# DIRECT PROBING OF CARRIER MOTION IN ORGANIC FIELD EFFECT TRANSISTOR BY OPTICAL SECOND HARMONIC GENERATION

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## Abstract

*We report an optical second harmonic generation measurement that allows direct probing of dynamical carrier motion in organic field effect transistors. Carrier injection and transport process are discriminated. The mobility and contact resistance of pentacene FETs are determined from the visualized diffusion-like carrier motion.*

## 1. Introduction

Since the discovery of conducting materials, organic material electronics has commanded increasing attention, and development of techniques that can probe carrier motion is highly motivated. Probing of carrier motion in organic materials is often exerted by means of time-of-flight (TOF) technique [1, 2]. In this measurement, a long-range carrier motion in organic materials sandwiched between metal electrodes is probed as a transient current, and the carrier behavior is analyzed using the generated transient current pulse. However the analysis leads to a puzzling situation in which there are many possible solutions to reproduce an observed current pulse, because the TOF probe the change of induced charge on electrodes. This means it is difficult to probe real carrier motion in organic materials by the TOF method. That is, it is difficult to know the exact carrier motion without directly probing it. Gauss's law, in Maxwell's electromagnetic field theory [3] suggests us an insightful principle for probing the carrier motion in organic materials. By probing the propagation of the electric field diverging from moving electrons and holes, the carrier motion could be visualized if the organic material surrounding the moving electrons and holes is polarized. Time-resolved microscopic optical second harmonic generation (TRM-SHG) is a technique that enables us to probe the propagation of the polarization induced by moving electrons and holes [4]. Hence using a CCD-camera, its motion is directly visualized.

## 2. Detection of Carrier motion by SHG

TRM-SHG technique directly probes carrier motion in organic materials. The concept is to probe the propagation of polarization induced in organic materials by moving carriers. According to the Maxwell-Wagner effect [5-7], at the interface between two materials with different relaxation times, charge $Q_s$ is accumulated. In organic field-effect-transistor (OFET), carriers injected from the source electrode are accumulated at the interface between active-organic layer and gate insulator, and they are conveyed along the channel by an external electric field $E_0$ applied. Injected carriers are excess charges and they are acting as a source of space charge field $E_s$ that can polarize the organic-active layer. Hence the electric field, E produced in the OFET is sum of the external and space charge fields. That is, $E = E_0 + E_s$. Obviously $E_0$ is a Laplace field and it does not change after applying voltages to the source, drain and gate electrodes. On the other hand, $E_s$ is a Poisson field, and it changes with time in accordance with carrier injection and accumulation. Of course it stabilizes in the limit in steady state. In this situation, nonlinear polarization P is induced by irradiation of laser, owing to the quantum coupling between electromagnetic fields and electrons in organic materials. As electron clouds of molecules are distorted by D.C. field, this kind of nonlinear polarization P is induced even in centro-symmetric molecular system, such as

inpentacene. That is, induced polarization is given as [8,9]

$$P(2\omega) = \chi^{(3)}(E_0 + E_s)E_i(\omega)E_j(\omega) \quad (3)$$

where $\omega$ represent the angular wave frequency of incident electromagnetic wave, and $E_j$ and $E_i$ represent the electric field of light, and $E_0$ and $E_s$ are the static electric field. The induced polarization $P(2\omega)$ is a source of second harmonic signal, and the SH enhanced is in proportion to $P(2\omega)$ as

$$I(2\omega) \propto \left|\chi^{(3)}E(0)E_i(\omega)E_j(\omega)\right|^2 \propto \left|P(2\omega)\right|^2 \quad (4)$$

where $I(2\omega)$ describes the SH intensity. From eqs.(3) and (4), it is clear that SH intensity distribution along the channel changes with change of the space charge field $E_s$ [10-12], thus with injected carrier propagation. TRM-SHG measurement is based on this principle, and this approach allows us nondestructive probing of a local electric field induced in materials because of the two-photon process, and also realizes selective probing of a local electric field distribution in multi-layer systems in device applications such as OFET and organic electro-luminescent (EL) device by choosing laser wavelength appropriately.

## 3. Experiment

TRM-SHG measurements were carried out using an experimental setup shown in Fig. 2(a) [9]. Through the objective lens, laser beam is incident onto the top-contact pentacene OFET. Fig. 2(b) shows the TRM-SHG image from the channel of pentacene FET with Au-source and drain electrodes. That image was obtained at various times after a positive voltage pulse was applied. Positive voltage pulses ($V_{pulse}$ = 100 V) were applied to the source electrode with the gate and drain electrodes shorted and grounded (see Fig. 2(a)). At $\tau = 0$ ns, the laser pulse coincides with the rising edge of the voltage pulse, and SHG signals are found near the edge of source electrode, indicating that carrier injection is just started, and a very high Laplace field $E_0(x)$ is formed only around source electrode. As clearly shown in the image, the emission band of SHG signal gradually moved along the channel from the source to drain electrode with elapsed time. Motion of the emission band from source electrode, not from drain, is the direct evidence for hole injection from Au-source electrode. That is, pentacene FET shows p-type behavior. On the other hand, Figure 2(c) shows SHG profile when a negative pulse ($V_{pulse}$ = −100 V) is applied. Under the negative bias, carrier injection from the electrode into pentacene is prohibited because the injection barrier for electron at pentacene/Au interface is quite high. Thus the strong electric field around the edge of electrode is maintained during bias application and the position of the SHG peak never moves; the SHG signals are concentrated around the edge of source electrode as shown in Fig. 2(c).

As mentioned above, it is clear that we can probe carrier motion in organic materials by monitoring the propagation of the electric field diverging from the carrier. In our recent study, we could show that the peak and shoulder of SHG signals migrate along the channel in a way of square-root of time [13], and the TRM-SHG experiment and numerical simulation, using two dimensional (2D) coupled diffusion-drift and the Poisson equations, well support this model.

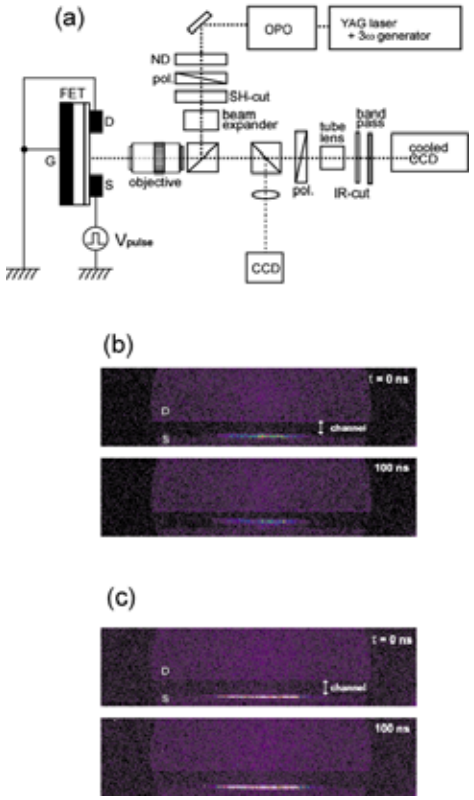


**Figure 1 Experimental configurations and results of the TRM-SHG measurement. (a) Schematic image**

**of the OFET device and electrical connection. SHG image from the FET channel for different delay tim es (upper) $\tau = 0$ and (lower panel) $\tau = 100$ ns and with applying ( b ) positive a n d ( c ) pulse to the source electrode.**

## 4. Summary

Using Time solved microscopic optical second harmonic generation (TRM-SHG), we could probe the propagation of the polarization induced by moving electrons and holes. Hence carrier motion is directly visualized.

## 5. References


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