High Responsivity and Wavelength Selectivity of GaN-Based Resonant Cavity Photodiodes

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The implementation of blue-light photodiodes based on InGaN in emerging technologies, such as free-space visible light communication (VLC), requires transformative approaches toward enhanced performance, miniaturization, and integration beyond current Si-based technologies. This work reports on the design and realization of high-performance InGaN-based resonant cavity photodiodes with high-reflectivity lateral porous GaN distributed Bragg reflectors. The well-controlled porosification of GaN on the 2-inch wafers enables design and fabrication of optical components, unlocking the potential of nitride semiconductors for several applications. These resonant-cavity-enhanced photodiodes, which have a 12 nm-thick optically active region, exhibit a high responsivity ($\approx 0.1 \text{ A W}^{-1}$) to blue-light even without any externally applied voltage. Furthermore, the device can operate as both an emitter and a detector of visible light at well-defined wavelengths with spectral overlap between the electroluminescence emission and photocurrent responsivity, meeting the requirement of wavelength selectivity, thermal stability, and low-power consumption for VLC, with potential for integration of different functionalities, that is, light emission and detection, on a single chip without additional light filters.

1. Introduction

Following the rapid development of GaN-based light emitting diodes (LEDs), visible light communication (VLC) has attracted considerable attention.\(^1\) VLC is secure and not restricted by electromagnetic interference or license requirements, offering a potential route to future wireless light communications beyond general lighting applications. To achieve high speed data transmission, the modulation bandwidth of the LED should be enhanced by optimization of the concentration and radiative recombination of carriers.\(^2\)–\(^4\) For the optical receiver of a VLC system, the quantum efficiency (QE) and temporal response of the photodetector are also important as they determine data transmission distance and rate. In particular, the miniaturization and simplification of free-space VLC systems for integration of emission and detection of light on a single chip require photodetectors with high sensitivity and wavelength selectivity matching the source’s emission spectrum.\(^5\)–\(^8\) Currently, Si-based photodetectors are used to detect blue light from GaN-based white LEDs by implementing a blue-filtering technology.\(^9\)–\(^11\) However, this technology suffers from low light transmittance, high cost and complexity of the VLC system. Furthermore, the broadband response of Si-based photodetectors causes undesirable interference effects between the detected and background signals.\(^12\),\(^13\) Alternatively, InGaN-based photodetectors could offer an alternative solution as they have a larger optical absorption coefficient and a band gap that can be tuned by the In-composition.\(^14\)–\(^18\) On the other hand, their QE tends to be limited by the deterioration of the crystal quality in structures with thick optical active regions.

Resonant cavities can increase the QE of InGaN photodetectors with thin absorber layers because of the increased optical field inside the cavity.\(^19\),\(^20\) Previous studies have reported GaN-based resonant cavity devices using different approaches (e.g., dual dielectrics, epitaxy, hybrid cavity structures, etc.).\(^21\)–\(^25\) However, due to limitations in the epitaxy and/or device fabrication, further developments are needed. On the other hand, the porosification of n-type GaN can enable the fabrication of distributed Bragg reflectors (DBRs) and their implementation in optical components.\(^26\)–\(^34\)

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In this work, we report on the high-performance InGaN/GaN resonant-cavity-enhanced photodiodes (RCEPD) with high responsivity and wavelength selectivity. The resonant cavity of the photodiode comprises a top Ta$_2$O$_5$/SiO$_2$ DBR and a bottom porous GaN DBR. By controlling the porosification of n-doped GaN, we realize porous GaN DBRs with high-reflectivity (>99.5%) and wide-stopband (~90 nm) for optimization of the absorption, emission and integrated spectral filtering of the diode. The photodiodes can operate even without any externally applied voltage, have a narrow-band selective detection at $\lambda = 466 \text{ nm}$ with a responsivity of up to 0.1 A W$^{-1}$, a high QE of $\approx 27.3\%$, and a rapid and linear response, which are all desirable properties for an optical receiver. Furthermore, our resonant-cavity-enhanced photodiode can operate as both an emitter and a detector of visible light with spectral overlap between the electroluminescence emission and the photocurrent responsivity, which can offer opportunities for electro-optics and photoelectric conversion in miniaturized and energy efficient VLC systems.

2. Experimental Results and Discussion

2.1. A Resonant-Cavity-Enhanced InGaN Photodiode with a Porous GaN DBR

Figure 1a shows the schematic layer structure and optical image (inset) of our InGaN/GaN photodiode with bottom and top DBRs, and metal contacts to the p- and n-type GaN layers. The cavity structure was designed for a main resonance at $\lambda = 500 \text{ nm}$ using the transfer matrix method to co-optimize the blue light absorption and the light emission properties of the active region. The optical field and refractive index distribution along the growth axis (2) are shown in Figure 1b. The indium tin oxide (ITO) and the InGaN/GaN multiple quantum well (MQW) regions are located at the node and antinode positions of the optical field, respectively, to reduce the absorption from the ITO layer and increase the coupling between the optical field and MQWs. A photodiode without the bottom and top mirrors was also fabricated and used as a control sample. Details of the fabrication process are in the experimental section.

Our samples were grown on the c-plane of a sapphire substrate by metal organic chemical vapor deposition (MOCVD), which is able to ensure accurate thickness and doping control of the epitaxial layers. The bottom mirror of the resonant cavity consists of a stack of 12 pairs of n$^+$-doped GaN (70 nm) and undoped (u) GaN (46 nm) layers. The stack is transformed into a porous GaN/u-GaN periodic array by electrochemical (EC) etching (Figure 1a). The refractive index of the porous GaN is controlled and tuned by varying the EC etching voltage. We have designed and fabricated several porous GaN DBRs and used porosification to optimize their reflectivity properties and refractive index-contrast (Figures S1 and S2, Supporting Information). Above the n$^+$-GaN/u-GaN stacked layers, a 730 nm-thick n-GaN layer (doped to $1 \times 10^{18} \text{ cm}^{-3}$) was grown as the n-type conductive layer followed by an InGaN/GaN (3/15nm) MQWs structure. The MQWs design was chosen for detection of blue light taking into account the Stokes’ shift between the luminescence and absorption spectra. Using the InGaN QWs as absorbers instead of a single InGaN layer helps to minimize the formation of defects during the growth. Also, it increases the overlap between the InGaN absorber and the antinode of the standing wave optical field inside the cavity. Finally, a 120 nm p-GaN layer (doped to $3 \times 10^{18} \text{ cm}^{-3}$) was grown as the p-type conductive layer. To improve current spreading, a 30 nm-thick ITO film was deposited on the p-GaN layer by electron beam evaporation. To minimize the absorption loss in the ITO layer and increase the photon-carrier coupling in the resonant-cavity, a phase-shift (PS) adjustment SiO$_2$ layer was used. Its thickness (144 nm) was calculated from the resonant condition $2m\beta + \phi_1 + \phi_2 = 2m\pi$, where $m = 1, 2, 3...$, $\beta = 2n\pi/\lambda$ is the propagation constant, $n$ is the effective refractive index, $\phi_1$ and $\phi_2$ are the reflected phases for the top and bottom DBRs, respectively. The SiO$_2$ layer was deposited on the ITO by magnetron sputtering. Subsequently, an optimized dielectric DBR consisting of five pairs of SiO$_2$/Ta$_2$O$_5$ layers were deposited by magnetron sputtering to form the top mirror of the resonant cavity (Figure S3, Supporting Information). Finally, a resonant cavity structure with a length of $\approx 1096 \text{ nm}$ was obtained.

2.2. High-Reflectivity Porous GaN DBR

Figure 2a shows the cross-sectional scanning electron microscopy (SEM) image of the resonant cavity structure and a porous GaN DBR. The well-defined interface between porous-GaN and undoped-GaN is achieved through the controlled modulation of the thickness and doping of the layers during the growth, as well as the high doping selectivity of...
the post-growth EC etching. No significant damage, such as warping and/or cracks of the layers, is observed. The porous layers comprise triangle-shaped pores, which are embedded between adjacent uniform layers of u-GaN. Furthermore, some pores take the shape of hemi circles as a result of the lateral annexation and broadening of nearby pores in n⁺-GaN.[30]

The etching occurs preferentially along specific crystal planes, as in traditional wet etching of GaN in alkali solution.[39] Figure 2b shows the reflectivity spectrum of the porous GaN DBR. The DBR has a high peak reflectivity (>99.5%) with a wide stopband centered at \( \lambda = 500 \text{ nm} \), which extends from \( \lambda = 453 \) to 543 nm, covering the blue and green light emission spectrum. This is the spectral range commonly used in VLC systems.[40]

We calculate the resonant cavity modes by simulating the electric field distribution and the reflectivity of the diode using the finite-difference time-domain (FDTD) method. The simulation is based on the layered structure measured by cross-sectional SEM (Figure 2a) and the refractive index in Figure 1b. Figure 2c shows the electric field distribution (log |\( E \)|) in the cross-sectional plane of the diode at \( \lambda = 500 \text{ nm} \). The electric field is mainly localized in the upper layers of the porous GaN. The intensity of the electric field in the bottom layers is almost the same as the background intensity, indicating that the porous GaN DBR acts as a good mirror at the central wavelength \( \lambda = 500 \text{ nm} \). Furthermore, standing wave fringes can be seen between the bottom porous GaN DBR and the top Ta₂O₅/SiO₂ dielectric DBR.

The reflectivity spectrum of the cavity in Figure 2d (black solid line) shows three resonant dips at \( \lambda = 465, 500, \) and 535 nm, corresponding to the resonant modes of the cavity. The full width at half maximum (FWHM) of the resonant mode at \( \lambda = 465 \text{ nm} \) compares with that required in VLC systems.[40] The three resonant wavelengths are in good agreement with the FDTD simulation (red dotted line) and the resonant modes measured by photoluminescence (PL) (blue solid line). Differences between the measured and calculated modes in the reflectivity spectra at \( \lambda < 450 \text{ nm} \) and \( \lambda > 550 \text{ nm} \) arise from deviations of the simulated structure from the real one, including the optical anisotropy of the porous GaN layers, which is not considered in our model. In the PL spectrum, the main resonant peak is centered at \( \lambda = 500 \text{ nm} \). It is narrower and more intense (=12 times) than that of the control sample. Weaker peaks can be also seen at \( \lambda = 465 \) and 535 nm and arise from the broad light emission of the InGaN/GaN MQWs (Figure S4, Supporting Information), resulting from the large lattice and thermal mismatch between InN and GaN.[37,41–44]

2.3. Resonant-Cavity-Enhanced Photodetector: High Responsivity and Spectral Selectivity

After the electrodes deposition, we first carried out chip-on-wafer (COW) mapping tests (Figure S5, Supporting Information) to probe the uniformity of the emission peak wavelength of the photodiodes within 0.5-inch wafers. The distribution of
the peak wavelength for the RCE photodiodes is more uniform than that of the control PDs. We assign this to the wavelength selectivity of the cavity structure. Following the COW mapping test, suitable photodiodes were selected from the wafers to examine their electrical and optical properties. Figure 3a shows the current–voltage (I–V) curves of both the RCEPD and control PD. The dark current, $I_{\text{dark}}$, of the RCEPD is similar to that of the control PD in both reverse and forward bias, indicating no visible degradation of the electrical properties following the EC etching used to create the porous GaN DBR. The responsivity ($R = I_{\text{ph}} / P$) spectra were measured in the range $\lambda = 440$–550 nm at $V = 0$ V under optical illumination with power $P = 25.8$ mW cm$^{-2}$. Here $I_{\text{ph}} = I_{\text{light}} - I_{\text{dark}}$ is the photocurrent, $I_{\text{light}}$ is current under optical illumination, and $S$ is the in-plane area of the device. The responsivity has maxima at $\lambda = 466$ and 499 nm (Figure 3b), in good agreement with the wavelength of the resonant cavity modes. An additional mode is also observed near $\lambda = 535$ nm (inset of Figure 3b). This is within the absorption edge of the InGaN/GaN MQWs, which tends to be weak and broad due to alloy disorder (Figure S4, Supporting Information).

The responsivity spectrum of the RCEPD has a peak $R = 0.102$ A W$^{-1}$ at $\lambda = 466$ nm with a narrow FWHM of 13 nm. A weaker peak ($R = 0.013$ A W$^{-1}$) is observed at $\lambda = 499$ nm with a FWHM of 16 nm. The weaker responsivity at longer wavelengths is due to the decreased absorption near the band edge of the InGaN QWs. The corresponding external quantum efficiency of the RCEPD is $\text{QE} = hcR/e\lambda$, where $h$, $c$, and $e$ are the Planck constant, speed of light and electron charge, respectively. The QE is shown in the inset of Figure 3b: the maximum value of QE is 27.3% at $\lambda = 466$ nm. This is $\approx$12 times higher than that of the control device (2.2%) at the same wavelength. Also, it is comparable to the QE of commercial Si-based detector-filter optical receivers and the highest reported value of QE for InGaN blue detectors with a absorber thickness of about 0.5 µm, 40 times thicker than the InGaN active region of our RCEPD. Thus the RCEPD can meet the requirement of high sensitivity and narrow-band detection of blue light for VLC, overcoming the limitations (e.g., background light and noise) of conventional structures, which employ a blue-filtering technology.

The I–V curves of the RCEPD were measured at different light powers $P$. For these experiments, a laser beam was focused by a convex lens on the device to a spot diameter of about 100 µm. Figure 3c shows the P-dependent I–V characteristics of the RCEPD at $\lambda = 466$ nm. The dark current increases with increasing negative bias, but remains small, demonstrating good rectification properties. Under illumination, the current increases with increasing $P$ and the I–V curves remain relatively flat in reverse bias. Also, the RCEPD maintains a high photoresponsivity even without any externally applied voltage, indicating an effective extraction of the photogenerated carriers by the built-in electric field of the junction.

The photocurrent $I_{\text{ph}}$ depends linearly on $P$ (Figure S6, Supporting Information), leading to a responsivity $R$ and specific detectivity $D^* = RS^{1/2}/(2\pi e\lambda)$ that are only weakly dependent

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**Figure 3.** Photoresponse of the resonant-cavity-enhanced InGaN photodiode (RCEPD). a) Current–voltage (I–V) curves in the dark of the RCEPD (red) and control PD (black). Inset: log(I–V) curves in reverse bias. b) Responsivity and QE (inset) versus photon wavelength at $V = 0$ V for the RCEPD and control PD. c) I–V curves of the RCEPD at $\lambda = 466$ nm for powers $P$ from 0 to 100 mW cm$^{-2}$. Responsivity d) and specific detectivity e) versus $P$ at $\lambda = 466$ nm and $V = 0$, −1, −2, −3, −4, −5 V. f) Temporal response of the photocurrent of the RCEPD under optical illumination with a 2 kHz light-switching frequency. Red lines are fits to the data.
on $P$ (Figure 3d,e).\textsuperscript{[47]} As shown in Figure 3d, $R$ increases monotonically with increasing reverse bias. This behavior is due to the corresponding increase of the electric field in the intrinsic region, shortening the carrier transit and recombination times (Figure S7, Supporting Information). As shown in Figure 3e, the specific detectivity $D^*$ reaches a maximum value of $8.4 \times 10^{11}$ Jones at $V = -2$ V. For $V < -2$ V, $D^*$ decreases due to the increase of the dark current. Therefore, the large RCEPD response depends linearly on the light intensity, which satisfies the requirement for linear detection of visible light and photoelectric signal conversion without signal distortion.

To evaluate the response time of the RCEPD, the device was illuminated with a LED ($\lambda = 470$ nm, FWHM $\approx 20$ nm) powered by a square-wave signal generator. The dynamic responses were recorded using a current amplifier and an oscilloscope for different modulation frequencies and applied biases (Figures S8 and S9, Supporting Information). As shown in Figure 3f, the dynamic response of the control device is well described by $I(t) = I_0 \left[1 - \exp(-t/\tau_r)\right]$ and $I(t) = I_0 \exp(-t/\tau_d)$, where $\tau_r$ and $\tau_d$ are the time constants for the rise and decay of the current. By fitting the rising and falling edges, we derive $\tau_r = 35$ $\mu$s and $\tau_d = 30$ $\mu$s at $V = 0$ V. The measured response time depends on the applied reverse bias and is primarily limited by the RC-time of the RCPED and the transit time of the carriers across the depletion region of the junction (Figure S9, Supporting Information). We envisage future developments by optimizing the layout of the device as well as reducing parasitic capacitance and resistance for fast, large data transmission in VLC. In particular, the high saturation electron velocity of nitrides ($>2 \times 10^7$ cm s$^{-1}$) offers opportunities for fast transmission beyond that enabled by traditional Si photodiodes.\textsuperscript{[48]}

### 2.4. Resonant-Cavity-Enhanced Emitter: Wavelength Selectivity and Thermal Stability

The light emitting properties of the photodiode are significantly improved by the implementation of the DBRs. Figure 4a,b show the electroluminescence (EL) spectra of the control and RCE devices for different injected currents. For $I = 1$ mA, the EL emission of the control device is peaked at $\lambda = 512$ nm, corresponding to the PL peak wavelength of the epitaxial structure (Figure S4, Supporting Information). With increasing current from 1 to 40 mA, the EL emission shifts from 512 to 487 nm due to the screening of the quantum-confined Stark effect by the injected carriers.\textsuperscript{[3,41,49]} A further increase of current up to 100 mA induces a small red-shift of the EL band to 494 nm due to self-heating.\textsuperscript{[50]} In contrast, the EL spectrum consists of three peaks centered at $\lambda = 466$, 497 and 529 nm, which do not blue-shift with increasing current. These peaks correspond to the designed resonant cavity modes (Figure 2d). In addition, only a small red-shift ($\approx 1$ nm) of the main resonant peak is observed with increasing current from $I = 1$ to 100 mA (Figure 4c), indicating an improved wavelength stability of the RCEPD.
essential requirement for reliable data communication. The FWHM of the main EL peak is ≈7 nm, which is much narrower than that of the control sample (FWHM = 42 nm, Figure 4d). The three EL emission modes also coincide with the PL peaks with a small difference between their positions due to different excitation conditions.

3. Conclusion
In conclusion, we have demonstrated high-performance InGaN/GaN resonant-cavity-enhanced photodiodes that make use of Ta2O5/SiO2 and lateral porous GaN DBRs. The bottom porous GaN DBR has a high reflectivity (>99.5%), a wide stopband (band width of 90 nm) and well-defined resonant cavity modes. The photodiodes can operate without any externally applied voltage, have a narrow-band selective detection at λ = 466 nm with a responsivity of up to 0.1 A W⁻¹, and a rapid and linear response, all desirable properties for an optical receiver. Furthermore, we have shown that the resonant cavity improves the light emitting properties of the photodiode, which can operate as a light emitting source at well-defined wavelengths under different current injection conditions. Thus, the GaN-based resonant-cavity-enhanced optoelectronic devices presented in this work offer opportunities to realize high-performance detectors and emitters with potential for large data communications bandwidth that can deliver increased functionality and low power consumption. With further improvement of InGaN crystal quality, these GaN-based resonant-cavity-enhanced photodiodes can offer a route to new technologies for visible light communication beyond Si-based technologies. In particular, the tunability of the refractive index of porous GaN via a well-controlled porosification method offers opportunities to design and fabricate novel optical components and unlock the potential of nitride semiconductors for several applications, beyond the capability of traditional optoelectronic devices in the current literature.

4. Experimental Section

Epitaxial Growth: The InGaN/GaN multi-layer structure was grown on a 2 inch c-face sapphire substrate by MOCVD. The sample contains 12 pairs of n-type GaN layers grown to a thickness of 350 nm, followed by a 70 nm thick n-type AlGaN layer, a 300 nm thick u-GaN buffer layer, and a 600 nm thick n-type GaN buffer layer. The n-type GaN layers were grown at a temperature of 600 °C under nitrogen atmosphere and before the EC etching of the n-GaN layer into porous GaN, the EC etching was carried out in a NaOH (1 M) solution at a voltage of 8 V using a high precise Keithley 2400 power supply, which was helpful to the stability of the etching voltage. In addition, a magnetic stirrer was used in the EC etching to promote the diffusion of ions into the porous GaN channels and the discharge of bubbles generated in the reaction.

Fabrication of the Photodiodes: A mesa area with diameter d = 200 μm was patterned by standard photolithography and ICP etching, followed by the opening of an aperture with diameter d = 100 μm on the SiO2 layer using a BOE solution. To improve the current spreading property, a 30 nm ITO film was deposited by electron beam evaporation on the exposed p-GaN and annealed at 550 °C under nitrogen atmosphere for 30 min to improve the ohmic contact. Then, Cr/Al/Ti/Au layers were deposited by electron beam evaporation to form the p-type and n-type electrodes. The electrodes were defined by standard lithography and lift-off techniques. To minimize the light absorption from the ITO layer and increase the photon-carrier coupling, a phase-shift adjustment SiO2 layer was also deposited on the ITO by magnetron sputtering. Finally, five pairs of Ta2O5/SiO2 dielectric stacks were deposited by magnetron sputtering with a quarter-wavelength pair of Ta2O5 (57.6nm) and SiO2 (85.6nm) to act as both the top Bragg reflector and the detection window covering from ~440 to 550 nm of the incident light.

Measurement Setup: The reflectivity spectra of the porous GaN DBR, the Ta2O5/SiO2 dielectric DBR, and the optical resonant cavity reflector and the detection window covering from 440 to 550 nm of the incident light were measured using a UV–vis near-infrared spectrophotometer (Varian Cary-5000). The PL measurements were carried at room temperature in a reflection geometry with excitation and detection of light along the growth axis. The excitation source was provided by a Diode Pumped Solid State laser of wavelength λ = 355 nm. The laser was focused onto the sample to a spot diameter d ≈ 2 μm. The EL spectra were measured at room temperature using an integrating sphere in the continuous-wave current mode. The photocurrent of the photodetector was measured using an Agilent semiconductor parameter analyzer B1500A, and the light output from a supercontinuum laser source (Fianium, WhiteLase CS390-1.5 Blue-UV Supercontinuum) was directed into a monochromator for single wavelength selection. The continuous output wavelength of this supercontinuum laser source ranges from 390 to 2400 nm. The incident optical power was measured using a calibrated power meter (Thorlabs GmbH., PM 100D). The power dependent response was measured using an attenuator to change the incident light power. The time-resolved high frequency response characteristics of the RCEPD were investigated by a digital oscilloscope, a power amplifier and a pulsed light source. Pulsed light was generated by a blue LED driven by a square-wave signal generator.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.
Keywords

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