Nano-SOI Photodetectors for High Sensitivity and Unique Functionality

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Nano-SOI Photodetectors for High Sensitivity and Unique Functionality

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***Abstract* —Silicon-on-insulator (SOI) has unique features as a material for photodetectors, such as optical confinement, carrier confinement and thermal isolation effects. This report discusses such features by taking SOI photodiode with surface plasmon antenna, SOI MOSFET single-photon detector and SOI MOSFET terahertz bolometer as examples.**

Keywords: Silicon-on-insulator (SOI), photodetector, surface plasmon antenna, single-photon detector, terahertz bolometer

I. Introduction

In the field of large-scale integrated circuits, silicon-on-insulator (SOI) holds distinctive position, but is not so popular as a material for photodetector mainly due to the small optical absorption in the limited thickness of the SOI layer. However, SOI actually has unique features for photodetectors as summarized in Fig. 1, which are optical confinement (waveguiding), carrier confinement, and thermal isolation effects. In this report, we will introduce photodetectors utilizing such features.

II. SOI PD with Surface Plasmon Antenna

To solve the problem of small optical absorption, surface plasmon (SP) antenna of metallic grating is placed above the lateral SOI pn-junction photodiode (PD) as shown in Fig. 2, which provides efficient coupling between the incident light and the waveguiding mode in the SOI layer, resulting in an order of magnitude higher light absorption [1].

Since this coupling is sensitive to the incident angles and polarization of the entering light as shown in Fig. 3, this PD can be used as an angle sensitive pixel (ASP) for monocular three-dimensional imaging, range finding, etc [2].

The refractive index (RI) of the media around the SP antenna also affects the optical coupling, which leads to the label-free biosensing based on the RI change induced by the biomolecules attached on the SP antenna surface [3].

III. SOI MOSFET single-photon detector

The carrier confinement in the body of SOI MOSFET results in a large threshold voltage change by the photogenerated minority carriers. As the MOSFET is scaled down, the sensitivity to the minority carrier becomes so high that even a single carrier can be detected, which realizes the single-photon detection [4]. In the particular example shown in Fig. 4, the positive substrate voltage (V_{SUB}>0) induces electron channel on the backside of the SOI layer, photogenerated holes are stored below the negatively biased lower gate (V_{LG}<0), and the presence of single holes are detected as discrete drain current levels.

Since this multilevel signal includes rising edges related to the photon entries and uncorrelated falling edges caused by the hole recombination (see analog-to-digital signal in Fig. 5), dedicated signal processing algorithm consisting of differentiation, integration and discrimination (see other signals in Fig. 5) is developed to detect the timing and the number of photogenerated holes. The proper operation of this processor is then verified by the numbers of generated holes that actually follow the Poisson statistics (Fig. 6) [5].

IV. SOI MOSFET Terahertz Bolometer

The SOI devices surrounded by SiO_2 with two orders of magnitude smaller thermal conductivity than that of Si experiences larger temperature rise for a given input power, which is beneficial in realizing high-sensitivity thermal detectors such as a bolometer [6]. The buried oxide is also useful as an etching stopper when a cavity for thermal isolation is formed inside the Si substrate. Fig. 7 shows an example of antenna-coupled terahertz bolometer in which the MOSFET is used as a temperature sensor. As shown in Table I, among various SOI-based temperature sensors, n-channel MOSFET has the largest responsivity due to its large voltage amplification, and p-channel one has the smallest noise-equivalent power (NEP) due to its small drain current noise [7].

V. Conclusion

SOI-based photodetectors that feature optical confinement, charrier confinement and thermal isolation effects are introduced in this report. These effects are useful not only in enhancing the sensitivity but also in realizing new functionality such as incident angle detection, biosensing, photon number discrimination, etc. These results open up a new opportunity for optoelectronic integrated circuits.

Acknowledgments

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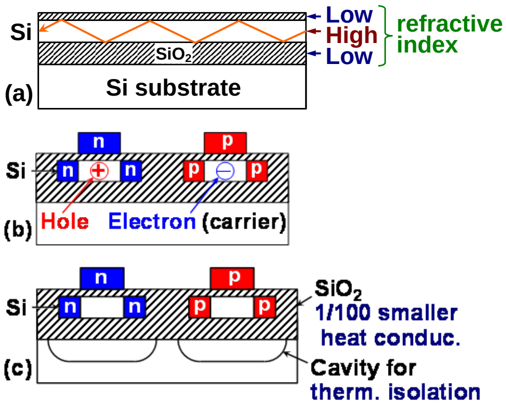
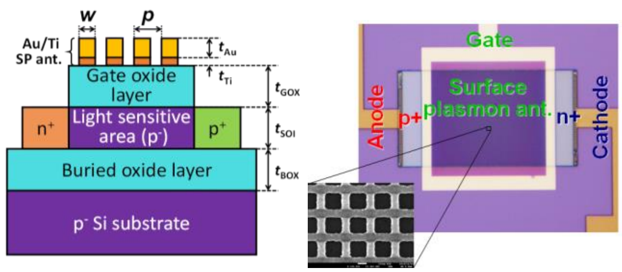


Fig. 1 Unique SOI features for photodetector. (a) Optical confinement (waveguiding) effect, (b) carrier confinement effect, and (c) thermal isolation effect.



(a) (b)

Fig. 2(a) Cross-sectional view of the SOI photodiode with surface plasmon antenna, and.(b) Tops view of the same.

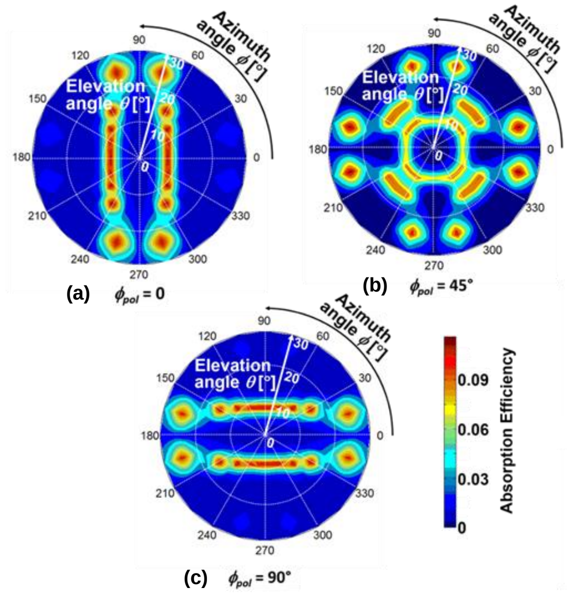


Fig. 3 Spatial sensitivity pattern of the SOI photodiode with surface plasmon antenna. Polarization angles ϕ_{pol} of the incident light are (a) 0°, (b) 45° and 90°, respectively [2].

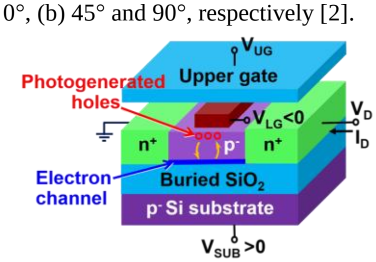


Fig. 4 Schematics of the SOI MOSFET single-photon detector.

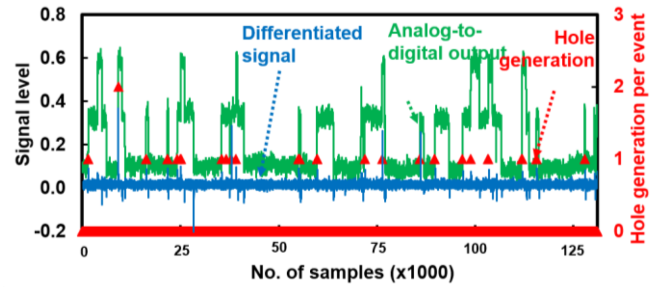


Fig. 5 Typical waveforms during the signal processing of the drain current.

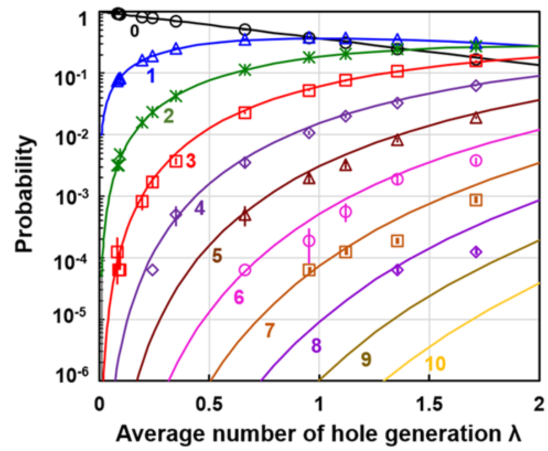


Fig. 6 Numbers of photo-generated holes in SOI MOSFET, which is found to follow the Poisson statistics [5].

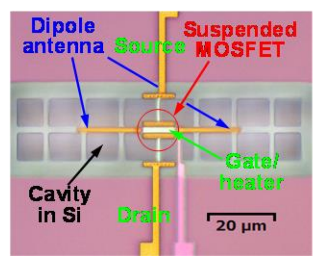


Fig. 7 Optical micrograph of the antenna-coupled terahertz bolometer with MOSFET-based temperature sensor.

Table I Comparison of the SOI CMOS-based temperature sensors for terahertz antenna-couple bolometer [7].

Sensors	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}