A New Photodetector on SOI

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***Abstract*— In this work, we present a novel type of photodetector based on the Z²-FET (*zero* impact ionization and *zero* subthreshold swing) device. A dynamic coupling effect is used to form the carrier injection barriers that block the current flow in the Z²-FET. Our TCAD simulation shows that under illumination, photoelectrons accumulating under the gate effectively reduce the hole injection barrier, modulating the turn-on voltage and leading to photoresponse with excellent sensitivity and unique advantages.**

I. INTRODUCTION

A band-modulation device named *zero* impact ionization and *zero* subthreshold swing FET (Z^2-FET) has been demonstrated on a silicon-on-insulator (SOI) substrate with promising applications. The Z^2-FET turn-on is based on a positive feedback mechanism between the flow of carriers and their injection barriers, and shows outstanding electrical performance with low subthreshold swing and high I_{ON}/I_{OFF} ratio [1]. Besides, the Z^2-FET exhibits gate-controlled hysteresis in its output characteristics and can be used as a one-transistor capacitorless DRAM (1T-DRAM) with high density and operation speed [2, 3], as well as electrostatic discharge protection (ESD) and charge sensing [4-6].

Photodetectors built on SOI substrates are of great interest, owing to low power consumption and high radiation resistance. Photodetection devices based on various operation mechanisms, such as diodes, transistors and interface coupling effect photodetectors (ICPDs) have been demonstrated in SOI technology [7-10]. In this work, we extend the application of the Z^2-FET to photodetection by modifying the device geometry and employing TCAD simulation (Synopsys Sentaurus). The dynamic coupling effect [11], is investigated and utilized in the Z^2-FET to create carrier injection barriers. Under illumination, photogenerated electrons accumulate under the top gate and screen the coupling. This lowers the carrier injection barrier and eventually triggers the positive feedback that turns on the device.

II. DYNAMIC COUPLING EFFECT IN Z^2-FET

The conventional Z^2-FET is built in SOI with ultrathin top Si layer (T_{si}), where the front gate bias effectively creates a hole injection barrier next to the drain electrode, see Fig. 1(a) for the geometry. However, for efficient photodetection, T_{si} needs to be thick enough to obtain reasonable quantum efficiency. Figure 1 shows the Z^2-FET structure with T_{si} = 200 nm as in Ref [7, 10]. A DC simulation of the output characteristics by sweeping V_D from 0 to 3 V and then back, at fixed V_G = 5 V and V_{BG} = –5 V is shown in Fig. 1(b). Clearly, unlike the Z^2-FET with ultrathin T_{si} [1–6], the output characteristics show neither sharp switch nor gate controlled hysteresis. This can be understood by considering the body potential along the channel direction extracted at top (gate oxide/channel) and bottom (channel/buried oxide) interfaces, shown in Fig. 1(c). The electron injection barrier due to V_{BG} is high at both top and bottom interfaces. In contrast, the hole injection barrier due to V_G is high only at top interface, but not at the bottom interface. This is due to the screening of the electric field produced by $V_G > 0$ by inversion electron charge, shown in Fig. 1(d). As a result, the bottom interface of the channel under the front gate is controlled more by $V_{BG} < 0$, which lets the hole current flow for all V_D and prevents sharp switching.

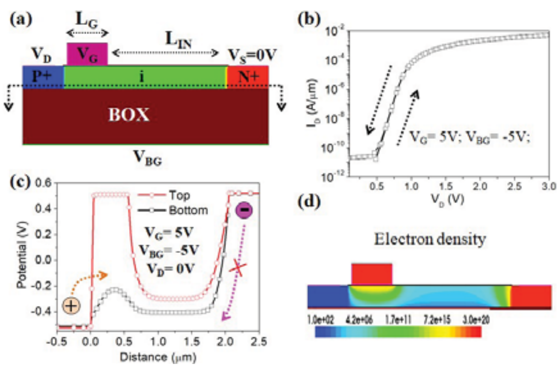

Fig. 1. (a) Schematic view of the simulated Z^2-FET with L_G = 0.5 µm, L_{IN}=1.5 µm, 200 nm top silicon film (T_{si}) and 500 nm BOX (T_{BOX}). (b) Simulated output characteristics with forward and backward sweeps for V_G = 5V and V_{BG} = –5V. (c) Potential barrier along the channel direction extracted in the channel at top and bottom interfaces. (d) Electron density distribution in the device, showing electron inversion under the front gate.

To rebuild the hole injection barrier and recover sharp switching, the front gate can be operated in pulsed mode. In Fig. 2(a), a V_G pulse rising from 0 to 5 V in 0.1 ms is applied after the V_{BG} was set at –5 V. Under a quick V_G pulse, thermal generation is too slow to produce enough electrons at the top interface to screen the electric field. This creates deep depletion in the Si channel, which rebuilds the hole injection barrier, as shown in Fig. 2(b). This is essentially the same dynamic coupling effect found in SOI-based MOSFETs and used for DRAM applications [11]. With the recovered hole injection barrier, an up and down sweep of V_D from 0 to 3 V and back, shortly after the V_G pulse shows output characteristics with sharp switching and hysteresis, similar to that of a conventional Z^2-FET, see Fig. 2(c).

III. PHOTODETECTION

The dynamic coupling effect which forms the hole injection barrier can interact with photo-generated carriers, and thus can be used for photodetection. Figure 3 shows the impact of light on the Z^2-FET. The device is biased with V_{BG} and V_G pulses to form the carrier injection barriers, as shown in Fig. 3(a). Shortly thereafter, the device is exposed to 5 ms long optical pulses of various intensities at a fixed λ = 520 nm wavelength.

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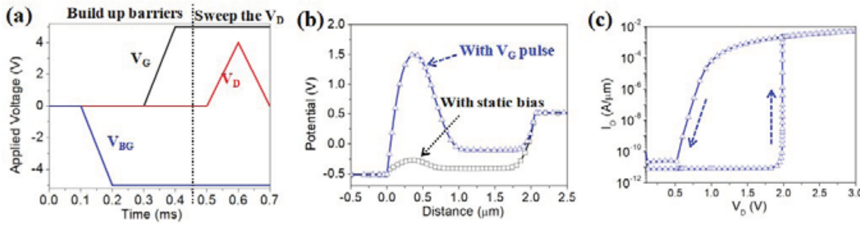

Fig. 2. (a) Bias waveforms applied to the device. (b) Comparison of potential distributions of the device under static and pulsed front-gate biasing. (c) Simulated I_D-V_D characteristics of the device under pulsed V_G operation

After illumination, a read-out $V_D = 0$ to 4 V voltage pulse is applied on the drain. The turn-on voltage (V_{ON}) is modulated by the light intensity, see Fig. 3(b). As the intensity increases, V_{ON} falls almost linearly. The sensitivity of the device is ~10 V per μW/cm^2·s of illumination, as extracted from V_{ON}-exposure relation. This is higher than in a standard CMOS sensor given the small area of the device [12].

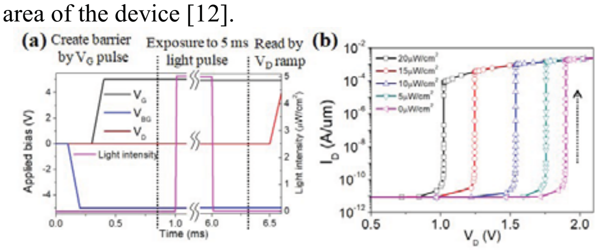

Fig. 3. (a) Waveforms of the applied biases and light signal. (b) I_D-V_D characteristics of the device under various illumination conditions.

The evolution of the hole injection barrier at the bottom interface of the body under a fixed $V_D = 1$ V and various illumination conditions is shown in Fig. 4(a). In the dark, the hole injection barrier remains high at ~1.5 V, so that the device stays in the OFF state. Under 5 μW/cm^2 illumination, the hole barrier initially is reduced linearly and then drops abruptly at 20 ms, switching the device to the ON state.

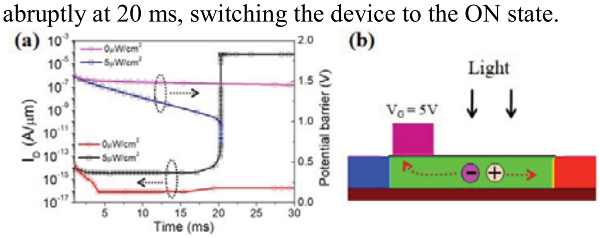

Fig. 4. (a) Evolution of the electron injection barrier and device current under various illumination conditions. (b) Schematic view of the generation and flow of the photoelectron.

The mechanism is illustrated schematically in Fig. 4(b). Incident light generates electron-hole pairs and the photoelectrons are attracted by V_G and accumulate at the top interface of the channel under the front gate. They screen the electric field from V_G and reduce the coupling between the top gate and the bottom of the channel. As more photoelectrons accumulate, the injection barrier at the bottom interface is reduced, eventually triggering the positive feedback that turns on the device sharply.

Compared to conventional CCD and CMOS sensors, the Z^2-FET photodetector directly outputs high current and converts the light exposure to voltage without need for an extra amplifier. Also, thanks to its random access ability established in the DRAM application [2, 3], a Z^2-FET photodetector array can read out without need of charge transfer or extra access transistors.

CONCLUSIONS

We propose and simulate a new photodetector, operating via the dynamic coupling effect in Z^2-FET. The hole injection barrier of the device are modulated by the photoelectrons through coupling effect. Illumination results in reduction of V_{ON} of the device. The sharp switch, huge I_{ON}/I_{OFF} (light/dark) current ratio and random access ability are attractive features for the application of Z^2-FET in photodetection.

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