Monolithic Integration of GaN-μLED and Si-MOSFET for Bio-application

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Keywords: MicroLED, Optogenetics, GaN, wafer bonding

ABSTRACT

A micro light-emitting diodes (LED) has been attention as an optical stimulation tool for optogenetics. In this study, a needle-type microLED probe was fabricated for neuroscience. In addition, the monolithic integration of microLED and Si-MOSFET using wafer bonding technique was challenged toward the realization of multifunctional devices.

1 INTRODUCTION

Micro light-emitting diodes (LEDs) has attracted attention as a bio-application as well as a microLED display. Optogenetics, which can selectively manipulate neural activity by light, is a new technology that has attracted in the field of neuroscience in recent years. By using this technology, an accurate understanding and operation of brain functions has been attempted because the spatial and temporal resolution of stimulation is very high compared to conventional electrical and/or drug stimulation. Optical fibers are generally used for optical stimulation [1]. Although these fibers are very effective method for this sake, they restrict the free movement of animals because they are connected to the animals. Therefore, it is difficult to achieve multipoint stimulation with high spatial and temporal resolution. On the other hand, the microLEDs are great potential as new optical stimulation device because they can be driven by a wireless power and can be placed in any location on one probe [2]. Figure 1 shows concept diagram of optical stimulus microLED device for optogenetics. The microLEDs need to have a needle-shape structure to insert easily into brain tissue. In the past decade, injectable micro LEDs have been transferred on flexible polyimide films [3], several invasive microLED probes have been developed [4].

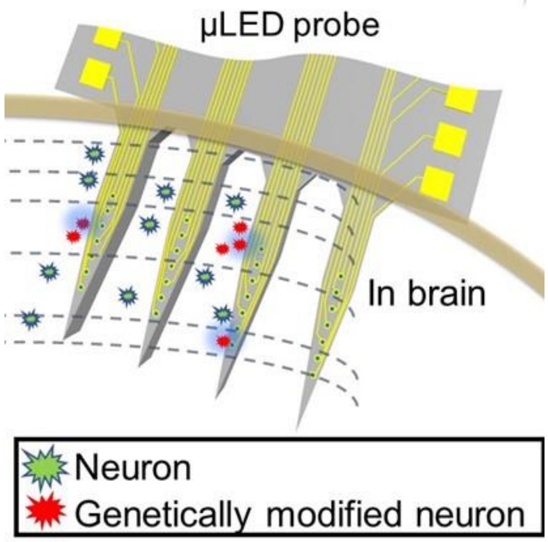

Fig. 1 Concept diagram of optical stimulus micro LED device for optogenetics. This probe has four shanks with several micro LEDs, which achieve multipoint stimulation to brain tissue.

The development of multifunctional devices is important to elucidate precise brain function. If integration technique of microLEDs and Si sensing devices is developed, it is possible to integrate electrical probes for recording cellular action potential and sensing devices for detecting light intensity and device temperature. It has been reported that microLEDs have been monolithically integrated on Si neural electrodes [5]. The integration technology of Si devices and microLEDs is important not only for bio-applications but also for microLED display applications. Because the integration of thin film transistors (TFTs) or complementary metal oxide semiconductor (CMOS) circuits with the microLEDs is a significant task to control a plurality of microLEDs. In this paper, we will report on fabrication of needle-type micro LED probe for neuroscience and monolithic integration of GaN based microLED and Si based MOS field effect transistor (MOSFET) using wafer bonding technique.

2 MicroLED neural probe for optogenetics

It is necessary to place microLEDs in the needle structure in order to insert into brain tissue. From the viewpoint of integration and miniaturization of microLED, a GaN LED epitaxially grown on Si substrate was prepared. Here the neural microLED probe with four shanks were fabricated. Six microLEDs with diameter of 20 μm and period of 170 μm were prepared on each shank. The probe tip was a needle shape with an angle of 10˚ to facilitate invasion of the brain tissue. The length of needle region should be designed to be 1~6 mm depending on the brain region to be observed. Here the length of probe was set to be 2 mm as an example. The microLED probe was fabricated by the following procedure. An InGaN-based LED/Si substrate with a wavelength of 460 nm was prepared. First, the mesa structures of the microLED for device separation were formed using mixed Cl_2/Ar inductively coupled plasma reactive ion etching (RIE). Next, a Ti/Al/Ti/Au (20 nm/20 nm/20 nm/50 nm) n-electrode was formed by electron beam (EB) evaporator. Then, a 300 nm-thick SiO_2 layer was deposited using plasma enhanced chemical vapor deposition. After a contact hole was opened for p-contact using buffered HF, an indium tin oxide (ITO) transparent electrode was formed for p-contact using EB evaporator and annealing under a mixed atmosphere of oxygen and nitrogen at 300 °C. Then, Ti/Au wires and pads were formed by EB evaporator. Finally, the LED chip was processed into a needle shape so that it could be inserted into the brain tissue.

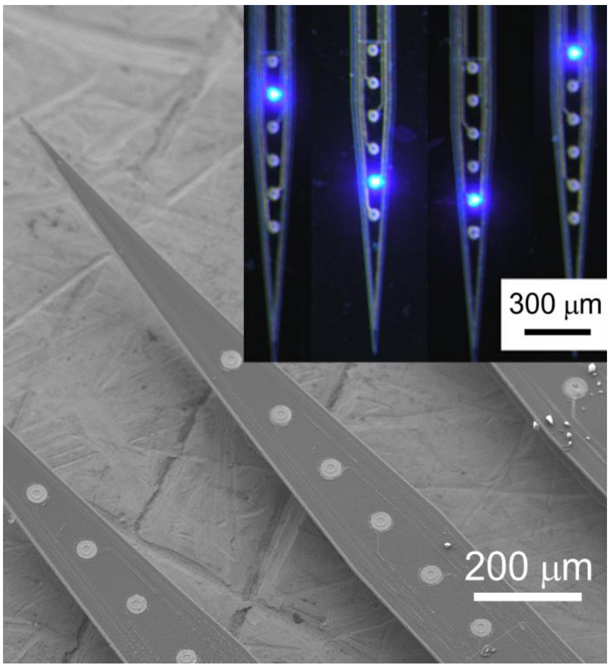

Fig. 2 A SEM image and emission image of neural optical probe. There are four shanks with six micro LEDs. The micro LED can be independently controlled by constant-current power supply. Here simultaneous emission from 4 different LEDs was observed.

Figure 2 shows a scanning electron microscopy (SEM) image of the fabricated neural optical probe. It was observed that there are four needle-shape shanks with six microLEDs. The rectification characteristics with turn on voltage of 3.5 V were observed for all the microLEDs. The inset of Fig. 2 shows emission image of microLEDs on the shank. These microLEDs can be independently controlled by power supply. Simultaneous emission from 4 different LEDs was observed. The light output at 100 μA was approximately 3 μW (10mW/mm^2). As a light output of 1 mW/mm^2 is generally required for the optical stimulation of the brain, this light intensity can sufficiently activate the neuron activity. Note that heat generation from LEDs is an issue because a slight change in device temperature can lead to stimulate or damage to the brain. In order to clarify the heat generation from the microLED, the temperature change was evaluated by thermal infrared camera. The device temperature increased by 0.3 °C from the original temperature when light output was 10 mW/mm^2, which is enough for animal experiment. This result suggest that this device can be an effective tool in neuroscience.

3 Monolithic integration of MicroLED and MOSFET

Multifunctional devices will be important in the future neuroscience. In particular, the integration of the optical stimulation device and the sensing device is an important task as well as integration of microLED and the drive circuit. Therefore, the integration technology of Si device and microLED is important. Although electrically connecting with different devices using flip chip bonding technology after fabricating each device is one of solutions, there are problems in thickness of device and fabrication of high density integrated device. In this study, the Si/SiO_2/InGaN-based LED wafer was proposed to achieve the multifunctional device. [6]

This special wafer was prepared by the following procedure. After depositing SiO_2 insulator on LED wafer by low pressure chemical vapor deposition (LP-CVD), the surface was polished by chemical mechanical polishing (CMP) for surface activated bonding (SAB). Then, 2-inch SiO_2/LED wafer and 4-inch silicon on insulator (SOI) was joined and high pressure (6000N/cm^2) was applied by SAB. A Si device layer was successfully transferred from SOI substrate to SiO_2/LED wafer. A thick Si device layer introduces defects or generated cracks in the Si device layer during annealing process in the device fabrication process. Therefore, the thickness of a Si device layer was designed to be 340 nm in this study. It is revealed from transmission electron microscopy (TEM) observation that a defect-free Si device layer without interfacial void structure was obtained on LED wafer. Based on this result, the monolithic integration of InGaN-based microLED and Si-MOSFET was fabricated [7]. A field SiO_2 film was deposited onto the wafer by plasma-enhanced chemical vapor deposition (PECVD). After opening active region of the field SiO_2 film for the MOSFET, Phosphorous and Boron ions were implanted to form a source and a drain, and to form a body contact. Then, a 25-nm-thick gate SiO_2 film was formed by wet oxidation at 900 °C for 15 min. This thermal process combined with activation of the ion implantation. Subsequently, the Si device layer was dry-etched by SF_6-based reactive ion etching (RIE) and the interlayer SiO_2 insulator was etched by buffered HF (BHF). Next, to fabricate a microLED, a mesa structure was formed by mixed Cl_2/Ar-based RIE for separating p-GaN and n-GaN layers, followed by the formation of a Ti/Al/Ti/Au n-contact and a Ni/Ag/Ni p-contact were deposited by EB evaporator. An Al metal gate and SiO_2 passivation layer were formed. Finally, after opening contact holes for the n-contact of the GaN-microLED, Al metal gate, and source/drain regions, Al-Silicide layer were deposited by sputtering and etched by Cl_2-based RIE. Figure 3 shows optical microscope image of microLED and Si-based n-MOSFET integrated on Si/SiO_2/LED wafer. When the n-MOSFET fabricated in the Si/SiO_2/InGaN-based LED wafer was measured, this I_D–V_{DS} characteristic was similar to that of an n-MOSFET fabricated on a Si bulk substrate. The transconductance of the n-MOSFET (W= 100 µm) was 0.62mS/mm at V_{DS} = 5V and the threshold voltage was approximately 0.8 V. For InGaN-based GaN microLED, typical rectification characteristics with turn on voltage of 3 V and blue emission were observed. A peak

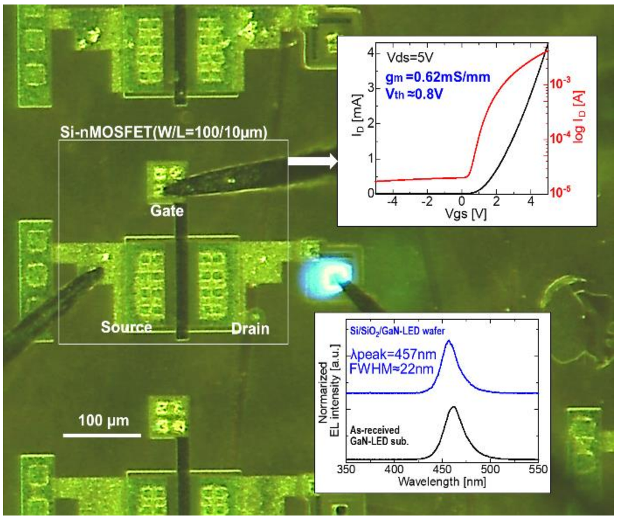

Fig. 3 Optical microscope image of microLED and Si-based n-MOSFET integrated on Si/SiO_2/LED wafer fabricated by surface activated bonding. Typical characteristics were observed. The turn on voltage and emission efficiency were 3 V and 7%. The transconductance of the n-MOSFET (W= 100 µm) was 0.62mS/mm at V_{DS} = 5V and the threshold voltage was approximately 0.8 V.

external quantum efficiency was approximately 7%, which suggest that there is no deterioration by this process. Finally, it was confirmed that microLED can be operated by gate voltage control of n-MOSFET. This achievement greatly proves the realization of multifunctional neural probe devices combined with microLED and Si devices as well as a microLED display.

4 CONCLUSIONS

MicroLED has been attracted for bio-application as well as microLED display. A wafer-level bonding technology is proposed as a monolithic integration technology for microLED and Si-based devices, which is a common issue in various application. The monolithic integration of microLED and Si-MOSFET was successfully fabricated. These devices shows typical characteristics without deterioration.

ACKMOWLEDGEMENT

This work was partially supported by The Precursory Research for Embryonic Science and Technology Agency, Naito Science and Engineering Foundation, Tokai Industry and Technology Foundation, and Research Foundation for Opto-Science and Technology. All device fabrication processes were carried out using the facilities of the Venture Business Laboratory (VBL) and Electronics-Inspired Interdisciplinary Research Institute (EIIRIS), Toyohashi University of Technology.

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