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Integrated Bio-Photosensor Array with CMOS Cascade Source-Drain Follower

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1. Introduction

Photo-sensor devices have been extensively studied in inorganic materials, where quantum efficiency is reported as 70 % for Si APD (avalanche photodiode), 20 % for InGaAs APD, and 10 % for PMT (photomultiplier tube). Quantum yield of photoelectric conversion of photosynthesis, which is chemical process occurring in plants, algae, and cyanobacteria, is known to be 100 % [1]. Recently, we have developed a new process to plug a molecular wire directly into a biological photosynthetic system to efficiently conduct the free electrons to a gold electrode [2]. By incorporating such biological materials with an integrated circuit, a totally new type of device can be realized. In this paper, photo detection using photosynthesis protein complex photosystem I (PSI) (a photoreception macro molecule) and CMOS integrated circuits is reported. Applying this system, as an imaging device, 4×3 image is demonstrated.

2. Materials and methods

Photons are converted to electrons by photosystem I (PSI) of *Thermosynechococcus elongates*, and the converted electronic charge is sensed by field-effect transistors. The structure is shown in Fig. 1. Isolation and purification of PSI were performed based on the previous report [3]. PSIs are fixed on the electrode by self-assembled monolayer (SAM) of 3-marcapto-1-propanesulfonic acid sodium salt (MPS) covering the Au electrode. The SAM has negative electronic charges, while ferredoxin around Fe-S clusters F_X, F_A and F_B of PSI have positive charges. As a result, the PSI is fixed on the electrode by Coulomb interaction. The electrons are transferred from Sodium L-Ascorbate (NaAs) and 2, 6-dichloroindophenol (DCIP) in the solution to PSI (Fig. 2). Under the illumination, reaction center chlorophyll a (P700) is active to release the electrons. The electrons are transferred along chlorophyll a (A_0), phylloquinone (A_1) and Fe-S clusters, and are finally trapped to the electrode by tunneling the SAM, leading to a potential change of the electrode. To sense the potential change, the extended-gate electrode is formed on the chip. 20 nm Ti and 500 nm Au layers are deposited, and are patterned by optical lithography and wet etching. Since the SiN layer as a protective film can easily trap electronic charges in the solution, causing light-induced potential drift, SU-8 layer is adopted on SiN to reduce the drift, resulting in a 4.255 μm×4.255 μm electrode. An ideal sensing circuit is that it does not influence the sensed system and that the output signal is independent of device parameters. To meet this requirement, source-drain follower is used (Fig. 3(a)) [3]. The relation between input and output is $V_{IN} = V_{OUT}$, and the circuit has high input resistance in both DC and AC operation. The sensor circuit has been manufactured by 1.2 μm standard CMOS process. The chip is set in a shield box, and a halogen lamp is used for a source of light. The wavelength is selected by a monochromator, and the light is focused on the chip surface through the optical fiber and the lens of a microscope. The solution contains 20 mM MES (2-Morpholinoethanesulfonic acid)–NaOH buffer (pH = 6.4), 100 mM $NaClO_4$, 250 mM NaAs and 25 mM DCIP.

3. Results

The photoresponse of PSI sensed by source-drain follower is presented. The light was turned ON/OFF every 90 second, and the wavelength and the intensity are 680 nm and 2.716 μW/cm^2 , respectively. As shown in Fig. 4, light illumination induced the change of about −2 mV in the output voltage. While the electrons from PSI are trapped in the electrode, O_2 in the solution pulls electrons out of the electrode. These incoming and outgoing electrons determine the electric potential of the electrode. Figure 5 shows the photoresponse as a function of light intensity. The output voltage change increases with increasing light intensity. It was saturated at 3 μW/cm^2 because the number of electrons injected by PSI per unit time reaches that which DCIP can recharge PSI with an electron. Figure 6 shows action spectrum of the photoresponse per intensity 1 μW/cm^2. It has the peak at 680 nm where PSI has the absorption peak. The fact indicates that we could detect the photoresponse of PSI [4]. To apply the photodetector as an image sensor, 4×4 sensor array was fabricated on the chip (Fig. 7(a)). The light without monochromator was patterned by a metal slit (Fig. 7(b)). To reduce the influence of drift, the output voltage of each cell was subtracted by that of the corresponding reference cell. We took the moving average of last eight samples to reduce noise. Figure 7(c) shows the image, where only the output voltage of the illuminated cells changed. This result indicates that an image of the light illumination pattern can be obtained by using our photodetectors.

4. Conclusion

The photoresponse of PSI was detected as the change of the output voltage with source-drain follower. In addition, the image has been taken with the sensor array on the chip. The measurement indicated that the bio-photosensor can be used as a imaging device. Since the quantum yield of PSI is 100%, single photon could be detected by PSI combined with a single-electron transistor.

References

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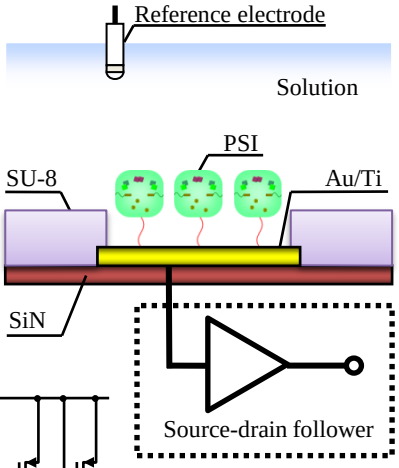

Fig. 1 Schematic of a PSI bio-photosensor. The source-drain follower detects photocurrent from PSI as a voltage change at the Au/Ti electrode. The SU-8 layer prevents the light induced drift by SiN electron traps.

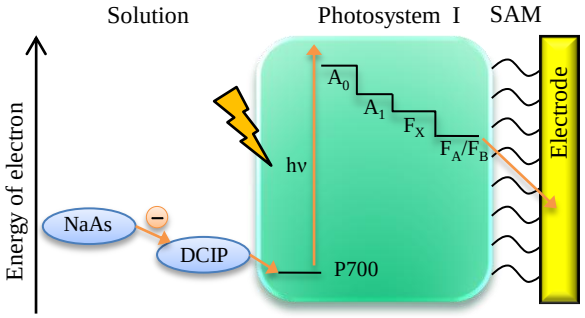

Fig. 2 Energy diagram of electron transfer. Under illumination , P700 is activated to release an electron. The electron is transferred along molecules in order, and is finally trapped to the electrode by tunneling the SAM. P700 then receives an electron from DCIP, which is reduced by NaAs.

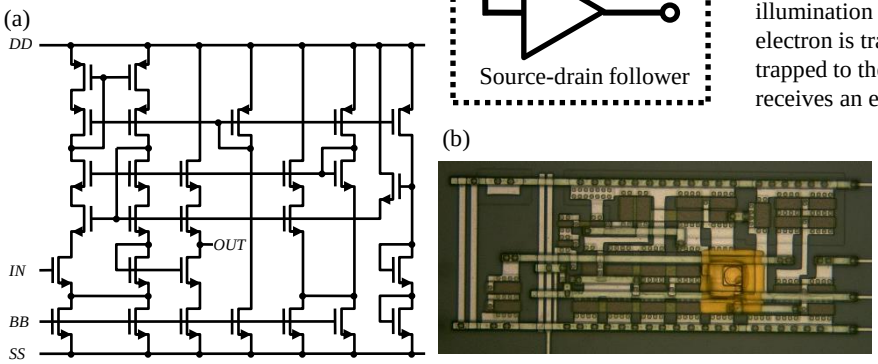

Fig. 3 Cascode source-drain follower. (a) Schematic circuit diagram. $V_{OUT} = V_{IN}$, and the circuit has high input resistance. The power supply voltages V_{DD} = 2.5 V, V_{SS} = –2.5 V, V_{BB} = –0.5 V. (b) Optical photograph of the sensor circuit.

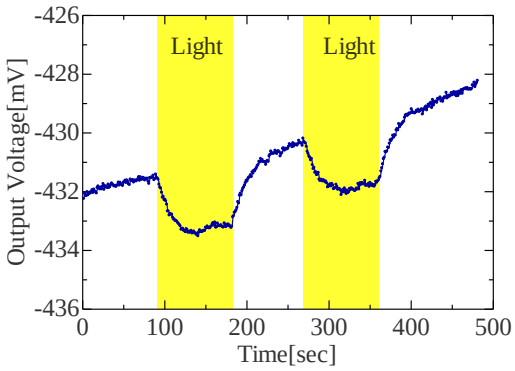

Fig. 4 The change of V_{OUT} induced by the light illumination. The light was turned ON/OFF every 90 sec. The wavelength is 680 nm and the intensity is 2.7 μW/cm^2. The change is about –2 mV.

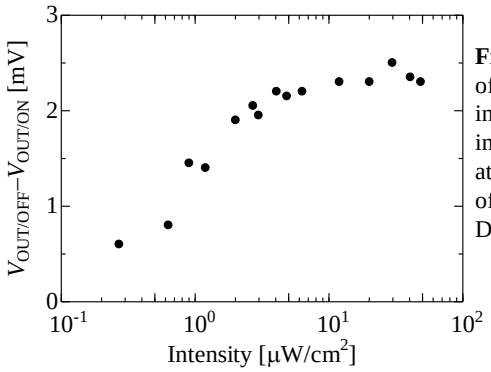

Fig. 5 Intensity dependence of photoresponce. While it increases with increasing intensity, the output saturates at 3 μW/cm^2 because the limit of electron transfer from DCIP is reached.

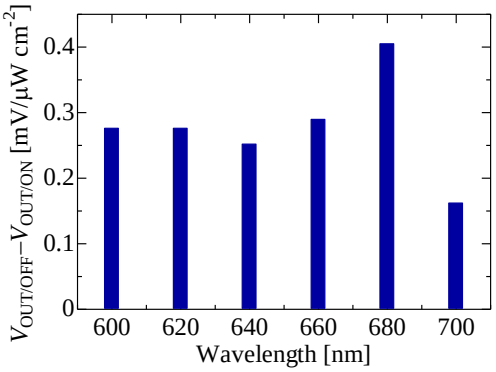

Fig. 6 Action spectrum of PSI. The difference of V_{OUT} before and after illumination was figured per intensity 1 μW/cm^{-2}. It has the peak at 680 nm where PSI has the absorption peak.

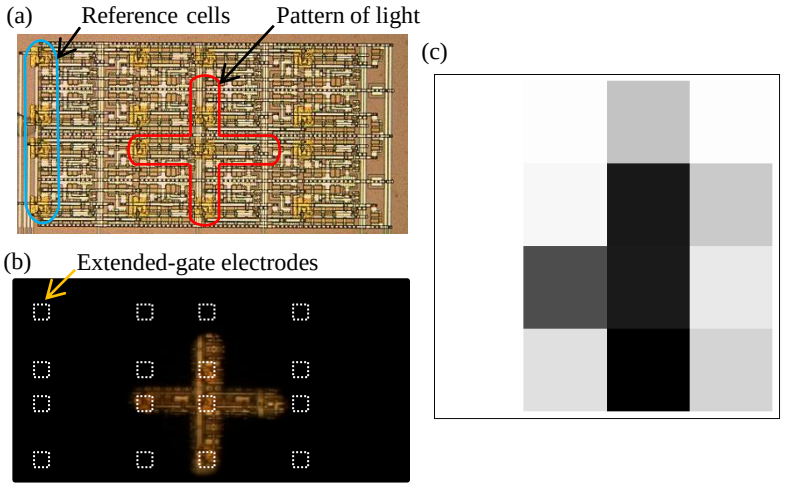

Fig. 7 Imaging with the sensor array. (a) Micrograph of 4×4 sensor array. In each row, the most left cell is used as a reference for the other three cells. (b) Optical photograph of illumination pattern. The four cells are illuminated. (c) Imaging of the photoresponse. For reducing the influence of drift, V_{OUT} of each cell was subtracted by that of the corresponding reference cell. We took the moving average of last eight samples to reduce noise. The difference of V_{OUT} from the initial value when the light is off was plotted as gray pattern which is relative to the absolute value. The change of four illuminated cells are negative, and the values are –1.3 to –1.9 mV, the change of other cells not illuminated are 0.4 to –0.3 mV.