International Journal of New Computer Architectures and their Applications (IJNCAA) 5(3): 119-126
The Society of Digital Information and Wireless Communications, 2015 ISSN 2220-9085 (Online); ISSN 2412-3587 (Print)

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

Kaikai Xu[*a], Siyang Liu[b], Jianming Zhao[a], Qi Yu[a], Weifeng Sun[b], and Guannpyng Li[c]
[a]State Key Laboratory of Electronic Thin Films and Integrated Devices,
University of Electronic Science and Technology of China, Chengdu, Sichuan, China 610054
[b]National ASIC System Engineering Research Center, Southeast University, Nanjing, China 210096
[c]California Institute for Telecommunications and Information Technology, Irvine, California 92697
[*]Email address: (kaikaix@uestc.edu.cn)

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 nano-particles in Si-in-SiN_x thin films [12], crystalline silicon LED [13, 14], and Si/SiO_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.

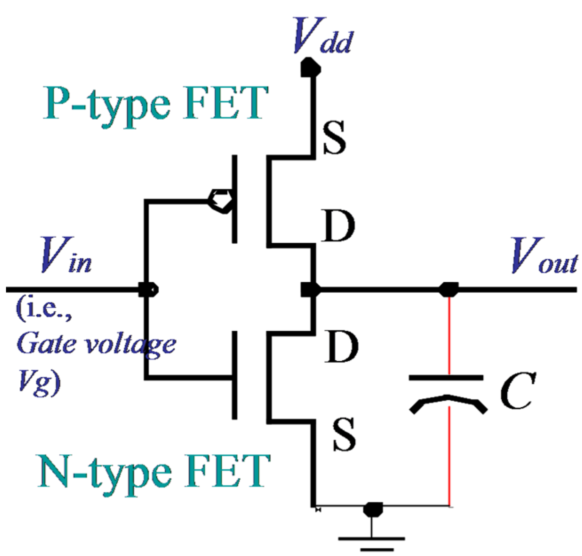


Figure 1. Schematic diagram of the CMOS inverter

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℃ for 5 hrs in a N_2 ambient and 2 hrs in an O_2 ambient. The gate dielectric of the device consists of 450 Å thick thermally grown silicon oxide.

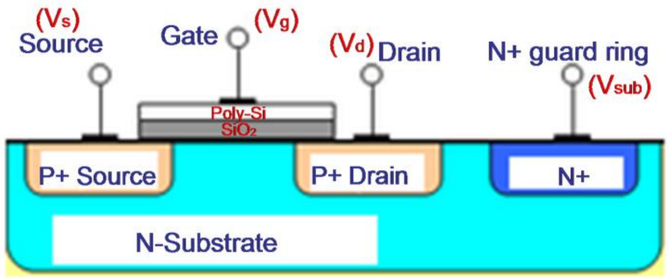


Figure 2. Schematic cross section of the light-emitting MOS device: gate width is 6 μm, gate length is 175.5 μm, N-Substrate surface doping concentration N_d ~$10^{16}cm^{-3}$, P^+ Source/Drain diffusion region doping concentration N_a ~$10^{19}cm^{-3}$, P^+ Source/Drain junction depth X_j ~0.5 μm. V_s is the source voltage, V_g is the gate voltage, V_d is the drain voltage, and V_{sub} is the substrate voltage

The PMOSFET sample was implanted with boron at 60 keV to a total fluency of 10^{13} ions/cm^2. The implantation energy (80 keV) has been chosen to have the projected range of the ion distribution roughly the same as in the N^+ guard ring which is for the ohmic-contact between substrate and electrode. After implantation, annealing at 850℃ for 30 minutes was performed in a N_2 flux to eliminate implantation defects and obtain the growth and agglomeration of Si residuals in thin films. The structure of the PMOSFET device is completed by the CVD deposition of a 4000Å thick n^+ poly-silicon layer. Finally, a metal ring consisting of an Al-Si-Cu layer (3 μm thick) completes the device structure, thus allowing device bonding to a standard TO_3 package. Fig. 2 shown a schematic cross section of the device.

3 RESULTS AND ANALYSIS

The key elements of silicon photonic systems are optical source capable of fast modulation, suitable transmission media, and fast optical detector or optically coupled power semiconductor devices.

The switching characteristics as associated with P^+N gated MOSFET silicon LED are reviewed. By employing the insulated-gate terminal that allows adjustment of "P^+ Source/Drain to N-Substrate" junction breakdown voltage (*BV*), it is demonstrated that the electro-optical modulation in the Si-PMOSFET device can be achieved using gate-controlled diodes. The PMOSFET device can operate as a Si-diode LED or a Si gate-controlled 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.

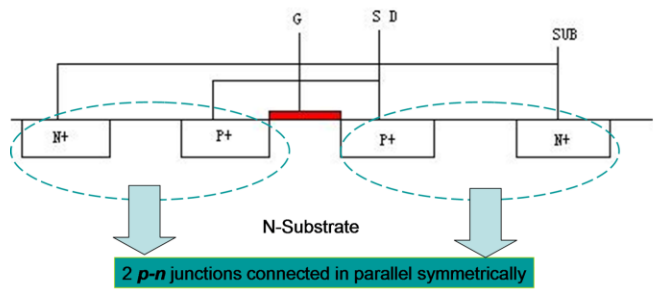
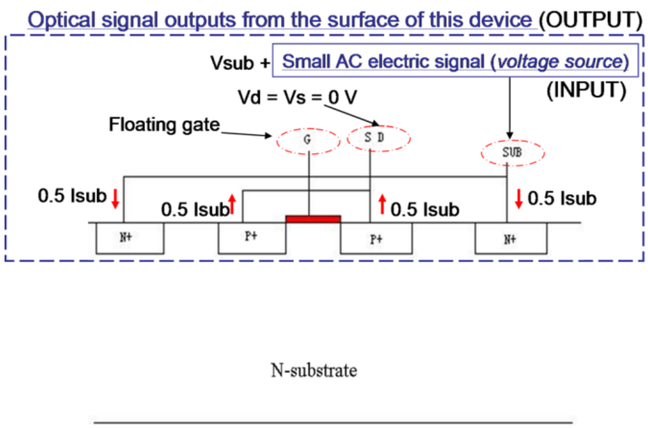


Figure 3. Schematic of the Si-PMOSFET device used in this study

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.



P-MOS Field Effect Transistor

Figure 4. V_{sub}, a dc source, is the reverse bias across the "P^+ S/D to N-Sub" junction; V_{sub} is varied to realize optical modulation in the two-terminal device

From the schematics shown in Fig. 4, it can be observed that the prerequisite for realizing the electric-optical modulation is that the p-n junction is in avalanche breakdown. At the same time, because of the unwelcome capacitive load to devices and circuits, the speed of modulation which is closely related to the depletion-layer capacitance is described by

$$C_{dep} = A\frac{\varepsilon_s}{W_{dep}} \qquad (1)$$

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

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

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

$$\frac{1}{C_{dep}^2} = \frac{W_{dep}^2}{A^2\varepsilon_s^2} = \frac{2\left(V_{bi}+V_{sub}\right)}{qN_d\varepsilon_s A^2} \qquad (3)$$

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

$$f \sim \frac{1}{2\pi RC_{dep}} \qquad (4)$$

Substituting Eq. (3) into Eq. (4), the modulation speed of the PMOSFET device working as two p-n junction diodes will be obtained as

$$f \sim \sqrt{V_{sub}} \qquad (5)$$

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 BV 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

$$C_{ox} = A_G \frac{\varepsilon_{ox}}{t_{ox}} \tag{6}$$

where C_{ox} denotes the capacitance of the metal-oxide-semiconductor (MIS) capacitor of the MOSFET, A_G is the area of gate, ε_{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

$$f \sim \frac{1}{2\pi RC_{ox}} \tag{7}$$

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.

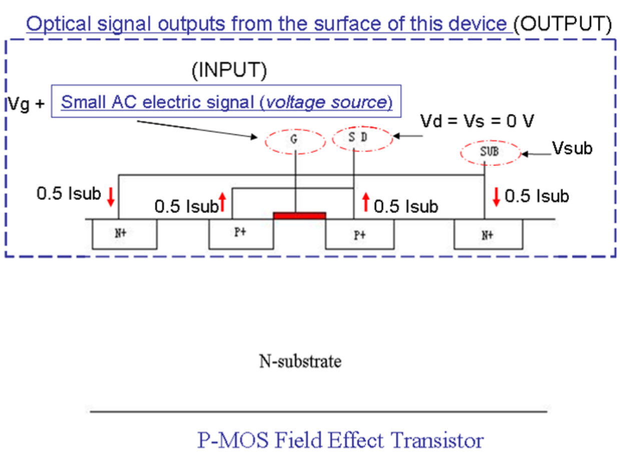


Figure 5. V_g , a dc source, is the gate voltage. V_{sub} , a dc source, is the reverse bias across the "P^+ S/D to N-Sub" junction, and V_g is varied to realize optical modulation in the three-terminal device

In order to bridge the theoretical formulas above and experimental data, the dynamic behavior of the Si-PMOSFET device should be further tested in future. Especially, in Si-diode LED we increase the avalanching current to increase the light intensity, whereas in Si gate-controlled diode LED an additional field is applied to increase the light intensity. In other words, the light intensity modulation in Si-diode LED requires direct modulation of the avalanching reverse current I_{sub}, whereas in Si gate-controlled diode LED the gate voltage V_g is varied to realize modulation via changing the electric field distribution. Overall, 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.

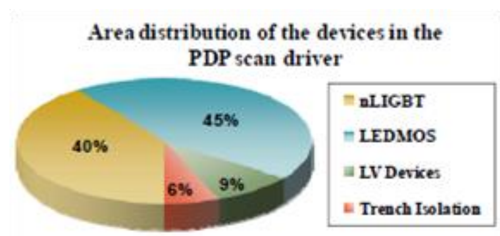


Fig. 6. Area distribution of the devices for the PDP scan driver IC

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.

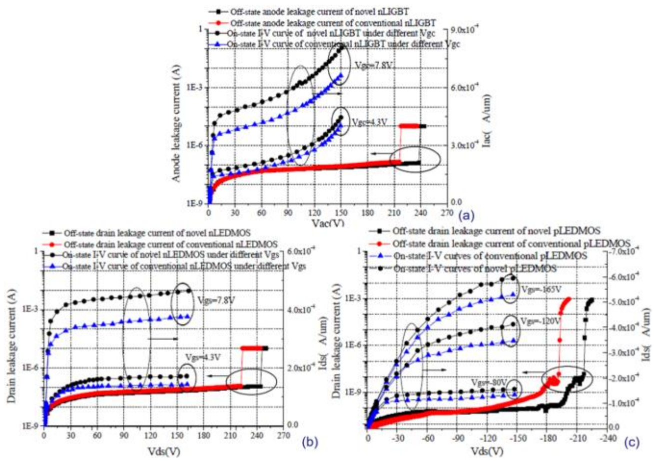


Figure 7. The experimental off-state and on-state I-V curves for: (a) the two nLIGBT devices with 3×1012cm-2 N-drift dose (W = 80 µm); (b) the two nLEDMOS devices (W = 80 µm); (c) the two pLEDMOS devices (W = 90 µm);

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].

ACKNOWLEDGMENT

This work is sponsored in part by the 1000-Talents Program of Sichuan Province, China, Scientific Research Foundation for the Returned Overseas Chinese Scholars. Dr. Kaikai Xu, would like to thank Mr. Eugene Worley of Qualcomm for some useful discussions. Encouragement from Prof. Bin Wu of the Ryerson University (Canada) is greatly appreciated. Owing to space restriction, it has only been possible to reference a few example from the large body of excellent published work consulted in preparing this paper. The authors would like to thank their colleagues in academe and industry for their many contributions to advancing the field of opto-coupler whether their work has been specifically cited here or not.

REFERENCES

1. CMOS, "the Ideal Logic Family," Fairchild Semiconductor Application Note, 77, (1983)
2. B. Jalali, "Can silicon change photonics?," Phys. Stat. Sol. (a), vol. 205, no. 2, 213-224, (2008)
3. L. Khriachtchev, "Silicon Nanophotonics: Basic Principles, Present Status and Perspectives," Pan Stanford Publishing, (2009)
4. W. Ng, M. Lourenco, R. Gwilliam, S. Ledain, G. Shao, and K. Homewood, "An efficient room-temperature silicon-based light-emitting diode," Nature, vol. 410, no. 6825, pp. 192-194, (2001)
5. M. Lourenco, M. Milosavljević, R. Gwilliam, K. Homewood, and G. Shao, "On the role of dislocation loops in silicon light emitting diodes," Appl. Phys. Lett., vol. 87, no. 20, 201105, (2005)
6. Y. Kanemitsu, K. Suzuki, H. Uto, Y. Masumoto, T. Matsumoto, S. Kyushin, K. Higuchi, and H. Matsumoto, "Visible photoluminescence of silicon-based nanostructures: porous silicon and small silicon-based cluster," Appl. Phys. Lett., vol. 61, no. 20, pp. 2446-2448, (1992)
7. M. Green, J. Zhao, A. Wang, P. Reece, and M. Gal, "Efficient silicon light-emitting diodes," Nature, vol. 412, pp. 805-808, (2001)
8. T. Hoang, P. LeMinh, J. Holleman, and J. Schmitz, "Strong efficiency improvement of SOI-LEDs through carrier confinement," IEEE Electron Dev. Lett., vol. 28, no. 5, pp. 383-385, (2007)
9. J. Zhao, G. Zhang, T. Trupke, A. Wang, F. Hudert, and M. Green, "Near-band edge light emission from silicon semiconductor on insulator diodes," Appl. Phys. Lett., vol. 85, no. 14, pp. 2830-2832, (2004)
10. S. Selvaraja, W. Bogaerts, P. Dumon, D. Thourhout, and R. Baets, "Subnanometer linewidth uniformity in silicon nanophotonic waveguide devices using CMOS fabrication technology," IEEE J. Sel. Topics Quantum Electron., vol. 16, no. 1, pp. 316- 324, (2010)
11. S. Pillai, K. Catchpole, T. Trupke, G. Zhang, J. Zhao, and M. Green, "Enhanced emission from Si-based light-emitting diodes using surface plasmons," Appl. Phys. Lett., vol. 88, no. 16, 161102, (2006)
12. Y. Wang, Y. Wang, L. Cao, and Z. Cao, "High-efficiency visible photoluminescence from amorphous silicon nanoparticle embedded in silicon nitride," Appl. Phys. Lett., vol. 83, no. 17, pp. 3474-3476, (2003)
13. J. Zhao, A. Wang, T. Trupke, and M. Green, "High efficiency bulk crystalline silicon light emitting diodes," Mat. Res. Soc. Symp. Proc., vol. 744, M4.7.1-6, (2003)
14. L. Ding, M. Yu, X. Tu, G. Lo, S. Tripathy, and T. Chen, "Laterally-current-injected light-emitting diodes based on nanocrystalline-Si/SiO_2 superlattice," Opt. Express, vol. 19, no. 3, pp. 2729-2738, (2011)
15. H. Song, and X. Bao, "Visible photoluminescence from silicon-ion-implanted SiO_2 film and its multiple mechanisms," Phys. Rev. B, vol. 55, no. 11, pp. 6988-6993, (1997)
16. S. Novikov, J. Sinkkonen, O. Kilpelä, and S. Gastev, "Visible luminescence from Si/SiO_2 superlattices," J. Vac. Sci. Technol. B, vol. 15, no. 4, pp. 1471-1473, (1997)
17. H. Finkelstein, M. Gross, Y. Lo, and S. Esener, "Analysis of hot-carrier luminescence for infrared single-photon upconversion and readout," IEEE J. Sel. Topics Quantum Electron., vol. 13, no. 4, pp. 959- 968, (2007)
18. T. Koch and U. Koren, "Semiconductor photonic integrated circuits," IEEE J. Quantum Electron., vol. 27, no. 3, pp. 641-653, (1991)
19. A. Krishnamoorthy and K. Goossen, "Optoelectronic-VLSI: Photonics Integrated with VLSI circuits," IEEE J. Sel. Topics Quantum Electron., vol. 4, no. 6, pp. 899-912, (1998)
20. R. Nagarajan, C. Joyner, R. Schneider et al., "Large-scale photonic integrated circuits," IEEE J. Sel. Topics Quantum Electron., vol. 11, no. 1, pp. 50-65, (2005)
21. A. Fang, M. Sysak, B. Koch, R. Jones, E. Lively, Y. Kuo, D. Liang, O. Raday, and J. Bowers, "Single-wavelength silicon evanescent laser," IEEE J. Sel. Topics Quantum Electron., vol. 15, no. 3, pp. 535- 544, (2009)
22. J. Bude, N. Sano, A. Yoshii, "Hot-carrier luminescence in Si," Phys. Rev., vol. 45, no. 11, pp. 5848-5856, (1992)
23. R. Zia, J. Schuller, A. Chandran, M. Brongersma, "Plasmonics: the next chip-scale technology," Materials Today, vol. 9, no. 7-8, pp. 20-27, (2006)
24. A. Lacaita, F. Zappa, S. Bigliardi, and M. Manfredi, "On the bremsstrahlung origin of hot-carrier-induced

photons in silicon devices," IEEE Trans. Electron. Dev., vol. 40, no. 3, pp. 577-582, (1993)

25. F. Gardes, G. Reed, N. Emerson, and C. Png, "A sub-micron depletion-type photonic modulator in Silicon on Insulator," Opt. Express, vol. 13, no. 22, pp. 8845-8853, (2006)
26. A. Chatterjee, B. Bhuva, and R. Schrimpf, "High-speed light modulation in avalanche breakdown mode for Si diodes," IEEE Electron Dev. Lett., vol. 25, no. 9, pp. 628-630, (2004)
27. L. Snyman, M. du Plessis, E. Seevinck, H. Aharoni, "An efficient low voltage, high frequency silicon CMOS light emitting device and electro-optical interface," IEEE Electron Device Letters, vol. 20, no. 12, pp. 614-617, (1999)
28. K. Xu, S. Liu, J. Zhao, W. Sun, and G. Li, "Analysis of simulation of multi-terminal electro-optic modulator based on p-n junction in reverse bias," Opt. Eng., vol. 54, no. 5, 057104, (2015)
29. M. du Plessis, H. Aharoni and L. Snyman, "Two- and multi-terminal silicon light emitting devices in standard CMOS/BiCMOS IC technology," Physica Status Solidi (a), vol. 201, no. 10, pp. 2225-2233, (2004)
30. S. Liu, W. Sun, T. Huang, and C. Zhang, "Novel 200V power device with large current capability and high reliability by inverted HV-well SOI technology," 25th International Symposium on Power Semiconductor Devices and ICs (ISPSD), pp. 115-118, (2013)
31. B. van Drieënhuizen and R. Wolffenbuttel, "Optocoupler based on the avalanche light emission in silicon," Sens. Actuators A, Phys., vol. 31, iss. 1-3, pp. 229-240, (1992)