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Wearable Line-Of-Sight Detection System Using Dye-Sensitized Photovoltaic Devices

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Abstract— **Detection of line-of-sight (LOS) has a variety of applications, such as communication tools for elderly or disabled people, assisting drivers, and effective location of traffic signs. To realize such promising applications, the LOS detecting system that does not restrict users' activities and is free from mental stress from the equipment is strongly demanded. In this paper, we propose a novel wearable LOS detection system that affects the users as little as possible both physically and mentally using dye-sensitized photovoltaic devices. The photovoltaic devices are transparent and generate voltage according to the incident light intensity. Arraying the devices on wearable eyeglasses, this system detects the difference in the reflection light from the pupil and the white of the eye and thus, the position of the pupil. This system is wearable as an eyeglass and hence, it does not disturb the activities and the eyesight of users. More importantly, it involves very little physical and psychological stress to users. We fabricated and characterized the photovoltaic device and demonstrated the feasibility of detecting the location of the pupil. We found it possible to meet the required reaction time of 100 ms by reducing the size of the device and to improve the accuracy of detecting the location of the pupil by arraying the devices.**

I. Introduction

RECENTLY, a variety of applications of LOS detection systems are being developed, such as communication tools for elderly or disabled people, assisting drivers, and effective location of traffic signs. The LOS can perform as a pointing device to present the information to viewers [1]. In early studies, using an external camera is the main stream method of detecting LOS, where fixed eye cameras and rather big wearable eye cameras are utilized. However, these methods have several problems that they restrict users' activities and cause physical and mental stress to the users [2]. The key to make the promising applications of the LOS detection practical, the systems free from restriction on users' activities and stress from the equipment are strongly demanded. In this study, we propose a novel wearable LOS detection system that affects the users as little as possible both physically and mentally using dye-sensitized photovoltaic devices fabricated on an eyeglass as illustrated in Fig. 1. The photovoltaic devices are transparent and generate voltage according to the incident light intensity. In this system, the devices are used as transparent photo sensors. Arraying the devices on wearable eyeglasses, this system detects the difference in the reflection light from the pupil and the white of the eyes and derives the LOS. Since this system is wearable and transparent, it does not limit user's activities nor block the eyesight of users. Wearable like an eyeglass, in particular, it provides very little physical and psychological stress to users. We fabricated and characterized the dye-sensitized photovoltaic devices and demonstrated the feasibility of detecting the location of the pupil using the single and arrayed devices.

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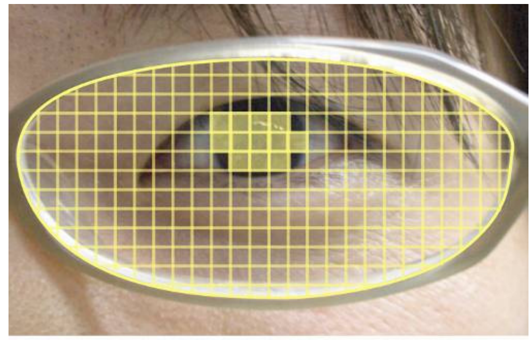

Fig. 1. Conceptual view of the wearable LOS detection system using transparent dye-sensitized photovoltaic devices.

II. Dye-Sensitized Photovoltaic Devices

A. Structure

Dye-sensitized photovoltaic devices are currently attracting widespread scientific and technological interests as a high efficiency and low-cost alternative to inorganic solar cells [3]. Fig. 2 presents the structure and the operation principal of the device. The device consists of two electrodes and an iodide and triiodide ion-containing electrolyte. The cathode has a highly porous nano-crystalline semi-conductive titanium dioxide (TiO_2) layer deposited on a transparent electrically conductive glass. Since TiO_2 absorbs only UV light, dyes are adsorbed on the TiO_2 layer to utilize the light with a wider range of frequency and to enhance the device performance. The counter electrode working as the anode is a transparent electrically conductive glass.

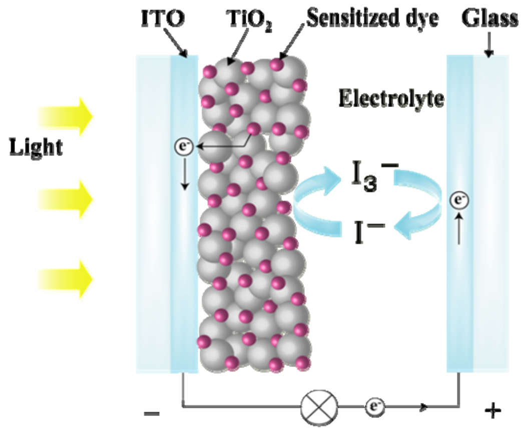

Fig. 2. The structure and the operation principle of the dye-sensitized photovoltaic device.

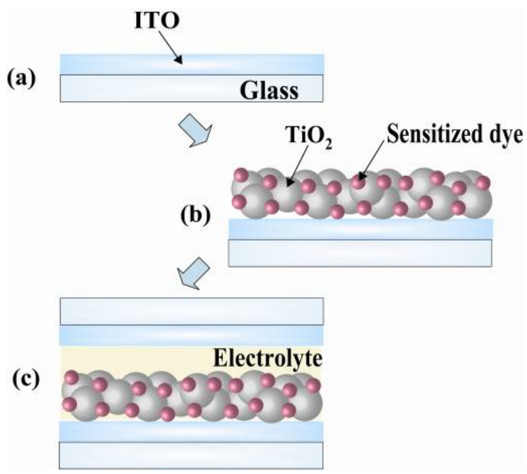

Fig.. 3. The fabrication processes of the dye-sensitized photovoltaic device.

The device is transparent with a color of the dyes.

B. Operation Principle

When light passes through an conductive glass, dyes are excited and transfer an electron to the semi conducting titanium dioxide layer via electron injection. The electron is subsequently transported through the porous TiO_2 layer and collected by the conductive layer on the glass. Within the electrolyte, the mediator (I^-/I_3^-) undergoes oxidation and regeneration. The electrons lost by the dyes to the TiO_2 are replaced by the iodide ion and triiodide ion, generating iodine or triiodide, which in turn obtains electrons at the counter electrode, culminating in current flows through the electrical load. This is how the device receives light energy and emits electricity [4]. This device has an interesting feature. It reacts strongly to the light that enters through the TiO_2 layer. Therefore, when the TiO_2 layer electrode is faced to the eyes, it can detect only the light reflecting from the pupil and white of the eye without being affected by the light incident on the device from the environment.

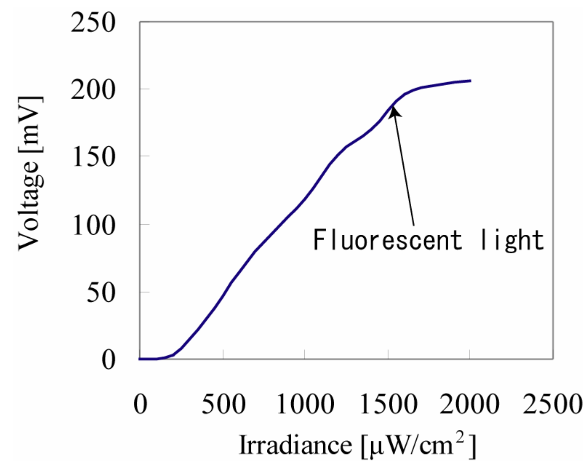

Fig. 4. The irradiance-voltage curve of the device with an active area of 1 cm^2 irradiated by a dimmer controlled light.

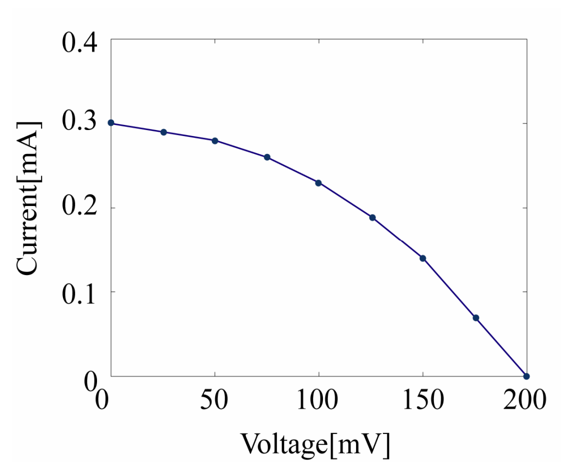

Fig. 5. The current-voltage (I-V) curve of the device with an active area of 1 cm^2 irradiated by the solar light.

C. Fabrication

Fig. 3 describes the fabrication processes of the device. (a) A conductive glass (12 Ω/Square Asahi Glass Fabritech, SnO_2 coated glass, A11DU80) is rinsed by ethanol. The TiO_2 layers are fabricated from TiO_2 coating solution containing TiO_2 nano-particles (Tayka TKC-303, TiO_2 average size 6nm). Scotch (3M) adhesive tapes are applied to the four sides of a conductive glass plate to form a mold into which the TiO_2 solution can flow. (b) The TiO_2 solution is distributed uniformly on the glass and the layer is dried in the air. After the tapes are removed, the device is annealed in the air at 450℃ for 30 minutes. Subsequently, it is dipped in rosehip and hibiscus flowers herb tea (Pompadour) for 30 minutes to adsorb the dyes to TiO_2 layer. (c) The electrolyte (0.5M potassium iodide and 0.05M iodine in water-free ethylene glycol) is dripped on the stained TiO_2 layer. Carbon is deposited on the counter electrode plate, which works as a catalyst. The counter electrode is placed on the top with a lateral offset.

D. Irradiance-Voltage and Current-Voltage

To characterize the fabricated photovoltaic device, the relationship between the irradiance and the voltage and that of the current and the voltage was evaluated. The irradiance-voltage curve measurements were conducted using an irradiance meter (Sakaki, HD2302.0 with LP471RAD, spectral coverage 400nm-1050nm) and a dimmer controlled light. As depicted in Fig. 4, the device started to generate the voltage when the irradiance was 200 $\mu W/cm^2$. The device was found to react not only to the solar light but also to such a weak light as a fluorescent light.

The current-voltage (I-V) curve was obtained by using a 500 Ω potentiometer as a variable load while the device was illuminated by the solar light. The I-V curve of the device with an active area of 1 cm^2 is shown in Fig. 5. The measured open-circuit voltages of the devices were 200-250 mV and the short-circuit photocurrents were 0.25-0.3 mA.

III. EXPERIMENT

A. Detection of the pupil

We conducted experiments of the detection of the pupil and white of the eye using the dye-sensitized photovoltaic device. We fabricated a 15x20 mm^2 device and placed the device in front of the eye with the TiO_2 electrode facing to the pupil as shown in Fig. 6. The distance between the pupil and the devices was set to be 10mm which is approximately the distance between the eyes and eyeglasses in common. We measured the output voltage when the pupil moves iteratively in the lateral direction. Fig. 7 shows the result of this measurement. When the white was in front of the device, the measured voltages were 280-290 mV. Whereas facing to the pupil, the device generated voltages of 250-260 mV. The results verified the feasibility of detecting the location of the pupil by the device. By arraying the devices, it is possible to improve the accuracy of the detection.

B. Reaction time

We evaluated the reaction time of the devices with respect to the size. The reaction time was measured using a photo transistor (Toshiba, TPS603A, reaction time 2μs) as a reference. Fig. 8 illustrates the experimental set-up. The photovoltaic device was positioned adjacent to the photo transistor. The incident light was turned on and off by the shutter. The data were acquired by a card-type PC date sampling system (Keyence NR-110). We measured the reaction time of 20-mm, 10-mm, 5-mm, and 3-mm-square devices. Fig. 9 shows the output voltage of the fabricated photovoltaic device 20 mm square in size and the photo transistor. The evaluated reaction time of 20-mm-square device was 190-210 ms, while that of 3-mm-square device was 80-120 ms. The result indicated that the reaction time becomes shorter for the smaller devices, which originates from the short diffusion time of the electrons in the small devices. It is possible to meet the required reaction time of 100 ms [5] by reducing the size of the device.

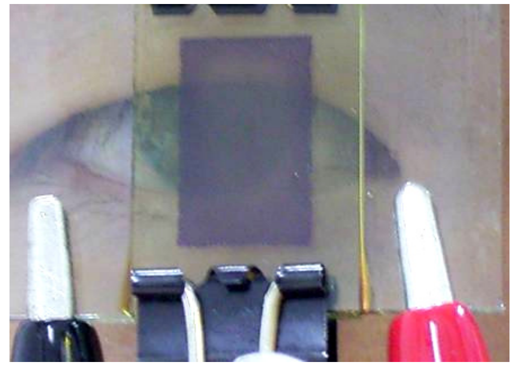

Fig. 6. An image of the experiments of detecting the pupil and white of the eye by the fabricated photovoltaic device.

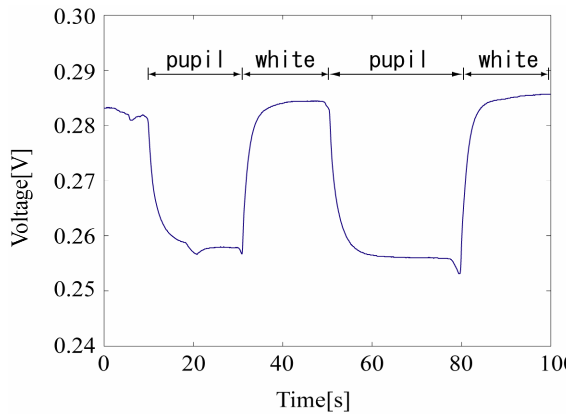

Fig. 7. The output voltage of the device.

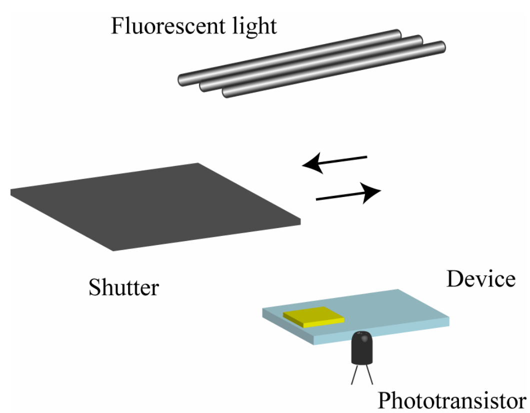

Fig. 8. The experimental set-up to evaluate the reaction time of the device.

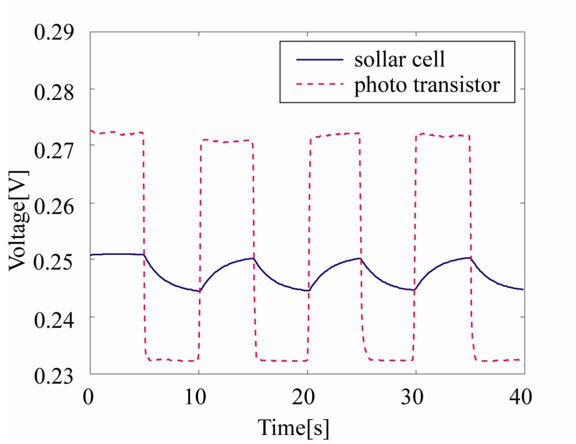

Fig. 9. The output voltage of the 20-mm-square device and the photo transistor.

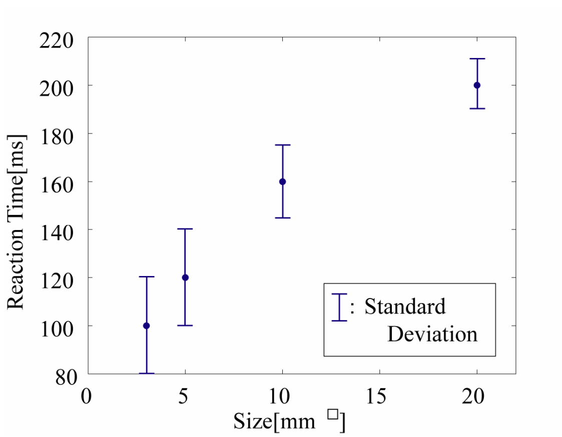

Fig. 10. The measured reaction time with respect to the size of the devices.

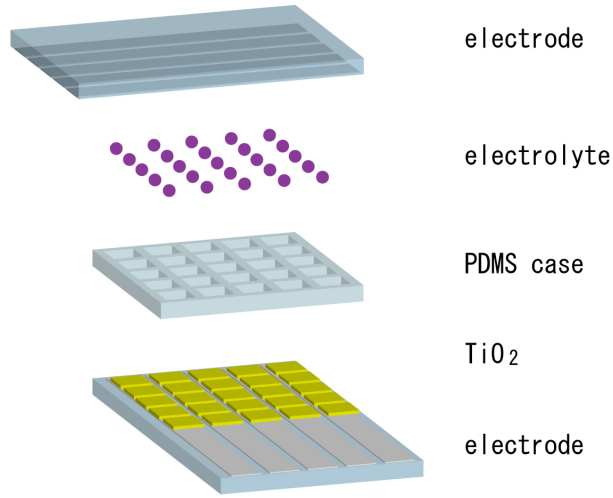

Fig. 11. The schematic fabrication processes of the photovoltaic device array

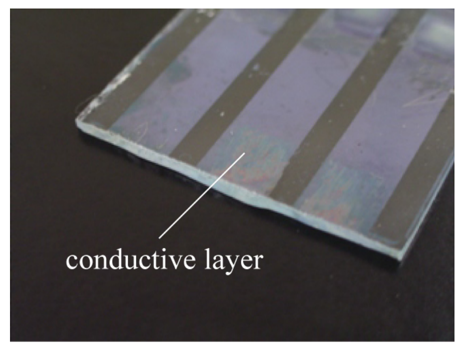

Fig. 12. The patterned conductive glass. The width of the conductive layer is 4 mm.

C. Fabrication of the dye-sensitized photovoltaic device array

To enhance the device performance of detecting the pupil, it is necessary to array the photovoltaic device. Fig. 11 shows the schematic fabrication processes of the arrayed device. We fabricated a 3x1 array of the device, each of which has a 3–mm-square active area.

First, we patterned the conductive glass (SnO_2) on glass substrates for both electrodes by photolithography. A photoresist (AZ) film was utilized as a protective mask and the SnO_2 layer was chemically etched by the mixture of hydrochloric acid (80ml) and ferric chloride solution (67ml). We placed zinc powders on the glass, which works as catalysts, and subsequently dip it into the etchant for 20 minutes. Fig. 12 shows a photo of the patterned conductive glass.

Positive photoresist (AZ) was used as a mold to pattern the TiO_2 layer. The TiO_2 solution containing the TiO_2 nano particles was flowed into the mold on the glass and dried in the air at 100℃ for 10 min. The photoresist mold was removed by the following UV exposure and development. Subsequently, the device was annealed in the air at 450℃ for 30 min and dipped in rosehip and hibiscus flowers herb tea for 30 min to adsorb the dyes to the TiO_2 layer. Fig. 13 shows the patterned TiO_2 layer 3-mm-square in size on the conductive glass.

PDMS (polydimethylsiloxane), which is a thermosetting polymer, is molded to form a casing to contain as well as seal the electrolyte. The mold was fabricated by a thick photosensitive polymer, SU-8. PDMS forms a covalent bond with glass surfaces after the surface is activated by oxygen plasma and brought into contact with the glass surface. The PDMS casing was treated by the oxygen plasma for 0.5 seconds at 50 W and subsequently, bonded to the glass. Fig. 14 shows the patterned conductive glass with the bonded PDMS case.

The electrolyte was dripped into the PDMS case with a micro pipette. The counter electrode is placed on the top of the TiO_2 electrode via the PDMS casing. Fig. 15 shows a photo of the 3 x 1 array of the photovoltaic devices.

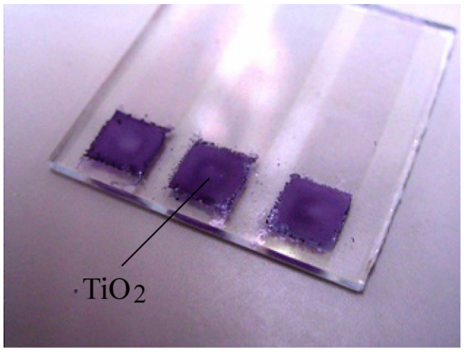

Fig. 13. The patterned TiO_2 electrode. An active area of the devices is 3-mm-square for each electrode.

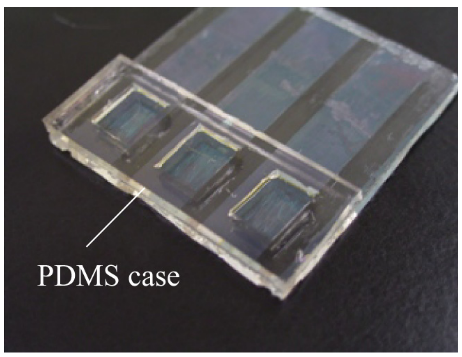

Fig. 14. The patterned conductive glass bonded the PDMS case. PDMS case was successfully bonded to the glass.

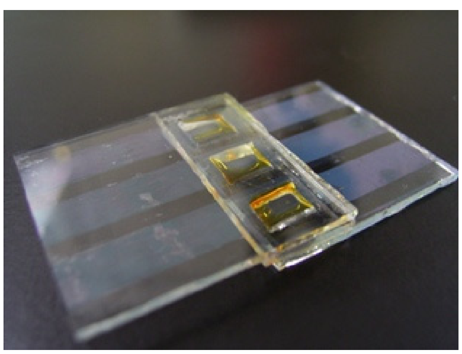

Fig. 15. The 3 x 1 array of the device. An active area of the each device is 3-mm-square.

D. *Experimental of the device array*

We conducted experiments to evaluate the fabricated device array. Fig. 16 illustrates the schematic experimental set-up. The device was located over a white paper with a black stripe that simulates the pupil. A fluorescent light was applied from above. We measured the output voltages from the arrayed devices when the paper was moved laterally. The data were acquired by the card-type PC date sampling system with a sampling frequency of 50Hz. The output voltages of the three devices vary associated with the movement of the paper as shown in Fig. 17. This result indicates that the photovoltaic devices array can detect the black and white region and thus, the position and the movement of the pupil.

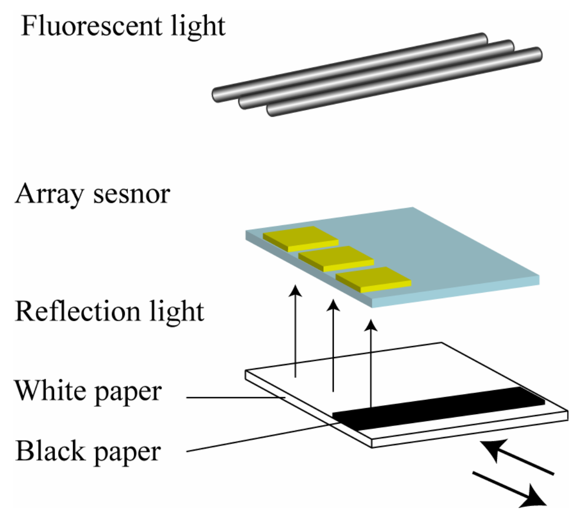

Fig. 16. The experimental set-up of detecting the white and black regions by the 3 x 1 device array

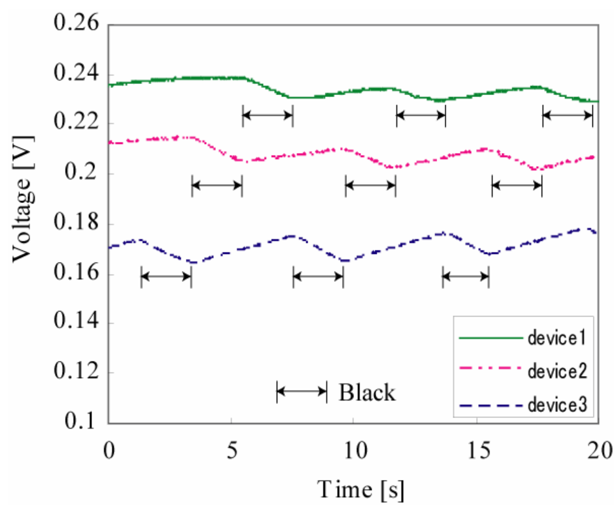

Fig. 17. The output voltages from the array. From the difference in the voltages the movement of the black region can be derived.

E. *Fabrication of the 3x3 device array*

We fabricated the array of 3x3 devices each of which has a 5–mm-square active area. Fig. 18 shows a photo of the 3x3 array of the photovoltaic devices. We are currently evaluating this device array.

IV. Conclusion

In this paper we proposed a novel wearable LOS system using dye-sensitized photovoltaic devices. The photovoltaic devices are transparent and can be manufactured on eyeglasses. The devices generate voltage according to the incident light intensity. By measuring the generated voltages by the reflection light from the eye, whose intensity is smaller from the pupil than from the white of the eye, the devices can detect the position and the movement of the eyes. Since the devices are wearable like eyeglasses, it does not restrict on

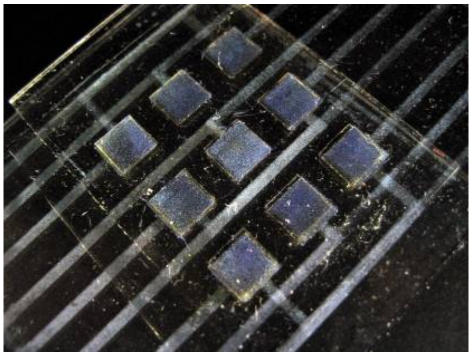

Fig. 18. The 3 x 3 array of the device. An active area of the each device is 5-mm-square.

the action and the eye sight of the users and, in particular, causes much less stress to the users than the previously developed LOS system.

We developed the fabricating processes of the transparent dye-sensitized photovoltaic devices. We characterized the fabricated photovoltaic device and verified that the device can detect the light as weak as a fluorescent light.

We demonstrated the feasibility of detecting the pupil and white of the eyes using the device by the output voltages. The voltage difference of 30 mV was obtained associated with the position of the pupil and white of the eye.

The reaction time of the devices was found to become shorter as the device size decreases. The reaction time of 20–mm-square device was 190-210 ms, while that of 3-mm-square device was 80-120 ms. It is possible to meet the required reaction time of 100 ms for the LOS application by reducing the size of the device.

It is possible to improve the detecting accuracy of the position of the pupil by arraying the devices. We developed the fabricating processes of the photovoltaic device array and fabricated a 3x1 array. The device array could successfully detect the position and the movement of the black stripe on a white paper that simulates the eye.

In future work, we develop the proposed LOS system with more arrays of the smaller devices, which can detect the position and the movement of the eye with a greater accuracy and a better response. In addition, by fabricating the device array on eyeglasses, we realize the practical LOS system free from physical as well as mental stress on the users.

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