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Observation of Carrier Behavior in Organic Field Effect Transistor with Electroluminescence under AC Electric Field

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1. Introduction

Organic materials have been used as electrical insulators in electronics and electrical engineering, where the mechanical flexibility and excellent insulating performance are the most attractive functions. On the other hand, organic electronic devices, such as organic field effect transistors (OFETs) and organic light emitting diodes (OLEDs), have called our attention since the discovery of high-mobility organic materials. To fully utilize the function of organic materials in electronic devices, understanding of carrier behavior in organic materials is important. For example, injected charges make a main contribution to organic semiconductor devices such as OLED and OFET, whereas carrier injection sometimes leads to the dielectric breakdown. Accordingly, it is challenge to observe and to know the role of carrier behavior and related phenomena in organic materials. Our goal is to distinguish the carrier behavior that does not lead to the breakdown of organic materials from the carrier behavior leading to the breakdown.

Electroluminescence (EL) is observed in organic materials as a carrier recombination phenomenon induced by electric field. Therefore, EL has been detected as a dielectric pre-breakdown phenomenon in polyethylene under AC electric field due to recombination of injected electrons and holes [1]. On the other hand, carrier injection accompanying high intensity EL has been found in anthracene single crystals under DC electric field by Helfrich and Schneider [2]. These facts indicate that EL is associated with the carrier behavior in organic materials in the presence of AC or DC electric field.

OFETs have been intensively studied as injection-type elements. Generally, most OFETs drive as a unipolar device since hole is dominantly injected from the Au source and drain electrodes. Recently, double-injection-type OFET was reported by Hepp et al [3], where EL is observed because of the recombination of injected electrons and accumulated holes at the drain electrode. This fact motivates us to observe the carrier behavior in organic materials in FET structure using EL phenomena, because the three-electrodes (source, drain and gate) structure is useful to observe and then control the carrier behavior in the material.

In a previous investigation with OFET, the carrier behavior was observed by EL under DC electric field [3], however, the observation of carrier behavior under AC electric field was not. In this report, we examined the carrier behavior in OFETs using the EL under AC electric field.

2. Experiment

We used tetracene (and pentacene) as active layer of bottom-contact OFET, where Au is used as source and drain electrodes. SiO_2 is used as gate insulator (500 nm thickness). Organic active layer was deposited in vacuum, and the film thickness was adjusted to about 200 nm using a quartz crystal microbalance.

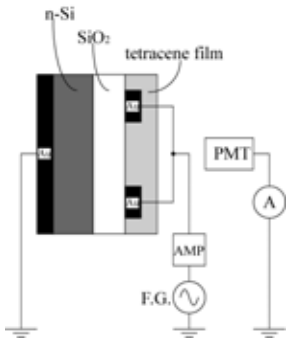

Fig. 1: Experimental Setup

AC voltage with an amplitude of 100 V was applied to the Au source and drain electrodes, which are

electrically shorted (see Fig. 1). Applied AC frequency was varied from 1 Hz to 500 kHz. The time-dependence of the EL intensity was monitored with photo-multiplier tube (PMT), and EL spectrum with photonic multi-channel analyzer (PMA).

3. Results and Discussion

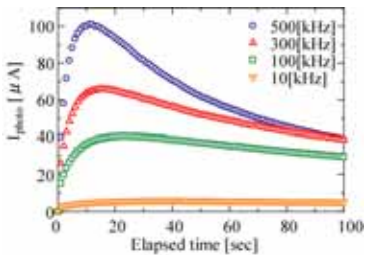

Fig.2: EL intensity of tetracene FET dependent on the elapsed time

Figure 2 shows the time-dependence of tetracene EL intensity under AC electric field. The EL intensity changed with one peak as time elapsed and it increased in proportion to AC frequency up to 500 kHz. This result indicates that electrons and holes are injected into the tetracene alternately and generates the EL caused by their recombination.

In our previous paper, the EL intensity monotonously decayed with elapsed time [4]. On the other hand, the EL intensity increased and then decreased with elapsed time in this study, indicating that two processes are involved in it. Taking into account these, we inferred that the increasing process of EL intensity was too short to detect it in our previous study.

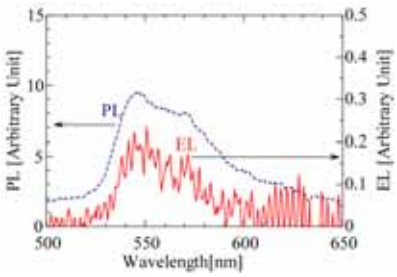

Fig. 3: EL and PL spectra of tetracene FET

Figure 3 shows the EL and photoluminescence (PL) spectra of tetracene FET. EL spectrum corresponds well with PL spectrum, which has a peak at a wavelength of about 545 nm. From this result, we considered that observed luminescence was intrinsic EL of tetracene [5], where electrons and holes injected from the Au electrodes into materials are main origins.

The properties of carrier behavior under AC electric field are discussed briefly as follows: The external quantum efficiency is derived as

$$\eta_{ext} = \gamma \cdot \eta_r \cdot \phi_p \cdot \eta_p \quad . \qquad (1)$$

Here γ is a coefficient representing charge balance and it varies with time. η_r is exciton formation efficiency, φ_p is internal quantum efficiency and η_p is extraction efficiency. Immediately after applying AC voltage, holes are mainly injected from the Au electrodes into materials because tetracene or pentacene FET drives as a hole-injection type element and the injected holes are gradually accumulated in the material around the electrodes. Then, a space charge field generated from accumulated holes pulls electrons into the material. On the other hand, there are many trapping-states at metal-organic interface [6], and excess holes are trapped in these states. Eventually, the trapping states are filled with holes, but electrons are allowed to inject into the material, probably assisted by the electric field formed by trapped holes. The EL and related phenomena are observed during the recombination of electrons and holes. In other words, γ changes in accordance with the change of the status of the trapping states, and results in the generation of the time-dependent EL with one peak.

4. Conclusion

We observed EL from tetracene and pentacene FET under AC electric field. The result indicates electrons and holes are injected into materials alternately, and EL is generated by their recombination.

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