xIlkogretim Online - Elementary Education Online,2021; Vol 20 (Issue 1): pp.2260-2264
http://ilkogretim-online.org
doi: 10.17051/ilkonline.2021.01.250

Silicon-On-Insulator Photodetectors: Opportunity and Challenge

Hiroshi Inokawa*, Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan, *inokawa.hiroshi@shizuoka.ac.jp
Hiroaki Satoh, Research Institute of Electronics, Shizuoka University, Hamamatsu, Japan
Anitharaj Nagarajan, Graduate School of Science and Technology, Shizuoka University, Hamamatsu, Japan, Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Chennai, India
Aruna Priya Panchanathan, Department of Electronics and Communication Engineering, SRM Institute of Science and Technology, Chennai, India
Revathi Manivannan, Graduate School of Science and Technology, Shizuoka University, Hamamatsu, Japan
Durgadevi Elamaran, Graduate School of Science and Technology, Shizuoka University, Hamamatsu, Japan

Abstract- Although the silicon-on-insulator (SOI) is not popular as a material for photodetectors due to the small light absorption in the thin silicon layer, it brings new opportunities in photodetectors based on the phenomena such as optical confinement, carrier confinement and thermal isolation. This report introduces the unique uses of such phenomena found in the SOI photodiode with surface plasmon (SP) antenna, SOI MOSFET single-photon detector and SOI MOSFET terahertz (THz) bolometer.This study aims to study the roles of digital media in affecting women with hijab. Women who wear hijab somehow spread through publications and media participation in the dissemination of Hijab types. The aim and their understanding of Hijab's mode have been challenged in studying the roles of media in influencing women. A comprehensive study of 60 women was carried out to assess if media in modernization Hijab affects women in the use of Hijab. Results have been presented, and it has been shown that the media is using its resources entirely to manipulate women who wear Hijab regardless of their true intent. Hijab apparel sales media to continue in the fashion line. The Islamic laws continue to be styled by Muslim women. Technology helps spread news or updates of the current Hijab mode to everyday Muslim people in today's modern world. Changes to the Hijab mode may be accepted as one of the fashion trends during this period. However, to not deceive Islam's missionary, the relevance or the real prospects should be strengthened by Hijab.

Keywords: silicon-on-insulator (SOI); surface plasmon (SP) antenna, single-photon detectior, terahertz (THz) bolometer.

I INTRODUCTION

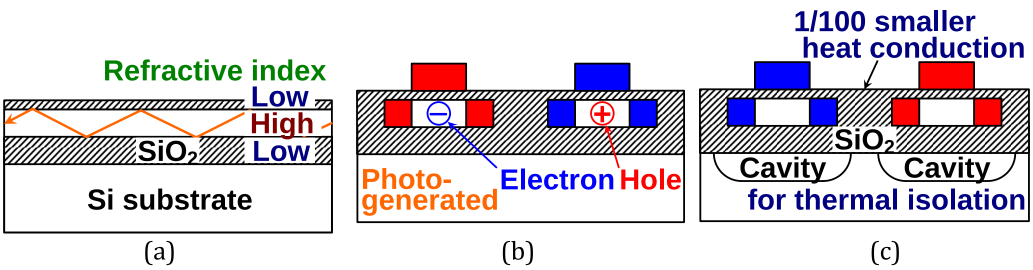


Figure 1. Unique characteristics of SOI for photodetection. (a) Optical confinement, (b) carrier confinement, and (c) thermal isolation.

Silicon-on-insulator (SOI) is a unique material consisting of single-crystal top silicon (Si) layer, buried Si dioxide (BOX) layer and supporting Si substrate. It features high-density integration and small parasitic capacitance, steep subthreshold slope, small substrate bias effect, *etc.* and therefore it has been used in the high-performance microprocessors, dedicated low-power electronics, RF switches, *etc.* Moreover, the ultrathin SOI is regarded as a viable solution for integrated circuits in 22-nm generation or later because of the excellent short-channel and low-power characteristics, and lower design cost compared to the fin-type FET technology.

Although the SOI is not popular for photodetectors due to the small light absorption in the thin Si layer, it actually provides distinctive features to them based on optical confinement, carrier confinement (floating body effect) and thermal isolation as illustrated in Figure. 1, which lead to enhanced light absorption, sensitive detection of photo-generated carriers (electrons or holes) and sensitivity enhancement in thermal detectors, respectively. In this report, some examples of such SOI characteristics found in photodiode (PD) with surface plasmon (SP) antenna, MOSFET single-photon detector, and MOSFET terahertz (THz) bolometer will be introduced.

II SOI PD WITH SP ANTENNA

In order to address the issue of low absorption efficiency in the thin SOI, the SP antenna consisting of a gold (Au) line-and-space (L/S) grating is placed above the lateral pn-junction PD [Figure. 2(a)], which resonantly enhances the absorption at a specific wavelength set by the grating period p [*e.g.* absorption efficiency for p= 300 nm reaches 60% at the wavelength of 700 nm as shown in Figure. 2(b)] 1.

This PD with SP antenna has wavelength and polarization selectivities, and is useful in hyperspectral imaging, polarized imaging, polarization-based optical communications, *etc.* Since the L/S grating serves as an optical coupler between incoming light and laterally propagating light in the SOI slab waveguide, the phase matching condition between the diffracted light and the waveguiding modes depends sensitively on the light incident angle. The spatial pattern of QE in the polar coordinate of azimuth and elevation angles is precisely analyzed [Figure. 2(c)], and the PD is found to surpass the conventional angle-sensitive pixel (ASP) in terms of angular resolution and QE 2,3. This will bring new opportunities in monocular three-dimensional (3D) imaging, lensless imaging, *etc.*

Since the phase matching condition is modulated by the refractive index (RI) of the medium around the SP antenna, the PD can also be used as a RI-based biosensor, in which the coupling between the analyte and the receptor at the sensor surface is detected as the change in the effective RI. We could successfully demonstrate that the detection limit was as small as 2.4×10^{-5} RI unit 4, which was comparable to that of conventional surface plasmon resonance (SPR) sensor. Note that the largest advantage of the proposed biosensor is that a large number of sensors can be integrated in a single chip, and thereby the throughput of the analysis can be greatly enhanced.

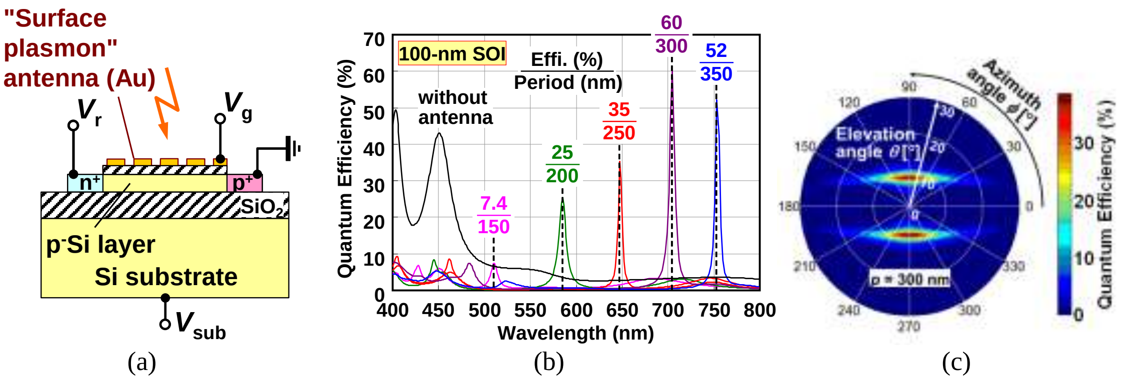
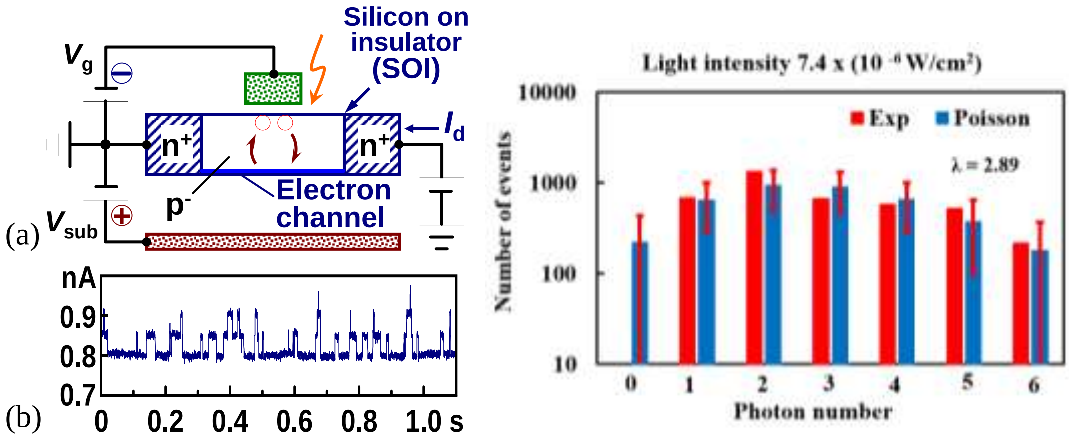


Figure 2. (a) Cross-sectional view of the SOI PD with SP antenna, (b) spectroscopic responce for various grating periods, and (c) incident angle dependence of the QE.

III MOSFET SINGLE-PHOTON DETECTOR

As the size of the MOSFET is shrunk to tens of nanometers, the charge sensitivity becomes so high that a single charge (*i.e.* individual electron or hole) can be detected. When holes are generated in the body of n-channel SOI MOSFET by the incident photons, holes are stored below the negatively biased top gate, and the presence of the holes are detected as the discrete change of the electron current in the bottom channel induced by the positively biased bottom gate (substrate) [Figure. 3(a)] 5. This type of single-photon detector features low dark count (~0.01 s^{-1}) even at room temperature, low-voltage (~1 V) operation and photon number resolution, which cannot be realized by the conventional single-photon detectors such as photomultiplier tube (PMT) and avalanche photodiode (APD).

The drawback of this nanometer-scale photodetector is the small QE due the small volume of Si for light absorption, which can be partially resolved by the use of the SP antenna 6. Another issue is the complex output signal waveforms [Figure. 3(b)] with rising and falling edges that correspond to hole generation by the photon incidence and spontaneous hole recombination, respectively, and current levels corresponding to number of stored holes that includes the memory of the previous hole generation and is not the same as the latest hole generation. In order to analyze the waveforms and find out the timing and number of generated holes in the latest photon incidence event, dedicated signal processing algorithm is developed and implemented to field programmable gate array (FPGA) to process the signal in real time 7. The proper operation of the signal processor is successfully verified by the photon number statistics [Figure. 3(c)] in a given observation time at various light intensities, which accurately follow the Poisson distribution.



(c)

Figure 3. Cross-sectional view of the SOI MOSFET single-photon detector, (b) drain current I_d waveform, and (c) an example of the photon number statistics.

The drawback of this nanometer-scale photodetector is the small QE due the small volume of Si for light absorption, which can be partially resolved by the use of the SP antenna 6. Another issue is the complex output signal waveforms [Fig. 3(b)] with rising and falling edges that correspond to hole generation by the photon incidence and spontaneous hole recombination, respectively, and current levels corresponding to number of stored holes that includes the memory of the previous hole generation and is not the same as the latest hole generation. In order to analyze the waveforms and find out the timing and number of generated holes in the latest photon incidence event, dedicated signal processing algorithm is developed and implemented to field programmable gate array (FPGA) to process the signal in real time 7. The proper operation of the signal processor is successfully verified by the photon number statistics [Fig. 3(c)] in a given observation time at various light intensities, which accurately follow the Poisson distribution.

IV SOI MOSFET THz Bolometer

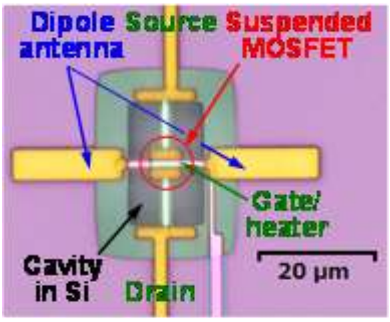


Figure 4. Optical micrograph of the SOI MOSFET bolometer.

The MOSFET fabricated in the SOI is surrounded by SiO_2 which has two orders of magnitude smaller thermal conductivity than that of Si, and therefore the temperature becomes higher for a given input power. In addition, the BOX can be used as an etching stopper for cavity formation inside the Si substrate resulting in the suspended structure with excellent thermal isolation. These features are beneficial in fabricating thermal detectors such as bolometers, in which reduction of the thermal conductance is the key to attain high sensitivity. We have successfully used the MOSFET as a temperature sensor for THz antenna-coupled bolometer 8, in which the polysilicon gate serves as the load resistance of the antenna to heat up the MOSFET (Figure. 4), and the change in the threshold voltage is amplified by the MOSFET itself to realize high responsivity, that is the ratio of output voltage to input power 9. As summarized in Table I, the responsivity of 5.16 kV/W obtained by the n-channel MOSFET and the noise-equivalent power (NEP) of 170 pW/Hz$^{1/2}$ by the p-channel MOSFET are the best among bolometers with various temperature sensors such as resistive thermistors, pn-junction diodes, etc, Table 1. Shows the Performance Comparison among the Bolometers with Different Temperature Sensors.

Table 1. Performance Comparison among the Bolometers with Different Temperature Sensors.

Bolometers	Noise@10Hz ($V/Hz^{1/2}$)	Responsivity R_v (V/W)	NEP ($W/Hz^{1/2}$)
N-channel MOSFET	1.27×10^{-6}	5.16 k	2.45×10^{-10}
P-channel MOSFET	2.79×10^{-7}	1.64 k	1.70×10^{-10}
Diode (w/o body doping)	2.08×10^{-7}	109	1.99×10^{-9}
Diode (with p-doping)	2.27×10^{-7}	106	2.15×10^{-9}
Resistive (n^+ single-Si)	2.70×10^{-8}	5.27	5.12×10^{-9}
Resistive (p^+ single-Si)	7.72×10^{-8}	12.8	6.01×10^{-9}
Resistive (n^+ poly-Si)	1.78×10^{-8}	2.69	6.59×10^{-9}

V CONCLUSION

In this report, SOI-based photodetectors that utilize the unique phenomena of optical confinement, charrier confinement and thermal isolation are introduced. These are effective not only to enhance the sensitivity but also to give new functionalities such as incident angle detection, biosensing, photon-number-resolving detection, *etc.* These results, together with the recent evolution of SOI CMOS technology, will lead to new opportunities in optoelectronic integrated circuits.

Acknowledgment

This work was supported by Japan-India Science Cooperative Program between JSPS and DST (Grant No. JPJSBP120207708), JSPS KAKENHI (Grant No. 18K04261), the Cooperative Research Project of the Research Center for Biomedical Engineering with RIE, Shizuoka University, and the Cooperative Research Project Program of RIEC, Tohoku University. The authors are indebted to the Solid State Division of Hamamatsu Photonics K.K. for providing the SOI photodiodes and MOSFETs.

References

1. H. Satoh, A. Ono, and H. Inokawa, "Enhanced Visible Light Sensitivity by Gold Line-and-Space Grating Gate Electrode in Thin Silicon-On-Insulator p-n Junction Photodiode," IEEE Trans. Electron Devices, Vol. 60, No. 2, pp. 812-818, 2013.
2. Nagarajan, S. Hara, H. Satoh, A. P. Panchanathan, and H. Inokawa, "Angular selectivity of SOI photodiode with surface plasmon antenna," IEICE Electronics Express, Vol. 17, No. 13, pp. 20200187_1-6, 2020.
3. Nagarajan, S. Hara, H. Satoh, A. P. Panchanathan, and H. Inokawa, "Angle-Sensitive Detector Based on Silicon-On-Insulator Photodiode Stacked with Surface Plasmon Antenna," Sensors, Vol. 20, No. 19, pp. 5543_1-14, 2020.
4. H. Satoh, K. Isogai, and H. Inokawa, "Optical Response of SOI Photodiode with Gold Line-and-space Grating to Biomolecular Interactions," Progress In Electromagnetics Research Symposium (PIERS) Abstracts, p. 260 (Xiamen, China, Dec. 17-20, 2019).
5. W. Du, H. Inokawa, H. Satoh and A. Ono, "SOI metal-oxide-semiconductor field-effect transistor photon detector based on single-hole counting," Optics Letters, Vol. 36, No. 15, pp. 2800-2802, 2011.
6. Y. Sharma, H. Satoh, and H. Inokawa, "Application of bow-tie surface plasmon antenna to silicon on insulator nanowire photodiode for enhanced light absorption," IEICE Electronics Express, Vol. 15, No. 11, pp. 20180328_1–10, 2018.

7. R. Manivannan, H. Satoh, and H. Inokawa, "Photon-number Statistics Observed by SOI MOSFET Single-Photon Detector with Real-time Signal Processing," IEEE Silicon Nanoelectronics Workshop (SNW-20) pp. 65-66 (Honolulu, HI, USA (Virtual), June 13-14, 2020).
8. Banerjee, H. Satoh, D. Elamaran, Y. Sharma, N. Hiromoto, and H. Inokawa, "Performance improvement of on-chip integrable terahertz microbolometer arrays using nanoscale meander titanium thermistor," J. Appl. Phys., Vol. 125, No. 21, pp. 214502_1-12, 2019.
9. D. Elamaran, Y. Suzuki, H. Satoh, A. Banerjee, N. Hiromoto, and H. Inokawa, "Performance Comparison of SOI-Based Temperature Sensors for Room-Temperature Terahertz Antenna-Coupled Bolometers: MOSFET, PN Junction Diode and Resistor," Micromachines, Vol. 11, No. 8, pp. 718_1-16, 2020.