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High temperature characteristics of monolithically integrated LED and MOS-channel HEMT in GaN using selective epi removal

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In this paper, we have investigated the high temperature characteristics of monolithically integrated LED and MOS-channel HEMT in GaN. The monolithically integrated LED/MOSC-HEMT was implemented by using a selective epi removal approach. The temperature dependence of optical and electrical characteristics of the integrated LED is found to be comparable to that of discrete GaN based LEDs. On-resistance of the MOSC-HEMT shows gradual increase with temperature (~1.6× increase from 25 °C to 225 °C) whereas LED LOP shows rapid decrease with temperature (~6× decrease from 25 °C to 225 °C). Light output of the integrated LED is modulated by the MOSC-HEMT gate bias up to 225 °C.

1 Introduction In recent years, the realization of high efficiency and low cost GaN based light emitting diodes (LEDs) for general purpose illumination has sparked interest in the development of 'value-added' lighting systems which are not possible with conventional lighting sources. Such value-added lighting systems aim to incorporate additional features into the lighting fixture such as visible light communication (VLC) and spectral tunability [1–4]. The data transfer rate of such VLC systems is currently limited by the bandwidth of the commercial LED modules which is limited to less than 50 MHz [2, 3]. Lighting modules require dedicated driver circuits which incorporate AC–DC converters, current sources and pulse width modulation control [5]. GaN based field effect transistors (FET) such as high electron mobility transistors (HEMTs) and metal–oxide–semiconductor (MOS) channel HEMTs have shown outstanding properties in terms of achieving high breakdown voltage, low on-resistance and high switching frequency [6–8]. Implementation of LED driver circuits using GaN based FETs can potentially increase their efficiency and improve switching frequencies. Further, monolithic integration of power, logic and LED components on a single chip can improve reliability and reduce cost of lighting modules and serve as a technology platform for the development of light emitting power integrated circuits (LEPICs) [9].

Previously, we have demonstrated monolithic integration of GaN LEDs and MOSC-HEMTs using a selective epi removal (SER) approach [10]. In this approach, the LED epilayer was grown on HEMT epi on sapphire substrate. The LED epi was selectively removed by etching to reveal the HEMT area. A MOSC-HEMT (enhancement mode) was fabricated in the HEMT area and serially connected with the LED. The light output of LED was fully modulated by applied gate bias on the MOSC-HEMT. Subsequently, other groups have demonstrated monolithic integration using both selective epi growth (SEG) [11] and selective epi removal [12].

It is also desirable to increase the operating temperature of electronic and optical devices which will simplify the design of heatsinks and thermal management of modules. This can lead to a large reduction in cost from lower requirements on packaging of the module. The fabrication of monolithically integrated HEMT-LED devices involves a number of additional processing steps compared to discrete LEDs/HEMTs such as selective epi removal by ICP-RIE and high temperature annealing processes to get optimal MOS channel properties which may affect the performance of integrated devices. Therefore it is important to quantify the performance of integrated devices as compared to discrete devices, especially at high temperatures. In this paper, we present a study of the high temperature performance of monolithically integrated LED/MOSC-HEMT device implemented by SER. The performance of integrated devices has been compared to that of discrete LEDs and MOSC-HEMTs.

2 Device fabrication Figure 1 shows the fabrication process of the monolithically integrated GaN LED/MOSC-HEMT device using selective epi removal (SER) approach. The starting HEMT epitaxial material was obtained from a commercial vendor which consisted of 20 nm unintentionally doped GaN capping layer, grown on 20 nm $Al_{0.23}Ga_{0.77}N$ barrier, grown on top of GaN buffer layer sapphire substrate. The LED epi was grown in-house by metal organic chemical vapour deposition (MOCVD). The LED epilayers consisted of 500 nm n^+ GaN, 90 nm unintentionally doped (UID) GaN, 180 nm of $In_{0.08}Ga_{0.92}N$/GaN multiple quantum well (MQW) structure, 20 nm of p^+ AlGaN electron blocking layer (EBL) and 130 nm of p^+ GaN. After epi growth, the LED epi was selectively etched in the HEMT areas to the n^+ GaN layer by using chlorine based ICP-RIE. This was followed by etching of 1.5 μm deep trenches around the HEMT areas for device isolation. After mesa etch, the remaining n^+ GaN layer on the HEMT areas was etched using ICP-RIE and the etching was stopped within 20 nm UID GaN cap. The 20 nm GaN cap serves a dual purpose of providing extra tolerance for the etch stop point as well as enhancing the breakdown voltage of the MOSC-HEMT [8]. This was followed by deposition of 500 nm SiO_2 using PECVD, densification by annealing in nitrogen ambient and patterning as field plate oxide. Subsequently, the submicron recess channel was patterned using electron beam lithography and etched by ICP-RIE. This was followed by treatment in tetra-methyl-ammonium-hydroxide (TMAH) at 85 °C for 15 min to remove dry etch damage to the MOS channel region [13, 14]. The sample was then thoroughly cleaned by RCA clean, Caro's clean and finally dipped in HCl solution to remove any native gallium oxide layer. A total of 50 nm SiO_2 was deposited by ALD as the gate dielectric followed by post-oxidation annealing in N_2 ambient at 1000 °C for 30 min. Polysilicon was then deposited using low pressure chemical vapor deposition (LPCVD), doped by $POCl_3$ and patterned as the gate electrode. A total of 1000 nm SiO_2 was then deposited using PECVD as the inter-layer dielectric (ILD). Ti/Al/Ni/Au was evaporated and annealed by rapid thermal annealing (RTA) at 800 °C for 1 min in N_2 to form ohmic

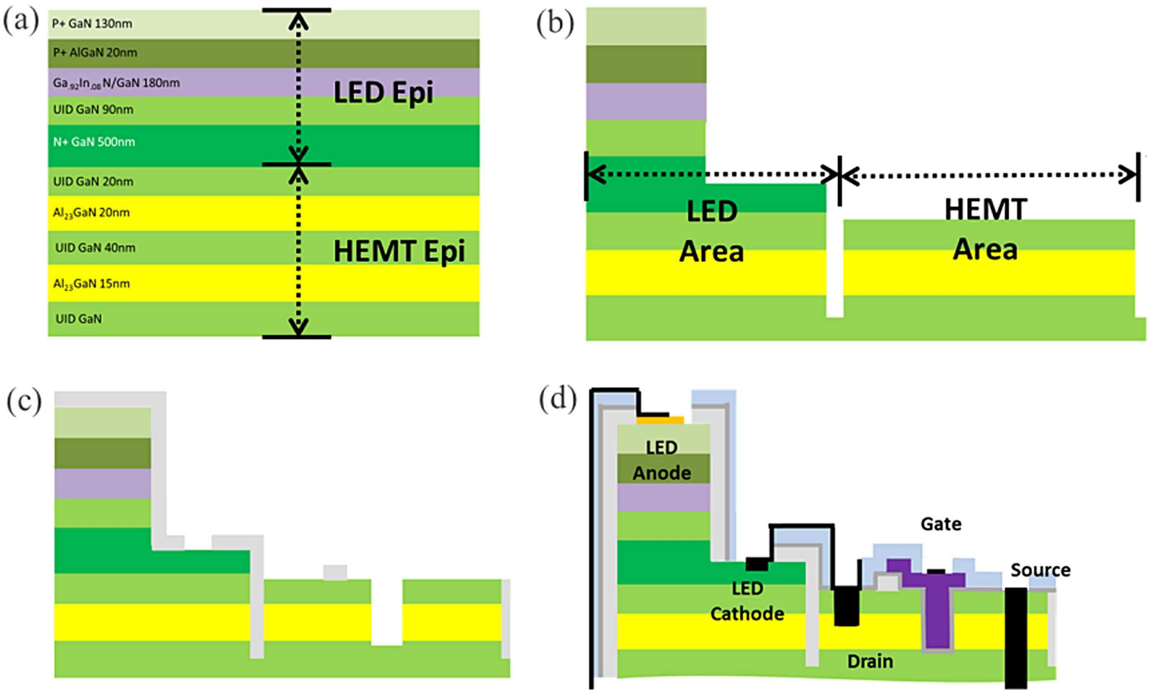

Figure 1 Schematic showing key fabrication process flow of monolithically integrated LED and MOSC-HEMT by SER (a) epi growth, (b) ICP-RIE etch to define LED and HEMT mesas, (c) e-beam lithography for submicron recess channel and (d) finished device after metallization.

contact with the MOSC-HEMT source/drain and the cathode contact of the LED. Thin Ni/Au was evaporated and annealed by RTA at 500 °C for 1 min in O_2 to form transparent ohmic contact with p^+ GaN (LED anode). Finally, Ti (200 nm)/Al (500 nm) was evaporated and patterned as the pad metal as well as the interconnect metal between the LED cathode and MOSC-HEMT drain contact.

3 Device characterization

3.1 Integrated LED characterization Figure 2(a) shows the *L–I–V* characteristic of an integrated LED with area of 300 µm × 300 µm. The integrated LED shows good linearity between light output power (LOP) and injection current. The turn-on voltage of the LED is 3.3 V. The electroluminescence (EL) emission spectrum of the LED is shown in Fig. 2(b) at different injection current levels. The peak emission wavelength is about 454 nm.

The performance of the integrated LED at elevated temperatures has been characterized in detail. All measurements were taken under pulsed conditions to minimize self-heating of the device. The area of the LED is 300 µm × 300 µm. Figure 3 shows the LOP of the integrated LED as a function of ambient temperature (normalized to LOP at room temperature). At 200 °C, LOP is about 16% of that at room temperature. This degradation in light output has also been observed for conventional InGaN/GaN blue LEDs [15], and has been attributed to increasing non-radiative recombination and carrier leakage out of the quantum wells. The EL emission spectrum measured at elevated temperatures is shown in Fig. 4(a) and the variation of peak emission wavelength with temperature is shown in Fig. 4(b). A redshift of 7 nm is seen in the peak wavelength from room temperature to 200 °C. The increase in emission wavelength is consistent with the decrease in bandgap of the active region with increasing temperature as described by the Varshni relationship. Redshift of similar magnitude (5–10 nm) over this range of operating temperatures has been measured by other groups on discrete InGaN/GaN blue LEDs [16, 17]. The above results indicate that the performance degradation of integrated LEDs at elevated temperatures is comparable to that of discrete LEDs.

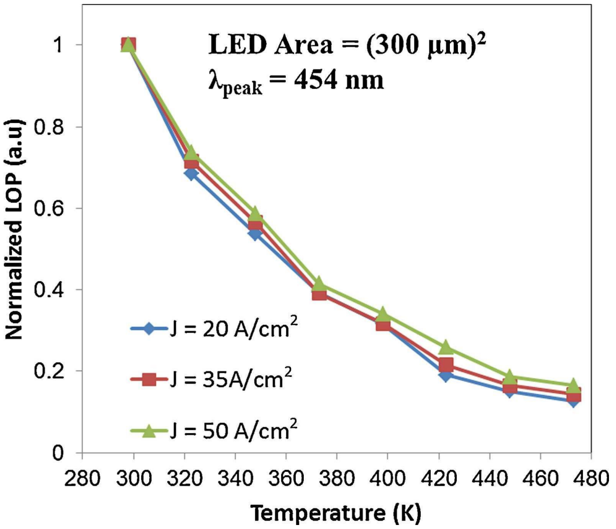

Figure 3 Normalized light output power of integrated LED as a function of ambient temperature at different injection current densities.

3.2 MOS-channel HEMT characterization Next the performance of the integrated MOSC-HEMT device was characterized at elevated temperature. Figure 5 shows the output (I_D–V_{DS}) characteristics of the integrated MOSC-HEMT with channel length (L_{ch}) of 0.3 µm and width of 800 µm at different temperatures. The device has a threshold voltage of 3 V and on-resistance of 110 Ω mm at room temperature. The on-resistance increased by 56% from room temperature to 225 °C (Fig. 5(d)). The on-resistance of integrated MOSC-HEMTs is higher than that

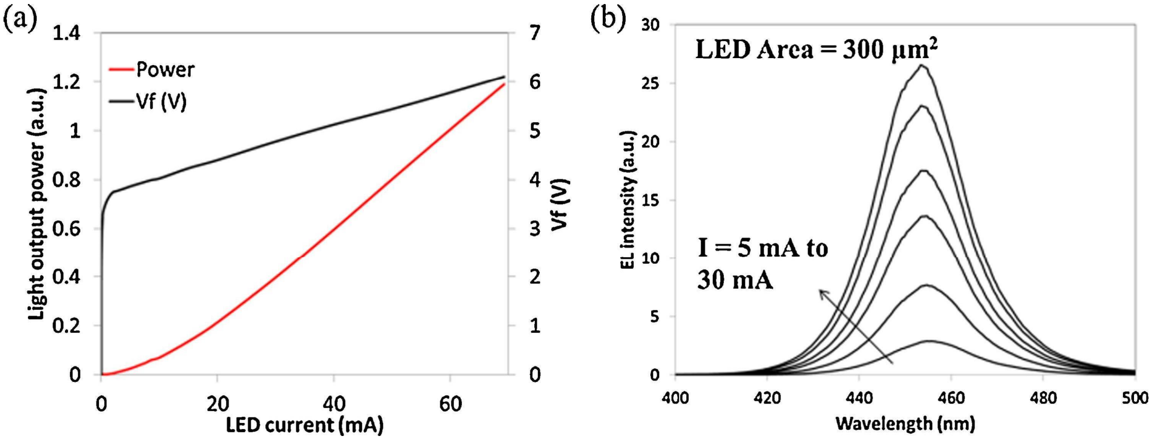

Figure 2 (a) *L–I–V* characteristic and (b) electroluminescence spectrum of the integrated LED.