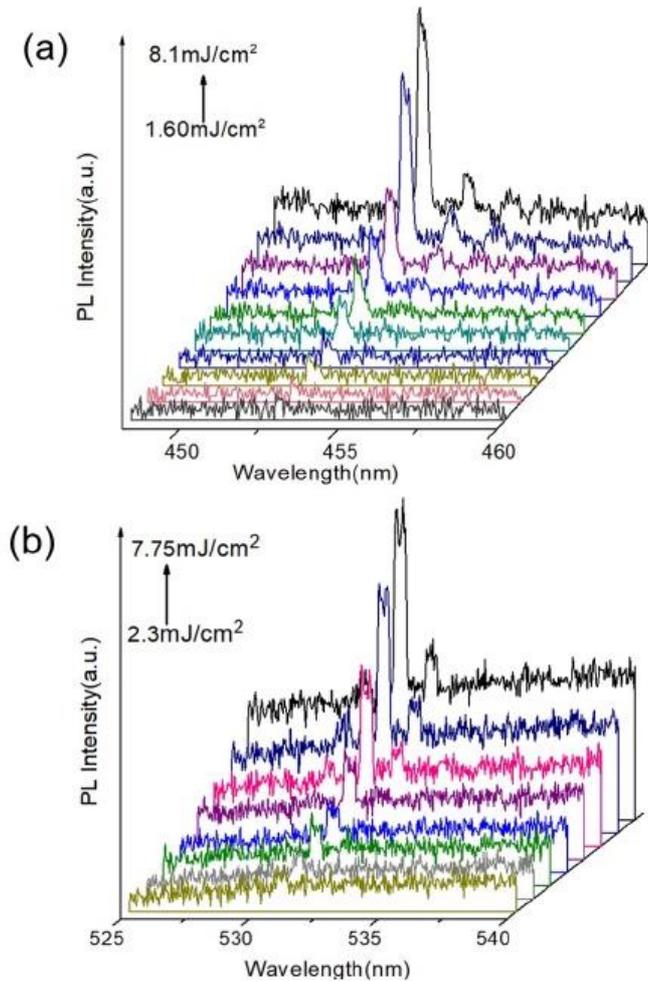
Microdisk wavelength/ substrate	Blue/ Si	Green/ Si	Blue/ sapphire
Etch pit density/cm <sup>2</sup>	$5.4 \times 10^8$	$1.4 \times 10^9$	$6 \times 10^8$
IQE	37%	25%	73%
r.m.s. roughness (before thinning)/nm	0.3	1.1	5.8
r.m.s. roughness (after thinning)/ nm	1.6	1.9	10.4
Threshold/mJ/cm <sup>2</sup>	2.9	3.5	7
Simulated Q factor	11000	5300	11000
Measured Q factor	3100	1700	1400

SEM images of the fabricated blue- and green-light emitting microdisks, with the microspheres still resting on top of the microdisks, are shown in Fig. 3(a) and (b). The etch depth is 450 nm, corresponding to the thickness of the film after thin-down. The microdisk thickness has been designed with the aid of 3D-FDTD simulation, details of which have been reported in Ref [8]. From the cross-sectional field intensity map shown in Fig. 3(d), it can be observed that the region of maximum electric field overlaps with the MQWs which results in enhancement of modal gain in the cavity. For comparison, the SEM image of thin-film microdisk fabricated from GaN-on-sapphire wafer is shown in Fig. 3(c). The fabricated microdisks are optically pumped under identical conditions, conducted in a micro-PL ( $\mu$ -PL) configuration using a diode-pumped solid-state (DPSS) emitting at 349 nm, 4 ns pulse width and 1 kHz repetition rate [7, 9, 13]. The PL signals are probed with an optical fiber, placed at an angle of 20°, dispersed by a spectrograph (Acton SP2500A), and detected by a Princeton Instrument PIXIS cooled charge-coupled device (CCD). Optical spectra collected from the blue light microdisk are plotted in Fig. 4(a), from which a spectral peak is observed at  $\sim 452$  nm when energy density reaches  $\sim 1.70$  mJ/cm<sup>2</sup>. With the increment of energy densities, an additional peak emerges at 454.5 nm, which agrees with the free spectral range (FSR) calculated to be in the range of 2.3 to 2.8 according to the equation  $FSR = \lambda^2 / 2\pi n_{eff} R$ . Similar observations are recorded from the optical spectra green-light microdisk plotted in in Fig. 4(b), where a spectral peak centered at  $\sim 532$

nm emerges when excitation energy density reaches  $2.4 \text{ mJ/cm}^2$ . The optical modes can be determined using the equation  $m\lambda = 2\pi n_{\text{eff}}R$ , where  $m$  is the azimuthal mode order. The peaks of the spectra in Fig.4(a) and (b) can thus be assigned to WGMs with  $m$  of 136, 137, 138 and 117,118,119 respectively. The plots of integrated PL intensity with increasing excitation energies of the blue and green microdisks are shown in Fig. 5(a) and (b). The S-shape plot of PL intensity shows nonlinear increment below and above the threshold, substantiating lasing action. The threshold of lasing is determined to be about  $2.9 \text{ mJ/cm}^2$  for  $\lambda=452 \text{ nm}$  for the blue microdisk, and  $3.5 \text{ mJ/cm}^2$  for  $\lambda=532 \text{ nm}$  for the green microdisk from the kinks of the plots shown in Fig.5. Given that the excitation laser signal is strongly attenuated by the  $\sim 250 \text{ nm}$  n-GaN layer before reaching the active region, the actual lasing threshold should be lower than the measured values [19]. From the trend of spectral line-width with increasing excitation energy densities, significant spectral narrowing from  $0.7 \text{ nm}$  to  $0.14 \text{ nm}$  full-width at half-maximum (FWHM) is observed for the blue microdisk, while the green microdisk experiences spectral narrowing from  $1.15 \text{ nm}$  to  $0.31 \text{ nm}$ , offering further evidence on the lasing behavior. Identical measurements taken from the microdisk processed by LLO are tabulated in Table 1 for comparison. Quality factors ( $Q$ ) of 3100 and 1700 are determined according to the equation  $Q = I/DI$  for the blue and green microdisks respectively, which are approximately one-third of their simulated values of 11000 and 5300 respectively from FDTD simulations that can be attributed to optical leakage due to surface roughness. In contrast, the measured  $Q$  factor of the microdisk from the GaN-on-sapphire wafer is merely one ninth of its simulated value, indicating much higher levels of optical leakage.

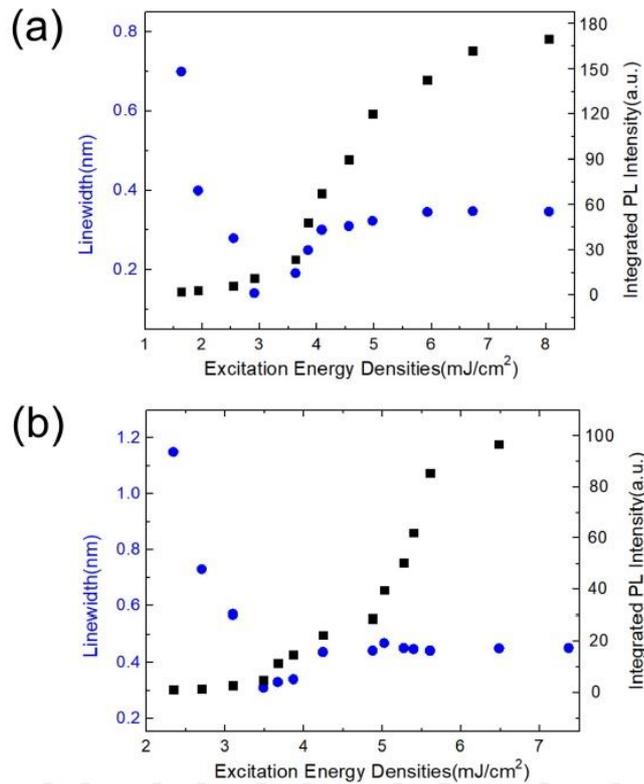


**Fig. 3.** SEM images of thin-film (a) blue microdisk (Si substrate), (b) green microdisk (Si substrate) and (c) blue microdisk (sapphire substrate). (d) Cross-sectional electric field intensity map of a portion of a microdisk from 3D-FDTD simulations.



**Fig. 4.** Room-temperature m-PL spectra of the microdisk with increasing excitation energy densities of (a) blue-light and (b) green light microdisks.

The performance of the blue thin-film GaN microdisk processed from a GaN-on-Si wafer has a distinct edge over its counterpart processed from a GaN-on-sapphire wafer in terms of threshold and quality factor, in spite of the markedly lower IQE that should lead to higher thresholds [20]. Between the blue and green thin-film microdisks processed from GaN-on-Si wafers, the green microdisk has a higher threshold that can be attributed to the lower IQE of the higher In content MQWs. Nevertheless, the performance is still superior to the blue microdisk processed from the GaN-on-sapphire wafer that has a rougher surface, highlighting the importance of surface smoothness to a GaN microdisk. The removal of the Si substrate by wet etching is much simpler and effective than LLO, while producing microdisks with much smoother surfaces leading to improved Q-factors. It can be envisaged that further performance improvements can be expected with increasing IQEs from the MQWs through optimization of the epitaxial growth processes, making electrical-injection microdisk lasers viable as the thin-film microdisk structure readily supports electrical injection, becoming integral components for monolithic or heterogeneous photonic integration.



**Fig. 5.** Plot of PL integrated intensities with increasing excitation energy densities in black and the trend of spectral width plotted in blue of (a)blue-light microdisk

#### 4. CONCLUSION

In conclusion, microdisks fabricated on GaN thin-film wafers through the wet-etch removal of Si substrate and microsphere lithography is demonstrated. Optical lasing with a low threshold of  $2.9 \text{ mJ/cm}^2$  and quality factor(Q) of 3100 at 453 nm is demonstrated, superior to their counterparts fabricated on thin-films processed from GaN-on-sapphire wafers through LLO of the sapphire substrate. The promising results are attributed to the smooth surfaces exposed after substrate removal by wet etching, which is retained after thin-down by plasma etching. The smoothness of this surface plays an important role in light confinement in the microdisk, being one of the largest surfaces of the microdisk.

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**Disclosures.** The authors declare no conflicts of interest.

**Data Availability Statement.** The data that supports the findings of this study are available within the article.

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