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GaN-based integrated photonics chip with suspended LED and waveguide

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ABSTRACT

We propose a GaN-based integrated photonics chip with suspended LED and straight waveguide with different geometric parameters. The integrated photonics chip is prepared by double-side process. Light transmission performance of the integrated chip verse current is quantitatively analyzed by capturing light transmitted to waveguide tip and BPM (beam propagation method) simulation. Reduction of the waveguide width from 8 μm to 4 μm results in an over linear reduction of the light output power while a doubling of the length from 250 μm to 500 μm only results in under linear decrease of the output power. Free-space data transmission with 80 Mbps random binary sequence of the integrated chip is capable of achieving high speed data transmission via visible light. This study provides a potential approach for GaN-based integrated photonics chip as micro light source and passive optical device in VLC (visible light communication).

1. Introduction

GaN-based material with excellent opto-electrical performance has been used in LED in the past decades. The emitted light of GaN-based LED covers a whole visible range from red to ultraviolet [1,2]. VLC is one of the most important applications of LED [3]. VLC uses high-speed response characteristics between light output power verse current to load signal on visible light [4]. The advantages of VLC includes low energy consumption, avoiding signal leakage, anti-interference and so on [5]. IC chip as signal processing module limits the development of VLC owing to quantum size effect and power consumption [6]. Recently, researchers pay attention to photonics chip allowing low power consumption, low cost and high volumes, aiming to its applications on ultra-high-speed VLC and so on [7]. GaN-based material is capable of emitting visible light signal, and could also be used to prepare passive photonics devices transmitting and processing visible light signal [8].

Hui et al. demonstrated waveguide devices using GaN/AlGaN materials and explored the applications in optical fiber communication (1.55 μm wavelength) [9]. Reported GaN-based passive photonics devices are mainly aimed to optical fiber communication with 1.55 μm wavelength. The transmission performance of GaN-based materials in visible range has not been fully studied. Sun et al. reported a blue–violet (413 nm) InGaN laser diode grown on silicon substrate with straight waveguide as light source at room temperature in 2016 [10]. These studies provide feasible solutions for integrated photonics chip as micro light source and passive devices used in VLC.

We reported suspended LED as micro light source prepared by double-side process on GaN-on-silicon platform [11]. We also studied an integrated photonics chip with suspended LED, waveguide and photodetector, and explored the potential applications of the integrated chip in VLC [12,13]. In this work, we conducted a quantitative analysis of light transmission performance and VLC performance of an integrated photonics chip with straight waveguide with different geometric parameters. Light transmission performance of the integrated chip is experimentally studied by analyzing the light output power from tip verse current. BPM simulation about light transmission performance is performed to support the experimental results. Free-space data transmission with 80 Mbps random binary sequence of the integrated photonics chip is capable of achieving high speed data transmission via visible light. This study provides a potential approach for GaN-based integrated photonics chip as micro light source and passive devices used in VLC. Schematic of integrated photonics chip with suspended LED and straight waveguide is shown in Fig. 1.

2. Fabrication and structures characterization

The integrated photonics chip is prepared on a commercial GaN-on-silicon platform (Lattice Power Corporation, China). LED layer consists of ~220 nm thick p-GaN layer, ~250 nm InGaN/GaN MQWs, ~3.2 μm thick n-GaN layer, ~400 nm thick undoped GaN layer and ~900 nm thick Al(Ga)N buffer layer. Silicon substrate is ~200 μm. The structures

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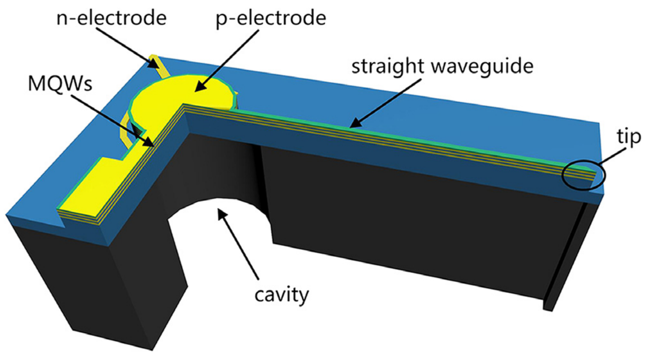

Fig. 1. Schematic of integrated photonics chip with suspended LED and straight waveguide.

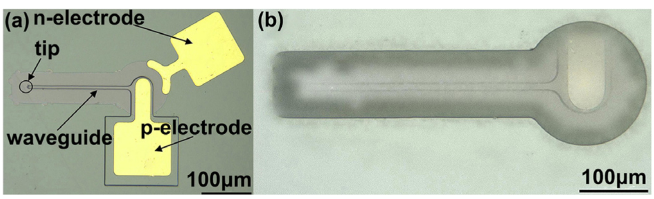

Fig. 2. Optical micrographs of integrated photonics chip with suspended LED and waveguide. (a) Top side, (b) back side (fully-focused image).

of integrated chip are patterned on the LED layer by photolithography. Then, the structures are transferred to the LED layer by FAB (fast atom beam) etching by 1.2 μm depth. FAB etching is generated by neutral etching species ions extracted from SF6 plasma, and it is capable of etching with high anisotropy and steep sidewall. FAB etching rate is 8 nm/min with 1.8 kV high voltage and 12 mA accelerated current. The patterns of LED p/n electrode are patterned by photolithography on the LED layer. Ni/Au (20 nm/180 nm) films are evaporated by EB (electron beam) evaporation. The p/n electrode is formed by lift-off process (removing unwanted photoresist with Ni/Au films by a positive resist stripper solution MS2001). The backside of silicon substrate is patterned and etched by deep reactive ion etching to remove silicon under the integrated chip. Fig. 2 shows the optical micrographs of the fabricated integrated chip with suspended LED and waveguide (width-8 μm, length-250 μm). The upper part of LED connected with waveguide is a semicircle with 50 μm diameter and a rectangle with 50 μm width and 60 μm length. The lower part is a square with 150 μm length. We fabricated four kinds of chips to study the light transmission performance of waveguide with different geometric parameters (width-4 μm/8 μm, length-250 μm/500 μm). Silicon under the integrated chip is totally removed, and a transparent LED layer is retained as shown in Fig. 2(b).

Fig. 3 presents the tip and side wall of waveguides. The design structures of tip are sharp corners to converge transmitted light via waveguides from LED. The fabricated tip of waveguide with 8 μm width is curved in Fig. 3(a), and a blurred tip of waveguide with 4 μm width is obtained in Fig. 3(c). The sidewall of waveguide with 8 μm width has high steepness and small roughness in Fig. 3(b). The waveguide with 4 μm width has a curved side wall in Fig. 3(d). The waveguide with 8 μm width has better fabrication quality than the waveguide with 4 μm width. Differences of fabrication quality could be attributed to the heat resistance during FAB etching step. The heat generated by FAB etching is more concentered on the photoresist waveguide patterns with smaller width. The patterns with smaller width are more unstable and easier to be removed by FAB etching. The heat concentration leads to the blurred tip and curved side wall of waveguide with 4 μm width.

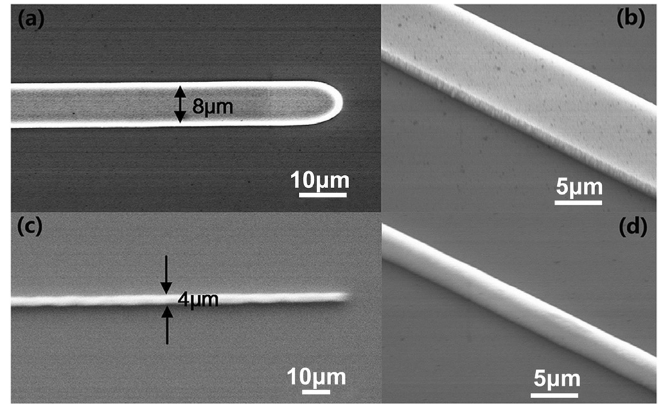

Fig. 3. (a) SEM image of tip of waveguide with 8 μm width, (b) SEM side view image of waveguide with 8 μm width, (c) SEM image of tip of waveguide with 4 μm width, (d) SEM side view image of waveguide with 4 μm width.

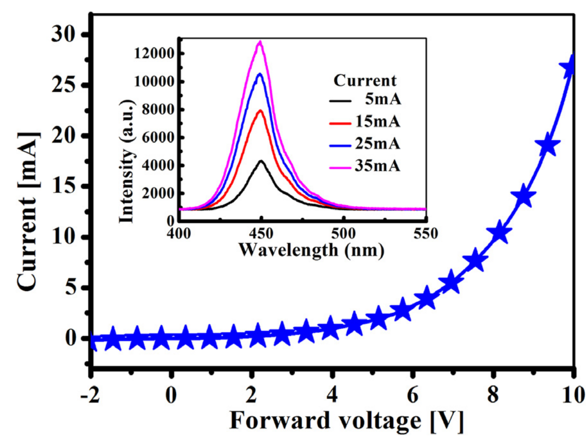

Fig. 4. I-V characteristics of integrated chip with suspended LED and waveguide. The inset shows EL characteristics of integrated chip.

3. Opto-electrical characterization

I-V (current–voltage) and EL (electroluminescence) characteristics of the integrated chip with waveguide (8 μm/250 μm) are measured by a probe station connected to a semiconductor device parameter analyzer (Agilent, B1500A) and a spectrometer in visible range. The I-V characteristics of integrated chip is consistent with the I-V characteristics of a typical LED. EL characteristics are measured by a microscopy system and a fibered-coupled photonic multi-channel analyzer (Hamamatsu, C10027). Light output power of integrated chip is strongly modulated by injection current. The ratio between the peaks of light output power verse 35 mA current and 5 mA current is about 2.98. The integrated chip is applicable to VLC by modulating the light output power [14]. (See Fig. 4.)

C-V (current–voltage) characteristics in Fig. 5 presents the negative capacitance behavior of the integrated chip with waveguide (8 μm/250 μm) under AC signal with different frequency. The negative capacitance behavior is more obvious for the integrated chip with freestanding membrane. The integrated chip with high modulation bandwidth could be achieved by reducing RC time constant, and lower RC time constant is always accompanied by a lower junction capacitance of LED [15,16]. The capacitance of integrated chip with freestanding membrane is reduced because of removal of silicon substrate as a bulky capacitive layer. The large area of silicon substrate adds a large parasitic capacitance to the capacitance of integrated chip, and the RC time constant reduces by removing silicon. In micro-LEDs, it is very common