The Optical-drive Type Organic Field Effect Transistor Utilizing the Organic Photoreceptor

Norio NAGAYAMA[1,2], Jin YOSHIKAWA[1], and Masaaki YOKOYAMA[2]; [1]Division of Advanced Science and Biotechnology, Graduate School of Engineering, Osaka University, [2]Center for Advanced Science and Innovation, Osaka University; Suita, Osaka/Japan

Abstract

By combining the n-type organic field-effect-transistor (OFET) and the double-layered hole-transportable organic photoreceptor (or organic photoconductor: OPC), an optical-drive type OFET was achieved. In this device, the change of electric potential in the OPC is detected as the channel current of the OFET. This device showed the increase in the source-drain current by the laser irradiation (780 nm) under applied the gate voltage. On the other hand, the current did not change by the laser irradiation, when there was no gate voltage. These results indicated that this current increasing by laser irradiation was originates from the drive of the OPC. Furthermore, the current hysteresis by the charge storage at the interface between OPC and insulator was confirmed, and the erasure of such stored charges was achieved by applying a reverse gate bias.

Introduction

In recent years, organic electronics devices represented for organic light-emitting diodes (OLEDs) have attracted considerable attention, because they have many advantages such as the low cost, the variety of materials choice, flexibility, and the convenient fabrication using the printing technique.

Especially, the organic transistor for driving OLEDs, which begin to have already commercialized, is actively studied. Organic field effect transistor (OFET, Fig.1), one of the organic transistor, is the device, in which the channel current between sources-drain electrode is controlled in the voltage of the gate electrode through insulator. Utilizing above features of organic materials, it is possible to simply fabrication the paper-like integrated circuits by the printing technique. And, the practical application of the light weight flexible display, of which the folding is possible, can be expected[1)].

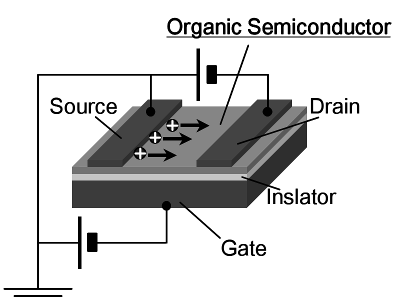

***Figure 1**. Typical device structure of organic field-effect transistor (OFET).*

On the other hand, the organic photoreceptor in Xerography is one of the technology field where the organic photoconductor (OPC) was practically used. In the xerographic process, the surface charge on the OPC is erased by photo-generated and transported carrier. In other words, the potential between electrode and surface is controlled by the photo-irradiation. Previously, we proposed the novel type of photoreceptor device consisting of insulator layer, pixel-like middle floating electrode, and OPC layer on the metal substrate, and we reported that the control of the surface potential at each pixel by the photo-irradiation was achieved in such photoreceptor[2)].

In this paper, by including such potential change shown in the OPC in the gate insulator part of OFET, optical-drive type OFET which controls the gate potential by the photo-irradiation to the OPC part is produced (Fig.2).

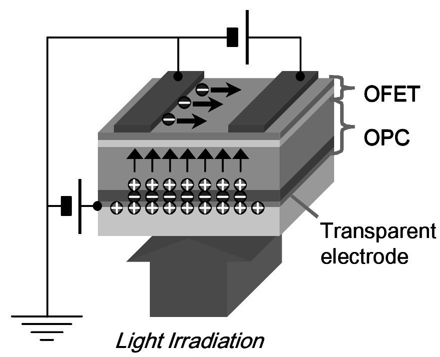

***Figure 2**. Device structure of optical-drive-type OFET proposed in this study.*

Device preparation and transistor characteristics measurements

Our proposed Optical-drive Type OFET device in this study has the structure which included the OPC in the gate insulator part of OFET. As a driving mechanism of this device, it can be expected that the channel current of OFET increases with the following steps: (1) by the photo-irradiation to the OPC, charge generation and transportation are produced. (2) by moved electric charge from CGL to CTL/insulator interface, the potential in gate electrode moves to the insulator of OFET.

In this study, the combination of hole transportable layered OPC (H-OPC) and OFET using n-channel organic semiconductor (n-OFET, a main carrier is electron) was chosen in order to achieve this driving mechanism. In this combination, the channel current of n-OFET increases by photo-generated hole moved to the H-OPC/insulator interface.

Although the driving mechanism described above can achieve even in the combination of electron-transportable OPC (E-OPC) and p-channel OFET (p-OFET, a main carrier is hole), or in the combination of "reversed" H-OPC (in which CGL and CTL are reversely laminated) and p-OFET, it was judged that the combination of n-OFET and H-OPC was the best from the viewpoint of the selection of irradiation light wavelength and simplicity of the lamination process.

H-OPC preparation

A preparation process of the layered H-OPC part of this device is shown in the following. Using ITO (indium-tin-oxide)-coated polyester sheets [with the etching to desirable shape] as substrates, a TiOPc (titanyl phthalocyanine, 50 wt.%) dispersed PVB (poly[vinyl butyral]) film, as a CGL (0.5 µm), was coated from THF solution by the wire-bar. After drying it *in vacuo* for one hour, a DEH (p-diethylaminobenzaldehyde diphenyl-hydrazone, 50 wt.%) doped PCz (bisphenole-Z polycarbonate) film, as a CTL (18.0 µm), was coated on it from dichloromethane solution. This layered H-OPC film was dried *in vacuo* for 3 hours to remove residual solvent. The chemical structures of these compounds are shown in Fig.3.

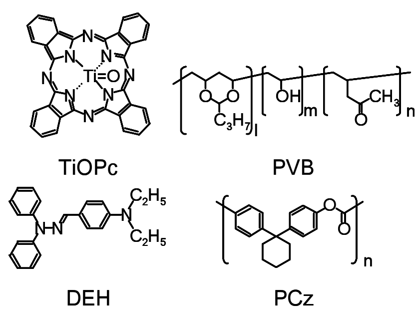

***Figure 3**. Chemical structures of compounds used for fabrication of the OPC part in our device*

n type-OFET preparation

On the layered H-OPC, a PVB film, as a gate insulator (700 nm), was laminated from 2-propanol solution by spin-coating method. Then as a organic semiconductor layer, PTCDI-C8H (Fig.4, N,N'-dioctyl-3,4,9,10-perylene tetracarboxylic diimide) was thermally evaporated onto PVB and its thickness was about 100 nm. Finally, a 300-nm-thick Au layer, as source and drain electrodes, was also thermally evaporated onto a PTCDI-C8H layer using the shadow mask in the form of a top-contact geometry. This device had a channel length (L) and a width (W) of 50 µm and 5.5 mm, respectively. Furthermore, PTCDI-C8H OFET device without H-OPC was also prepared as a reference sample.

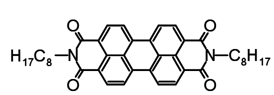

***Figure 4**. Chemical structures of PTCDI- C8H which used as n-type semi-conductor*

Transistor characteristics measurement

The electrical characteristics of this device were examined with a Agilent Technology 4155C semiconductor parameter analyzer in vacuum chamber (about 1×10^{-3} Torr). The photo-response was carried out using the semiconductor laser light (780 nm), in which TiOPc has the high sensitivity. The laser light was illuminated at the area of channel region between source and drain electrodes from the substrate (polyester sheet) side of the devices.

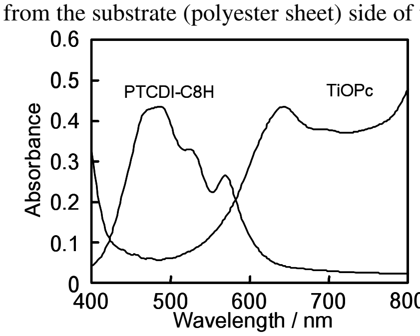

***Figure 5**. Absorption spectra of TiOPc dispersed PVB film and PTCDI-C8H evaporated thin film*

Absorption spectra of TiOPc film, as CGL in OPC part, and PTCDI-C8H film, as semiconductor layer in OFET part, were shown in Fig.5. It can be disregarded that the carrier generation in OFET by the laser irradiation causes current modulation, because only TiOPc has the absorption band at the laser wavelength of 780 nm.

Transistor performance in PTCDI-C8H

First as a reference sample, a transistor performance in PTCDI-C8H OFET device without H-OPC was examined. The output characteristics (drain current: $I_{D\text{-}S}$ versus drain voltage: $V_{D\text{-}S}$ with various gate voltage: $V_{G\text{-}S}$) for the n-channel OFET of PTCDI-C8H was shown in Fig.6.

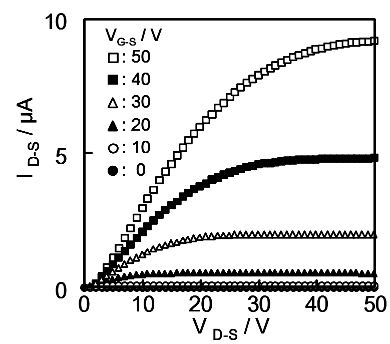

***Figure 6**. Output characteristics of PTCDI- C8H n-OFET devices fabricated on PVB insulator for different source-drain voltage.*

It showed well-defined linear and saturation characteristics. Parameters of device performance, such as field-effect mobility (μ_{FET}), and threshold voltage (V_{Th}), were obtained from following equation:

$$I_{D\text{-}S} = \mu_{FET}\, W\, Ci\, (\, V_{G\text{-}S} - V_{Th}\,)^2 / 2L \qquad (1)$$

where L is the channel length, W the channel width, and Ci the capacitance per unit area of the gate dielectric layer. The calculated μ_{FET} and V_{Th} by plotting $I_{D\text{-}S}$ (at $V_{D\text{-}S}$ = 50 V)$^{1/2}$ vs $V_{G\text{-}S}$ are 4×10^{-2} cm^2 V^{-1} s^{-1}, and 13 V, respectively. And the current ratio of the on and off states (I_{On}/ I_{Off}) is 1.5×10^3. These values were almost equivalent to that obtained from the device using the silicon/silicon oxide as gate/insulator substrate. Furthermore, it was confirmed that the transistor characteristic in this device completely did not change, when it was irradiated with the laser (780 nm).

Transistor performance in optical-drive type OFET

Next, the transistor characteristic of the optical-drive type OFET, in which consisting of n-OFET using PTCDI-C8H and H-OPC, was examined.

Change of output characteristics with laser irradiation

Output characteristics of the optical-drive type OFET in the dark or under laser irradiated were shown in Fig.7(a) and 7(b) respectively.

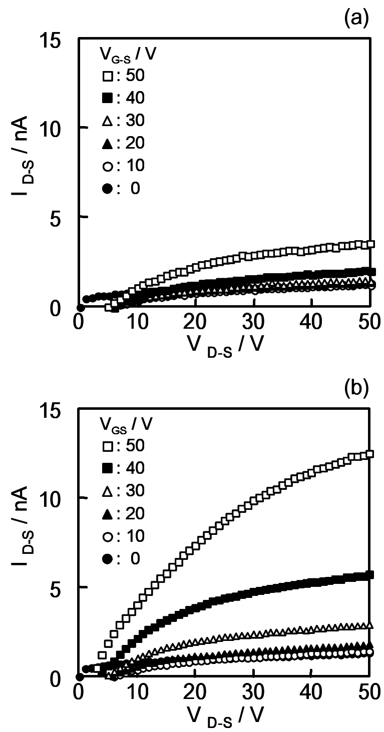

***Figure 7**. Output characteristics of PTCDI- C8H OFET devices fabricated on OPC for different source-drain voltage. (a): dark-state, (b): photo-state (irradiated by laser)*

Although the slight modulation current in the nano-ampere region was observed in the dark condition, this device showed about 4 times the increase in I_{D-S} measured under laser irradiation. This result indicated that OPC layer worked as an insulator in the dark condition operated by the laser irradiation, and the gate potential changed due to the hole carriers transported to the OPC/insulator interface. However, current values in this device under laser irradiation were smaller as 3 orders than PTCDI-C8H OFET shown in Fig.6. This reason is because the photo-generated hole carriers were not sufficiently transported, since the field intensity of 50 V (gate voltage in OFET part) in the OPC layer with the thickness of 18 μm is low.

Current hysteresis after laser irradiation

Figure 8 shows the output characteristics of this device in the dark condition after laser irradiation.

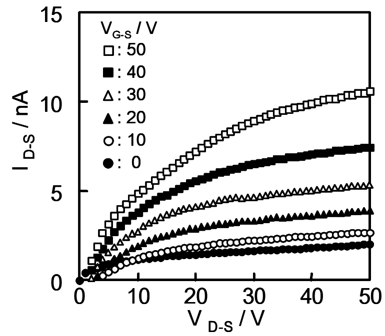

***Figure 8**. Output characteristics of PTCDI-C8H n-OFET devices fabricated on OPC for different source-drain voltage after laser irradiation.*

The device showed large I_{D-S} value further than that in the first dark condition. In comparison with I_{D-S} value measured under laser irradiation, I_{D-S} after laser irradiation was large value in the gate voltage of 40 V or less, though I_{D-S} under laser irradiation is high in 50 V. Considering that the output characteristics were measured in order from low to high gate voltage, it seemed that the hole carriers generated and transported in OPC layer, and gradually accumulated at the OPC/insulator interface during the voltage sweep. Thus, the "ON-state" that the gate potential changes as well as the case of the laser irradiation would be retained, when the laser was cut off.

Repetition characteristics by laser irradiation

The change of output characteristics with the repetition of laser irradiation was measured, and the I_{D-S} value at 50 V of V_{D-S} in each V_{G-S} was extracted (Fig.9).

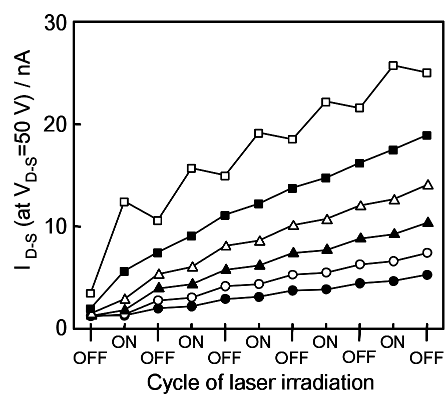

***Figure 9**. Dark- and photo-state drain current at 50 V drain-source voltage as a function of number of treatment.*

The I_{D-S} value at 50 V of V_{G-S} was increased by the laser irradiation, and slightly decreased, after the light was cut off. On the other hand, I_{D-S} values at other low V_{G-S} were further increased, after the light was cut off, since the measurement order influenced. As we described in the preceding subsection, these results clearly indicated that the hole carriers generated and transported in OPC layer, and gradually accumulated at the OPC/insulator interface. Therefore, such storage process of hole carriers should be included for output characteristics under laser irradiation. Then, the transfer characteristic of this device was evaluated using the ID-S values in the dark condition after the laser irradiation.

Figure 10 shows the $I_{D\text{-}S}$ (at $V_{D\text{-}S}$ = 50 V)$^{1/2}$ vs. $V_{G\text{-}S}$ plots (as a transfer curve in FET characteristics) parametric in laser irradiation cycles. These transfer characteristics show clearly that the $I_{D\text{-}S}$- $V_{G\text{-}S}$ curves are not substantially changed in gradient, but are rather displaced by a shift in the onset-voltage (the voltage in which the current begins to increase) by laser irradiation.

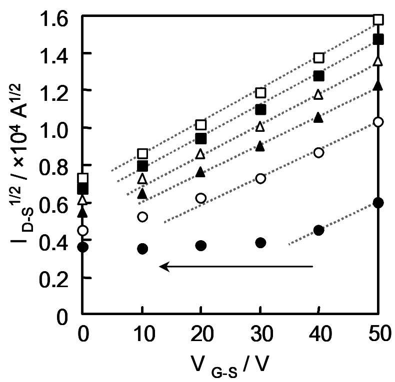

***Figure 10**. Transfer characteristics of PTCDI-C8H n-OFET devices fabricated on OPC parametric in laser irradiation cycles..*

At the beginning, we anticipated the driving mechanism of this device as follows. The OPC, which worked as insulator in the dark condition, behaves as an electric conductor by the laser irradiation. And then, the channel current increases, since the substantial gate insulator thins. In such case, only the gradient of the transfer curve should increase without the onset-voltage changing. Contrary to our expectation, the shift in the onset-voltage without the changes in gradient was observed in our device. Such shift in the onset-voltage was reported in the organic phototransistor devices, in which the organic semiconductor layer was directly excited by photo-irradiation and additional charge carriers were generated in channel region[3]. Taking these reports into account, it can be supported that the depression type driving was observed in our device, since the charge carrier was induced in semiconductor layer by the electric charge which accumulated between OPC/insulator interfaces. In addition to the electric characteristics of our proposed optical-drive type OFET, the current which increased by the laser irradiation was retained for 1 hour in the condition that the voltage was not applied, and it is possible to erase the stored charge by the applying a reverse gate bias.

Summary

In this paper, by combining the n-type OFET (n-OFET) and the double-layered hole-transportable OPC (H-OPC), an optical-drive type OFET was achieved. This device would be operated by charge carrier induced in the organic semiconductor layer by the charge storage to the OPC/insulator interface with the photo-irradiation. Furthermore, it is possible to erase such stored charge at the OPC/insulator interface by applying a reverse gate bias. These results indicated that this device can be utilized as an organic memory device.

References

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Author Biography

Norio Nagayama received his B. Eng. and M. Eng. degrees in imaging science from Chiba University in 1992 and 1994, and received his D. Eng. degree in process engineering from Osaka University in 2000. He has been an Assistant Professor at Osaka University since 1998. He is a member of the Imaging Society of Japan, and he received Research Encouragement Award of the Society of Electrophotography of Japan in 1997 and same Award of the Imaging Society of Japan in 2004. His research interests focus on applications of organic semiconductors.