The Ring-Shaped CMOS-Based Phototransistor With High Responsivity for the UV/Blue Spectral Range

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***Abstract*—The ring-shaped phototransistor with a floating bulk enclosed by a ring-shaped photodiode is proposed to enhance the responsivity for the ultraviolet/blue spectral range. The P-channel metal–oxide–semiconductor field-effect transistor and N-channel metal–oxide–semiconductor field-effect transistor phototransistors were manufactured using a standard 0.35-μm complimentary metal–oxide–semiconductor (CMOS) technology. When the phototransistors were illuminated with 400-nm light, the measurement results for 3-V bias demonstrated a responsivity higher than 1500 A/W, which is also superior to that of other reported photodetectors manufactured using a standard CMOS technology. Even for very small bias voltages such as 0.1 V, the phototransistor can exhibit a responsivity of 17.9 A/W.**

***Index Terms*—Optical receivers, optoelectronic devices, photodetectors, phototransistors.**

I. Introduction

The development of a photodetector with high responsivity for the ultraviolet (UV)/blue spectral range has attracted much interest for many applications, such as biochemical analysis and optical storage systems [1]–[4]. For biochemical analysis, the detection of the optical properties changed by chemical reactions is a competent approach to examine various important biological molecules. Through the chemical reactions, the change of the emitted—or absorbed—light intensity is generally less than 1 μW. Regarding the reported methods, the luminol/H_2O_2/HRP reaction involves the emission of 425-nm light [1], and the ABTS/H_2O_2/HRP reaction involves the absorption of 415-nm light [2]. For optical storage systems, an optical pickup unit detects the laser light (less than 1 μW) reflected from a storage disc and converts it into electrical output signals [3]. The recording density of the disc is determined by the minimum spot size that the laser light can be focused on, and the spot size is proportional to the laser wavelength. Therefore, a higher recording density can be obtained by using the laser of a shorter wavelength [4]. Compared with CD (780 nm) and DVD (650 nm), the Blu-ray Disc (405 nm) has a larger storage capacity and becomes a noticeable trend in the optical storage technology.

Much work has been devoted to the realization of photodetectors using a standard complimentary metal–oxide–semiconductor (CMOS) technology or CMOS-compatible technologies in the last decade [1]–[11]. This is owing to its low cost, high throughput, and the capability for integration with consequent circuits without any process modification. A conventional CMOS photodiode can easily be formed by utilizing an $N^+/P_{\rm well}$, $P^+/N_{\rm well}$, or $N_{\rm well}/P_{\rm sub}$ junction, but the responsivity for the UV/blue spectral range is low (about 0.2 A/W) [12]. Circumventing this drawback, a phototransistor can have a current amplification under moderate bias through the internal transistor action [13]. However, little work has been conducted on the phototransistor manufactured using a standard CMOS technology for the UV/blue spectral range.

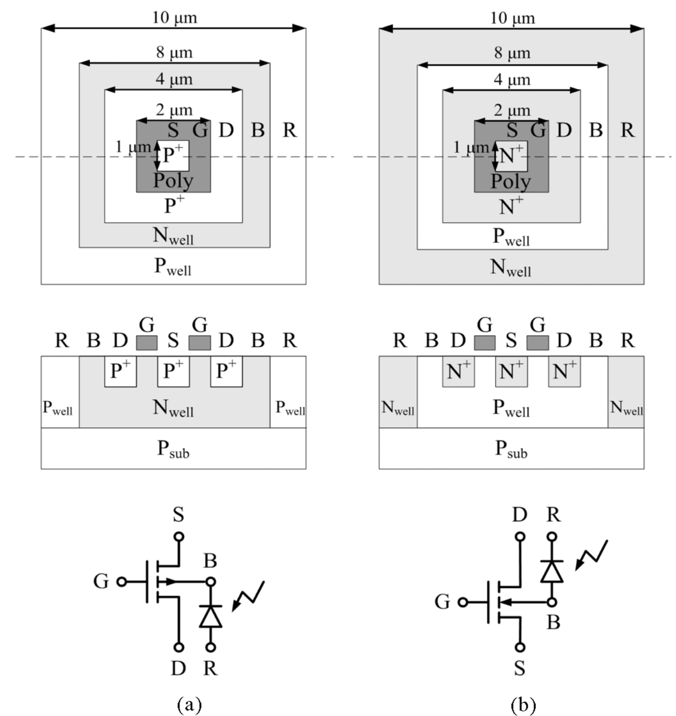

Fig. 1. Top view, cross section, and equivalent symbol of the proposed (a) PMOS phototransistor and (b) NMOS phototransistor.

In this research, the CMOS phototransistor was designed, fabricated, and measured. It exhibited an enhanced responsivity for the UV/blue spectral range.

II. Device Structure and Operating Principle

The device structures of the proposed P-channel metal–oxide–semiconductor field-effect transistor (PMOS) and N-channel metal–oxide–semiconductor field-effect transistor (NMOS) phototransistor based on CMOS technology are shown in Fig. 1(a) and (b), respectively. For the PMOS phototransistor, the P^+ source is placed in the center with the

Manuscript received December 05, 2008; revised March 20, 2009. First published April 17, 2009; current version published June 17, 2009.

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Digital Object Identifier 10.1109/LPT.2009.2020176

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ring-shaped poly-silicon gate and P^+ drain, while the N_{well} bulk (B) is enclosed by the P_{well} ring (R). For the NMOS phototransistor, the N^+ source is placed in the center with the ring-shaped poly-silicon gate and N^+ drain, while the P_{well} bulk (B) is enclosed by the N_{well} ring (R). In both cases, the phototransistor can be regarded as a metal–oxide–semiconductor field-effect transistor (MOSFET) with a photodiode connected across the bulk (B) and the square ring (R), as shown in Fig. 1.

Serving as an optical sensor, the phototransistor leaves the bulk floating and mainly uses the $N_{\text{well}}/P_{\text{well}}$ junction to separate photogenerated electron-hole pairs [8]. The photogenerated carriers drifting into the bulk would change the bulk potential, and thereby change the threshold voltage as well as the output drain current.

For the UV/blue incident light, most photogenerated carriers are very close to the surface (within 0.2 μm). Using the proposed ring-shaped layout style, the near-surface depletion region of the outer $N_{\text{well}}/P_{\text{well}}$ ring-shaped photodiode is enlarged and superior to that of a conventional MOSFET with the same area, so as to cause a larger shift amount of the threshold voltage. Hence a larger photocurrent response I_{ph} could be expected.

Regarding the proposed phototransistors, the bulk is left floating, while the applied fixed ring-source voltage V_{RS} is negative for PMOS and is positive for NMOS. The bulk-ring voltage V_{BR} resulting from the illumination can be described by the transposed diode equation [13]

$$V_{\text{BR}} = V_{\text{th}} \ln\left(1 + \frac{I_{\text{BR(ph)}}}{I_{\text{BR0}}}\right) = V_{\text{th}} \ln\left(1 + \frac{k_1 P_{\text{opt}}}{I_{\text{BR0}}}\right) \quad (1)$$

where V_{th}, $I_{\text{BR(ph)}}$, I_{BR0}, and P_{opt} are the thermal voltage, the photocurrent of the bulk-ring diode, the saturation current of the bulk-ring diode, and the incident optical power density, respectively; k_1 is functions of material parameters, transistor bias voltages, and the depletion region area of the $N_{\text{well}}/P_{\text{well}}$ junctions. Thus the resulted bulk-source voltage V_{BS} can be expressed as $V_{\text{BS}} = V_{\text{BR}} + V_{\text{RS}}$. For illuminated PMOS, V_{BS} is negative since its N_{well} bulk accumulates excess electrons; for illuminated NMOS, V_{BS} is positive since its P_{well} bulk accumulates excess holes.

The shift amount of the threshold voltage ΔV_T due to the bulk charge effect is given by [13]

$$\Delta V_T = \frac{\sqrt{2\varepsilon_s q N_B}}{C_{\text{ox}}}\left(\sqrt{2\psi_B - V_{\text{BS}}} - \sqrt{2\psi_B}\right) \quad (2)$$

where ε_s, q, N_B, C_{ox}, and ψ_B are the permittivity of silicon, the unit electric charge, the doping concentration of the bulk, the oxide capacitance per unit area, and the bulk Fermi level from the intrinsic Fermi level, respectively. When PMOS and NMOS phototransistors are illuminated, the absolute value of the threshold voltage $|V_T|$ will both become smaller.

The photocurrent response I_{ph} is the difference in the output drain current, which can be expressed as

$$I_{\text{ph}} = |I_D - I_{D0}| \quad (3)$$

where I_D and I_{D0} denote the output drain current of the phototransistor with and without illumination, respectively. It implies that I_{ph} of the phototransistor will increase with the $N_{\text{well}}/P_{\text{well}}$ sensing area A, the channel aspect ratio W/L, and the bias voltages $|V_{\text{GS}}|$ and $|V_{\text{DS}}|$.

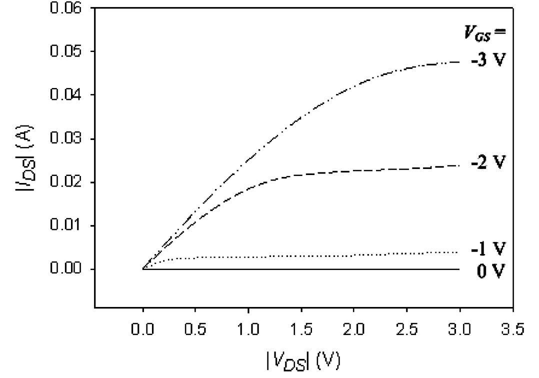

Fig. 2. Measured I–V characteristics of the PMOS phototransistor without illumination.

Overall, with advantages of the ring-shaped structure and the MOSFET amplification, the proposed CMOS phototransistor is expected to perform a better responsivity than conventional CMOS-based photodetectors.

III. Experimental Results

The proposed PMOS and NMOS phototransistors were respectively duplicated and concatenated to form each 10×10 array with a total area of 100 μm$\times$ 100 μm, and they were manufactured using the Taiwan Semiconductor Manufacturing Company (TSMC) 0.35-μm standard CMOS technology. To characterize these phototransistors, a UV/blue LED (Centenary 40327) with a peak of 400 nm was used as the light source, while its light intensity was adjusted by a power supply (Agilent E3631A). A reference photodetector and a pinhole were introduced to measure the optical power density for various bias voltages applied to the LED. A precision semiconductor parameter analyzer (HP 4156A) and a test fixture (HP 16058A) were used to characterize the CMOS photodetectors.

Fig. 2 shows the measured current–voltage (I–V) characteristics of the PMOS phototransistor without illumination. The bias conditions were as follows: the source was grounded, the drain voltage swept from 0 to -3 V, the gate voltage stepped from 0 to -3 V, the bulk was floating, and the ring voltage was fixed at -3 V.

While the phototransistors were illuminated, the output drain current varied in response to the light intensity. For the PMOS phototransistor with $|V_{\text{DS}}| = 3$ V, the measured photocurrent responses are shown in Fig. 3(a). The larger the $|V_{\text{GS}}|$ was, the larger the $|I_D|$ as well as the I_{ph} were. The photocurrent response divided by illumination intensity gives the DC responsivity, and the results are shown in Fig. 3(b). With $V_{\text{GS}} = -3$ V, the phototransistor exhibited a responsivity higher than 1500 A/W when the illumination intensity was less than 1 μW, as the condition for applications in optical storage and most biochemical detection. This responsivity is 7500 folds higher than that of a conventional silicon P/N junction photodiode (about 0.2 A/W) [12]. In addition, when the illumination

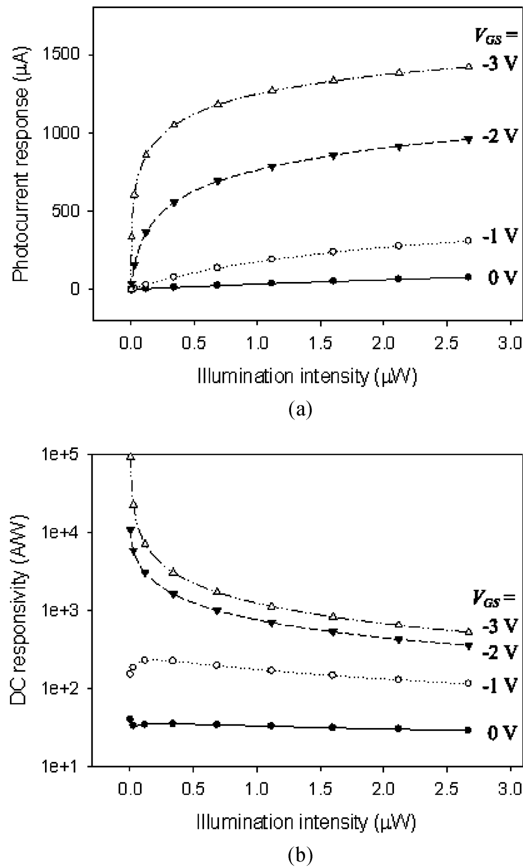

Fig. 3. Optoelectronic characteristics of the PMOS phototransistor for $V_{\mathrm{DS}} = -3$ V with various V_{GS}: (a) photocurrent response versus illumination intensities and (b) DC responsivity versus illumination intensities.

TABLE I
UV/BLUE RESPONSIVITY OF THE CMOS PHOTODETECTORS

Device Type	Ref.	λ (nm)	Bias (V)	R (A/W)
Conventional PD	[9]	400	3	0.23
NPN PT	[10]	420	5	0.25
Avalenche PD	[11]	380	14.5	5.3
PMOS PT	This work	400	0.1	17.9
			1	1100
			2	1700
			3	1700
NMOS PT	This work	400	0.1	2.3
			1	2600
			2	2900
			3	1500

(PD: photodiode, PT: phototransistor)

intensity was about 0.1 μW, a higher responsivity of 7200 A/W can be achieved.

Even for very small bias voltages such as $V_{\mathrm{GS}} = V_{\mathrm{DS}} = -0.1$ V, the phototransistor can successfully detect the change of illumination intensity and exhibited a responsivity of about 17.9 A/W. The dark current was less than 1 nA.

Table I summarizes the measured responsivities for the PMOS and NMOS phototransistors under various bias conditions ($V_{\mathrm{GS}} = V_{\mathrm{DS}}$) with illumination of 0.7-μW 400-nm light. The characteristics of other reported photodetectors manufactured in a standard CMOS technology are also compared [9]–[11]. The difference between the PMOS and NMOS phototransistor mainly results from that the $\mathrm{N_{well}}$ bulk of PMOS is distinguished from $\mathrm{P_{sub}}$, whereas the NMOS has a larger bulk region since $\mathrm{P_{well}}$ is inherently connected with $\mathrm{P_{sub}}$. For further applications in integrated circuits or sensor arrays, the floating $\mathrm{P_{well}}$ of NMOS phototransistor can be separated from the $\mathrm{P_{sub}}$ by introducing a deep-$\mathrm{N_{well}}$. Among these CMOS photodetectors, the proposed phototransistor exhibits a higher responsivity but at the expense of bandwidth. The measured dynamic responsivities for 1 Hz, 1 kHz, and 1 MHz were about 1700, 800, and 600 A/W, respectively. However, the bandwidth is sufficient for applications in biochemical analysis.

IV. CONCLUSION

In this letter, the ring-shaped phototransistor with a floating bulk enclosed by a ring-shaped photodiode based on CMOS technology is proposed for applications in the UV/blue spectral range with a high responsivity. Experimental results demonstrated that the responsivity for 400-nm light was higher than 1500 A/W, which is also superior to that of other reported photodetectors manufactured in a standard CMOS process. Even for very small bias voltages such as 0.1 V, the phototransistor can exhibit a responsivity of 17.9 A/W. The proposed device structure is therefore an attractive option in applications for the UV/blue spectral range.

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