

Article ID: 1000-7032(2014)03-0342-07

Near Infrared Photoresponsive Organic Field-effect Transistors by Utilizing Pentacene/Lead Phthalocyanine Heterojunction

ZHOU Mao-qing¹, LI Yao¹, YAO Bo¹, LYU Wen-li¹, PENG Ying-quan^{1,2*}

(1. Institute of Microelectronics, School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China;

2. Key Laboratory for Magnetism and Magnetic Materials of The Ministry of Education, Lanzhou University, Lanzhou 730000, China)

* Corresponding Author, E-mail: ypeng@lzu.edu.cn

Abstract: Photoresponsive organic field-effect transistors (phOFETs) were fabricated by utilizing organic heterojunction based on pentacene and lead phthalocyanine (PbPc). Under a near-infrared light illumination (wavelength 808 nm and a power intensity of 124 mW/cm²), the heterojunction photoresponsive organic field-effect transistors (HJ-phOFETs) exhibited a maximum photosensitivity of 4.4×10^4 , and a maximum photoresponsivity of 118 mA/W, which were 766 times and 785 times higher than that of PbPc single-layer phOFET, respectively. It was observed that the maximum photosensitivity and the maximum photoresponsivity stabilized around 5.4×10^4 and 326 mA/W after 120 h, respectively. The high performance of HJ-phOFET is attributed to the utilization of PbPc as photosensitive layer which has high absorbance in near infrared region (NIR) and pentacene as channel layer with high hole mobility. These results indicate that the HJ-phOFET based on pentacene and PbPc is proved to be a NIR photodetector with excellent photosensitivity and stability.

Key words: heterojunction; pentacene; PbPc; near infrared; photoresponsive organic field effect transistor

CLC number: TN386

Document code: A

DOI: 10.3788/fjxb20143503.0342

基于并五苯/酞菁铅异质结的近红外光敏有机场效应管

周茂清¹, 李尧¹, 姚博¹, 吕文理¹, 彭应全^{1,2*}

(1. 兰州大学物理科学与技术学院 微电子研究所, 甘肃 兰州 730000;

2. 兰州大学 磁学与磁性材料教育部重点实验室, 甘肃 兰州 730000)

摘要: 采用并五苯(Pentacene)和酞菁铅(PbPc)两种有机材料作为有源层,制备了异质结有机光敏场效应管。在波长为808 nm、强度为124 mW/cm²的近红外光照条件下,异质结phOFET获得最大的光暗电流比达 4.4×10^4 ,栅压为-50 V时的最大光响应度为118 mA/W,比单层酞菁铅phOFET分别高出766倍和785倍。在经过120 h后,器件的最大光暗电流比和最大光响应度分别稳定于 5.4×10^4 和326 mA/W附近。由于在异质结phOFET中采用了对近红外光具有高吸收效率的酞菁铅作为光敏层,而高空穴迁移率的并五苯材料作为靠近栅介质的沟道层,光生载流子的产生与传输能力得到了有效的提高。实验结果表明,基于并五苯/酞菁铅的有机异质结应用于光敏有机场效应管的结构设计中,可以使phOFET成为一种同时具有良好光敏性及稳定性的近红外光探测器件。

关键词: 异质结; 并五苯; 酞菁铅; 近红外; 光敏有机场效应管

收稿日期: 2013-11-20; 修订日期: 2013-12-08

基金项目: 国家自然科学基金(1097407); 教育部博士点基金(2011021111005)资助项目

1 Introduction

In recent years, photoresponsive organic field-effect transistors (phOFETs) have attracted increasing research interests due to their low cost, mechanical flexibility. Comparing with organic photodiodes (OPDs), phOFETs possess great application prospect because of their higher sensitivity and lower noise levels^[1-3]. The heterojunction structure has been widely used for organic electronic devices to improve their performance, naturally, which is also applied in phOFETs to enhance the device photosensitivity and the transport speciality of carrier^[3-5]. Nevertheless, most organic heterojunctions adopted in the organic electronic devices are anisotype heterojunction, similar to the p-n heterojunctions in inorganic semiconductor devices, which contain two semiconductors with dissimilar types of conductivity. Moreover, the isotype organic heterojunctions consisting of two semiconductors with same types of conductivity have been rarely studied and applied^[6-7]. Although superior performance can be achieved in many organic devices with the anisotype heterojunction structure, most n-type organic semiconductor materials are very sensitive to moisture and oxygen as exposed to air, which may lead to a rapid decline or invalidation of devices. The p-p organic heterojunctions applied in organic electronic devices can not only achieve high performances but also are able to possess excellent stability, which are beneficial to the researches of phOFETs^[8-10].

In this paper, a near-infrared heterojunction photoresponsive organic field effect transistors (HJ-phOFETs) with pentacene and lead phthalocyanine (PbPc) as active layer were fabricated, in which silver (Ag) was used as the source and drain electrodes. PbPc, as a good NIR photoresponsive material with a strong absorption in the near infrared (NIR) region (780 ~ 900 nm), has been widely applied in organic solar cells (OSCs) and NIR photodetectors^[11-12]. Pentacene is a typical hole transport organic material with high mobility, and the hole mobility of single crystal pentacene OFET reaching up to $35 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ was reported^[13].

Pentacene is very suited for using as an active layer in red photodetectors due to its high absorption in red light^[14]. Therefore, it can be considered that PbPc plays the part of the NIR photosensitive layer and pentacene acts as the channel transport layer in the structure of HJ-phOFETs. Under NIR illumination, photo-induced excitons are generated in PbPc layer and diffuse to other zone due to concentration gradient. The diffused excitons nearby the source electrode dissociate into free electrons and holes under the strong electric field of electrode/semiconductor interface, and then the free holes transport in the pentacene channel layer. The HJ-phOFETs, in which generation of photo-induced excitons and transportation of carriers occur in different active layers, show high photoresponsivity and excellent stability.

2 Experiments

Pentacene and PbPc were purchased from J&K Chemical Ltd., and Sigma-Aldrich Ltd., respectively, and used as received. Bottom-gate top-contact geometry was adopted to fabricate the phOFETs, as shown in the inset of Fig. 1. A heavily n-doped Si substrate with a resistivity of $0.03 \Omega \cdot \text{cm}$ acted as the gate electrode, on which there was a 950 nm thermally grown SiO_2 layer as the gate dielectric. The substrates were ultrasonically cleaned by acetone, ethanol and de-ionized water, and was dried with N_2 gas blowing and baked in an oven at $60 \text{ }^\circ\text{C}$ for 30 min. Then the surface of cleaned SiO_2 was treated with octadecyl silane (OTS) by vapour deposition

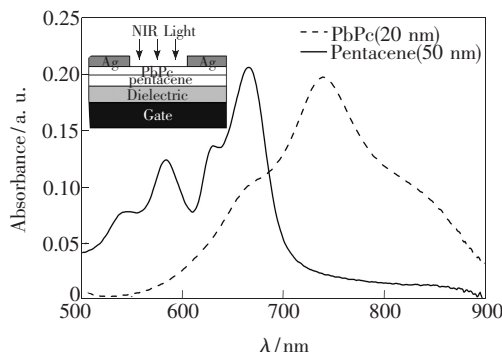


Fig. 1 UV-Vis absorption spectra of PbPc (dash) and pentacene (solid) thin film. Inset: Schematic structure of the HJ-phOFET.

in an oven at 120 °C for 2 h. For the device fabrication, a 50-nm-thick pentacene film was deposited on the top of SiO₂ substrate by vacuum thermal evaporation. The vacuum was kept at 2×10^{-3} Pa and the substrate temperature at 65 °C during the deposition. Then a 20-nm-thick PbPc film was vacuum deposited on the top of the pentacene film. Ag as source/drain electrodes was vacuum deposited through a shadow mask which defined a channel length (L) and width (W) of $25 \mu\text{m} \times 2 \text{mm}$. Meanwhile, single-layer OFETs with pentacene and PbPc as the active layers respectively were fabricated for comparison.

For optical absorption measurement, single-layer thin films of pentacene (50 nm) and PbPc (20 nm) were vacuum deposited on cleaned quartz substrates, respectively. TU-1901 spectrometer was used for the measurements of absorption spectra. For the measurement of photosensitive effects, a NIR laser diode with a wavelength of 808 nm and a power intensity of 990mW/cm^2 was used. Different neutral filters were used to obtain variable optical power intensity for illumination. The measurement was implemented in a vacuum environment ($< 10 \text{Pa}$), and all devices were preserved under a vacuum of about 10 Pa.

3 Results and Discussion

As shown in Fig. 1, the absorption spectrum of the PbPc film exhibits strong absorption in the NIR region, while the pentacene film exhibits strong absorption in the visible light region and no significant absorption in the NIR region. Hence, the absorbance of organic heterojunction based on pentacene/PbPc at 808 nm is comparable to that of a neat PbPc film.

Fig. 2 shows the output and transfer characteristic curves of single-layer PbPc phOFET in the dark and under illumination. Typical p-type operating characteristic is observed. In the dark, the drain current I_d is merely -0.6nA at the gate-source voltage $V_{gs} = -50 \text{V}$ and the drain-source voltage $V_{ds} = -50 \text{V}$. For illumination with a power intensity of 124mW/cm^2 , I_d increases to -2.4nA at $V_{gs} =$

-50V and $V_{ds} = -50 \text{V}$, which is 4 times the size of that in the dark. This result indicates that there is an evident photoresponse of PbPc phOFET under NIR illumination. According to theory of FETs, the saturation drain current is given by:

$$I_{d,\text{sat}} = \frac{W}{2L} \mu_{\text{sat}} C_i (V_{gs} - V_{th})^2, \quad V_{ds} \geq V_{gs} - V_{th}, \quad (1)$$

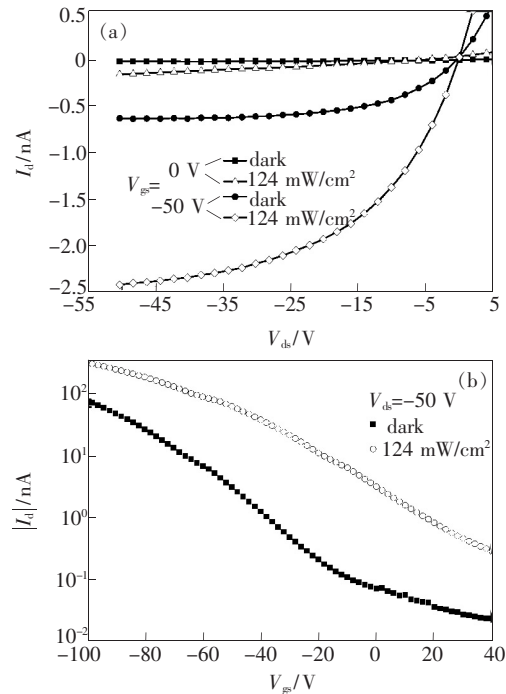


Fig. 2 (a) Output characteristics of PbPc single-layer phOFET in the dark (solid) and under illumination (open). (b) Transfer characteristics of PbPc single-layer phOFET.

from where threshold voltage V_{th} and the saturated carrier mobility μ_{sat} of phOFETs can be extracted^[15]. The threshold voltage of PbPc phOFET in the dark ($V_{th,\text{dark}}$) is -48V and the saturated holes mobility in the dark ($\mu_{\text{sat,dark}}$) is $5.5 \times 10^{-5} \text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$. Under illumination, V_{th} shifts forward to -33V and μ_{sat} increases to $5.8 \times 10^{-5} \text{cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$. The variation of V_{th} may result from the photo-generated holes accumulated at the interface between electrode and semiconductor and at the interface between gate dielectric and semiconductor under illumination^[16].

An important parameter of phOFETs is photosensitivity (P), which is defined as the ratio of the photocurrent to the dark current^[15]:

$$P = \frac{I_{\text{ph}}}{I_{\text{dark}}} = \frac{I_{\text{ill}} - I_{\text{dark}}}{I_{\text{dark}}}, \quad (2)$$

where I_{ph} is the photocurrent, I_{dark} is the drain current in the dark and I_{ill} is the drain current under illumination. Another important parameter is photoresponsivity (R)^[15], defined as following:

$$R = \frac{I_{\text{ph}}}{P_{\text{opt}}} = \frac{I_{\text{ill}} - I_{\text{dark}}}{P_{\text{inc}}A}, \quad (3)$$

where P_{opt} is the effective optical power on the channel of the device, P_{inc} is the incident optical power intensity, A is the effective illuminated area, namely, the channel area of device ($L \times W$). Enhancement of photosensitivity and photoresponsivity of phOFETs is beneficial to lower the noise levels of devices and improve the precision of photodetectors. The maximum photosensitivity of PbPc single-layer phOFET is calculated from Fig. 2(b) and Eq. (2) to be 57. And a maximum photoresponsivity of PbPc single-layer phOFET of 0.15 mA/W was obtained at $V_{\text{gs}} = -50$ V and $V_{\text{ds}} = -50$ V (see Table 1). Ag was utilized as the source and drain electrodes, whose work function (4.26 eV) was seriously mis-matched with the highest occupied molecular orbital (HOMO)

of PbPc (5.2 eV)^[11,17]. Therefore, a high barrier is formed at Ag/PbPc interface and which further hindered the holes-injection from source electrodes to PbPc layer. Furthermore, the hole mobility of PbPc thin film is very low, which impedes transferring of the massive photo-induced carriers, as a result, I_{dark} and R of PbPc single-layer phOFET are both poor.

The output and transfer characteristic curves of HJ-phOFET in the dark and under illumination are displayed in Fig. 3. The dark current of HJ-phOFET is -750 nA at $V_{\text{gs}} = -50$ V and $V_{\text{ds}} = -50$ V, which is 1 250 times larger than that of PbPc single-layer phOFET. The great improvement of dark current (I_{dark}) at HJ-phOFET operating is attributed to the high mobility of pentacene channel layer. For illumination with a power intensity of 124 mW/cm², the drain current of HJ-phOFET increases to -1 358 nA, as a result the photocurrent ($I_{\text{ph}} = 608$ nA) is 337 times larger than that (1.8 nA) of PbPc single-layer phOFET. The V_{th} and μ_{sat} in the dark of HJ-phOFET are calculated from Fig. 3 and Eq. (1) to be -36 V and 2.5×10^{-2} cm² · V⁻¹ · s⁻¹, respectively. Under illumination, the V_{th} shifts forward to -31 V and the μ_{sat} changes to 2.7×10^{-2} cm² · V⁻¹ · s⁻¹. From the data of Fig. 3 and Eq. (2) ~ (3), a maximum photosensitivity of 4.4×10^4 and a maximum photoresponsivity of 118 mA/W are obtained for HJ-phOFET at $V_{\text{gs}} = -50$ V and $V_{\text{ds}} = -50$ V. High hole-mobility pentacene has a HOMO of 5.0 eV^[17], which matches well with that of PbPc. As a result, the free holes dissociated from photo-generated excitons can easily transmit to the drain electrode through pentacene conducting channel, which significantly improves the photosensitive characteristics of devices.

The results were obtained at $V_{\text{gs}} = -50$ V and under illumination with a power intensity of 124 mW/cm². Stability is an important parameter for photoelectronic devices. Fig. 4 shows the maximum photosensitivity, the maximum photoresponsivity ($V_{\text{gs}} = -50$ V and $V_{\text{ds}} = -50$ V) and the saturation hole mobility of HJ-phOFET in the dark as function of the storage time in a low vacuum around 10 Pa.

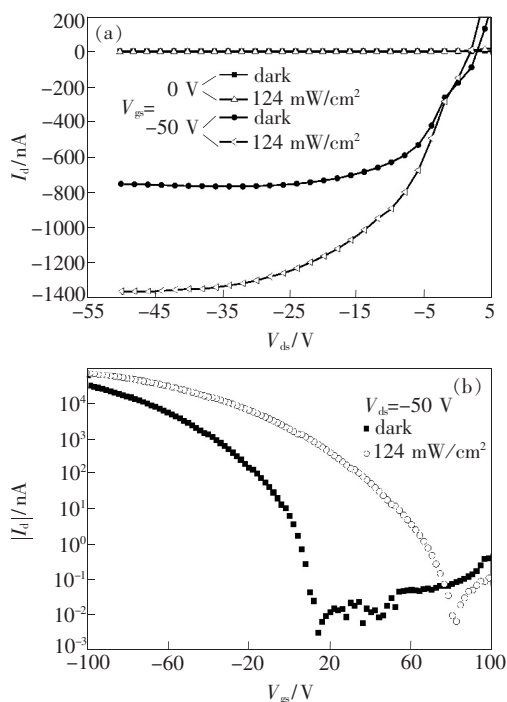


Fig. 3 (a) Output characteristics of pentacene/PbPc HJ-phOFET in the dark (solid) and under illumination (open). (b) Transfer characteristics of pentacene/PbPc HJ-phOFET.

Table 1 Device performance details

Devices	$I_{ph}/$ nA	$R_{max}/$ (mA · W ⁻¹)	P_{max}	$V_{th,dark}/$ V	$V_{th,ill}/$ V	$\mu_{p,dark}/$ (cm ² · V ⁻¹ · s ⁻¹)	$\mu_{p,ill}/$ (cm ² · V ⁻¹ · s ⁻¹)
PbPc	1.8	0.15	57	-48	-33	5.5×10^{-5}	5.8×10^{-5}
HJ-phOFET	608	118	4.4×10^4	-36	-31	2.5×10^{-2}	2.7×10^{-2}

It can be seen from Fig. 4, the maximum photoresponsivity and saturation hole mobility both increase over time and then stabilize around constant values. After 120 h, the maximum photoresponsivity of HJ-phOFET increases from 118 mA/W to 326 mA/W, and the maximum photosensitivity increases from 4.4×10^4 to 5.4×10^4 . Furthermore, the saturation hole mobility of HJ-phOFET in the dark shifts from 2.5×10^{-2} cm² · V⁻¹ · s⁻¹ to 3.5×10^{-2} cm² · V⁻¹ · s⁻¹. The saturation hole mobility increase of HJ-phOFET in 120 h later leads to enhancement of the maximum photoresponsivity and the maximum photosensitivity. Because pentacene is a p-type organic semiconductor with good air-stability, and it is reported that phthalocyanines organic materials are also stable materials, thus the HJ-phOFET fabricated based on these can exhibit a good stable performance^[18-21].

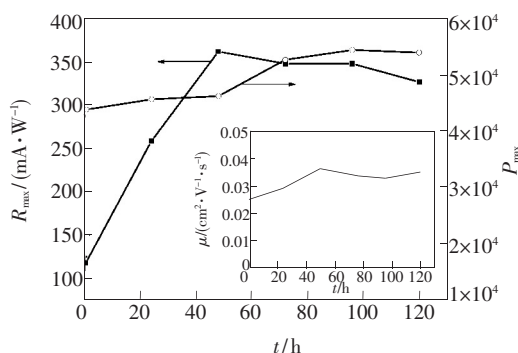


Fig. 4 The maximum photoresponsivity at $V_{gs} = -50$ V, $V_{ds} = -50$ V and the maximum photoresponsivity of HJ-phOFET as function of storage time. Inset: The saturated hole mobility of HJ-phOFET in the dark as function of storage time.

Most OFETs operate at unipolar transportation mode, that is, unipolar carriers (electrons or holes) primarily contribute to channel current as OFETs work. The high injection barrier which is resulting from the energy-level mismatch, interfacial effect and series-resistance effect^[22-23] enormously decrea-

ses the field-effect mobilities and the drain currents of heterojunction OFETs. By comparison of pentacene single-layer OFET and HJ-phOFET, it is found that the drain current and holes mobility of pentacene single-layer OFET (not here) are both much less than those of HJ-phOFET in the dark. The utilization of Ag as the source and drain electrodes causes an energy difference existing between the work function of Ag and the HOMO of pentacene, and a positive dipole layer is formed at the Ag/pentacene interface, which will result in a hole injection barrier of 0.8 eV at the Ag/pentacene interface, and obstruct the holes injecting into pentacene layer inevitably^[17], consequently, the dark current and hole mobility of pentacene single-layer phOFET are both much lower. When PbPc thin film is inserted between Ag and pentacene, PbPc can be regarded as the buffer layer for Ag and pentacene contact and enhance the injection efficiency of holes greatly^[24]. The electron affinity of PbPc (3.9 eV) is 1.0 eV higher than that of pentacene (2.9 eV), and the energy gap (E_g) of pentacene (2.1 eV) is much larger than that of PbPc (1.3 eV), these may cause that the holes in PbPc layer move to pentacene and a hole depletion layer is formed in PbPc^[7-8,17]. The hole depletion region in the PbPc layer mainly consisting of negative fixed-charge may lower the injection barrier of holes, in consequence the dark current and hole mobility of HJ-phOFET increase greatly in contrast with single-layer phOFET. When the HJ-phOFET is illuminated by a NIR light, the operation mechanism of HJ-phOFET can be described as: (I) Generation of photo-induced excitons in PbPc layer. (II) Diffusion of photo-induced excitons to the source electrode in PbPc layer. (III) Dissociation of excitons into free holes and electrons at the electrode/ semiconductor interface. (IV) Extraction of electrons by the source and transportation of

holes in pentacene layer^[25]. The factors impacting on photosensitive properties of phOFETs are most probably the match of material energy levels, carrier mobility and interfacial effect of organic layers. For PbPc single-layer phOFET and HJ-phOFET, a huge number of free holes generated under illumination may enhance the carrier density in channel, and result in a decline of threshold voltage. However, there is almost no absorption of pentacene in the NIR region around 808 nm, the characteristics of pentacene OFETs are essentially unchanged under illumination. The well match of energy levels of PbPc and pentacene and the high hole mobility of pentacene facilitate the transportation of photo-induced carriers, as a consequence the photosensitive performance of HJ-phOFET is enhanced enormously. However, since pentacene with a high hole mobility is used as the channel layer, the dark current of HJ-phOFET correspondingly increases and exceeds the value of photo-generated current, which will instead hinders the dissociation of photo-induced excitons and thereby degrades the performance of photosensitive detectors. For this case, it is predicted that the adoption of a p-type organic materials with high photosensitivity and a p-type organic materials with high

mobility will be able to realize the excellent and stabilized phOFETs by appropriate modulation of energy levels.

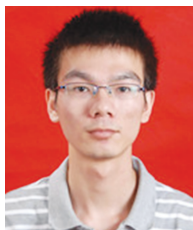
4 Conclusion

HJ-phOFET based on pentacene and PbPc was fabricated, and its photosensitive characteristics were analyzed compared with single-layer phOFET. The results indicate that better photosensitive performance is achieved in HJ-phOFET than that in single layer phOFET. Under 808 nm and 124 mW/cm² NIR illumination, a maximum photosensitivity of 5.0×10^4 and a maximum photoresponsivity of 118 mA/W ($V_{gs} = -50$ V) are obtained in HJ-phOFET; while the maximum photosensitivity and photoresponsivity of single-layer phOFET are 57 and 0.15 mA/W, respectively. It is demonstrated that the organic heterojunctions with high hole-mobility pentacene as the channel transportation layer and high absorbance PbPc as NIR photosensitive layer are beneficial to the dissociation of photo-induced excitons and the transportation of holes, which will greatly enhance the photo-induced current and improve the HJ-phOFET performance.

References:

- [1] Mukherjee B, Mukherjee M, Choi Y, *et al.* Control over multifunctionality in optoelectronic device based on organic photo-transistor [J]. *ACS Appl. Mater. Interf.*, 2010, 2(6):1614-1620.
- [2] Clark J, Lanzani G. Organic photonics for communications [J]. *Nat. Photon.*, 2010, 4(7):438-446.
- [3] Chen D Q, Yao B, Fan G Y, *et al.* Influence of donor-acceptor layer sequence on photoresponsive organic field-effect transistors based on palladium phthalocyanine and C₆₀[J]. *Appl. Phys. Lett.*, 2010, 102(16):163303-1-5.
- [4] Marjanović N, Singh T B, Dennler G, *et al.* Photoresponse of organic field-effect transistors based on conjugated polymer/fullerene blends [J]. *Org. Electron.*, 2006, 7(4):188-194.
- [5] Kim F S, Guo X G, Watson M D, *et al.* High-mobility ambipolar transistors and high-gain inverters from a donor-acceptor copolymer semiconductor [J]. *Adv. Mater.*, 2010, 22(4):478-482.
- [6] Lou Y H, Xu M F, Wang Z K, *et al.* Dual roles of MoO₃-doped pentacene thin films as hole-extraction and multicharge-separation functions in pentacene/C₆₀ heterojunction organic solar cells [J]. *Appl. Phys. Lett.*, 2013, 102(11):113305-1-4.
- [7] Wang H B, Wang X J, Huang H C, *et al.* Isotype heterojunction between organic crystalline semiconductors [J]. *Appl. Phys. Lett.*, 2008, 93(10):103307-1-3.
- [8] Wang H B, Wang X J, Yu B, *et al.* p-p isotype organic heterojunction and ambipolar field-effect transistors [J]. *Appl. Phys. Lett.*, 2008, 93(11):113303-1-3.
- [9] Yi M D, Huang J Y, Ma D G, *et al.* High gain in hybrid transistors with BALq₃/Alq₃ isotype heterostructure emitter [J].

- Appl. Phys. Lett.*, 2008, 92(24):243312-1-3.
- [10] Pan F, Tian H K, Qian X R, *et al.* High performance vanadyl phthalocyanine thin-film transistors based on fluorobenzene end-capped quaterthiophene as the inducing layer [J]. *Org. Electron.*, 2011, 12(8):1358-1363.
- [11] Shen L, Xu Y, Zhang X D, *et al.* Short-circuit current density improvement of inverted polymer solar cells using PbPc to enhance photon absorption over 600 nm [J]. *Sol. Energy Mater. Sol. C*, 2010, 94(12):2451-2454.
- [12] Kim H J, Shim H S, Kim J W, *et al.* CuI interlayers in lead phthalocyanine thin films enhance near-infrared light absorption [J]. *Appl. Phys. Lett.*, 2012, 100(26):263303-1-4.
- [13] Jurchescu O D, Popinciuc M, Van Wees B J, *et al.* Interface-controlled, high-mobility organic transistors [J]. *Adv. Mater.*, 2007, 19(5):688-692.
- [14] Yao B, Lv W L, Chen D Q, *et al.* Photoresponsivity enhancement of pentacene organic phototransistors by introducing C₆₀ buffer layer under source/drain electrodes [J]. *Appl. Phys. Lett.*, 2012, 101(16):163301-1-4.
- [15] Hamilton M C, Martin S, Kanicki J. Thin-film organic polymer phototransistors [J]. *IEEE Trans. Elect. Dev.*, 2004, 51(6):877-885.
- [16] Suchand Sangeeth C S, Stadler P, Schaur S, *et al.* Interfaces and traps in pentacene field-effect transistor [J]. *J. Appl. Phys.*, 2010, 108(11):113703-1-7.
- [17] Park J H, Cho S W, Park S H, *et al.* The effect of copper hexadeca fluorophthalocyanine (F₁₆CuPc) inter-layer on pentacene thin-film transistors [J]. *Synth. Met.*, 2010, 160(1):108-112.
- [18] Kagan C R, Afzali A, Graham T O. Operational and environmental stability of pentacene thin-film transistors [J]. *Appl. Phys. Lett.*, 2005, 86(19):193505-1-3.
- [19] Kumaki D, Yahiro M, Inoue Y, *et al.* Air stable, high performance pentacene thin-film transistor fabricated on SiO₂ gate insulator treated with β-phenethyltrichlorosilane [J]. *Appl. Phys. Lett.*, 2007, 90(13):133511-1-3.
- [20] Baran J D, Larsson J A. Theoretical and experimental comparison of SnPc, PbPc, and CoPc adsorption on Ag(111) [J]. *Phys. Rev. B*, 2010, 81(7):075413-1-12.
- [21] Ahmad A, Collins R A. FTIR characterization of triclinic lead phthalocyanine [J]. *J. Phys. D: Appl. Phys.*, 1991, 24(10):1894-1897.
- [22] Wang H B, Yan D H. Organic heterostructures in organic field-effect transistors [J]. *NPG Asia Mater.*, 2010, 2(2):69-78.
- [23] Zaumseil J, Sirringhaus H. Electron and ambipolar transport in organic field-effect transistors [J]. *Chem. Rev.*, 2007, 107(4):1296-1323.
- [24] Chen F C, Kung L J, Chen T H, *et al.* Copper phthalocyanine buffer layer to enhance the charge injection in organic thin-film transistors [J]. *Appl. Phys. Lett.*, 2007, 90(7):073504-1-3.
- [25] Heremans P, Cheyns D, Rand B P. Strategies for increasing the efficiency of heterojunction organic solar cells: Material selection and device architecture [J]. *Acc. Chem. Res.*, 2009, 42(11):1740-1747.



周茂清(1990-),男,湖南永州人,硕士研究生,2011年于兰州大学获得学士学位,主要从事有机半导体器件的研究。

E-mail: zhoumq07@126.com



彭应全(1963-),男,甘肃天水人,教授,博士生导师,1992年于德国柏林洪堡大学获电子学工程师学位和理学博士学位,主要从事有机电子器件基础理论与性能的研究。

E-mail: yqpeng@lzu.edu.cn