A Novel Photodetector Using MOS Tunneling Structures

C. W. Liu, *Member, IEEE*, W. T. Liu, M. H. Lee, W. S. Kuo, and B. C. Hsu

***Abstract*—A metal/oxide/p-Si structure with the ultrathin oxide is utilized as a photodetector. At positive gate bias, the dark current of the photodetector is limited by the thermal generation of minority carrier in the inversion layer. The high growth temperature (1000 °C) of the gate oxide can reduce the dark current to a level as low as 3 nA/cm^2. As biased in the inversion layer, the tunneling diode works in the deep depletion region with the soft pinning of oxide voltage, instead of the pinning of surface potential, very different from the conventional MOS diode with thick oxide.**

***Index Terms*—MOS tunneling diode, photodetector, rapid thermal oxide.**

I. INTRODUCTION

THE INTEGRATION of light emitters and detectors in a CMOS compatible process makes the optical interconnects feasible for ULSI circuits [1]. The same MOS tunneling structures used in this study for both light emitters and detectors allow a duplex transmission of optical interconnects [2]. As the gate oxide scales down to the tunneling region, the gate electrode itself can be used as a collector to collect the photo-excited carriers tunneling from the semiconductor. Meanwhile, this MOS tunneling photodetector can be potentially integrated in CMOS image sensors [3], [4], by connecting the gate of this diode and the source of transfer gate in a typical four-transistor pixel [3].

II. DEVICE FABRICATION

The ultrathin gate oxide of the NMOS diode was grown by rapid thermal oxidation on 1–5 Ω-cm p-type wafer at the 900–1000 °C. The gas flows were 500 sccm nitrogen and 500 sccm oxygen at reduced pressure. After the growth of the ultra thin oxide, the sample was *in situ* annealed in nitrogen for 10 min at 900 °C. The thickness was measured by ellipsometer. The MOS diodes had Al or indium tin oxide (ITO) gate electrodes with various circular areas defined by photolithography.

III. DEVICE OPERATION

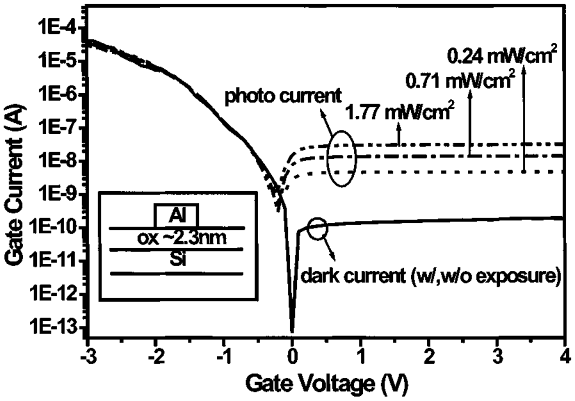

Fig. 1. Dark and photo currents of an NMOS tunneling detector. The inset is the device structure.

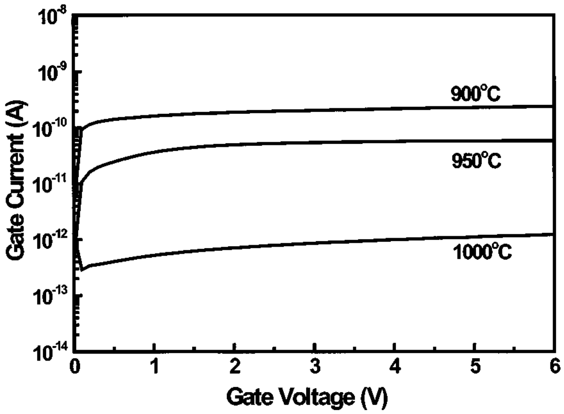

Fig. 2. Dark currents of NMOS tunneling detectors with oxide grown at different temperatures.

Fig. 1 shows the current–voltage (*I–V*) curves of an Al/2.3 nm oxide/p-Si detector with an area of 3.2×10^{-4} cm^2. The photocurrent was excited by metal halide lamp with a spectrum similar to sun. At the negative bias, the electron current tunnels from the Al gate to the p-Si and emits bandgap photons by the radiative recombination with the holes in the accumulation layer [5]. The dark and photocurrents are relatively constant in the log scale for the positive bias larger than 0.2 V. The dark current is basically limited by the thermal generation rate of minority electrons in the inversion layer of the p-Si, if the tunneling rate of the minority carrier through the oxide is sufficiently effective. Since the tunneling process is controlled by the oxide voltage, at the large enough gate bias (>0.2 V), the tunneling rate is not a limiting factor for electron current from the p-Si to Al gate. With the photo excitation, the generation rate of electrons in the inversion layer increases and thus the gate current increases. The dark current at room temperature is significantly reduced as the growth temperature of oxide increases, and reaches 3 nA/cm^2 at the growth temperature of 1000 °C (Fig. 2). Therefore, it is believed that the dark current is primarily generated at the interface between Si and oxide. For reference, the dark currents of the

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The authors are with the Department of Electrical Engineering, National Taiwan University, Taipei, Taiwan, R.O.C. (e-mail: chee@cc.ee.ntu.edu.tw).

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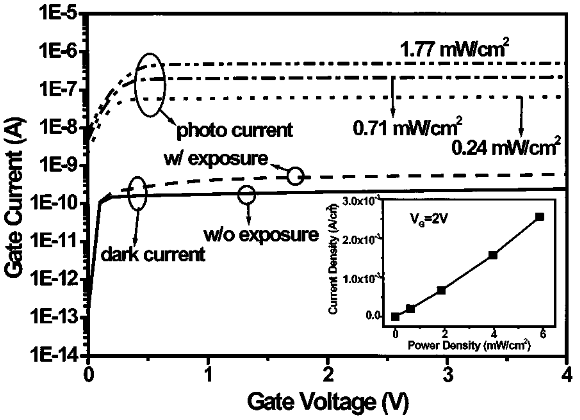

Fig. 3. Dark and photo currents of a NMOS detector with the transparent ITO gate electrodes. The inset is the photocurrent dependence on the light intensity.

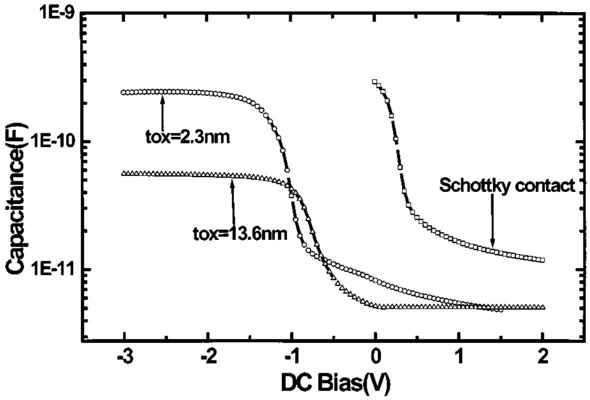

Fig. 4. *C–V* (100 KHz) measurements for an NMOS tunneling detector, a conventional NMOS diode with thick oxide, and an Al/p-type Schottky diode.

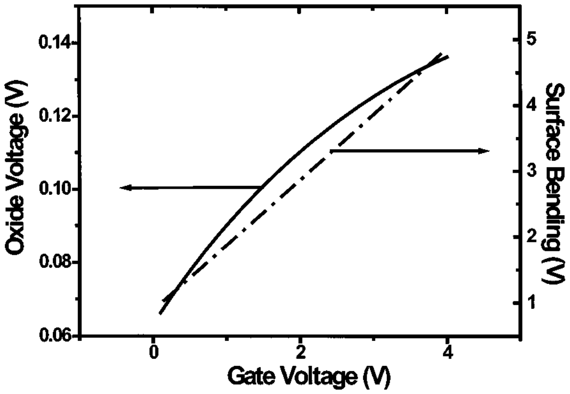

Fig. 5. Oxide voltage and surface potential versus gate voltage.

photodiode and the classical Schottky diode were 6–12 nA/cm^2 [3] and 0.1 A/cm^2, respectively. The implantation damage in the photodiode process does not occur in the MOS tunneling diode. This can reduce the dark current of the MOS tunnelling diode. An ITO electrode is used to allow the light to pass through the gate, and thus the photocurrent increases by a factor 20 (Figs. 1 and 3). However, the dark current of some ITO diodes degrades after the photo current stress (Fig. 3). The reliability issue may restrict the applications of this diode. The quantum efficiency of the photodiode processed in a CMOS process is 25–30% [6]. Due to the depletion closer to the surface and transparent ITO gate, the quantum efficiency of our diode is estimated about 80% (the inset of Fig. 3). The light absorption, which is attenuated exponentially with the depth, by the shallower collection region in this novel detector yields higher quantum efficiency. To further increase the gate voltage, most of the gate voltage drops on the p-Si to form a deep depletion region, and the oxide voltage increases very slightly, defined as soft pinning. Fig. 4 shows the high-frequency capacitance–voltage (*C–V*) curves of an Al/p-Si Schottky diode, an NMOS tunneling diode with ultra thin (2.3 nm) oxide, and a conventional NMOS diode with thick (13.6 nm) oxide. Both the Schottky diode and the NMOS tunneling diode reveal a continuous decrease of capacitance as the positive gate voltage increases, while the conventional NMOS diode still maintains the relatively constant gate capacitance. This indicates that the depletion widths in both the Schottky diode and the NMOS tunneling diode increase, but the depletion width of the conventional NMOS keeps constant, as the positive gate voltage increases. The deep depletion in the NMOS tunneling diode is formed for the large positive gate bias. Since there is no permanent inversion layer, the device has a very good linearity up to the photo exposure of 6 mW/cm^2 (the inset of Fig. 3).

IV. NUMERICAL ANALYSIS

The oxide voltage can be obtained from the following equations:

$$
\begin{gathered}
V_{OX} = -\frac{Q_I + Q_B}{C_{OX}}, \quad I_S = \Gamma \cdot Q_I, \\
Q_B = \sqrt{qN_A \kappa_{si} \varepsilon_o (2\varphi_S)}, \quad V_G = V_{FB} + V_{OX} + \varphi_S, \\
\Gamma = A \cdot \exp\left\{ -C \frac{t_{OX}}{V_{OX}} \left[\phi_O^{3/2} - (\phi_O - V_{OX})^{3/2} \right] \right\}
\end{gathered}
$$

where

Γ	transmission rate, estimated by WKB (Wentzel–Kramers–Brillouin) methods in the direct tunneling region;
Q_I	inversion charge;
Q_B	bulk charge;
I_s	measured dark current in Fig. 1.

The parameters used in the calculation are $A = 3 \times 10^{-4} s^{-1}$, $C = 1 \times 10^7$ V$^{-0.5}$cm^{-1}, $t_{OX} = 2.3$ nm, $\phi_O = 3.15$ eV, $N_A = 10^{16}$ cm^{-3}. The results of V_{ox} (oxide voltage) and Φ_s (surface potential) vs positive gate voltage are shown in Fig. 5. It is clear that most of gate voltage drops on surface potential. The oxide voltage is only 0.14 V at the gate voltage of 4 V.

V. SUMMARY

A novel photodetector using the NMOS tunneling structures was demonstrated. The leakage of inversion carrier through ultra thin oxide makes the device to operate in the deep depletion region. The dark current is limited by the thermal generation process and can be reduced by the high growth temperature of oxide.

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