New Organic Phototransistor With Bias-Modulated Photosensitivity and Bias-Enhanced Memory Effect

Hsiao-Wen Zan and Shih-Chin Kao

***Abstract*—A simple and effective method to adjust organic thin-film transistor photosensitivity was proposed. First, the full suppression of light-induced threshold-voltage shift was successfully demonstrated by applying negative gate bias during illumination. Then, the light-induced threshold-voltage shift that was modulated from 0 to 13.5 V was achieved by changing the drain and source bias from +15 to −15 V. Plausible mechanisms were proposed and verified. After light removal, the memory ability of the threshold-voltage shift was also greatly enhanced by the bias effect. The results demonstrate a sensitive organic phototransistor with memory ability by adjusting suitable bias conditions.**

***Index Terms*—Bias modulation, memory, organic thin-film transistor (OTFT), photosensitivity, phototransistor, stress.**

I. INTRODUCTION

PENTACENE-BASED organic thin-film transistors (OTFTs) are known to be good phototransistors and exhibit pronounced threshold-voltage shift (ΔV_{th}) under illumination [1]–[3]. Compared with photodiodes [4], [5], phototransistors provide higher responsivity because the variations of both channel conductance and the threshold voltage greatly enhance the photocurrent [6], [7]. When OTFTs are used as switching elements or circuit components, however, light-induced ΔV_{th} causes serious reliability problems. The light-induced ΔV_{th} can be attributed to electron trapping in the interface between the gate dielectric and the active layer [1], [2], [7]. As a result, increasing the interface-state density leads to a more significant light-induced ΔV_{th} [1]–[3], [6]. Gate-bias stress was also found to enhance the ΔV_{th} under illumination because the positive gate-bias stress produces extra negative-charged defects [1], [2].

The suppression of light-induced ΔV_{th}, however, has never been performed. In this letter, a fully suppressed ΔV_{th} by using negative gate-bias stress during illumination was successfully demonstrated. Additionally, a new bias-modulation method and a new bias-enhanced memory effect were proposed in this letter. When applying biases on drain and source electrodes with grounded gate during illumination, the light-induced ΔV_{th} is modulated from 0 to 13.5 V by changing the drain and source bias from positive to negative. Bias-induced unbalance between the electron and hole concentrations is proposed to explain the experimental results. After removing the light, ΔV_{th} is also sustained by applying negative drain and source biases. Reading the ΔV_{th} signal by scanning the transfer characteristics does not erase the ΔV_{th} signal. Removing the bias refreshes the device to its original condition. The newly discovered phenomenon opens a way to switch one OTFT from a sensitive phototransistor to a memory device by suitably designing the time-sequential bias conditions.

II. EXPERIMENTAL SETUP

In this study, conventional top-contact pentacene-based TFTs were used. A 100-nm-thick thermal oxide was grown on heavily doped Si wafers to serve as the gate dielectric. Without using surface treatment on the thermal oxide, pentacene obtained from Aldrich (purity: 99.9%) without purification was evaporated through a shadow mask onto the thermal oxide to form the active layer. The deposition rate was set at 0.5 Å/s with the substrate temperature as 70 °C and the pressure at around 1×10^{6} torr. After the formation of a 100-nm-thick pentacene, a 100-nm-thick gold was deposited through the shadow mask to form source/drain contacts. The device's channel width and length were defined as 1000 and 600 μm, respectively. A light-emitting diode backlight was used as the light source to irradiate the sample from the top with a fixed brightness of 500 cd/m^2. The device was measured at room temperature in ambient air. The threshold voltage (V_{th}) was extracted by using the linear-region equation. The ΔV_{th} is defined as $V_{\mathrm{th}} - V_{\mathrm{th}}^{\mathrm{ini}}$, where $V_{\mathrm{th}}^{\mathrm{ini}}$ is the initial threshold voltage before illumination or bias stress.

III. RESULTS AND DISCUSSION

First, the suppression of light-induced ΔV_{th} by applying negative gate-bias stress is demonstrated. As shown in Fig. 1(a), the initial transfer characteristics (line) and those after a 500-s illumination (symbols) are compared. Without bias stress, the transfer characteristics obviously shift by +2.04 V after a 500-s illumination. When a gate bias of −10 V is applied during illumination, the transfer-characteristic shift is significantly suppressed. The threshold voltage and mobility (in the inset) extracted from the transfer characteristics after a 500-s illumination are plotted as a function of gate-bias stress voltage as shown in Fig. 1(b). Before and after a 500-s illumination with different gate biases, unchanged mobility indicates a constant device temperature, since the field-effect mobility is expected to increase with temperature in organic semiconductors [7]. Obviously, ΔV_{th} is effectively suppressed by increasing the gate bias from 0 to −15 V. The ΔV_{th} in dark under negative gate-bias stress is also shown by the dashed line in

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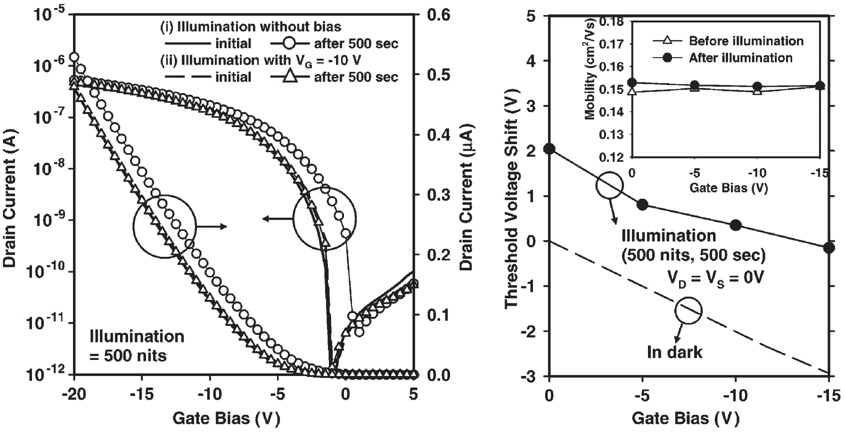
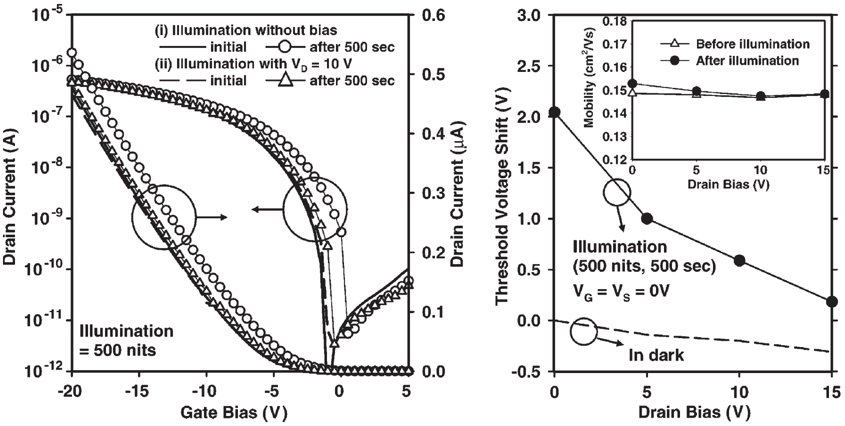


(a) (b)

Fig. 1. (a) Transfer characteristics of OTFTs before and after a 500-s illumination. The stress conditions are the following: $V_G = 0$ and -10 V, $V_{\mathrm{DS}} = 0$ V. (b) Threshold-voltage shift and (in the inset) mobility under illumination as a function of negative gate bias. The threshold-voltage shift under gate-bias stress in dark is shown by the dashed line.



(a) (b)

Fig. 2. (a) Transfer characteristics of OTFTs before and after a 500-s illumination. The stress conditions are the following: $V_D = 0$ and 10 V, $V_{\mathrm{GS}} = 0$ V. (b) Threshold voltage shift and (in the inset) mobility as a function of positive drain bias. The threshold-voltage shift under drain-bias stress in dark is shown by the dashed line.

Fig. 1(b). The gate-bias influence on light-induced ΔV_{th} is due to the compensation between the bias-induced positive-charged states and the light-induced negative-charged states. A similar compensation phenomenon was proposed by Gu *et al.* [8] when studying the ΔV_{th} recovery behavior.

Then, the drain-bias influence on the light-induced ΔV_{th} was studied when the source and gate electrodes were grounded. As shown in Fig. 2(a), initial transfer characteristics and those after a 500-s illumination with and without drain-bias stress are compared. The shift of the transfer characteristics was suppressed by applying positive drain bias. Fig. 2(b) shows the extracted threshold voltage and the mobility (in the inset) as a function of drain-bias stress voltage after a 500-s illumination. The results are similar to those in Fig. 1(b). However, the mechanism should not be the compensation effect as previously described because the drain-bias stress in dark only causes slight threshold-voltage shift as shown by the dashed line in Fig. 2(b).

Under illumination, the electron-trapping effect competes with the electron-hole recombination effect. It is plausible that when the light-induced holes are removed from pentacene through the drain contact, less recombination probability gives rise to more electron trapping and, hence, larger ΔV_{th}. A band diagram from source to drain is shown to explain the proposed mechanism. As shown by case A in Fig. 3(a), when a positive drain bias is applied, the lowered Fermi energy (E_F) in the drain electrode leads to a downward band bending of pentacene near the drain side. The band bending confines the light-induced holes in the channel to recombine with the light-induced electrons. As a result, the electron trapping is suppressed, and the ΔV_{th} is reduced.

If the proposed mechanism is correct, the following three cases will also exist. As shown by case B in Fig. 3(b), the negative drain bias creates an upward band bending in pentacene and helps light-induced holes to flow out from pentacene into the drain electrode. Enlarged light-induced ΔV_{th} is expected. For case C, as shown in Fig. 3(c), applying positive source and drain biases simultaneously should further confine the light-induced holes and reduce ΔV_{th} when comparing with case A. Applying negative source and drain biases as shown by case D in Fig. 3(d), on the contrary, leads to a more significant ΔV_{th} when comparing with case B. These expected phenomena are successfully observed in Fig. 4(a) when the light-induced ΔV_{th} is plotted as a function of the applied bias (V_{app}) in case A to case D.

After removing irradiation, the source and drain biases also help sustain the light-induced ΔV_{th}. The recovery behavior of

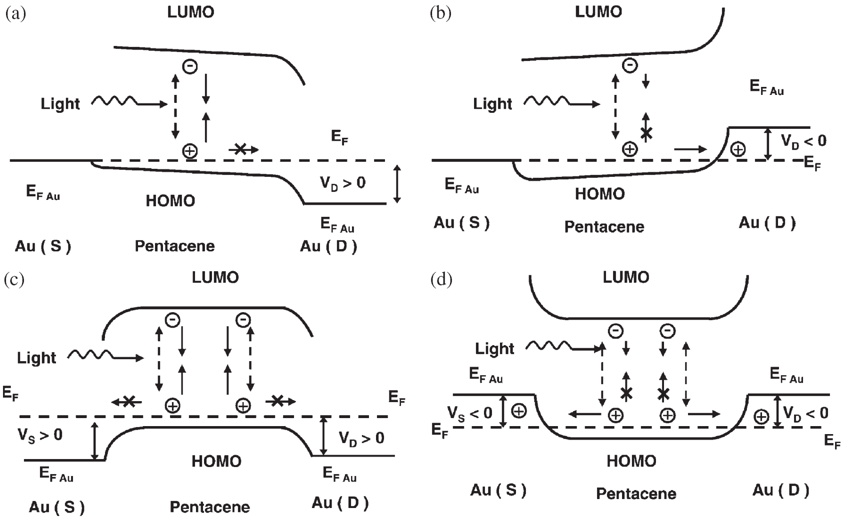
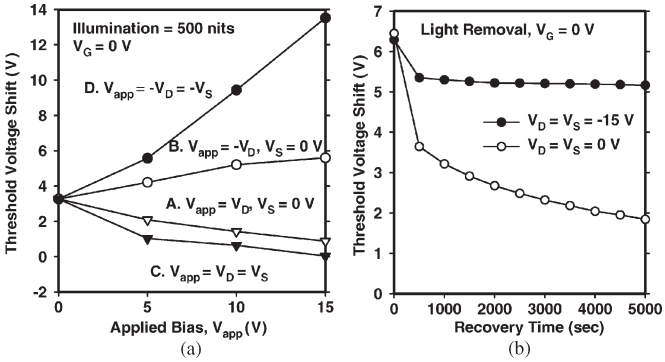


Fig. 3. Energy-band diagram of OTFTs from source to drain when devices are under illumination and bias conditions as (a) case A: positive drain bias with grounded source and gate, (b) case B: negative drain bias with grounded source and gate, (c) case C: positive source and drain biases with grounded gate, and (d) case D: negative source and drain biases with grounded gate.



(a) (b)

Fig. 4. (a) Light-induced ΔV_{th} (after a 500-s illumination) as a function of applied bias (V_{app}). V_{app} can be only V_D or both V_D and V_S. Cases A, B, C, and D correspond to the four band diagrams in Fig. 3. (b) After light removal, the light-induced ΔV_{th} as a function of recovery time under various drain and source biases ($V_D = V_S = 0$ V, or $V_D = V_S = -15$ V) with grounded gate. V_{th} is extracted by scanning the transfer characteristics using $V_{\mathrm{GS}} = 5$ to -40 V, and $V_{\mathrm{DS}} = -5$ V.

the light-induced ΔV_{th} is depicted in Fig. 4(b). With almost identical initial light-induced ΔV_{th}, the recovery of ΔV_{th} after light removal is plotted as a function of the recovery time with different bias conditions. It is known that after light removal, the equilibrium condition in pentacene is rebuilt. For devices recovery with $V_D = V_S = V_G = 0$ V, the holes produced by thermal generation or by source and drain injection recombine with trapped electrons in pentacene. The light-induced ΔV_{th} is eliminated with recovery time as shown by the white circle symbols in Fig. 4(b). For devices recovery with $V_D = V_S = -15$ V, and $V_G = 0$ V, however, the negative drain and source bias impedes the injection of holes. The trapped electrons in pentacene are mostly kept, and the light-induced ΔV_{th} is sustained. In our experiment, the light-induced ΔV_{th} was sustained for over 5000 s and was erased by removing the drain and source biases or by applying positive drain and source biases. The measurement of the device transfer characteristics every 500 s did not affect the ΔV_{th} signal.

IV. CONCLUSION

A fully suppressed ΔV_{th} by using negative gate-bias stress during illumination has been successfully demonstrated and explained by the compensation between the bias-induced positive-charged states and the light-induced negative-charged states. Additionally, a new biasing method has been proposed to modulate the light-induced ΔV_{th} from 0 to 13.5 V and to sustain the ΔV_{th} after removing the light. The new discovered phenomenon has enabled an easy modulation of the sensitivity and the memory ability of organic phototransistors.

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