Voltage-Controlled GaN HEMT-LED Devices as Fast-Switching and Dimmable Light Emitters

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***Abstract*—This letter reports a novel voltage-controlled light emitter with fast switching speed and dimming capability using a monolithically integrated GaN HEMT-LED device. The integrated HEMT-LED device, with a transconductance of 113 mS/mm and large light emitting area (450 × 470 μm^2), exhibits a fast switching speed of 15 MHz. When functioning as an optical transmitter, a data rate of 16.7 Mbit/s was demonstrated. By reducing the duty cycle of the pulsed gate voltage from 100% to 0.1%, the light intensity decreased accordingly, and a linear pulse-width modulation dimming performance with a wide dimming range (0.1%–100%) and high dimming ratio (51 282:1) was achieved.**

***Index Terms*—Switching, dimming, HEMT-LED, monolithic**

I. Introduction

MODULATED light emission from LEDs at various frequencies (from several Hz to several hundred MHz) is finding an increasing number of applications such as liquid crystal display (LCD) backlighting [1]–[3], LED-based spectroscopy [4], visible light communication (VLC) [5], and optogenetic technology [6]. With the development of high-contrast LCD display backlighting for medical and astronomical applications [7], [8], dimmable LED illumination with a wide range for energy-saving is required [9]. For VLC with a high data transmission rate [10], a fast modulation speed is essential for the LED light sources.

As a current-driven device, an LED light source is conventionally driven by a constant current and is modulated with various methods such as pulse width modulation (PWM), pulse frequency modulation (PFM), and pulse code modulation (PCM), in which the LED current is used as a feedback parameter. Very complex control loops and overvoltage protection schemes are always needed [11], [12] and the complexity will further increase [13] when more LED branches are adopted. In contrast, when the LED voltage is used as the feedback parameter, the control loop can be made simpler, and multiple voltage outputs can be flexibly adjusted for various applications [14]. Thus, voltage-controlled LEDs are highly preferable as a modulated light source.

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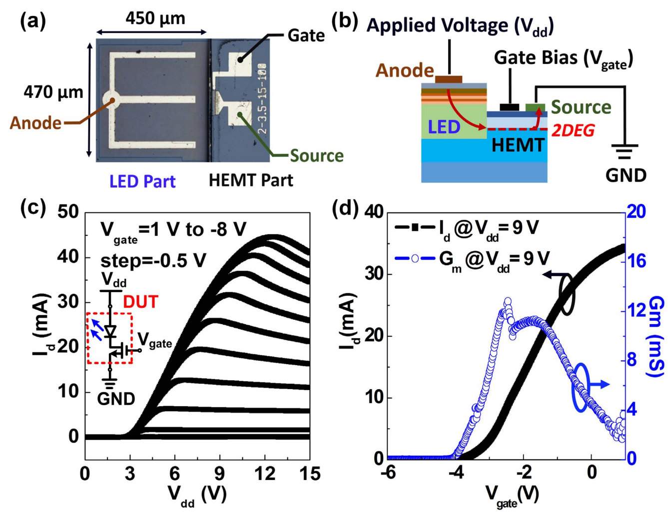

Fig. 1. (a) Microscope image of the integrated HEMT-LED device consisting of an LED with 450 × 470 μm^2 light emitting area and a HEMT with 100 μm-width gate, 2 μm-length gate and 30 × 100 μm^2 active area; (b) illustration of the device cross-section and current path shown by a red arrow; (c) I-V characteristics and equivalent test circuit (inset); and (d) transfer characteristics of the integrated HEMT-LED.

Recently, GaN power devices such as enhancement-mode GaN HEMTs (E-mode HEMTs), are being investigated to replace conventional silicon devices in LED drivers to enhance switching speed and reduce power loss [15]. Thus, the monolithic integration of a GaN HEMT with an LED to form a three-terminal compact emitter is promising to achieve a voltage-controlled light source with high performance [16].

In this letter, we demonstrate fast switching and dimming capability of a voltage-controllable light emitter using a monolithically integrated GaN HEMT-LED device. This emitter shows a stronger current drive capability and superior switching speed, compared to a recent report of an integrated Si MOSFET-μ LED counterpart [17]. The dimmable HEMT-LED device can potentially enable various applications including dimmable illumination, high-contrast-ratio display and VLC.

II. Experiment

Figs.1 (a) and (b) show the microscope image and schematic of the integrated HEMT-LED device. The equivalent circuit of the device is shown in the inset of Fig. 1(c) and the

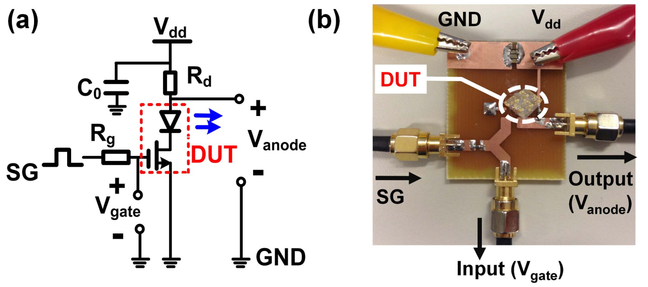

Fig. 2. (a) Switching test circuit; (b) designed PCB for the test circuit with a SMA connection, and an oscilloscope to measure the input and output voltage.

growth/fabrication processes were reported in [16]. When applying a voltage (V_{dd}) between the anode of the LED and the grounded source of the HEMT, current flows from the anode, through the n-GaN layer and 2-DEG channel, to the source. On-off modulation and the brightness of the device are controlled by its gate voltage V_{gate} and anode voltage V_{dd}. Figs. 1(c) and (d) plot the I-V characteristics and transfer curve of the HEMT-LED device, which shows the voltage-controlled properties through the gate and drain terminals. In addition, we also note that the HEMT-LED has a much higher transconductance (113 mS/mm), than the reported 0.62 mS/mm of the Si MOSFET-μ LED configuration in [17]. The GaN HEMT-LED configuration here shows a much stronger current drive capability than the Si MOSFET-μ LED, based on the nature of GaN devices, namely, high-power and high-speed. To further demonstrate the voltage-controlled modulation, a switching test circuit was built, as shown in Fig. 2. The integrated LED can be turned on and off by a pulsed gate voltage provided by an external signal generator (SG).

III. Results And Discussion

We first used the integrated HEMT-LED device as an optical transmitter by modulating the frequency of its input pulsed gate voltage. As shown in Fig. 3(a), the HEMT-LED device combined with an external circuit was used as a transmitter, and an external photodiode with a trans-impedance amplifier (TIA) was used as a receiver. The HEMT-LED device can be well modulated by its pulsed gate voltage provided by an external signal generator (SG), with a fixed duty cycle of 50% at 1 $\sim$ 20 MHz, as shown in Fig. 3(b). Despite the much larger LED size (470 × 450 μm^2) here, a higher switching speed was measured in comparison with the 10 MHz switching speed of the Si MOSFET-driven micro-LED (30 × 30 μm^2) in [17]. To characterize the data transmission rate of this system, a pseudorandom binary sequence (PRBS) generated by a field-programmable-gate array (FPGA) was used as the input signal. Judging from the eye diagrams in Fig. 3(c), the data rate reached up to 16.7 Mbit/s without using any pre-distortion, equalization or complex modulation schemes.

A performance comparison between the reported Si MOSFET-μ LED and the GaN HEMT-LED here is presented in Table I, the HEMT-LED shows great potential as a modulated high-intensity light source for high data rate communication applications. Despite of the 182 times higher transconductance, the mere 5 MHz improvement in switching

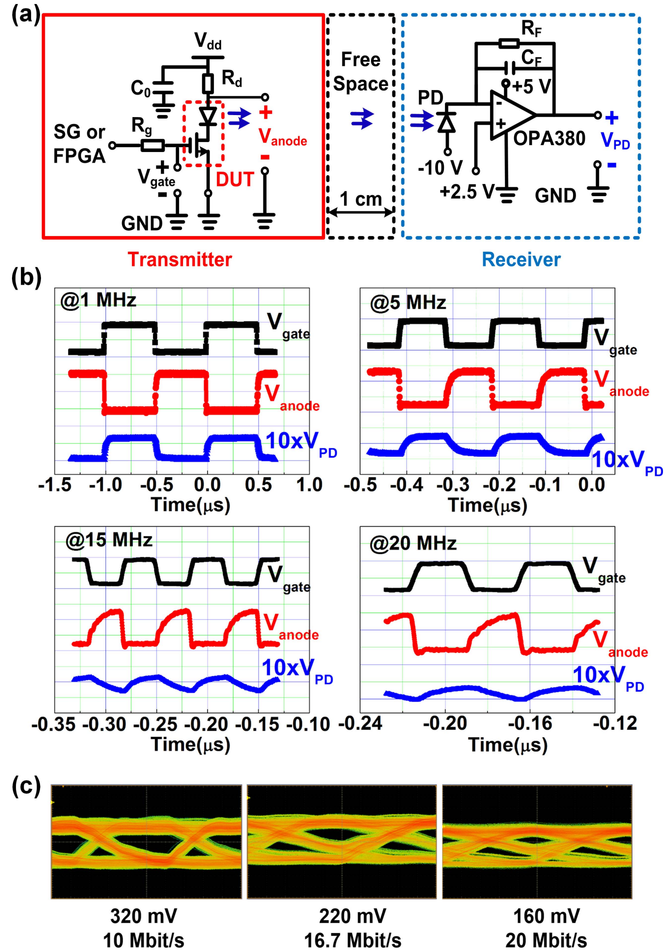

Fig. 3. (a) VLC system based on the HEMT-LED device; (b) switching waveforms of the integrated HEMT-LED device at different frequencies with a fixed 50% duty cycle; and (c) eye diagrams and eye-openings with various PRBS data rates.

TABLE I

Device Performance Comparison With Reference Work

	[17]	This work
Integrated Device	Si MOSFET-LED	GaN HEMT-LED
Transistor size (W_g/L_g)	100 μm/10 μm	100 μm/2 μm
Transconductance (g_m)	0.62 mS/mm	113 mS/mm
LED active area	30 ×30 μm^2	450 ×470 μm^2
Switching Speed	10 MHz	15 MHz @ 36 mA

speed for our GaN HEMT-LED can be attributed to a much larger LED capacitance resulting from its 235 times larger LED active area, limiting the HEMT-LED switching speed. If high intensity application is not needed, scaling down of the LED size to tens of micrometers as a micro-LED (e.g., diameter: 24 μm) will enable much lower capacitance and an estimated bandwidth of 600 MHz can be achieved accordingly [3].

Secondly, the dimming capability of the HEMT-LED device as an illumination light source can also be achieved by simply tuning the duty cycle of its input gate voltage. Figs. 4(a) (b) and (c) show typical input and output waveforms

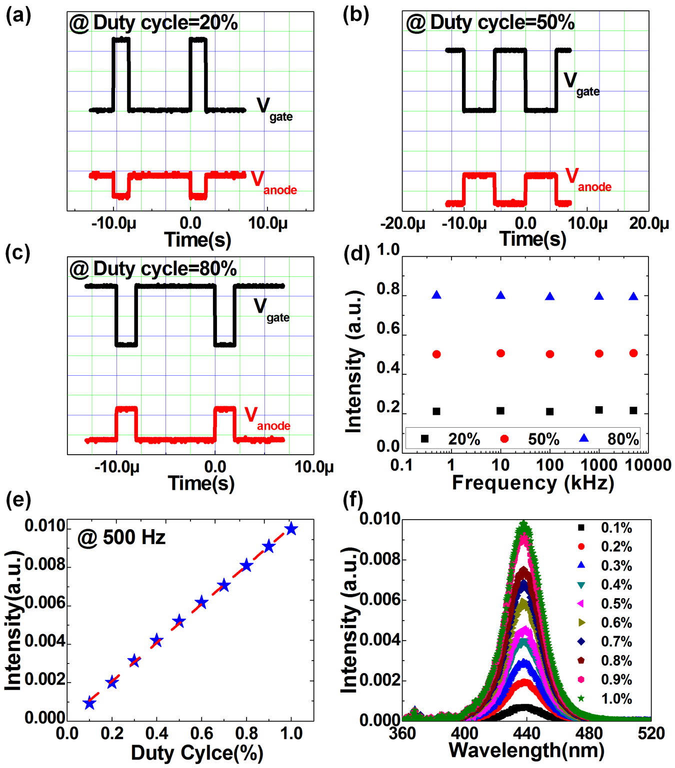

Fig. 4. Switching waveforms of the input signal at 500 Hz with (a) 20% duty cycle; (b) 50% duty cycle; (c) 80% duty cycle; (d) measured PWM performance curves from 500 Hz to 5 MHz with 20%, 50% and 80% duty cycles; (e) normalized light intensity at 500 Hz and (f) light emission spectra at 500 Hz with the duty cycle ranging from 0.1% to 1%. For normalization, all light intensities are divided by the light intensity at 500 Hz when duty cycle is 100%.

of the HEMT-LED device under three different duty cycles at 500 Hz. It can be seen from Fig. 4(d) that as the duty cycle increased, the measured light intensity increased linearly at different frequencies. Moreover, such linearity could still be maintained when the duty cycle varied from 0.1% to 1%, corresponding to a light intensity of 41 μW to 0.42 mW without an obvious peak wavelength shift in emission spectra, as shown in Figs. 4(e) and (f). Since the light intensity of the HEMT-LED device could be dimmed down linearly from 100% to 0.1% of its maximum light intensity at 500 Hz, a typical voltage-controlled PWM dimming performance has been achieved with a dimming range of 0.1% to 100% via simply adjusting its gate voltage, without adopting a complex current regulator or gate driver.

The dimming function of the voltage-controlled HEMT-LED device is also highly desirable for LCD display backlighting application. The rise time of current response from 10% to 90% of its maximum amplitude and fall time from 90% to 10% of its maximum amplitude were 2.6 ns and 26.6 ns, respectively, as shown in Fig. 5(a). At 500 Hz, the response pulse width of the HEMT-LED current was 39 ns. With the dimming ratio defined as the maximum duty cycle of the LED current divided by the minimum duty cycle [7], the HEMT-LED device has achieved a dimming ratio of 51,282:1 at 500 Hz for high-contrast-ratio backlighting, higher than the 50,000:1 ratio

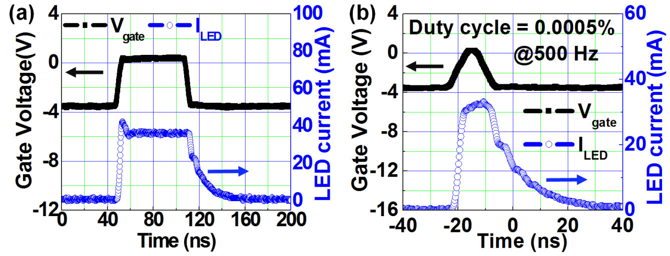

Fig. 5. (a) Current response of the HEMT-LED to a 120 ns width gate pulse; (b) current response of the HEMT-LED to a 10 ns width gate pulse.

of an eight-channel LED backlight driver [18]. This indicates the potential application of the HEMT-LED device for LCD display backlighting with a high contrast ratio.

IV. Conclusion

In conclusion, use of the three-terminal HEMT-LED device for voltage-control of the light intensity/frequency with high modulation speed has been demonstrated, by directly adjusting the frequency and duty cycle of the voltage pulse applied on the HEMT-LED gate terminal. The HEMT-LED shows a high transconductance of 113 mS/mm, a high data transmission rate of 16.7 Mbit/s, a wide PWM dimming range of 0.1% to 100% and a fast transient response of 39 ns at 500 Hz. With the monolithically integrated HEMT-LED device, we have achieved a fast-switching, dimmable light emitter for illumination, LCD display backlighting and VLC applications.

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