Array of GaN micro-LED chips and monocrystal Si CMOS pixel circuit chips mounted on flexible substrate

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ABSTRACT

This paper proposes new micro-LED display fabrication processes. GaN micro-LED and monocrystal Si CMOS chips with pixel circuit to drive LED are mounted in an array shape on a flexible substrate using laser lift-off processes. The emission intensity of LED could be successfully controlled by pulse-width modulation.

1. INTRODUCTION

Micro-light emitting diode (LED) display using inorganic GaN LED has received much attention because of its outstanding features such as high contrast, high speed, high dynamic range with long lifetime [1]. Realizing high-speed mass transfer of micro-LED chips from the LED wafer to the display backplane substrate with high-yield is a challenging issue to commercialize micro-LED [2]. To transfer GaN LED from the sapphire wafer to another substrate, laser lift-off (LLO) has been extensively used, where GaN LED chips can be removed from the sapphire substrate resulting from a rapid thermal decomposition of GaN which yields metallic Ga and N_2, by laser irradiation [3]. Using this technique, we have proposed high-yield mass transfer method based on the laser lift off technology [4,5].

For current liquid crystal displays (LCDs) and organic LED displays, low-temperature poly-Si (LPTS) thin film transistors (TFTs) as well as IGZO TFTs were employed for active-matrix pixel circuits fabricated on the display backplane substrate. It is generally recognized that, monocrystal Si complementary metal-oxide-semiconductor (CMOS) technology based on mature technology using high-quality Si wafer, exhibits superior electrical properties as compared to those of LTPS TFTs as well as IGZO TFTs, i.e., monocrystal Si CMOS field effect transistors (FETs) exhibit high mobility, low subthreshold swing with good stability against various electrical stresses with lower variation in these characteristics between devices. Therefore, especially for micro display applications, integration of GaN LED and monocrystal Si CMOS circuit are expensively studied by direct wafer bonding processes as well as the monolithic device fabrications using GaN on Si wafers or Si on GaN wafers [6]. In addition, to realize high-performance electronic system on flexible substrate, transfer processes of monocrystal Si CMOS chip to polyethylene terephthalate substrate using Meniscus force ware proposed [7]. Based on the above background, we are recently considering the possibility that the mass transfer processes can be applied to not only the micro-LED chip but also monocrystal Si CMOS chip with the active-matrix pixel circuit to realize high-performance micro-LED display, as shown in Fig. 1. Using this method, it is also expected that display modules can be flexibly manufactured depending on desired display size and resolution which is adequate to the small-lot production of many products.

Pixel circuits of Si CMOS chip is designed to drive LED by pulse-width modulation (PWM), because PWM can suppress wavelength shifts generated depending on the LED current density [8]. It is also considered that Si CMOS with high current drivability is adequate to apply PWM.

In this study, both micro-GaN LED chips and monocrystal Si CMOS chips with pixel circuits were implemented in an array shape to the flexible printed circuits (FPC) polyimide substrate using LLO, and the emission of GaN LED was controlled by PWM.

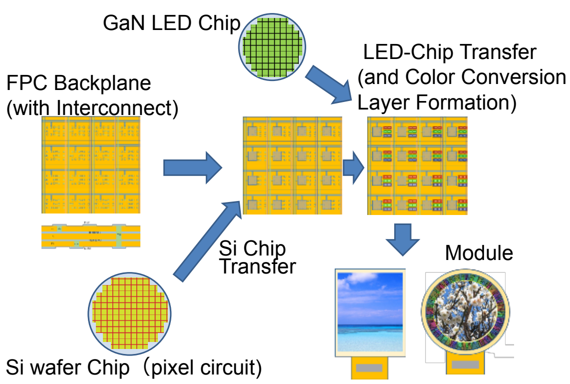

Fig. 1: Proposed micro-LED fabrication processes introducing Si chips with pixel circuits.

2. ARRAY FABRICATION RESULTS

2.1 GaN Micro-LED Chip

Fig. 2(a) shows the micro-LEDs used in this study, which were manufactured on 4-inch sapphire wafer by Nitride Semiconductor Co., Ltd. The LED chip size was 16 x 48 um, and an electrode size of both anode and cathode was 17um × 12 um. The LED with an emission wavelength of UV range (385 nm) was used, because we propose full color-converted micro-LED display using UV micro-LED and three types of color conversion layer (CCL) including patterned fluorescent materials to excite RGB (red, green, and blue) emissions [4,5]. Note that this paper focused on fabrication processes of implementation of LED and Si chips to the flexible substrate and PWM drive of the UV-LED. Fabrications of CCL layer will be discussed elsewhere. Figs. 2(b) and 2(c) shows typical current – voltage (I_F – V_F) and electroluminescence intensity – I_F characteristics of GaN LED, respectively. The I_F range between a few μA to 20 μA was used to drive GaN LED in this study.

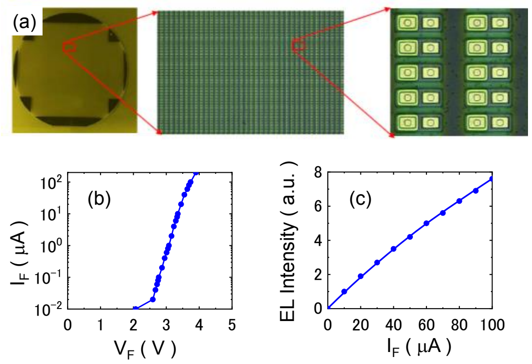

Fig. 2: (a) GaN-LEDs used in this study. (b) Current - voltage and (c) electroluminescence intensity - current characteristics of GaN-LED.

2.2 Monocrystal Micro-Si Chip

Fig. 3(a) shows the circuit diagram of the monocrystal Si chip (GaN LED is also shown). The circuit had 3T-1C structure to drive the LED by PWM. The instantaneous LED current in PWM operation was controlled by adjusting the gate-source voltage (V_{GS}) of the drive transistor M1. V_{GS} was set to V_{DATAL} which was supplied from the data line via switch transistor M2, and stored at the capacitor C1. Drain of M1 transistor was connected to the anode of the LED via emission control transistor M3 which controlled duty ratio of the LED emission. The transistor M1 was designed to operate at the saturation region, i.e., $V_{DS} > V_{TH} - V_{GS}$ where V_{DS} and V_{TH} respectively are drain to source voltage and a threshold voltage of transistor M1. Thus, the source to drain current (I_{DS}, equal to the LED current) was almost independent of V_{DS}, and mainly depends on V_{GS} (=V_{DATAL}) which was controlled from the data line. This configuration can suppress fluctuation of the LED current (I_{LED}) even if the LED voltage (and hence V_{DS} of M1) fluctuates.

The Si chip was fabricated by the conventional 1-poly 2-metal Si CMOS processes. The supply voltage (V_{DD}) was 10 V. All MOSFETs in Fig. 3(a) was enhancement type PMOS. The width (W) and the length (L) of PMOSFETs of the drive transistor (M1) and the switch transistors (M2, M3) were 4 μm/6 μm and 4 μm/1 um, respectively. Fig. 3(b) shows microscope images of fabricated Si chips array on Si wafer and the extended image of one chip. As shown in the figures, Si chips were fabricated in 360 μm pitch with respect to both vertical and horizontal direction, and each chip was a square shape with a size of 180 μm × 154 μm. To supply signals and powers to the Si chip, 10 μm × 10 μm pads were placed on the periphery of the chip. As discussed later, the Si wafer with these Si chips were transferred to the FPC substrate with the same pitch (70 ppi) using the carrier quartz substrate.

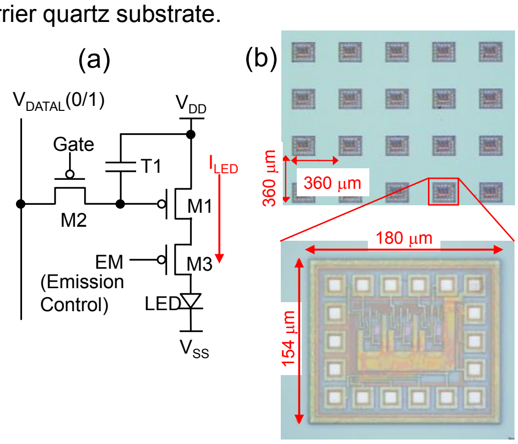

Fig. 3: (a) Circuit diagram of Si chip. (b) Microscope images of Si chip fabricated on the Si wafer.

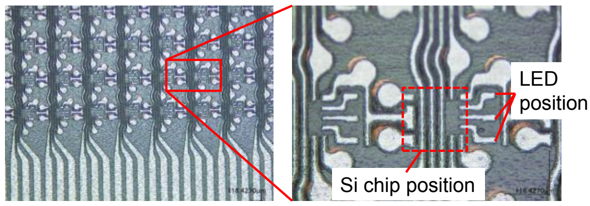

Fig. 4: FPC substrate on which the interconnect pattern was fabricated.

2.3 FPC Substrate

FPC substrate was used as a backplane of micro-LED array. Fig. 4 shows the photograph of a 25-μm thick polyimide FPC substrate before implementing LED and Si chips. Two layered Interconnect pattern was fabricated on the substrate using the conventional semi-additive electro and electroless copper plating processes. Copper thickness was 3 μm. Minimum line and space width was 14 μm/12 μm. Via pattern diameter was 70 μm with hole diameter of 20 μm. First (bottom) layer consisted of the source line as well as the signal line. These lines were branched and connected to the pads of LED and Si chip through the top layer Cu interconnect pattern. Pixel pitch was 360 μm, which corresponded to 70 ppi, as described before. Copper surface was covered by Au with a thickness of approximately 0.1 μm by electroless plating, to electrically connect the Si chip and the LED chip.

2.4 Fabrication Processes

Fig. 5 shows the process steps of micro-LED array fabrication. The processes consisted of (1) transfer of the Si chip from the Si wafer to the carrier quartz substrate (Fig. 5(a)), (2) transfer of GaN-LED from the sapphire substrate to FPC substrate on which interconnect was fabricated (Fig. 5(b)), and (3) transfer of Si chips to the FPC substrate (Fig. 5(c)). Fig. 5(a) shows the Si-chip transfer to the carrier quartz substrate. First, the Si wafer on which the pixel circuits were formed (Fig. 3(b)) was mounted on the quartz substrate using doble sided UV tape. Note that the UV tape was widely used for dicing processes of Si wafer. The wafer was thinned to 30 μm from the back side by back grinding, which was followed by the photo lithography and dry etching to isolate each Si chip. Then, as shown in Fig. 5(a), the Si chips were transferred to another quartz substrate which was used as the carrier substrate using cardo photosensitive resin adhesive materials named VPA developed by NIPPON STEEL & SUMIKIN CHEMICAL CO., LTD. Using VPA, adhesive layer could be patterned and selectively formed on the LED array area by photo lithography. In this transfer process, the original and the carrier quartz substrate was combined and pressed (50 N) at 120ºC. After cooling, the UV tape could be removed and the transfer was completed.

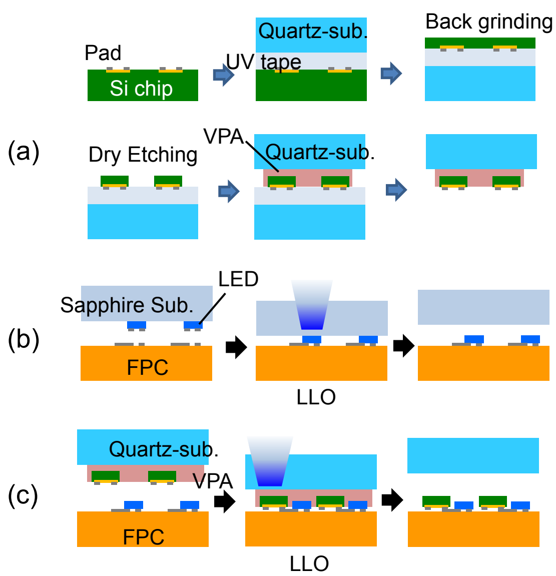

Fig. 5: Fabrication processes of GaN-LED and Si chip array on FPC substrate.

Before the transfer of Si chip to the FPC substrate, GaN-LED was transferred to the FPC substrate as shown in Fig. 5(b). The FPC substrate (with interconnect patterns) and sapphire substrate (with GaN LEDs) were aligned to each other and combined, and both pads of both substrates were connected using solder by pressing (50 N) at 260ºC. After that, GaN-LED chips were transferred to the FPC substrate by LLO using the equipment developed by V-Technology [4,5]. The equipment used pico-second pulse laser with a wavelength of 266 nm, and can maintain the shift in position to within ± 2 μm.

After mounting LEDs on the FPC substrate, Si chips were transferred to the FPC substrate as shown in Fig. 5(c). The FPC substrate and the carrier quartz substrate (with Si chips) were aligned to each ohter and combined, and both pads of both substrates were connected using solder with pressing (50 N) at 260ºC. Then, the carrier quartz substrate was removed and the fabrication of the array of micro-LED and the Si chip was completed. To remove carrier quartz substrate, we also used laser lift off technique using the same LLO equipment as that was used for LLO of GaN-LED. By irradiating the laser to the quartz substrate side, it has been confirmed that VPA was evaporated without any serious damage induced to the Si chips and the FPC substrate with GaN-LEDs and interconnect pattern. Fig. 6 shows photograph of the array of GaN-LEDs the Si chips fabricated by the proposed process flow. GaN-LEDs were successfully emitted by supplying current from the Si chips.

Fig. 6: Fabricated array of GaN-LEDs and the Si chips. GaN-LED was emitted by supplying current from Si chips.

3. MESUREMENT RESULTS

Fig. 7(a) shows transfer characteristics (I_{DS} – V_{GS}) of M1 transistor at V_{DS} = -5 V. Threshold voltage V_{TH}, which was determined as the gate voltage at which the drain current multiplied by L/W equals to 100 nA, was -1.1 V.

Fig. 7(b) shows the LED current I_{LED} as a function of V_{DATAL}, which indicated controllability of I_{LED} by V_{DATAL}. In this measurement, 125 LEDs were controlled by the same V_{DATAL}, and I_{LED} in Fig. 8 represents the total LED current, as labeled in the vertical axis. V_{DD} and V_{SS} were 8 V and 0 V, respectively, and the duty ratio was set at 50% by EM signal. Because LED was operated at approximately 3V as shown in Fig. 2(b), V_{DS} of M1 was approximately -5 V. For V_{DATAL} larger than approximately 7 V, the LED current did not flow, because M1 was off. When V_{DATAL} decreased from 7V, total I_{LED} increased as V_{DATAL} decreased (and hence $|V_{GS}|$ of M1 increased). For V_{DATAL} of approximately 2 V or less, increase in the LED current stopped at approximately 3 mA (which corresponded to approximately 24 μA for each M1 transistor), because operation region of M1 became out of the saturation region. The results showed good controllability of I_{LED} by V_{DATAL} for the appropriate V_{DATAL} region. Next, we tested PWM operation. Fig. 8(a) shows the typical results, where waveforms of total I_{LED}, EM signals in 1 flame (60 Hz) showed at the oscilloscope were shown. V_{DATAL} was fixed at 3.4 V, and the cases of PWD data of 255 are shown. PWM operation was successfully obtained as shown in the figure. In Figs 8(b) and 8(c), waveforms of total I_{LED} at PWM data =100 (0110 0100) and 1 (0000 0001) are shown respectively, as an example. We have confirmed that all tone can be obtained.

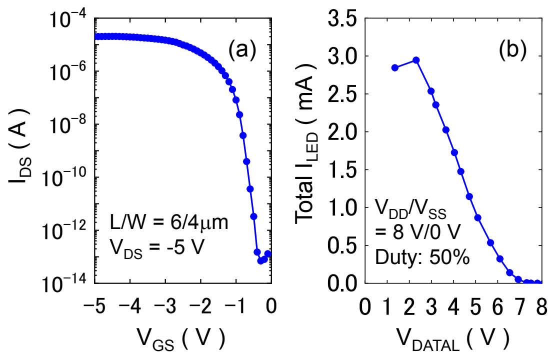

Fig. 7: (a) Transfer characteristics of M1 transistor. (b) LED current vs. V_{DATAL}.

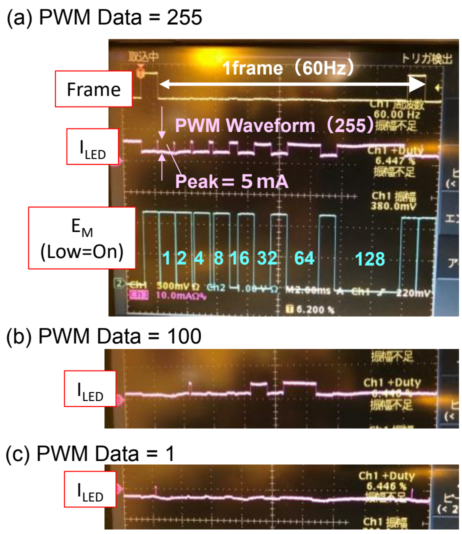

Fig. 8: PWM operation results.

4. CONCLUSIONS

New micro-LED display fabrication processes are proposed. GaN micro-LED and monocrystal Si micro-chip with pixel circuit to drive LED are mounted in an array shape on a flexible substrate using laser lift-off processes. The emission intensity of LED could be successfully controlled by PWM. The proposed micro-LED fabrication technology using monocrystal Si CMOS chip will greatly contribute to development of micro-LED display.

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