Voltage-controlled Micro-LEDs integrated with an AlGaN/GaN High Electron Mobility Transistors

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ABSTRACT

A voltage-controlled micro-LED is achieved by integrating with an AlGaN/GaN high electron mobility transistor (HEMT). The implementation method involves a lateral integration of micro-LED and HEMT by selective area regrowth (SAR). The HEMT could provide a maximum current density of 1128 A/cm^2 for micro-LED. The brightness of the micro-LED can be modulated through pulse width modulation (PWM) on the gate bias.

1. Introduction

InGaN/GaN LEDs have been widely applied in solid-state lighting for decades due to their excellent performances, such as high brightness, efficiency, and long lifespan [1, 2]. In recent years, research into micro-LEDs for intelligent lighting, visible light communication, and displays has been attracting increasing attention [3]. As light emission components, modulation of the LED brightness is required. Since the brightness of a LED is very sensitive to voltage, a current source is usually used for LED driving. A voltage-controlled LED is preferred due to simpler driving scheme and reduced parasitic parameters. The same material system allows HEMT and LED to be monolithically integrated on the same epi wafer, forming a voltage-controlled LED [4-6]. LED brightness modulation by HEMT would benefit from excellent properties like high on-state current, low off-state current, and high reliability of HEMT. The previous publication reported a metal interconnection-free integration scheme for standard LED and HEMT [7]. A LED and a HEMT are connected laterally by the SAR method. Epi structure of the LED is selectively regrown on the HEMT wafer. However, reports on voltage-controlled micro-LEDs for display are very limited. In this work, we proposed a high-performance voltage-controlled and dimmable micro-LED with a dimension of 50μm using a similar method as mentioned in Ref. [7]. The monolithically integrated micro-LED can be used in future micro-LED displays. The schematic diagram of the voltage-controlled micro-LED is shown in Fig. 1.

2. Experiment

Firstly, a 2-inch AlGaN/GaN HEMT was grown on a (001) sapphire substrate in an Aixtron metal-organic chemical vapor deposition (MOCVD) system. A selective

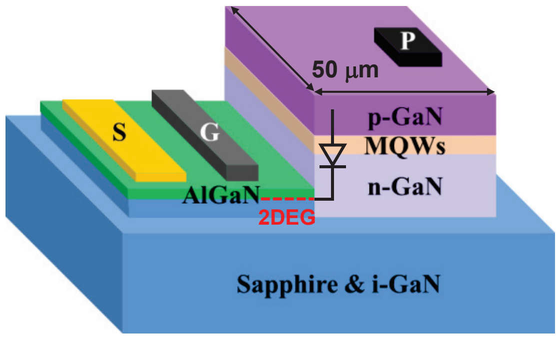

Fig. 1 Schematic diagram of voltage-controlled micro-LED

area etching is conducted on the HEMT epi to expose the buffer for micro-LED regrowth. Then, an n-GaN layer, multiple quantum wells, and a p-GaN layer were deposited in sequence with the SiO_2 as the selective regrowth mask. Atomic force microscopic (AFM) was used to monitor the surface morphology before and after regrowth. The RMS of the as-grown HEMT surface is 1.51 nm and increased to 3.44nm after the ICP etching. After the SAR, the RMS of the LED surface was reduced to 1.43 nm, indicating a smooth surface morphology. Afterward, the SiO_2 regrowth mask was entirely removed by BOE wet etching. Then, the micro-LED and HEMT are naturally connected by the two-dimensional electron gas (2DEG) and n-GaN layers as illustrated in Fig. 1. The fabrication of the device started with device isolation by ICP etching. After that, the source ohmic contact of HEMT was formed by e-beam evaporating of 20/150/50/80 nm thick Ti/Al/Ni/Au metal stack, followed by a rapid thermal annealing (RTA) at 850 °C for 30 s in N_2 ambient. The current spreading layer (CSL) of the LED was formed by the deposition of 50 nm ITO and RTA annealing. F- Implantation was then applied to define the active area of the HEMT with LED protected by the photoresist. After that, the gate of HEMT was formed by depositing a 20/200 nm Ni/Au metal stack. Finally, a 20/150/50/80 nm Ti/Al/Ni/Au metal stack was deposited as the p-electrode of the LED.

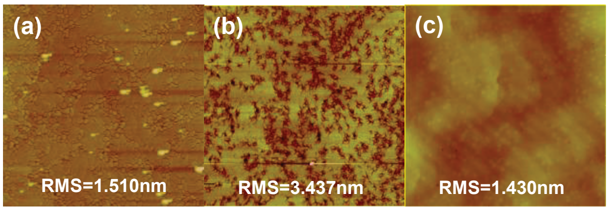

Fig. 2 10 μm × 10 μm AFM images of (a) as-grown HEMT, (b) etched surface of HEMT, and (c) regrown surface of Micro-LED

3. Results and Discussion

Electrical characterizations were performed using an Agilent 4156C semiconductor parameter analyzer. The integrated micro-LED and HEMT exhibit electrical properties similar to the HEMT. Fig. 3 (a) plots the double sweep transfer curves in log scale with the V_{DS} at 10 V and V_G varying from 1 V to -6 V. Forward sweep curve and backward sweep curve coincide exactly with no hysteresis. The threshold voltage V_{TH} is -3.05 V, defined at I_D=1 μA/mm. The device shows a subthreshold swing of 65.30 mV/dec and a high transconductance G_m of 139.72 mS/mm. It is worth noting that a driven current with only several μA is enough to turn on the micro-LED. Therefore, the off-state I_{DS} should be low enough to turn off the micro-LED. Off-state I_{DS} of the HEMT is ~2×10-5 mA/mm (200 pA), indicating the capability of turning off the micro-LED by depleting the 2DEG. The on/off ratio could reach 3×10^7. Fig. 3 (b) shows the output characteristics with V_G reducing from 1 V to -5 V. The 3 V positive shift of the curves compared with the conventional output curve is due to the turn-on voltage

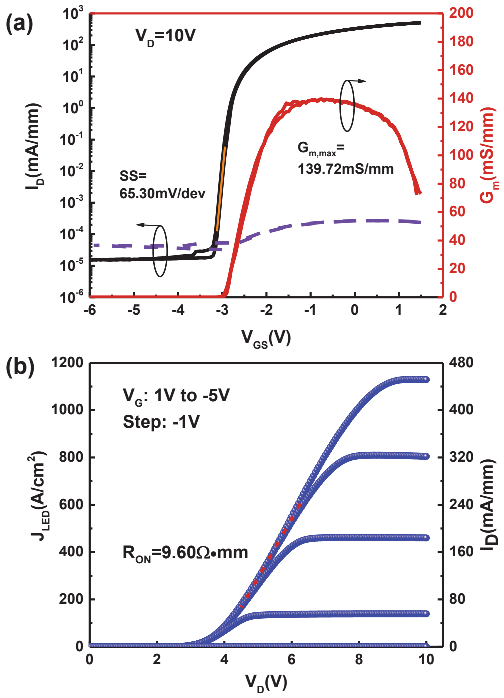

Fig. 3 Transfer and output characteristics of the voltage-controlled micro-LED

of the micro-LED. The turn-on voltage of the device can be extracted as 3.32 V at J_{LED}=20 A/cm^2 with zero gate bias. The maximum J_{LED} can reach as high as 1128 A/cm^2 at V_G=1 V. After entering the saturation region of the HEMT, the device shows a constant I_{DS} (J_{LED}), indicating the stability of micro-LED against V_D fluctuations.

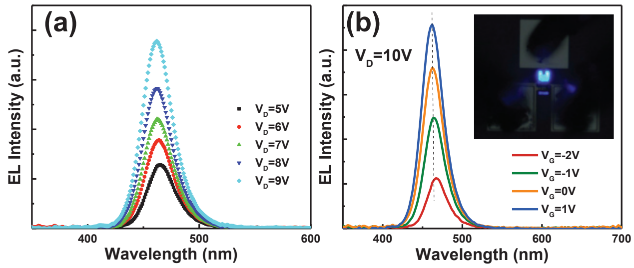

Fig. 4 EL spectra of the micro-LED under modulation of both (a) drain bias and (b) gate bias

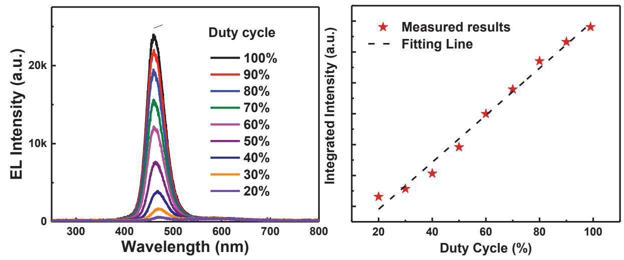

Fig. 5 (a) EL spectra of the micro-LED under gate pulse width modulation and (b) intensity with a function of duty cycle

Fig.4 shows the micro-LEDs electroluminescence (EL) spectrum under voltage modulation. Fig. 4(a) shows the drain bias modulation with constant V_G, while Fig. 4(b) is under gate bias modulation with constant V_D. The micro-LED emits blue light with a peak wavelength of 460 nm. The device exhibits a capability of both drain and gate bias modulation of light output intensity. EL intensity increases with the increase of the V_G due to the increased 2DEG density in the HEMT channel and therefore increased current provided by the HEMT. In addition, the micro-LED also has the capability of light output intensity modulation through PWM on gate bias. The EL spectrum of the micro-LED under different duty cycles is plotted in Fig. 5 (a). The signal generator provides a square function with a frequency of 50 kHz as the input signal to the gate electrode. The cycle duty increased from 20% to 100% with an increasing step of 10%. Fig. 5(b) plots the EL intensity with the increase of the duty cycle. The linear fitting line shows that PWM has good linearity in modulating the brightness of micro-LED.

4. Conclusion

In conclusion, a voltage-controlled and dimmable micro-LED is proposed in this work by integrating micro-LED with HEMT using the SAR method. The micro-LED device exhibits good electric and optical performance. Unlike the traditional current-driven micro-LED, the light intensity of micro-LED could be modulated by gate voltage modulation and gate pulse width modulation.

References

[1] S. J. R. o. M. P. Nakamura, "Nobel Lecture: Background story of the invention of efficient blue InGaN light emitting diodes," vol. 87, no. 4, p. 1139, 2015.

[2] I. J. R. o. M. P. Akasaki, "Nobel Lecture: Fascinated journeys into blue light," vol. 87, no. 4, p. 1119, 2015.

[3] J. Lin and H. Jiang, "Development of microLED," Applied Physics Letters, vol. 116, no. 10, p. 100502, 2020.

[4] Y. Cai, C. Zhu, W. Zhong, P. Feng, S. Jiang, and T. J. A. M. T. Wang, "Monolithically Integrated μLEDs/HEMTs Microdisplay on a Single Chip by a Direct Epitaxial Approach," 2021.

[5] Z. Li, J. Waldron, T. Detchprohm, C. Wetzel, R. Karlicek Jr, and T. Chow, "Monolithic integration of light-emitting diodes and power metal-oxide-semiconductor channel high-electron-mobility transistors for light-emitting power integrated circuits in GaN on sapphire substrate," Applied Physics Letters, vol. 102, no. 19, p. 192107, 2013.

[6] Z. Liu, J. Ma, T. Huang, C. Liu, and K. May Lau, "Selective epitaxial growth of monolithically integrated GaN-based light emitting diodes with AlGaN/GaN driving transistors," Applied Physics Letters, vol. 104, no. 9, p. 091103, 2014.

[7] C. Liu, Y. Cai, Z. Liu, J. Ma, and K. M. Lau, "Metal-interconnection-free integration of InGaN/GaN light emitting diodes with AlGaN/GaN high electron mobility transistors," Applied Physics Letters, vol. 106, no. 18, p. 181110, 2015.