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Simultaneous light emission and detection of InGaN/GaN multiple quantum well diodes for in-plane visible light communication

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ABSTRACT

This paper presents the design, fabrication, and experimental characterization of monolithically integrated p-n junction InGaN/GaN multiple quantum well diodes (MQWDs) and suspended waveguides. Suspended MQWDs can be used as transmitters and receivers simultaneously, and suspended waveguides are used for light coupling to create an in-plane visible light communication system. Compared to the waveguide with separation trench, the calculated total light efficiency is increased from 18% to 22% for the continuous waveguide. The MQWDs are characterized by their typical current-voltage performance, and the pulse excitation measurements confirm that the InGaN/GaN MQWDs can achieve the light emission and photodetection at the same time. The photocurrent measurements indicate that the photocurrent is modulated by a bias voltage and that the photons are being supplied from another transmitter. An experimental demonstration is presented showing that the proposed device works well for in-plane full-duplex communication using visible light.

1. Introduction

For radio frequency (RF) communications, it was once considered impossible to receive and transmit on the same channel because of self-interference [1]. However, some recent works indicate that self-interference cancellation can be used to realize full-duplex RF communications [2–5], which can double the throughput of the entire communication system. Extracting a useful signal from the received distorted signal is challenging because the power of the unwanted self-interference can be billions of times stronger (100 dB+) than that of the desired signal. Therefore, highly accurate analog and digital circuits must work cooperatively to remove the self-interference. Such sensitive and expensive structures may not be practical for cost-sensitive situations, e.g., in portable devices. Are there any simpler ways to achieve full-duplex communications? Visible light communications (VLC) might be the answer.

In a VLC system, the emitter emits modulated light to deliver signals via visible light, and the detector senses the light through photon-electron conversion and thus extracts the signals [6–10]. Normally, the detector that absorbs the light cannot also emit light. However, a p-n junction InGaN/GaN multiple quantum well diode (MQWD) can perform both light emission and photodetection [11,12], enabling the realization of full-duplex communication on the same channel using visible light. On the basis of GaN-on-silicon platform, light source, waveguide and photo detector can be integrated on a single chip, in which visible light is emitted. The visible light is determined by the emission wavelength of InGaN/GaN MQWs.

In-plane VLC is achieved through light propagation between the emitter and the detector rather than across short electrical wires [13–17]. In our previous work, the modulated light from the emitter was guided by suspended waveguides and transported to the detector. An isolation trench located in the waveguide was used to separate the two p-GaN regions in the in-plane VLC system, leading to an abrupt change in the light propagation along the waveguides [18]. Here, we report the realization of an in-plane VLC system consisting of two InGaN/GaN MQWDs and suspended waveguides on a single chip, fabricated on a 2 in. GaN-on-silicon platform using a wafer-level technique [19,20]. Both the p-GaN and InGaN/GaN multiple quantum well (MQW) layers on top of the waveguides are removed to generate a continuous waveguide architecture. The waveguide height is thus reduced, and the fabrication process is simpler, especially for further nanoscale photonic integration. Simulations and experiments are conducted to characterize the proposed photonic integrated circuit.

2. Results and discussion

Fig. 1 shows a schematic illustration of the device structure. The in-plane VLC system is implemented on a 2 in. GaN-on-silicon wafer,

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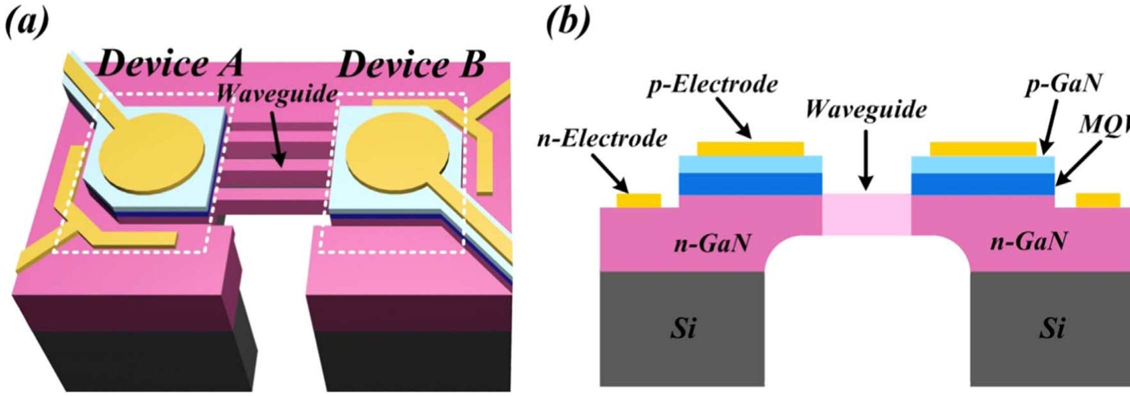

Fig. 1. A schematic of the device structure: (a) top view; (b) side view.

which is thinned to 200 µm thickness for further silicon removal by chemical mechanical polishing. The device layers consist of a ~220 nm-thick p-GaN layer, 250 nm-thick InGaN/GaN MQWs, a ~3.2 µm-thick n-GaN layer, a ~400 nm-thick undoped GaN layer, a ~900 nm-thick Al(Ga)N buffer layer, and a silicon substrate. Because the InGaN/GaN MQWDs serve as LED and photodiode simultaneously, the fabrication technology for creating the integrated optoelectronic device is identical to that for an InGaN/GaN MQWs-based LED and photodiode. The top layer is defined by photolithography and etched down to n-GaN to form an isolation mesa by inductively coupled plasma reactive ion etching (ICP-RIE) with Cl_2 and BCl_3 hybrid gases. A thick p-contact is used to suppress the light emission from the top escape cone. Both p- and n-type contacts are then formed by Ni/Au (20 nm/180 nm) evaporation, followed by a rapid thermal annealing at 500 °C in an N_2 atmosphere. Next, the waveguides, in which both the top p-GaN layer and the InGaN/GaN MQWs layers are removed to form the isolation for the two InGaN/GaN MQWDs, are patterned and etched by ICP-RIE. The top device structures are protected by thick photoresist and the silicon substrate is patterned by back-side alignment photolithography. Deep reactive ion etching is conducted to remove the silicon substrate, and back wafer etching of the suspended membrane is performed to obtain a membrane-type in-plane VLC system.

Fig. 2(a) shows a scanning electron microscope (SEM) image of the fabricated in-plane VLC system. Devices A and B, which are used as transmitters and receivers simultaneously, are suspended InGaN/GaN MQWDs. The 70 µm-diameter p-electrodes are fabricated on the isolation mesa, which has a 10 µm-wide gap to the n-electrode. The barrier capacitance can be decreased by reducing the size of electrode, leading to an improved bandwidth of the LEDs. GaN/GaInN nanowire array LED grown on silicon has been demonstrated a high speed over 1 Gbps [21]. The light coupling between device A and device B is realized through the in-plane connection by three 80 µm-long, 2.47 µm high, and 10 µm-wide suspended waveguides. Compared with the previous waveguide structures, the waveguide height is reduced, leading to a decrease in the confined optical modes. Fig. 2(b) illustrates a three-dimensional atomic force microscope (AFM) image of the suspended waveguides. The waveguide has a smooth top surface and the measured root mean square roughness is 1.16 nm, as obtained by an ICP-RIE process. The scattering loss is low with small surface roughness. The measured height of the isolation mesa is 525 nm.

The light propagation properties of the suspended waveguide are evaluated using the finite difference time domain method (FDTD). For simplicity, the refractive index of GaN used is 2.45. Because there are six escape cones for a planar emitter [22], a point-like source with a wavelength of 450 nm is adopted for the simulation. Most of the emitted light is confined inside the suspended structure as a result of the large index contrast between GaN and air [23–27]. The light emitted from the emitter at the end of the waveguide couples into the suspended waveguide and laterally propagates along it. The detector at the other end of the waveguide senses the guided light and completes the photon–electron conversion. Fig. 3 illustrates the FDTD simulation

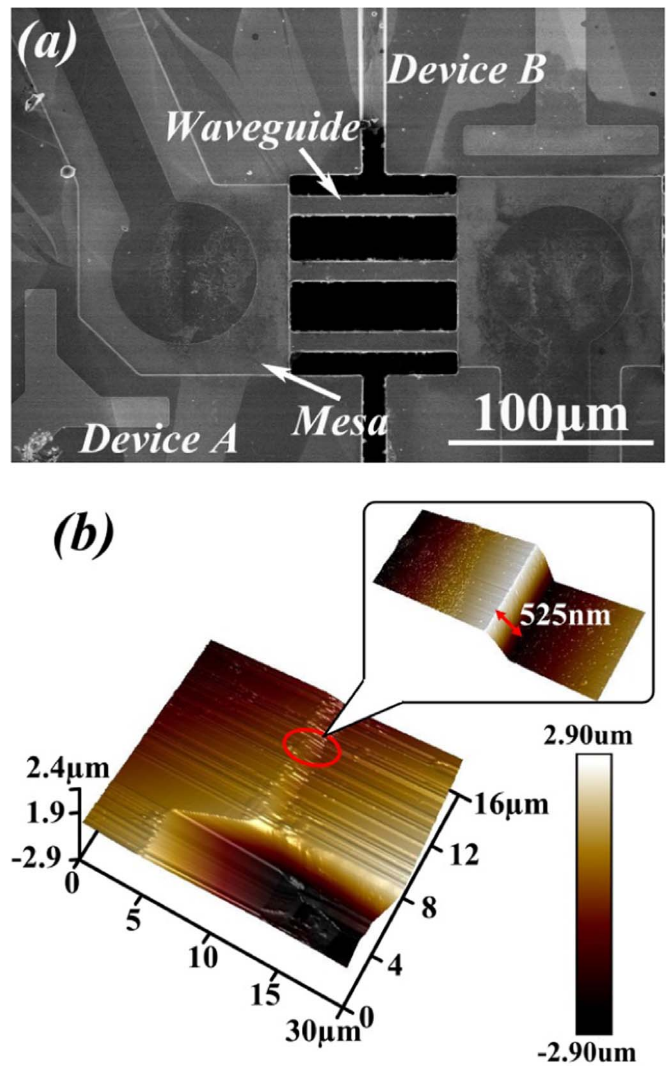

Fig. 2. (a) SEM image of the fabricated in-plane VLC system, (b) an AFM image of the suspended waveguide.