Heterogeneous Integration of 20x10 µm Blue Micro-LEDs/Pixels on GaN HEMTs for Visible Light Communication

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ABSTRACT

The development of next-generation communication networks aims to provide faster and more reliable solutions in a small form factor. Visible light communication (VLC) has emerged as a promising complementary technology to traditional radio frequency wireless communication due to its exceptional efficiency, high modulation speeds, and freedom from the congested radio spectrum. Recent advancements have focused on gallium nitride (GaN)-based micro-light-emitting diodes (microLEDs) for VLC. However, these microLEDs typically require high injection current densities and high-frequency operation, necessitating the use of independent drivers and resulting in bulky systems. This study presents an innovative approach to overcome these limitations by heterogeneously integrating of 20x10 μm^2 blue microLEDs using transfer printing onto a GaN-based high electron mobility transistor (HEMT) target wafer grown on silicon carbide (SiC) substrate. This integration allows for a compact, single-chip platform where the emission from a single microLED is modulated by tuning the gate voltage of its GaN HEMT. The resulting on-chip system achieves with a modulation bandwidth of 100 MHz, maintaining a small form factor. Our findings suggest that this approach holds significant promise for the development of future large-scale VLC systems on a single chip, offering broad application prospects.

Keywords: Transfer printing, microLEDs, GaN HEMTs, heterogeneous integration, on-chip photonics, visible light communication

1. INTRODUCTION

The rapid increase in data traffic across communication networks and the growing need for higher data transmission rates have led to the exploration of alternative communication technologies. Visible Light Communication (VLC) has emerged as a promising solution, offering significant advantages over traditional radio frequency (RF) communication, such as the availability of an untapped, wide bandwidth in the optical spectrum and immunity to RF interference. VLC can potentially support data rates well beyond what is achievable with RF technologies, especially in high-density environments like indoor networking, vehicular communication, and the Internet of Things (IoT).

Among the various optical devices for VLC, microLEDs, especially those based on Gallium Nitride (GaN), have shown great potential due to their high efficiency, high brightness, and fast modulation capabilities [1,2]. GaN-based microLEDs can support high current densities and fast switching speeds, making them suitable for short-range VLC applications. However, current GaN microLED-based systems face challenges such as the need for high injection current densities to achieve high-speed modulation, as well as the reliance on external, bulky drivers to operate these devices at high frequencies. These issues limit the miniaturization and integration potential of such systems.

GaN HEMTs are well-known for their high-speed operation and low power consumption, making them ideal candidates for driving optical devices such as microLEDs [3]. By modulating the gate voltage of a GaN HEMT, it is possible to control the current through the microLED, enabling high-frequency modulation without the need for external drivers. However, integrating GaN microLEDs and GaN HEMTs on a single chip has remained challenging due to differences in the material properties and fabrication processes.

In this study, we propose a novel approach to integrate GaN-based microLEDs with GaN HEMTs on a SiC substrate using transfer printing [1]. This integration allows for a compact, single-chip system in which the light emission of the microLED is modulated by the gate voltage of the GaN HEMT. The resulting device achieves a modulation bandwidth of 100 MHz, offering a potential pathway toward scalable and energy-efficient VLC systems.

2. MATERIALS AND METHODS

2.1 GaN Micro-LED Fabrication

The fabrication of GaN-on-Si microLEDs began with the growth of the devices on (111)-oriented silicon substrates using metal-organic chemical vapor deposition (MOCVD). The process involved the deposition of a GaN buffer layer followed by an InGaN active region that forms the light-emitting quantum wells. After the epitaxial growth, the microLEDs were patterned into 20 µm × 10 µm (emission area) using photolithography, and their structure was defined through inductively coupled plasma (ICP) etching. To facilitate electrical contact, Ni/Ag/Ni/Au layers were evaporated as the p-metal and reflective layer. The mesa was etched further with ICP, and n-metal contacts were formed by evaporating Ti/Al/Ti/Au. A silicon dioxide (SiO_2) layer was then deposited over the entire structure via plasma-enhanced chemical vapor deposition (PECVD), followed by the opening of contact areas for both p- and n-contacts. The p-bond pad metal was formed by evaporating titanium gold (Ti/Au) as given in Figure 1. To ensure the microLEDs remained securely attached during subsequent release, a silicon nitride (SiN) tether was used to hold the devices in place.

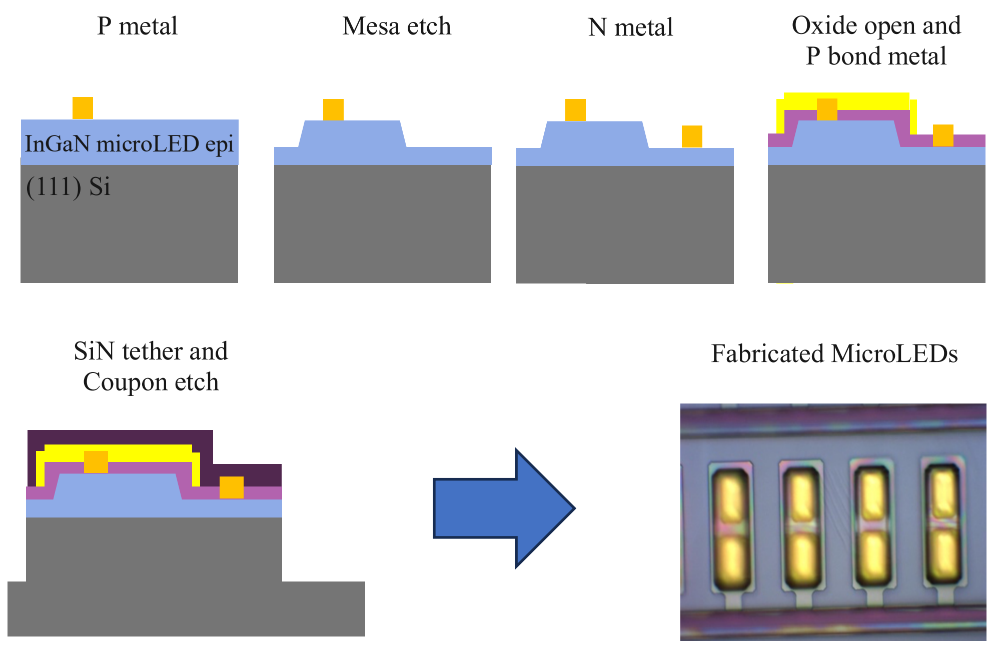

Figure 1: Schematic of the fabrication process for GaN-on-Si microLEDs.

2.2 GaN HEMT Fabrication

The fabrication of a HEMT on a SiC substrate involves a series of well-defined steps to ensure optimal performance and reliability. GaN HEMTs were grown on a high-quality SiC substrate using Metal-Organic Chemical Vapor Deposition (MOCVD). The device structure consisted of a GaN buffer layer, followed by an AlGaN/GaN heterostructure, which forms the high-electron-mobility channel. Starting with a 15 mm × 15 mm sample, the source and drain (S/D) regions were defined using photolithography and Inductively Coupled Plasma (ICP) etching, with source/drain metal contacts deposited using a multi-layer evaporative process of Ti/Al/Ni/Au. The metal stack was then annealed to ensure proper contact formation, minimizing contact resistance between the metal and the semiconductor. A mesa isolation was carried out to define the active region of the device, isolating the gate region from the source and drain. Subsequently, a gate metal stack consisting of Ni/Au/Ni was evaporated to form the gate contact, establishing a stable Schottky barrier at the gate interface (Figure 2).

These steps are essential for the fabrication of GaN/AlGaN HEMTs on SiC substrates, where the high thermal conductivity of SiC facilitates effective heat dissipation, enabling the device to operate efficiently at high power levels and frequencies. The combination of these controlled fabrication steps ensures the reliable performance of GaN HEMTs for applications requiring high-speed, high-power operation.

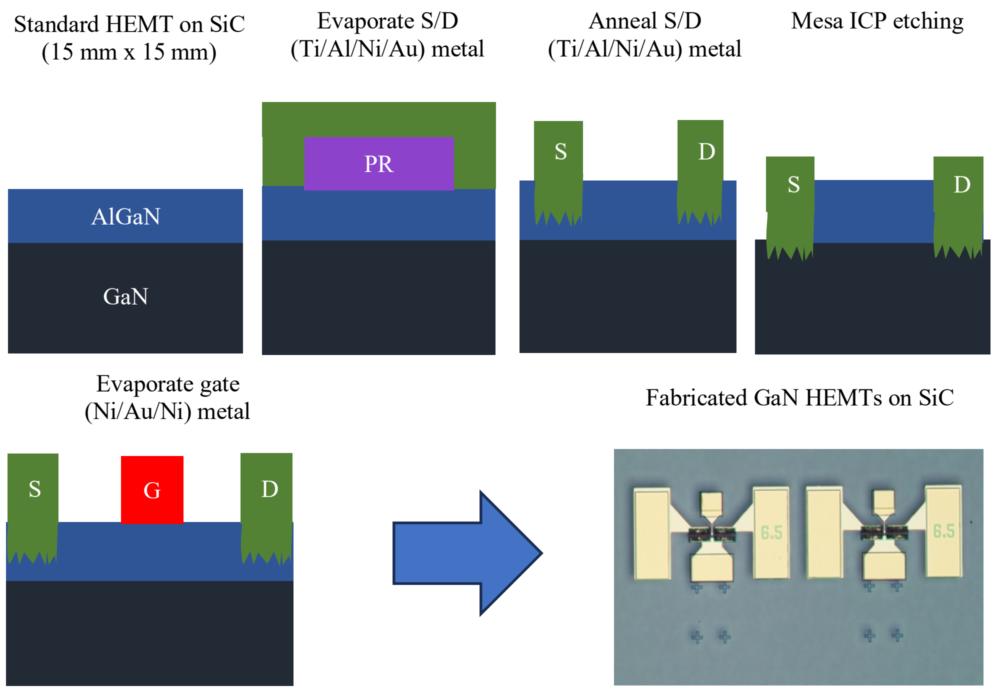

Figure 2. Schematic of the fabrication process for GaN/AlGaN HEMTs on SiC substrates.

2.3 Heterogeneous Integration Enabled by Transfer Printing

The release and transfer of microLEDs from a silicon substrate were successfully achieved through a controlled and precise process involving selective etching with tetramethylammonium hydroxide (TMAH) solution. A 5% concentration of TMAH was used at a temperature of 70°C to induce anisotropic etching of (111)-oriented silicon. The etching process exhibited a significantly faster rate along the <1–10> direction compared to the etching along the (111) planes. This directional etching behavior enabled the removal of a thin silicon layer beneath the GaN (gallium nitride) epilayer, effectively undercutting the microLEDs while preserving the integrity of the underlying SiN-based anchor points. The SiN anchors served as stable tethers, keeping the microLEDs securely attached to the silicon substrate throughout the process [4,5].

The etching and release of the microLEDs were completed within 12 minutes, a result of efficient and selective etching process. The SiN tether, which was specifically designed to anchor the microLEDs during the etching process, provided necessary mechanical stability and ensured that the microLEDs remained securely attached, without any risk of detachment or structural damage (Figure 3a, b). As a result, the microLEDs were released intact, with no visible degradation in quality or performance, thanks to the preservation of the SiN anchors.

Once the microLEDs were fully undercut and released from the silicon substrate, they were carefully transferred to a polydimethylsiloxane (PDMS) stamp. PDMS, due to its flexible and conformal properties, proved ideal for transferring delicate micro-scale devices like microLEDs. The conformal nature of the PDMS stamp allowed for precise handling, alignment, and positioning of the microLEDs without applying excessive mechanical stress. During the transfer process, mild pressure was applied to lift the microLEDs from the silicon substrate, further minimizing any risk of mechanical deformation or damage.

Following the successful transfer of the microLEDs onto the PDMS stamp, the microLEDs were precisely aligned and transferred onto a HEMT structure, which was fabricated on a SiC substrate (Figure 3c, d). This step demonstrated the compatibility of the microLEDs with advanced semiconductor platforms, opening up opportunities for integration with high-speed and high-performance optoelectronic devices.

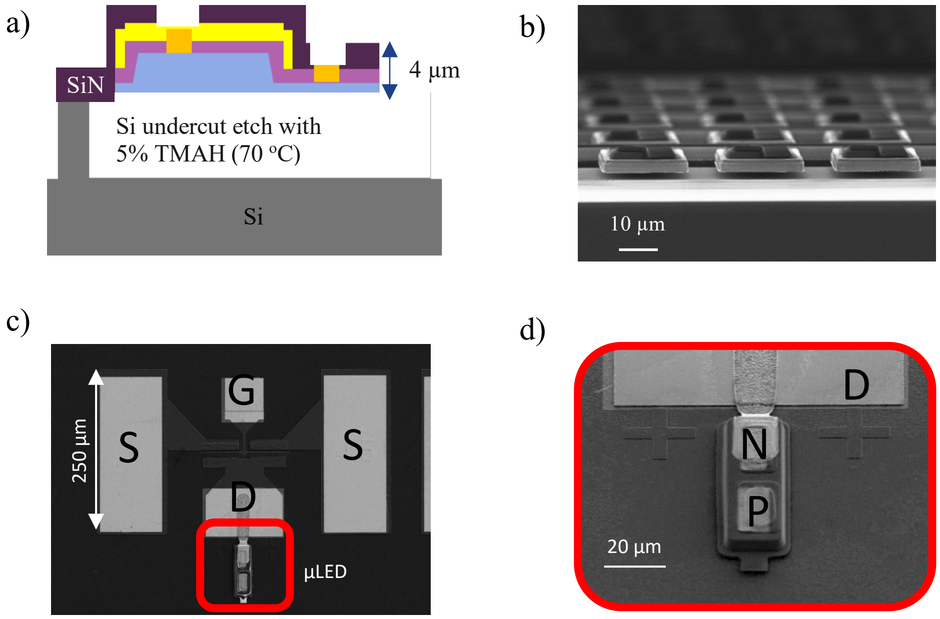

Figure 3. MicroLED Release, Transfer, and Integration Process. (a) Schematic depicting the undercutting of microLEDs from the silicon substrate via selective etching using a tetramethylammonium hydroxide (TMAH) solution. (b) Image showing the microLEDs still securely attached to the SiN anchors following the etching process. (c) Transfer of the microLEDs onto a GaN-based high electron mobility transistor (HEMT) structure on a SiC substrate. (d) High-magnification view of the final transfer of the microLEDs onto the GaN-based HEMT structure on the SiC substrate.

3. RESULTS AND DISCUSSION

3.1 Experimental Setup

The measurement setup, as shown in Figure 4, represents an experimental arrangement designed to characterize a transfer-printed flip-chip microLED array (20x10 µm) integrated onto a GaN HEMT target. The primary objective is to study the modulation behavior of the microLED in response to the high-speed electrical control provided by the GaN HEMT, all within a single-chip integration. The GaN HEMT, acting as a high-speed transistor, plays a crucial role in modulating the current supplied to the microLED, thereby enabling precise control over its optical output.

The microLED array is integrated onto a GaN HEMT that is grown on a SiC substrate, which serves as a common platform. The SiC substrate ensures efficient power transfer and minimizes parasitic losses, enhancing the overall performance of the device.

To enable precise control over the electrical characteristics of the GaN HEMT, the gate voltage is regulated by a Keithley sourcemeter. This adjustment allows fine-tuning of the transistor's threshold voltage, thus modulating the current flowing through the microLED. A second Keithley sourcemeter is used to supply the drive current to the microLED, ensuring a stable and accurate current supply necessary for optimal light emission. The use of two sourcemeters allows independent control of both the GaN HEMT's switching behavior and the microLED’s operating current, making it possible to isolate and study the interactions between these components.

For evaluating the dynamic frequency response of the integrated microLED, a Vector Network Analyzer (VNA) was included in the setup. The VNA was essential for measuring the impedance and frequency-dependent behavior of the device, providing crucial insights into the modulation speed and overall performance of the microLED when driven by the

GaN HEMT. The VNA's ability to analyze the microLED's response to varying frequencies allows an assessment of its bandwidth, which is particularly important for high-speed optical modulation applications.

High-speed whisker probes were used to interface with the devices under test. These probes provided low-resistance electrical contact, minimizing signal loss and enabling dynamic testing of both the microLED and the GaN HEMT. The Gate-Source (GS) probe was specifically connected to the gate terminal of the GaN HEMT, allowing real-time monitoring of the gate voltage and the transistor's switching behavior. This connection was essential for assessing the electrical characteristics of the GaN HEMT, such as its threshold voltage, on/off switching speed, and modulation efficiency (Figure 4a).

A high-speed photodiode was positioned at the output to detect the optical emissions from the microLED. This photodiode allows for real-time analysis of the light emitted by the microLED during operation, providing valuable data on its modulation characteristics (Figure 4b). By measuring both the intensity and temporal response of the emitted light in conjunction with the electrical control from the GaN HEMT, the setup offers understanding of the interplay between electrical modulation and optical output.

Overall, this setup provided a platform for exploring the performance of microLEDs in high-speed modulation applications and enables in-depth analysis of the interaction between the optical and electrical domains in integrated microLED-on-GaN HEMT systems.

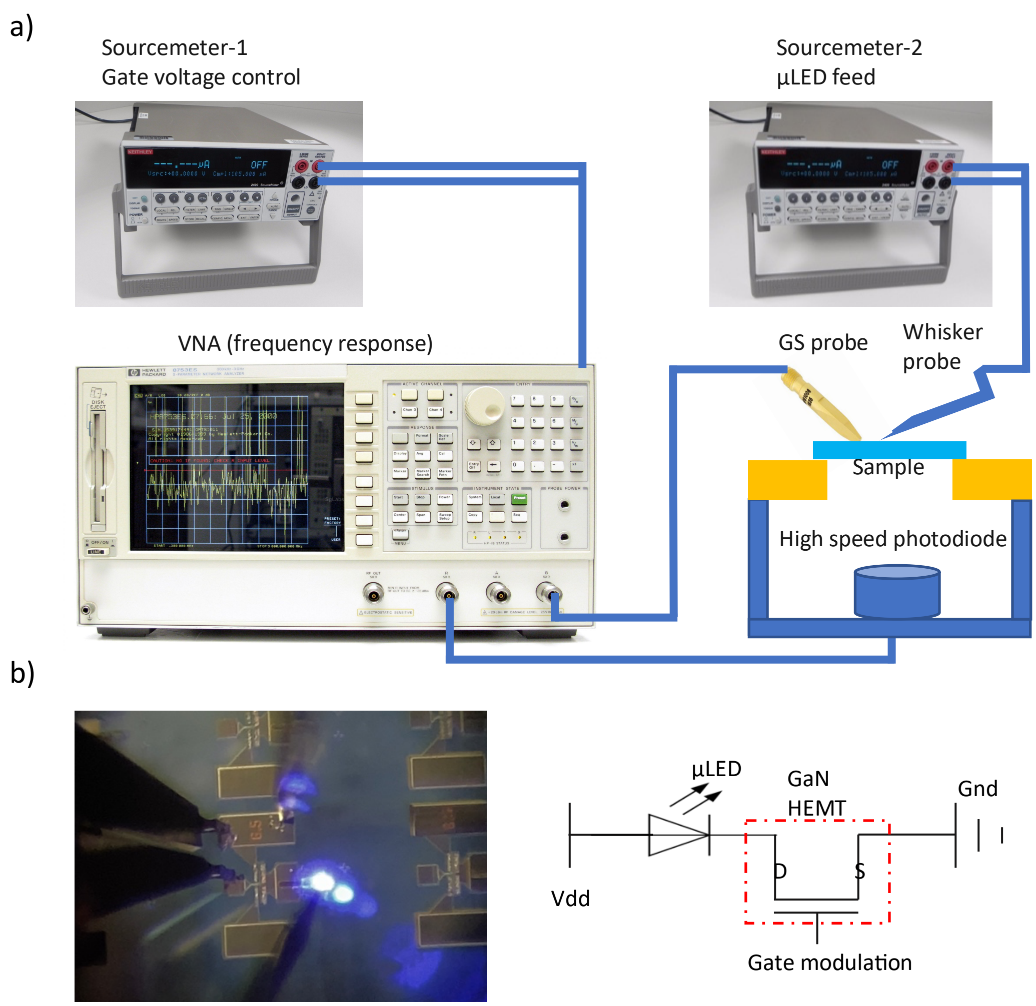

Figure 4. a) Experimental setup. b) Modulation of microLED by GaN HEMT during operation.

3.2 System-on-Chip (SoC) Testing

The experimental data presented offers a comprehensive evaluation of the electro-optical and frequency characteristics of transfer-printed microLEDs integrated with GaN HEMTs on a single chip platform.

Figure 5a provides the light-current-voltage (L-I-V) characteristics of a 20x10 μm^2 microLED, highlighting a turn-on voltage of 2.6 V and a measured optical power of 0.24 mW at a current density of 250 A/cm², indicating efficient performance at high current levels. Figure 5b demonstrates the drain-source current (I_{ds}) as a function of supply voltage (V_{dd}) for various gate voltages, revealing that I_{ds} reaches zero at a gate voltage of -4V, effectively switching the device off. This behavior is further substantiated in Figure 5c, where electroluminescence (EL) intensity is shown to decrease at gate voltages beyond -4.2V, confirming the device's transition to the "off" state. In Figure 5d, the power (in dB) versus frequency (log scale) for different current levels (2 mA, 3 mA, and 4 mA) at a gate voltage of -3.2V provides insights into the device's frequency response. The measured 3 dB modulation bandwidth at 100 MHz demonstrates the dynamic performance of the microLED integrated with the GaN HEMT, indicating that the single-chip platform is capable of moderate-frequency modulation. These findings underscore the device's electro-optical efficiency, gate-controlled switching behavior, and dynamic response, offering an understanding of its operational limits and performance under varying conditions.

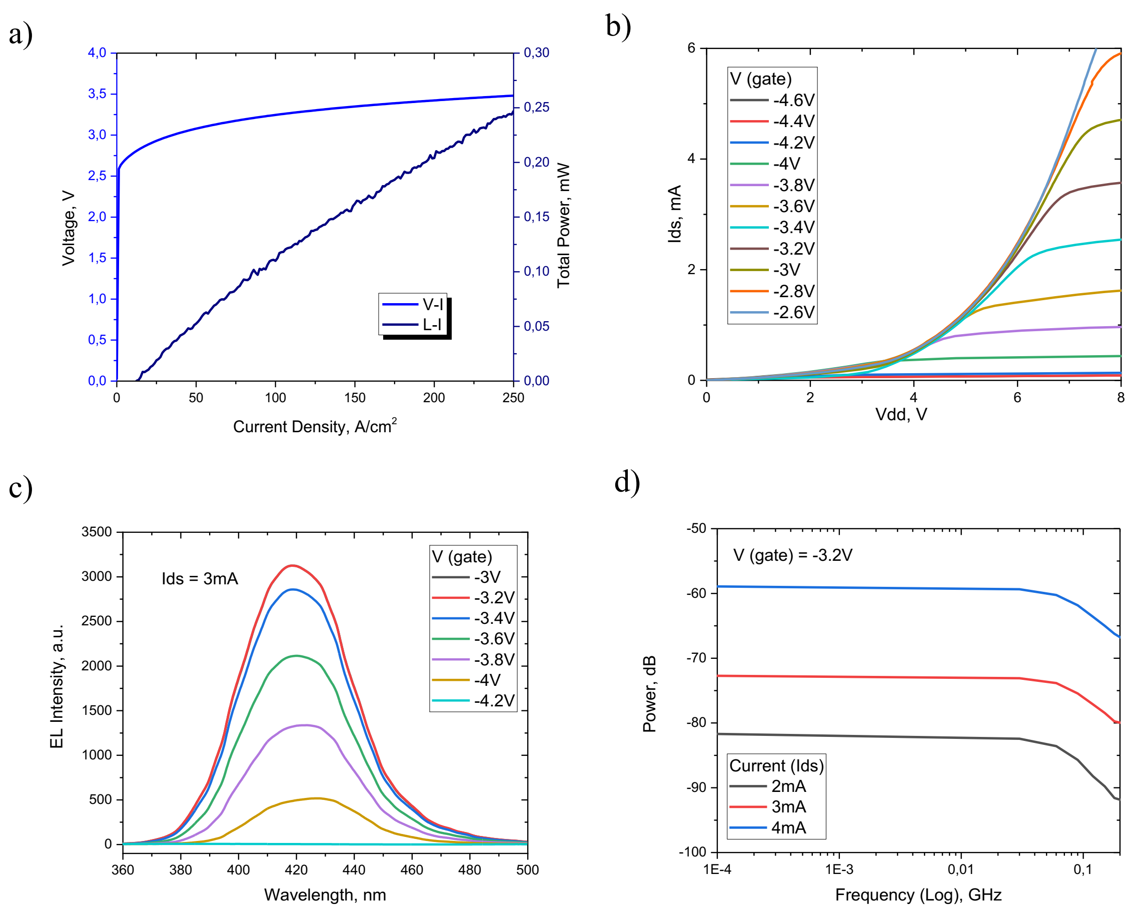

Figure 5. Electro-optical and frequency characteristics of transfer-printed microLEDs integrated with GaN HEMTs on a single-chip platform. (a) L-I-V characteristics of a 20x10 μm^2 microLED. (b) Drain-source current (I_{ds}) as a function of supply voltage (V_{dd}) for various gate voltages, with Ids reaching zero at a gate voltage of -4V. (c) EL intensity versus gate voltage, indicating a decrease in EL intensity as the gate voltage exceeds -4.2 V, confirming the "off" state. (d) Power versus frequency (log scale) for different current levels (2 mA, 3 mA, and 4 mA) at a gate voltage of -3.2V, showing a 3 dB modulation bandwidth of 100 MHz, demonstrating the dynamic frequency response of the integrated microLED-GaN HEMT device.

4. CONCLUSION

The integration of GaN-based microLEDs and GaN HEMTs on a SiC substrate represents a significant advancement in optoelectronic systems, with broad implications for high-frequency, high-speed applications such as optical interconnects and next-generation display technologies. These integrated devices are critical for scenarios that demand both high optical efficiency and rapid response times. This single-chip platform enhances device performance by combining the advantages of microLEDs for optical emission with GaN HEMTs for precise electronic control, resulting in a compact, energy-efficient system.

A key achievement of this work is the ability to modulate the microLED's light emission using the gate voltage of the GaN HEMT, eliminating the need for external drivers. This integration simplifies system architecture, reduces power consumption, and demonstrates the potential of combining photonic and transistor-based technologies on a single chip. Experimental results, including LIV characteristics of the microLED, gate voltage modulation of the GaN HEMT, and a 3 dB modulation bandwidth of 100 MHz, showcase the platform's versatility and low-power operation potential.

Although a modulation bandwidth of 100 MHz was successfully demonstrated, the primary objective was to develop a functional SoC. Future advancements will focus on integrating high-performance GaN HEMTs to enable modulation speeds extending into the gigahertz range and beyond. With further optimization of the device architecture and the incorporation of advanced GaN HEMTs, substantial improvements in performance are anticipated.

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