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High Sensitivity Photodetector with Self-Amplification Capability

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We propose an SOI MOS photodetector with high sensitivity for visible light. High current gain, unlike other silicon based photodetectors, originates from lateral bipolar action caused by a floating substrate effect of SOI. The current gain strongly depends on channel length of the photodetectors as $\beta \propto L_{\text{eff}}^{-2}$. The current gain as much as $\beta = 1{,}000$ was successfully obtained for $L_{\text{eff}} = 1.0\mu$m. Intrinsic response time for optical pulses was 19μsec for the photodetector with channel length of 0.7μm. The high current gain inherent in the small size SOI MOS photodetector and its process compatibility with conventional CMOS make it possible for the photodetectors to be implemented into high density silicon integrated circuits.

1. INTRODUCTION

The principal requirements for the monolithic photodetectors on Si LSI's are (1) process compatibility with the normal silicon technology, (2) compact and simple device structure with high sensitivity, (3) operation under the drive voltage levels available from standard silicon circuits, typically a 5 V swing, and (4) very low dark current. The aim of this paper is to demonstrate a new silicon photodetector with high current gain which meets the requirements above.

Figure 1 shows a cross section of the photodetector: a normal n-channel SOI(Silicon On Insulator) MOSFET. The drain electrode of the photodetector is positively biased while the gate electrode is negatively biased so as to cut off the channel current. In this way, the photodetector operates as a lateral bipolar device. Figure 2 shows a schematic diagram of the operation principle of the photodetector. Under illumination, electrons and holes generate in SOI film. The generated electrons diffuse into the positively biased drain region while the holes remain in SOI film as majority carriers, resulting in the increase of SOI film potential. The positively charged holes remaining in the SOI film bias pn junction forward, leading to large drain current. Thus, the key of the operation principle is the "self-biased" base under illumination: no base electrode is required.

2. EXPERIMENTAL RESULTS AND DISCUSSION

n-channel LDD(Lightly Doped Drain) SOI MOSFETs used for the experiments are fabricated using a SIMOX wafer with top silicon thickness of 170 nm. The gate oxide thickness is 15 nm and the buried oxide 400 nm. The p-type SOI film was prepared with 35 keV boron ion implantation at a dose of 1.0×10^{11} cm $^{-2}$. Then, the wafers were annealed in nitrogen ambient for 60 minutes at 1100 ℃. After depositing CVD polysilicon of 0.3 μm, the source/drain regions were implanted to a dose of 4.0 $\times\ 10^{15}$ cm $^{-2}$ with arsenic ions. Other processes used for the photodetector fabrication are the same as those for standard CMOS fabrication.

Figure 3 shows typical V_{g}-I_{d} characteristics in the cut-off region of the SOI MOSFETs (photodetectors).

Large drain current for illuminated MOSFETs is the result of the lateral bipolar action of the photodetector caused by the holes remaining in SOI film (virtual base) under illumination. Note that the drain current without illumination is well below 10^{-12} A, while the drain current under illumination is on the order of 10^{-8} A for $L_{\text{eff}} = 1.0$ μm. Furthermore, the drain current of illuminated SOI MOSFET with channel length of $L_{\text{eff}} = 1.0$ μm is about 100 times as much as that with $L_{\text{eff}} = 20.0$ μm despite of much smaller illuminated area.

Figure 4 represents the relation between I_{d} and channel length of illuminated SOI MOSFETs. The measured drain current for the photodetectors with $L_{\text{eff}} > 0.7\mu$m is well expressed as

$$I_{\text{d}} \propto L_{\text{eff}}^{-1}. \tag{1}$$

The sharp increase of the drain current for $L_{\text{eff}} < 0.7\mu$m is partly attributed to punch-through phenomena; there exists significant dark current for the photodetectors with channel length below 0.5 μm.

We evaluated the current gain of the photodetectors by comparing with photocurrent of a photodiode on the SOI. Figure 5 shows the measured current gain β (= drain current/electron-hole pair generation rate) as a function of channel length. For the photodetectors with channel length of $L_{\text{eff}} > 0.7\mu$m, β is roughly proportional to the following expression as

$$\beta \propto L_{\text{eff}}^{-2}. \tag{2}$$

This can be explained with a lateral bipolar transistor model. The self-biased base voltage, V_{EB}, is defined as

$$\frac{D_{\text{h}} p_{\text{n}}}{L_{\text{h}}} \left[\exp\left(\frac{qV_{\text{EB}}}{k_{\text{B}}T} \right) - 1 \right] = \gamma I_{\text{ph}} - \frac{(p - p_0)}{\tau}, \tag{3}$$

where γ is quantum yield of electron-hole generation and I_{ph} photon dose. Other physical parameters have conventional meanings. The equation above indicates that the net flow (F in Fig.2) of holes across the emitter/base boundary equals to generation rate (G) of electron-hole pairs minus recombination rate (R) of excess holes in SOI film. Since the second term of right hand side is small enough to be neglected, β is derived from a standard bipolar device model in which base width is given by L_{eff}

$$\beta \simeq \frac{2D_{\text{h}}\tau}{L_{\text{eff}}^2}. \tag{4}$$

To derive the equation above, we assumed $qV_{\text{EB}} > k_{\text{B}}T$. Note that the current gain of photodetectors under illumination is inversely proportional to the "square" of the channel length as shown in Eq.(2), unlike conventional bipolar transistors in which the current gain $\beta \propto L_{\text{eff}}^{-1}$.

Figure 6 shows the experimental setup for measuring the pulse response of the photodetector. SOI MOS photodetector is illuminated by He-Ne laser light pulses obtained through an AO (Acoustic Optic) modulator. The output voltage is monitored by an oscilloscope. The waveform of the output is depicted in Figure 7. The rise and fall times are about as large as 40 μsec. This is, however, due to the existence of large parasitic capacitance in the external circuit. Intrinsic response time of the photodetectors, t_{resp}, is strongly affected by potential distribution in the SOI film because excess majority carriers in the base (channel) region rapidly drift into the emitter (source) after shutting off the laser light. Although the intrinsic response time estimated by using a least square fit procedure was 19μsec for $L_{\text{eff}} = 0.7\mu$m as shown in Fig.8, it is expected that the SOI MOS photodetector with deep submicron channel length well responds to MHz optical pulses.

3. CONCLUSIONS

We proposed a new photosensor with high sensitivity which is compatible with conventional IC fabrication processes. Very large current gain due to self-bias effect is achieved; β = 1,000 for the device with $L_{\text{eff}} = 1.0\mu$m. Since smaller size photosensors has the larger current gain, the newly proposed sensors are suitable for monolithic integration into conventional large scale IC's. The physical mechanism of high current gain was interpreted by a theoretical model. Furthermore, The intrinsic response time of SOI MOS photodetector with $L_{\text{eff}} = 0.7\mu$m was estimated as 19μsec.

ACKNOWLEDGMENT

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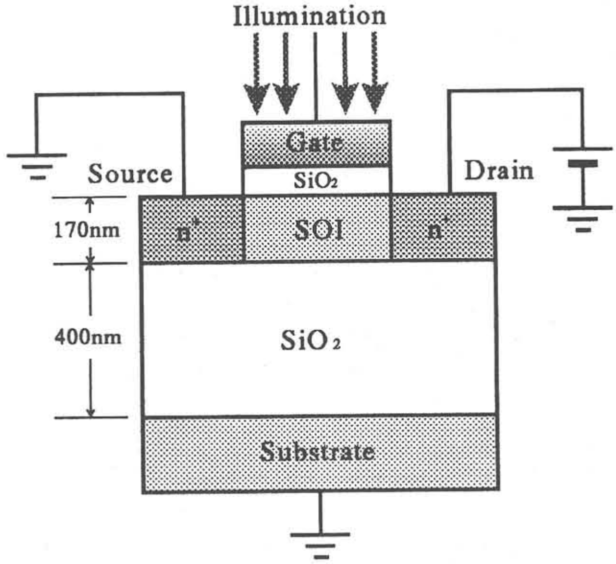

Fig. 1 Schematic cross section of n-channel SOI MOS photodetector under illumination.

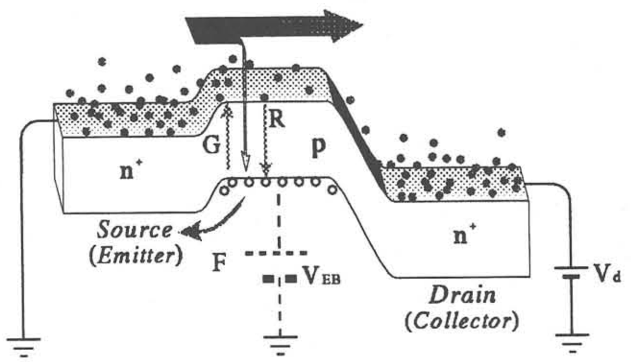

Fig. 2 Schematic energy band diagram of self-biased photodetector under illumination. Virtual self-bias voltage, V_{EB}, is determined from G (generation rate of holes) $-$ R (recombination rate of electron-hole pairs) = F (hole flux flowing into the source).

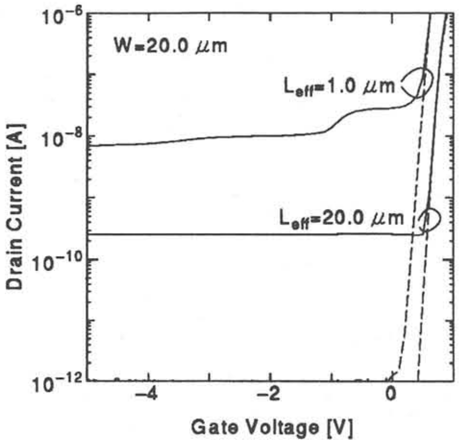

Fig. 3 Drain current characteristics of SOI MOS photodetectors with (solid curves) and without (dashed curves) illumination at $V_d = 0.1$V.

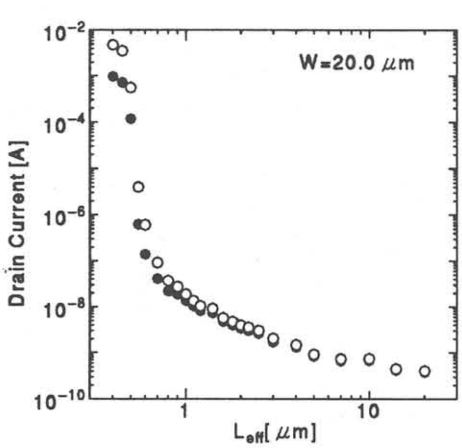

Fig. 4 Drain current of illuminated photodetectors as a function of channel length measured at V_g = -2.0V. Drain voltages are 0.1V(●) and 0.5V(○).

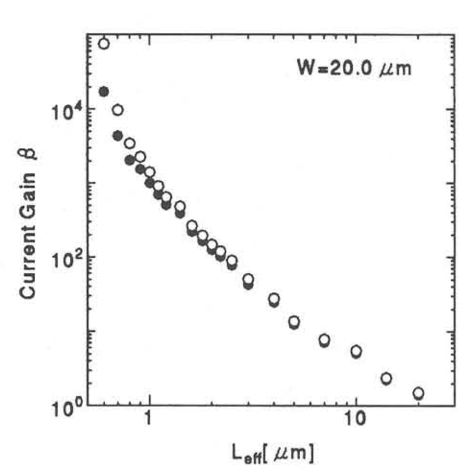

Fig. 5 Experimentally extracted current gain of SOI MOS photodetectors as a function of channel length at $V_g = -2.0$V. Drain voltages are 0.1V(●) and 0.5V(○).

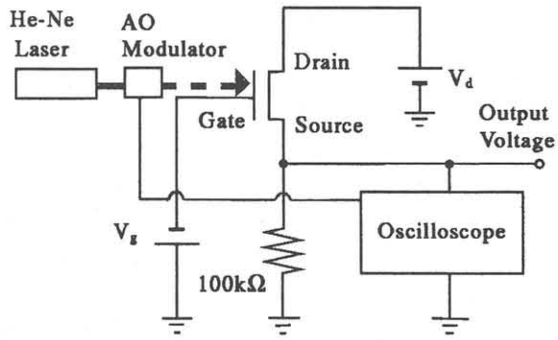

Fig. 6 Measurement system for optical response of the SOI MOS photodetector. Light pulses are obtained through the AO(Acoustic Optic) modulator. Output voltage is monitored by an oscilloscope.

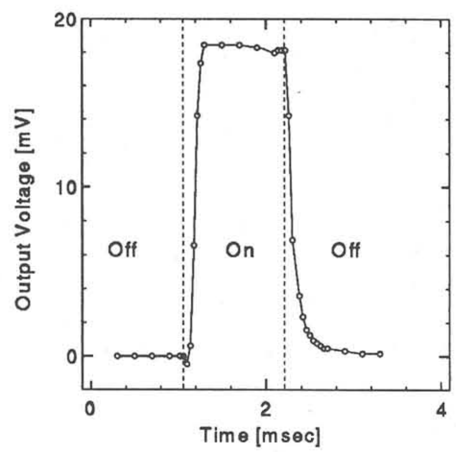

Fig. 7 Optical response of the photodetector under the laser pulse illumination. The response is measured using the circuit shown in Fig.6. "On" and "Off" stand for "with illumination" and "without illumination", respectively. Channel length is 0.7μm. $V_g = -2.0$V and $V_d = 2.0$V.