Monolithic Integration of AlGaN/GaN HEMT on LED by MOCVD

Zhao Jun Liu, *Member, IEEE*, Tongde Huang, *Student Member, IEEE*, Jun Ma, Chao Liu, and Kei May Lau, *Fellow, IEEE*

***Abstract*— Monolithic integration of high-performance AlGaN/GaN high-electron mobility transistors (HEMTs) and blue light emitting diodes (LEDs) on sapphire substrates has been demonstrated by metal organic chemical vapor deposition selective growth technique. The integrated HEMT-LED exhibits a peak transconductance (G_m) of 244 mS/mm, a maximum drain current (I_d) of 920 mA/mm, and an ON-resistance (R_{on}) of 2.6 $\Omega \cdot$ mm. The forward voltage (V_F) of the LED is 3.1 V under an injection current of 10 mA. The integrated LED emits modulated light power efficiently at a wavelength of 470 nm by a serially connected GaN HEMT, showing potential applications such as solid-state lighting, displays, and visible light communications.**

***Index Terms*— AlGaN/GaN, high electron mobility transistor (HEMT), light emitting diode (LED), metal organic chemical vapor deposition (MOCVD).**

I. Introduction

III-NITRIDE compound semiconductors have been widely used in two important types of devices: light emitting diodes (LEDs) and high electron mobility transistors (HEMTs) [1], [2]. LED technologies for lighting and displays are maturing rapidly and GaN-based HEMTs are gaining ground in power electronic and RF applications for their unique properties. AlGaN/GaN devices with high breakdown and low specific on-resistance (R_{on}) have been demonstrated [3]–[6].

Taking advantage of the high frequency and output current capacity of HEMTs, they can be adopted as the driving transistors of LEDs for many applications such as solid-state lighting, displays, and visible light communications (VLCs). Sharing a common material platform, III-nitride based LEDs and HEMTs monolithically integrated on the same substrate offer a number of advantages. For example, the parasitic resistance and capacitance due to wire-bonding can be greatly reduced, thereby increasing the power efficiency of the driving circuit. It is known that the failure of LED systems is usually caused by the peripheral components and packaging. With an on-chip AlGaN/GaN HEMT driver, the reliability of LED system can be improved, fully utilizing the long-lifetime superiority of GaN LED chips. Having high power/area efficiency, AlGaN/GaN HEMTs can provide output current over 1A with a width/length (W_g/L_g) ratio of 1 mm/1 μm. A monolithic dimmable LED light source is feasible by integrating HEMTs with high-power LEDs (HEMT-LEDs) on the same substrate. However, two major issues should be considered in achieving successful monolithic integration technology of HEMT-LED. The first issue is to make a choice between metal-organic chemical vapor deposition (MOCVD) selective epitaxial growth and selective epitaxial removal. Dry etching has been employed to expose the HEMT or LED grown below the other structure [7], [8]. The dry etching will unavoidably introduce plasma damage, and is difficult to control the etching depth without an etching stop-layer. The other issue is how to allocate the thermal budget in considering the growth order of the LED and HEMT structures by the high-temperature MOCVD process. In this letter, we report monolithically integrated HEMT-LEDs on the same sapphire substrate using selective growth technique by MOCVD. The HEMTs were selectively regrown on top of the LED epitaxial layers. Moreover, the distribution of thermal budget was discussed for the first time to evaluate the balance between the buffer thickness and LED performance. The growth conditions were chosen to minimize degradation of both the HEMT and LED. The integrated HEMT-LEDs have comparable performance to discrete HEMTs and LEDs.

II. Experiment

The AlGaN/GaN HEMTs were grown in an Aixtron MOCVD system on a 2-inch LED epitaxial structure grown on a sapphire substrate. Before HEMTs growth, 500-nm SiO_2 was deposited as a growth mask on the LED epi-structure by plasma enhanced chemical vapor deposition (PECVD) and then patterned by buffered oxide etchant (BOE). The HEMT epi-structure grown in the open windows consisted of, from bottom to top, a 170-nm unintentionally doped (UID) GaN layer, a 55-nm AlGaN layer with Al composition of 15%, a 150-nm UID GaN channel layer, a 1-nm AlN spacer, and a 20-nm AlGaN barrier layer. Considering the LED-epi underneath, the growth temperature of the HEMT-epi was 1045 °C, which was 100 °C lower than our normal HEMTs growth temperature [4], [5]. A similar standard HEMT structure was

Manuscript received December 3, 2013; revised December 23, 2013 and January 5, 2014; accepted January 13, 2014. This work was supported by the Research Grants Council Theme-Based Research Scheme of the Hong Kong Special Administrative Government under Grant T23-612/12-R "Cost-effective and eco-friendly LED system-on-a-chip." The review of this letter was arranged by Editor R. Quay.

The authors are with the Department of Electronic and Computer Engineering, The Hong Kong University of Science and Technology, Hong Kong (e-mail: eekmlau@ust.hk).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2014.2300897

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

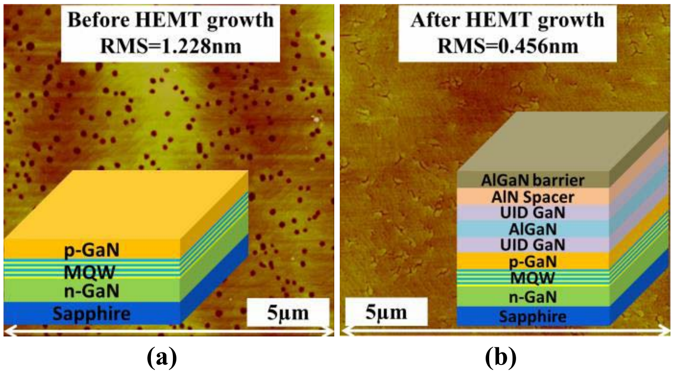

Fig. 1. Surface morphology of the LED epi-layer (a) before and (b) after HEMT epi-layer growth.

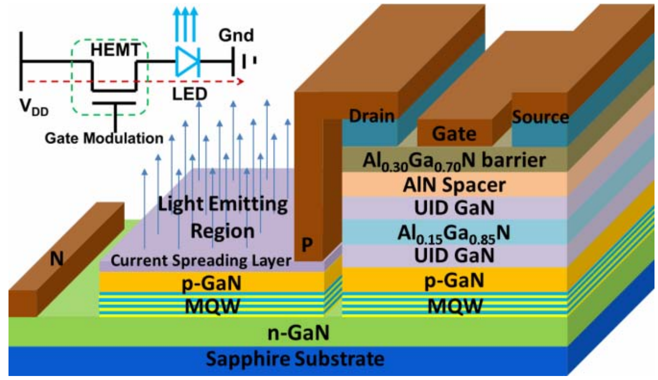

Fig. 2. Cross-sectional schematic of the finished HEMT-LED on sapphire substrate. The inset shows the equivalent circuit diagram of the device.

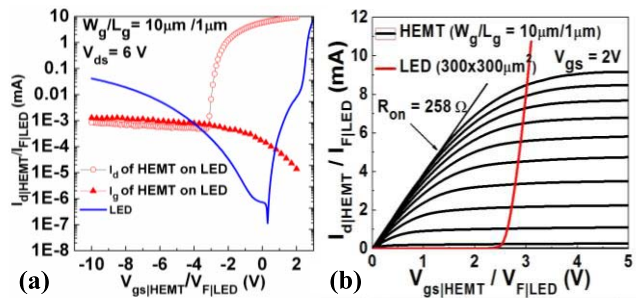

Fig. 3. (a) DC transfer characteristics and (b) output characteristics of the HEMT and LED.

grown on sapphire for comparison. The surface morphology of each sample was investigated by atomic force microscopy (AFM). Fig. 1 shows the surface morphology of the LED-epi before and after HEMT-epi growth with a scanned area of 5×5 μm^2. The root mean square (RMS) were 1.23 nm and 0.46 nm before and after HEMT-epi growth, respectively. The original p-type surface of the LED-epi was intentionally roughened for enhanced light extraction, as shown in Fig. 1(a). After HEMT-epi growth, the surface became smoother with the "pits" filled and transformed into some line-shape defects on the HEMT-epi surface [Fig. 1(b)]. These defects originated from the pits on the p-GaN surface may be responsible for the somewhat large leakage current of the HEMT devices. Further growth condition optimization and use of un-roughened LED wafers will be beneficial for even lower leakage current.

After epi-growth, the SiO_2 growth mask was completely removed by BOE. Mesas for the HEMTs were created using Cl_2-based inductively coupled plasma (ICP) selective etching with the LED regions protected by photoresist. Next, mesas of the LEDs were created using ICP with the HEMT region protected by photoresist. Source/drain ohmic contacts of the HEMTs were formed by e-beam evaporation of Ti/Al/Ni/Au and rapid thermal annealing (RTA) at 850 °C for 30 seconds in N_2 [4]. A current spreading layer (CSL) of the LED was formed by e-beam evaporation of Ni/Au and RTA at 570 °C for 5 minutes in an air atmosphere [9]. Then Ti/Al/Ti/Au metal layers were evaporated as p- and n-electrodes of the LEDs and patterned by lift-off. Subsequently, Ni/Au gate metallization of the HEMTs were realized. Currently, the electrical connection between the HEMT and LED was implemented by metal wire-bonding, which will be replaced by metal lines in future mask designs. Fig. 2 shows the cross-sectional schematic of the finished HEMT-LED.

III. Results and Discussion

Fig. 3 shows the DC characteristics of the HEMT-LED. The transfer curve of the HEMT and the I-V curve of the LED are plotted in Fig. 3(a). The AlGaN/GaN HEMT grown on LED has a peak transconductance (G_m) of 244 mS/mm at $V_{ds} = 2$ V. The OFF-state drain leakage current (I_{off}) is 7.5×10^{-4} mA (7.5×10^{-2} mA/mm) for the 10×1 μm^2 ($W_g \times L_g$) transistor. From the output curve ($I_d - V_d$) of the HEMT shown in Fig. 3(b), the maximum output current and R_{on} are 9.2 mA (920 mA/mm) and 258 Ω (2.58 Ω · mm), respectively. The forward voltage (V_F) of the 300×300 μm^2 LED is 3.1 V under an injection current of 10 mA.

The capacitance-voltage (C-V) characteristics of the HEMTs grown on LED-epi and HEMTs grown on the bare sapphire are compared. The C_{max} of both are around 2.77 nF, whereas, the C_{min} of the HEMT on LED is about 100 pF, almost two orders of magnitude higher than that (4.4 pF) of the HEMT on sapphire. Since the 2DEG shields the electric field at voltages higher than V_{th}, the capacitance of the HEMT structure dominates and C_{max} is kept at the same level. The C_{min} of HEMT on LED is much higher, which is caused by the relatively thin HEMT buffer layer (375 nm) and highly-conductive LED-layer underneath. C_{gb} and C_{bs} [see Fig. 4(a)] are capacitances related with the p-GaN body layer, which are significantly larger than C_{gs} in pinch-off condition. As a result, the C_{min} is determined by C_{gb} & C_{bs}, and thus the buffer thickness. On the other hand, since an additional leakage path exists between gate and drain via the p-GaN layer, a thicker buffer is preferred from the breakdown-voltage perspective. However, a much thicker buffer layer by prolonged growth time will definitely degrade the LED multiple quantum well (MQW) quality and increase V_F. This is a trade-off between the buffer thickness of HEMT and the performance of LED. As a result, a 375-nm thick buffer and a growth temperature lowered by 100 °C were utilized in our experiment to minimize the thermal budget on LEDs.

S-parameter measurements were carried out for the HEMT-LEDs in the frequency range of 0.1-39.1 GHz using an Agilent 8722ES network analyzer with HP4142B monitoring the DC-bias conditions. On-wafer open-circuit

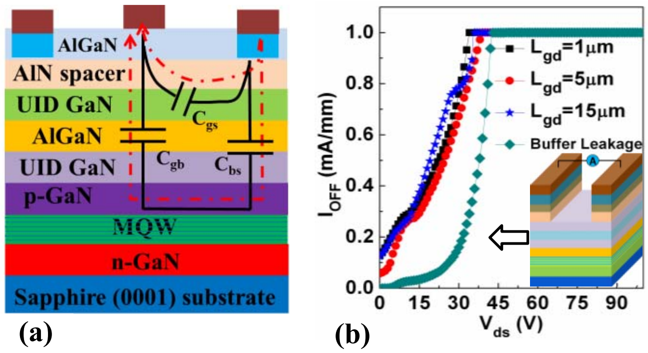

Fig. 4. (a) Cross-sectional view of the circular Schottky gate diode of HEMT-LED as used for C-V measurements. Dotted red lines represent the potential leakage paths. The C_{gs}, C_{gb}, and C_{bs} are gate-source, gate-body, and body-source capacitances, respectively. The spacing between gate and source is ∼15 μm. (b) BV_{off} of the HEMT-LED with varied source-drain spacing. The inset is the measured buffer structure.

pads were used to deembed the parasitic pad capacitances from the S-parameters. f_T and f_{MAX} were measured to be 7.4 and 7.5 GHz, respectively. The RF performance is limited by the large parasitic C_{gb} and C_{bs} [Fig. 4(a)] due to the thin buffer layer and conductive LED heterostructure underneath. The OFF-state breakdown voltage (BV_{off}) of the HEMT-LED with gate-drain spacing (L_{gd}) of 1 μm was 34 V [Fig. 4(b)]. The buffer breakdown voltage was also measured to be 42.5 V [inset in Fig. 4(b)]. The HEMT on LED showed lower breakdown voltage with larger leakage current than that of typical HEMTs grown on sapphire substrates. The breakdown voltage is limited mainly by two factors. The first one, as mentioned above, is the parasitic leakage channel of the p-GaN layer. The other one is the background carrier density of the UID-GaN grown at a lower temperature. For GaN HEMTs in dimmable LED lighting applications, the buffer leakage current of HEMTs should be minimized for low power consumption and better controllability of LEDs. Further optimization of the buffer growth condition is under investigation by adding intentional carbon-doping to compensate for the background carrier concentration. The results will be discussed in other reports. With control voltages V_{DD} and gate modulation voltages applied to the HEMT-LED, as shown in the circuit configuration of Fig. 2, the HEMT-LED emitted modulated blue light (470 nm) under modulated gate-bias. The forward current and light output power (LOP) versus the applied voltages are plotted in Fig. 5. In most of the applications, LEDs operate in the forward mode at voltages larger than the V_F.

Resistors are typically used in the driving circuits of LEDs to control the operating current and the light output. Power dissipated by the resistors is wasted and generates heat in the circuits [10]. The use of a HEMT with low R_{on} to convert the current control mode to gate voltage control mode will be more efficient. The HEMT ($W_g/L_g = 100/1$ μm) shows good controllability over the emission brightness of the LED via the injected current, demonstrating viability of the integrated device for a wide range of applications such as smart lighting, micro-displays, and VLCs. The integrated HEMT-LED shows much better modulation capability and smaller V_F than that reported recently in [7] and [8].

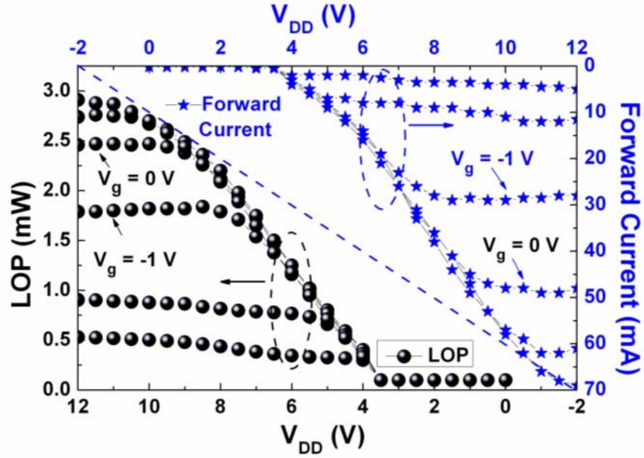

Fig. 5. HEMT-LED has modulated light emission under gate-bias and modulated I-V and LOP-V characteristics of the HEMT-LED.

IV. Conclusion

We have demonstrated a novel monolithic AlGaN/GaN HEMT-LED by MOCVD selective growth. The fabricated HEMT-LED exhibits a peak I_d and extrinsic G_m of 920 mA/mm and 244 mS/mm, respectively. The V_F of the LED under 10-mA injection current is 3.1 V. The blue light emission of the LED can be effectively modulated by the transistor gate voltages. The influence of thermal budget on the performance of the HEMTs and LEDs is investigated. Further optimization is needed in our next generation integrated devices.

Acknowledgment

The authors would like to thank X. Lu, K. M. Wong, W. C. Chong, K. H. Tam and H. X. Jiang for their fruitful discussions.

References

[1] S. Pimputkar, J. S. Speck, S. P. DenBaars, *et al.*, "Prospects for LED lighting," *Nature Photon.*, vol. 3, no. 4. pp. 180–182, 2009.

[2] U. K. Mishra, L. Shen, T. E. Kazior, *et al.*, "GaN-based RF power devices and amplifiers," *Proc. IEEE*, vol. 96, no. 2, pp. 287–305, Feb. 2008.

[3] Y. Uemoto, D. Shibata, M. Yanagihara, *et al.*, "8300V blocking voltage AlGaN/GaN power HFET with thick poly-AlN passivation," in *Proc. IEEE IEDM*, Dec. 2007, pp. 861–864.

[4] T. D. Huang, X. L. Zhu, and K. M. Lau, "Enhancement-mode AlN/GaN MOSHEMTs on Si substrate with regrown source/drain by MOCVD," *IEEE Electron Device Lett.*, vol. 33, no. 8, pp. 1123–1125, Aug. 2012.

[5] T. D. Huang, Z. J. Liu, X. L. Zhu, *et al.*, "DC and RF performance of gate-last AlN/GaN MOSHEMTs on Si with regrown source/drain," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3019–3024, Oct. 2013.

[6] H. Lee, D. Piedra, M. Sun, *et al.*, "3000-V 4.3-mΩ•cm^2InAlN/GaN MOSHEMTs with AlGaN back barrier," *IEEE Electron Device Lett.*, vol. 33, no. 7, pp. 982–984, Jul. 2012.

[7] F. G. Kalaitzakis, E. Iliopoulos, G. Konstantinidis, *et al.*, "Monolithic integration of nitride-based transistor with light emitting diode for sensing applications," *Microelectron. Eng.*, vol. 90, pp. 33–36, Feb. 2012.

[8] Z. Li, J. Waldron, T. Detchprohm, *et al.*, "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," *Appl. Phys. Lett.*, vol. 102, no. 19, p. 192107, 2013.

[9] K. M. Lau, K. M. Wong, X. B. Zou, *et al.*, "Performance improvement of GaN-based light-emitting diodes grown on patterned Si substrate transferred to copper," *Opt. Exp.*, vo1. 19, no. S4, pp. A956–A961, 2011.

[10] W. Y. Leung, T. Y. Man, and M. Chan, "A high-power-LED driver with power-efficient LED-current sensing circuit," in *Proc. Solid-State Circuits Conf.*, Sep. 2008, pp. 354–357.