NOVEL SEMICONDUCTOR DEVICES BASED ON SOI SUBSTRATE

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ABSTRACT

In this work, we review our recent studies on several novel devices built on silicon-on-insulator (SOI) substrates. The sharp-switching Z^2-FET, based on a feedback mechanism, has been demonstrated as suitable for many applications. The PISD, capable of *in-situ* photoelectron sensing, has been used as a one-transistor active pixel sensor (1T-APS). Furthermore, an SOI/MoS_2 heterojunction FET has been demonstrated as both a photodetector with a dynamic response spectrum and as a novel one-transistor wavelength detector (1T-WD) with an output signal sensitive to the variation of wavelength rather than intensity.

Keywords—Silicon-on-insulator (SOI), low subthreshold swing, memory, photodetector, image sensor, 2D heterojunction materials

INTRODUCTION

Silicon-on-insulator (SOI) substrates have been widely used to fabricate integrated circuits (ICs) with high density, low power consumption and high operation frequency. They possess some unique advantages, such as reduced short channel effect, low parasitic leakage and capacitance [1-3].

We review two categories of novel devices based on SOI substrates that we developed in recent years: CMOS-compatible devices and SOI-2D hybrid devices. First, zero subthreshold swing and zero impact ionization FET (Z^2-FET) and photoelectron *in-situ* sensing device (PISD) are fully CMOS-compatible and have been demonstrated in cutting-edge VLSI technology [4, 5]. They are used as sharp switches in memory and image sensing applications, with extraordinary performance compared to conventional counterparts. Second, by combining SOI and the 2D semiconductor MoS_2 material, hybrid devices with unique functionalities have been demonstrated, such as the interface coupled photodetector (ICPD) showing a dynamically modulated response spectrum and the one-transistor wavelength photodetector (1T-WD) that is only sensitive to the incident wavelength λ rather than intensity [6, 7].

CMOS-COMPATIBLE DEVICES

The Z^2-FET is essentially a lateral p-i-n diode with the undoped channel partially covered by the front gate, see Fig. 1(a). Thanks to its feedback mechanism, the device turns on very sharply and shows gate-controlled hysteretic behavior, see Fig. 1(b) and (c). The Z^2-FET presents subthreshold swing (SS) < 1mV/dec, much lower than the conventional MOSFET limit. The gate-controlled hysteresis can be utilized in dynamic RAM (DRAM), static RAM (SRAM) and flash memory applications [8, 9]. Figure 1(d) shows the measured waveforms of Z^2-FET used as a DRAM. It has high density, high access speed and low power consumption compared to conventional 1T-1C DRAM. There are also many other applications of Z^2-FET, such as electro-static discharge (ESD) protection, photodetection, sharp logic switch and ion-sensitive sensor [10-12].

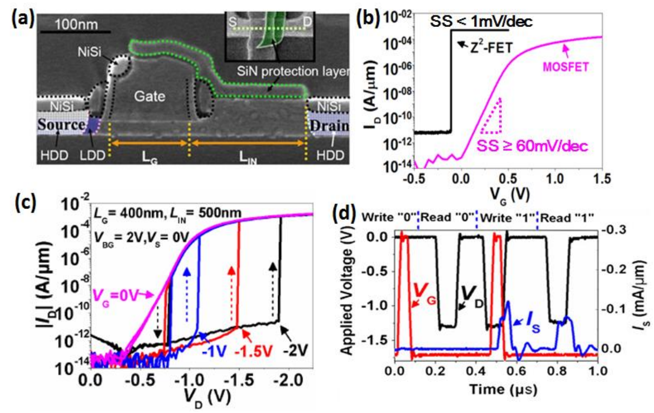

Fig. 1 (a) Z^2-FET structure with (b) I_D-V_G and (c) I_D-V_D characteristics. (c) Operating sequence of Z^2-DRAM.

A completely different SOI substrate-based device is shown in Fig. 2(a). A novel deep depletion effect in the SOI substrate is observed in the pseudo-MOS configuration, useful for photodetection application when combined with a backgate V_{BG} pulse, see Fig. 2(b) [13]. This mechanism was further elaborated into a fully CMOS-compatible PISD, schematically shown in Fig. 2(c) [5].

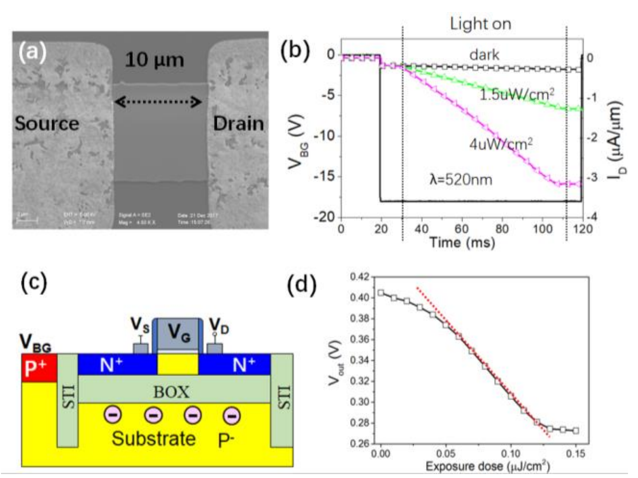

Fig. 2 (a) Original pseudo-MOS device prototype without a front gate and (b) photoelectrical characteristics. (c) Schematic view of the PISD and (d) the photoelectrical characteristics of a device fabricated in an advanced 22 nm FD-SOI process.

In the PISD, photoelectrons generated in the SOI substrate accumulate at the BOX/Si interface. The accumulated photoelectron modulates the threshold voltage (V_{th}) of the

MOSFET in the top Si channel, as illustrated in the experimental results of Fig. 2(d). The PISD is truly a one-transistor active pixel sensor (1T-APS), as it achieves photosensing, charge integration, buffer amplification and random access with only one transistor. The PISD is more compact than a conventional CMOS image sensor that combines a photodiode with three transistors.

SOI-2D MATERIAL HYBRID PHOTODETECTORS

Photodetectors with novel functionalities can be obtained by integrating 2D materials with SOI substrates. Figure 3(a) shows the SOI/MoS_2 heterojunction FET, where the MoS_2 is used as gate to control the SOI channel [6]. The device behaves as normal junction FET. However, photoelectrical measurements show that the response spectrum is tunable with the applied bias. As shown in Fig. 3(b), the increase of back-gate voltage from –9 V to zero can shift the peak of the response spectrum from the near-infrared (near-IR) to ultra-violet (UV). This is mainly attributed to the switch of photosensing junction between SOI and MoS_2 materials. The capability of modulating the response spectrum dynamically is attractive for multi-spectral photodetection and imaging.

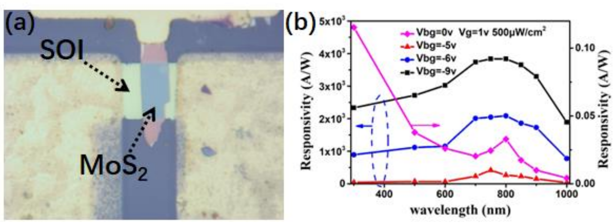

Fig. 3 (a) Heterojunction FET combining SOI and MoS_2, and (b) optical responsivity as a function of backgate bias V_{BG}.

Another interesting device obtained by combining MoS_2 and SOI is the one-transistor wavelength detector (1T-WD) [7]. It is essentially a MOSFET with MoS_2 as the top gate isolated with an HfO_2 dielectric from the thin 12nm Si channel, see Fig. 4(a). Both the top MoS_2 and the Si substrate act as photogates, but with opposite signs due to different doping polarities in the MoS_2 and bottom Si. As a result, the device shows ambipolar photoresponse: the zero photoresponse voltage shows a strong dependence on wavelength, but is not sensitive to the light intensity, as shown in Fig. 4(b). This wavelength detection property could be attractive for a number of applications.

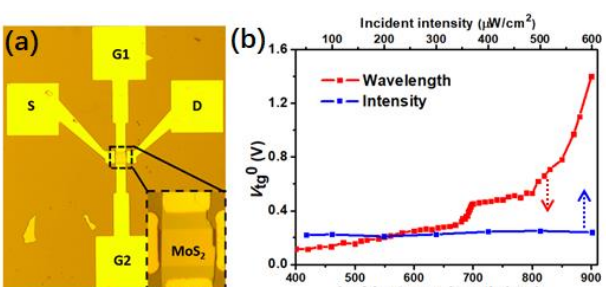

Fig. 4 (a) Structure of the 1T-WD combining SOI and MoS_2. (b) Photoresponse of the device under various light intensity and wavelength.

CONCLUSION

We have invented several novel devices based on SOI substrates. Of them, the Z^2-FET and PISD are fully compatible with advanced CMOS processing but are based on different device physics compared to conventional MOSFETs and exhibit high performance. On the other hand, SOI and MoS_2 have been combined to form hybrid devices leading to new photodetection functionalities, such as voltage-tunable response spectrum and photoresponse modulated only by incident wavelength.

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