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Progress and Prospects of GaN-based VCSEL from Near UV to Green Emission

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Abstract

GaN is a great material for making optoelectronic devices in the blue, blue-violet and green bands. Vertical-cavity surface-emitting lasers (VCSELs) have many advantages including small footprint, circular symmetry of output beam, two-dimensional scalability and/or addressability, surface-mount packaging, good price-performance ratio, and simple optics/alignment for output coupling. In this paper, we would like to (1) Review the design and fabrication of GaN-based VCSELs including some technology challenges, (2) Discuss the design and metalorganic chemical vapor deposition (MOCVD) growth of electrically pumped blue VCSELs and (3) Demonstrate world first green VCSEL using quantum dots (QDs) active region to overcome the 'green gap'.

1. Introduction

The concept of vertical cavity surface emitting lasers (VCSELs) was first proposed in 1977 by Prof. Kenichi Iga and his colleagues, and the first device was demonstrated in 1979 [1, 2]. Since then VCSELs related research became a fast growing field and VCSELs were soon been commercialized in 1994. During the past two decades, most of the efforts were focused on the optimization of operation characteristics of near infrared spectral range. The most matured material system for commercial VCSELs fabrication is GaAs-based compound semiconductors due to its relatively larger refractive index difference and minor lattice constant mismatch. And the lasing wavelength could be tuned to cover the spectra from red to near infrared by adjusting the AlGaAs or InGaAs active layer composition. For longer wavelength application, InP-based materials could also be used as the active gain mediums combined with the well established GaAs/AlGaAs distributed Bragg reflectors (DBR) via wafer bonding method.

But for a long time most of the other portion of the visible spectral range except red light had not been realized in VCSELs technology yet. There were two major obstacles that hindered the development of short wavelength VCSELs: one is the lack of high...
refractive index difference materials that could be directly grown on specific substrates and allowing the subsequent epitaxial growth of short wavelength active gain medium, and the other reason is related to the gain medium itself. Until early 90’s it was still very difficult to obtain high quality and low defect density direct bandgap compound semiconductors with emission wavelength in green, blue and near ultra-violet (near-UV) range. Previously there were three promising materials with sufficiently large bandgap that can emit short wavelength visible light including 6H–SiC, ZnSe and GaN. However SiC possessed the indirect-transition property which tended to obstruct the application of fabricating high brightness light emitting devices. Though ZnSe and GaN are direct bandgap materials, it was very difficult to obtain bulk crystal and p-type doping at that time. In 1989, Akasaki and Amano’s research group introduced Mg-doping in GaN and subjected to take an additional low energy electron beam irradiation to activate the Mg impurity and act as an acceptor. This method successfully realized the epitaxially grown p-GaN thin film for the first time [3]. They realized the first p-n homojunction GaN-based light emitting diode (LED) in 1992. Soon after the double-heterostructure InGaN/GaN LEDs were demonstrated by Nakamura et al. in 1994 [4]. Because of their pioneering work in developing InGaN/GaN related light emitting devices and materials and significant contribution in modern solid-state lighting technology, Akasaki, Amano and Nakamura were awarded the Nobel Prize in Physics in 2014.

For the lack of bulk crystal and lattice-matched substrates, most of the GaN thin films were epitaxially grown on extrinsic foreign substrates such as SiC or sapphire [5]. But the large difference in lattice constants and linear thermal expansion coefficients between GaN-based materials and SiC or sapphire substrates usually resulted in high density of threading dislocation and deterioration of the crystal quality. The operation mechanism of LED is basically spontaneous emission with relatively higher tolerance to these defects. But for laser diodes these defects and dislocation could be fatal and eventually cease the stimulated emission process. In 1996 Nakamura’s group utilized two-flow metalorganic chemical vapor deposition (MOCVD) method to grow InGaN multi-quantum-wells (MQWs) laser diodes and successfully demonstrated the first GaN-based semiconductor laser with lasing wavelength of 408.3 nm and a narrow spectral width of 0.2 nm. The laser diodes could be operated under continuous wave (CW) and room temperature (RT) condition but the lifetime was merely 1 second [6] due to large heat generation. Two years later the same group introduced the epitaxially laterally overgrown (ELOG) of GaN for the fabrication of laser diodes and achieved RT CW operation with estimated lifetime of 10000 hours because of the significant reduction of threading dislocations [7], and the output power was further enhanced to 420mW [8].

2. Design and Fabrication of GaN-based VCSELs

Now that the gain medium issue for short wavelength laser diodes had been adequately solved, the remaining question was how to integrate high reflectivity mirrors to form the resonant cavity for VCSELs application. In 1996, Iga et al. proposed the
possibility of short wavelength VCSELs [9] and almost at the same time Redwing et al.
reported the first optically pumped GaN-based VCSEL under RT condition. The device
comprised a 10µm-thick GaN active layer sandwiched between 30 pairs of Al$_{0.40}$Ga$_{0.60}$N
(397Å) /Al$_{0.12}$Ga$_{0.88}$N (372Å) top and bottom DBRs and was fully epitaxially grown on
sapphire substrate with a thin AlN (150Å) buffer layer and a 2µm-thick Al$_{0.12}$Ga$_{0.88}$N
spacer layer [10]. According to theoretical simulation the reflectivity of these DBRs were
only 84-93% and resulted in an unfavorable high threshold condition of 2.0MW/cm$^2$.

Unlike the mature AlGaAs/GaAs DBRs, the relatively lower refractive index
difference and larger lattice mismatch of the GaN material system including AlN/GaN,
AlGaN/GaN, AlInN/GaN and AlGaN/AlN are two major inherent disadvantages of
growing fully epitaxial DBRs for GaN-based VCSELs application. Introducing high
refractive index difference dielectric materials such as TiO$_2$/SiO$_2$, SiO$_2$/Ta$_2$O$_5$ and
SiO$_2$/HfO$_2$ could help to increase the reflectivity and decrease the required DBRs pair
number. In 1998 Arakawa et al. combined an epitaxially grown 35-pair Al$_{0.34}$Ga$_{0.66}$N/GaN
bottom DBRs, a 3-λ cavity comprised a 184-nm-thick In$_{0.1}$Ga$_{0.9}$N active layer and 6-pair
TiO$_2$/SiO$_2$ top DBRs was evaporated on top of the cavity. The reflectivity of top and
bottom DBRs were 98% and 97%, respectively [11]. They observed a lasing wavelength
of 381nm with 0.1nm spectral width (resolution limit) above threshold at 77 K under
optical excitation. Soon after Song et al. used reactive ion beam sputtering to deposit 31
and 26 layers of λ/4 SiO$_2$/HfO$_2$ as the bottom and top dielectric DBRs on both side of the
active region comprised 5 InGaN/GaN quantum wells. The reflectivity of bottom and top
dielectric DBRs were measured to be 99.9% and 99.5%, respectively. As a result the
cavity quality factor (Q-factor) was estimated to be exceeding 600 [12].

The aforementioned pioneering works in optically pumped GaN VCSELs
represented three categories of device structure including fully epitaxially grown [10],
hybrid epitaxial/dielectric [11] and double dielectric DBRs [12], as illustrated in Fig. 1.
2.1 Mechanical issue:

The design and fabrication of GaN-based VCSELs is a series of compromise processes. Several key issues must be taken into consideration including mechanical properties, optical characteristics and electrical conductivity of each layer in the structure. For example, the most commonly used epitaxial DBR in GaN-based optoelectronic devices is Al$_x$Ga$_{1-x}$N/Al$_y$Ga$_{1-y}$N system grown on sapphire substrate. The thermal expansion coefficients of GaN, AlN and sapphire in a-axis are 5.59×10^{-6}/K, 4.2×10^{-6}/K and 7.5×10^{-6}/K, respectively [13-15]. Besides of the large difference in thermal expansion coefficient, the lattice mismatch between GaN and AlN is about 2.4% which will induce significant tensile strain in epitaxial layers and lead to the formation of cracks which eventually deteriorate the optical quality of the AlN/GaN DBRs. Adjusting Al or Ga mole fraction in Al$_x$Ga$_{1-x}$N compound can help to reduce the strain accumulation during DBRs deposition and minimize the possibility of crack formation, but the refractive index contrast will also be decreased and more DBR pairs are necessary to maintain the high reflectivity for laser operation. In 2000, Ng et al. used molecular beam epitaxy (MBE) to deposit AlN/GaN DBRs on (0001) sapphire substrate. According to the lower magnification cross-sectional transmission electron microscopy (TEM) image of the complete DBR structure shown in Fig. 2 (a), the interfaces between AlN and GaN seemed to be sharp and abrupt. The peak reflectance were between 97% and 99% with DBRs period number ranged from 20.5 to 25.5 pairs. The reflectance spectrum of the best sample was centered at 467nm with a stopband width of 45 nm and a peak reflectivity up to 99% as shown in Fig. 2(b) [16]. Meanwhile Wang’s group utilized MOCVD to deposit AlN/GaN DBRs and the cross-section TEM images were shown in Fig. 3 [17, 18]. The interfaces between AlN and GaN were also straight and clear under lower magnification in Fig. 3(a), but in the close-up enlargement image shown in Fig. 3(b), V-shaped groove

![Fig. 1. Schematic illustration of three different configurations of GaN-based VCSELs with (a) Fully epitaxial, (b) Hybrid epitaxial/dielectric and (c) Double dielectric DBRs.](image)
defects can be observed at the GaN-on-AlN interfaces, even after the introduction of a series of 5.5-pairs AlN/GaN superlattice (SL) for strain relaxation purpose. The formation of V-shaped defects was ascribed to various origins including stacking fault and surface undulation [19]. The reflectivity of this 20-pair GaN/AlN crack-free DBR with SL insertion layers could be up to 97%.

Fig. 2. (a) Cross-sectional TEM image of MBE-grown AlN/GaN DBR stack where the bright layers correspond to AlN and the dark layers represent GaN; (b) Simulated and measured reflectance spectra of this DBR [16].

Fig. 3. (a) Cross-sectional TEM image of 20-pair AlN/GaN DBR with SL insertion layers under lower magnification and (b) Partially enlargement of the 5.5-pair AlN/GaN SL and the V-shaped defects [18].

It was found that lower epitaxial growth temperature [20] and grown on AlN template [21] could help to improve the mechanical strain issue and obtain good quality
AlN/GaN heterointerfaces. Ive et al. demonstrated AlN/GaN DBRs directly grown on 6H–SiC(0001) wafers without buffer layer which could reach a peak reflectivity of 99% [22]. The authors claimed that their DBRs structure approached a strain-compensated state and as a result the formation of cracks could be suppressed. But the drawback is that the SiC wafers are relatively more expansive compared with widely used sapphire substrates. Carlin and Ilegems proposed an alternative approach of using 20-pair AlInN/GaN DBRs with smaller lattice mismatch and obtained 90% peak reflectivity and 35nm stopband width centered at 515nm [23]. For AlGaN/GaN DBRs the lattice mismatch within ±0.5% is sufficient to avoid relaxation, but in this case the maximum index contrast is only about 3%. In the other hand index contrast up to 8% could be obtained with AlInN/GaN DBRs and the lattice mismatch was limited to ±0.25%. Despite the reported theoretical advantages of AlInN/GaN DBRs, it is difficult to grow high quality AlInN thin film due to composition inhomogeneity and phase separation.

2.2 Optical issue:
Unlike the aforementioned sophisticated epitaxially grown nitride-base materials and various different approaches [24], dielectric materials including metal oxides have been well-developed and widely used for thin film coating in optical industry. A wide variety of deposition methods could be used for dielectric DBRs preparation including sputtering, electron beam evaporation, chemical vapor deposition (CVD), pulse laser deposition (PLD) and atomic layer deposition (ALD), etc. Commonly used dielectric DBRs including TiO$_2$/SiO$_2$, SiO$_2$/Ta$_2$O$_5$ and SiO$_2$/HfO$_2$ have been successfully used for GaN-based VCSELs fabrication due to their high index contrast and potentially higher peak reflectivity with fewer pairs and wider stopband width [11, 12][25]. Dielectric DBRs don’t need to conduct current and are typically undoped, so the impurity scattering loss and absorption can thus be minimized. Because of the relatively shorter cavity length and smaller gain medium volume of VCSELs compared with conventional edge emitting laser diodes, a higher reflectivity of the resonant cavity (i.e., high Q-factor) are essential for stimulated emission. This makes dielectric DBRs almost inevitable in GaN-based VCSELs application due to the difficulty of obtaining high reflectivity epitaxial DBRs.

2.3 Electrical issue:
But unfortunately dielectric DBRs couldn’t conduct current to drive the VCSELs. Though some research group claim they successfully grown Si-doped n-type AlN/GaN DBRs on SiC substrate and might be suitable for GaN-based VCSELs application [22], most of the epitaxially grown AlN/GaN DBRs were undoped and the VCSELs operation was performed under optical pumping. Until 2008 Wang’s group demonstrated the first electrically pumped GaN-based VCSELs [26], most of the electrically pumped devices still relied on complicated intra-cavity or flip-chip contact for current injection due to the use of dielectric DBRs. There are some fabrication process design considerations for electrically pump GaN VCSELs including injection current confinement and current
crowding induced thermal lensing effect and gain-cavity resonance detuning, etc. which will be described in the following sections.

3. Optically pumped GaN-based VCSELs

One of the inherent advantages of VCSELs is single longitudinal mode due to the relatively shorter cavity length on the order of a few half emission wavelengths. Optical waves will form standing wave patterns in the cavity. For the purpose of obtaining maximum gain the active layers must be placed exactly on the antinode position which corresponds to the maximum of standing waves. This can help to enhance the coupling between laser mode and active region and to reduce the threshold condition. Therefore the extremely precise control of cavity length and active layer position is essential for VCSELs operation. In the beginning GaN active layer could not be directly grown on dielectric materials, GaN-based VCSELs still need to be grown on epitaxial DBRs. If the GaN VCSELs consisted of fully epitaxially grown nitride DBRs been classified as type I, the devices comprised both nitride and dielectric DBRs could be categorized as type II GaN VCSELs. Later the laser lift off (LLO) and chemical-mechanical polishing (CMP) technology became more stable and reliable which eventually made it real of using both dielectric DBRs as top and bottom mirrors of the cavity. And this derived the third types of GaN-based VCSELs with double dielectric DBRs.

3.1 With hybrid DBRs:

GaN-based VCSELs with hybrid DBR were first reported by Arakawa’s group [11] [27]. The structure was grown on a (0001)-oriented sapphire substrate with a 30 nm GaN nucleation layer and 400 nm GaN buffer layer, a nitride DBR comprising of 43 pairs of 38 nm-thick GaN and 40 nm-thick Al\textsubscript{0.34}Ga\textsubscript{0.66}N, followed by 195 nm-thick GaN spacer layer and the multiple quantum wells (MQWs) consisting of 26 periods of 5 nm In\textsubscript{0.01}Ga\textsubscript{0.99}N barrier and 3 nm In\textsubscript{0.1}Ga\textsubscript{0.9}N quantum well, and a subsequent 18 nm GaN. The dielectric DBR was comprised of 15 pairs of 48 nm ZrO\textsubscript{2} and 68 nm SiO\textsubscript{2}, which was evaporated on the top of the epitaxially grown GaN-based materials to form a vertical resonant cavity. The cavity length was designed to be equal to 2.5\textlambda and the peak reflectivity of epitaxial nitride DBR (bottom) and dielectric DBR (top) were 98% and 99.5%, respectively. According to the lasing wavelength of 399 nm and the spectral linewidth of the cavity resonant mode of 0.8 nm, the cavity quality factor (Q factor) of 500 can be obtained through the equation Q=\textlambda/\Delta\textlambda.

The planar VCSEL structure was etched by reactive ion etching to form disk-shape structures with diameter of 18\textmu m and arranged into two-dimensional arrays with 22\textmu m spacing. The devices were optically pumped at room temperature with a He-Cd laser (\textlambda=325 nm) normally incident on the sample surface and focused to a 20\textmu m-diameter spot with an objective lens. The stopband width of the cavity was only 14nm due to the small refractive index contrast between Al\textsubscript{0.34}Ga\textsubscript{0.66}N and GaN, i.e. the \Delta n was only 0.12. When gradually increased the optical pumping power a transition of the spectral width from 0.8 nm to 0.1nm could be observed. This phenomenon is a direct evidence of lasing action.
because the spontaneous emission with broader spectral width below threshold could be filtered by the resonant cavity, and became very sharp emission peaks with much narrower spectral width above threshold.

Wang’s group incorporated aforementioned AlN/GaN epitaxial DBRs with periodical SL insertion layer for strain relaxing grown on (0001)-oriented sapphire substrate with a 30 nm GaN nucleation layer and 2µm GaN buffer layer [17], the bottom DBR consisted of 29-pair AlN/GaN with 6 period SL insertion layers. The 5λ cavity composed of 790nm-thick Si-doped n-GaN cladding layer on top of the epitaxial DBR, followed by MQWs active region consisted of ten 2.5nm-thick In₀.₂Ga₀.₈N quantum wells and 7.5nm-thick GaN barriers, and a 120nm-thick Mg-doped p-GaN cladding layer. After the epitaxial growth of nitride-based half cavity, eight pairs of Ta₂O₅/SiO₂ dielectric DBR was deposited by electron beam evaporation and the VCSEL structure with hybrid DBR was completed. The designed center wavelength was 460nm with a relatively large stopband of 70nm due to the large index contrast of Ta₂O₅ and SiO₂. The reflectance and photoluminescence (PL) spectra of the GaN VCSEL with hybrid DBRs were shown in Fig. 4(a) [18]. According to the measured cavity mode at 464.2nm and full-width-at-half-maximum (FWHM) of 0.61nm, the cavity Q factor was about 760.

The sample was optically pumped at room temperature to verify lasing action with a frequency-tripled Nd:YVO₄ 355nm pulsed laser. The pulse width was about 0.5ns at a repetition rate of 1kHz. The pumping beam was focused to a spot with diameter ranged between 30 to 60µm and normally incident to the VCSEL sample surface. The output power-excitation energy relation was shown in Fig. 4(b), there was an obvious threshold point when pump energy reached about 55nJ, which corresponded to a energy density of 7.8mJ/cm². The inset in Fig. 4(b) was laser emitting intensity in logarithmic scale, and the difference of the emission intensity before and after threshold can be clearly verified with a spontaneous coupling factor β of about 6×10⁻².

![Fig. 4](image-url)
Table 1 summarized the characteristics of optically pumped GaN-based VCSELs with hybrid DBRs. The first optically pumped fully epitaxially grown GaN VCSEL was also listed for reference.

<table>
<thead>
<tr>
<th>Year</th>
<th>Researcher/Institution</th>
<th>Bottom DBR x pairs</th>
<th>Top DBR x pairs</th>
<th>Operation Condition</th>
<th>Pumping spot size (µm)</th>
<th>λ (nm)</th>
<th>FWHM (nm)</th>
<th>Threshold condition</th>
<th>Q-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996</td>
<td>ATMI &amp; U Mass. [10]</td>
<td>Al&lt;sub&gt;0.40&lt;/sub&gt;GaN&lt;sub&gt;0.60&lt;/sub&gt;N/Al&lt;sub&gt;0.12&lt;/sub&gt;GaN x30</td>
<td>Ga&lt;sub&gt;0.88&lt;/sub&gt;N x30</td>
<td>RT, pulse</td>
<td>70</td>
<td>363.5</td>
<td>&lt;0.5</td>
<td>2.0 MW/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>/</td>
</tr>
<tr>
<td>1998</td>
<td>U. Tokyo [11]</td>
<td>Al&lt;sub&gt;0.34&lt;/sub&gt;GaN&lt;sub&gt;0.66&lt;/sub&gt;N/GaN x35</td>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;/TiO&lt;sub&gt;2&lt;/sub&gt; x6</td>
<td>77K, pulse</td>
<td>400</td>
<td>381</td>
<td>&lt;0.1</td>
<td>1.5 µJ</td>
<td>/</td>
</tr>
<tr>
<td>1999</td>
<td>U. Tokyo [27]</td>
<td>Al&lt;sub&gt;0.34&lt;/sub&gt;GaN&lt;sub&gt;0.66&lt;/sub&gt;N/GaN x43</td>
<td>ZrO&lt;sub&gt;2&lt;/sub&gt;/SiO&lt;sub&gt;2&lt;/sub&gt; x15</td>
<td>RT, pulse</td>
<td>20</td>
<td>399</td>
<td>&lt;0.1</td>
<td>43 nJ</td>
<td>500</td>
</tr>
<tr>
<td>2000</td>
<td>Brown U. &amp; Sandia [28]</td>
<td>Al&lt;sub&gt;0.25&lt;/sub&gt;GaN&lt;sub&gt;0.75&lt;/sub&gt;N/GaN x30</td>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;/HfO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>RT, quasi-CW</td>
<td>~20</td>
<td>383</td>
<td>&lt;0.1</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>2005</td>
<td>NCTU [29][30]</td>
<td>AlN/GaN x25</td>
<td>Ta&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;/SiO&lt;sub&gt;2&lt;/sub&gt; x8</td>
<td>RT, pulse</td>
<td>60</td>
<td>448</td>
<td>0.25</td>
<td>1.5 µJ or 53 mJ/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>320</td>
</tr>
<tr>
<td>2007</td>
<td>U. Southampton [31]</td>
<td>Al&lt;sub&gt;0.82&lt;/sub&gt;In&lt;sub&gt;0.18&lt;/sub&gt;N/GaN x39.5</td>
<td>SiO&lt;sub&gt;2&lt;/sub&gt;/Si,N&lt;sub&gt;4&lt;/sub&gt;x13</td>
<td>RT, pulse</td>
<td>60</td>
<td>~422</td>
<td>0.37</td>
<td>50 W/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>/</td>
</tr>
<tr>
<td>2013</td>
<td>NCTU [18]</td>
<td>AlN/GaN x29</td>
<td>Ta&lt;sub&gt;2&lt;/sub&gt;O&lt;sub&gt;5&lt;/sub&gt;/SiO&lt;sub&gt;2&lt;/sub&gt; x8</td>
<td>RT, pulse</td>
<td>30~60</td>
<td>~449</td>
<td>0.17</td>
<td>~55 nJ or 7.8 mJ/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>760</td>
</tr>
</tbody>
</table>

3.2 With dielectric DBRs:

Higher mirror reflectivity could help to increase the cavity Q factor and minimized the required threshold gain for VCSELs operation. Because of the lower index contrast of GaN-based materials, the maximum reflectivity of nitride DBRs could hardly be as high as that of high contrast dielectric DBRs. Theoretically utilizing double dielectric DBRs could help to minimize mirror losses and decrease the threshold gain of VCSELs, but generally high crystal quality semiconductor gain mediums are very difficult to be epitaxially grown on amorphous dielectric layers. Even though the aforementioned ELOG GaN still needed some homogeneous nucleation or buffer layers in the initial stage of thin film deposition. High power UV lasers had been used to separate the epitaxial GaN thin film from sapphire substrate [32][33] and Song et al. adopted this technology to fabricate double dielectric DBR GaN VCSELs and demonstrated optical pumping laser operation under room temperature [12][34].

Wang’s group also used laser lift-off (LLO) method to fabricate GaN-based VCSELs with double dielectric DBRs. The GaN active region were grown on (0001)-oriented sapphire substrate with a 30 nm GaN nucleation layer and 4µm GaN buffer layer. The MQWs consisted of ten periods of 5nm-thick GaN barriers and 3nm-thick In<sub>0.1</sub>Ga<sub>0.9</sub>N quantum wells with a 200nm-thick GaN capping layer. A subsequent dielectric DBR comprised of 6 pairs SiO<sub>2</sub>/TiO<sub>2</sub> was evaporated on top of the GaN active region with a measured reflectivity of 99.5% at 416nm [37]. They etched the sample to form disk-like arrays for the purpose of enhancing adhesion between epitaxial layers and silica substrate. Then the structure was subjected to LLO process with a KrF excimer laser radiation at
248nm to remove the sapphire substrate. After being separated from the substrate, the exposed GaN surface was further polished to obtain a smooth and flat surface with roughness of about 1 nm. Subsequently 8 pairs SiO$_2$/Ta$_2$O$_5$ dielectric DBR with reflectivity of 97% at 416nm was deposited to form a complete resonant cavity. The remaining thickness of the GaN epitaxial structure after LLO and polishing process was controlled to be 4µm, which corresponded to 24.5λ.

The optical pumping was carried out at room temperature by using Nd:YVO$_4$ 355nm laser with pulse width of about 0.5ns at a repetition rate of 1kHz. The laser beam was focused to a spot size of about 40µm in diameter and normally incident on the VCSEL sample from SiO$_2$/Ta$_2$O$_5$ DBR side [37]. The relation of emission intensity and excitation energy of the fabricated devices was shown in Fig. 5(a). The threshold excitation energy was about 270nJ and corresponded to an energy density of 21.5mJ/cm$^2$. According to the inset of Fig. 5(a), the difference of the emission intensity below and above threshold can be distinctly verified with a spontaneous coupling factor β of about 1.1×10$^{-2}$.

The inset of Fig. 5(b) shown the spontaneous mode below threshold with a regular spacing of about 7nm corresponding to a cavity length of 4.3µm, which is close to the thickness of the remaining epitaxial cavity.

![Fig. 5. (a) Laser output power as a function of the excitation energy at room temperature [18] and (b) Emission spectra of the GaN VCSEL with double dielectric DBRs [38].](image)
Zhang et al. at Xiamen University also utilized double dielectric Ta$_2$O$_5$/SiO$_2$ DBRs for the fabrication of GaN-based VCSELs. In 2008 they demonstrated the first GaN-based VCSELs with emission wavelength in blue-green spectral region and the lasing wavelength was about 498.8nm [39]. In 2009 Zhang’s group pushed the emission spectra to shorter wavelength of 397.3nm [41]. These successful experiments constructed the foundation of realizing electrically pumped GaN-based VCSELs, and eventually led to the invention of InGaN quantum dot (QD)-based dielectric DBR VCSELs to cover the “green gap”, which will be described later in this paper.

Table 2 summarized the characteristics of previously reported optically pumped GaN-based VCSELs with dielectric DBRs, the first optically pumped fully epitaxially grown GaN VCSEL was also listed for reference.

<table>
<thead>
<tr>
<th>Bottom DBR x pairs</th>
<th>Top DBR x pairs</th>
<th>Operation Condition</th>
<th>Pumping spot size (µm)</th>
<th>λ (nm)</th>
<th>FWHM (nm)</th>
<th>Threshold condition</th>
<th>Q-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996 ATMI &amp; U Mass. [10]</td>
<td>Al$<em>{0.4}$Ga$</em>{0.6}$N/Al$<em>{0.12}$Ga$</em>{0.88}$N</td>
<td>RT; pulse</td>
<td>70</td>
<td>363.5</td>
<td>&lt;0.5</td>
<td>2.0 MW/cm$^2$</td>
<td>/</td>
</tr>
<tr>
<td>1999 Brown U. &amp; HP [12]</td>
<td>SiO$_2$/HfO$_2$ x15.5</td>
<td>HfO$_2$/SiO$_2$ x13</td>
<td>RT</td>
<td>100</td>
<td>≈437</td>
<td>0.7</td>
<td>/</td>
</tr>
<tr>
<td>2000 Brown U. &amp; Agilent [34]</td>
<td>SiO$_2$/HfO$_2$</td>
<td>HfO$_2$/SiO$_2$</td>
<td>258K, quasi-CW</td>
<td>20</td>
<td>403</td>
<td>&lt;0.1</td>
<td>32 mW</td>
</tr>
<tr>
<td>2003 Seoul National U [35]</td>
<td>SiO$_2$/HfO$_2$ x11.5</td>
<td>SiO$_2$/HfO$_2$ x11.5</td>
<td>RT, pulse</td>
<td>&gt;120</td>
<td>≈391</td>
<td>/</td>
<td>160kW/cm$^2$</td>
</tr>
<tr>
<td>2003 NTT [36]</td>
<td>SiO$_2$/ZrO$_2$</td>
<td>SiO$_2$/ZrO$_2$</td>
<td>RT, pulse</td>
<td>21</td>
<td>401</td>
<td>0.87</td>
<td>5.1mJ/cm$^2$</td>
</tr>
<tr>
<td>2006 NCTU [37]</td>
<td>Ta$_2$O$_5$/SiO$_2$ x8</td>
<td>SiO$_2$/TiO$_2$ x6</td>
<td>RT; pulse</td>
<td>40</td>
<td>415.9</td>
<td>0.25</td>
<td>270 nJ or 21.5 mJ/cm$^2$</td>
</tr>
<tr>
<td>2006 NCTU [38]</td>
<td>Ta$_2$O$_5$/SiO$_2$ x8</td>
<td>SiO$_2$/TiO$_2$ x6</td>
<td>RT; pulse</td>
<td>40</td>
<td>414</td>
<td>0.25</td>
<td>270 nJ or 21.5 mJ/cm$^2$</td>
</tr>
<tr>
<td>2008XMU [39]</td>
<td>Ta$_2$O$_5$/SiO$_2$ x13.5</td>
<td>Ta$_2$O$_5$/SiO$_2$ x12.5</td>
<td>RT; pulse</td>
<td>150</td>
<td>498.8</td>
<td>0.15</td>
<td>42.2 µJ or 189 µJ/cm$^2$</td>
</tr>
<tr>
<td>2008XMU [40]</td>
<td>SiO$_2$/Ta$_2$O$_5$</td>
<td>SiO$_2$/Ta$_2$O$_5$</td>
<td>RT, pulse</td>
<td>150</td>
<td>449.5</td>
<td>&lt;0.1</td>
<td>2.3µJ or 6.5 mJ/cm$^2$</td>
</tr>
<tr>
<td>2009XMU [41]</td>
<td>Ta$_2$O$_5$/SiO$_2$ x13.5</td>
<td>Ta$_2$O$_5$/SiO$_2$ x13.5</td>
<td>RT, pulse</td>
<td>150</td>
<td>397.3</td>
<td>0.13</td>
<td>16µJ/pulse</td>
</tr>
<tr>
<td>2013XMU [42]</td>
<td>Ta$_2$O$_5$/SiO$_2$ x12.5</td>
<td>Ta$_2$O$_5$/SiO$_2$ x11</td>
<td>RT, pulse</td>
<td>50</td>
<td>431.0</td>
<td>0.3</td>
<td>3.2 mJ/cm$^2$</td>
</tr>
<tr>
<td>2014XMU [43]</td>
<td>Ta$_2$O$_5$/SiO$_2$</td>
<td>Ta$_2$O$_5$/SiO$_2$</td>
<td>RT, pulse</td>
<td>50</td>
<td>425.7</td>
<td>&lt;1</td>
<td>150 µW</td>
</tr>
<tr>
<td>2015XMU [44]</td>
<td>Ta$_2$O$_5$/SiO$_2$ x12.5</td>
<td>Ta$_2$O$_5$/SiO$_2$ x11</td>
<td>RT, pulse</td>
<td>50</td>
<td>425</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

4. Electrically pumped GaN-based VCSELs

For electrically pumped GaN-based VCSELs, there are three critical challenges that limit the performances of the devices. One is the lack of the suitable substrates. Growth on usual sapphire substrates results in very high defect density in GaN films. The other is the difficulty in obtaining high-quality and high-reflectivity DBRs due to the large lattice
mismatch between GaN and AlN layers. The third is the requirement of low-resistance p-type contact for injection of the carriers into the active region. Among these, the high-quality and high-reflectivity DBRs are of great importance. There are two kinds of device structures, including hybrid DBR structure and double dielectric DBR structure. For the hybrid DBR structure, the resonant cavity is formed with an epitaxial nitride bottom DBR and a dielectric top DBR. The use of the epitaxial bottom DBR can avoid the complicated process flow. However, the crystal growth remains challenging and high-quality and high-reflectivity nitride DBRs are difficult to achieve. For the double dielectric DBR structure, the microcavity is formed with double dielectric DBRs, and the device requires complex fabrication process, such as substrate lift-off or thinning and bonding process. The high-reflectivity and large-stopband DBRs can be realized in dielectric materials with less number of pairs. However, accurate cavity length control is difficult due to the laser lift-off technique [38] and the smooth surface is also a key factor due to the polishing and thinning technique [45]. The reported GaN-based VCSELs with these two structures are discussed in the following.

2.1. With hybrid DBRs

The first electrically pumped GaN-based VCSEL was reported with hybrid DBR structure by National Chiao Tung University (NCTU) in Taiwan in April 2008 [26]. The device was started from material growth on sapphire substrate. The epitaxial layers mainly consisted of a 29-pair AlN/GaN bottom DBR, a 790-nm-thick Si-doped n-type GaN, 10-pair In_{0.2}Ga_{0.8}N/GaN (2.5 nm/7.5 nm) MQWs, and a 120-nm-thick Mg-doped p-type GaN. The MQWs were located at the anti-nodes of light field in the microcavity for enhancing the coupling of photons and the cavity mode. The 5.5-pair AlN/GaN superlattices (SLs) were inserted into the AlN/GaN bottom DBR (peak reflectivity of 99.4%) to reduce the biaxial tensile strain in the DBR [17], and 8-pair Ta_{2}O_{5}/SiO_{2} dielectric DBR (peak reflectivity of 99%) was deposited as the top mirror to form the hybrid structure. The total cavity length was designed to be 5 \lambda. A 200-nm-thick SiNx and a 240-nm-thick ITO were employed as current confinement layer and current spreading layer, respectively. Fig. 6 shows the typical schematic diagram of the GaN-based VCSEL with hybrid DBRs. The device with an aperture diameter of 10 µm operated under continuous wave (CW) conditions at 77 K at the wavelength of 462.8 nm. The turn-on voltage and threshold current density were 4.1 V and 1.8 kA/cm², respectively. Fig. 7 shows the laser emission spectrum at different injection current levels with the inset of CCD image of the emission from the aperture. It can be seen a clear transition from spontaneous to stimulated emission, but a non-uniform emission intensity across the emission aperture with several bright emission spots, which can be attributed to the In non-uniformity that causes a non-uniform spatial gain distribution [46]. In addition, the device exhibits a divergence angle of \sim11.7° and a degree of polarization (DOP) of 80%. The primary factors that prevents room temperature (RT) CW lasing may be the
employment of the thick ITO layer that induces significant optical loss, and the lack of the electron-blocking layer (EBL) that induces carrier overflow.

Fig. 6. Typical schematic diagram of the GaN-based VCSEL with hybrid DBRs.

![Schematic diagram](image)

Fig. 7. Laser emission spectrum at different injection current levels with the inset of CCD image of the emission from the aperture.

![Laser emission spectrum](image)

To further improve the performances of GaN-based VCSELs with hybrid DBRs, the same group at NCTU demonstrated a RT CW lasing in August 2010 [47], by reducing the ITO thickness to 30 nm and adding an AlGaN EBL. The epitaxial structure on a sapphire substrate is composed of a 29-pair AlN/GaN DBR using SLs to reduce the tensile strain, an 860-nm-thick n-GaN, 10-pair InGaN/GaN (2.5 nm/12.5 nm) MQWs, a 24-nm-thick AlGaN EBL, a 110-nm-thick p-GaN, and a 2-nm-thick p⁺-InGaN for p-contact improvement. A 10-pair Ta₂O₅/SiO₂ dielectric DBR was deposited as the top mirror. The device has a turn-on voltage and threshold current density of 4.3 V and 12.4 kA/cm², respectively. The laser emission wavelength is 412 nm with a linewidth of 0.5 nm. The device shows a maximum output power of ~37 µW, a divergence angle of 8° and a DOP of only 55%. The improved performances can be attributed to the employment of thin ITO layer combining with a thin heavily doped p-type InGaN contact layer to reduce the optical loss and the incorporation of AlGaN EBL to reduce the electron overflow to p-GaN layer.
Electrically pumped GaN-based VCSELs with hybrid DBRs were also reported by Ecole Polytechnique Federale de Lausanne (EPFL) in Switzerland in October 2012 [48]. The VCSELs with hybrid DBRs combining a defect-free highly reflective lattice-matched 41.5-pair $\text{Al}_{0.8}\text{In}_{0.2}\text{N}/\text{GaN}$ bottom DBR with a 7-pair $\text{TiO}_2/\text{SiO}_2$ dielectric top DBR (peak reflectivity of 98.4%) were fabricated on free-standing (FS) c-plane GaN substrate, which makes the process much easier and ensures the optimal crystalline quality. The active region of 5-pair $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}/\text{In}_{0.01}\text{Ga}_{0.99}\text{N}$ (5 nm/5 nm) MQWs was sandwiched between n-GaN (960 nm) and $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}$ EBL/p-GaN (20 nm/120 nm). The p-type RIE surface treatment [49, 50] was used for confining the current in an aperture with a diameter of 8 $\mu$m, and a $\lambda/4$ ITO layer was used as the current spreading layer. The total cavity length was 7 $\lambda$. Fig. 8 shows the output power and cavity mode FWHM as a function of the pulsed current, with the inset of near field real space imaging of a lasing VCSEL. The device emitted at the wavelength of 420 nm with a maximum output power of $\sim$330 $\mu$W. Besides, the device exhibited a high threshold current density of 140 kA/cm$^2$, which can be ascribed to large absorption losses in the thick ITO layer and the insufficiently high top DBR reflectivity. The calculations show that the lasing threshold can be greatly decreased to 10 kA/cm$^2$ by properly reducing the ITO thickness and tuning its position with respect to the optical field.

Fig.8. Output power and cavity mode FWHM as a function of the pulsed current, with the inset of near field real space imaging of a lasing VCSEL.

Many other efforts have been made to further investigate GaN-based VCSELs with hybrid DBRs. It is well known that inserting an AlGaN EBL is a useful approach to suppress electron overflow to p-GaN layer. However, the large polarization field in AlGaN EBL induced band bending between the last barrier of MQW and EBL layer reduces the effective barrier height for electrons [51]. The overflow of electrons outside the active region could recombine with the holes in p-GaN, resulting in the degraded performances. To solve the issue, several kinds of EBL have been proposed in GaN-based LEDs to improve the electron blocking capability, such as AlGaN/GaN SL EBL, AlInN/GaN SL EBL, Al-graded bulk AlGaN EBL, multiquantum barrier (MQB) EBL
[52-55]. Using the similar methods, the group at NCTU reported GaN-based VCSELs with hybrid DBRs, replacing the conventional AlGaN bulk EBL by a composition-graded EBL (GEBL) and MQB EBL [56, 57] in 2014 and 2015, respectively. For the VCSEL with GEBL [56], the epitaxial structure fabricated on a sapphire substrate consisted of a 25-pair AlN/GaN DBR, an 880-nm-thick n-GaN, 10-pair In$_{0.1}$Ga$_{0.9}$N/GaN (2.5 nm/10 nm) MQWs, a p-AlGaN GEBL with Al graded from 0% to 25%, and a 100-nm-thick p-GaN. The SiNx and ITO were deposited for current confining and spreading, respectively. And a 10-pair Ta$_2$O$_5$/SiO$_2$ dielectric DBR were deposited as the top mirror. For the VCSEL with MQB EBL [57], it was grown on the GaN substrate with the similar fabrication process and device geometry, except a 5-pair In$_{0.15}$GaN/In$_{0.02}$GaN (4 nm/8 nm) MQWs and MQB EBL with 5-pair Al$_{0.15}$Ga$_{0.85}$N/GaN (2 nm/2 nm) SLs. Fig. 9(a) and (b) shows calculated energy band diagrams of the VCSELs with GEBL and MQB EBL in comparison with the VCSEL with conventional bulk EBL, respectively. For the VCSEL with conventional bulk EBL, the band bending occurs in the active region, resulting from the polarization-induced electric field, which separates the electrons and holes to the opposite sides of the QWs. Besides, it can be obviously seen that a band bending occurs at the interface of the last quantum barrier/EBL due to the large lattice mismatch, inducing an electron or hole barrier height. By incorporating a GEBL or a MQB EBL, the electron barrier height in the conduction band effectively increased, while the hole barrier height in the valence band decreased. It leads to the improvement in capability of the hole transport across the EBL as well as the electron confinement, which is very beneficial to reduce electron leakage current and enhance hole injection efficiency. The VCSELs with hybrid DBRs using GEBL and MQB EBL exhibit RT CW lasing with a reduced threshold current density of 9.2 kA/cm$^2$ and 10.6 kA/cm$^2$, respectively, as compared to that of the VCSEL using conventional bulk EBL. In addition, the maximum output power of 0.9 mW can be obtained in the VCSEL using MQB EBL. Furthermore, in 2016, the researchers at National Taiwan University of Science and Technology (NTUST) and NCTU together proposed a GaN-based hybrid DBR VCSEL by using a silicon-diffusion-defined current blocking layer for lateral confinement [58]. The micro cavity using a 10-pair InGaN/GaN MQW active region was defined by a 25-pair AlN/GaN bottom epitaxial DBR and an 8-pair TiO$_2$/SiO$_2$ top dielectric DBR. With selective silicon diffusion method, diffused p-GaN region can be converted to n-GaN and thus attains current-blocking effect. This diffused region plus depleted region formed a 3-dimentional current confinement structure, which can effectively prevent current from spreading laterally. Low threshold currents of 0.5 and 0.6 mA with the corresponding threshold current densities of 7.1 and 3.1 kA/cm$^2$ were achieved for the VCSEL with the aperture diameter of 3 and 5 $\mu$m, respectively, under the CW operation at RT. The VCSELs with the aperture diameter of 3 and 5 $\mu$m emitted at the wavelengths of 411.2 and 407.5 nm with the linewidths of 0.4 and 0.6 nm, respectively. Additionally, the 3-$\mu$m-diameter VCSEL exhibited a small FWHM divergence angle of ~5°, implying near single-mode operation.
Fig. 9. Calculated energy band diagrams of the VCSELs with (a) GEBL and (b) MQB EBL in comparison with the VCSEL with conventional bulk EBL.

Besides the above research groups, the group at Meijo University (Meijo-U) in Japan also has done much work on GaN-based VCSELs with hybrid DBRs. They demonstrated many VCSELs with hybrid DBRs using different structures in 2016, such as periodic gain structures (PGSs), thick InGaN QWs, n-type conducting AlInN/GaN DBR [59-61]. The VCSEL using PGSs [59] contained a 4.5 $\lambda$-thick cavity with a 40-pair AlInN/GaN bottom DBR and an 8-pair Nb$_2$O$_5$/SiO$_2$ dielectric top DBR on a FS-GaN substrate. The epitaxial layers consisted of a 400-nm-thick n-GaN, two identical 5-pair InGaN/GaN (3 nm/6 nm) active regions with a 45-nm-thick Mg-doped GaN intermediate layer, a 20-nm-thick p-AlGaN EBL, a 60-nm-thick p-GaN, and a 10-nm-thick p$^+$/n$^-$-GaN contact layer. The SiO$_2$ aperture with a diameter of 8 $\mu$m was formed and the ITO was deposited as current spreading layer. Because of the different effective mass and mobility of electron and hole, the uniform carrier injection into the active regions is a key issue [62, 63]. By adopting an optimum Mg concentration in the intermediate layer of the PGSs, the uniformity of carrier injection into the two active regions was improved. The VCSEL with the PGSs exhibited a RT CW lasing at the wavelength of 409.9 nm with a FWHM of 0.07 nm and a high threshold current density of 16.5 kA/cm$^2$. One of the possible reasons for the high threshold current density is the low optical confinement factor induced by the thin QWs in the VCSELs. By replacing the 5-pair thin In$_n$Ga$_{1-n}$N (3 nm/6 nm) QWs by thick In$_n$Ga$_{1-n}$N (6 nm/6 nm) QWs as the active region, the VCSEL achieved a low threshold current density of 7.5 kA/cm$^2$ with a narrow (0.4 nm) emission spectrum of 413.5 nm peak wavelength under CW operation at RT, which can be attributed to the
advantages of thick QWs [60], including high optical confinement factor, sufficient overlap between electron and hole wave functions, and uniform carrier injection under high current density. In addition, a new approach by using n-type conducting AlInN/GaN DBR for VCSEL was proposed [61]. A very short 1.25λ-thick cavity was achieved in the VCSEL, which is different from the large cavity length in most of GaN-based VCSELs with insulating DBRs. The 46-pair n-type conducting AlInN/GaN DBR was prepared by the modulation doping of Si and exhibits a very high peak reflectivity of >99.9% and a good electrical conductivity with the contact resistance of <7.8x10⁻⁴ Ω•cm². The epitaxial layers were grown on a FS-GaN substrate. After the deposition of the 46-pair Si-doped AlInN/GaN bottom DBR, a 50-nm-thick n-GaN, 5-pair InGaN/GaN (3 nm/6 nm) MQWs, a 20-nm-thick p-Al₀.₂Ga₀.₈N EBL, a 60-nm-thick p-GaN, and a 10-nm-thick p⁺-GaN contact layer were grown on the bottom DBR continuously, followed by the deposition of SiO₂, ITO, and 8-pair Nb₂O₅ dielectric top DBR, respectively. With the vertical current injection through the n-type conducting bottom DBR, the VCSEL lased at the wavelength of 405.1 nm with a FWHM of 0.08 nm and a threshold current density was 5.2 kA/cm² under the CW operation at RT. Further optimization of the modulation doping of Si in terms of resistivity, absorption and thickness control was suggested to improve the device performances.

The light output power is one of the major challenges in GaN-based VCSELs, as that of the above reported VCSELs with hybrid DBRs is still below 1 mW. In 2016, the same group at Meijo-U reported a 1.7 mW RT CW GaN-based bottom-emitting VCSEL [64] with a 40-pair AlInN/GaN bottom DBR and an 8-pair Nb₂O₅/SiO₂ dielectric top DBR on a GaN substrate, by optimizing growth conditions of bottom DBR, tuning layer thickness, and considering DBR reflectivity. The VCSEL structure was similar to the previous one [60]. Furthermore, the largest output power of 3 mW for an electrically pumped GaN-based VCSEL with the similar structure was also reported by Meijo-U group [65], and its temperature dependence was further investigated. The VCSEL emitted at 414.6 nm with a FWHM of 0.1 nm and a threshold current density of 14 kA/cm² under CW condition at RT. The maximum output power was 3 mW under bottom-emitting configuration, and decreased with the temperature increasing. A CW operation can be achieved up to 95 °C, and the lowest threshold current density of 13.2 kA/cm² was obtained at 65 °C.

The performances in electrically pumped GaN-based VCSELs with hybrid DBRs to date were summarized in Table 3.

Table 3. Performances in electrically pumped GaN-based VCSELs with hybrid DBRs.

<table>
<thead>
<tr>
<th>Sub. Operation</th>
<th>Environ.</th>
<th>Aperture d (µm)</th>
<th>λ (nm)</th>
<th>FWHM (nm)</th>
<th>Jth (kA/cm²)</th>
<th>Pmax (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 NCTU [26]</td>
<td>Sapphire</td>
<td>77K CW</td>
<td>10</td>
<td>462.8</td>
<td>0.15</td>
<td>1.8</td>
</tr>
<tr>
<td>2010 NCTU [47]</td>
<td>Sapphire</td>
<td>RT CW</td>
<td>10</td>
<td>412</td>
<td>0.5</td>
<td>12.4</td>
</tr>
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</table>
2.2. With dielectric DBRs

To avoid the difficulty of fabricating epitaxial nitride DBRs with high reflectivity and high quality, introducing both bottom and top dielectric DBRs in electrically pumped GaN-based VCSELs is an alternative approach. In this section we will review the progresses realized in electrically pumped GaN-based VCSELs with dielectric DBRs and then simply introduce the most recent results in green emitting VCSELs. Benefits from the higher refractive index contrast in dielectric material systems, it is easy to fabricate DBRs with a high reflectivity and a broad stopband without having to deposit too many pairs. To realize the double dielectric DBR configuration in GaN-based VCSELs where the bottom dielectric DBR is embedded between the suspending substrate and the GaN cavity membrane, the device after the deposition of the bottom DBR is usually needed to be flip-chip bonded on a suspending substrate and the original substrate is then removed to allow the deposition of a top DBR. The removal of original substrate could be achieved by laser lift-off (LLO) [45, 66-69], chemical mechanical polishing (CMP) [70-72] and photodelectrochemical etching (PEC) of a sacrificial layer [73-78]. The schematic structure of the electrically pumped double dielectric DBR VCSEL fabricated through this bonding and substrate transferring method is illustrated in Fig. 10(a). More recently, epitaxial lateral overgrowth (ELO) was used to fabricate double dielectric DBR VCSELs without substrate transferring [79, 80]. In this case, the bottom dielectric DBR was firstly deposited and patterned on a GaN substrate, then the substrate was put into the MOCVD furnace to grow the following epitaxial laser structure and the bottom dielectric DBR was buried in the regrown GaN material. The schematic structure of the electrically pumped double dielectric DBR VCSEL fabricated through ELO is illustrated in Fig. 10(b).
The first electrically pumped dielectric DBR VCSEL was demonstrated by Nichia Corporation in December 2008 and RT CW lasing was realized [45]. The VCSEL structure was grown on a (0001)-oriented sapphire substrate by MOCVD. The active region consisted of 2-pair 9-nm-thick InGaN QWs and 13-nm-thick GaN barrier layers. For the purpose of electrical pumping and current confinement, an 8µm current injection aperture was formed by patterning a SiO₂ layer deposited on a p-type GaN layer. A 50-nm-thick ITO layer was employed as current spreading layer and to form a p-type ohmic contact. Subsequently, an 11.5-pair SiO₂/Nb₂O₅ DBR was deposited to form the backside mirror. The sample was then bonded onto a Si substrate and the sapphire substrate was removed by LLO technique. Then, the n-type GaN was thinned to be about 7λ using CMP technique. Finally, a 7-pair SiO₂/Nb₂O₅ DBR was formed to complete the VCSEL structure. Fig. 11(a) shows the schematic sketch of their GaN-based dielectric DBR VCSEL with a vertical current injection configuration. Fig. 11(b) shows the emission spectra. The device was emitting in violet spectrum region and the lasing behavior was clearly observed. The threshold current density of the device was 13.9 kA/cm², while the maximum output power was about 0.14 mW. In the following year, they reported a dielectric DBR VCSEL with a higher output power of 0.62 mW and a longer lifetime by preparing the epitaxial wafer on a c-plane GaN substrate instead of a sapphire substrate [70]. The device structure was the same as illustrated in Fig. 11(a). The GaN substrate was removed by mechanical polishing and CMP after the device had been bonded to a Si substrate. The emitting wavelength of the device was 420 nm and the threshold current density was 15.9 kA/cm². Both the VCSELs using sapphire and GaN substrate had shown filamentary lasing in the aperture, but the lasing spot size in the VCSEL fabricated using a GaN substrate appears to be larger than that in the VCSEL fabricated using a sapphire substrate and this may be responsible for the higher maximum output power in the VCSEL. The longer lifetime of the devices fabricated using a GaN substrate is mainly because of their lower dislocation density and/or larger lasing spot.
size. Later in June 2012, they realized RT CW lasing of blue and pulsed lasing of green electrically pumped dielectric DBR VCSELs [71]. The epitaxial layers were also prepared on c-plane GaN substrates by MOCVD. The blue GaN-based VCSEL had a threshold current density of 3 kA/cm$^2$ and a threshold voltage of 3.3V. The emitting wavelength was 451 nm and the maximum output power was 0.70 mW. The green GaN-based VCSEL emitting at 503 nm had a threshold current density of 28 kA/cm$^2$ and a threshold voltage of 6.3 V under pulsed current operation. Its maximum output power was estimated to be over 0.80 mW. Fig. 12 shows the dispersion of the device parameters reported by Nichia Corporation in the threshold current and laser emission wavelengths under CW or pulsed current operation. The emitting wavelength covers from the violet to blue-green regions. The threshold current gradually increases as the laser emission wavelength becomes longer. This is mainly due to the quantum confinement Stark effect (QCSE) in QW structure, which separates the hole and electron wave functions and then reduces the radiative recombination probability [81]. The QCSE mainly originates from the piezoelectric polarization caused by the high crystal strain due to the large lattice mismatch between GaN and InGaN and will be stronger when the emission wavelength of QW is longer. Publications of electrically pumped dielectric DBR VCSELs with similar device structure and fabrication process from a few groups followed. In September 2012, researchers from Panasonic Corporation in Japan reported the RT CW lasing of violet dielectric DBR VCSELs and 5×5 GaN-based VCSEL array was fabricated [72]. The emitting wavelength was around 400 nm and multi-longitudinal mode emission was observed due to the relatively long cavity length (~6 µm). The maximum output power was about 3 µW. In June 2014, researchers from Xiamen University (XMU) reported the RT CW lasing of dielectric DBR VCSELs with a high quality factor (~3570) cavity [66]. The threshold current density of the device was 1.2 kA/cm$^2$ and the maximum output power was about 0.5 µW. Later in 2016 and 2017, they further reported InGaN quantum dot (QD)-based dielectric DBR VCSELs emitting in “green gap”. The emission wavelength ranges from extended from 491.8 to 565.7 nm and more details will be discussed later. In October 2017, the researchers at NCTU reported a high-temperature operation dielectric DBR VCSEL. The device emitting at 402 nm could operate at temperatures of up to 350 K under pulsed current injection. The threshold current density at 300 K was 8.9 kA/cm$^2$ and the peak output power exceeded 20 µW at RT [69]. The effective high-temperature laser performance can be attributed to the well-matched gain-mode offset and the flip-chip-bonded VCSEL configuration with reduced lateral size of the bottom DBR.
In September 2012, researchers from University of California, Santa Barbara (UCSB), reported the first nonpolar GaN-based dielectric DBR VCSEL [73]. Nonpolar III-nitride materials have several advantages for VCSELs, including weaker QCSE, lower transparency current densities and higher peak gain, as compared with c-plane III-nitride materials [82, 83]. The epitaxial wafer was prepared on a FS m-plane GaN substrate by MOCVD. Instead of removing the GaN substrate by CMP, PEC etching was utilized to undercut an intracavity-embedded In\textsubscript{0.12}Ga\textsubscript{0.88}N sacrificial layer so as to remove the substrate and expose the backside of the cavity and then the top dielectric DBR could be fabricated. Fig. 13(a) shows the device structure before substrate removal by PEC etching and Fig. 13(b) shows the SEM image of air gap formed during the PEC etching. This approach realized the precise control of the cavity length based on epitaxial layer thicknesses. A patterned SiN\textsubscript{x} dielectric layer and an ITO layer were deposited as current confinement layer and current spreading layer, respectively. Lasing spectrum is illustrated.
in Fig. 13(c). RT single-longitudinal-mode lasing at 411.9 nm with a peak output power of 19.5 µW was obtained under pulsed condition. The device was driven with 30 ns pulses at a duty cycle of 0.03% and the threshold current was approximately 70 mA. The authors attributed the relatively high threshold current to the excessive optical loss in the cavity and leakage currents caused by cracking during the bonding process. Then in July 2014, based on the same device structure and fabrication process, they reported nonpolar GaN-based dielectric DBR VCSEL with a polarization ratio of 100% [74]. The emission spectrum was polarized along the [1210] a-direction and the ultra-high polarization ratio was resulted from the intrinsic anisotropic gain of m-plane InGaN/GaN QWs. The device also worked under pulsed operation and the threshold current decreased from 70 mA to 40 mA, as compared with the first generation of nonpolar device under the same temperature. The maximum output power was 32 µW. In July 2015, they further proposed a nonpolar GaN-based dielectric DBR VCSEL with an Al ion implanted aperture to realize current confinement [75]. The devices showed a 1 V decrease in voltage when compared with devices with the SiN$_x$ current confinement layer. The use of an ion implanted aperture was also expected to improve the lateral confinement over SiN$_x$ apertures by enabling a planar ITO design. To minimize the scattering loss, a 1/4 $\lambda$ thick of multilayer ITO with the RMS roughness on the order of the epitaxial roughness (0.282 nm) was deposited. RT single-longitudinal-mode lasing at 406 nm was realized under pulsed operation with a threshold current density of 16 kA/cm$^2$ and a peak output power of 12 µW. The device also showed a 100% polarization ratio. Later in September, they reported nonpolar dielectric DBR VCSEL introducing a III-nitride tunnel junction (TJ) on the p-GaN as the intracavity contact instead of the commonly used ITO layer [76]. The threshold current density decreased from 8 to 3.5 kA/cm$^2$ and the maximum output power increased from 80 to 550 µW when compared with an equivalent device with an ITO contacting layer. The authors attributed the improvement of device performance to the intrinsic threshold modal gain enhancements as well as the low internal loss from the intracavity contact achieved by a TJ. In January 2016, they reported nonpolar dielectric DBR VCSEL with a PEC etched air gap aperture [77]. The MQW region was selectively removed by PEC lateral undercut etching and the air-gap formed in the passive area of the device was expected to achieve efficient current confinement within the aperture as well as optical confinement in lateral direction at the same time. An ITO layer was utilized as current spreading layer. The device showed a threshold current density of 22 kA/cm$^2$ and a maximum output power of 180 µW. Later in June 2016, they reported nonpolar dielectric DBR VCSEL employing both TJ contact and ion-implanted aperture [78]. Small signal frequency modulation response of the device was measured and a -3dB modulation bandwidth of 1 GHz with an ultra-low capacitance of <1 pF was obtained.
Fig. 13. (a) Device structure fabricated by UCSB before the substrate removal by PEC etching, (b) SEM image of the air gap formed during PEC etching, and (c) the corresponding lasing spectrum [73, 74].

The dielectric DBR VCSELs mentioned above are all based on substrate transferring through which the device structure is bonded onto a suspending plate and then the original substrate is removed. In May 2015, researchers from Sony cooperation in Japan reported RT CW operation of dielectric DBR VCSELs fabricated using ELO [79]. The bottom electric DBR was embedded in GaN by ELO, which allows fabrication steps such as polishing and bonding to be eliminated. Accurate control of cavity length could also be realized. The VCSELs exhibited a threshold current density of 16 kA/cm$^2$ at a lasing wavelength of 446 nm and the maximum output power was 0.9 mW. Later in July 2016, they reported VCSELs with ELO bottom dielectric DBR and a current confinement aperture formed by boron implantation. The maximum output power was increased to 1.1 mW [80]. Fig. 14(a) and (b) shows the schematic device structure and the cross-sectional SEM image of ELO DBR structure. The L-I-V curve and emission spectrum were illustrated in Fig. 14(c) and (d).
Fig. 14. (a) Device structure of dielectric DBR VCSEL fabricated by Sony Cooperation employing both ion planted aperture and ELO DBR, (b) SEM image of the DBR structure, (c) the corresponding L-I-V curve, and (d) lasing spectrum [80].

In recent years, many efforts have been devoted to this enterprise. Electrically pumped dielectric DBR VCSELs with QWs as the active region lasing at various wavelengths from near violet to blue-green have been realized as reviewed above. However, for devices emitting in the green region, only pulsed lasing at 503 nm was obtained [71] and expanding the emission to a longer wavelength in green is still difficult and generally accompanied by an increase in the threshold current density. It is well known that InGaN QWs suffer from a serious drop of emitting efficiency in green region (typically 500-600 nm), which is called “green gap” [84]. To obtain green or longer wavelength emission, a higher In content in the InGaN QW layer is necessary. However, it will cause high-density defects and strong build-in electric field, which are the dominant reasons accounting for the low emission efficiency. Employing semipolar and nonpolar GaN substrates during epitaxial growth could decrease the built-in electric field in QW layers in some degree by eliminating spontaneous polarization induced electric field [85, 86]. However, these approaches cannot eliminate the strain which comes from the large lattice mismatch between GaN and InN, and thereby the strain-induced defects and piezoelectric field in the InGaN QWs cannot be eliminated. This strain becomes even pronounced when the In content is higher.

To release the strain, the adoption of nanoscale QDs is an effective approach. Semiconductor QDs can be formed during the epitaxial growth of a highly strained layer.
The formation of QDs by Stranski-Krastanov (SK) growth mode is driven by the strain itself, and the strain remaining in the QDs can be significantly reduced as compared with the case of a two dimensional QW epitaxial layer [87]. The QDs can also provide strong three-dimensional confinement of excitons in a small volume, which impedes carriers from being captured by defects or dislocations and increases the peak gain as well as the emission efficiency [88, 89]. Using InGaN QDs as the active region, edge emitting semiconductor lasers emitting in green (524 nm) and even in red (630 nm) have been demonstrated by researchers of University of Michigan [90, 91]. Lasing actions were obtained even on lattice-mismatched substrates and polar surfaces. These results indicate the potential for fabricating VCSELs emitting in the “green gap” by employing InGaN QDs.

Considering the unique properties of QDs in green region, researchers at XMU with their collaborators fabricated electrically pumped dielectric DBR VCSEL using InGaN QDs as the active region [67, 68]. The epitaxial wafer containing a QD active region was grown on a c-plane sapphire substrate using MOCVD [92]. The QDs with ~27% In content have diameters ranging from 20 to 60 nm, and the average height is ~2.5 nm. Fig. 15(a) and (b) shows the device structure and the AFM image of the uncapped QDs in the active region, respectively. The ITO and SiO$_2$ were used as current threading layer and confinement layer, respectively. The device was bonded on a copper mount to improve thermal dissipation and device structure was similar with dielectric DBR VCSELs fabricated through substrate transferring as reviewed above. RT CW lasing at different wavelengths in green region was obtained. The lasing wavelength extended from 491.8 to 565.7 nm, covering the most part of “green gap”. The emission wavelength, threshold current and CW lasing are the record results for GaN-based VCSELs. Fig. 16 shows the lasing spectra of devices emitting at different wavelength and the corresponding L-I-V curves.

![Device structure of the InGaN QD-based dielectric DBR VCSEL](image)

![AFM image of the uncapped QDs](image)

Fig. 15. (a) Device structure of the InGaN QD-based dielectric DBR VCSEL, (b) AFM image of the uncapped QDs [68].
Fig. 16. Lasing spectra and the corresponding L-I-V curves of three different devices fabricated by the same QD wafer [68].

The performances in electrically pumped GaN-based dielectric DBR VCSELs to date were summarized in Table 4.

Table 4. Performances in electrically pumped GaN-based VCSELs with dielectric DBRs.

<table>
<thead>
<tr>
<th>Epi. Sub.</th>
<th>Sub. Transfer</th>
<th>Operation</th>
<th>Aperture d (µm)</th>
<th>λ (nm)</th>
<th>FWHM (nm)</th>
<th>$J_{th}$ (kA/cm²)</th>
<th>$P_{max}$ (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008 Nichia [45]</td>
<td>Sapphire</td>
<td>LLO</td>
<td>RT CW</td>
<td>8</td>
<td>414</td>
<td>0.03</td>
<td>13.9</td>
</tr>
<tr>
<td>2009 Nichia [70]</td>
<td>GaN</td>
<td>CMP</td>
<td>RT CW</td>
<td>8</td>
<td>420</td>
<td>1.6</td>
<td>15.9</td>
</tr>
<tr>
<td>2011 Nichia [71]</td>
<td>GaN</td>
<td>CMP</td>
<td>RT CW/RT Pulsed</td>
<td>8/1</td>
<td>451/1</td>
<td>3/1</td>
<td>0.7m/</td>
</tr>
<tr>
<td>2012 Panasonic [72]</td>
<td>GaN</td>
<td>CMP</td>
<td>RT CW</td>
<td>10</td>
<td>503</td>
<td>1</td>
<td>28</td>
</tr>
<tr>
<td>2012 UCSB [73]</td>
<td>GaN</td>
<td>PEC</td>
<td>RT Pulsed</td>
<td>10</td>
<td>411.9</td>
<td>0.25</td>
<td>89</td>
</tr>
<tr>
<td>2014 UCSB [74]</td>
<td>GaN</td>
<td>PEC</td>
<td>15-40°C</td>
<td>7</td>
<td>407</td>
<td>/</td>
<td>89@15°C</td>
</tr>
<tr>
<td>2014 XMU [66]</td>
<td>Sapphire</td>
<td>LLO</td>
<td>RT CW</td>
<td>10</td>
<td>422</td>
<td>0.2</td>
<td>1.2</td>
</tr>
<tr>
<td>2015 UCSB [75]</td>
<td>GaN</td>
<td>PEC</td>
<td>RT Pulsed</td>
<td>12</td>
<td>406</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>2015 UCSB [76]</td>
<td>GaN</td>
<td>PEC</td>
<td>RT Pulsed</td>
<td>12</td>
<td>417</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>2015 Sony [79]</td>
<td>GaN</td>
<td></td>
<td>RT CW</td>
<td>8</td>
<td>446</td>
<td>0.05</td>
<td>16</td>
</tr>
<tr>
<td>2016 UCSB [77]</td>
<td>GaN</td>
<td>PEC</td>
<td>RT Pulsed</td>
<td>12</td>
<td>417</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>2016 UCSB [78]</td>
<td>GaN</td>
<td>PEC</td>
<td>RT Pulsed</td>
<td>10</td>
<td>419</td>
<td>0.6</td>
<td>23</td>
</tr>
<tr>
<td>2016 Sony [80]</td>
<td>GaN</td>
<td></td>
<td>RT CW</td>
<td>8</td>
<td>453.9</td>
<td>0.05</td>
<td>35.8</td>
</tr>
</tbody>
</table>
Development trend and emerging application of GaN-based VCSELs

VCSELs have become popular light sources due to their advantages such as low power consumption, inherent single longitudinal-mode emission, easy integration into two-dimensional arrays, circular beam shape to facilitate coupling to optical fibers, on-wafer testing which significantly reduces the production cost [93]. Different from well-established GaAs and InP material systems where the VCSEL emits in the infrared regime, GaN-based VCSELs can provide available emission wavelengths in the ultraviolet to visible regime so that more applications could benefit from such a light source. The development trend and emerging application of GaN-based VCSELs, including high-resolution printing, lighting and displays, visible light communication, miniature atomic clocks, and military and medical applications, will be briefly discussed as follows.

a) High-resolution printing

Compared with a single laser tube, the devices in two-dimensional VCSEL arrays can scan simultaneously, which can greatly improve the scanning speed and prolong the service life of laser printers. To meet the market requirements, Fuji Xerox has launched the world first laser printer (DocuColor 1256 GA) introducing 780-nm single-mode 8×4 GaAs VCSEL arrays in the light exposure system in 2003 [94]. The VCSELs features uniform performances with a small variation in both divergence angle and output power. Thanks to the shorter emission wavelengths of GaN-based materials, a smaller diffraction spot can be obtained so that the resolution of printers can be increased. Moreover, GaN-based blue and green emitting VCSELs combined with infrared lasers can achieve full color printing.

b) Lighting and displays

In solid-state-lighting (SSL), visible spectrum commercial LEDs suffer from serious efficiency droop [95, 96]. An LED bulb contains many LEDs so that a large part of the wafer is dedicated to just one LED bulb, resulting in a high cost. However, laser-based sources can provide peak efficiencies at much higher current densities and may circumvent efficiency droop limitations [97-99]. Besides, VCSELs with a smaller volume can offer circular-symmetric beam. The emission of VCSELs is directional and can be more readily captured and focused, which could lead to the possibility of new and more compact luminaires. Adopting VCSELs as light sources also contributes to the reduction of the power consumption. All are compelling reasons to pursue VCSELs for SSL.
application. Moreover, the individually addressable elements in a two-dimensional VCSEL array would enable tailor-made, dynamic emission patterns for smart lighting systems. Due to the tunable wavelengths from ultraviolet to visible, GaN-based VCSELs could also be of great interest for laser display application, such as pico projectors, head-up-displays and near-eye displays [100], which do not require so much optical output power.

c) Visible light communication

VCSELs have many advantages over conventional edge-emitting laser (EEL), such as high modulation speed at low drive currents, circular symmetric low-divergent output beam, easy to couple with optical fiber. In addition to lighting, there is an opportunity to leverage the capabilities of VCSELs for visible light communication (VLC). Though LED-based VLC systems are paving the way to commercialization, the performance of those emitters is limited by the spectral bandwidth and slow frequency response due to long carrier lifetimes associated with the spontaneous emission process [101, 102]. A laser would offer a light source with a much narrower spectrum and much higher modulation speed. High modulation performances have been achieved for GaN-based LDs including a data transmission rate of 2.5 Gbps for a blue-violet LD with a high modulation bandwidth of 1.4 GHz [103], and recently, both a high modulation bandwidth of 2.6 GHz and a record data transmission rate of 4 Gbps for a blue LD measured with a UV-extended high-speed photodiode [104]. A VCSEL could offer additional advantages compared to an EEL, as mentioned above.

d) Miniature atomic clocks

The atomic clocks can be divided into two kinds, including microwave atomic clock and optical atomic clock. Optical atomic clock has a higher accuracy in theory since the frequency of optical atomic clock is four orders of magnitude higher than the microwave atomic clock. At present, many groups have carried out the research of optical atomic clocks. Varieties of ions (Al⁺, In⁺, Sr⁺, Ca⁺, etc.) [105-108] or neutral atoms (Sr, Yb, Mg, Ca, Hg, etc.) [109-111] suitable for the frequency standard of optical band have been found by researchers. A chip-scale atomic clock needs to be modularized and miniaturized so that a small size and low power consumption light source is required. In 2000, the demonstration of an all-optical atomic clock using a modulated VCSEL [112] rather than a RF cavity paved the way to dramatically reduce the size and power consumption of atomic frequency standards. Near ultraviolet GaN-based VCSEL is also required for optical clock based on calcium ion. Low power and stable VCSEL plays an important role in promoting the development of miniature atomic optical instruments.

e) Military and medical application

The short wavelength (400-500 nm) lasers also have a broad application in military and medical fields. Blue and green light is the window of light propagation in the ocean. The optical loss of wavelengths between 470 nm to 504 nm in water is 100 times smaller than that in other bands. Therefore, blue and green lasers can be used for the deep-sea exploration and submarine communication system [113]. In the field of medical treatment,
blue lasers can be used in surgical operations while ultraviolet lasers can be used for early treatment of cancer. In medical diagnosis, the detection of skin and esophagus cancer is now possible without the use of biopsy by using laser-induced fluorescence at a wavelength of 410 nm [114, 115]. GaN-based lasers have also recently been used in early diagnosis of oral cancer [116], where VCSELs could offer additional advantages such as a low-divergent circular-symmetric output beam and improved high-speed performance. It will more conducive to the development of these industries if high performance GaN-based VCSELs could be developed.

6. Future prospects

The lasing action of GaN-based hybrid DBR VCSELs under CW electrical pumping at 77 K were reported by NCTU in 2008 [26] and the CW electrically pumped GaN-based dielectric DBR VCSEL at RT was demonstrated by Nichia later in the same year [45]. So far, ultraviolet (~400 nm), blue (~450 nm) and green light (~500 nm) RT CW lasing have been achieved by a few academic researchers and large-scale semiconductor enterprises, as mentioned in the above sections. Though large 3 mW RT CW lasing of the GaN-based VCSEL was obtained by Meijo-U recently [65], the output power of most devices is below 1 mW, and the lifetime of the devices has still been rarely reported. Only Nichia mentioned in the paper that the device with a sapphire substrate ceased lasing within 2 minutes. On the contrary, using a GaN substrate instead can reduce defect density in the material, and the device can continue lasing for 10 minutes [70]. However, the use of GaN substrate still has not been able to achieve a higher output power. On the other hand, due to the presence of high density defects and large polarization field in In-rich InGaN, green VCSELs are more difficult to obtain. The QCSE due to the large polarization field spatially separates the hole and electron wave functions, which causes lower internal quantum efficiencies and an increased threshold current. Recently, with InGaN QD active region, XMU’s group has effectively overcome these problems, extended the emission wavelength to the record 565.7 nm, and demonstrated VCSELs emitting at wavelengths covering most of the “green gap” [68]. The study to date shows that the GaN-based VCSELs are much more technically difficult than the GaAs- and InP-based VCSELs and the challenge of the GaN-based VCSELs is to enhance the laser performances. In future, high-performance and practical GaN-based VCSELs with different wavelengths will be more focused by researchers. However, there are still some challenges in improving the device performances. The defect density in materials is an important issue which increases the threshold current of the device and causes heat effects. Thus, it is necessary to improve the key technology in epitaxial growth so that the defects in materials can be reduced. Importantly, several issues should be considered in the design of GaN-based VCSELs, including optimizing a good current spreading contact structure with reduced optical loss for carrier injection, enhancing p-GaN layer conductivity and the uniformity of the MQW active region, improving heat dissipation for the increase of output power, increasing the reflectivity of high-quality
DBRs for the reduction of threshold current, etc. It is of great significance to achieve high-performance GaN-based VCSELs. In addition, investigation on deep-ultraviolet and red GaN-based VCSELs will become the next hot topic. Compared with blue and green VCSEL, they are more difficult and have not been reported yet.

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