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Highly Sensitive PMOSFET Photodetector and Its Application to CMOS Active Pixel Sensor

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In this paper, a highly sensitive p-channel metal oxide field effect transistor (PMOSFET) photodetector fabricated using a standard complementary metal oxide semiconductor (CMOS) process is described. The photodetector is configured by the floating gate/n-well tied PMOSFET. The device has similar I_{DS}-V_{DS} characteristics to a general PMOSFET when the incident light power instead of the gate voltage is supplied and has a transient response fast enough that there is no image lag in its application to an imager with television resolution. A 1 × 16 CMOS active pixel sensor using the PMOSFET photodetector was also designed and fabricated using 1-poly and 2-metal 1.5 μm CMOS technology. The unit pixel of this sensor consists of a PMOSFET photodetector and four n-channel metal oxide field effect transistors (NMOSFET). Its area is 86 μm × 90.5 μm and fill factor is 12%. Even though the pixel has a relatively small its fill factor, a sufficient photocurrent can be obtained. A highly sensitive pixel is feasible with the use of the photodetector with current amplification and the pixel circuit with voltage gain.

1. Introduction

Over the past few years, the availability of CMOS image sensors has grown rapidly in the market for image systems, owing to the rapid progress in the development of CMOS technologies, and they are regarded as strong competitors against charge-coupled devices

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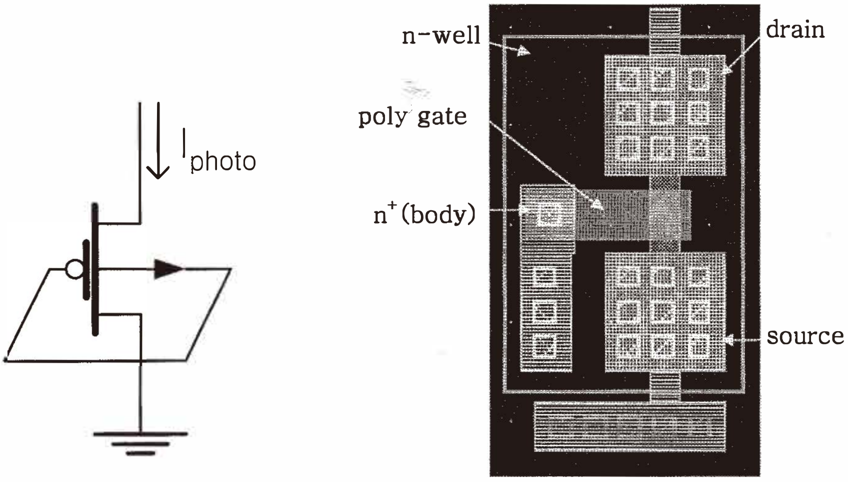
(CCDs).(1,2) CCDs have larger gain and better noise characteristics than CMOS image sensors, but demand a high supply voltage and special fabrication processes. On the other hand, CMOS imagers have several merits as compared with CCDs, such as a low supply voltage, low power consumption, a standard CMOS process, and easy integration with on-chip peripheral electronic systems.(1,2,7) A P-N junction photodiode is commonly employed as a photodetector in CMOS image sensors. As the photodiode in the image pixel is enlarged in order to improve the sensitivity or increase the photocurrent, the pixel pitch is increased and the integration density of CMOS image sensors is decreased. For this reason, there are many on-going research activities seeking to improve the sensitivity as well as the size of the photodetector (3–6) and pixel circuit.(7,8)

In this study, a highly sensitive PMOSFET photodetector that can improve the performance as well as reduce the size was designed and its optical characteristics were measured. Additionally, a CMOS active pixel sensor (APS) based on the PMOSFET photodetector was designed and fabricated using 1.5 μm standard CMOS technology.

2. Experiments

2.1 *PMOSFET photodetector*

A schematic and a device layout of the PMOSFET photodetector are shown in Fig. 1. This device was originally proposed by Zang *et al.*(4) The photodetector is formed by a PMOSFET with a floating gate tied to an n-well and fabricated using a standard CMOS process. A cross-sectional view and an energy band diagram of the PMOSFET photodetector are shown in Fig. 2. The Fermi level of an n^+ polysilicon gate differs from that of an n-well. This causes band bending in the upper region of the buried channel and the height of the hill from the level at the Si/SiO$_2$ interface is nearly equal to the difference in the



(a) (b)

Fig. 1. (a) Schematic and (b) layout of the PMOSFET photodetector.

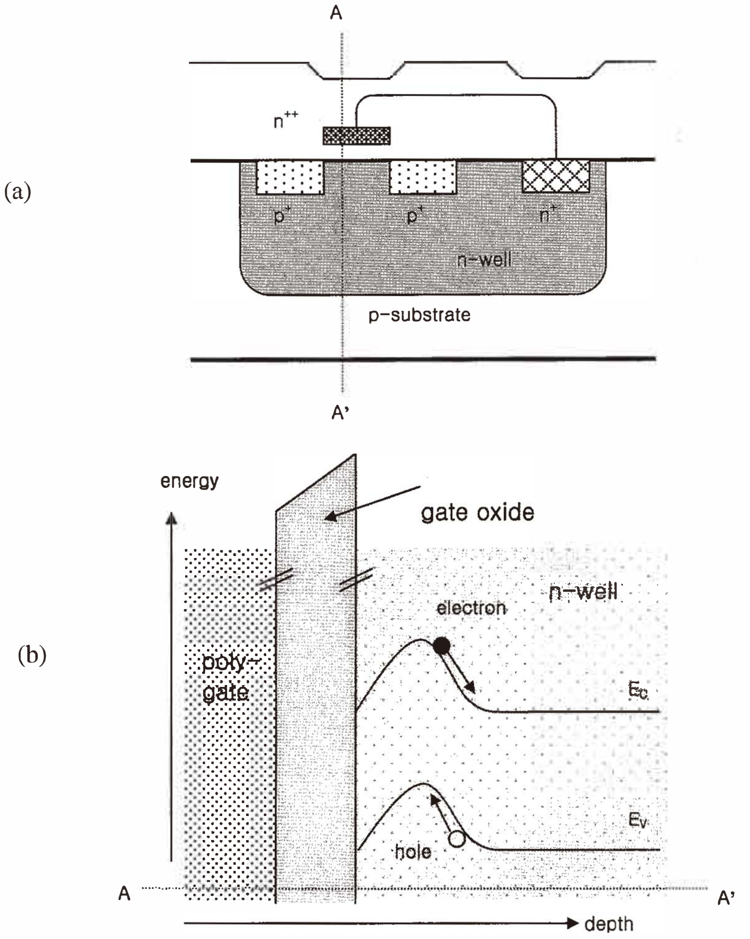


Fig. 2. (a) Cross-sectional view and (b) vertical energy band diagram of the PMOSFET photodetector.

Fermi level between the n^+ polysilicon and the n-diffused outlet. It should be noted that a buried channel PMOSFET is actually used in order to obtain the desired threshold voltage in a CMOS process using an n^+ polysilicon gate.

The basic operational principle of the PMOSFET photodetector is as follows.(4) A vertical electric field caused by the above-mentioned band bending shown in Fig. 2 separates the photogenerated electron-hole pairs. The holes drift toward the buried channel and then are quickly swept to the drain by bias voltage. On the other hand, the electrons move away to a neutral region of the n-well and are effectively accumulated owing to their potential barriers being higher than those of the holes.(4,5) This means that the operational principles of the PMOSFET photodetector are similar to those of a hetero-junction bipolar transistor.(5) These accumulated electrons lower the potential barrier of the holes which flow from the source to the drain and are fed back to the gate through the gate/n-well connection, acting as negative gate voltage. Thus, the photocurrent is highly amplified.(4,5) Consequently, the PMOSFET photodetector, the drain current of which is proportional to the incident light power, can obtain an amplified photocurrent and has high sensitivity.

2.2 *Active pixel sensor*

A schematic and a layout of the unit pixel making up the designed active pixel sensor, which is a CMOS image sensor with an active amplifier/buffer within each pixel,(1,2) are shown in Fig. 3. The designed unit pixel consists of a PMOSFET photodetector and four NMOSFETs including an active load. The load located in the upper portion of the layout

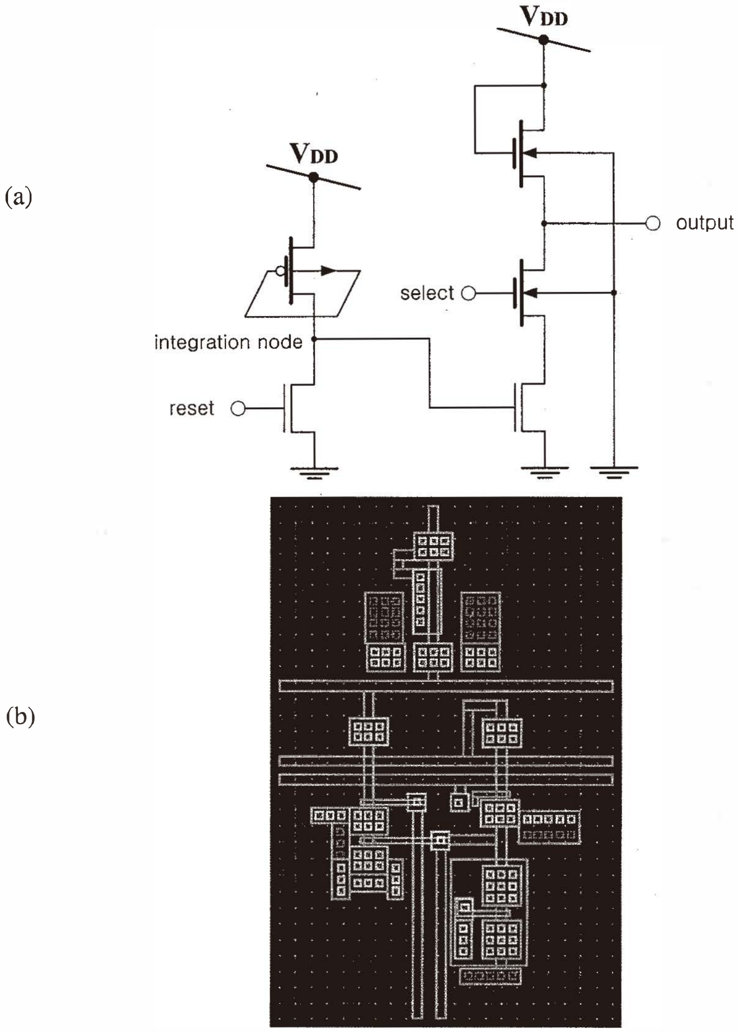


Fig. 3. (a) Schematic and (b) layout of the unit pixel.

is commonly used for a column. The operational procedure of this circuit is as follows. First, the charge integration node is reset to a ground level as an external reset pulse is supplied. The electrons in the n-well respond only to incident light and are not reset by the external reset pulse. After the reset pulse goes down, the parasitic capacitor at the charge integration node is charged up by a photocurrent caused by light illuminated to the PMOSFET photodetector. Next, these charges are inverted and amplified by a common source circuit when a select pulse is supplied. Finally, the output voltage in proportion to the incident light power is obtained by timely sampling. The general architecture of an APS has a source follower output stage as a buffer in each pixel.(1,2,7) However, in this study, an APS that has a common source output stage as an amplifier was designed in order to obtain an appropriate gain for low-illumination application. The unit pixel size is 86 μm × 90.5 μm and its fill factor is 12%, whereas other researchers using a similar structure report fill factors of 20~30%.(1,2,7) This result indicates that the proposed photodetector and the pixel configuration make possible a scaled-down pixel without degradation of performance, so that a more integrated image chip can be produced.

3. Results and Discussion

An I_{DS}-V_{DS} characteristic curve of the fabricated PMOSFET photodetector as a function of incident light power is shown in Fig. 4. The PMOSFET under measurement was operating in the common drain mode with a different illumination level instead of the gate bias voltage. The light source used in the experiment was a halogen lamp and the optical power was measured at a 600 nm wavelength. An optical transient response of the

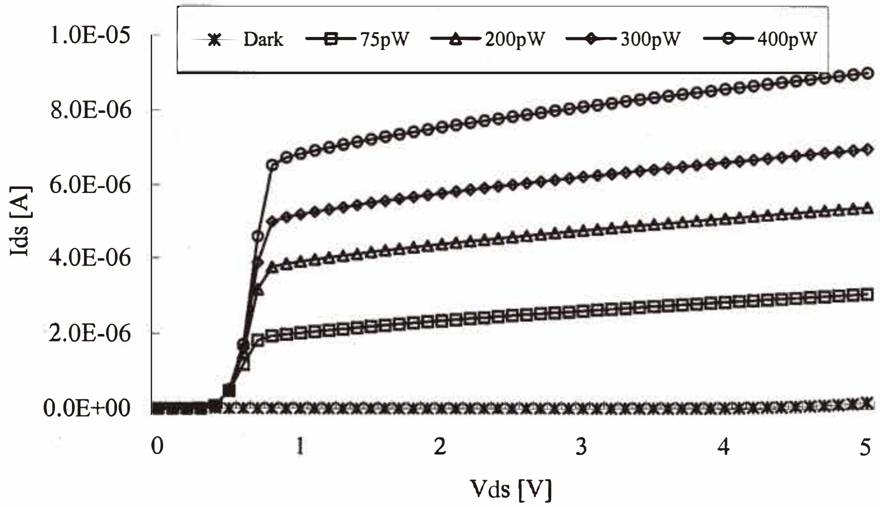


Fig. 4. Optical characteristic of the PMOSFET photodetector (V_{DS}-I_{DS} curve).

PMOSFET photodetector was measured with an external resistor of 10 kΩ for a He-Ne laser ($\lambda = 633$ nm). This is related to electron accumulation and removal in the n-diffused well. As shown in Fig. 5, the rise and fall times of 120 μs and 270 μs, respectively, were measured.

A comparison of a photocurrent per unit area for several photodetectors fabricated using the same CMOS process is shown in Table 1. The process used was not optimized for these photodetectors. The PMOSFET photodetector used in this work has higher optical sensitivity than a photo-BJT or a photodiode. This means that, as mentioned above, the proposed photodetector has better performance even though it occupies a smaller area.

Verification of the designed APS circuit has been performed using star-HSPICE (Avanti corporation). A simulation result for the output voltage of the designed pixel under several illumination levels is shown in Fig. 6. Incident light power was modeled by the

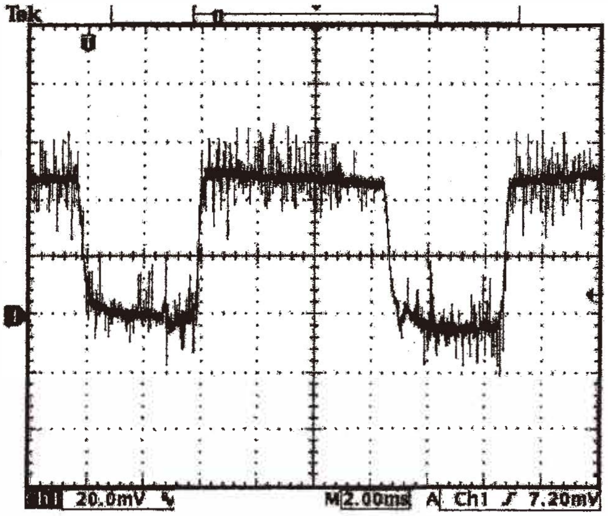


Fig. 5. Optical transient response of the PMOSFET photodetector with 10 kΩ for a He-Ne laser (λ = 633 nm).

Table 1
Comparison of photocurrent per unit area for a photodiode, a photo-BJT and a PMOSFET photodetector in the same CMOS process.

Photocurrent per unit area	Photodiode	Photo-BJT	PMOSFET photodetector
A/m^2	0.47×10^3	1.26×10^3	9.48×10^3

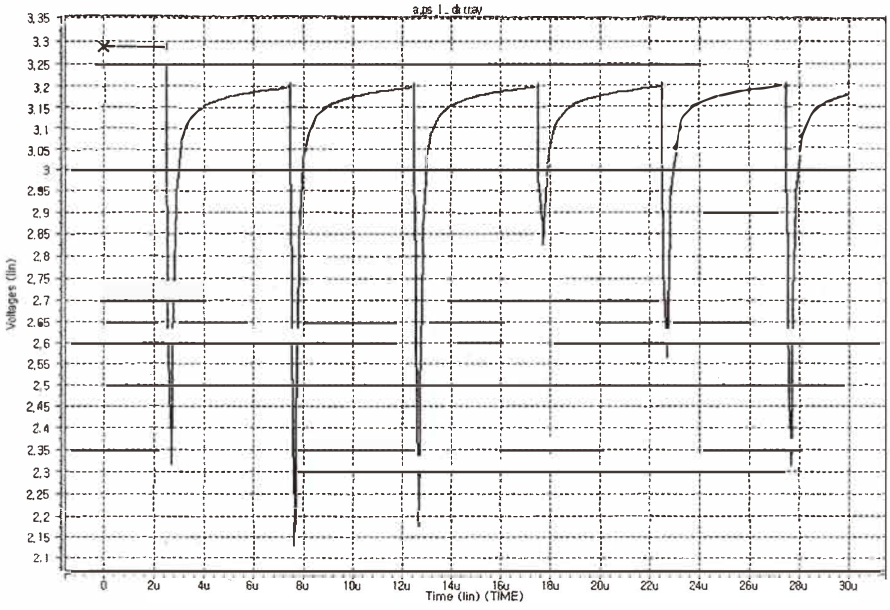


Fig. 6. Simulated pixel output under several illumination levels.

effective gate voltage of the PMOSFET. The amplitude of the negative spike in the waveform shown in the figure is in proportion to the light power; that is, the deepest spike corresponds to the highest light power.

As a function of illuminated light power on the chip, charge-up characteristics at the integration node are shown in Fig. 7. It was confirmed that the stronger the light illumination, the more rapid the charge-up. As a result, an output voltage which is in proportion to the incident light power can be obtained if sampled at a proper time.

An image acquisition system consists of a pixel array and peripheral components such as an analog to digital converter, a signal processor, digital control logic, and display unit. A block diagram of the designed imaging system using the fabricated APS chip is shown in Fig. 8. Voltage waveforms measured at several key nodes of the APS chip are shown in Fig. 9. The control signals are shown at a time. The operational principle as stated above could be certified through the charged up waveform at the integration node, its inverted and slightly amplified voltage waveform at the pixel output node, and the sampled and held signals at the A/D converter input node.

Finally, one-dimensional image patterns obtained through the liquid crystal display (LCD) panel are shown in Fig. 10, in which the focused light beam on the image chip was traced from the left to the right. Each pixel of the chip was mapped into rectangular 4 × 4 dots of the LCD panel. The highlighted point has no black dot, the darkest point has 16

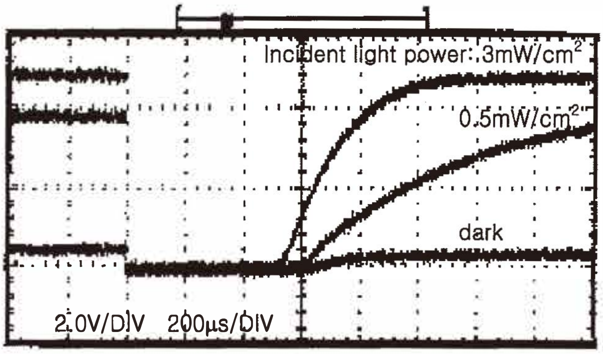


Fig. 7. Charge-up characteristics at the integration node as a function of the incident light power.

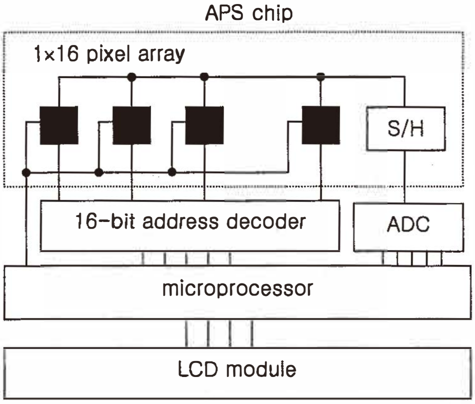


Fig. 8. Block diagram of the image sensor system consisting of the fabricated chip and peripheral components.

black dots, and gray levels are indicated by the intermediary numbered black dots. Although it is somewhat noisy, the illuminated position can be roughly identified from the resultant LCD pattern.

4. Conclusion

A PMOSFET photodetector which has high sensitivity owing to current amplification has been presented. The PMOSFET photodetector with the floating gate tied to the n-well has good optical characteristics and shows a higher photocurrent per unit area compared to the photodiode and photo-BJT fabricated in the same CMOS process. The optical transient

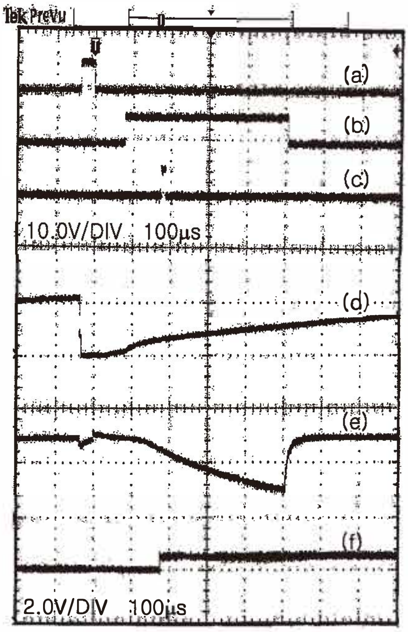


Fig. 9. Control signal and measured voltage waveform at several key nodes of the APS chip. (a) reset pulse, (b) select pulse, (c) sampling pulse, (d) charge integration node, (e) pixel output node and (f) sample and hold output node.

Fig. 10. One-dimensional image pattern through the LCD panel under the tracing light beam. (a) left side, (b) center and (c) right side.

response of this device has rise and fall times of 120 μs and 270 μs, respectively. In addition, an active pixel sensor was designed and fabricated for the purpose of applying the PMOSFET photodetector to an image sensor. The unit pixel of this sensor consists of a PMOSFET photodetector and four NMOSFETs and has a pixel size of 86 μm × 90.5 μm, and a fill factor of 12% which is better than those of other devices based on a photodiode.

Thus, a more integrated image chip can be achieved. The proposed APS has small voltage gain and exhibits well-defined and highly sensitive characteristics as the incident light power varies. Additionally, the one-dimensional 16-channel image sensor array performs well under the tracing light beam. In conclusion, this APS using the PMOSFET photodetector can be applied to image acquisition systems particularly in low illumination conditions.

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Reference

1 E. R. Fossum: IEEE Trans. Electron Dev. **44** (1997) 1689.
2 S. K. Mendis, S. E. Kemeny, R. C. Gee, B. Pain, C. O. Staller, Q. Kim and E. R. Fossum: IEEE J. Solid-State Circuits **32** (1997) 187.
3 H. Zimmermann: Sensors and Materials **13** (2001) 189.
4 W. Zhang and M. Chan: IEEE Trans. Electron Dev. **48** (2001) 1097.
5 Y. Nagamune, T. Noda, Y. Ohno, Y. Arakawa, H. Sakaki and M. Watanabe: Jpn. J. Appl. Phys. **36** (1997) 1955.
6 I. Inoue, N. Tanaka, H. Yamashita, T. Yamaguchi, H. Ishiwata and H. Ihara: IEEE Trans. Electron Dev. **50** (2003) 43.
7 J. I. Nakamura, S. E. Kemeny and E. R. Fossum: IEEE Trans. Electron Dev. **42** (1995) 1693.
8 K. Yonemoto and H. Sumi: IEEE J. Solid-State Circuits **49** (2002) 746.