# The Optical-drive Type Organic Field Effect Transistor for Driving the Electronic Paper

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## Abstract

*Previously, by combining the organic field-effect-transistor (OFET) and the organic photoreceptor (organic photoconductor: OPC), an optical-drive type OFET was achieved. In this paper, in order to clarify the driving mechanism of this device, changes in channel current were evaluated after independently operating OPC part. As the results, the increase in the channel current at gate 0 V was observed, after the OPC independently operated by laser irradiation under applying gate voltage. Furthermore, utilizing the charge injection from gate electrode to OPC, the increase in the channel current was observed without laser irradiation. And, another device structure, in which the carrier generation layer (CGL) in OPC part was removed, was examined.*

## Introduction

In recent years, organic electronics devices 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 display devices is actively studied. One of their targets is toward flexible display application. Organic field effect transistor (OFET), one of the organic transistors, is the device, in which the channel current between sources-drain electrodes 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[1)].

We have previously reported that the optical-drive type OFET (figure 1) was achieved by combining the OFET and the organic photoreceptor (organic photoconductor: OPC) [2)].

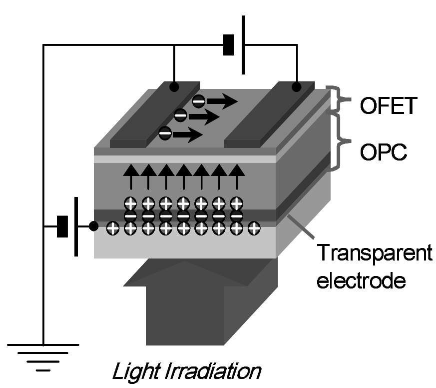


***Figure 1**. Device structure of optical-drive-type organic field-effect-transistor (OFET) proposed in this study.*

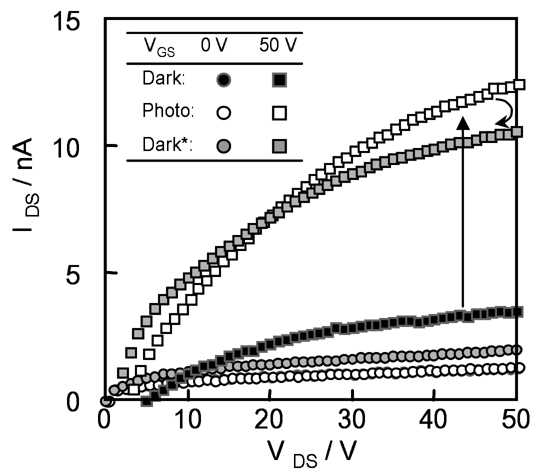


***Figure 2.** Changes in output characteristics (source-drain current versus source-drain voltage ) of the optical-drive-type OFET; dark-state (Dark), photo-state (Photo), and dark-state after laser irradiation (Dark*).*

This device was proposed by the idea of incorporating the potential change shown in the OPC into the gate insulator part of OFET. As shown in figure 2, this device showed the increase in the channel current by the laser irradiation (780 nm) under applied the gate voltage. Furthermore, it was found that the hysteresis current existed after the photo-irradiation (see figure 2, from photo-state to dark-state after laser irradiation), and this hysteresis current was erasable. As a driving mechanism of this device, we proposed following processes; the carriers were induced in the organic semiconductor layer by the carriers which accumulated in the interface between OPC and insulator, and then, the channel current increases. However, those measurements in previous work, in which both OPC and OFET parts were simultaneously operated, complicated the understanding of their driving mechanism.

In this paper, in order to clarify the driving mechanism of this device, changes in channel current were evaluated by separately operating each of OPC and OFET. Concretely, it was a method of observing the OFET output characteristic, after the OPC independently operated. Furthermore, by utilizing hole injection from the gate electrode to the OPC layer, the device, which operated by accumulating the electric charge in the interface without irradiating the light, was also examined.

## Device preparation and transistor characteristics measurements

In this study, the combination of hole transportable layered OPC and OFET using n-channel organic semiconductor was chosen, because that this combination was the best from the viewpoint of the selection of irradiation light wavelength and simplicity of the lamination process.

### *Fabrication of OPC layer*

A fabrication process of the layered OPC 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 carrier-generation-layer (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 poly-carbonate) film, as a carrier-transport-layer (CTL, 18.0 μm), was laminated on it from dichloromethane solution by the wire-bar. This layered OPC film was dried *in vacuo* for 3 hours to remove residual solvent. The chemical structures of these compounds are shown in figure 3.

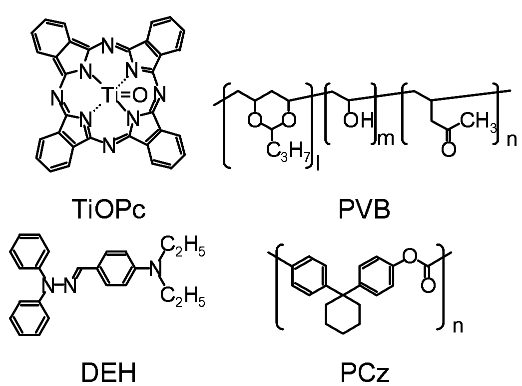


*Figure 3. Chemical structures of compounds used for fabrication of the OPC part in our device*

### *Fabrication of OFET part onto OPC*

On the layered 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 (figure 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.

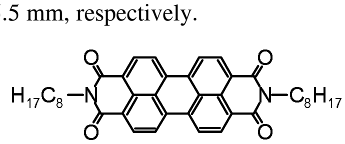

***Figure 4**. Chemical structures of PTCDI- C8H which used as n-type semi-conductor*

### *Transistor characteristics measurement*

The electrical characteristics of this device were examined with a Agilent Technology 4155C semiconductor parameter analyzer in vacuum chamber (about $1\times10^{-3}$ 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.

## Changes in channel current after OPC independently operated

As described above, the charge storage by the OPC drive could not be clearly observed, because it was a method of measuring output characteristics under the photo-irradiation in previous report. Then in this study, the evaluation was carried out by the method of measuring the channel current after the OPC independently operated.

### *The change of output characteristics by the laser irradiation*

Output characteristics in the device as-prepared (initial dark state), and in the device after the OPC independently operated by laser irradiation for 30 seconds under applying the gate-source voltage ($V_{GS}$) of 50 V, were shown in figure 5.

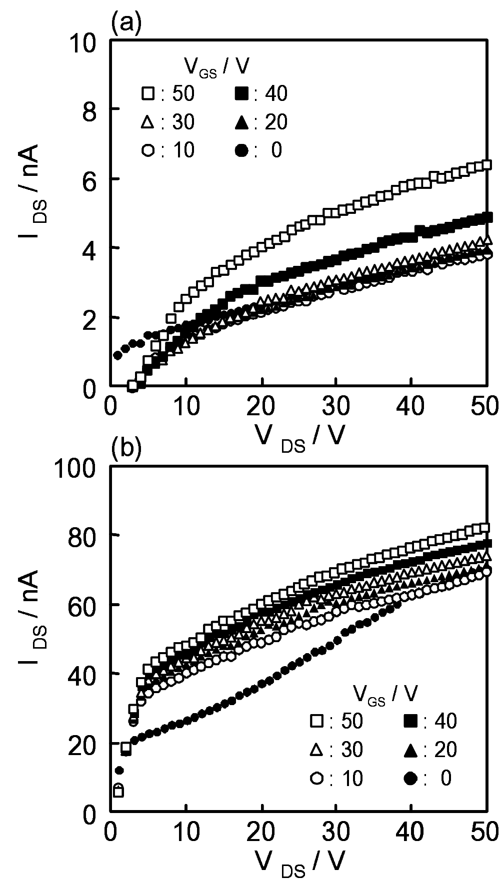


***Figure 5.** Output characteristics of the optical-drive- type OFET for different gate voltages. (a): dark-state, (b): after laser irradiation for 30 sec under applying gate voltage of 50 V.*

In the device at initial dark state (figure 5(a)), the slight modulation current in the nano-ampere region was observed. And, the channel current ($I_{DS}$) at 50 V of both $V_{GS}$ and drain-source ($V_{DS}$) voltages was about 6.4 nA. On the other hand, in the device after the OPC independently operated by laser irradiation for 30 seconds (figure 5(b)), $I_{DS}$ value at 50 V of both $V_{GS}$ and $V_{DS}$ reached 83 nA, which is larger than one order of that in the device at initial dark state, although the width of modulation current by applying the $V_{GS}$ was still small. In other words, $I_{DS}$ at 0V of $V_{GS}$ increases by independently operated the OPC. This result indicates that the channel was formed in the organic semiconductor layer by the drive of the OPC.

### *Laser irradiation time dependence*

Next, by changing the laser irradiation time under applying the gate voltage, similar output characteristics were measured. Figure 6 shows the changes in $I_{DS}$ at 0 V of $V_{GS}$ by laser irradiation time.

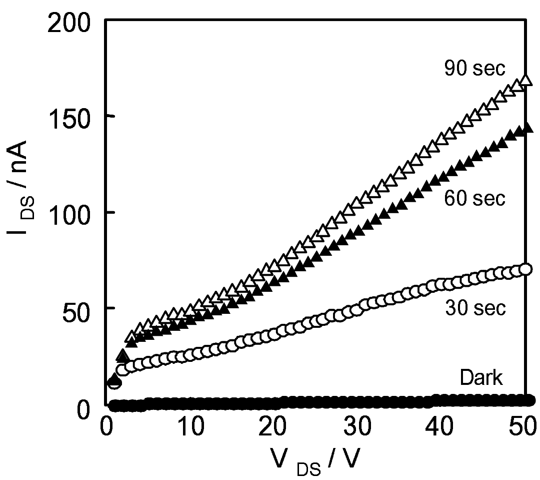


***Figure 6.*** *Changes in channel current ($I_{DS}$) at 0 V of gate voltage ($V_{DS}$) by laser irradiation time.*

It was observed that $I_{DS}$ at 0 V of $V_{GS}$ increased with the laser irradiation time, and such increase of currents showed saturation tendency. In the device operated the OPC for 90 seconds, $I_{DS}$ values reached 40 times larger than that of the as-prepared device. This result indicates that $I_{DS}$ increased by the carrier which accumulated in the OPC/insulator interface by the drive of the OPC. Although relatively large current modulation was achieved in our proposed device, there is a problem that the driving time obtaining the sufficient current modulation is very long.

## Utilizing charge injection from gate electrode

In our proposed optical-drive type OFET, the guideline for obtaining large current modulation approach is "the field intensity applied to the OPC is increased". And, improvement of the OPC performance, especially the improvement of carrier mobility, is necessary in order to improve response speed.

From above viewpoint, when two following improvement was examined, it was found that current modulation (increasing) and the retainment of such increased current could be achieved by utilizing the injected carrier from gate electrode:

(1) Thickness of OPC was reduced in order to increase the field intensity,
(2) Polysilane (inset of figure 7), which has higher hole mobility than DEH, was used as HTL.

### *Device using polysilane as HTL*

The device configuration and its fabrication procedure were almost same as the former device, except for changing HTL form DEH to polysilane (poly[methyl(phenyl)silane], PMPS), and its thickness was reduced to 10 μm. Output characteristics of this device in the dark state is shown in figure 7.

Although only the slight modulation in low $V_{GS}$ (to 30 V) of about 1.5 times was observed, the modulation began to increase over 40 V, and in 50 V, it reached about 30 times larger value than at 0 V of $V_{GS}$. And, $I_{DS}$ in 50V of $V_{GS}$ kept increasing without showing saturation region observed in usual OFET. This result indicates that the hole injection from ITO gate electrode to OPC using PMPS as HTL may occur by applying the gate voltage.

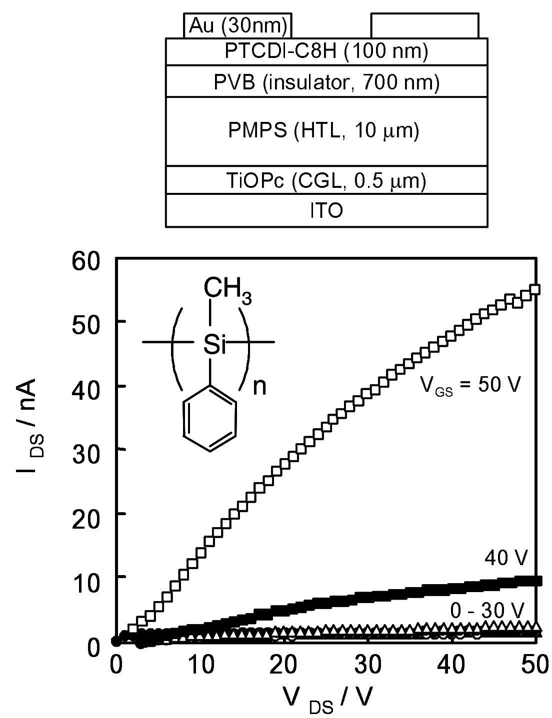


***Figure 7.*** *Device structure (top) and output characteristics (bottom) of the optical-drive- type OFET with PMPS-HTL for different gate voltages under dark condition.*

Then next, $I_{DS}$ in 0V of $V_{GS}$ after it applied 50V of $V_{GS}$ without laser irradiation was observed. The change of $I_{DS}$ at 0 V of $V_{GS}$ with 50V of $V_{GS}$ applying time is shown in figure 8.

Only in the applying of $V_{GS}$, the increase in $I_{DS}$ at 0 V of $V_{GS}$ equal to the laser irradiation in the device shown in figure 6 was observed. Furthermore, $I_{DS}$ increased with the applying time of $V_{GS}$, and $I_{DS}$ after it applied 50V of $V_{GS}$ for 120 seconds was larger as 2 orders than that of the device in initial state (as-prepared). This result clearly indicates that the charge injection from the ITO electrode by the gate voltage applying occurred in this device.

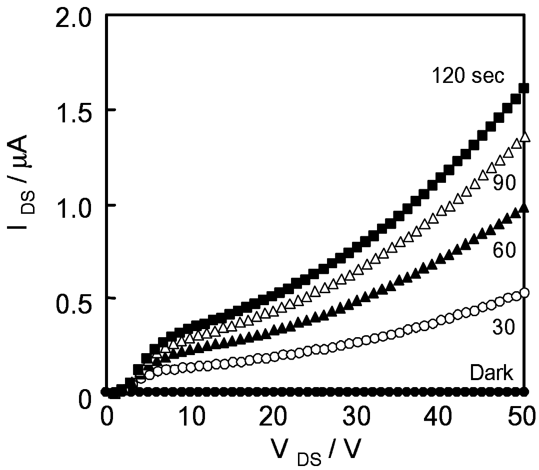


***Figure 8.*** *Changes in channel current ($I_{DS}$) at 0 V of gate voltages in the optical-drive-type OFET with PMPS-HTL by the 50 V of $V_{GS}$ applying time.*

## *Device using very thin HTL*

Next, in order to positively utilize the hole injection from the gate electrode, the device which introduced thin HTL instead of the OPC was examined. In the device of thin HTL (thickness: 200 nm), the charge injection from gate electrode efficiently occurs, since field intensity increases. The change of off current (the channel current as the gate electrode is the float condition) with 50V of $V_{GS}$ applying time is shown in figure 9.

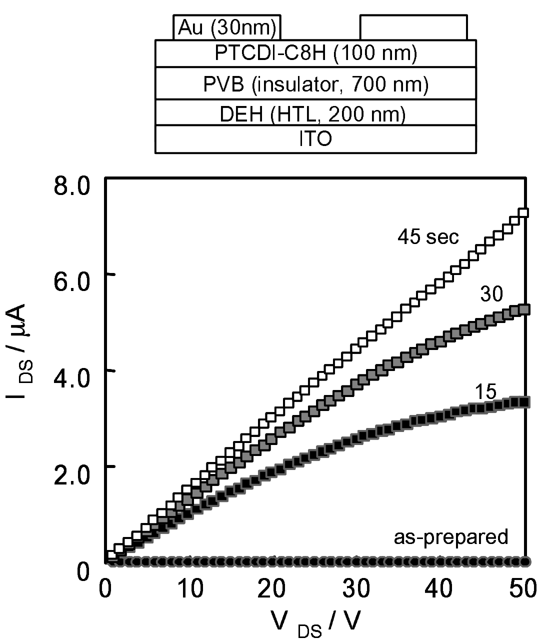


***Figure 9.*** *Changes in off current in the optical-drive-type OFET with thin-HTL by the 50 V of $V_{GS}$ applying time.*

The off current increased with the applying time of $V_{GS}$, and the off current after it applied 50V of $V_{GS}$ for 45 seconds was larger as 3 orders than that of the device in initial state (as-prepared).

Finally, following points are written additionally: although $V_{GS}$ applying time in about few minutes was necessary for the sufficient current modulation which utilized hole injection from gate electrode in the above-mentioned measurement, the very high response was observed, when the gate voltage was applied in the condition that the current flowed in the channel. This fact indicates that the current modulation in this device originates from not only the carrier storage in OPC/insulator interface but also carrier induction in organic semiconductor.

## Summary

In our proposed optical-drive type OFET, the increase in the channel current after the OPC independently operated was confirmed. This result proves the driving mechanism that this device induces the carrier in organic semiconductor layer due to the charge storage at insulator interface by the OPC drive. And, utilizing hole injection from gate electrode to OPC or HTL by electric field of gate voltage, it was shown that the action mode as a memory device which does not utilize the photo-irradiation was achievable.

Using the channel current modulation in the OPC type device by laser irradiation or in the HTL type device by applying gate voltage as the image writing process, both devices are available as a driving device of electronic paper.

## References

[1] For example, Evaluation and Application of Organic Transistor Material, ed by K. Kudo, CMC(2005).
[2] Norio Nagayama, Jin Yoshikawa, and Masaaki Yokoyama: "The Optical-drive Type Organic Field Effect Transistor Utilizing the Organic Photoreceptor", Proceeding of NIP22: International Conference on Digital Printing Technologies (Denver, Colorado, USA), pp-17-20 (2006).

## 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.*