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High-bandwidth green semipolar (20-21) InGaN/GaN micro light-emitting diodes for visible light communication

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ABSTRACT: The light-emitting diode (LED) is among promising candidates of light sources in visible light communication (VLC); however, strong internal polarization fields in common c-plane LEDs, especially green LEDs result in low frequency and limited transmission performance. This study aims to overcome the limited 3-dB bandwidth of long-wavelength InGaN/GaN LEDs. Thus, semipolar (20-21) micro-LEDs (µLEDs) were fabricated through several improved approaches on epitaxy and chip processes. The µLED exhibits a 525 nm peak wavelength and good polarization performance. The highest 3-dB bandwidth up to 756 MHz and 1.5 Gbit/s data rate was achieved under a current density of 2.0 kA/cm². These results suggest a good transmission capacity of green semipolar (20-21) µLEDs in VLC applications.

KEYWORDS: semipolar GaN, micro light-emitting diode, visible light communication, high-bandwidth.

INTRODUCTION

Light-emitting diodes (LED) and µLEDs are suitable as light sources for visible light communications (VLC) owing to their advantages such as high bandwidth, low power, and being license-free.1-2 Hence, VLC-LEDs have been regarded as candidates for underwater wireless optical communication (UWOC), polymer optical fiber communication (POF), and light-fidelity (Li-Fi) networks applications. Green VLC-LEDs are particularly suitable for POF and UWOC applications because they produce only a small loss in the plastic fiber and seawater.3,4 The limitation of the 3-dB bandwidth for a VLC-LED device can be described by the following equation:

\[ f_{3dB} = \frac{\sqrt{3}}{2\pi} \left( \frac{1}{\tau} + \frac{1}{\tau_{\text{nr}}} + \frac{1}{\tau_{\text{RC}}} \right), \]  \( \text{(1)} \)

where \( \tau \) is the lifetime of minority carrier, \( \tau_r \) is the lifetime of radiative carrier, \( \tau_{\text{nr}} \) is the lifetime of nonradiative carrier, and \( \tau_{\text{RC}} \) is the RC time constant. In order to increase the \( f_{3dB} \) bandwidth, it is preferable to shorten \( \tau_r \) but not \( \tau_{\text{nr}} \) because the carrier radiative lifetime has been established as the dominant factor limiting the \( f_{3dB} \) bandwidth for LED devices with an active area close to micro-size or less.5 In this situation, \( \tau_r \) depends on the injected current density and is equal to \( B^T \times N \), where \( B \) and \( N \) denote the radiative coefficient and the carrier density, respectively. Thus, equation (1) takes the following form when a bimolecular recombination mechanism is assumed:

\[ f_{3dB} = \frac{\sqrt{3}}{2\pi} \times \sqrt{\frac{BJ}{qd}}, \]  \( \text{(2)} \)

where \( J \) denotes the injected current density, \( q \) stands for the elementary charge, and \( d \) is the active region thickness. Thus, equation (2) implies that higher 3-dB bandwidth can be realized by either increasing the operation current density, typically 5 to 10 kA/cm² for c-plane multiple quantum wells (MQWs) LEDs, or reducing the chip size to obtain a higher injected current density.6 However, the commercially available GaN LEDs are usually grown on (0001) “polar” c-plane GaN, which can result in a strong quantum-confined Stark effect (QCSE) leading to the reduced efficiency (i.e., efficiency droop) under high injected current density conditions.7 The QCSE is caused by the natural structure of GaN, a hexagonal crystal with wurtzite structure, where the existence of spontaneous polarization is due to the highest symmetry compatible.8 Meanwhile, the MQWs sustain a large piezoelectric field due to the strain-induced polarization from the lattice mismatch between InGaN and GaN. These internal polarization fields along the c-plane (z-axis) cause charge to accumulate at the heterojunction in MQWs, leading to the tilt of the energy band. The wave-function distribution of electrons and holes will be spatial separated, resulting in low carrier radiative recombination rate and low internal quantum efficiency. QCSE also leads to wavelength-shift and efficiency droop with increasing injected current density.7,9 Moreover, the QCSE in InGaN/GaN MQWs increases due to stronger polarization, larger lattice mismatch, high defect density, and stronger strain caused by the increase in indium (In) composition.10 These phenomena in InGaN/GaN LEDs are the “green gap”, limiting the development of green LEDs in the past decades.11 The 3-dB bandwidth will be limited by QCSE when LEDs are utilized as optical transmitters for wireless communications.

One approach to overcome QCSE is to fabricate nonpolar structures on bulk GaN.12 The polarization field can be completely eliminated when the growth orientation of the InGaN / GaN MQWs crystal plane lies perpendicular to the polar planes, e.g., along the (11-20) or the (1-100). However, such nonpolar a- or m-plane LEDs still emit a
short wavelength of < 510 nm with low EQE, low output power due to low In incorporation, and poor epitaxial material quality. The incorporation of In atoms into the semipolar plane has a much lower chemical potential requirement than that for both polar and nonpolar surfaces since the semipolar GaN surface has a lower repulsive interaction with the In atoms. Consequently, semipolar GaN crystals can accommodate a much higher In content, which is beneficial for long-wavelength MQWs in InGaN/GaN devices. The most promising growth orientation for GaN-based long-wavelength devices is the semipolar plane. The applications of the semipolar (20-21) and (20-2-1) epitaxial structures have been proven to effectively suppress the effects of QCSE and bridge the green gap with a larger output power. These superior devices can be achieved by free-standing GaN crystals that are prepared by either hydride vapor-phase epitaxy or ammonia-thermal epitaxial methods; however, they are still limited by the difficulty of obtaining GaN substrates. Until now, the GaN substrate is still an expensive material, commonly produced in small dimensions (e.g., 2-inch wafers). This problem limits the mass-production of semi-polar and nonpolar devices.

Since 2000, the progress of epitaxial processes for manufacturing nonpolar and semipolar structures can be divided on the basis of heteroepitaxy on substrates like sapphire, Si, SiC, and free-standing bulk GaN substrates. Subsequently, epitaxial lateral overgrowth (ELOG) and orientation controlling epitaxy (OCE) are investigated for growing semipolar GaN with large-area by patterned substrates. Recent progress in heteroepitaxy has been achieved with selective area growth (SAG) of semipolar GaN from the inclined sidewall on striped sapphire or Si substratum. It is theoretically possible to access any orientation of GaN on large-size foreign substrates by OCE or SAG still produces stacking faults (SFs) with a certain magnitude of defect density while GaN coalesces to form a continuous film. In contrast to c-plane devices grown on sapphire, the initial development of semipolar and nonpolar GaN heteroepitaxy suffered from a high density of SFs consisting of basal-plane SFs (BSFs) and prismatic SFs (PSFs) associated with BSFs, which lead to a high defect density in the epitaxial layer. In the case of c-plane-grown GaN, the SFs cannot extend to the surface, and thus their influence can be ignored. However, the SF planes are parallel or inclined to the growth orientation of nonpolar or semipolar GaN. Consequently, SFs can cross over the upper layers and extend to the active region. Both BSFs and PSFs are supposed to affect the property of the semipolar GaN device. Most defects, which grow along the underlying epitaxial layer, also affect the number of defects in the active region. The existing defects in the active region of a GaN-based optical-electrical device act as non-radiative recombination centers to capture electrons via phonon emission. An electron captured by the defects can then recombine with a valence band hole, again accompanied by the emission of phonons. Thus, an electron falls from the conduction band to the valence band via at least two transitions; however, most of the energy released is dissipated as heat. This non-radiative recombination process also called the Shockley-Read-Hall (SRH) recombination or trap-assisted recombination. This is also related to the droop effect of the LEDs. In order to improve the epitaxial quality and achieve high-performance devices, it is important to further eliminate SFs. In our previous study, we investigated a SAG technique utilizing a Germanium-doped (Ge-doped) process to realize SF-free semipolar (20-21) LEDs on large scale (4-inch) patterned sapphire substrates. The performance of this device was comparable to the free-standing semipolar device with an emission wavelength of 455 nm, a spectral linewidth of 22 nm, and a maximum EQE of 24%. These results indicate that the semipolar GaN devices has the potential for developing high-speed VLC applications owing to the elimination of QCSE and improved material quality.

In this work, long-wavelength (initial wavelength 540 nm) InGaN/GaN VLC-LEDs with a high 3-dB bandwidth were realized using semipolar epitaxy and µLED structure. The superior optical-electrical properties of this work were developed by an advanced epitaxial process and chip structure design. For instance, atomic layer deposition (ALD) was introduced to eliminate the surface defects caused by the size effect and reduce the leakage current. As a result, the semipolar (20-21) µLED achieves the highest-ever 3-dB bandwidth in long-wavelength InGaN/GaN LED devices, to the best of our knowledge.

EXPERIMENTS

The epitaxial process of semipolar (20-21) GaN on a (22-43) PSS is carried out through a low-pressure metalorganic chemical vapor deposition (MOCVD). The offset angle of the (22-43) sapphire was adjusted to fit the (20-21) GaN surface precisely with the substrate surface. The angle between (20-21) GaN and c-plane GaN is 75.09°, while the angle between (22-43) sapphire and c-plane GaN is 74.64°. Hence, the final offset angle is 0.45°. The (22-43) PSS was prepared using photolithography and inductively coupled plasma reactive-ion etching (ICP-RIE) process. The depth and width of the grooves and terraces for the linear trenches are 1 µm, 3 µm, and 6 µm, respectively. Beyond the selected c-plane sapphire sidewall, a self-aligned technique of angled evaporation was used to deposit silicon oxide on the surfaces of the entire substrate. After preparing the substrates, semipolar (20-21) GaN was grown. In the early stage of epitaxy, Ge-doping was used to avoid the formation of SFs during GaN coalescence. The detailed principle of elimination for SFs can be found in our previous work. An 8-µm-thick undoped GaN was grown after the adjacent Ge-doped GaN stripes coalesced, resulting in a bulk layer approximately 10 µm thick. The wafer was then removed from the MOCVD set-up and planarized using the chemical-mechanical planarization process to achieve a smooth surface for growing InGaN/GaN LED on (20-21) GaN templates. The LED structure consisted of a 1.5-µm-thick n-type GaN, followed by 3 pairs of InGaN/GaN MQWs as the active region and a 100-nm-thick p-type GaN layer.

The µLED process starts with the deposition of a 200-nm-thick indium tin oxide (ITO) layer, followed by using HCl solution and ICP-RIE for etching the ITO film and the
1-μm-depth mesa, respectively. The sample was then annealed at 450°C under atmospheric ambiance via a rapid thermal process to form a p-type ohmic contact. Subsequently, Ti/Al/Ti/Au with a thickness of 20/150/10/100 nm was deposited as the electrodes. ALD technology was introduced for growing the passivation layer of the VLC µLED device. The passivation layer of aluminum oxide (Al₂O₃) was grown in an argon (Ar) environment at 300°C by applying the cycle for trimethylaluminum (TMA) and H₂O, with Ar purging. After depositing a 30-nm-thick passivation layer, 200-nm-thick SiO₂ layer was grown by plasma enhanced chemical vapor deposition (PECVD) and the via hole process by ICP-RIE. Ti/Al/Ni/Au was deposited again as the pad metal and sidewall reflector. Finally, the rear side of the wafer was deposited with a distributed Bragg reflector (DBR).

RESULTS AND DISCUSSION

In Fig. 1(a), the National Chiao Tung University logo is visible clearly as a reference through a 4-inch semipolar (20-21) green LED epitaxial wafer and 2-inch commercially available c-plane InGaN/GaN LED wafer with its rear side polished. The high degree of transparency for both wafers reveals the uniformity and low defect density. Large-area, low-cost epitaxial technology helps increase the application potential of semipolar LEDs. The SEM image (Fig. 1(b)) shows the complete LED epitaxial layer and labels the crystalline planes of GaN with a surface normal direction toward (20-21) GaN. In a previous study, Ge doping was found that can change the growth rate of N-polar (000-1) facets and decelerate the growth rate of (101-1), resulting in the elimination of SFs generated in the (000-1) facets. This method significantly improves the quality of heteroepitaxial semipolar GaN and achieves XRD rocking curves of the on-axis (20-21) plane with the full width at half maximum (FWHM) of 192 and 217 arc sec to the rocking axis perpendicular or parallel to the patterned stripes, respectively.²⁴ Comparable with those of c-plane epitaxy, these values suggest the bulk GaN layer with a high crystal quality. Further, in Fig. 1(c), the µLED device has been optimized by various designs to achieve high performance in VLC properties. The core technologies in the concept of this device are as follows:

(i) The electrode has been minimized to reduce the capacitance in order to reach a small RC time constant.

(ii) The circular active area and the electrode used to improve the spreading of current and enhance the electrical performance.

(iii) An Al₂O₃ layer deposited by the atomic layer deposition (ALD) was utilized to erase the influence of sidewall defects from the etching process.

(iv) The DBR on the rear side was deposited by the evaporation machine and consisted of multiple pairs of SiO₂/TiO₂. The designed thickness of SiO₂/TiO₂ layer in each pair was 72 nm and 50 nm, respectively.

Some previous studies have stated that the influence of sidewall defects increase as the chip size decreases.²⁶,²⁷ In particular, when the LED device achieves a micrometer scale, traditional passivation methods such as the PECVD process, is no longer useful owing to the large leakage current of the µLED device. ALD dielectric thin films have
been regarded as an effective passivation technique in the 
µLED area.\textsuperscript{28} The rear DBR can achieve a reflectivity of 
90% for wavelengths between 460 to 550 nm with a number of 
10.5 pairs in this work and helps enhance the output power.\textsuperscript{29}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{(a) J-V curve of semipolar µLEDs; (b) EL spectra at different currents, and an image of lighting from device; (c) wavelength shift and FWHM as a function of currents; (d) EL spectra at 50 mA along the x'- and y'-directions, and the polarization ratio at different currents.}
\end{figure}

Figure 2 summarizes the optical and electrical 
performance of semipolar (20-21) µLEDs. The current 
density versus voltage (J-V) curve is shown in Fig. 2(a). The 
current density was normalized by the active region area, 
and the maximum applied current of 50 mA corresponds to 
2546 A/cm\textsuperscript{2} in this study. The 2.2 V turn-on voltage is 
regarded as a reasonable performance of the green µLED. 
This result indicates good material properties and device 
processes. It's worth noting that this device shows a 
relatively larger resistance which may cause by the inverse 
polarization due to the additional energy barriers in MQWs 
or the poor ohmic contact in the p-type region.\textsuperscript{30} But the 
large resistance cannot significantly affect the 3-dB 
bandwidth of the device because of the extremely small 
capacitance for microscale LEDs.\textsuperscript{7} The inset in Fig. 2(a) 
demonstrates a J–V curve at the reverse voltage, which is 
used to observe the leakage current. The low leakage current 
density (about 10\textsuperscript{-6} A/cm\textsuperscript{2}) achieved under -8 V can be 
attributed to the ALD passivation process and the low defect 
density in semipolar (20-21) GaN. Several studies report the 
proportional relationship between the leakage current and 
the defect density.\textsuperscript{28, 31, 32} Moreover, sidewall defects and 
surface recombination dominate the generation of leakage 
currents as the chip size shrinks in GaN-based LED devices. 
These surface states are mainly caused by the sidewall 
damage during the dry etching. J. Kou \textit{et al.} also 
demonstrated that the injection capability for carriers was 
severely affected by sidewall defects, reducing the device 
performance.\textsuperscript{26} Wang \textit{et al.} reported a comparison of ALD 
and PECVD passivation for µLED devices.\textsuperscript{28} The results 
show that ALD has a marked passivating effect while PECVD fails to confine the leakage current for µLEDs 
smaller than the chip size specified. The above description 
illustrates the importance of the ALD passivation process in 
this study and µLED related applications. In Fig. 2(b) and 
(c) demonstrate the electroluminescence (EL) emission 
spectra and the spectral properties for the semipolar (20-21) 
µLED with increasing injected current (5 mA as an interval), 
respectively. The inset in Fig. 2(b) illustrates a photograph of µLED operating at 10 mA. The µLED device illustrates a 
peak-wavelength shift of 14.9 nm and becomes stabilized 
from 5 to 50 mA. This wavelength shift can be considered a 
good performance compared to common c-plane devices. It 
originates in the reduced polarization-related electric field, 
and flattens the energy bandgap of the quantum wells, 
implying an improved QCSE. Meanwhile, the FWHM of the 
emission spectra is only 3 nm change (including the 
maximum change) from 5 to 50 mA, which indicates low 
defect density and good uniformity in the distribution of In 
atoms. Furthermore, the higher polarization ratio is an 
advantage of semipolar LEDs compared with c-plane-grown
LEDs. Fig. 2(d) illustrates the EL spectra of the semipolar μLED at 50 mA with the polarizer aligned along the [1-210] and [10-1-4] directions, which are defined as the \( x' \)- and \( y' \)-directions that correspond to the maximum and minimum intensities through the polarizer, respectively. The following equation can be used to determine the optical polarization ratio:

\[
\rho = \frac{I_{x'} - I_{y'}}{I_{x'} + I_{y'}},
\]

where \( I_{x'} \) and \( I_{y'} \) denote the integrated intensities of EL spectra in the \( x' \)- and \( y' \)-directions, respectively. The polarization ratio is 0.3 for the EL spectra at 50 mA, and this value is consistent with previous studies. In GaN-based semipolar LEDs, a longer wavelength (i.e., higher In content) exhibits a larger polarization ratio because of the optical transition between the conduction band and the highest valence band. The inset in Fig. 2(d) illustrates the polarization ratio with increasing injected currents. The plotted data illustrate that the polarization ratio is independent of the injected current. These results suggest that the InGaN layers were homogeneous in the MQWs. Such polarization characteristics can be applied to polarization-division multiplexing to increase the data transmission rate and introduce another degree of freedom that can multiply the transmission capacity, compared to the traditional VLC works.

Figure 3 presents the time-resolved photoluminescence (TRPL) measurement of the semipolar (20-21) μLED and commercial c-plane green μLED as a reference, produced by Epistar Inc. with PL peak wavelengths of 534 and 529 nm, respectively. TRPL measurements were conducted at a low power of 20 μW at room temperature to ensure that excitonic recombination dominates the recombination process. The carrier decay dynamic parameter of the InGaN / GaN LED system can be derived from a double-exponential fit representing a decline in PL of two components by relaxing localized excitons, and the excitonic relaxation of free carriers and localized states, respectively. The normalized TRPL trace \( I(t) \) can be used to calculate the minority carrier lifetime \( \tau \) as follows:

\[
I(t) = \alpha_1 \exp\left(-\frac{t}{\tau_1}\right) + \alpha_2 \exp\left(-\frac{t}{\tau_2}\right),
\]

\[
R_i = \frac{\alpha_i}{\sum_{i=1}^{n} \alpha_i},
\]

where \( \alpha_i \) and \( \tau_i \) (for \( \alpha_2 \) and \( \tau_2 \)) define as the fast or slow decay components corresponding to localized excitons and excitonic relaxation of free carriers and localized states, respectively, and \( R_i \) is the relative ratio factor. Using the parameter extracted from fitting results (as the table shown in Fig. 3), the minority carrier lifetime \( \tau \) of each sample found to be 2.65 ns and 9.00 ns, respectively. The shorter lifetime of semipolar samples are due to the weak polarized field and flat energy gap distribution which lead to larger electron-hole wave-function overlap reducing the \( \tau_x \) and the smaller In fluctuations that reduce the \( \tau_y \) in a comparison between the semipolar and c-plane samples. Faster carrier recombination corresponds to the higher 3-dB bandwidth in similar LEDs. Further, Zhao et al. revealed that faster carrier transport in semipolar devices also contributes to the weaker phase-space filling effect which was determined for the low-droop phenomenon in semipolar LEDs because of small QCSE and short carrier lifetimes using the consistency between theoretical and experimental results. The aforementioned advantages imply that a semipolar LED is capable of simultaneously achieving high modulation speed and maintaining high efficiency with increasing injected current owing to low droop performance.
impressive performance of the 3-dB bandwidth, the eye diagrams of the semipolar µLED were clear and open at both 1.0 and 1.5 Gb/s in Fig. 4(d). However, the eye area was no longer clear when the data rate toward to 2 Gb/s due to the relatively low signal-to-noise ratio. It is expected to obtain a higher data rate through high-level modulation methods in the future.

Figure 5 shows the benchmark of the 3-dB bandwidth versus the current density for the long-wavelength (> 500 nm) InGaN LED devices with different achievements. In 2008, Lai et al. illustrated a c-plane green (peak wavelength 510 nm) LED and achieved a bandwidth of 330 MHz under a 2.2 kA/cm² injected current density.39 Wu et al. demonstrated a bandwidth close to 463 MHz for the c-plane (peak wavelength 500 nm) LED with a 75-µm aperture diameter incorporating the improvement of a ring-shaped electrode, and achieved a high data rate in 2014 and 2018, respectively.40, 41 J. Li et al. demonstrated a surface plasma coupled method to enhance the 3-dB bandwidth for the c-plane green (peak wavelength 540 nm) LEDs that achieve 80 MHz frequency under 100 mA using a normal chip 418 µm in diameter.42 In 2016, Corbett et al. reported green (peak wavelength of ~550 nm) LED devices grown on semipolar (11-22) GaN templates and showing a 100 MHz bandwidth under 30 mA.43 In 2018, Mei et al. introduced a perovskite quantum dots converted white LED with 83 MHz bandwidth, which provides another approach to realize VLC application.44 In 2020, Khoury et al. demonstrated the first monolithic white semipolar (20-21) LEDs and achieved a 660 MHz bandwidth with a chip diameter of 20 µm.45 To the best of our knowledge, this study shows the highest 3-dB bandwidth of 756 MHz (at 2.0 kA/cm²) achieved by long-wavelength InGaN LED devices. Based on our previous results for semipolar (20-21) LED technology, this device has been improved in terms of the Ge-doped epitaxial process, chip structure design, and ALD passivation.

CONCLUSION
In conclusion, a high 3-dB bandwidth semipolar (20-21) long-wavelength InGaN/GaN μLED has been demonstrated. The SF-free semipolar LED is successfully fabricated, and its superior optical-electrical performance indicates good epitaxial quality through the improvement of the Ge-doped SAG process. By introducing chip structure optimization and ALD passivation, this device shows the highest 3-dB bandwidth of 756 MHz at 2.0 kA/cm² with a 525 nm peak wavelength and high polarized properties. The breakthrough in this 3-dB bandwidth allows semipolar LEDs an attractive part to realize VLC at high speed.

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Notes
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50-μm semipolar micro-LED and its frequency response performance.