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Semipolar (2021) InGaN/GaN micro-photodetector for gigabit-per-second visible light communication

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This paper investigated the use of semipolar InGaN/GaN multiple quantum well based micro-photodetectors (μPDs) as the optical receiver for visible light communication (VLC). The fabricated semipolar μPDs exhibited a low dark current of 1.6 pA at −10 V, a responsivity of 0.191 A W−1, and a −3 dB modulation bandwidth of 347 MHz. A high data rate of up to 1.55 Gbit s−1 was achievable by utilizing the extended bandwidth of more than −10 dB, and based on a straightforward non-return-to-zero on-off keying modulation scheme. This development demonstrated the feasibility of wavelength-selective detection scheme using semipolar μPD for high-data-capacity VLC systems.

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Recently, the demand for high bit-rate communication links has grown progressively owing to the ever-increasing number of wireless devices; and due to the emergence of the era of the internet-of-things, and the internet-of-underwater-things in future smart cities.1–3 Limited bandwidth in the conventional micro-and-millimeter frequency band is expected to get congested over the next decade. In recent years, visible light communication (VLC) links, which utilize the 400–790 THz band, are envisioned as the next-generation high-throughput approach to mitigate the bandwidth congestion in conventional communication links.1,2) Optical carriers offer high bit-rate, license-free, and electromagnetic-interference-free communication links in the absence of fiber networks, e.g. for indoor navigation systems,3) underwater wireless optical communication,4) water-to-air communication,5) and vehicle-to-vehicle communication.6)

In particular, compositionally-tunable group-III-nitride-based optical transmitters, e.g. light-emitting diodes (LEDs),7–9) laser diodes (LDs),10–15) and superluminescent diodes,16–18) have been widely developed and demonstrated with data rates of up to a few gigabit-per-second (Gbit s−1) for VLC systems. Comparatively, the advances in optical receivers are still lagging behind and hinder the improvement of data rate in VLC.9,13,19) Conventional silicon-based photodetectors (PDs) are widely employed in VLC systems due to their low-cost and compatibility with state-of-the-art complementary metal-oxide-semiconductor technology. However, the wide absorption coverage present in silicon-based PDs cannot guarantee high wavelength-selectiveness and high signal-to-noise ratios (SNR), which are paramount for practical VLC systems.20) Moreover, the responsivity of silicon-based PDs typically reduce to less than 0.1 A W−1 for wavelengths shorter than 400 nm owing to the lower penetration depths of ultraviolet (UV)-to-blue photons in the silicon layer.21) On the other hand, compositionally-tunable group-III-nitride-based PDs could offer a wavelength-selective response with a high rejection ratio to improve the received optical signals and SNR ratios. Previous group-III-nitride PDs have so far been characterized as stand-alone devices and not demonstrated in VLC systems.22–24) Our prior work highlighted a c-plane InGaN/GaN multiple quantum well (MQW) μPD with a −3 dB modulation bandwidth of 71.5 MHz and a VLC link of up to 3.2 Gbit s−1 utilizing orthogonal frequency-division multiplexing, which inherently requires higher computational power and for achieving higher data capacity.25,26) A device that can utilize the on-off keying (OOK) technique to achieve Gbit s−1 data capacity is therefore attractive.

Compared to c-plane (polar) InGaN/GaN MQW-based devices grown on sapphire substrates, semipolar and non-polar devices exhibit quantum wells with improved overlapped of electron and hole wavefunctions, and therefore enhances the radiative recombination efficiency. These devices have thus far showed excellent characteristics in terms of lower efficiency droop,26,27) narrower emission linewidth,28,29) shorter carrier lifetime,29,30) and higher temperature stability than conventional c-plane based devices.31) In particular, Monavarian et al. reported a high −3 dB bandwidth of up to 260 MHz for LEDs grown on the semipolar (2021) orientation, which is comparatively larger than the conventional polar LEDs that exhibit a modulation bandwidth of 75 MHz.30) The semipolar structure grown along the (2021) plane has also experimentally shown to exhibits higher indium incorporation efficiency as compared to non-polar and polar devices due to lower repulsive interaction.32,33) This allows the growth of InGaN with high indium content at a relatively higher temperature with improved crystal quality that is necessary for high-performance compositionally-tunable optoelectronic applications. These inherent advantages of having a broad modulation bandwidth and higher crystal quality demonstrated in semipolar devices are advantageous for high-speed, wavelength-selective VLC links and on-chip optical interconnections.34,35)

Herein, we demonstrated high-performance surface-absorbing semipolar InGaN/GaN PIN-based μPD grown on a (2021) free-standing GaN substrates, exhibiting high...
wavelength-selectiveness and high-speed optical receivers for Gbit s\(^{-1}\) VLC link. In achieving the high-performance, we measured and characterized the photoelectrical performance in terms of responsivity, specific detectivity, noise equivalent power (NEP), and linear dynamic range (LDR). Subsequently, a 1 m long VLC link based on the \(\mu\)PD as the optical receiver and a 405 nm LD as the transmitter was established. The modulation response was evaluated and the highest achievable data rate was measured by implementing a straight-forward intensity-modulation direct-detection scheme based on non-return-to-zero on–off keying (NRZ-OOK).

Figure 1 shows the schematic diagram of the \(\mu\)PD fabricated on a semipolar InGaN/GaN MQW-based structure. The structure was grown on a semipolar (20\(\bar{2}\)I) GaN substrate using metal-organic chemical vapor deposition. The structure consists of \(\sim 1 \mu m\) Si-doped \(n\)-GaN, 5 periods of In\(_{0.15}\)Ga\(_{0.85}\)N/GaN (3 nm/9.5 nm) MQW active region, \(\sim 350 \text{ nm}\) Mg-doped \(p\)-GaN, and a 15 nm heavily Mg-doped \(p\)-GaN cap layer. The inset of Fig. 1 shows a representative transmission electron microscopy (TEM) image of a semipolar (20\(\bar{2}\)I) MQW structure. The transparent contact of Ni/ITO (10 nm/250 nm) was deposited by sputtering followed by rapid thermal annealing at 600 °C for 1 min. Then, the mesa structures were defined using a Cl\(_2\)-based inductively coupled plasma reactive ion etcher. A 225 nm SiO\(_2\) layer was then deposited using plasma-enhanced chemical vapor deposition to act as an insulating layer between the metal pad of the top-most \(p\)-GaN layer and the other GaN layers. Lastly, Ti/Au (20 nm/300 nm) layers were deposited using an e-beam evaporator to act as the metal contacts. The fabricated \(\mu\)PDs have a circular mesa with diameters of 80 \(\mu m\). Similar devices with less than 100 \(\mu m\) in diameter have been widely reported elsewhere with a minimal effect on the parasitic resistor–capacitor time constants.\(^{8,22,24,25}\) While under illumination, the \(\mu\)PDs exhibited a photocurrent \((I_{\text{photo}})\) of 9.08 \(\times\) 10\(^{-9}\) A and 1.98 \(\times\) 10\(^{-8}\) A at –10 V with an excitation wavelength of 370 nm and 400 nm, respectively. There was a clear separation of up to 4 orders of magnitude between \(I_{\text{dark}}\) and \(I_{\text{photo}}\). The low background noise and high separation ratio is highly advantageous for the high-sensitivity optical receiver in a low-power VLC systems. As the key figure of merit, the responsivity \((R_s)\) of the \(\mu\)PD was also determined with Eq. (1):

\[
R_s = \frac{I_{\text{photo}} - I_{\text{dark}}}{P_{\text{inc}}},
\]

where \(P_{\text{inc}}\) is the incident light intensity. As shown in Fig. 2(b), the peak responsivity is located at 400 nm with 0.191 A W\(^{-1}\) at 400 nm. –10 V. The \(\mu\)PDs exhibit a low dark current \((I_{\text{dark}})\) of 1.6 \(\times\) 10\(^{-12}\) A at –10 V, and with the corresponding dark current density of 3.18 \(\times\) 10\(^{-8}\) A cm\(^{-2}\). The low \(I_{\text{dark}}\) in the range of pA surpasses other polar GaN-based structures demonstrated elsewhere.\(^{22,24,25}\)
increase in the reflectance of the ITO layer. The rejection ratio was also estimated by dividing the $R_\lambda$ at 400 nm by that at 450 nm, which yields a high ratio of more than 53. The characteristic of wavelength-selectivity demonstrated in the semipolar $\mu$PD is pertinent to ensure a high SNR in the VLC system. The inset of Fig. 2(b) shows the micrograph of the fabricated semipolar $\mu$PD.

Additionally, the specific detectivity ($D^*$) and NEP which govern the SNR yielded by the $\mu$PDs is quantified with Eq. (2):

$$D^* = \frac{\sqrt{A}}{\text{NEP}} = \frac{(R_\lambda)(\sqrt{A})}{\sqrt{2\epsilon I_{\text{dark}}}},$$  

where $A$ is the area of device expressed in cm$^2$ and $\epsilon$ is the elementary charge. As shown in Fig. 3(a), under the illumination of a 400 nm light source, the highest $D^*$ of $3.41 \times 10^{12}$ cm Hz$^{1/2}$ W$^{-1}$ was achieved when the device was operated in the zero-bias mode. Following the increase in the reverse bias voltage, the $D^*$ reduced gradually to $1.89 \times 10^{12}$ cm Hz$^{1/2}$ W$^{-1}$ at $-10$ V due to the increase of $I_{\text{dark}}$ as observed in Fig. 2(a). Correspondingly, the NEP yielded a minimum value of $2.08 \times 10^{-15}$ W Hz$^{-1/2}$ at 0 V and increased substantially to $3.75 \times 10^{-15}$ W Hz$^{-1/2}$ at $-10$ V. The resultant $D^*$ and NEP outperform other reported c-plane InGaN MQW-based $\mu$PDs (e.g. $D^*$ of $1.45 \times 10^{11}$ cm Hz$^{1/2}$ W$^{-1}$ and NEP of $4.89 \times 10^{-14}$ W Hz$^{-1/2}$), and thus guarantee a low-noise-floor for VLC systems. Figure 3(b) shows the measured current density under 400 nm illumination with various light intensities ranging from $1.24 \times 10^{-3}$ to $2.06$ mW cm$^{-2}$. The bias voltage is fixed at $-10$ V, where it exhibits the highest $R_\lambda$. The current density shows a linear response across the measurement range, in which the LDR of the semipolar $\mu$PD can be determined based on Eq. (3):

$$\text{LDR} = 20 \log \frac{P_{\text{sat}}}{P_{\text{low}}},$$  

where $P_{\text{sat}}$ is the light intensity where the current density begins to deviate from the linear region and $P_{\text{low}}$ is the measured lowest light intensity. Based on the linear fitting of the measured data, the coefficient of determination ($R^2$) was 0.998, which indicates an adequate linear fitting. As observed in Fig. 3(b), the LDR could exceed more than 64.41 dB, due to the fact that the current density did not saturate even at the maximum available light intensity of $2.06$ mW cm$^{-2}$.

Subsequently, the small-signal frequency response of the semipolar $\mu$PDs were characterized and evaluated. For the frequency bandwidth measurement, a 405 nm LD (>500 MHz) mounted onto a customized thermoelectric cooler integrated laser mount (SaNoor Technologies, SN-LDM-T-405) is used as the transmitter. The LD was then connected to the output channel of a vector network analyzer (VNA) (Agilent Technologies, E5061B) through a bias-tee (Mini-Circuits, ZFBT-4R2GW). On the receiver end, the semipolar $\mu$PD is connected to the input channel of the VNA through a radio frequency coaxial ground-signal probe, a linear amplifier (Mini-Circuits, ZHL-6A+), and a bias-tee (Mini-Circuits, ZFBT-4R2GW). Prior to the measurement, the VNA was pre-calibrated using an E-calibration module (Agilent Technologies, 85093-6010). Figure 4(a) shows the small-signal frequency response of the $\mu$PD from 300 kHz to 1 GHz under various reverse bias voltage values. The dotted line marks the $-3$ dB bandwidth where the spectral density drops to half of its value, as well as the usable $-10$ and $-20$ dB extended bandwidth. Under different bias voltages, the estimated $-3$ dB bandwidth is also summarized in Fig. 4(b). In the zero-bias mode, the $\mu$PD exhibited a $-3$ dB bandwidth of approximately 52.6 MHz and gradually increased to 347.5 MHz at $-8$ V. The large modulation bandwidth remained saturated down to $-10$ V. The demonstrated large $f_{\text{MB}}$ of up to 347.5 MHz surpasses other reported polar GaN-based $\mu$PDs and is ideal for developing high bit-rate optical communication links.

After characterizing the small-signal frequency response of the $\mu$PD, a 1 m long VLC link based on a NRZ-OOK modulation scheme with a 2$^{10-1}$ pseudorandom binary sequence (PRBS) data stream, was established to evaluate the maximum achievable data rate. Figure 5(a) shows the experimental setup for the VLC link, which consisted of a 405 nm LD as the transmitter and the semipolar $\mu$PD as the optical receiver on the other end. On both ends, the transmitter and receiver were connected to bias-tees in order to provide the DC bias to both devices, as well as to provide the modulated alternating current (AC) signal to the transmitter while the signal were extracted from the receiver. The transmitter was then connected to a bit-error-ratio (BER) tester (Agilent Technologies, J-BERT N4903B) for signal.
generation. Additionally, the received signal from the μPD was pre-amplified through a linear amplifier (Mini-Circuits, ZHL-6A+) before connecting it to the BER tester. The 405 nm LD was modulated under a DC bias of 65 mA which provided an optical power of approximately 45.7 mW, while the AC amplitude was set at 1.8 V. The eye diagrams were captured using a digital communication analyzer (Agilent Technologies, Infinium DCA-J 86100C). Figure 5(b) shows the BER versus data rate of the 1 m VLC link with the semipolar μPD as the optical receiver. Under the biasing condition of −10 V, a maximum data rate of up to 1.55 Gbit s\(^{-1}\) with a BER of 0.98 × 10\(^{-3}\) was obtained, which is well below the forward error correction limit of 3.8 × 10\(^{-3}\). The insets in Fig. 5(b) show the corresponding eye diagrams at 1.55 and 1 Gbit s\(^{-1}\). Lower data rates were obtained when the μPD was reverse-biased at lower reverse bias voltages, e.g. 1.34 Gbit s\(^{-1}\) at −5 V and 0.92 Gbit s\(^{-1}\) at −3 V (not shown), as evidenced from the reduced modulation bandwidth shown in Fig. 4(b). It is essential to note that the direct NRZ-OOK modulation scheme used in this work is simple and relatively easy to implement compared to more complex higher-order modulation schemes, e.g. quadrature amplitude modulation and phase-shift keying, which often require channel estimation and high computational complexity to combat the nonlinear distortion and enhance the data rate within a limited bandwidth.9,15,25 Table S1 is available online at stacks.iop.org/APEX/13/014001/mmedia summarizes the key performance of reported group-III-nitride-based PDs designed for VLC links (see supplementary data). As compared to other InGaN/GaN MQW-based μPDs, our semipolar devices feature substantially lower dark current and higher EQE, while the lower noise-level and larger modulation bandwidth realize Gbit s\(^{-1}\) transmission over 1 m based on compositionally-tunable group-III-nitride-based receiver.

In conclusion, our work demonstrates semipolar InGaN/GaN MQW-based μPDs as the optical receiver with data rates of up to 1.55 Gbit s\(^{-1}\) in a 1 m long VLC link based on a simple and direct modulation scheme, i.e. NRZ-OOK. The large \(f_{-3\text{dB}}\) of up to 347 MHz surpasses other c-plane devices that typically exhibit less than 100 MHz of usable bandwidth. The low dark current density (3.18 × 10\(^{-8}\) A cm\(^{-2}\)) and wavelength-selectivity characteristics (340–420 nm) with high rejection ratio (53-fold) in the semipolar μPDs further ensure low noise-floor and high SNR that are viable for implementation in high bit-rate VLC systems, as well as, for future group-III-nitride on-chip photonic systems.

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Fig. 4. (Color online) (a) Normalized frequency response of the device under different bias conditions measured from 0 to −10 V at interval of −1 V. (b) Measured −3 dB bandwidth as a function of bias voltage.

Fig. 5. (Color online) (a) Schematic diagram of the experimental setup for the VLC link using the semipolar InGaN/GaN μPD as the photoreceiver and a 405 nm LD as the transmitter over a 1 m long distance. (b) BER versus data rate of the VLC link based on NRZ-OOK modulation scheme with a \(2^{10}\)-1 PRBS data stream. Insets show the eye diagrams obtained at 1 and 1.55 Gbit s\(^{-1}\).