Integration of Micro-Light-Emitting-Diode Arrays and Silicon Driver for Heterogeneous Optoelectronic Integrated Circuit Device

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1. Introduction

Recently, because of the rapid development in information processing technology, signal processing devices have required the handling of a batch system of massive information. In spite of the continuous research on the miniaturization of large-scale integrated circuits (LSIs), as expected, current LSI devices are faced with limitations in size and speed.12) For instance, the performance of a microprocessor has been improved by increasing the number of metal oxide semiconductor field-effect transistors (MOSFETs) and clock frequency. However, nowadays, the microprocessor has been improved by increasing the number of metal oxide semiconductor field-effect transistors (MOSFETs) and clock frequency. Furthermore, to investigate the driver for handling massive parallel information, a simple multifunctional driver was designed, fabricated, and flip-chip-bonded using a gold compliant bump and anisotropic conductive adhesive with micro-LED arrays.

In this paper, we proposed the possibility of implementing a single chip device for realizing optoelectronic integrated circuits (OEICs). Micro-light-emitting-diode (LED) arrays and a complementary metal–oxide–semiconductor (CMOS) pulse width modulation (PWM) silicon driver were designed, fabricated, and operated on a single chip. The micro-LED arrays were separated by a dry etching method into 64 pixels of 8 × 8, each with a size of 30 × 30 μm² and operated in 3 V at 100 μA. The PWM Si driver was well operated and modulated using various control signals.

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reactive ion etching (ICP-RIE) was used for the dry etching of the mesa structure. ICP-RIE was used at 120 W for 4 min in Cl₂/SiCl₄/Ar at a pressure of 0.6 Pa. Then, a SiO₂ insulating layer was deposited by plasma-enhanced chemical vapor deposition (CVD) and etched using buffered hydrofluoric acid (BHF). For the n-type electrode, Ti/Al/Ti/Au was deposited using an e-beam evaporator and annealed in N₂ ambient at 800°C for 3 min in a rapid-thermal annealing (RTA) system. For the p-type electrode, Ni/Au was evaporated and annealed in a N₂ + O₂ mixture at 500°C for 10 min.²¹–²⁴

The circuit design for the fabrication of the LED driver was obtained by a standard CMOS process. All circuit design, simulation, and layout were performed using Cadence Virtuoso. First, we designed a two-stage operational amplifier (OPAMP) for use as a sawtooth waveform generator and a comparator. All parameters of the MOS transistor were calculated for output offset state voltage. The designed bias circuit was of the simple cascade type and the start-up circuit was achieved using a current mirror for operating the differential amplifier. Various parameters of n-MOS and p-MOS are listed in Table I. The sawtooth waveform was used at the input of the comparator, which compares sawtooth waves with control signals and the generated pulse-width-modulated signal at the output. In this circuit, the output frequency of the PWM signal can be changed by varying the connected resistor.

We have designed advanced compact multifunctional control drivers instead of comparators in order to reduce the size of the driver, as shown in Fig. 2. This circuit is different from the previously reported PWM comparator, which could be controlled by adjusting the control signal \( V_{\text{REF}} \). By introducing a clock control transistor and a capacitor, it can deal with massive parallel information. The proposed drivers of p-MOS and n-MOS (M2, M3) transistors are analogous to the previously reported PWM comparator using sawtooth and \( V_{\text{REF}} \) control signals. M1 and C1 are the transmission gate for the implementation of clock control and the capacitor for the transmission of information during the refresh period by clock operation, respectively. In this circuit, the sawtooth signal of the M2 gate is compared with the signal of the M3 gate, which has been controlled by adjusting \( V_{\text{REF}} \) and the clock. Then, the compared signal is transferred to the inverter (M4, M5) for positive control by adjusting \( V_{\text{REF}} \). M6 was introduced for output signal switching and current control of the micro-LED.

The device was fabricated by a 2.5 μm CMOS process. n-type (100) silicon wafer with a resistivity range of 3.38–4.65 Ω cm was used for the fabrication of drivers. The flip-chip bonding process was performed at Kyushu University and Stanley Electronics in Japan. Details of the fabrication process for the compliant bump have been reported by Watanabe and coworkers.²⁵,²⁶ Before the bonding process, bumps of n-contacts and p-contacts were leveled using a pressure plate. Then, anisotropic conductive adhesive was coated using a dispenser, which is four-diagonally on the opposite side of the bumps on each aluminum pad. The mounting process for the LED arrays and flip-chip pad was carried out at 80°C for 120 s as pretreatment and bonded at 270°C for 30 s.

### Table I. List of various parameters of MOS.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>n-MOS</th>
<th>p-MOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Threshold voltage (V)</td>
<td>0.8</td>
<td>-1.4</td>
</tr>
<tr>
<td>Gate oxide thickness (nm)</td>
<td>7.6 x 10⁻⁸</td>
<td>9.3095</td>
</tr>
<tr>
<td>Transconductance coefficient (μA/V²)</td>
<td>30.427</td>
<td>9.3095</td>
</tr>
<tr>
<td>Mobility (cm²/V s⁻¹)</td>
<td>670</td>
<td>205</td>
</tr>
<tr>
<td>Oxide capacitance (F/cm²)</td>
<td>4.541.6 x 10⁻⁸</td>
<td>205</td>
</tr>
</tbody>
</table>

### 3. Results and Discussion

The obtained specific contact resistance of the p-contact was 7.99 x 10⁻³ Ω cm². The fabricated LEDs were operated at 3 V at 100 µA. Figure 3 shows the current density vs voltage plot. The inset shows the electroluminescence (EL) characteristics. The wavelength peaks were approximately
450 nm for the LEDs and the full width at half maximum (FWHM) was approximately 22.5 nm. The fabricated micro-LED driver was gold-wire-bonded and packaged for the measurement of the device characteristics. The operation characteristic of the LED driver was measured using a digital phosphor oscilloscope (Tektronix DP04104). The DC power supply (ShibaSoku PA15A) was used as an input and control voltage source for the driver. The generated sawtooth signal was $3 V_{p-p}$ based on the reference voltage of the voltage divider. This signal was applied to the input terminal of the comparator to modulate the PWM signal. The operation of the comparator was controlled by adjusting the control voltage signal ($V_{\text{REF}}$) at various duty cycles. When the control voltage signal ($V_{\text{REF}}$) is more intense than the sawtooth signal, the output signal of the comparator is $+V_{\text{DD}}$ (5 V). In contrast, when it is less intense, the output signal will be the ground state (0 V). Therefore, the response signal can be controlled to be high or low as required by adjusting the control signal voltage as various widths. The fabricated micro-LED arrays and PWM Si driver images are shown in Figs. 4(a) and 4(b), respectively. Figure 4(a) shows the micro-LED arrays, which were deposited on aluminum on the n-contact and p-contact for evaluating the characteristic of each micro-LED. Figure 4(b) shows the fabricated Si driver chip, in which the bias, sawtooth, comparator circuit, and flip-chip bonding pad were integrated. The experimental results of the PWM Si driver are shown in Fig. 5, which revealed the modulated PWM waveforms, sawtooth waveform, and control signal of the proposed circuit for the micro-LED. The frequency was controlled at 1.3 and 300 kHz using resistors of 7 MΩ and 1.2 kΩ, respectively. The LED was operated using a modulated current signal of 1.5 mA. It was possible to control the brightness intensity by adjusting the duty ratio.

Figures 6(a) and 6(b) show the images of the second type of micro-LED driver. Figure 6(a) shows a Si driver that can individually control each pixel using 64 drivers. The size of the driver was $250 \times 175 \mu m^2$, as shown in Fig. 6(b), which is approximately 10 times smaller than the previously reported comparator of the PWM generator. Figure 7 shows the output characteristics of the sawtooth and modulated waveforms of the multifunctional micro-LED driver. The DC power supply and waveform generator (Advantest R6144 programmable DC voltage/Agilent 33220A, function/arbitrary waveform generator) were used as the supply voltage source of the control signal and the input clock signal source with various frequencies, respectively. The fabricated driver was well operated by controlling $V_{\text{REF}}$ and the clock. The output current of the driver was approxi-
the flip-chip method, which used a gold compliant bump and anisotropic conductive adhesives to fabricate a single chip device for realizing heterogeneous OEICs. These results demonstrate that CMOS Si LSI and III–V compound devices can be integrated in single chip heterogeneous OEICs.

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Fig. 8. (Color online) Microscopy image of Au compliant bumps and flip-chip image of micro-LED arrays and Si driver.

nately 300 μA (at the size of MOSFET-M6 with 5 μm gate length and 20 μm gate width) and 600 μA (at the size of MOSFET-M6 with 5 μm gate length and 40 μm gate width). However, duty ratio control was possible up to 80%. This result is attributed to the minimum size width and length ratio (W/L) of the p-MOS gate, which is presumed to increase the internal resistance, and to the shift in the transfer characteristic of the p-MOS transistor shown by the following equation:

\[ I_D = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} (|V_{gs}| - |V_t|)^2, \]

where \( \mu_p \) is the hole mobility, \( C_{ox} \) is the oxide capacitance per unit area, \( W \) is the width of the MOSFET, and \( L \) is the length of the MOSFET. Figure 8 shows a microscopy image of Au compliant bumps on an aluminum pad and a flip-chip-bonded image of the LED arrays and PWM Si driver. Each part of the compliant bumps had surface and basal diameters and a height of 13, 35, and 25 μm, respectively. The bonded micro-LED arrays (8 × 8, each of the 4 pixels connected) were operated using the Si driver.

4. Conclusions
In this work, we have designed and fabricated micro-LED arrays with a Si driver for heterogeneous OEICs for the analog optical signal processing of GaN-based LED arrays as prototypes of heterogeneous OEICs. Micro-LED arrays of 64 pixels of 8 × 8, each with a size of 30 × 30 μm², were fabricated and evaluated to optimize the experimental conditions for determining the electrical and optical characteristics of micro-LEDs. The fabricated Si PWM driver was well operated and showed good control of the function of pulse modulation as compared with the sawtooth waveform and control signal in the frequency range of 1.3 to 300 kHz using a resistor. The multifunctional Si driver was designed and fabricated for more compact and functional control of individual micro-LED arrays by introducing clock control and a transmission capacitor. The evaluated characteristics of the multifunctional drivers were controlled up to 80% of the duty ratio. The micro-LED arrays and driver were bonded by