ABSTRACT: The demand for on-chip multifunctional optoelectronic systems is increasing in the Internet-of-Things era. Spectral emission–detection overlap endows an InGaN/GaN quantum well diode (QWD) with an intriguing capability to detect and modulate light emitted by itself, which is of great interest when merging electronics and photonics together on a single chip for the development of advanced information systems. When biased and illuminated at approximately the same time, the InGaN/GaN QWD can achieve light emission and detection simultaneously. Herein, we experimentally demonstrate the simultaneous emission–detection phenomenon and analyze the irreversibility of spectral emission–detection overlap according to energy diagram theory, which may answer why the QWD can only detect and modulate higher-energy photons than those emitted by itself.

INTRODUCTION

Monolithic integration of photonics with electronics shows a promising approach for realizing a high-speed, low-power optoelectronic system on a chip. However, this goal should overcome substantial limitations for the integration of photonic functions of light emission, modulation, and detection. Multifunctional devices are highly needed for unifying electronics and photonics on a single chip. By inserting the InGaN/GaN quantum well (QW) structure into a p–n junction, the InGaN/GaN quantum well diode (QWD) inherently exhibits multiple functionalities of light emission, detection, modulation, and energy harvesting. In particular, spectral emission–detection overlap endows the QWD with the capability to detect and modulate the light emitted by the device-sharing identical QW structure. All transmitters, receivers, and modulators are key components for a monolithic photonic circuit on a single chip. Hence, one can integrate the InGaN/GaN QWD-based transmitter, receiver, and modulator into a single chip to establish an information system, wherein all these components share an identical QW structure and the data communication among them is realized through photons. A variety of GaN monolithic photonic circuits have been reported using a standard foundry process. There is the desire to realize a compact optoelectronic system on a chip. Park et al. developed an ion bombardment approach to create regions of high electrical resistance, producing arrays of InGaN/GaN light-emitting diodes (LEDs) with a resolution as high as 8500 pixels per inch. Moreover, Zheng et al. reported the monolithic integration of enhancement-mode n-channel and p-channel GaN field-effect transistors to construct a family of elementary GaN CMOS logic gates. These works pave promising routes to monolithically integrate GaN photonics with electronics on a tiny chip.

Enlarging spectral overlap will enhance the performance of the GaN monolithic multicomponent system. However, only shorter-wavelength light photons emitted from one QWD can be detected and modulated by the diode-sharing identical QW structure, indicating that light emission and detection inside the diode are irreversible processes. Here, we fabricate InGaN/GaN QWDs using standard LED process flow and experimentally demonstrate its simultaneous emission–detection operation. To answer why the QWD can only detect and modulate higher-energy photon than that emitted by itself, we analyze the irreversibility of spectral emission–detection overlap according to energy diagram theory.

EXPERIMENTAL METHODS

The top epitaxial III-nitride films are grown on a sapphire substrate by a commercially available metal-organic chemical vapor phase deposition. The III-nitride diode consists of a 350 nm thick p-type Mg-doped GaN layer, a 500 nm thick InGaN/GaN MQW active layer, and a 1500 nm thick n-type Si-doped GaN layer. We use the existing LED fabrication steps to manufacture InGaN/GaN QWDs, whose optical microscopic image is shown in Figure 1a. Comb electrode architectures are
used, and the electrode widths are 25 and 35 μm for p- and n-electrodes, respectively. The Ni/Al/Ti/Pt/Ti/Pt/Au metal pads, which are used for the contact metallization for both p- and n-GaN regions, are deposited by e-beam evaporation, followed by a metal lift-off process and rapid thermal annealing. After polishing the sapphire substrate down to 200 μm, the chips were finely diced and separated from a 100 mm in-diameter GaN-on-sapphire wafer. The chip is 0.2 mm thick, 4.12 mm wide, and 5.49 mm long, and its weight is 105 mg. In association with a Keysight B1500 semiconductor device analyzer, a 200 μm in-diameter multimode fiber collects the emitted light through a lens system and sends it to an Ocean Optics HR4000 spectrometer for electroluminescence (EL) characterization. The Oriel IQE-200B (Newport Corp) installed with a xenon lamp is used for the responsivity measurements. Figure 1b illustrates the spectral emission−detection overlap for the QWD. When the diode operates as an emitter, the light emission increases with increasing injection currents from 10 to 30 mA, leading to a conversion from electrical energy and information into optical ones. The dominant EL peak is measured around 531.4 nm at an injection current of 30 mA. In addition to efficient light emission, the QWD can also function as a photodiode at zero or under reverse bias. It absorbs light photons to liberate electron−hole pairs, transcribing photons into electrons. The QWD is able to modulate the light since its responsivity is greatly influenced by the bias voltage. Therefore, the QWD can be used as an LED, a photodiode, a modulator, and an energy harvester. The spectral emission−detection overlap is clearly observed, enabling the QWD with the capability to absorb light at wavelengths matching those of its own emission profile. Therefore, a bidirectional communication system is able to be established using a pair of identical QWDs, wherein one diode of the pair sends information and the other detects the incoming light encoded with data.26,27 Combining transmission and reception capabilities into a single QWD would allow miniaturized and compact architectures and reduce material consumption.

RESULTS AND DISCUSSION

In particular, when biased and illuminated simultaneously, the QWD can integrate the previously competing light-detecting and light-emitting operations at the same time. Figure 2a schematically illustrates the simultaneous emission−detection phenomenon of the InGaN/GaN QWD. Figure 2b shows an optical image of the light-emitting chip without external illumination. The diode is biased at 2.1 V to emit green light. To further experimentally confirm this operation, we shine light on the diode using a commercialized white LED, which is generated by combining a 450 nm blue III-nitride LED with a 528 nm yellow phosphor. The light source pulses its light with square wave signals with a filling factor of 0.5. When the QWD is biased at −4 V, the photocurrent magnitude is approximately 215.8 μA, as shown in Figure 3a. The photocurrent magnitude gradually decreases when the bias voltage increases. Figure 3b shows that the light-induced current is around 193 μA at zero bias. The coexistence of light emission and detection occurs when we turn on the QWD and shine external light on it at the same time. In this case, the QWD can emit and detect light simultaneously. Figure 3c shows that the forward current is
approximately 442 μA and the photocurrent decreases to 113 μA when a 1.9 V forward voltage is applied to the QWD. In this case, the QWD operates in the simultaneous emission–detection mode. The injection current increases to 3316 μA rapidly with increasing the forward voltage to 2.0 V, which leads to a significant enhancement in the light emission. As shown in Figure 3d, the photocurrent magnitude decreases to 101 μA. Owing to the charge accumulation effect, the current shows a sloping profile. Compared with the injection current, the photocurrent is relatively small and the light emission plays the main role in the competing coexistence. However, light-detecting behavior still occurs. A proof of concept of the simultaneous emission–detection operation is experimentally illustrated in Visualization 1 of the Supporting Material. Consequently, the QWD array can be developed as a multifunctional display to simultaneously realize display and imaging.28

At this point, one interesting question arises: why can the device only detect shorter-wavelength photon than that emitted by itself? Combining the energy diagram theory and the second law of thermodynamics, we try to explain the physics of the irreversibility of the spectral emission–detection overlap. Figure 4 illustrates a schematic energy diagram for a QWD, wherein the energy is plotted vertically and the horizontal lines are for each allowed value of the energies $E_0$, $E_1$, $E_2$, and $E_3$. The energy $E_0$ in the valence band is the lowest possible condition, and several possible transitions are demonstrated. When we inject current into the diode, the electrons in one of these conduction bands absorb energy to drop to a lower state and radiate energy in the form of light. According to the law of the conservation of energy, the frequency of the emitted light is determined by the difference in energy. For example, the frequency of the light, which is liberated in a transition from energy $E_3$ to energy $E_0$, is

$$\omega_{30} = (E_3 - E_0)/h$$

(1)

The symbol $h$ is the Planck constant, which is the proportionality constant relating a photon’s energy to its frequency.29 Other possible transitions would be from energy $E_3$ to energy $E_2$, energy $E_2$ to energy $E_1$, and energy $E_1$ to energy $E_0$. Then, these define spectral emission lines. Conversely, the holes absorb photons of right frequencies to go up from the valence band to different conduction bands when we shine light on the diode.30 In a reversible process, we can obtain

$$\omega_{03} = \omega_{02} = (E_3 - E_0)/h$$

(2)

As a matter of fact, the reversible process is an idealization. According to the second law of thermodynamics, an
irreversible process occurs in reality and the total entropy of the system always increases. Therefore, the holes require higher energy (it will absorb higher-frequency photons) to climb up a potential hill to get to the conduction bands and remain in these states. We can imply that
\[ \omega_{\text{h1}} \geq \omega_{\text{h0}} = \frac{E_2 - E_3}{h} \quad (3) \]

The equation is an elegant conclusion: the irreversibility between emission and detection spectra of the QWD occurs, and only higher-energy photons absorbed by the diode can provide enough energy. As a result, at the modulator and receiver sides in a GaN-based monolithic photonic circuit, one should explore sophisticated techniques to realize a red shift in the responsivity spectra. Consequently, more light photons emitted from the transmitter can be modulated and detected.

## CONCLUSIONS

Owing to the intriguing spectral emission–detection overlap, multifunctional InGaN/GaN QWDs are attractive to meet the increasing demands for complex, compact optoelectronic system on a chip, wherein identical diodes are merged together to separately function as a transmitter, a modulator, and a receiver on a single chip. In particular, the QWD can emit and separately function as a transmitter, a modulator, and a receiver on a single chip. In the development of parallel display-to-display data communication, We experimentally demonstrate the simultaneous emission–detection operation and unveil the physical mechanism of the spectral emission–detection overlap. These findings are helpful to merge GaN electronics and photonics together on a single chip for the development of an advanced information system.

## ASSOCIATED CONTENT

- Supporting Information
  The Supporting Information is available free of charge at https://pubs.acs.org/10.1021/acsomega.2c00562.
  A video showing a proof of concept of the simultaneous emission–detection operation (MP4)

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### Author Contributions

Y.J. and Y.J.W. conceived and designed the experiments, analyzed the data, and drafted the paper. P.Z.L. performed the device measurements. All authors reviewed the manuscript.

### Notes

The authors declare no competing financial interest.

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