Opportunities for Employing IGBT in Photo-switch based on Silicon Avalanche LEDs

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ABSTRACT

A comprehensive approach for the practical realization of silicon light-emitting devices (Si-LEDs) with emitting visible light in the 400 to 900 nm wavelength region is discussed. Prototype Si-LEDs are fabricated in the standard CMOS technology, using the same processing procedures with other components. Since fully integrated silicon photon-receivers with Si-LED on the same chip will largely improve the overall system performance, monolithic integration leads to lower cost and smaller size. Some structural details and performances of several practical two and three-terminal Si-LEDs are presented. In this paper, we report on further progress that has been made with regard to modeling of the physical processes in realizing an increase in the optical emission power, as well with regard to higher frequency modulation capability of such device. The theory of silicon optical modulation based on p-n junction in reverse bias is primarily discussed. Initial investigations indicate that the Si-LEDs have a very fast inherent modulation bandwidth capability, and the upper limit derived value for the expected maximum modulation of the device could be in the range of a few hundred GHz. According to the best of our knowledge, despite the low efficiency, the Si-LEDs show potential for on-chip electro-optical communication.

KEYWORDS

Silicon, optoelectronics, micro-optical devices, electro-optical modulation, PN junction

1 INTRODUCTION

Modern MOSFET technology has advanced continuously since its beginning in the 1950s. The complementary nature of p-type FETs and n-type FETs makes it possible to design low-power circuits called CMOS or complementary MOS circuits, as presented in Fig. 1. Because of the advantages of low power dissipation, short propagation delay, controlled rise and fall times, and noise immunity equal to 50% of the logic swing, the CMOS process is defined as the standard fabricating technology for semiconductor devices and electronic circuits in industry [1].

Silicon is well known as the core material of the electronic industry, but it has some difficulties with photonic application because silicon, which has an indirect band-gap of 1.12-eV, emits light only weakly by band-to-band transitions or by defect states to band transitions in the near infrared [2]. However, because of silicon’s mature processing technology, low cost, CMOS compatibility and compactness, the development of silicon photonics is welcomed by many scientists [3].

Recently, a large variety of the attempts, such as dislocation loop light-emitting diode [4, 5], porous silicon [6], light emitting from rear locally diffused solar cell [7], silicon light-emitting diodes in silicon-on-insulator [8–11], silicon nanoparticles in Si-in-SiNx thin films [12], crystalline silicon LED [13, 14], and Si/SiO\textsubscript{2} super-lattices luminescence [15, 16], have been made to increase the efficiency of Si-based light emitters. These Si light sources have achieved relatively high efficiency [17], but all of these technologies are quite complicated and can not be easily integrated into the standard Si-CMOS process technology [18–21].

In contrast to the light emitters above, Si-diode LED can be easily realized using standard Si-
CMOS process technology without any additional process. Because of the full compatibility with the standard Si-CMOS process, the silicon light-emitting device (Si-LED) is capable of integrating with other silicon devices or circuits to realize monolithic integration in optoelectronics. It is widely known that most of the injected carriers in a forward biased silicon diode are recombined non-radiatively due to silicon’s indirect band structure. Instead, a reverse-biased silicon-diode can emit visible light in the depletion region under avalanche breakdown [22]. Since the breakdown condition is generally regarded as being a solid state analog of a gas discharge plasma [23], Bremsstrahlung [24] (i.e., braking radiation) by hot electrons in the Coulomb field of charged impurities was previously treated as the major cause of the photon emission previously.

![Figure 1. Schematic diagram of the CMOS inverter](image)

A Si-PMOSFET device is fabricated to investigate the difference between silicon gate-controlled-diode LED and silicon-diode LED. In contrast to silicon-diode LED, the major advantage of silicon gate-controlled-diode LED is the existence of the insulated-gate terminal which can make the Si-PMOSFET device work as two identical parallel connected gate-controlled-diodes (i.e., the “P+ Source/Drain to N-Substrate” junction with varying gate voltage). Generally speaking, in silicon-diode LED the increase in light intensity is achieved by increasing the electric field through increasing the reverse-bias voltage; whereas in silicon gate-controlled-diode LED the increase in light intensity is achieved by increasing the electric field through an increase in the gate voltage. In addition, it is noted that, in the case of silicon gate-controlled-diode LED, the reverse-bias of the “P+ Source/Drain to N-Substrate” junction is fixed. It was reported that, at the same reverse current (i.e., the current flowing through the reverse-biased p-n junction), the emitted light intensity in gate-controlled-diode structure is much higher than that in the diode structure. In fact, simulated results in this paper indicate that the field in the gate-controlled-diode is one order of magnitude higher than that in the diode, and it is shown that the gate-terminal produce light intensity enhancement in reverse-biased silicon p-n junctions.

The paper is will attempt to give some flavor of the history, current status, and future prospects of the research field of silicon light-emitting devices. Section 2 will introduce the structure and fabrication of the Si-PMOSFET device. Section 3 will consider technologies for the modulation of light intensity in the silicon-diode LED case and in the silicon gate-controlled-diode LED case. Section 4 will describe applications to the insulator gate bipolar transistor (IGBT) in the power ICs. Section 5 will present the opto-coupler applications. Finally, Section 6 will make a conclusion.

2 DEVICE STRUCTURE AND CONFIGURATIONS

Standard 3-µm CMOS process with self-aligned technology is utilized for device fabrication. The device consists of MOS capacitor fabricated on a lightly doped <100> Si n-type substrate (525 ± 25 µm thick with a resistivity of 0.8–1.2 Ω × cm). Oxidation is performed at 1200°C for 5 hrs in a N₂ ambient and 2 hrs in an O₂ ambient. The gate dielectric of the device consists of 450 Å thick thermally grown silicon oxide.
diode LED. The main features of switching transitions of Si-diode LED and Si gate-controlled diode LED are characterized, and a model developed to explain the modulation speed is then reviewed. The upper limit derived value for the expected maximum modulation of the device can be in the range of a few hundred GHz. Despite of its low efficiency, the Si-PMOSFET light-emitting device (Si-PMOSFET LED) will be a potentially key component for silicon photonic integrated circuits for future computing I/O applications.

This section especially focuses on the comparison in light intensity modulation between the Si-diode LED mode and the Si gate-controlled diode LED mode. Fig. 3 shows a schematic diagram of the Si-PMOSFET device.

### 3.1 Si-diode LED

As shown in Fig. 3, without the function of gate voltage $V_g$, the Si-PMOSFET device will act as two p-n junction diodes in parallel and the reverse bias of the “P+ Source/Drain to N-Substrate” junction will be equal to the substrate voltage $V_{sub}$ if source and drain are both grounded. To realize electro-optical modulation, the small-signal is electrically input from the two terminals of the p-n junction using the $V_{sub}$ as the DC voltage carrier, and then the small-signal as an optical signal is output from the light emitting region of the device.
Substituting Eq. (3) into Eq. (4), the modulation speed of the PMOSFET device working as two p-n junction diodes will be obtained as

$$f \sim \sqrt{\frac{1}{2\pi R C_{dep}}}$$

(5)

It has been shown by 2-D device simulation that the p-n junction based silicon modulator has a fast intrinsic response time of ~7 ps [25]. Since the total capacitance of the reverse-biased silicon diode is less than 3 pF, it is found that silicon diode has an intrinsic frequency capability of GHz in theory by taking the dynamic series resistance into account [26].

However, the current Si-diode is by no means optimized for performance, and the device can be improved by optimizing the doping profile and p-n junction placement to increase phase efficiency. By applying the gate voltage, a field induced junction optimizes the silicon p-n junction, thus making the device a Si gate-controlled diode LED.

3.2 Si gate-controlled diode LED

As shown in Fig. 3, by applying a gate voltage $V_g$, the Si-PMOSFET device will act as two gate-controlled diodes in parallel and the reverse bias of the “P+ Source/Drain to N-Substrate” junction, which is equal to the substrate voltage $V_{sub}$ if source and drain are both grounded, has a certain value in the mode of gate-controlled-diode.

Due to the variation in gate voltage $V_g$, the breakdown voltage $B V$ of the “P+ Source/Drain to N-Substrate” junction will be changed, thus resulting in the modulation of breakdown current and its corresponding light intensity. Since the reverse-bias $V_{sub}$ is fixed to function as a DC voltage source, the small electric signal will be input from the gate terminal.

From the schematics shown in Fig. 5, the DC section of gate voltage $V_g$ will be the carrier for the electric signal input while the optical signal output is constituted by photons emitted from the light emitting active region in the Si-PMOSFET device. In contrast to the mode of Si-diode LED, the modulation speed of the three-terminal Si gate-controlled-diode LED is determined by

$$C_{dep} = A \frac{\varepsilon_s}{W_{dep}}$$

(1)

where $A$ is the cross-section area, $\varepsilon_s$ is the permittivity of silicon, and the depletion width is given by

$$W_{dep} = \sqrt{\frac{2\varepsilon_s (V_{bi} + V_{sub})}{qN_d}}$$

(2)

where $V_{bi}$ is the built-in potential of the “P+ Source/Drain to N-Substrate” junction, $V_{sub}$ is the reverse bias of this junction, $N_d$ is the background concentration (i.e., doping concentration of the N-Substrate), and $q$ denotes the elementary charge. Substituting Eq. (1) into Eq. (2), it becomes

$$\frac{1}{C_{dep}^2} = \frac{W_{dep}^2}{A^2 \varepsilon_s^2} = \frac{2(V_{bi} + V_{sub})}{qN_d \varepsilon_s A^2}$$

(3)

which implies the capacitance is inversely proportional to the reverse-biased voltage. On the other hand, the 3-dB frequency is

$$f = \frac{1}{2\pi R C_{dep}}$$

(4)
where \( C_{ox} \) denotes the capacitance of the metal-oxide-semiconductor (MIS) capacitor of the MOSFET, \( A_g \) is the area of gate, \( \varepsilon_{ox} \) is the permittivity of SiO\(_2\), and \( t_{ox} \) is the thickness of the SiO\(_2\) layer. Accordingly, the speed of modulation in this case is expressed as

\[
f \sim \frac{1}{2\pi RC_{ox}}
\]  

(7)

In addition, both avalanche and Zener breakdowns are inherently fast process, and operation of silicon-based LED at a frequency of 10 GHz was reported [27]. A clear and better understanding of the modulation phenomena in the three-terminal Si gate-controlled diode LED operating in the depletion mode is presented in Ref. 28.

Si-diode LED is a conventional current driving device based on avalanche breakdown, but Si gate-controlled diode LED can be defined as a field-emission device in which both avalanche and tunneling processes occur together [29].

4 POTENTIAL APPLICATIONS AS OPTICAL SWITCH FOR POWER IGBTS

The power device is known as one of the most important components for driving HDTV Plasma Display Panel (PDP). It is noted that the PDP driver IC always requires that the integrated power devices have high off-state breakdown voltages (BV) and large current capability in order to make the system operate.

According to the area distribution of the devices in the PDP scan driver IC shown in Fig. 6, it is seen that the power devices, including the n-type lateral insulator gate bipolar transistor (nLIGBT) and the lateral extended drain MOS (LEDMOS), take up 85% area of the IC.

200 V nLIGBT, nLEDMOS and pLEDMOS devices are fabricated using the SOI technology [30]. The measured electrical results, observing larger current drivability and higher off-state BV in the three devices, are shown in Fig. 7.
Figure 7. The experimental off-state and on-state I-V curves for: (a) the two nLIGBT devices with 3x10^{12} cm^{-2} N-drift dose (W = 80 \mu m); (b) the two nLED MOS devices (W = 80 \mu m); (c) the two pLED MOS devices (W = 90 \mu m);

An opto-coupler is a device consisting of a LED and a photodiode coupled to input and output amplifiers that transforms an electric signal into an optical one in order to transfer data that is galvanically isolated. Several advances have been made in opto-coupler technology that improve performance and current input. The desirable features are low manufacturing cost, compact packaging and resistance to rugged. The potential of high modulation speed satisfies the data transmission speed advantages. Since the opto-coupler requires CMOS chip as a receiver, the Si-LED is the primary choice as the optical transmitter.

5 OPTO-COUPLER APPLICATIONS

Optical coupling is increasingly used in systems where complex communications must occur across a galvanic isolated boundary. Specially, in factory automation there exists a need for various pieces of equipment to communicate with each other and with a central computer via a bus. Because many of these pieces of equipment involve power devices, disruptive transient electrical signals are generated. To prevent these signals from corrupting the communication bus, optical isolation is used.

Industrial control applications also require opto-coupler. An example is the motor controller which includes sophisticated DSP based functions. Optical isolation is used by the motor controller to control the electrical power to the motor and to monitor the motor’s response both electrically and mechanically. In addition, the so-called Internet of Thing (IoT) requires the control of many actuators using internet communication. There are cases were the internet controller will need to be isolated from the actuator because of severe noise generated in the actuator such as inductive spikes. Typically, today’s opto-coupler manufactures place only a single GaAs LED chip on the sending side of the opto-coupler. It is left up to the user to provide an interface to the electrical requirements of the LED. This typically entails using discrete components to convert logic level signals or other types of signals to a signal suitable for driving the LED. With a silicon based LED, however, interface circuits can be built on the same chip as the LED thus eliminating the need for external, discrete components. Thus, the ability to place circuits on the LED side reduces component count.

Integration of the light emitting function with silicon allows two distinct advantages over existing technology. One is the integration of a complex circuit function on the LED side of an opto-coupler. GaAs LED technology does not support circuit functions. The other is the potential to make multiple bi-directional transmit and receive channels using only two pieces of silicon in a single package. Using SOI offers the potential to integrate both the receive and the transmit functions onto a single chip. The resulting higher level of integration not only lowers cost, but simplifies manufacturing for both opto-coupler manufacturer and the customer. An added caveat is that many opto-coupler do not require high bandwidths with 1 MHz being adequate.

6 CONCLUSIONS

Research on efficient light emission from silicon devices that are compatible with standard CMOS fabrication technology have been investigated. The Si-LED, as a direct electro-optic modulator, will be used for massively parallel optical interconnects, with potential for on-chip and chip-
to-chip optical links. Anticipated applications include electro-optic isolator for power ICs [31].

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