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REVIEW
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Research Progress of Gallium Nitride Microdisk Cavity Laser

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Whispering gallery mode (WGM) cavities provide resonance configurations for light propagation through internal reflection, achieving high Q factors, low thresholds, and small mode volumes. GaN-based materials exhibit high freedom in band engineering and are highly compatible with contemporary semiconductor processing technology. Recently, lasers from artificial GaN microdisks, obtained by combining the excellent material properties of GaN with the advantages of WGM, have attracted considerable research attention. These have a wide application scope in optical communication, display, and optoelectronic integration. In this review, we summarize the recent advances in GaN-based WGM microlasers, including the fabrication methods for GaN microcavities, observations of optical pumped GaN microdisk lasing, lasing mechanisms, comparison of Q factors, lasing modes, and threshold properties, commonly used light field control techniques, and mode clipping methods. Furthermore, we introduce the recent advances in electrically driven GaN-based laser diodes, followed by research challenges and strategies for promising applications, such as electrically pumped lasers and optoelectronic chip integration.

Keywords: GaN, microcavity, lasing properties, laser diode, whispering gallery mode (WGM)

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INTRODUCTION

An optical microcavity confines light propagation through resonant recirculation. In the past few decades, there has been extensive research on the applications and challenges of this technology (Chen Y et al., 2021; Rupprecht et al., 2021; Tian et al., 2021). Based on the structure of a microcavity, lasing can be classified into three categories: The first is random lasing that is typically observed in semiconductor nanopowders or -films, where light is amplified along closed loop feedback paths resulting from recurrent scattering at crystal boundaries. The second is F-P lasing observed in nanorods, where light is amplified along the two end planes of the nanorod perpendicular to the nanorod axis. For random lasing observed in semiconductor nanopowders or -films, the scattering loss of crystal particles is large, and the lasing mode is difficult to control. For F-P lasing observed in nanorods, the transmission losses of the end planes are very large, and it is not easy to obtain high-quality low-threshold lasing. Compared to this, whispering gallery mode (WGM) lasing exhibits a significantly higher quality factor (Q), smaller mode volume, and lower lasing threshold because of the extremely weak optical loss of the total internal reflection (TIR) at the cavity boundary. The research on WGM lasing started in the 1970s, and early WGM lasing was realized on GaInP/InP (λ = 650 nm), ZnSe/CdS (λ = 510 nm), ZnO/SiO_2 (λ = 390 nm), and InGaN/GaN (λ = 370 nm) substrates. In recent years, WGM lasing has promoted the development of several applications, such as thermal sensing and aerial mapping (Xu et al., 2018), photonic gyroscope (Xia et al., 2019), and biological imaging (Knapper et al., 2016).

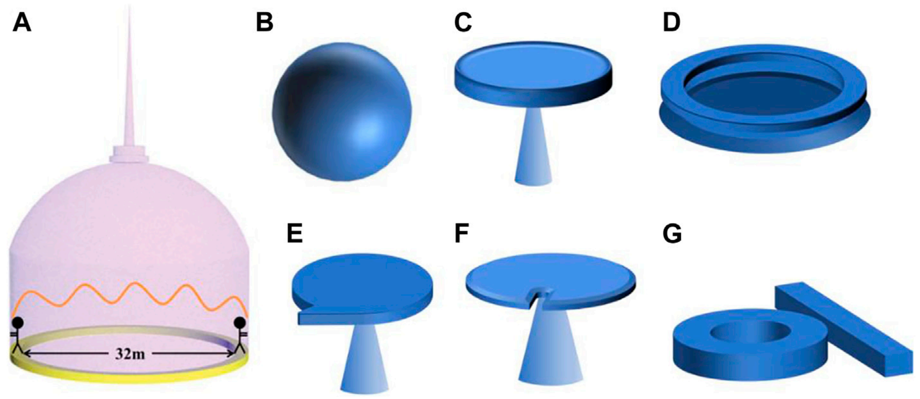

FIGURE 1 | Schematic of various WGM resonators with different structures: **(A)** dome of St Paul's Cathedral in London (Yang et al., 2015), *reprinted with permission© WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim* (Yang et al., 2015); **(B)** microsphere; **(C)** microdisk; **(D)** microring; **(E)** microdisk with chamfering; **(F)** microdisk with slit; **(G)** hybrid microcavities.

With advances in materials science, there has been considerable research interest in nitrides. GaN, a representative third-generation semiconductor material, has a high refractive index and a direct band gap of 3.4 eV, and it is compatible with existing semiconductor processing technologies (Chung et al., 2010; Hill and Gather, 2014). There has been extensive research on the laser characteristics of GaN microcavities with different structures, such as hexagonal prisms, spheres, and strips (Feng et al., 2018; Shi et al., 2021). Prof. K.W. Choi of the University of Hong Kong's research group (Li K. H et al., 2015; To et al., 2020) fabricated suspended circular and hemispherical microcavities supported by silicon columns using silica spheres as masks and obtained blue light lasers. Prof. Feng Yun's research group of Xi'an Jiaotong University (Li et al., 2017; Li et al., 2018) prepared 3D microdisk cavities by material crimping and obtained low-threshold ultraviolet (UV) lasers. Prof. Sun Qian's research group at the Institute of Semiconductors, Chinese Academy of Sciences (Wang et al., 2019), fabricated GaN microdisks using standard semiconductor processes, such as photolithography and reactive ion etching, and achieved electrically driven UV lasers. The above GaN microcavity lasers are based on WGM lasing and are widely used in quantum technology, UV spectrum manipulation, microdisplay, and visible light communication (Miao et al., 2016; Yang et al., 2019).

In this review, we summarize the recent advances in GaN microlasers. In *Introduction*, the classification of microcavites, advantage and typical reported of GaN microdisk laser was presented. The fabrication methods of GaN microdisk was then introduced in *Design and Fabrication of III-N Micro- and Nanoresonantors*. In *Optically Pumped GaN Microcavity Lasing*, the lasing mechanisms, including the mode evolution, Q factor, and threshold characteristics, are reviewed. The commonly used light field control techniques and mode clipping methods are introduced in *Tailoring the Lasing Mode of GaN Microcavities*. Then, recent advances in GaN-based microlasers, such as vertical laser diodes and microdisk laser diodes, are introduced in *Electrically Driven GaN Laser Diodes*. Finally, *Optoelectronic Chip Integration* presents further research challenges of the potential applications of large-scale on-chip integration.

DESIGN AND FABRICATION OF III-N MICRO- AND NANORESONATORS

The idea of WGMs was presented several hundred years ago when the phenomenon of acoustic propagation was observed in the dome of St Paul's Cathedral in 1912 (Yang et al., 2015). Winters et al. observed that if they were all standing near a wall (Winters and Coburn, 1979; **Figure 1A**), people could hear murmurs from anywhere in the gallery. This phenomenon also applies to light; that is, light can be reflected and confined to an infinite number of microsphere or microdisk cavities to enhance light–matter interactions (Kang et al., 1998; Rahmani and Jagadish, 2018). Since the 20th century, this phenomenon has been widely implemented in applications such as biosensors, optical communications, displays, and light sources (Skromme et al., 1999; Ferreira et al., 2016; Irmer et al., 2016; Zhang et al., 2016; Guo et al., 2019; Jiang et al., 2019; Toropov et al., 2021). To adapt to different applications and obtain high-quality and low-threshold lasers, microcavities of various shapes have been designed and fabricated (**Figures 1B–G**). The device architectures have smooth faces that ensure excellent optical properties.

Some typical methods used to achieve GaN microstructures are molecular beam epitaxy (MBE) (Li and Waag, 2012; Higashiwaki et al., 2014), hydride vapor phase epitaxy (HVPE) (Lai et al., 2021; Seredin et al., 2021), and metal-organic chemical vapor deposition (MOCVD) (Peng et al., 2021; Wang et al., 2021). The resulting GaN structures have atomic-level smooth surfaces and low density of dislocations; moreover, the lasing thresholds are typically low, and the Q factors are high. However, these cavities have several obvious limitations. For example, the cavity structures are relatively fixed, such as hexagonal disks, microrods, or pyramidal cavities. With the development of top-down micro- and nanofabrication technologies, microcavities with controllable structures can be fabricated, resulting in chip-integrated semiconductor devices (Borselli et al., 2005; Xiao et al., 2008; Tamboli et al., 2009; Jiang et al., 2016; Sellés et al., 2016; Yonkee et al., 2016; Tabataba-Vakili et al., 2018; Yao and Yang, 2020).

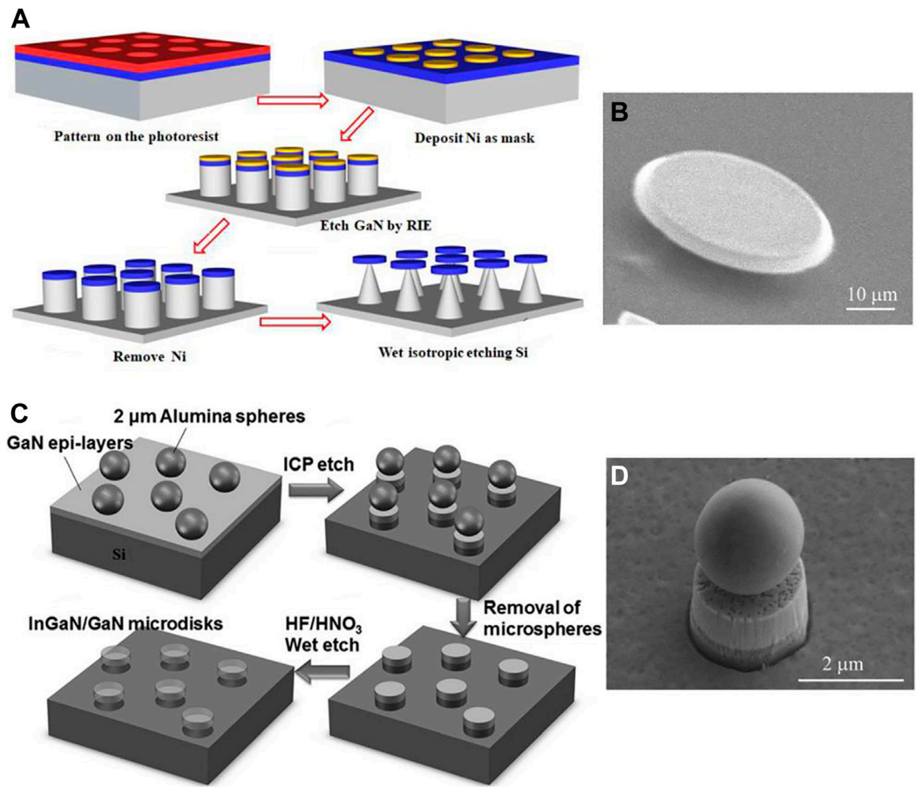

FIGURE 2 | Schematic of fabrication of GaN microdisks with **(A)** an Ni hard mask and **(C)** a sphere metal mask. SEM images of the **(B)** floated GaN microdisk fabricated by the Ni hard mask (Zhu et al., 2018), *reprinted with permission© Optical Society of America* (Zhu et al., 2018), and **(D)** GaN microdisk fabricated with the sphere mask (Zhang Y. et al., 2014), *reprinted with permission© AIP Publishing LLC* (Zhang Y. et al., 2014).

Our group introduced an experimental etching process to develop GaN-based microdisks (Zhu et al., 2018) (schematic illustration in **Figure 2A**). GaN microdisks in a grid pattern can be fabricated with Ni hard masks on a commercial GaN-on-silicon substrate with photolithography followed by dry and isotropic wet etching of silicon. As opposed to GaN microdisks manufactured using photoresist masks, this process can also be conducted using SiO_2 and Al microsphere masks (**Figure 2C**). Zhang Y et al. (2014) fabricated GaN microdisks using microsphere lithography followed by dry and wet etching (**Figure 2B**). In this design, Al microspheres (diameter = ~2 μm) were used as hard masks, and thus, the fabricated microdisks had diameters <2 μm. As illustrated in **Figure 2D**, the microdisk is much smaller than those reported in studies of Vicknesh et al. (2007) or Woolf et al. (2014).

OPTICALLY PUMPED GAN MICROCAVITY LASING

Resonant Mode Calculation and Main Parameters

Compared with other types of lasing cavities such as F-P, WGM lasing has a higher quality factor (Q) and lower laser threshold owing to the small optical loss on cavity boundaries (Khurgin and Noginov, 2021). However, the nature of resonance is the same for all these laser structures. In theory, the resonance mode of a cavity depends on its optical length (L), and the mode is fitted using the following equation:

$$m\lambda = L \tag{1}$$

For F-P mode cavities, $\mathbf{L} = 2n_{eff}l$. For WGM cavities, $\mathbf{L} = \pi n_{eff}D$. Here, m is the number of angular momentum modes, $\boldsymbol{\lambda}$ is the central wavelength, n_{eff} is the effective refractive index, l is the length of the F-P cavity, and D is the diameter of the microdisk (Zhu G. Y. et al., 2020; Qin et al., 2021a). As seen in the above equation, for the same lasing mode, the WGM cavities are smaller than the F-P ones.

The typical parameters used to characterize the lasing properties of microdisks are as follows: quality factor (Q), mode volume (V), free spectral range (FSR), and threshold value (P_{th}). $\mathbf{Q} = \boldsymbol{\lambda}/\boldsymbol{\Delta\lambda}$ represents the light confinement ability of the microcavity, where λ is the peak wavelength and $\boldsymbol{\Delta\lambda}$ is the full width at half maximum (FWHM) (Matsko and Ilchenko, 2006). Q can also be expressed as a product of angular frequency, ω, and decay time, τ, that is, Q = ωτ. Mode volume is a parameter that describes the ability to confine the trapped light within a certain volume in the spatial domain of an optical cavity (Luo et al., 2021). It is given as the ratio of the stored energy of light and the maximum energy density (Srinivasan et al., 2006):

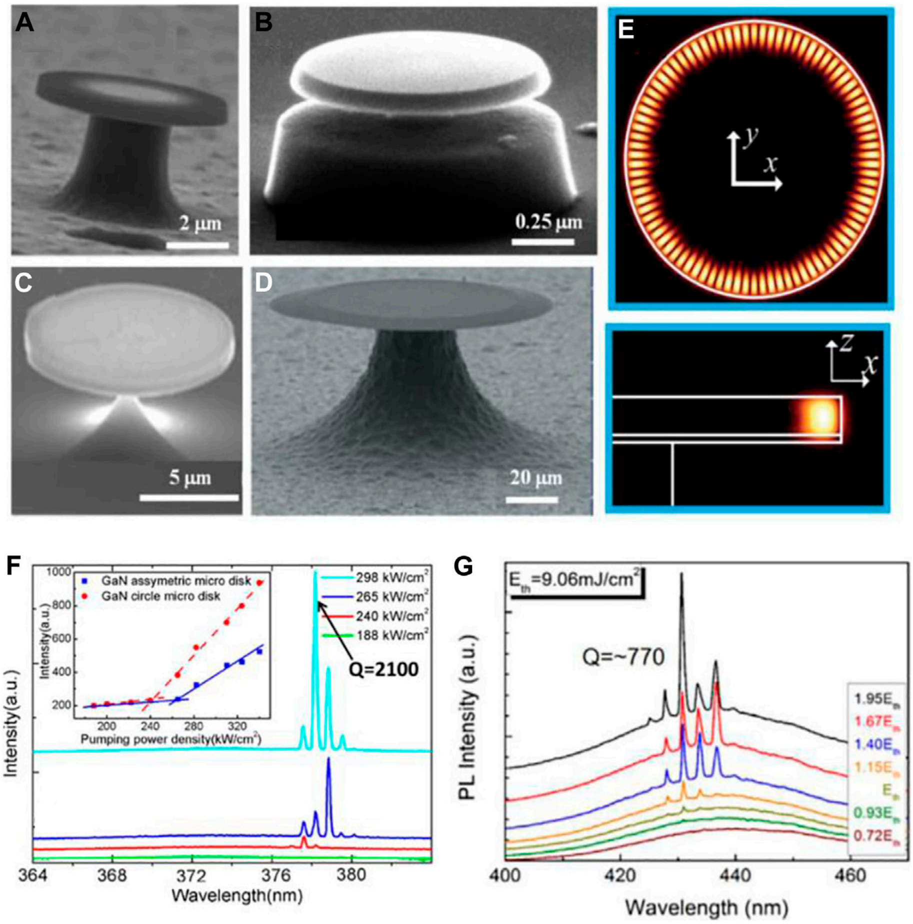

FIGURE 3 | (A–D) GaN microdisk cavity lasers with various morphologies (Yan et al., 2009; Zhang X et al., 2014; Bogusławski et al., 2018; Liu et al., 2019); **(E)** WGM lasing simulation results of microdisk cavities; **(F)** lasing spectra of the GaN microdisk in the UV region; **(G)** lasing spectra of the GaN microdisk in the blue region (Zhang X et al., 2014; Zhu et al., 2017). Reprinted with permission© AIP Publishing (Yan et al., 2009; Zhu et al., 2018).

$$V_m = \frac{\int \varepsilon(r)\left|E(r)\right|^2}{(\varepsilon(r)E^2(r))_{max}} d^3r \tag{2}$$

where $\varepsilon(r)$ is the optical permittivity and $E(r)$ is the electric field density. A smaller mode volume of a microcavity implies that higher optical field confinement can be achieved (Robinson et al., 2005; Jiang et al., 2020).

FSR is the resonant wavelength or frequency interval of two adjacent modes (Chen H et al., 2021). If we ignore refractive index dispersion, FSR is calculated using the following equation:

$$\mathbf{FSR} = \frac{\lambda^2}{2\pi nR} \tag{3}$$

Threshold value (P_{th}) is another important parameter of lasing properties. Exploring the limits of low-threshold lasing is one of the key goals in the development of nanocavity lasers (Streiff et al., 2003). Most GaN microdisk lasers are fabricated using GaN quantum well (QW) materials. For GaN microdisks, Q is in the range 650–5,500 and P_{th} is < 270 kW/cm^2. Microdisk cavities based on GaN materials have the advantages of high Q factors, small mode volumes, and low thresholds (Michler et al., 2000; Simeonov et al., 2008; Aharonovich et al., 2013; Wang et al., 2018).

WGM Lasing in GaN Microdisk Cavities

WGM lasing has a higher Q, lower lasing threshold, and smaller mode volume than other types of lasers. This is because the TIR on cavity boundaries can ensure weak optical loss. Owing to its excellent performance, WGM microcavity lasing has attracted considerable attention for several applications such as single-particle label-free sensing, microdisplays, imaging, and scanning (Vahala, 2003; Miller, 2009; Stock et al., 2013); GaN UV lasing has attracted considerable attention in optics research (Choi et al., 2011; Tabataba-Vakili et al., 2020). Typical results are presented in **Figure 3**, and several resonator structures (**Figures 3A–D**), such as spherical, disk, toroidal, and microbubble, have been demonstrated in recent years (Seo et al., 2003; Kwon et al., 2008; Sumetsky, 2010; Ward et al., 2014; Dong et al., 2017; Wang et al., 2017). As seen in **Figure 3E**, light is well confined in the x–y plane of GaN microdisks. The low- and high-order modes are confined

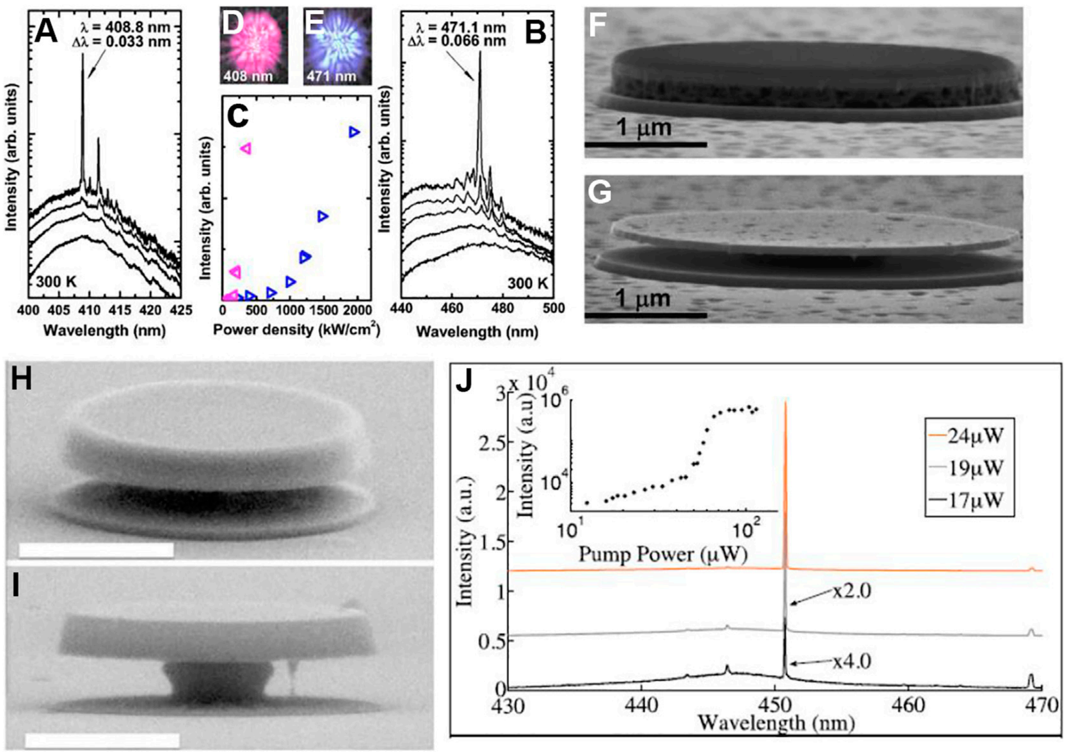

FIGURE 4 | Lasing properties of GaN microcavities (Simeonov et al., 2008), reprinted with permission© AIP Publishing (Simeonov et al., 2008). Lasing spectra of GaN microcavities with **(A)** low and **(B)** high In content. **(C)** Threshold curves of GaN microcavities. Optical microscopy images with false color **(D,E)**. SEM images of AlGaN **(F)** before and **(G)** after removal of the oxidation sacrificial layer. Lasing properties of floating GaN microstructures with a quantum well layer (Woolf et al., 2014): **(H,I)** SEM images; **(J)** lasing spectra with the threshold curve as an inset image, reprinted with permission© PNAS Publishing (Woolf et al., 2014).

in the thickness of the microcavity along the z-axis. Typical GaN lasing has a symmetric resonance spectrum, such as lasing spectra in **Figure 3F** reported by Zhu et al. (2017). Optically pumped lasing at room temperature has excitation energy densities in the range 188–298 kW/cm^2. Optical resonances in multiple modes were observed in the gain range of 376–380 nm. Similar results are presented in **Figure 3G**, obtained by Zhang X et al. (2014). Optically pumped lasing was achieved at excitation energy densities of 9.06 mJ/cm^2, and the obtained values of Q were approximately 770 at a lasing peak value of ~430.2 nm. Although GaN microdisk lasers have been widely studied, owing to the rotational symmetry of these WGM cavity structures, they typically generate planar isotropic laser emission, resulting in extremely low collection efficiency in free space. Future studies should attempt to address this drawback (Yan et al., 2009; Bogusławski et al., 2018; Liu et al., 2019).

First, the smoothness of the optical cavities should be improved, as roughness and thickness of the cavity considerably influence its lasing properties. According to Alexander's results, finite-thickness microdisks cannot address the degeneracy of the WGM doublets; however, these can limit their accessible Q factors to some extent (still very high) (Nosich et al., 2007). Based on this idea, Simeonov et al. (2008) demonstrated selective wet chemical etching for an AlInN sacrificial layer lattice-matched to GaN for the fabrication of air-gap photonic structures (**Figures 4A–G**). Optically pumped lasing at a wavelength of 408.8 and 471.1 nm was achieved under continuous wave (CW) laser pumping. Woolf et al. (2014) fabricated low-threshold lasers with high-quality optical cavities and gain materials of InGaN quantum dots or QWs. GaN microdisks with diameter = 1.2 μm and thickness = 200 nm were set as the resonant cavities (**Figures 4H,I**). Lasing oscillation with a main wavelength of approximately 450 nm and Q value of approximately 5,500 was realized with a threshold value of 184 μW (**Figure 4J**). Tamboli et al. (2007) realized lasing in microdisk arrays with diameter = 1.2 μm under continuous lasing operation at room temperature; the threshold was approximately 270 W/cm^2, and Q was approximately 3,700. This research aimed to reduce the thickness of microdisks to the thickness of the quantum well layer.

Second, the cavity shape should be designed appropriately. Typically, the μ-PL system, which can provide uniform pump-laser beams with diameter = 20–50 μm, is used to measure the PL properties of GaN microcavities. Light in WGMs is usually limited to the periphery of the microdisks; therefore, the internal volume of the microdisk structure only slightly affects the laser properties. However, it also leads to energy loss due to light absorption in the cavity. For cavities with gain properties, gain, γ, should be introduced in the active region and a continuous condition should be added for the tangential

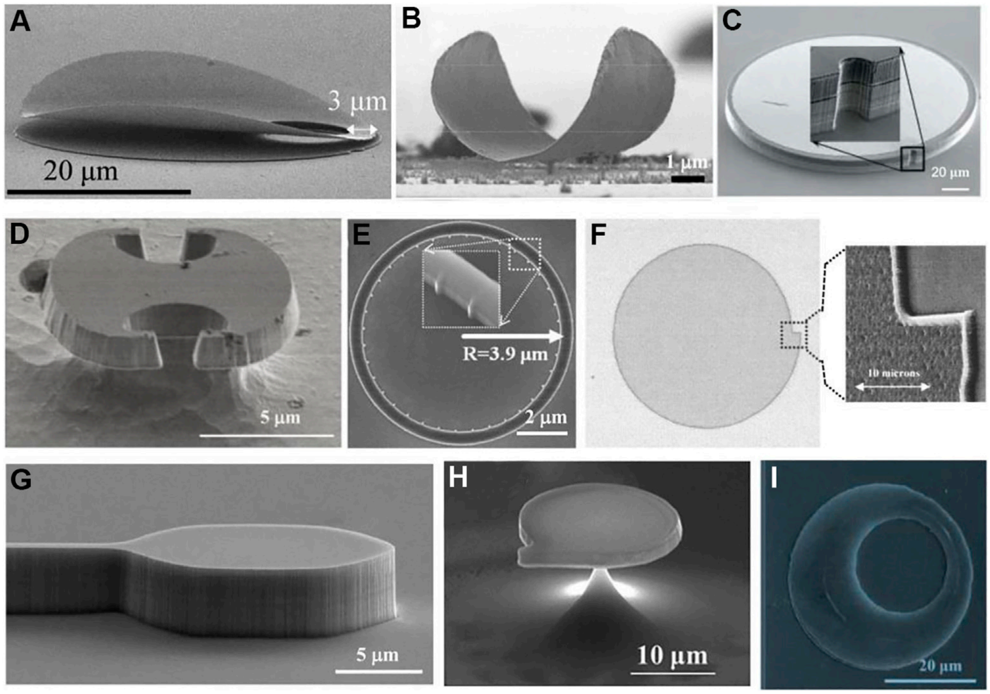

FIGURE 5 | (A,B) Microring with an off-centered embedded hole and warped structure (Li et al., 2018; Zhang et al., 2021). **(C)** Notched elliptical microcavity quantum cascade lasers (Wang et al., 2010). **(D)** Microdisk with a self-focusing structure (Zhu et al., 2019). **(E)** Microdisk with grating structures (Cai et al., 2012). **(F)** Spiral microcolumn cavity (Ben-Messaoud and Zyss, 2005). **(G)** Circular-side hexagonal resonator (CSHR) microlasers (Xiao et al., 2017). **(H)** Microdisk with a corner (Zhu et al., 2017). **(I)** Microdisk with a hole (Zhang et al., 2020). Reprinted with permission© PNAS Publishing (Wang et al., 2010),© IOP Publishing (Zhu et al., 2019),© American Association for the Advancement of Science (Cai et al., 2012),© AIP Publishing (Ben-Messaoud and Zyss, 2005; Zhu et al., 2018),© OSA Publishing (Xiao et al., 2017; Zhang et al., 2020).

component of the field on the boundary of this region (Smotrova et al., 2005). Reducing the disk size and thickness of the cavity is a useful strategy for achieving high-quality lasing. A ring-shaped active region can be as narrow as 0.2 μm and still provide the same value of the material gain threshold with the same mode as that in the uniformly active disk (Rex et al., 2001). In 1999, Zeng et al. (1999) studied the optical resonance modes in InGaN/GaN multiple-quantum-well microring cavities. Zhu et al. (2020a) obtained floating GaN microring lasing using the Burstein–Moss effect at room temperature. Zhang et al. (2020) designed and fabricated an asymmetric microring cavity by introducing a GaN-based eccentric microring with an inner hole located off the center; they achieved low threshold values and unidirectional lasing emission.

Third, realization of multi-functional microcavities such as single-mode or directional radiation is a popular research topic. A serious drawback of microdisk lasers is the low directionality of light emission inherent circular cavities. The isotropic lasing emission of WGM lasing typically limits their applications in several fields. To overcome this drawback, rotational symmetry of the microcavity should be broken by introducing defects in the mode field region or by forming an asymmetric/deformed cavity structure (Wang et al., 2010; Liu et al., 2012; Zhan et al., 2015). To control the emission direction of GaN microdisks, Zhang et al. (2021) fabricated a microring with diameter = 40 μm (**Figure 5A**) and an off-centered embedded hole and warped structure of strained III-nitride quantum well multilayers. In a similar previous study (Zhang et al., 2020) (**Figure 5I**), unidirectional and single-mode lasing was achieved. Compared with other studies, this study could more conveniently realize mode control of lasing properties (Zhizhchenko et al., 2019). Zhu et al. designed microdisks with corners (**Figure 5H**) (Zhu et al., 2017) and self-focusing structures (**Figure 5D**) (Zhu et al., 2019) to engineer the mode number and emission direction of the cavity. Li et al. (2018) presented a three-dimensional (3D) WGM with a self-bending microdisk, which comprised strain-released AlGaN/GaN bilayer films (**Figure 5B**); it provided more WGM photon degrees-of-freedom in the vertical direction compared to the two-dimensional WGM distributed in the horizontal direction. Xiao et al. (2017) demonstrated circular-side hexagonal resonator (CSHR) microstructures (**Figure 5G**) to realize unidirectional emission single-mode microlasers. Spiral microcolumns, slits, gratings, and notched elliptical structures were also introduced to the microcavities (**Figures 5C,E,F**) (Ben-Messaoud and Zyss, 2005; Wang et al., 2010; Cai et al., 2012), realizing lasing resonant. All these structures ensure that light radiates at a specific angle.

FDTD simulation (Chen and Wang, 2007; Jiang et al., 2012) is a conventional method to characterize the direction and mode characteristics of GaN lasing. Due to the isotropy of a cavity with a circular structure, the light field is uniformly circular, and it has an obvious standing wave shape. As shown in **Figure 6A**,

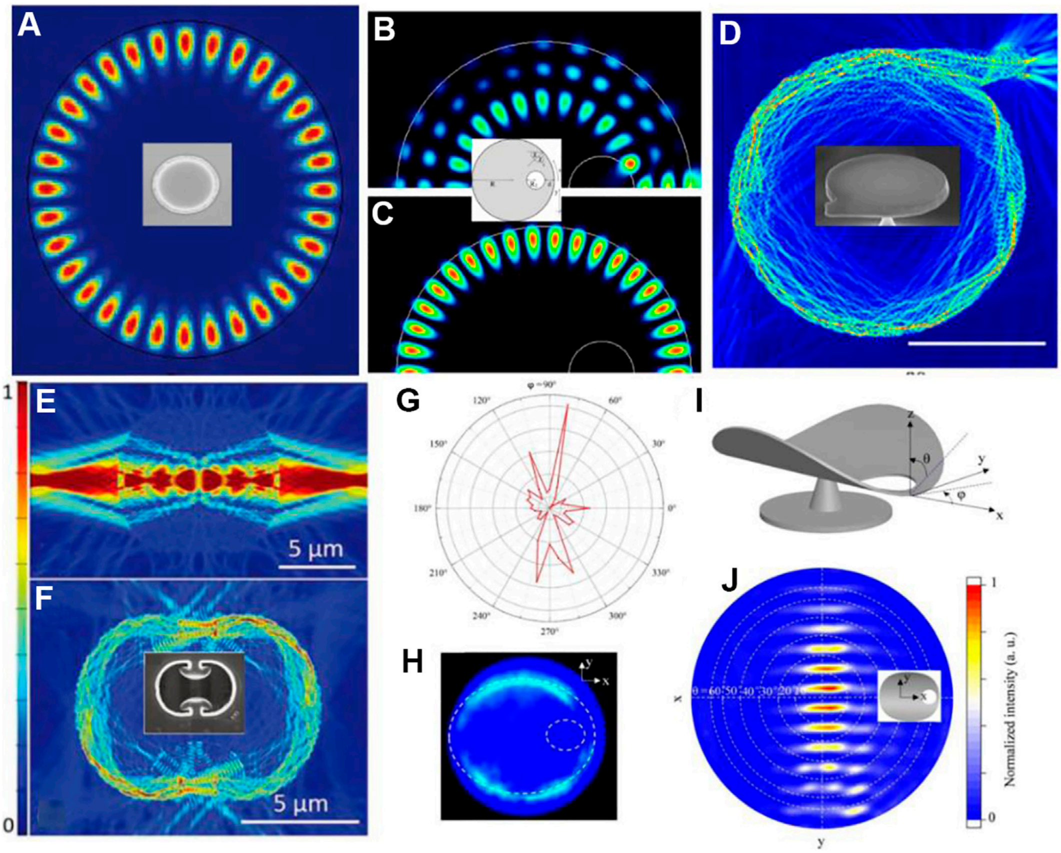

FIGURE 6 | FDTD simulation results of a **(A)** microdisk (Tamboli et al., 2007), **(B,C)** microdisk with a hole (Wiersig and Hentschel, 2006), **(D)** GaN microdisk with a corner (Zhu et al., 2017), and **(E,F)** GaN Penrose microcavity (Zhu et al., 2019). **(G)** PL intensity of the laser mode at 441.3 nm in various detection angles. **(I)** Illustration of warped microdisks in a 3D spherical coordinate system. **(H)** CCD image of the warped microring. **(J)** Far-field pattern of the warped microring calculated by FDTD (Zhang et al., 2021). Reprinted with permission© Nature Publishing Group (Tamboli et al., 2007),© American Physical Society (Wiersig and Hentschel, 2006),© AIP Publishing (Zhu et al., 2018),© IOP Publishing (Zhu et al., 2019),© 2021 Chinese Laser Press (Zhang et al., 2021).

Tamboli's work indicated a first-order mode visible at wavelength = 418 nm with a distinct number of standing wave modes (Tamboli et al., 2007). Puchtler et al. (2015) presented high-quality factor devices comprising nitrides and simulated the optical field distribution. Wiersig and Hentschel (2006) demonstrated a microdisk with a hole, shown in **Figures 6B,C**; it showed a faint resemblance to a WGM, but it implied a clear directed emission due to refractive escape. The directional emission is clearer in Zhu et al.'s work (Zhu et al., 2017); it had a chamfer in the disk (SEM image in **Figure 5H**). **Figure 6D** shows light emitted from the corner of the disk. It is more interesting in their other work, in which GaN microdisks with focus effect were designed (SEM image in **Figure 5D**) (Zhu et al., 2019). The simulation results of two lasing peaks at wavelengths of 375.3 and 377.3 nm were consistent with the experimental lasing spectra (**Figures 6E,F**). These modes are focused on the two sides of the cavity. Lasing of warped microring in Zhang's work (Zhang et al., 2021) presented clear anisotropic characteristics (**Figures 6G,I**). Light is efficiently collected and plotted in **Figure 6H**. The far-field of the warped microring illustrated in **Figure 6J** had the same anisotropic characteristics (0–30°). This indicates that the warped microring has a small far-field angle.

TAILORING THE LASING MODE OF GAN MICROCAVITIES

Compared with multi-mode lasers, output lasing with short modes, even a single mode, is valuable for practical applications (Xu et al., 2012; Feng et al., 2014; Nakajima et al., 2019). Conventional experimental schemes, such as reducing the cavity size and introducing structures such as gratings, slots, or nano-antennas, have been widely utilized to achieve single-mode lasers. Fujita and Baba (2002) introduced saw tooth structures for GaInAsP–InP microcavities (**Figure 7A**). Moiseev et al. (2017) introduced antenna structures on the side of InAs microdisks (**Figure 7E**). Bogdanov et al. (2015) etched slits on the surface of InAs microdisk cavities using focused ion beam technology (**Figure 7D**). All above research has observed laser mode regulation in microdisk cavities. Our group (Zhu G. Y. et al.,

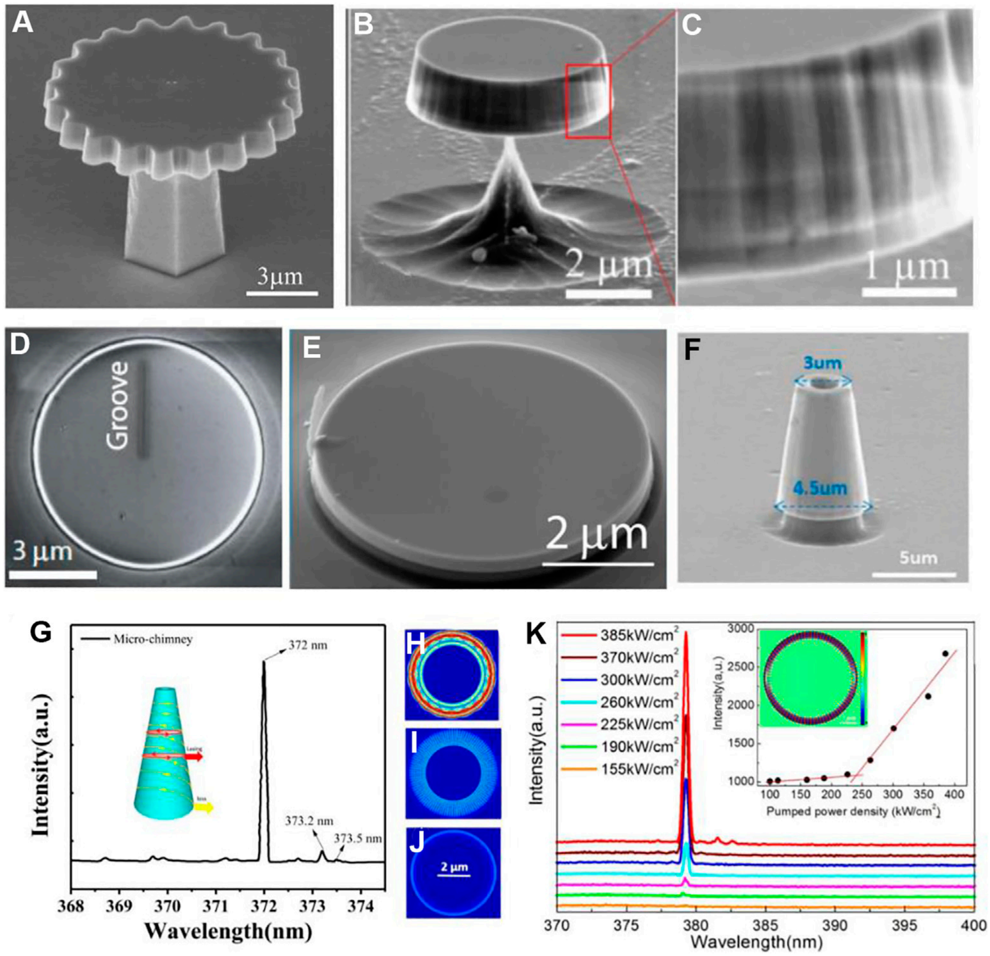

FIGURE 7 | (A) Microdisk with a saw tooth structure for a GaInAsP–InP microdisk (Fujita and Baba, 2002). SEM images of the GaN microdisk with a **(B,C)** grating along the side (Zhu et al., 2018), **(D)** slit (Bogdanov et al., 2015), and **(E)** Pt antenna structure (Moiseev et al., 2017). **(F)** SEM images, **(G)** lasing spectra, and **(H–J)** optical field distribution of the microchimney cavity (Zhu G. Y. et al., 2020). **(K)** Power-dependent lasing spectra of the GaN microdisk (Zhu et al., 2018). Reprinted with permission© AIP Publishing (Fujita and Baba, 2002),© *Optical Society of America* (Bogdanov et al., 2015; Zhu et al., 2018),© ACS Publishing (Moiseev al., 2017),© Elsevier Publishing (Zhu G. Y. et al., 2020).

2020) realized quasi-single-mode ultraviolet WGM lasing from microchimney cavities under optical pumping (**Figure 7F**). Lasing spectra in **Figure 7G** imply single-mode resonance of approximately 372 nm. Compared to other works, the lasing of microchimney cavities directs light along the cavity and obtains a spiral path of light (**Figures 7H–J**). In our other works (Zhu et al., 2018), a grating structure was introduced to floating GaN microdisks. Single-mode lasing (**Figures 7B,C,K**) was realized in this structure. With increasing pumping power, lasing resonance appeared at approximately 379.25 nm. Based on electrical field distribution, WGM lasing was confirmed; this study is similar to Wang's work (Wang et al., 2018). Although laser mode regulation can be achieved, the above methods may introduce damage to the microcavity. It may reduce the quality of the microcavity laser and increase the laser threshold. The effect of large-scale changes in alignment indexing caused by small changes in the measurement value is defined as the Vernier effect (Wang Y. Y et al., 2016; Liu et al., 2021). It is also applied in optical systems. The FSR can be controlled by adjusting the size of microcavity. A common mode can be selected by using two devices with similar spectra. With the Vernier effect, the lasing can maintain low laser threshold and high Q value. By designing the coupling cavity and using the Vernier effect, mode selection can be realized while improving laser quality. Xu et al. (2012) achieved a single-mode laser by coupling two GaN microrods near each other. A single microcavity produced a multi-mode laser, while the coupling of two cavities produced a single-mode laser. This lasing mode engineering can even be generalized to dynamic mode regulation (Yang et al., 2018; Peng et al., 2019; Qin et al., 2021b).

ELECTRICALLY DRIVEN GAN LASER DIODES

Owing to their advantages in wide-emission ranging from UV to near-infrared (IR) and direct band gap, GaN materials have been

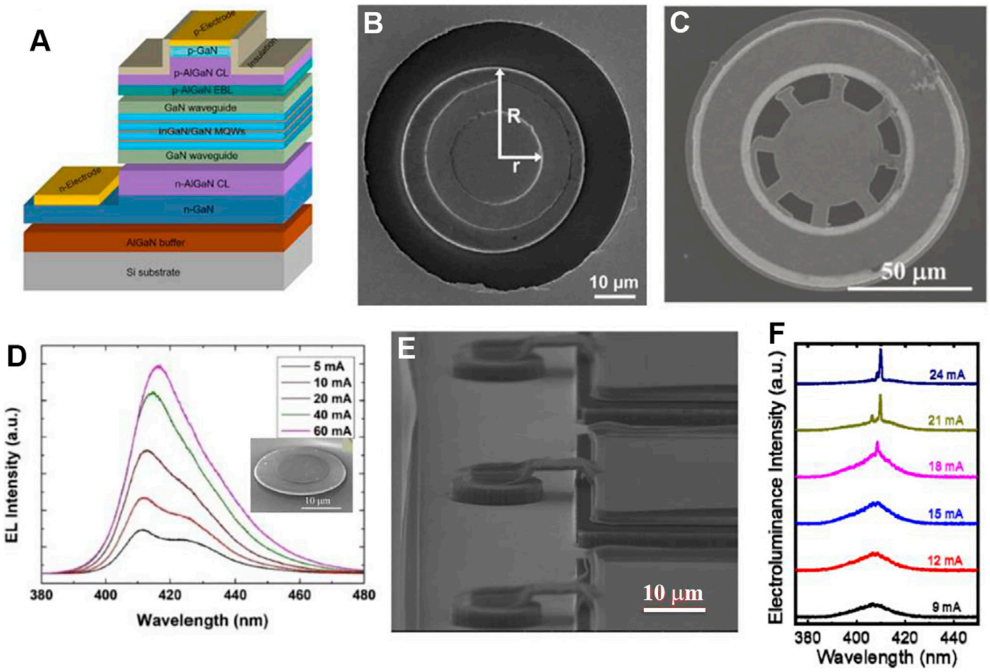

FIGURE 8 | (A) Typical layer structure of the GaN-based laser diode (LD) on an Si substrate. **(B,E)** SEM images of the GaN microdisk for electrically driven lasing (Wang et al., 2020; Feng et al., 2021) and **(C)** GaN microwheel for LED (Zhu et al., 2020b). EL spectra of the **(D)** GaN microdisk (Mei et al., 2021) and **(F)** microdisk laser (Wang et al., 2020). Reprinted with permission© Elsevier Publishing (Feng et al., 2021),© IOP Publishing (Zhu et al., 2019).

widely used for high-efficiency light-emitting diodes (LEDs) and LDs (Strawbridge et al., 2011; Lu et al., 2014; Ding et al., 2021; Jmerik et al., 2021; Yulianto et al., 2021). III-Nitride LDs have been widely used in displays, lighting, and optical storage and have shown considerable potential for applications in monolithic integration, visible light communication, optical clocks, material processing, quantum technology, and medical instruments. GaN lasers can be fabricated on GaN, sapphire, SiC, or Si substrates (Lee et al., 2017; Sun et al., 2018). Most contemporary GaN-based LDs are produced on two-inch free-standing (FS) GaN substrates (~$4,000/pc), because of which the LD chip costs 2–3 orders of magnitude higher than LEDs grown on Si or sapphire substrates. The most recent research results indicate that the III-nitride semiconductor laser directly grown on Si is a potential on-chip light source for Si photonics. Moreover, it may greatly lower the manufacture cost of laser diodes and further expand their applications. Due to its low cost, large volume, low resistivity, and high thermal conductivity, the GaN-on-Si substrate has become a popular research topic in recent years (Bao, 2017; Jiang et al., 2017).

A typical layer structure of GaN-based LDs on Si substrates is seen in **Figure 8A** (Feng et al., 2021). It presents InGaN/GaN MQWs and optical cladding layers. For poor cavity quality, it presented normal spontaneous radiation (**Figure 8D**) (Mei et al., 2021). Violet, blue, and near-UV LDs were realized in structures with better-quality cavities (Zhang et al., 2003; Christ et al., 2004; Roehrens et al., 2010). Popular research groups in this field are Sun Qian's research group of the Semiconductor Institute of Chinese Academy of Sciences and the SINANO research group. Feng et al. (2021) used a "sandwich-like" architecture with upper and lower AlGaN cladding layers to design lasing structures (**Figure 8B**). They demonstrated confinement of the optical field in InGaN-based microdisk lasers grown on Si substrates. Lasing resonance was observed under a 250 mA-driven current threshold (**Figures 9C,D**). To further reduce the optical loss, Zhu et al. (2020b) designed and fabricated a perovskite-coated GaN microwheel structure (**Figure 8C**). This device exhibited two emission peaks near 438 and 512 nm (**Figures 9A,B**). However, only spontaneous radiation in the blue range was observed. Recently, Wang et al. (2020) fabricated GaN microdisks with diameter = 10 μm. Lasing resonance with a high Q factor was realized under current driven <18 mA (**Figures 8E,F**).

OPTOELECTRONIC CHIP INTEGRATION

Optoelectronic integration technologies compatible with large-scale low-cost silicon electronics are considered promising approaches to overcome the speed and bandwidth limitations of communication and computing technologies (Moerman et al., 1997; Hao et al., 2021). However, the drawbacks of Si-based materials, such as narrow and indirect band gaps, are not conducive to optoelectronic devices with gain. To overcome this, silicon-based GaN has been used to fabricate integrated devices (Shih et al., 2005; Ogihara et al., 2008; Pham et al., 2013). Compared with Si, nitride compound semiconductors (AlGaN or InGaN) have tunable and direct optical band gaps,

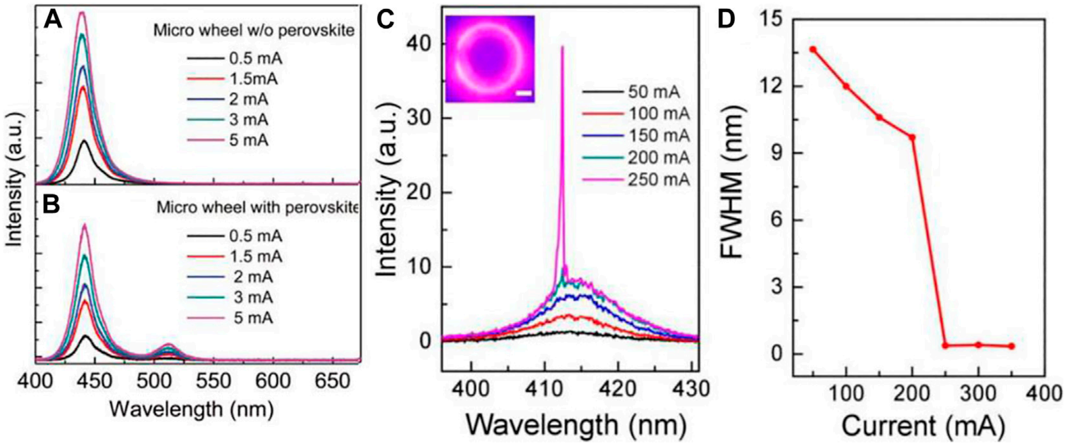

FIGURE 9 | EL spectra of a GaN microwheel **(A)** without and **(B)** with $CH_3NH_3PbBr_3$ at varying currents (Zhu et al., 2020b). **(C)** EL spectra of an as-fabricated InGaN-based microring laser grown on an Si substrate (Feng et al., 2021). **(D)** Relationship between the FWHM of EL spectra and the pulsed injection current in **Figure 9C**. Reprinted with permission© Elsevier Publishing (Feng et al., 2021),© IOP Publishing (Zhu et al., 2019).

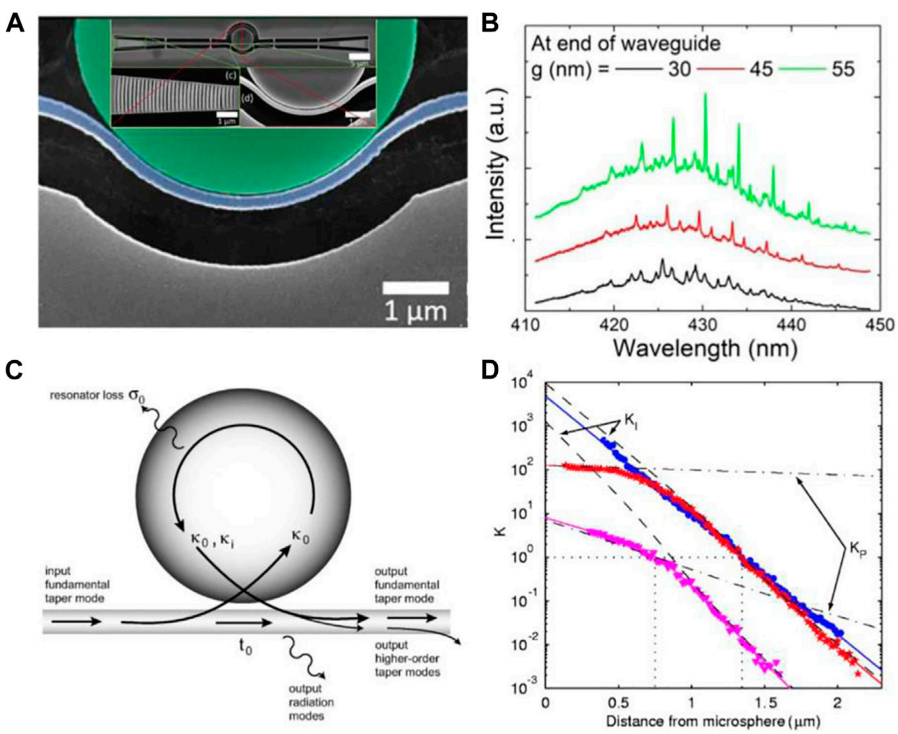

FIGURE 10 | (A) Coupling structure in an active GaN microdisk laser with bus waveguide on an Si substrate. **(B)** Lasing spectra of coupled structures with different coupling distances (Tabataba-Vakili et al., 2019). **(C)** Schematic diagram of the waveguide coupled with a microcavity. **(D)** Relationship between the coupling distance and the coupling coefficient (Spillane et al., 2003). Reprinted with permission© APS Physic Publishing (Spillane et al., 2003).

and these are compatible with traditional micromachining processes. Hence, coupling WGM microdisk lasers with waveguides can enable the monolithic integration of GaN microdisks or microrings with other structures (Koseki et al., 2009). Witzens et al. (2005) realized the monolithic integration of vertical-cavity surface-emitting lasers with in-plane waveguides. Tabataba-Vakili et al. (2019) demonstrated a critical coupling structure on an active GaN microdisk laser with bus waveguide on an Si substrate (**Figures 10A,B**). Lasing parameters, such as thresholds and Q factor, can be controlled by varying the coupling distance. As shown in **Figure 10B**, the resonance mode in the range of 410–450 nm was obtained. The evanescent tail of resonance in GaN

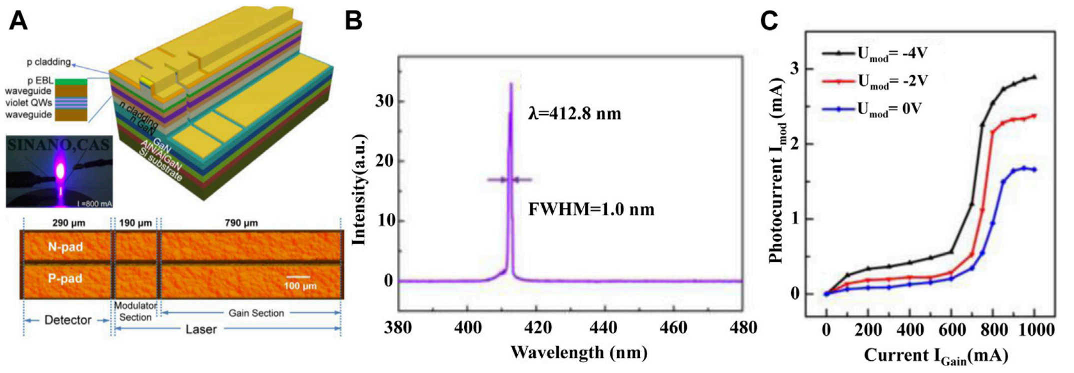

FIGURE 11 | (A) Schematic diagram of integrated devices; **(B)** lasing spectra of GaN LDs; **(C)** photocurrent response curves at different bias voltages (Feng et al., 2018). Reprinted with permission© IEEE Xplore Publishing (Feng et al., 2018).

microdisks is coupled by the bus waveguide on the side, and transmission through the waveguide can be detected in the back of the waveguide. According to Rasoloniaina's reports (Rasoloniaina et al., 2014) and (Spillane et al., 2003) shown in **Figures 10C,D**, the resonance mode is coupled with different coupling distances and can be quantized. The transmission through the waveguide can be explained based on the gap between the microdisk and the waveguide.

By combining optically pumped GaN laser structures and chip-integrated LED or LD structures, waveguide and photoelectric detectors on the Si substrate have been studied and used in high-speed communication (Schinkel et al., 2009; Li X et al., 2015; Wang Y et al., 2016; Tanaka et al., 2017). As shown in **Figure 11**, Feng et al. (2018) fabricated on-chip-integrated GaN-based lasers, modulators, and photodetectors grown on Si substrates (**Figures 11A,B**). A multi-quantum well structure with 290 μm (LD region), 190 μm (modulation region), and 790 μm (PD region) was designed and fabricated. EL with an FWHM of 1 nm and peak position of 412.8 nm was realized in this study. The photocurrent in the PD is presented in **Figure 11C** and modulated basis the bias voltage.

SUMMARY AND PROSPECT

In this study, we review recent advances in the realization of GaN microstructures, observations of WGM lasing, and the corresponding lasing mode engineering. The WGM lasing mechanism is summarized as the total reflection of the inner wall. The Q factor, mode volume, FSR, and threshold value are important parameters to evaluate the quality of microcavity. GaN microdisks are prepared using two types of methods, namely, direct growth using CVD or MBE and fabrication using photolithography followed by wet and dry etching. Optically pumped lasing has been obtained in GaN microstructures such as microdisks or microrings. Engineering of lasing properties such as mode number tailoring or emission direction controlling is well studied. Methods such as introduction of holes, corners, metal antennas, and slits are used to control the emission direction, and special structures such as grating or saw tooth are introduced to tailor the lasing mode. Decreasing the thickness of the cavity and improving the sidewall roughness are key issues to optimize the Q factor or threshold value of the cavity. The aim of studying optically pumped WGM lasing is to obtain electrically injected lasing. By decreasing the gain region, floating the cavity, or improving the surface condition, an electrically injected WGM laser can be realized for a cavity with diameter ≤10 μm. Further research challenges in GaN microdisk lasing are the fabrication of microstructures with smooth surfaces and steep side walls. In addition, the design and preparation of special microstructures for achieving high-performance electrically pumped lasers and integrated device design are also popular topics for future research.

AUTHOR CONTRIBUTIONS

GZ gave the article structure and organized the manuscript. FG, YS, MT, and BJ summarized the work. FQ edits the manuscript. XL and YW gave some comments on the content and structure of the manuscript.

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