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Unification of Irreversibility and Energy Diagram Theory

Pengzhan Liu, Ziqian Qi, Jianwei Fu, Yuan Jiang, and Yongjin Wang*

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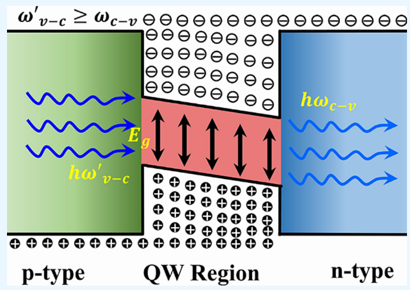
ABSTRACT: A simultaneous emission-detection phenomenon occurs when a quantum well (QW) diode is biased with a forward voltage and illuminated with a shorter-wavelength light beam. The diode is able to detect and modulate light emitted by itself due to its spectral emission-detection overlap. Here, two identical QW diode units separately function as a transmitter and a receiver to establish a wireless light communication system. In association with energy diagram theory, we explain the irreversibility between light emission and light excitation in the QW diode, which may help us deeply understand various expressions in nature.



INTRODUCTION

Quantum well (QW) diodes that inherently exhibit multi-functionalities of light emission, detection, modulation, and energy harvesting have great potential for the development of monolithic optoelectronic systems.[1−11] In particular, their emission spectra partially overlap with their responsivity spectra due to the same QW active region, and thus, the QW diode is able to detect, modulate, and harvest the light emitted by itself.[12,13] By using the same fabrication process flow, we can monolithically integrate different QW diodes into a single chip,[14−17] in which all these components share identical QW structures. Zhang et al. demonstrated a monolithic GaN optoelectronic system consisting of a transmitter, a waveguide, a beam splitter, receivers, and a monitor,[18] in which light emission, propagation, and detection can be manipulated, and data communication among them is realized through photons. Moreover, an interesting phenomenon in which the QW diode simultaneously emits and detects light occurs when the device is biased with a forward voltage and illuminated with a shorter-wavelength light beam,[19] endowing the device with the capability to perform light emission and detection at the same time. Both the injected electrons and the released electrons accumulate together inside the QW diode and are translated into dynamic electrical signals for full-duplex optical communication[20] and simultaneous illumination imaging.[21]

However, the obtained results still directly lead to the following question: why does the QW diode only detect, modulate, and harvest higher-energy photons than those emitted by itself in reality,[22] indicating that light excitation is irreversible to light emission? Here, we use two identical QW diode units to establish a wireless light communication system and investigate the irreversibility between light emission and light excitation in the QW diode to reveal the physical mechanism behind this behavior.

RESULTS AND DISCUSSION

Figure 1a shows an optical microscope image of a typical Cree XHP70 QW diode unit. The individual QW diodes have a square size of 1.48 mm × 1.48 mm, and the whole device has a square size of 3.04 mm × 3.04 mm. Four identical QW diodes are attached to a printed circuit board (PCB) solder pad and connected in series. As shown in Figure 1b, this unit leads to a 12 V configuration and can be used as a transmitter or a receiver.

The CREE XHP70 QW diodes are InGaN-based and emit blue light. The thin-film flip-chip geometry is used to for the fabrication of QW diodes, which can reduce forward voltage and improve light extraction. Figure 2a shows the cross-sectional scanning electron microscopy (SEM) image of the InGaN-based QW diode. The whole device thickness is around 150 μm. As shown in Figure 2b, the responsivity spectra of the QW diode, which are measured by using an Oriel IQE-200B (Newport Corp.), are both wavelength dependent and voltage dependent, offering the potential for a wide range of applications from photodiodes and modulators to energy harvesters. The electroluminescence (EL) spectra are measured by combining a lens system and an Ocean Optics HR4000 spectrometer. There are different conduction bands inside the real QW structures, allowing possible transitions to generate broad EL spectra. The light emission intensities are current dependent, enabling the development of emitters for illumination and transmitters for light communication. The EL and responsivity spectra show an approximate 50 nm

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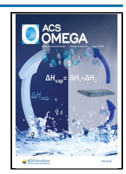

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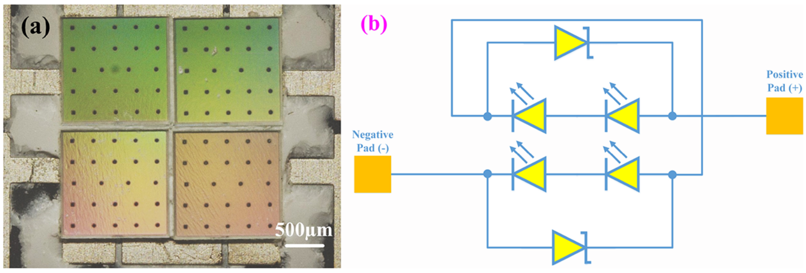

Figure 1. (a) Optical microscopy image of the QW diode unit. (b) 12 V configuration.

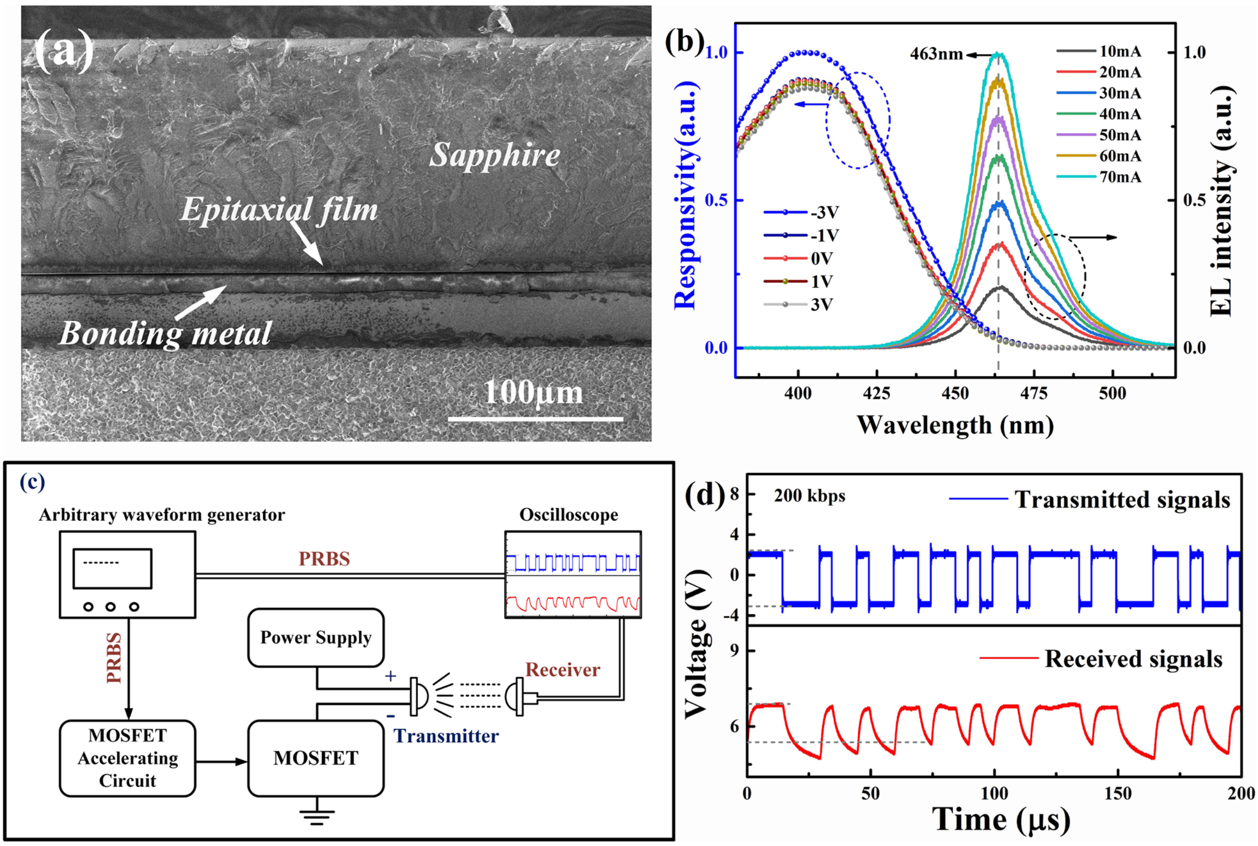

Figure 2. (a) Overall cross-sectional SEM image of the InGaN-based QW diode; (b) measured EL and responsivity spectra of the QW diode; (c) schematic diagram of a wireless light communication system using two identical QW diode units; (d) comparisons between PRBS signals transmitted and received at a communication rate of 200 kbps.

wavelength overlap for the response to higher-energy photons, suggesting that the QW diode can detect and modulate photons emitted by itself. Two diodes sharing identical QW structures can be separately used as a transmitter and a receiver to form a wireless light communication system.[23−28] Gao et al. monolithically integrated different diodes with identical QW structures into a single chip to produce a waterproof optoelectronic system,[29] in which the QW diodes acted as a transmitter, a receiver, and an energy harvester. In particular, the simultaneous emission-detection phenomenon occurs when we shine a shorter-wavelength light beam onto the device and apply a forward voltage to it at the same time, providing a number of promising applications from full-duplex light communication to simultaneous illumination imaging. Figure 2c shows a schematic diagram of a wireless light communication system using two identical QW diode units. They function as the transmitter and the receiver in the system. There is no focus lens, and the light directly shines onto the receiver over a transmission distance of 10 cm. In association with a RIGOL DG952 arbitrary waveform generator, the transmitter pulses its emitted light with pseudorandom binary sequence (PRBS) signals at a rate of 200 kbps, in which the offset voltage is 12 V. At the receiver end, the QW diode unit at zero bias captures this information-coded light and converts the photons back into electrical signals. Without additional circuit amplification, these signals are directly sent to a RIGOL MSO 5074 digital oscilloscope for characterization. Figure 2d compares the transmitted PRBS signals and the received ones. A proof of concept of the wireless light communication using two identical CREE XHP70 QW diodes is experimentally illustrated in Visualization 1 of the Supplementary Material.

Figure 3a illustrates a schematic diagram of a QW diode operating as a light-emitting diode. When we inject a current into the diode, the electrons in the conduction band absorb energy and then drop to a lower state, radiating energy in the form of light. According to the law of the conservation of

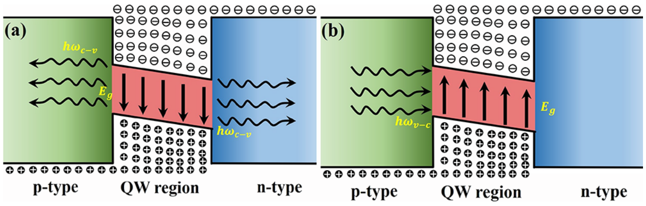

Figure 3. (a) Schematic illustration of QW diode operation modes: (a) light emission and (b) light detection.

energy and Planck's equation,[30] the frequency of the emitted light is determined by the difference in the energy. For example, the frequency ω_{c-v} of the light generated in a transition from the conduction band to the valence band is

$$\omega_{c-v} = E_g/h \tag{1}$$

The symbol E_g is the energy gap between the valence band and the conduction band, and h is the Planck constant, which is the proportionality constant relating the energy of a photon to its frequency. Conversely, the QW diode acts as a photodiode in a reversible process. As illustrated in Figure 3b, shining light onto the QW diodes activates them and allows holes in the valence band to transition to different conduction bands. The ideal reversible process will not expend any energy or entail an entropy increase. The photon energy is equal to the QW energy gap, and the frequency ω_{v-c} of the light is given as

$$\omega_{v-c} = \omega_{c-v} = E_g/h \tag{2}$$

According to the second law of thermodynamics, the total entropy of the system always increases during an irreversible process. Therefore, only photons that provide energy higher than the energy gap E_g can liberate hole−electron pairs inside the QW region to generate a photocurrent. The required frequencies ω_{v-c} of photons that allow holes in the valence band to transition to different conduction bands can be written as

$$\omega'_{v-c} \geq \omega_{c-v} = E_g/h \tag{3}$$

The irreversibility of the spectral emission-detection overlap shown in Figure 1b can be well explained using eq 3. We further extend our work to obtain a comprehensive understanding of the relations among *energy*, *mass*, *space*, and *time*. The law of conservation of energy provides insight into the relations among energy, mass, space, and time, wherein time and space are equivalent and the mass of a body is a measure of its energy. Suppose that we can make one object disappear in a given space−time coordinate system, and a certain amount of energy will be released. According to Einstein's memorable equation,[31] we can arrive at the following equation:

$$E = m \times v^2 = mv^2 = mc^2 \tag{4}$$

The symbol v is the velocity of radiation. In one coordinate system, the ratio of space s to time t can be treated as the velocity v. This means that energy equals mass times the square of the velocity of light when mass is completely converted into energy in one coordinate system at the velocity of light c. A very large amount of energy will be released when we completely convert a tiny amount of matter into energy in the form of photon radiation. Moreover, the energy of a photon is a constant times the frequency according to the statement of Planck. The energy is proportional to the frequency ω as follows:

$$E = h\omega \tag{5}$$

One may accurately determine the fundamental physical Planck's constant h through experimental measurements. Hence, in an idealized reversible process, we can transform photons into a body if we can manipulate an enormous amount of energy at the velocity of light c by using an extraordinary force. However, an irreversible process occurs. In the irreversible process, the energy and velocity required to completely convert energy into a body can be written as

$$E = mv^2 = m \times \left(\frac{s}{t}\right)^2 \geq mc^2 = h\omega \tag{6}$$

Then, we can obtain

$$s \cdot v \geq {}^{h}\!/_{m} \tag{7}$$

The symbols t and s are the time and space that the force acts through, respectively. This equation happens to come out of the Heisenberg uncertainty principle. The simple formula that involves the general relations among the energy, mass, space, and time of a body is a different manifestation of the second law of thermodynamics.

■ CONCLUSIONS

In summary, the QW diode exhibits an intriguing phenomenon due to its spectral emission-detection overlap. The diode is able to emit and detect light simultaneously, making it possible to merge identical diodes together to separately function as a transmitter, a modulator, and a receiver on a single chip. Combining the irreversible process and energy diagram theory, we reveal the physical mechanism of the spectral emission-detection overlap. That the device only detects and modulates shorter-wavelength photons than those emitted by itself is associated with the irreversibility between light emission and light excitation in the QW diode. We further extend our work and arrive at the view that the Heisenberg uncertainty principle is a different manifestation of the second law of thermodynamics, which may help us deeply understand various expressions in nature.

■ ASSOCIATED CONTENT

Supporting Information

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A proof of concept of the wireless light communication using two identical CREE XHP70 QW diodes (MP4)

■ AUTHOR INFORMATION

Corresponding Author

Yongjin Wang − *GaN Optoelectronic Integration International Cooperation Joint Laboratory of Jiangsu Province, Nanjing University of Posts and Telecommunications, Nanjing 210003, China;* orcid.org/0000-0001-8109-4640; Email: wangyj@njupt.edu.cn

Authors

Pengzhan Liu − *GaN Optoelectronic Integration International Cooperation Joint Laboratory of Jiangsu Province, Nanjing University of Posts and Telecommunications, Nanjing 210003, China*

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Ziqian Qi − *GaN Optoelectronic Integration International Cooperation Joint Laboratory of Jiangsu Province, Nanjing University of Posts and Telecommunications, Nanjing 210003, China*

Jianwei Fu − *GaN Optoelectronic Integration International Cooperation Joint Laboratory of Jiangsu Province, Nanjing University of Posts and Telecommunications, Nanjing 210003, China*

Yuan Jiang − *GaN Optoelectronic Integration International Cooperation Joint Laboratory of Jiangsu Province, Nanjing University of Posts and Telecommunications, Nanjing 210003, China*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.3c02189

Author Contributions

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

Notes

The authors declare no competing financial interest.

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