Impact of Illumination on the Charge Injection and Accumulation in Organic Transistors

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1. Introduction

Organic field-effect transistors (OFETs) are widely used as logic devices in organic electronics applications [1] because of their low-cost fabrication and reliable performance. Fundamental research studies have focused on charge transport in organic semiconductors [2], while applied research efforts have mainly directed to improve the carrier mobility or decrease the threshold voltage [3]. However, the high sensitivity of the organic semiconductors to the environment has motivated us to further study of the device performance under various circumstances. It has been reported that illumination will influence the electrical properties of OFETs in both carrier transport and injection [4]. Here we applied illumination to the samples with and without silver nanoparticles (Ag NPs). We have proven that Ag NPs acted as hole trapping centers in previous studies [5]. In this study, we introduce another charge origin instead of applied electric field, the photo generation into the devices. The pentacene OFETs are used here for an illustration of the illumination influence on organic device properties. The reason of using Ag NPs is to see whether illumination can help to reduce the amount of trapped holes when electrons are generated after photo-generation. The effects are further investigated using the impedance spectroscopy (IS)technique and current-voltage measurements. Finally the results are shown well supported by the Maxwell-Wagner model [6] analysis.

2. Experiment

The Ag NPs encapsulated in oleic acid/oleylamine were synthesized according to the method published in detail elsewhere [7]. NPs were dissolved in chloroform (Sigma-Aldrich) prior the spreading on the water subphase (18.2 M Ω cm) of the Langmuir trough using a microsyringe (Hamilton, Reno, NV). The floating layer was allowed to equilibrate for 30 min before the compression. This time was found to be sufficient for the solvent evaporation and monolayer formation. Subsequently the Ag NPs monolayer was deposited on the solid substrate using the modified Langmuir-Schäffer (horizontal lifting) technique. Organic devices used in experiments were top-contact pentacene OFETs. Heavily doped Si wafers with a 100 nm thick thermally prepared silicon dioxide (SiO₂) insulating layer were used as the base substrates. The Ag NPs monolayer was deposited onto Si wafers prior to the deposition of pentacene (100 nm in thickness). During the deposition of pentacene, the pressure was kept at less than 10^{-4} Pa and the deposition rate was fixed at 0.5 Å/sec, which monitored by quartz crystal microbalance.

After the deposition of pentacene, gold electrodes (source and drain electrodes) of thickness 100 nm were deposited on the pentacene surface. The designed channel length (L)and width (W) were 30-100 µm and 3 mm, respectively. Fabricated devices were characterized by the standard steady-state current-voltage (I-V) measurement using a Keithley 2400 SourceMeter to determine contact resistances and effective mobilities. The capacitancevoltage C-V and IS measurements were performed using a Solartron 1260 impedance gain/phase analyzer, where C-Vscan was performed at a frequency of 100 Hz. All measurements were done in laboratory ambient atmosphere. The evaporation of pentacene and gold electrodes for devices with and without NPs SAM were carried out simultaneously to ensure uniform device preparation conditions.



Figure 1 (a) Sketch of the top contact structure of organic field-effect transistor (OFET) with Ag NPs SAM for I-V and *IS* measurements and (b) the stabilized Ag NP structure. The diameter is about 8 nm.

3. Results and discussion



Figure 2 The transfer characteristics of pentacene OFET for devices with and without NPs (in dark and under illumination)

Figure 2a illustrates the transfer characteristics of the pentacene OFET with and without a Ag NPs monolayer under dark and illuminated conditions. The pentacene OFET with Ag NP layer exhibits the trapping of holes

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which is represented by huge threshold voltage shift (-17 V) with respect to the pentacene OFET with bare SiO_2 gate insulator (+3 V) which is equivalent to 670 nC/cm² of trapped holes by assuming that trap density at the pentacene-gate insulator interface is given as $Q = \Delta V_{th} \cdot C_{e}$. Here ΔV_{th} and C_{e} represent threshold voltage shift and gate insulator capacitance respectively. In other words, each NP molecule can trap upto 3 holes. However, when both the devices were exposed to illumination, the on/ off ratio decreases by two orders. The reason is because of the existence of off current without the carrier injection takes a place. In other words, the charge carriers have no relation with the injection properties, but they are generated in the bulk of the organic semiconductor film. As a result, the creation of hole-electron pair and free photo-carriers subsequently in pentacene occurred during illumination and when V_{gs} is positive, the holes repel positive bias at semiconductor-gate insulator interface and eventually reached drain electrode and produces current. This can be proven by a significant positive shift of threshold voltage (3.2 V to 14 V) which indicates trapping of electrons induced by photoirradiation at semiconductor-gate insulator interface upto 370 nC/cm². While for sample with NPs, the shift of V_{th} is from -17 V to 19 V and this is equivalent to 1200 nC/cm^2 of trapped electrons which is three times more. The illumination causes the free electron-hole pairs via the exciton generation and dissociation. The pentacene film is well-known due to its high hole mobility as well as low electron mobility. As a result, the holes are transported and contribute to the output current, while electrons behave as immobile charges and create the space-charge field only. Hence, the negative charges trapped in organic semiconductor film leads to the positive threshold voltage shift. The more positive shift of the threshold voltage in device with NPs compared to the reference results may have an origin in higher trap density (presence of negative charges in NP itself) as well as higher exciton generation/dissociation due to presence of NPs. However, further investigations are required.

Figure 3(a) shows the contact resistance R_c change with applied voltage for both the sample in dark and under illumination condition. As expected, the device with Ag NPs exhibits higher contact resistance up to an order. After illumination, the contact resistance for both devices decreased. In this point of view the illumination enhances carrier injection. However, when we evaluated the potential drops under the electrode $(V_{drop}=I_{ds}R_c)$, we have found that they remained almost unchanged (Fig. 3(b)) even after illumination. The results are explained by photocurrent contribution which seemingly increases the total output current/ mobility and thus the appearing contact resistance decreases. However, the detailed analysis shows that the voltage drop on the injection electrode representing the injection properties is conserved because the energy barrier on injection electrode is not influenced by illumination. In other words, no photo-assisted injection is present there due to enough thick metal electrodes (100 nm). In other words injection and transit time ratio had been found conserved

which had been reported [8]. Further, the photo-generated charges present in the channel region only; therefore, the space-charge field of excess charges has no influence on the metal-organic interface. In a similar manner the discussion can be carried out for the device with NP also. The charge trapping causes low currents and subsequently the high R_c , but the injection properties are defined by the energy barrier on the metal-organic interface only. This points out the transport limitation of the devices, since the channel conductivity change has significantly stronger impact on device performance compared to the charge injection. Therefore illumination shows negligible influence on carrier injection.



Figure⁰ 3: The (a) contact⁶ resistance and (b) potential drop of pentacene OFET with and without NPs (in dark and under illumination)

4. Conclusions

We have demonstrated the impact of illumination on OFET samples with and without Ag NPs. Illumination results in positive shift of threshold voltage for both devices due to the photo-carriers generated *i.e.* increase in negative charge accumulation in accordance with low electron mobility in pentacene. There is a significant decrease of R_c when illuminated on NPs sample at the beginning of the bias. It is suggested that the illumination compensates the space-charge field due to field formed by photocarrier. Note that potential drop is always conserved, thus the injection properties do not change even though the photocarriers are generated in the OFET channel region.

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