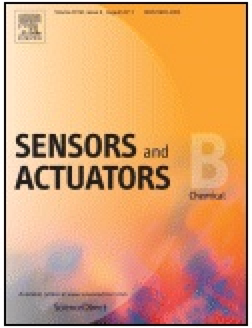
Sensors and Actuators B: Chemical

An international journal devoted to research and development of chemical transducers



ISSN: 0925-4005
Imprint: ELSEVIER

Sensors & Actuators, B: Chemical is an interdisciplinary journal dedicated to covering research and development in the field of chemical sensors, actuators and microsystems. The scope of the journal encompasses, but is not restricted to, the following areas:•Sensing principles and mechanisms•New materials development (transducers and sensitive/recognition ... click here for full Aims & Scope

Additional Information

Editorial Board

Readers

- Access Full-Text
- Volume/Issue Alert

Authors

- Submit an Article
- Track Your Accepted Articles
- Guide for Authors
- Author Information Pack
- Webshop

Librarians

- Ordering Information and Dispatch Dates
- Abstracting/Indexing

Editors

Actions

- Submit Article
- Order Journal
- Recommend to Friend
- Bookmark this Page
- Subscribe to RSS feed

Facts & Figures

Impact Factor: 3.083

IMCS 2012 - The 14th International Meeting

Sensors and Actuators B 156 (2011) 657–661

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

The study of the photo-response characteristics of organic photosensors integrated with pentacene based thin film transistors

Shin Woo Jeong, Jin Wook Jeong, Seongpil Chang, Tae Yeon Oh, Seung Youl Kang, Kyoung Ik Cho, Byeong-Kwon Ju*

Display and Nanosystem Laboratory, College of Engineering, Korea University, Anam-dong, Seongbuk-Gu, Seoul, 136-713, Republic of Korea

ARTICLE INFO

Article history:
Received 6 October 2010
Received in revised form 26 January 2011
Accepted 8 February 2011
Available online 15 February 2011

Keywords:
Photo-response
Organic photo sensor
P3HT/PCBM
Organic thin film transistor
Flexible electronics

ABSTRACT

We have investigated the photo-response characteristics of organic photosensors (OPS) integrated with pentacene based thin film transistors (TFTs). The fabricated device configuration is PEN/ITO/PEDOT:PSS/(poly(3-hexylethiophene)/phenyl-C61-butyric acid methyl ester) (P3HT/PCBM)/Al and PDMS/Au/(poly-4-vinyphenol) (PVP)/pentacene/Au. In order to study the effect of the applied voltage to the pentacene-TFT on the OPS, each device is connected in series. The response current is tuned dependant on the gate-source voltage and the anode-source voltage. The change of the photo induced ON current in the integrated device is measured under light illuminations ranging from 50 mW/cm^2 to 500 mW/cm^2; the corresponding photo-response ($\Delta I/I_0$) of the devices varied from 0.16 to 1.9. We found that the photo-response characteristic is high at the low anode-source voltage and high gate-source voltage.

1. Introduction

Flexible large-area electronics using organic thin-films have had considerable attention among scientists researching optoelectronic applications. Since the conventional approach is based on rigid silicon and glass substrates, it is difficult or cost-prohibitive to achieve large-area, low-cost, light-weight compatibility with plastic substrates. And, the organic material has a large potential to engender flexible optoelectronic applications by tuning its molecular structure [1]. The required devices needed for flexible electronics can be divided into the passive elements and active circuit elements, such as diodes, transistors, and sensor arrays integrated into flexible substrates [2]. For the active circuit elements, not only single devices but also the integration of transistors including their organic and inorganic (a-Si) counterparts with a photosensor or an OLED have been demonstrated, motivated by the need to detect and display the image information on flexible substrates [3–6]. In addition, these research areas are worthy of study because the integration of photosensors, transistors, solar cells and OLEDs will be required for systems on chip. From a chemical engineering perspective, conjugated polymers have been widely used for light radiation detection; the previous research topics have focused on high efficiency [7,8], wide band gaps [9,10], large area processing [11,12], stability [13,14], free transparent electrodes [15,16] and others [17,18] because the opto-induced charge transfer properties of the organic materials largely depend on the material engineering or manufacturing process. However, the electrical characteristics, when they are integrated into organic thin film transistors (OTFTs), have been rarely studied. The quantitative understanding of the electrical operation is necessary in order to enable the design of an optimum organic photosensor. Moreover, in order to realize functional image processing, the variable-sensitivity of photosensor cell is a demanding technology when applied to sensor arrays because these complex elements need to be integrated into the operation of these functions at each pixel.

In this paper, we investigate the photo response characteristics in integrated organic photo sensors with a (poly(3-hexylethiophene)/phenyl-C61-butyric acid methyl ester) (P3HT/PCBM) blend as the active layer and OTFTs with a pentacene organic semiconductor. Both of these organic active layers used for the sensor and the driving part are favorable materials for plastic substrates. We demonstrate the organic photo sensors and the OTFTs can be used on the same substrate in a stacked configuration. The various photo response characteristics dependant on the gate-source and anode-source voltages of the OTFTs were analyzed.

2. Experiment

2.1. Fabrication of the organic photosensor

Two kinds of devices were fabricated at the same time. The glass is used for easy handling of the plastic substrate; the samples were

* Corresponding author at: Department of Electrical Engineering, Korea University, Anam-Dong, Seongbuk-Gu, Seoul 136-701, Republic of Korea.
Tel.: +82 2 3290 3237; fax: +82 2 921 1325.
E-mail address: bkju@korea.ac.kr (B.-K. Ju).

0925-4005/$ – see front matter
doi:10.1016/j.snb.2011.02.013

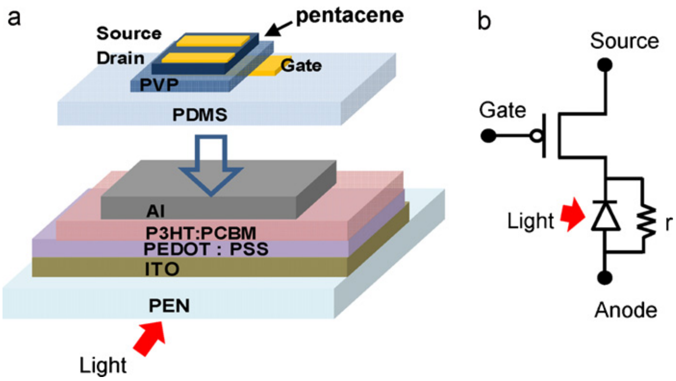


Fig. 1. (a) The schematic diagram of the devices, which is integrated with a pentacene thin film transistor on an organic photosensor. (b) The equivalent circuit diagram of the integrated sensor and transistor. The inner resistance is described.

cleaned according to the conventional wet cleaning process (isopropyl alcohol for 10 min in ultrasonic bath and dried on a hot plate). The sample preparation was realized without protection to air and moisture at clean room. The ITO anode electrode was prepared using the pre-coated 125 μm thin polyetherthylenenaphthalate (PEN) substrates. The sheet resistance is 20 Ω/sq.; the film thickness is 150 nm. We conducted the ITO patterning using photolithography. The PEDOT:PSS (Bayer) layer was then spin-coated at 1200 rpm. To make a P3HT/PCBM 1:0.8 weight ratio solution, P3HT is dissolved in chlorobenzene to make a 22 mg/ml solution, followed by stirring the solution for 3 h at room temperature. The cathode layer of the OPS was formed with 90 nm thick aluminum, which was deposited by thermal evaporation using a shadow mask. The size of the OPS electrode for each active area is 3 mm × 3 mm. The finished (P3HT/PCBM) films were annealed on top of a hotplate at 150 °C for 10 min in air. The prepared devices are briefly covered by pentacene-TFT made onto PDMS substrate.

2.2. Fabrication of pentacene thin film transistor

Evaporated-pentacene was used as an active layer for the OTFTs at room temperature due to its uniformity and reproducibility as an organic semiconductor [19]. Fig. 1(a) shows the OPS structure of the ITO/PEDOT:PSS/P3HT:PCBM/Al and the pentacene-thin film transistor on the poly(dimethylsiloxane) (PDMS) (Dow corning, Sylgard 184) substrate. In order to integrate the OPS device and OTFT onto the same substrate, about 1 mm of PDMS was used as the flexible substrate of the pentacene thin film transistor. A 140 nm thick Au gate was evaporated on the PDMS through the shadow mask. The powders of poly-4-vinyphenol (PVP) (Mw = 25,000) was dissolved with poly(melamine-co-formaldehyde) (PMF) (used as the PVP thermal cross-linker) using propylene glycol monomethyl ether acetate (PGMEA). The concentration of PVP in PGMEA solution was 15 wt% and the thickness was about 750 nm. The cross-link was completed by an annealing process at 200 °C for 10 min. The pentacene was evaporated in the thermal evaporation system (DOV Co., Ltd.) under a vacuum pressure of 2×10^{-6} Torr, at room temperature. The deposition rate was controlled to 0.3 Å/s. The channel length and width was 100 μm, 500 μm, respectively which were patterned through shadow mask by thermal evaporator. In order to reduce the exposure to air, the Au electrodes and the aluminum electrodes of the OPS were evaporated continuously in the same chamber.

2.3. Measurements

The current density versus voltage (J–V) measurements were performed using a Keithley model 2400 source measuring unit (see the supporting data). The current voltage (I–V) characteristics of the transistors were measured using a semiconductor parameter analyzer (Keithley 4200 SCS) in a dark box. The light illumination was done using a class-A sola simulator with a 150 W Xenon lamp (Newport); its light intensity was adjusted using a NREL-calibrated mono Si solar cell, with a KG-2 filter, for an approximately AM 1.5 G1 sun light intensity. The calibration was performed using a G425 silicon photodiode, which was NIST-calibrated as a standard.

3. Results and discussions

The equivalent circuit shown in Fig. 1(b) represents the serial connection of the OPS and the transistors; the discussion of our work is based on the gate-source voltage and anode-source voltage as an experimental parameter. The operation of the whole circuit under the dark state can be estimated by the current versus the applied voltage, as seen in Fig. 2(a). The ON current value of a sensor-transistor is lower than the single transistor for every case of the gate-source voltage conditions because the series resistance of sensor is included. And, the dark current of OPS can be largely reduced due to the same reason. Fig. 2(b) shows that a dark current of around 49 pA flowed from the anode to the source (−0.3 V to −0.9 V) at a zero gate-source voltage. This value of dark current is sufficiently low to necessitate a sensor array that needs numerous unit cells [20]. And the decreased series resistance of devices as gate-source voltage increase implies that the accumulated charge by electric field on gate is helpful to increase the current of circuit. The current–voltage characteristic of OPS under light illumination ranging from 50 mW/cm^2 to 500 mW/cm^2 is shown in Fig. 2(c). The photo induced current is linearly increased and the calculated series resistance under light illumination is varied from 0.05 MΩ to 3.2 MΩ (range of applied voltage is −0.1 V to −0.9 V).

We studied the photo response characteristics of the light dependent photo-response current for the anode-source voltage versus time while the light is illuminated about 10 s for each different light intensity range (50 mW/cm^2, 200 mW/cm^2, 300 mW/cm^2, 500 mW/cm^2). In Fig. 3(a)–(c), the photo induced current between anode-source of each condition plotted increased as gate-source voltage increases. And the maximum anode-source current in Fig. 3(c) is −0.7 μA. The minimum anode-source current is 26 nA when the gate-source voltage is −5 V and 50 mW/cm^2 light intensity (see supporting data). From this result, we can assume that a more than 8-bit dynamic range $(I_{max} - I_{dark})/I_{min} - I_{dark})$ is possible under the subdivided light intensity because the photo induced current is coincident with the trend of the light intensity. The reason for the current increase upon the gate-source voltage is due to the large accumulated hole carrier level at the transistor channel layer. And, it is observed that the photo response is inversely proportional to the anode-source voltage. We think that this can be attributed to the relatively increased dark current to the photo induced current. Although, the electric field dependent separation of the charge carriers is likely increased, the flow of the accumulated hole carriers to the drain is limited by the reverse bias at the photo sensor. Finally, the observed degradation of the current curves over time or increased gate bias is attributed to the charge trapping [21].

Fig. 4 shows the variable photo-response according to the light intensity. The photo response ($\Delta I/I_0$) of the devices ranged from 0.16 to 1.9. This photo response characteristic is comparable to similar photo detectors using organic materials [22]. However, the photo response ($(I - I_0)/I_0$), especially at the 500 mW/cm^2, is not linear to the light intensity over every applied condition of the gate-source and anode-source voltages. This is due to the fact that the drain current of the thin film transistor is easily saturated by the large photo induced current so the combined current of the anode-source current is reduced [22]. Through this trend of vari-

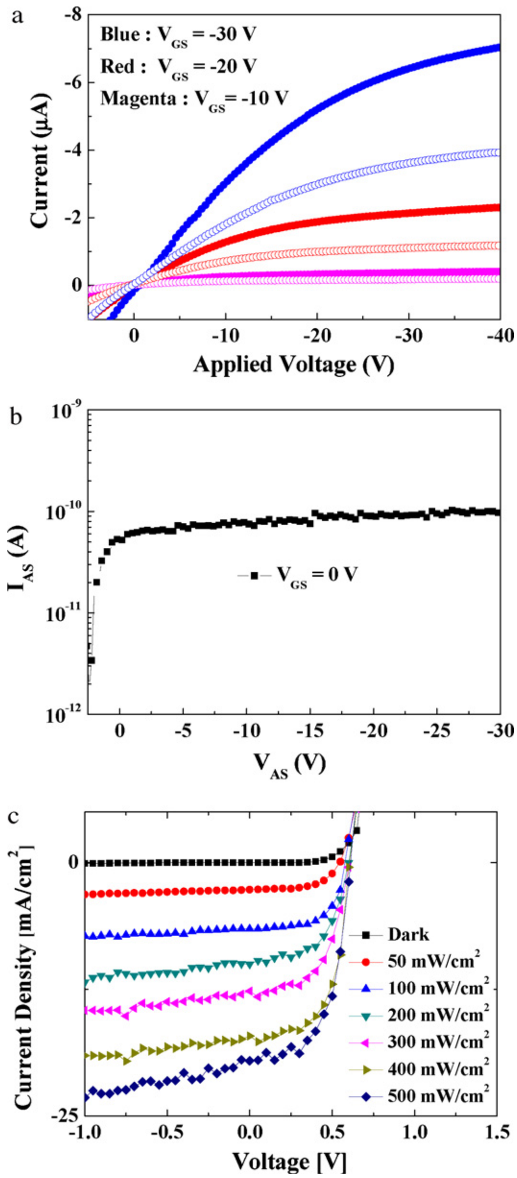


Fig. 2. (a) The current versus voltage (*I*–*V*) characteristics of the sensor-transistor and the separated transistor. The open symbol indicates a separated transistor and the closed one is for the sensor-transistor under the dark state (b). The dark current of the sensor-transistor at a gate-source voltage of 0 V as the anode-source voltage is swept from 5 V to −30 V. (c). The current density-voltage (*J*–*V*) characteristics of separated photo sensor.

ance of photo-response. The appropriate range of light power for the organic photo sensor can be estimated.

The resistance curves at every voltage bias conditions of the circuit plotted in Fig. 5 shows the total resistance of the sensor-transistor under dark state is changed from 1.42 MΩ to 19.6 MΩ. These figures indicate that the voltage distribution to OPS is lower than −0.4 V and its estimated resistance is 0.05 MΩ to 1 MΩ, when we compare the series resistance in current–voltage characteristic of OPS based on Eq. (1). Thus, the OTFT takes dominant part in the variable photo-response including photo-induced current from the OPS because the photo-response in sensor-transistor is strongly affected by the total resistance under dark state with voltage bias.

$$I_{AS} = \frac{V_{AS}}{R_{OTFT}^{dark} + R_{OPS}^{light}} \quad (1)$$

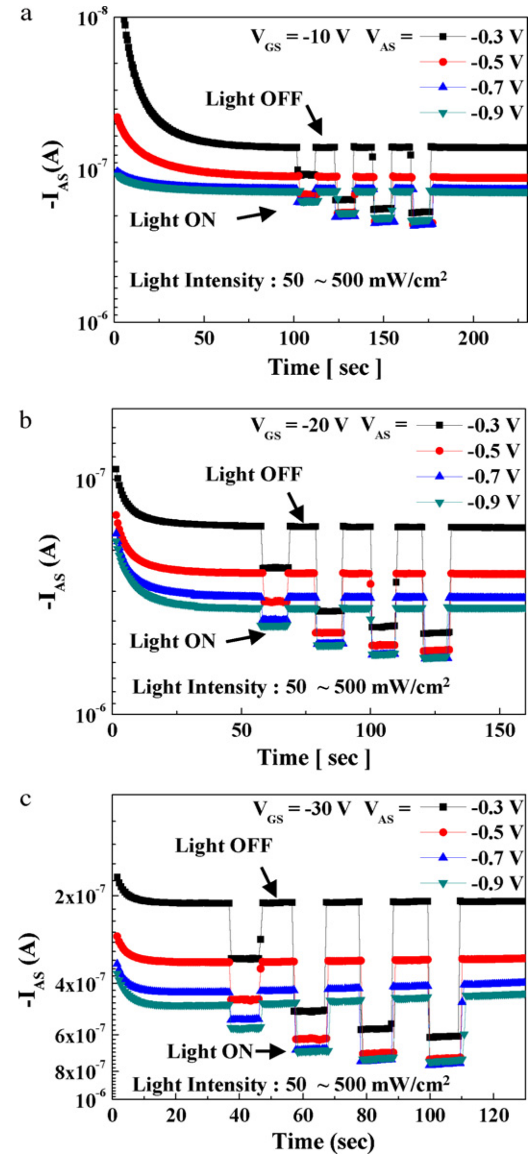


Fig. 3. The anode-source current versus time when the irradiated light intensity is varied from 50 mW/cm² to 500 mW/cm² (the corresponding activated photocurrent is plotted from left to right). The gate-source voltage of the pentacene thin film transistor is tuned from (a) −10 V, (b) −20 V, and (c) −30 V.

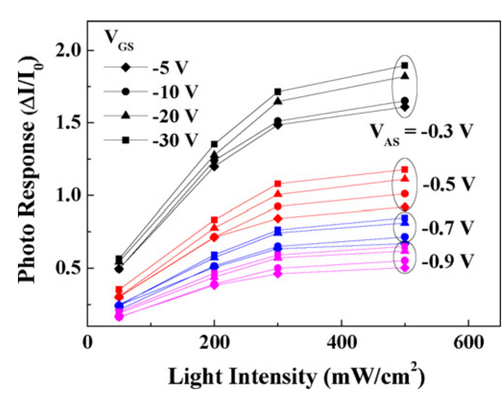


Fig. 4. The plot of the photo-response = $(I_{photo} - I_{dark})/I_{dark}$ versus time with a light intensity from 50 mW/cm² to 500 mW/cm². The curves of the photo response are divided into 4 groups according to anode-source voltage which is varied from −0.3 V to −0.9 V.

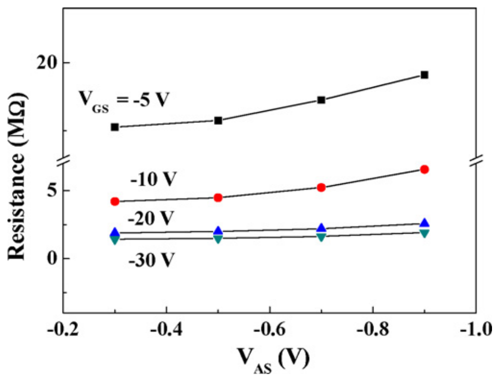


Fig. 5. The plot of the total resistance versus the anode-source voltage, which is calculated from the anode-source current dependent on the gate-source and anode-source voltage.

Additionally, the decreased photo response at high anode-source voltage and low gate-source voltage can be explained through the tendency in Fig. 5 because the increased resistance disturbs the current flow at fixed voltage. In this electrical characteristic, however, there are another factors are remained such as charge carrier mobility, life time and temperature, which is worth to be considered in expanded experiment [23–25]. But, our simple estimate on series resistance from *I–V* curves clarified that the photo-response of integrated OPS to TFT and the variance of measured values upon voltage biases are dependent on not only the light power but also the both gate-source and anode-source voltage. This device configuration and its electrical characteristics under various light intensities or bias conditions can be applied in multiple detectors which require low dark current. In addition, the organic materials used as sensing area and device structure based on flexible substrates has large potential applications such as vapor-phase detectors, mechanical sensors or actuators.

4. Conclusions

In summary, the photo-response characteristic of an organic photosensor (OPS) was investigated under various illuminations when the pentacene based thin film transistors (TFTs) are connected in series. The variable photo-response has an effective increase in the ON-state anode-source current due to the photons absorbed in the P3HT/PCBM blend. The induced photo current by light flows to the drain of the whole circuit and the accumulated hole carriers at the channel of OTFT is combined. The current from OPS is diminished by the large inner resistance of the OTFT in the linear region so that the anode-source current varied from 10^{-9} A to 10^{-7} A at low voltage to anode-source (shown in Fig. 3). These current levels and voltages can enable the low power consumption and dynamic range of photo detection, making it suitable for a photo sensor that needs many sensor pixels. Therefore, this work suggests the possibility of applications using programmable flexible organic photo sensor arrays with organic TFT backplane.

Acknowledgments

This work was supported by the IT R&D Program (Grant No. 2008-F-024-02, Development of Mobile Flexible (Input/Output Platform) of MKE in Korea, Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No. 2009-0083126) and the Industrial-Educational Cooperation Program between Korea University and Samsung Electronics.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.snb.2011.02.013

References

[1] T. Sano, Y. Nishio, Y. Hamada, H. Takahashi, T. Usuki, K. Shibata, J. Mater. Chem. 10 (2000) 157–161.
[2] R.H. Reuss, B.R. Chalamala, A. Moussessian, M.G. Kane, A. Kumar, D.C. Zhang, J.A. Rogers, M. Hatalis, D. Temple, G. Moddel, B.J. Eliasson, M.J. Estes, J. Kunze, E.S. Handy, E.S. Harmon, D.B. Salzman, J.M. Woodall, M.A. Alam, J.Y. Murthy, S.C. Jacobsen, M. Olivier, D. Markus, P.M. Campbell, E. Snow, Proc. IEEE 93 (2005) 1239.
[3] L. Zhou, A. Wanga, S.C. Wu, J. Sun, Appl. Phys. Lett. 88 (2006) 083502.
[4] T.N. Ng, W.S. Wong, M.L. Chabinyc, S. Sambandan, R.A. Street, Appl. Phys. Lett. 92 (2008) 213303.
[5] M. Zirkl, A. Haase, A. Fian, H. Schon, C. Sommer, G. Jakopic, G. Leising, B. Stadlober, I. Graz, N. Gaar, R. Schwodiauer, S. Bauer-Gogonea, S. Bauer, Adv. Mater. 19 (2007) 2241.
[6] T. Someya, Y. Kato, S. Iba, Y. Noguchi, T. Sekitani, H. Kawaguchi, T. Sakuria, IEEE Trans. Electron Devices 52 (2005) 11.
[7] C. Zhang, S.W. Tong, C. Jiang, E.T. Kang, D.S.H. Chan, C. Zhu, Appl. Phys. Lett. 93 (2008) 043307.
[8] J.Y. Kim, K. Lee, N.E. Coaters, D. Moses, T.Q. Nguyen, M. Dante, A.J. Heeger, Science 317 (2007) 222.
[9] S. Bertho, G. Janssen, T.J. Gleij, B. Conings, W. Moons, A. Gadisa, J. D'Haen, E. Goovaerts, L. Lutsen, J. Manca, D. Vanderzande, Sol. Energy Mater. Sol. Cells 92 (2008) 753–760.
[10] M.H. Petersen, Ol. Hagemann, K.T. Nielsen, M. Jorgensen, F.C. Krebs, Sol. Energy Mater. Sol. Cells 91 (2007) 996–1009.
[11] C. Lungenschmied, G. Dennler, H. Neugebauer, S.N. Sariciftci, M. Glatthaar, T. Meyer, A. Meyer, Sol. Energy Mater. Sol. Cells 91 (2007) 379–384.
[12] M. Niggemann, B. Zimmermann, J. Haschke, M. Glatthaar, A. Gombert, Thin Solid Films 516 (2008) 7181–7187.
[13] R. Franke, B. Maennig, A. Petrich, M. Pfeiffer, Sol. Energy Mater. Sol. Cells 92 (2008) 732–735.
[14] M. Jorgensen, K. Norrman, F.C. Krebs, Sol. Energy Mater. Sol. Cells 92 (2008) 686–714.
[15] J.Y. Lee, S.T. Connor, Y. Cui, P. Peumans, Nano Lett. 8 (2008) 689–692.
[16] Y.F. Lim, S. Lee, D.J. Herman, M.T. Lloyd, J.E. Anthony, Appl. Phys. Lett. 93 (2008) 193301.
[17] Y. Kim, A.M. Ballantyne, J. Nelson, D.D.C. Bradley, Org. Electron. 10 (2009) 205–209.
[18] T. Taima, J. Sakai, T. Yamanari, K. Saito, Sol. Energy Mater. Sol. Cells 93 (2009) 742–745.
[19] M. Shtein, J. Mapel, J.B. Benziger, S.R. Forrest, Appl. Phys. Lett. 81 (2002) 2.
[20] J.C. Blakesley, R. Speller, Med. Phys. 35 (2008) 225.
[21] A. Salleo, R.A. Street, J. Appl. Phys. 94 (2003) 1.
[22] C. Kyle Renshaw, X. Xu, S.R. Forrest, Org. Electron. 11 (2010) 175.
[23] V.D. Mihailetchi, L.J.A. Koster, J.C. Jummelen, P.W.M. Blom, Phys. Rev. Lett. 93 (2004) 21.
[24] A. Pivrikas, N.S. Sariciftci, G. Juska, R. Osterbacka, Prog. Photovolt.: Res. Appl. 15 (2007) 677–696.
[25] V. Shrotriya, G. Li, Y. Yao, T. Moriarty, K. Emery, Y. Yang, Adv. Funct. Mater. 16 (2006) 2016–2023.

Biographies

Shin Woo Jeong received his BS degree in electronic and computer engineering from University of Seoul, Seoul, Korea, in 2008, and the MS degree in electronic and computer engineering from University of Seoul, Seoul, Korea. From 2010, he is currently working toward the PhD degree in electronics and electrical engineering at Korea University, Seoul, Korea. His current research interests include flexible integrated circuits for sensor applications.

Jin Wook Jeong From 2006, he has been working toward the PhD degree in electronics and electrical engineering, Korea University, Seoul, Korea. His current research interests include organic semiconductors in sensor applications and their flexible organic electronics applications.

Seongpil Chang received BS the degree in electronic and information engineering from Seoul national University of Technology, Seoul, Korea, in 2007, and the MS degree in electronics and electrical engineering from Korea University, Seoul, Korea, in 2009. From 2009, he is currently working toward the PhD degree in electronics and electrical engineering at Korea University, Seoul, Korea.

In 2007, he joined Korea Institute of Science and Technology (KIST), Seoul, as a student researcher, and has researched for the oxide-semiconductor and their applications. His current research interests include oxide semiconductors for flexible electronics and the applications of functional polymers for lithography

Tae Yeon Oh received the BS degree in electrical engineering from Korea University, Seoul, Korea, in 2009. From 2009, he is currently working toward the Integrated

Master's & Doctoral Program in electronics and electrical engineering at Korea University, Seoul, Korea. His current research interests include flexible organic electronics with organic thin-film transistors (OTFTs) using nano imprinting method.

Seung Youl Kang received BS degree in physics from Seoul National University, Seoul, Korea, in 1987, and MS, and PhD degrees in physics from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 1990 and 1994, respectively. Since he joined ETRI in 1994, he has been involved in flexible display technology, such as organic TFTs on plastic substrate and electronic paper. Currently, his research interests include an electronic paper, flexible electronics, applications of meta-materials and wireless power transfer systems.

Kyoung Ik Cho received the BS degree in materials science from Ulsan Institute of Technology in 1979, and the MS and PhD degrees in material science and engineering from Korea Advanced Institute of Science and Technology, in 1981 and 1991, respectively. He joined the Electronics and Telecommunications Research Institute (ETRI) in 1981. He has been working on the development of advanced display devices, and new electronic devices and materials. His current research interests include oxide TFT and transparent display, and flexible electronic devices.

Byeong Kwon Ju received the MS degree from the Department of Electronic Engineering, University of Seoul, Seoul, Korea, in 1988, and the PhD degree in semiconductor engineering from Korea University, Seoul, in 1995. In 1988, he joined the Korea Institute of Science and Technology (KIST), Seoul, where he was engaged in the development of silicon micromachining and micro-sensors as a principal research scientist. In 1996, he spent six months as a visiting research fellow with the Microelectronics Centre, University of South Australia, Australia. Since 2005, he has been an associate professor with Korea University, where his main interests are in flexible electronics (OLED and OTFT), field emission devices, MEMS (Bio and RF), and carbon nanotube-based nano systems. He is a member of the Society for Information Display (SID), the Korea Institute of Electrical Engineering (KIEE), and the Korea Sensor Society. He has authored or co-authored over 240 publications.