ICPD: an SOI-based photodetector with high responsivity and tunable response spectrum

J. Wan[1*], WZ. Bao[1], JN. Deng[1], ZX. Guo[1], XY. Cao[1], BR. Lu[1], YF. Chen[1], A. Zaslavsky[2], S. Cristoloveanu[3] and M. Bawedin[3]

[1]State key lab of ASIC and System, Fudan University, China
[2]Department of Physics and School of Engineering, Brown University, Providence, RI02912, USA
[3]IMEP-LAHC, INP-Grenoble/Minatec, CS50257, Grenoble 38016, France
Email: jingwan@fudan.edu.cn

Abstract

A novel photodetector based on a silicon-on-insulator (SOI) substrate is demonstrated experimentally in this work. The device uses the interface coupling effect in an SOI transistor structure to amplify the photocurrent, and thus achieves extremely high responsivity up to 6×10^4 A/W. The responsivity of the device under ultraviolet (UV) light is much higher than that under visible and near-infrared light, which implies potential application in visible-blind UV detection. Furthermore, a MoS_2 gate is combined with the SOI-based photodetector to tune the response spectrum and shift it to the near-infrared band. With high reponsivity and tunable response spectrum, the ICPD device can find many interesting applications.

1. Introduction

Silicon-on-insulator (SOI) devices have been attracting interest from both research and industry communities thanks to their unique characteristics compared to bulk Si. They are not only widely used in conventional integrated circuit (ICs) due to such advantages as low-power and high-frequency operation, as well as radiation hardness, but also as a flexible substrate for novel device concepts [1, 2]. SOI is also a wonderful substrate for optical waveguide and a variety of photonic devices, and thus can be used in optical communication and optical-based sensors [3, 4].

Photodetectors based on SOI substrates play a vital role in electronic-photonic integrated circuits (EPICs) to convert optical signals to the electrical domain. Due to the low-power and radiation hardness nature of the SOI, SOI-based photodetectors can also find application in aerospace imaging systems. A challenge for SOI photodetectors is the thin top Si channel. Due to the requirement to suppress the short channel effects (SCEs) in modern ICs, the top Si channel is typically less than 10 nm thick, leading to very poor quantum efficiency in light absorption. Conventional p-i-n photodiodes built in top Si layer of SOI show modest responsivity (down to 0.0075 A/W) [5]. In order to enhance the performance, photodetectors with internal gain and much improved responsivity have also been demonstrated. Photodetectors based on gate-body tied MOSFET structures achieve responsivity up to 1000A/W [6], while a bipolar transistor built in a nanowire yielded a responsivity of ~100A/W [7]. Alternatively, instead of relying on absorption in the thin top Si layer, an embedded p-n photodiode has been placed in the Si substrate for photodetection in Ref.[8, 9].

Previously, we proposed a novel SOI-based photodetector named interface-coupled photodetector (ICPD) and reported comprehensive simulation results and preliminary experimental data [10]. The ICPD uses the interface coupling effect to amplify the photocurrent, and achieves high responsivity. In this work, we study the device operation as a function of illumination wavelength λ. The responsivity reaches 6×10^4 A/W at $\lambda = 300$ nm, much higher than that in visible and near-infrared regions. We also demonstrate a novel variant of the ICPD: MoS_2 layer is transferred onto the top Si channel and serves as the control gate. The response of the device with an MoS_2 gate changes dramatically, with the peak responsivity shifting to the near-IR. The high responsivity and tunable response spectrum of the ICPD are attractive features for photodetection application.

2. Device structure and response spectrum

Figure 1 shows schematically the configuration and operating principle of the ICPD. The device structure is similar to a MOSFET, except for the gaps between the gate and source/drain electrodes. As explained previously [10], these underlaps are helpful to improve the photoresponsivity. At negative backgate bias ($V_{BG}<0$), a hole channel is formed at the bottom interface of the Si film and conducts current between source and drain. Under incident illumination, the photogenerated electrons are attracted by the positively biased front gate (V_G) and accumulate at the top interface of the film. The accumulated electrons screen the electric field from the front gate and thus reduce the coupling between the front gate and the bottom hole channel, which results in higher hole current than for the device operated in the dark. In other words, the threshold voltage of the back channel is lowered by illumination. The mechanism of operation is similar to the MSD effect in SOI transistors where the front channel was formed by band-to-band tunneling rather than by illumination [11]. Note that photogenerated electrons do not contribute to the photocurrent, but rather change the coupling to the back hole channel, which provides internal gain.

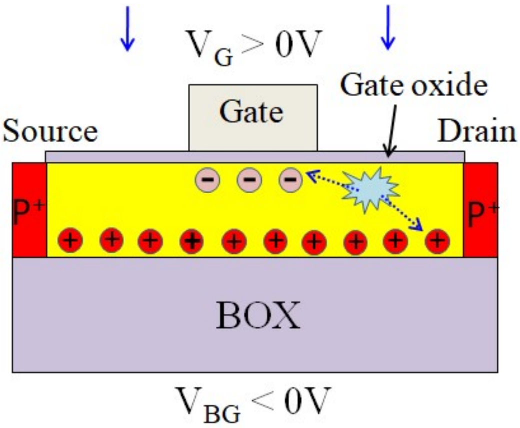

Fig. 1 Schematic illustration of the operating principle of the ICPD.

The device was fabricated in a fully CMOS-compatible process. The SOI substrate used for fabrication has a 200 nm top Si layer, 500 nm buried oxide (BOX) and a lightly p-doped (10^{15} cm^{-3}) substrate. The isolation of the device is achieved by photolithography followed by wet etching in TMAH. Then, 150nm thick aluminum (Al) is deposited at the source/drain metallization and 30 nm ALD-deposited Al_2O_3 is used as the gate oxide. The gate electrode is formed by e-beam lithography and deposition of 150 nm Al. The device is eventually annealed at 500 °C. The top-down scanning electron microscope (SEM) image of the fabricated device is shown in Fig. 2. The channel length (gap between the source and drain) and width are both 10 µm. The gate placed at the middle of the channel is 1 µm long, see Fig. 2.

The device is measured under various front and back gate voltages. Figure 3(a) shows the I_D-V_{BG} characteristics at a fixed V_D = -1 V and V_G ranging from -1 V to 2 V with a step of 1 V. The device functions as a p-type FET, due to the formation of p-doped S/D regions via Al diffusion, as already explained in our previous report [10]. As V_G increases from -1 V to 2 V, the threshold voltage (V_{th}) of the back channel shifts dramatically and becomes more negative, see Fig. 3. This indicates a strong coupling between the front gate and the bottom interface, which is essential for amplification of the photocurrent in the ICPD.

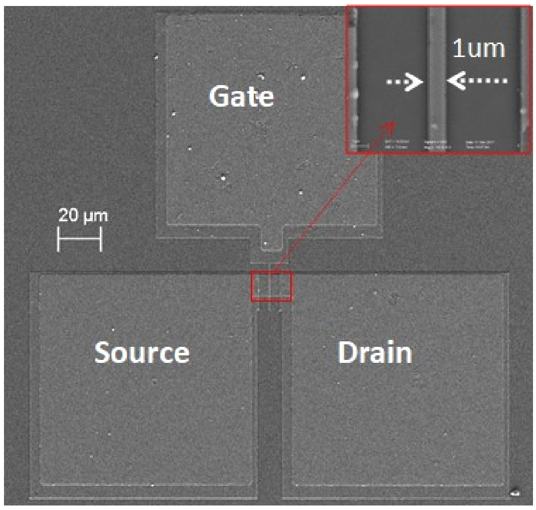

Fig. 2 Top-down SEM image of the fabricated device.

The device was then measured under various illumination conditions. Figure 3(b) compares the I_D-V_{BG} curves of the device in the dark and under λ = 520 nm illumination at 100 µW/cm^2 intensity (produced by wavelength-tunable monochromatic source). Under illumination, the V_{th} is less negative and drain current of the device is increased significantly, see Fig. 3(b).

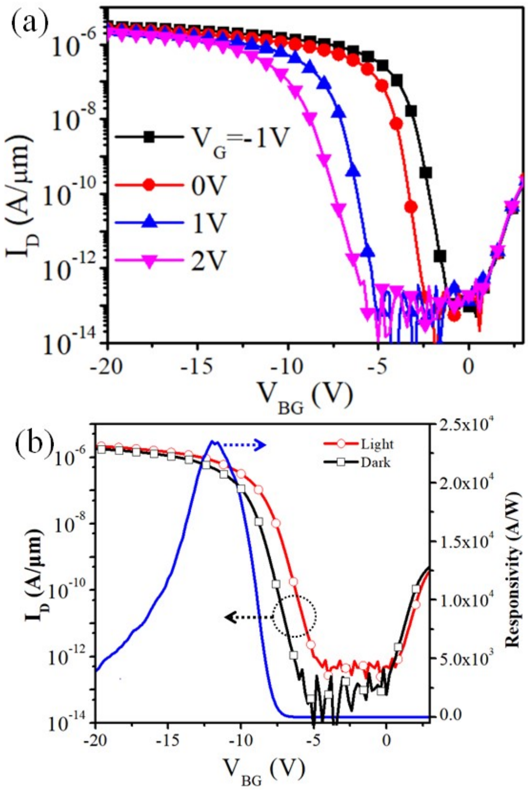

Fig. 3 (a) I_D-V_{BG} characteristics of the device as a function of V_G. (b) Shift of V_{th} under illumination and device responsivity.

The responsivity is defined as the change in the drain current due to illumination divided by the light power received by device. The relation between responsivity and V_{BG} is shown in Fig. 3(b), with a peak of 2.4×10^4 A/W at V_{BG} = -12 V.

The response spectrum is obtained by extracting the responsivity of the device as a function of λ in the 300–1000 nm range, see Fig. 4. As the device operates in subthreshold region under V_{BG} = -8 V, the responsivity increases by more than 3 decades as λ is reduced from 1000 to 300 nm. A similar trend is observed for operation in moderate inversion under V_{BG} = -12 V. The responsivity reaches around 6×10^4 A/W at λ = 300 nm. The UV-sensitive spectrum is due to thin top Si layer which absorbs light more efficiently at shorter wavelengths. This feature could be attractive for flame detection, missile warning and UV communications [12, 13]. The thickness of the top Si layer can be further reduced in order to achieve better blindness to visible light.

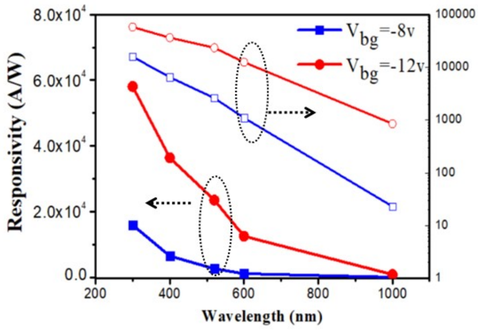

Fig. 4 Responsivity spectrum of the ICPD under V_{BG}= -8 and -12 V. The responsivity is plotted in both linear and logarithm scales.

3. ICPD with MoS_2 gate

In applications such as optical communication and image sensing, high responsivity in visible and near-IR bands is required. Here, at λ = 700–1000 nm, both conventional SOI photodetectors and the ICPD have relatively low performance (see Fig. 4 for the ICPD results). In order to shift the sensitivity range and produce an ICPD with high responsivity in the visible and near-IR, we propose a novel device architecture using an MoS_2 gate. Two-dimensional semiconductor materials, such as molybdenum disulfide (MoS_2), have been attracting wide research interest especially for photodetection applications. Photodetectors with MoS_2 show high responsivity especially in visible and near-infrared regions [14, 15].

With the MoS_2 gate deposited directly on top of the Si film, our device operates in the JFET mode, see the top-down image in Fig. 5 [16]. The MoS_2 layer is around 45 nm thick, confirmed by the atomic force microscope (AFM). The MoS_2 can efficiently absorb the incident light, which is further amplified by the source-drain channel built in SOI.

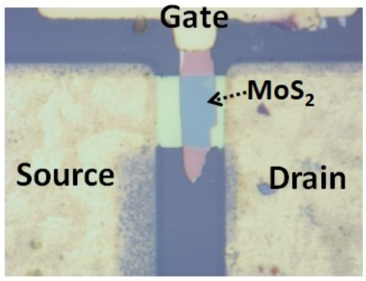

Fig. 5 Top-down image of the ICPD with MoS_2 gate under microscope.

Device characteristics under various gate biases and illumination conditions at fixed V_D = -1V are shown in Fig. 6. The comparison of dark current between V_G = -1 and +1V in Fig. 6 shows that the I_D-V_{BG} characteristics are strongly shifted, compared to the metal-gated devices in Fig. 3(a). The MoS_2 gate exerts effective control over the channel. Under illumination at λ = 750 nm with 500 $\mu W/cm^2$ intensity, the V_{th} of the back channel increases (becomes less negative) under V_G = 1V. On the other hand, a negatively biased front gate is not able to accumulate photoelectrons and thus no apparent shift of V_{th} is observed in Fig. 6. The responsivity exhibits a similar trend to the conventional ICPD with a peak close to 4000 A/W at V_{BG} = -9 V. The peak responsivity is somewhat lower than in the conventional ICPD of Fig. 3, probably due to the short lifetime in MoS_2 causing lower internal gain.

The device with the MoS_2 gate was then measured under illumination with various wavelengths. Figure 7 shows the response spectra of the device operating in both linear and subthreshold regions under V_{BG} = -9 and -5 V respectively. Unlike the conventional ICPD, which has high responsivity in the UV band, the MoS_2-gated device shows high responsivity in near-IR band with a peak at 750 nm. This response spectrum is attributed to the excellent light absorption by the MoS_2 gate.

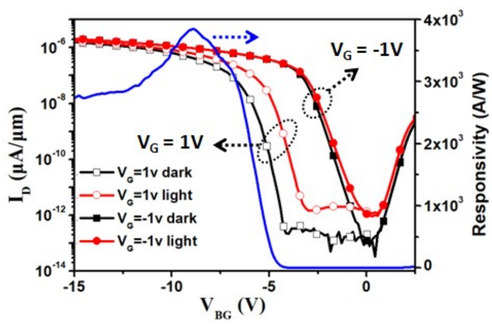

Fig. 6 I_D-V_{BG} characteristics and responsivity of the MoS_2-gated device for V_G= -1 and 1 V, in the dark and under illumination.

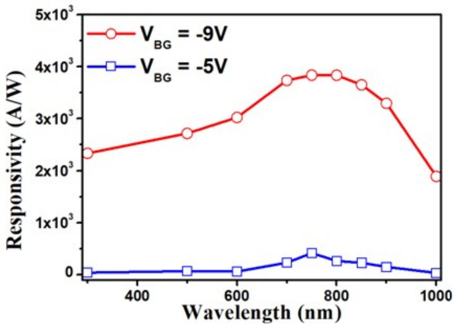

Fig. 7 Response spectra of the MoS_2-gated ICPD at V_{BG}= -5 and -9 V.

Compared to photodetectors based on pure MoS_2, the ICPD with MoS_2/SOI heterostructure combines the advantages of both MoS_2 absorption and Si channel characteristics. The MoS_2 gate absorbs long-wavelength light more efficiently than Si, while the Si channel has higher mobility and better contact formation than MoS_2. This provides both high quantum efficiency and high internal gain, and leads to promising responsivity, especially under long wavelength illumination.

4. Summary

The ICPD uses interface coupling to amplify the photocurrent and achieves high responsivity of up to 6×10^4 A/W at $\lambda = 300$ nm. The response spectrum of the conventional ICPD exhibits high sensitivity in the UV and can be potentially used for visible-blind UV detection. For near-IR operation, an MoS_2-gated variant of the ICPD has also been demonstrated. The use of an MoS_2 gate is helpful for the absorption of long-wavelength light and thus shows enhanced responsivity in the near-IR region. Combining ICPDs with and without the MoS_2 gate, a tunable response spectrum can be achieved, which is very attractive for multi-band photodetection.

Acknowledgments

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