Z^2-FET: a multi-functional device used for photodetection

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ABSTRACT

In this work, we explore the application of Z^2-FET in photodetection with TCAD simulation. Dynamic coupling effect is used to build up the carrier injection barrier and restore the feedback mechanism in Z^2-FET with thick Si layer. The device is then used for photodetection in two operation modes, where the photoelectron accumulating at the front gate interface reduces the turn-on voltage (V_{ON}) with a sensitivity up to 10V/(μJ/cm^2). With high output current and one-transistor random access ability, Z^2-FET can find potential application as compact one-transistor active pixel sensor (1T-APS).

INTRODUCTION

Z^2-FET (zero impact ionization and zero subthreshold swing FET) is a novel device operating with feedback mechanism between carriers flow and injection barriers [1]. It has extraordinary switching performances, with subthreshold swing SS < 1mV/dec, ON current I_{ON} > 1 mA/μm and ON/OFF ratio > 10^{10} [2]. The gate-controlled hysteresis in its output characteristics is further exploited for one-transistor DRAM application with high integration density and access time down to 1 ns [3, 4]. Owing to its fast switch and gate-controlled hysteresis, STMicroelectronics Inc. has integrated it with 28nm and 14nm fully depleted silicon-on-insulator (FD-SOI) process for electrostatic discharge protection (ESD), showing superior performance compared to conventional ESD devices [5]. Besides, Z^2-FET also find applications in flash memory, ion-sensitive sensor and co-integration in flexible substrate[6, 7].

Due to the low leakage and radiation-hardness of SOI substrate, the photodetector in SOI substrate is of great interest for potential low-power imaging application in aerospace system [8, 9]. In this work, the dynamic coupling effect in Z^2-FET is studied and extended to the photodetection application. Under illumination, the V_{ON} of Z^2-FET is reduced almost linearly as the light intensity increases, due to the coupling between the photoelectron and carrier injection barrier.

DYNAMIC COUPLING EFFECT

Conventional Z^2-FET is built on FD-SOI substrate, in which the thin top Si layer guarantees that injection barriers are formed in the whole channel. However, for photodetection application, the Si layer needs to be typically thicker than 200 nm to absorb the light efficiently. Figure 1(a) shows our simulated Z^2-FET structure with L_G = 0.5 μm, L_{IN}=1.5 μm, 200 nm top silicon film (T_{si}) and 500 nm BOX (T_{BOX}). Under a static bias of V_G = 5V and V_{BG} = –5V, the output characteristics, as V_D sweeps from 0V to 2.5V, does not show sharp switch and hysteresis which are typically observed in a conventional Z^2-FET, see the black curve in Fig. 1(b).

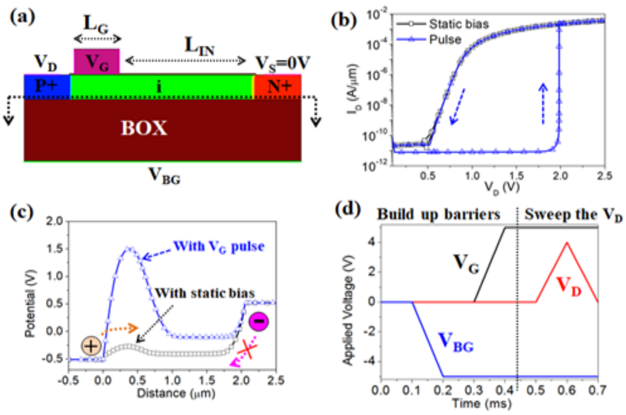

Figure1. (a) Schematic view of the simulated Z^2-FET structure. Comparison of (b) I_D-V_D characteristics with both sweeping forward and backward, and (c) potential profile of the device under static bias and pulse on the gate. (d) Waveforms of the applied bias on the device

The potential profile of the channel is investigated to understand this effect. The black curve in Fig. 1(c) shows the profile of the device, cut along the horizontal direction at the bottom of the channel. The hole injection barrier under the front gate almost disappears though the electron barrier near the source is still high. Without the hole barrier, the feedback process does not function. This is attributed to the thick top Si layer (200 nm), in which the inversion electron in the front-gate/channel interface screens the control of the front gate. Thus, the front gate fails to control the bottom part of the channel, just as in a partially depleted SOI (PD-SOI) MOSFET.

Dynamic coupling effect was initially found in PD-SOI MOSFET, where a fast gate pulse deeply depletes the channel before the thermal-generated electron accumulates at the front interface. It has been further exploited for one-transistor DRAM (1T-DRAM) application [10]. Here, it is used to rebuild the potential barrier. Instead of using static bias, a positive V_G pulse is applied following a negative V_{BG} pulse, as shown in Fig. 1(d). Sweeping the V_D forward and backward reveals the recovery of the sharp switch and hysteresis, see the blue curve in Fig. 1(b). As confirmed by the potential profile in Fig. 1(c), the potential barrier of hole is recovered due to the dynamic coupling effect by the applied pulse.

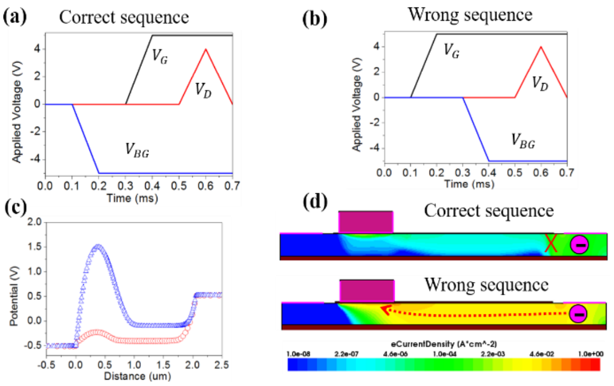

Figure 2. (a) and (b) correspond to different bias waveform sequence, respectively. (c) Potential results caused by different V_G and V_{BG} sequence. (d) Schematic view of the electrons flowing in channel under different bias sequence.

The potential formation is also affected by the sequence of the applied biases. The correct sequence shown in Fig. 2(a), same as Fig. 1(d), has been proven an effective approach to form the potential barriers for feedback mechanism, see the blue curve in Fig. 2(c). While an unexpected result is observed when V_G pulse is applied ahead of V_{BG} pulse, in which the potential barrier is much lower, as red curve shows in Fig. 2(c). We define this condition the wrong sequence, see Fig. 2(b). Since there is no V_{BG} pulse set firstly to form electron barrier, plenty of electrons from N^+ area flow into channel during the positive V_G pulse. These electrons shield the effect of V_G and reduces the potential barrier. Therefore, the correct sequence is V_{BG} pulse followed by V_G pulse, as shown in Fig. 2(a).

PHOTODETECTION APPLICATION

The dynamic coupling effect in Z^2-FET can be used for photodetection purpose. As seen in Fig. 3(a), the photogenerated electron is attracted by the $V_G > 0$ and accumulates at the front interface. This reduces the hole potential barrier at the bottom interface, just as the thermal-generated electron does. With lower hole barrier, the turn-on voltage is reduced. Figure 3(a) shows the bias and illumination conditions applied on the device. The carrier injection barriers are built by the V_G and V_{BG} pulses, followed by exposure to a 5 ms light pulse with a fixed wavelength of 520 nm and various intensity. After, V_D sweeps from 0V to 2.5V to investigate the I_D-V_D characteristics.

Figure 3(c) shows the output characteristics of the device after exposure to various light intensity. The turn-on voltage of the device is apparently reduced with higher light intensity. As explained above, this is due to the reduction of hole injection barrier by the photoelectrons. The relation between the V_{ON} and light intensity is almost linear and modulated by V_G, see Fig. 3(d). With higher V_G, the V_{ON} increases due to higher potential barrier, while the reduction slope is almost the same. The photodetection sensitivity extracted is around 10V/(μJ/cm^2), higher than that of a CMOS image sensor considering the small area of the device [11].

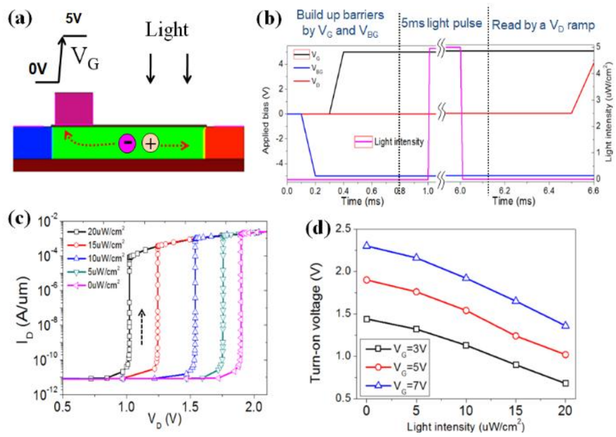

Figure 3. (a) Operation principle of the Z^2-FET used for photodetection. (b) Waveforms of the applied bias and light pulse on the device. (c) I_D-V_D characteristics of the device under various light intensity. (d) Relation between V_{ON} and light intensity under various V_G.

In addition, Fig. 4 shows an alternative operation mode where the sequence between V_D and light pulse is exchanged. As explained before, V_{BG} and V_G are firstly biased to build up the potential barriers in channel. The following V_D pulse is too low to overcome the injection barrier. As the device is shined by a light, more and more photo-electrons are accumulated under the front gate. This keeps reducing the hole injection barrier and eventually triggers the device, as seen in Fig. 4(a).

In this operation mode, higher light intensity produces photo-electrons faster, and thus the device turns on early, see Fig 4(b). This operation mode, in which the device is turned by a certain exposure dose, is very useful as an exposure triggered switch.

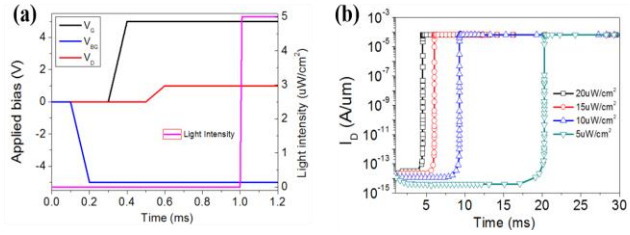

Figure 4. (a) Waveforms sequence of the alternative operation mode for photodetection application. (b) Relation between I_D and time under various light intensity when V_D=1V.

CONCLUSION

The dynamic coupling effect in the Z^2-FET with thick top Si layer is investigated which helps to restore injection barrier and feedback. This effect is used for photodetection showing high sensitivity up to 10V/(μJ/cm^2). Compared with conventional CCD and CMOS sensors, which requires charge transfer and extra transistors for signal amplification, the Z^2-FET used for photodetection directly converts light intensity into turn-on voltage and output high current. Besides, the one-transistor random access ability derived from its 1T-DRAM application makes it very promising for one-transistor active pixel sensor (1T-APS) application with more compact size compared to CMOS sensor.

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