Pentacene-Based Organic Phototransistor With High Sensitivity to Weak Light and Wide Dynamic Range

Hsiao-Wen Zan, *Member, IEEE*, Shih-Chin Kao, and Shiang-Ruei Ouyang

Abstract—**In this letter, the channel length effect, combined with the photoelectric field effect of organic phototransistors, has been investigated for the first time. Reducing the channel length and applying a positive gate bias during illumination enhance electron trapping effectively and hence improve the photoresponsivity of a pentacene-based phototransistor. The sensing dynamic range and the photosensitivity to very weak light (in the range of microwatts per square centimeter) are also discussed through the interaction between deep trapped states, interface energy-band bending, and photoexcited electrons.**

Index Terms—**Channel length, pentacene, photoresponsivity, phototransistor, thin-film transistor (TFT).**

I. INTRODUCTION

ORGANIC thin-film transistors (OTFTs) have attracted much attention because of their low-temperature processing, flexibility, and lightweight [1], [2]. Aside from serving as a switch in display, an OTFT exhibits high photoresponsivity (R_{ph}) and can be used as an organic phototransistor (OPT) [3]–[5]. Under illumination, excitons generated in a pentacene film dissociate into electrons and holes. Holes can be well conducted without being significantly trapped. Light-induced electrons, on the contrary, are easily trapped by deep electron-trapping states in a pentacene film [6]. When electrons are trapped close to the organic/dielectric interface, OPT exhibits pronounced light-induced threshold-voltage shift $(\Delta V_{\mathrm{TH}}^{\mathrm{Light}})$ [3], [7]. $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ increases the photocurrent at a fixed gate bias and thus enhances R_{ph}. Recently, many reports found that the R_{ph} or $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ of OPT can be significantly enlarged by applying an electric field during light irradiation (named as photoelectric field effect in this letter) [4], [7]. However, the influences of electric field and channel length on electron trapping have not been studied under illumination. When OPT is used to detect light signals with various intensities, the dynamic detecting range is not also investigated. In this letter, pentacene-based OPTs with different channel lengths are used to detect light signals with various intensities. The electric field effect, channel length effect, and dynamic detecting range under repeated operation are discussed.

II. EXPERIMENTAL SETUP

Conventional top-contact pentacene-based TFTs were used. Spinning poly(methyl methacrylate) (PMMA) onto $\mathrm{SiO_2}$ serves as a dual-layer gate dielectric. The inset of Fig. 1(a) shows the device geometry. The thickness of both $\mathrm{SiO_2}$ and PMMA layers is 100 nm. Unpurified pentacene obtained from Aldrich was evaporated through a shadow mask onto the PMMA layer. The deposition rate was set at 0.5 Å/s, while the substrate was kept at room temperature. After the formation of 100-nm-thick pentacene, 100-nm-thick gold was deposited through the shadow mask to form source/drain contacts. The device channel length (L) varied from 100 to 600 μm, while the channel width (W) was fixed at 1000 μm.

A white-light-emitting diode (LED) was used as backlight to irradiate the sample from the top. The device was measured at room temperature and in ambient air. The threshold voltage was extracted using the linear region equation [8].

III. RESULTS AND DISCUSSION

Before stress or irradiation, devices exhibit a field-effect mobility and a threshold voltage of 0.36 $\mathrm{cm^2/V \cdot s}$ and -14.5 V, respectively. The subthreshold slope is 0.9 V/decade for devices with channel lengths varying from 200 to 600 μm and is 2.7 V/decade for devices with channel lengths of 100 μm. First, $(\Delta V_{\mathrm{TH}}^{\mathrm{Light}})$ is investigated using bias stress to control the light-induced threshold voltage shift. $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ is defined as V_{th}–$V_{\mathrm{th}}^{\mathrm{ini}}$, where $V_{\mathrm{th}}^{\mathrm{ini}}$ and V_{th} are threshold voltages under illumination before and after bias stress. The white-light source is used to illuminate the device $(W/L = 1000\ \mu\mathrm{m}/200\ \mu\mathrm{m})$ with an intensity of 600 $\mu\mathrm{W/cm^2}$ for 100 s. During illumination, bias stress is also applied using different stressed gate biases ($V_{\mathrm{GS}}^{\mathrm{st}}$'s). The stressed drain bias $(V_{\mathrm{DS}}^{\mathrm{st}})$ is 0 V or equal to $V_{\mathrm{GS}}^{\mathrm{st}}$. The source electrode is grounded. Before and after the 100-s illumination with different stress conditions, transfer characteristics are measured promptly under illumination. Then, $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ is shown as a function of $V_{\mathrm{GS}}^{\mathrm{st}}$ in Fig. 1(a). White circles represent $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ for the grounded drain, while black circles represent $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ for $V_{\mathrm{DS}}^{\mathrm{st}} = V_{\mathrm{GS}}^{\mathrm{st}}$. When $V_{\mathrm{GS}}^{\mathrm{st}} = 0$ V, $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ is a small positive value because of electron trapping. When a negative gate bias is applied during illumination, $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ shifts to become negative owing to the compensation between the light-induced electron trapping and the bias-induced hole trapping. Applying a positive gate bias obviously enhances $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ owing to electron trapping. Effective electron trapping results from the separation of light-generated excitons and the equilibrium of trapping and recombination. The separation of excitons can be enhanced by an electric field through field-induced dissociation [4], [6], [7]. In our study, the electric field across the channel film close to the source/drain electrodes (vertical field) is usually much higher than the electric field along the channel length from the source to drain electrodes (lateral

---

Manuscript received October 1, 2009; revised November 15, 2009. First published January 19, 2010; current version published January 27, 2010. This work was supported by the National Science Council (NSC-98-2627-B009-008). The review of this letter was arranged by Editor P. K.-L. Yu.

The authors are with the Department of Photonics and the Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan (e-mail: hsiaowen@mail.nctu.edu.tw).

Digital Object Identifier 10.1109/LED.2009.2037591

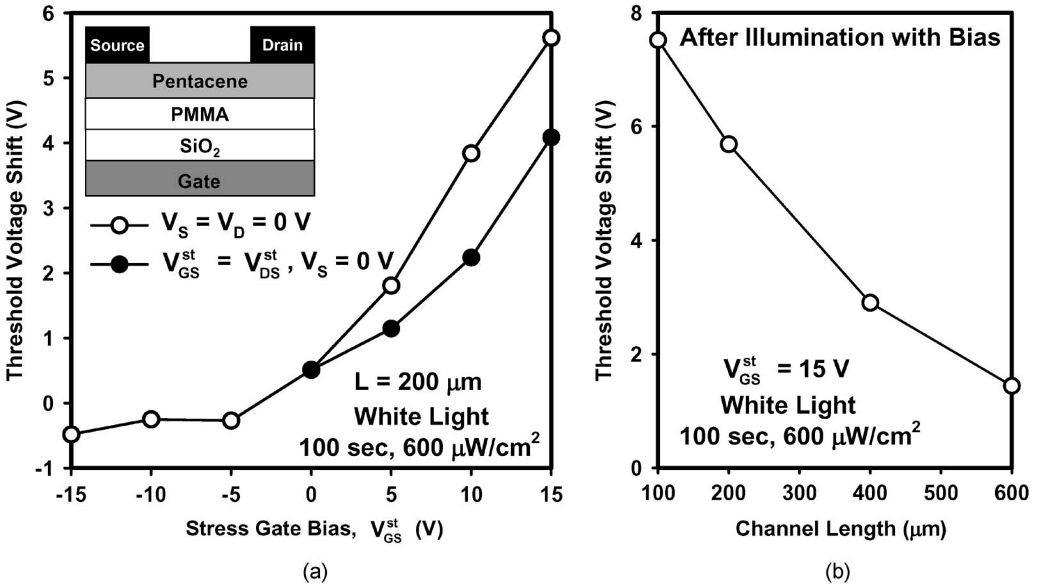

Fig. 1. (a) Light-induced threshold-voltage shift $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ as a function of gate bias. The bias conditions are as follows: $V_D = V_S = 0$ V and $V_{\mathrm{DS}}^{\mathrm{st}} = V_{\mathrm{GS}}^{\mathrm{st}}$, $V_S = 0$ V. (b) Light-induced threshold-voltage shift $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ as a function of channel length.

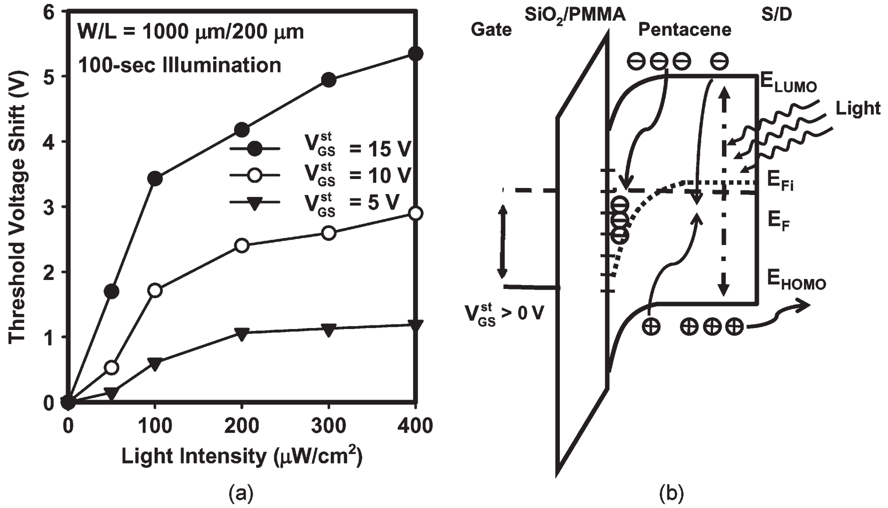

Fig. 2. (a) $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ as a function of light intensity under various gate biases. (b) Energy-band diagram of OPT from the gate to the drain/source when devices are under illumination with a positive gate bias.

field). A high vertical field (higher than 2×10^4 V/cm [9]) may be effective in dissociating excitons. Additionally, a vertical electric field causes downward band bending at the organic/dielectric interface to provide empty trapping states [10]. A lateral field, on the other hand, may facilitate the removal of holes through the source electrode to prevent recombination [11]. As shown in Fig. 1(a), when $V_{\mathrm{DS}}^{\mathrm{st}}$ changes from 0 V to be equal to $V_{\mathrm{GS}}^{\mathrm{st}}$, the vertical electric field is reduced, and the lateral electric field is increased. $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ is significantly reduced when $V_{\mathrm{DS}}^{\mathrm{st}} = V_{\mathrm{GS}}^{\mathrm{st}}$, implying that $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ is dominated by the vertical field rather than by the lateral field. The removal of holes, however, is still found to be essential when we compare $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ for devices with L varying from 600 to 100 μm, as shown in Fig. 1(b). Reducing L significantly increases $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$. Because the removal of light-induced holes is more effective near the source/drain electrodes than in the center of the channel, increasing L reduces the portion of the source/drain-affected areas and suppresses $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$. The channel length effect reveals that the removal of light-induced holes through the source/drain electrodes is necessary to allow the light-induced electrons to be effectively trapped by the deep states.

Then, $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ with 100-s illumination is shown as a function of light intensity (P_L) under various gate biases in Fig. 2(a). When $V_{\mathrm{GS}}^{\mathrm{st}} = 5$ V, $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ is small and saturates when P_L reaches 200 μW/cm^2. By increasing $V_{\mathrm{GS}}^{\mathrm{st}}$ from 5 to 15 V, $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ is enlarged, and the saturation point moves to be under higher P_L. Because increasing P_L increases the number of excitons, enhanced electron trapping and enlarged $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ with increasing P_L are reasonable. When the trapping states are fully occupied, increasing P_L can no longer enhance electron trapping, and $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ saturates at a fixed value. A band diagram from the gate to the drain/source is depicted to explain the proposed mechanism, as shown in Fig. 2(b). Changing the gate bias from 5 to 15 V makes the energy band

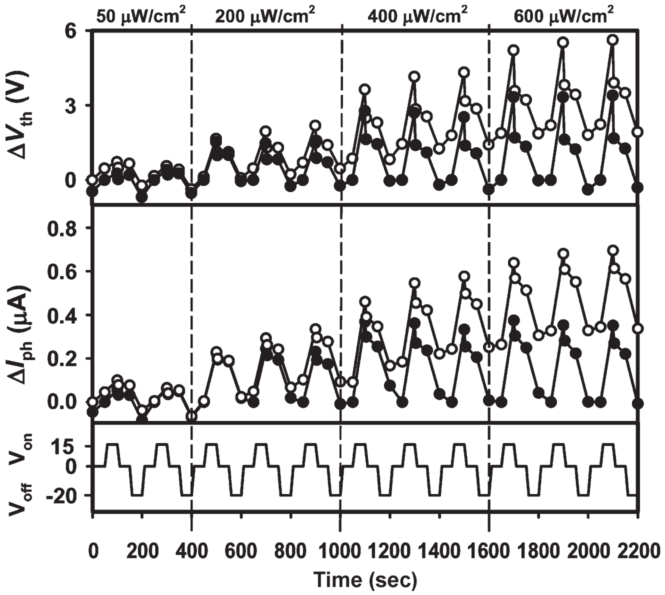

Fig. 3. $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ and photocurrent difference ΔI_{ph} measured by applying a periodic gate bias under various light intensities. The $V_{\mathrm{GS}}^{\mathrm{st}}$ waveform consists of sequential four potential steps (15 V, 0, -20, and 0 V). $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ and ΔI_{ph} normalized to the initial value of every cycle is also shown by black circles.

at the dielectric/organic interface to bend down further. The number of electron-trapping states below the Fermi energy is increased. This allows more photogenerated electrons to be trapped and provides a larger response window to different P_L. Also, for a very weak light such as $P_L = 50\ \mu\mathrm{W/cm}^2$, increasing $V_{\mathrm{GS}}^{\mathrm{st}}$ can effectively enlarge $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ and R_{ph}. If no stressed bias is applied on OPT, it is almost impossible to detect the weak light with $P_L = 50\ \mu\mathrm{W/cm}^2$. When $V_{\mathrm{GS}}^{\mathrm{st}} = 30$ V, the R_{ph} of OPTs with L as 100 μm is 40 A/W under white-light irradiation ($P_L = 50\ \mu\mathrm{W/cm}^2$) and 92 A/W under blue-LED irradiation (465 nm and 50 $\mu\mathrm{W/cm}^2$). It is summarized that increasing the gate bias during illumination can effectively increase the detection dynamic range and enhance the sensing ability related to very weak light intensity in the range of microwatts per square centimeter.

Finally, repeated sensing behavior is confirmed by applying a periodic gate bias onto devices during illumination. As shown in Fig. 3, the $V_{\mathrm{GS}}^{\mathrm{st}}$ waveform consists of four sequential potential steps (15, 0, -20, and 0 V). Every potential step has a 50-s duration. $V_{\mathrm{GS}}^{\mathrm{st}}$ such as +15 V determines the sensing period. $V_{\mathrm{GS}}^{\mathrm{st}}$ such as -20 V is used to accelerate the recovery of the sensing signal. $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ and photocurrent variations (ΔI_{ph}) are plotted as a function of time. ΔI_{ph} is defined as I_{ph}–$I_{\mathrm{ph}}^{\mathrm{ini}}$, where $I_{\mathrm{ph}}^{\mathrm{ini}}$ is the drain current measured promptly under irradiation. Although long-time integration (several tens of seconds) is needed to obtain significant ΔI_{ph} and $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$, its application on a large-area flexible scanner is possible. During scanning, OPTs are turned off (with a positive gate bias). They are turned on only in the signal reading cycles. This is beneficial for power savings. During the recovery period, an incomplete recovery is due to an incomplete compensation between electron and hole trapping and can be treated as noise. The noise can be eliminated if the variation of $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ and ΔI_{ph} in the sensing period is used as a sensing index, as shown by the black symbols in Fig. 3.

IV. CONCLUSION

The $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ and R_{ph} of pentacene-based OPTs have been greatly improved by applying a positive gate bias during illumination or by reducing the channel length. It is verified that even when the vertical electric field plays a dominant role in enhancing $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$, the removal of light-induced holes through the source/drain electrodes is necessary to allow the light-induced electrons to be effectively trapped by the interface states. When increasing P_L, the maximum $\Delta V_{\mathrm{TH}}^{\mathrm{Light}}$ of OPT was restricted owing to the fixed amount of interface trap states under a constant gate bias. Increasing the positive gate bias extends the response window to larger P_L and improves R_{ph} to very weak light. Finally, the repeated OPT response to different P_L is confirmed by applying a periodic voltage signal cycle. These results are useful to design OPTs in image sensor array.

To date, the origin of electron-trapping states is not clear. We had measured the devices in vacuum to suppress the influence of oxygen and water. A significant photoelectric field effect was still observed. Further studies need to be conducted to explore the mechanism in depth.

ACKNOWLEDGMENT

The authors thank Prof. H.-F. Meng for his helpful suggestion.

REFERENCES

[1] L. Zhou, A. Wanga, S.-C. Wu, J. Sun, S. Park, and T. N. Jackson, "All-organic active matrix flexible display," *Appl. Phys. Lett.*, vol. 88, no. 8, p. 083 502, Feb. 2006.

[2] H. S. Tan, T. Cahyadi, Z. B. Wang, A. Lohani, Z. Tsakadze, S. Zhang, F. R. Zhu, and S. G. Mhaisalkar, "Low-temperature-processed inorganic gate dielectrics for plastic-substrate-based organic field-effect transistors," *IEEE Electron Device Lett.*, vol. 29, no. 7, pp. 698–700, Jul. 2008.

[3] M. Debucquoy, S. Verlaak, S. Steudel, K. Myny, J. Genoe, and P. Heremans, "Correlation between bias stress instability and phototransistor operation of pentacene thin-film transistors," *Appl. Phys. Lett.*, vol. 91, no. 10, p. 103 508, Sep. 2007.

[4] Y. Guo, C. Du, C.-A. Di, J. Zheng, X. Sun, Y. Wen, L. Zhang, W. Wu, G. Yu, and Y. Liu, "Field dependent and high light sensitive organic phototransistors based on linear asymmetric organic semiconductor," *Appl. Phys. Lett.*, vol. 94, no. 14, p. 143 303, Apr. 2009.

[5] Y.-Y. Noh, D.-Y. Kim, and K. Yase, "Highly sensitive thin-film organic phototransistors: Effect of wavelength of light source on device performance," *J. Appl. Phys.*, vol. 98, no. 7, p. 074 505, Oct. 2005.

[6] K. Harada, M. Riede, K. Leo, O. R. Hild, and C. Michael Elliott, "Pentacene homojunctions: Electron and hole transport properties and related photovoltaic responses," *Phys. Rev. B, Condens. Matter*, vol. 77, no. 19, p. 195 212, May 2008.

[7] M. C. Hamilton, S. Martin, and J. Kanicki, "Thin-film organic polymer phototransistors," *IEEE Trans. Electron Devices*, vol. 51, no. 6, pp. 877–885, Jun. 2004.

[8] R. A. Street, M. L. Chabinyc, F. Endicott, and B. Ong, "Extended time bias stress effects in polymer transistors," *J. Appl. Phys.*, vol. 100, no. 11, p. 114 518, Dec. 2006.

[9] R. R. Chance and C. L. Braun, "Intrinsic photoconduction in anthracene single crystals: Electric field dependence of hole and electron quantum yields," *J. Chem. Phys.*, vol. 59, no. 5, p. 2269, Sep. 1973.

[10] C. B. Park, T. Yokoyama, T. Nishimura, K. Kita, and A. Toriumi, "Molecular ordering and interface state modification for reducing bias-induced threshold voltage shift in pentacene field-effect transistors," *J. Electrochem. Soc.*, vol. 155, no. 8, p. H575, 2008.

[11] H.-W. Zan and S.-C. Kao, "New organic phototransistor with bias-modulated photosensitivity and bias-enhanced memory effect," *IEEE Electron Device Lett.*, vol. 30, no. 7, pp. 721–723, Jul. 2009.