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Evidence of Electron Trapping Center at Pentacene/SiO_2 Interface

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1. Introduction

Recently, the stability issue has been embossed as one of the greatest concerns in the field of organic electronics for archiving the real device application.[1] It is widely believed that the device instabilities commonly observed as hysteresis or threshold voltage shift (ΔV_T) in the conjugated molecule devices dominantly result from the charge trapping effect.[2] Therefore, to understand the trapping phenomena at the insulator/organic interface is a crucial for improving the device reliability. Moreover, the minority carrier effect in the organic electronics has been ignored due to its lower contribution to the FET operation. However, the fact that the device feature is significantly influenced by the photo-irradiation [3] suggests a possible role of minority carriers as well as that of majority carriers on the characteristics variation. Besides, it is underlying for new application such as organic photo-sensor or organic photo-memory which uses the irradiation effects to understand material properties and device physics under the light in the research of the organic electronics. [4]

The purpose of this work is to understand the mechanism of the threshold voltage shift under the light. Here, we present clear evidences for the electron trapping at the pentacen/SiO_2 interface that plays a significant role in the device instability.

2. Experimental Details

Three-terminal devices have been obtained in the top contact geometry. To avoid the device instability derived from the gate leakage or tunneling, thermally oxidized 500-nm thick SiO_2 was used as a gate dielectric on a lightly doped n-Si wafer served as a gate electrode. A 60-nm thick pentacene film was deposited using thermal evaporation, keeping the substrate at room temperature (R.T) and a rate of 0.5 Å/s. After the active layer formation, the device fabrication was completed by the evaporation of a 50-nm thick Au on top of the pentacene layer. All electrical measurement was performed in vacuum (< 10^{-4} Pa) at R.T to avoid an ambient effect, i.e., oxygen or H_2O.

3. Results and Discussion

The devices were illuminated from the top as shown in the inset of **Fig. 1 (b)**. Light source was provided by a xenon lamp in the range from 400 to 800 nm with the band-pass filter. The intensity of the light was set at 22.4 mW/cm^2, monitored by a Si photodiode. Typical p-channel FETs behavior is exhibited in the dark and under irradiation shown as output characteristics in **Fig. 1(a)**. A large increase of the drain current is clearly observed for the irradiated device. It has been reported that the main contribution of the current enhancement can be caused by the effect of exciton generation in the channel [3]. However, we think under the light with the photon energy higher than the optical band gap of organic material, the device characteristics should be also strongly affected by the photo-excited carrier injection from the metal electrodes into the organic film as well as the exciton generation. **Fig. 1(b)** also shows the bi-directional transfer characteristics for the devices with W/L=800/50 μm in the dark and under illumination. ΔV_T and hysteresis remarkably increases as well as the off-current increases under illumination.

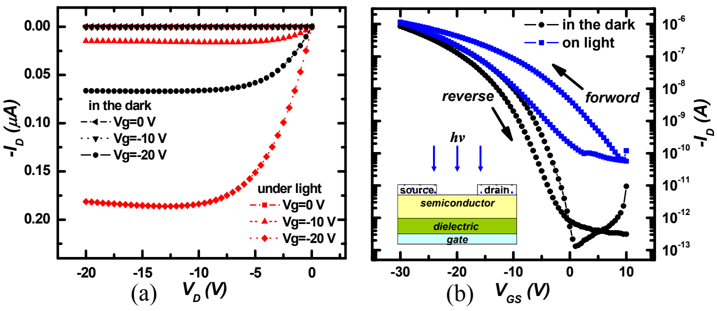

Fig. 1 Output (a) and bi-directional transfer characteristics (b) variation in the dark and under visible irradiation.

Our central result is presented in **Fig. 2**. The device was characterized by the different sign of the depletion bias in the dark and under the light. As given in **Fig 2(b)**, in the dark, the transfer characteristics of the device are independent for the split starting voltage. A good agreement of I-V curves with the virgin sweep is obtained even if the device is set at a different depletion stress. On the other hands, under irradiation, the V_T of -9 V, -4.5 V, -0.5 V and + 4.5 V has been observed on the forward sweep when the device is driven into the depletion bias of 0 V, +10 V, +20 V and +30 V, respectively, as shown in **Fig 2(a)**. The magnitude of hysteresis also increases with the depletion bias increase.

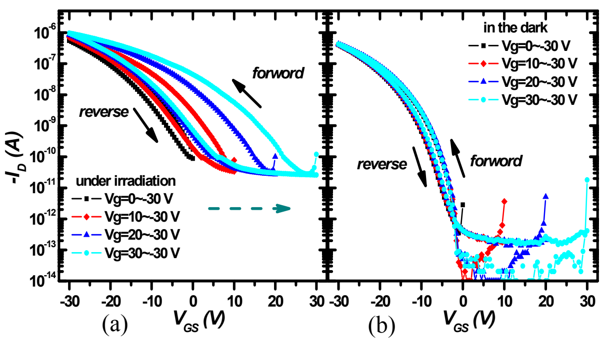

Fig. 2 Threshold voltage shift and hysteresis behaviors according to depletion bias variation under irradiation (a) and in the dark (b).

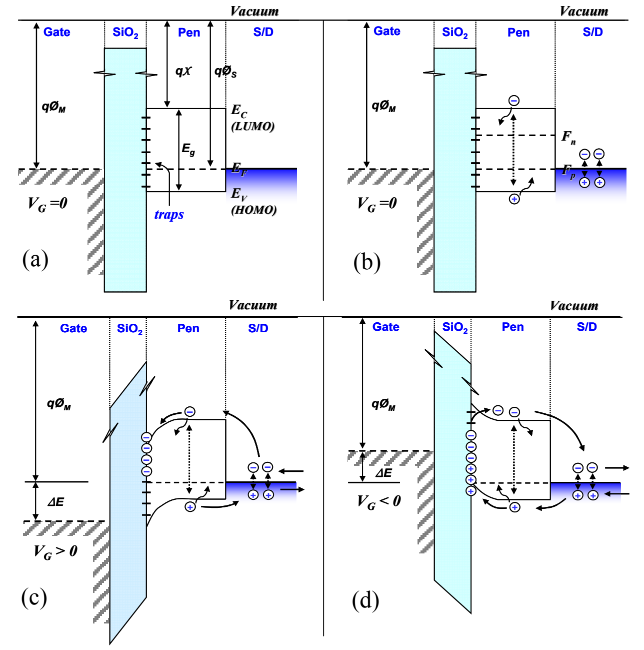

Fig. 3 Band diagrams according to ambient and the bias variation; (a) V_G= 0 in the dark and (b) V_G= 0, (c) V_G> 0 and (d) V_G< 0 under irradiation with the energy higher than optical band gap.

Fig. 3 shows a model for the threshold voltage shift controlled by the different charge capturing according to the light and the bias condition. (a) When the device is set in the dark, unipolar carrier (hole) only works for the carrier transport and trapping, since the minority carrier injection is restricted due to the energy barrier between LUMO level in pentacene and the metal electrodes. However, (b) the photo irradiation on the device with the energy over the band gap leads to the generation of a number of the excess free carriers in pentacene. (c) In the case that the device is set with the depletion bias under irradiation, an equal amount of the negative charges in accordance with ΔV_T is first occupied in localized trapping sites. Besides, the charge capturing to the deeper states is accelerated by the increase of the depletion bias, resulting in further positive shift of V_T. However, (d) when the gate bias is set at the onset voltage of the device, the negative charge trapping is suspended and some negatively trapped states cause the de-trapping due to the reverse biasing effect. The applied negative bias also leads to the positive charge capturing in the same manner as (c). But, if the trapped electron is immobile, the de-trapping or the compensation with the positive charge in the previously occupied state is restricted even by the reverse sweeping.

The estimation of the initial V_T recovering has been carried out to evaluate the trapped charge lifetime as a function of time in the dark condition. **Fig. 4(a)** shows the ΔV_T of -13.6 and -8.2 V after the depletion bias stressing of +40 V during 5 min at the light intensity of 22.4 and 10.8 mW/cm^2, respectively. The exponential decay function was excellently fitted for the stressed device under irradiation with two time-constants (τ): $\Delta V_T=\Delta V_{T1}\exp(-t/\tau_1)+\Delta V_{T2}\exp(-t/\tau_2)+\Delta V_T(\infty)$. This result shows the charge trapping in pentacene consists of at least two separate components; fast and slow. In particular, the photo-induced ΔV_T corresponding to the short lifetime constant (τ_1) regime sensitively responds to the irradiated

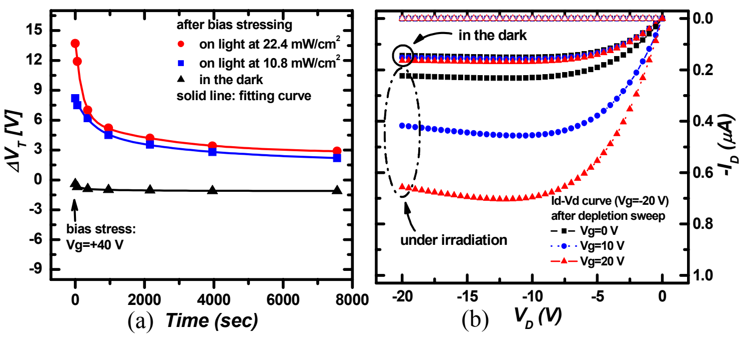

Fig. 4 (a) Recovering of initial threshold voltage after the +40V stressing. Time-constants of the device stressed under the light at 22.4 mW/cm^2; τ_1= 210 and τ_2= 2558. (b) Output characteristics variation after depletion bias stress in the dark and under irradiation, respectively.

intensity of the light. It is thought that most of the excited and injected negative carriers in pentacene would be trapped soon from the shallow state first without the contribution of the carrier transport in p-channel. Therefore, the charge trapping in this regime is more strongly affected by the excess carrier amount in proportion to the irradiated photon density. It is also inferred that an intrinsic memory effect with a long lifetime (τ_2) is associated with the deep level tapping sites.

In p-type semiconductor, the negative charge trapping raise the channel potential in the active region. **Fig. 4 (b)** shows output characteristics variation according to the depletion bias stress and the optical excitation. Each I_D-V_D curves was measured at a fixed gate bias of -20 V after the previous sweeping of I_D-V_D with one of depletion gate bias of 0, +10, +20 V in both ambient. In the dark condition, the dependence of the depletion bias on the current variation is hardly observed. However, the drastically increased extra current is achieved after the depletion stress under irradiation. This result show the negative charges stored by the optical excitation and the depletion stress yields the extra hole population in the channel to balance the negative trapped charge. Moreover, the degradation of drain current after I_D-V_D overshoot indicate that the de-trapping of the stored negative charge with a long lifetime (τ_2) by the reverse bias effect.

4. Conclusions

The photo-induced ΔV_T mechanism is studied. The device instability is accelerated by the electron trapping when the device is exposed under the light in the depletion bias. The stored negative charges lead to the extra hole injection into the channel to balance the carrier population. The trapped charge life time is well described by two lifetime constants which would be associated with the tapping sites in the forbidden states of pentacene.

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