Integrated Circuits, Optics, and Sensors Using Organic Field Effect Transistors and Photodetectors

Ioannis Kymissis
[1]Department of Electrical Engineering, Columbia University, New York, NY 10027 U.S.A.
TEL:1-212-854-4023, e-mail:johnkym@ee.columbia.edu

Keywords : Photodetectors, pentacene, PVDF, OFET

Abstract

Organic field effect transistors are excellent candidates for addressing and local amplification elements for large area electronics because they can easily be processed at low temperatures on essentially arbitrary substrates. We present the use of these devices in an active matrix photodetector and as a buffer for a strain sensor.

1. Introduction

Organic field effect transistors have been applied to a range of sensing and switching applications where the ability to fabricate large area devices at low temperatures and on flexible substrates are advantageous. Two areas of particular interest have been the detection of mechanical stimuli and the detection of light using OFET-coupled photodetectors.

2.1 Active Matrix Organic Photodetectors

Organic semiconductors can form a variety of high quantum efficiency photodetectors based on planar heterojunctions, bulk heterojunctions, and phoroconductors. These photodetector elements can be used to create large area matrixed photodetectors for a number of future applications including contact scanners [1] and x-ray sensors [2].

One approach to creating a low temperature, additive active matrix photodetector is to use a photoconducting material together with an OFET array. One commercially available photoconductor material, γ-phase titanyl pthalocyanine (γ-TiOPC), can be processed into a crystalline dispersion which is air stable, unlike heterojuction-based devices which require encapsulation for protection against water vapor and oxygen attack. γ-TiOPC enjoys a low exciton dissociation energy [3], allowing the excitons to be separated by a relatively small externally applied field. The dissociation field is constant in these devices, whereas in a heterojunction device the built in field at least partially contributes to exciton separation.

There are several challenges which need to be overcome to interface γ-TiOPC to OFETs. The first challenge is one of impedance matching. A vertical sandwich of γ-TiOPC at practical pixel sizes (10-100 microns across and 1-5 microns thick) has a resistance which is too low to switch using an OFET of comparable size.

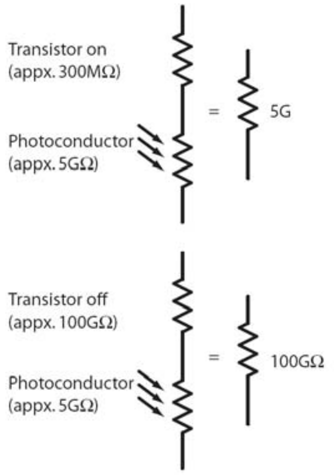

Figure 1 Switching strategy for active matrix photodetector. Because the transistor impedance is high, the photodetector also needs to be designed with a high impedance to match.

The solution to this problem is to increase the impedance of the photodetector element by switching from a vertical charge flow device (i.e. a sandwich architecture) to a lateral charge flow device using interdigitated electrodes. This allows tuning of the photodetector impedance into a range easily switchable by the transistor.

A second challenge is to find a strategy to isolate the photodetecting elements from each other. One solution to this problem is to use a diode-connected transistor addressing scheme, which reduces crosstalk by powering only one row at a time. A second solution is to print the photoconductor into islands. Other solutions are also possible, including use of current guarding and providing a separate switched supply for each row of photodetectors.

Two generations of photodetectors have been fabricated and tested, using diode connected transistor isolation [4] and a series transistor-photoconductor device with a patterned and printed photoconductor [5]. The fabrication process for each is summarized in Figs. 2, 3, and 4.

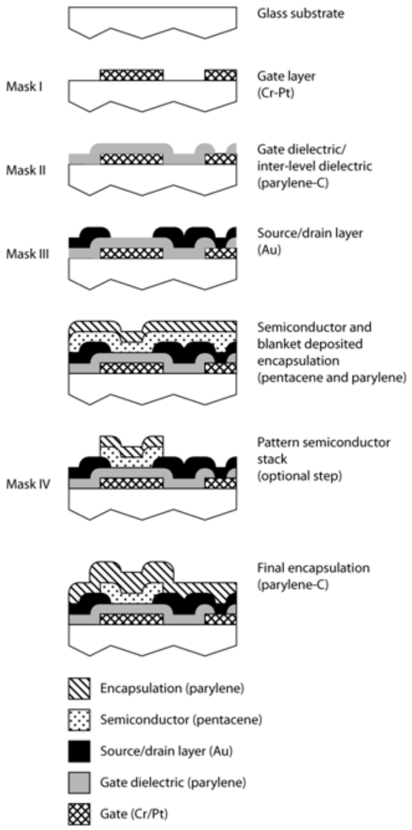

Figure 2. General lithographic OFET process flow, based on the process described in [6].

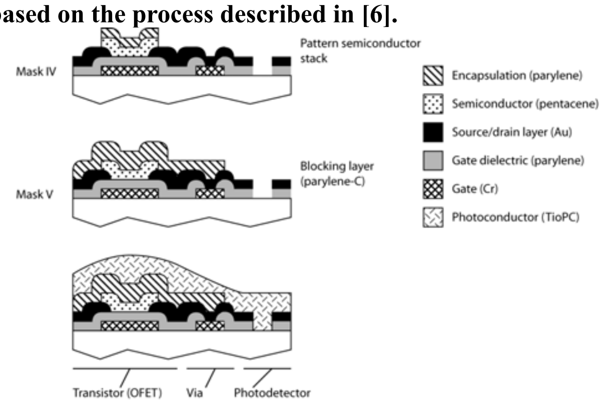

Figure 3. The last two steps of the active matrix photodetector process using a diode connected array and a blanket coated photoconductor.

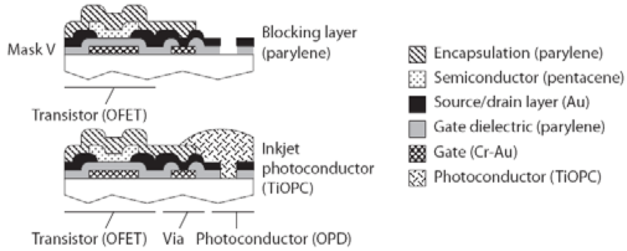

Figure 4. The last two steps of the active matrix photodetector process using printing for photoconductor isolation

Testing of the devices was performed using patterned light sources, results for both devices are shown in Figs. 5 and 6.

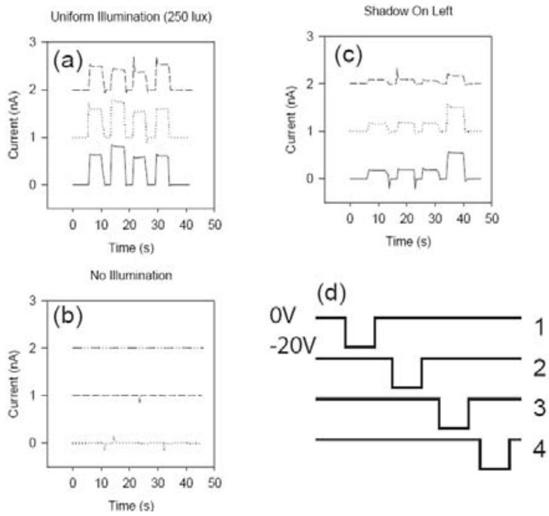

Figure 5. Photodetection results from diode connected array. The device is able to detect a shadow in (c).

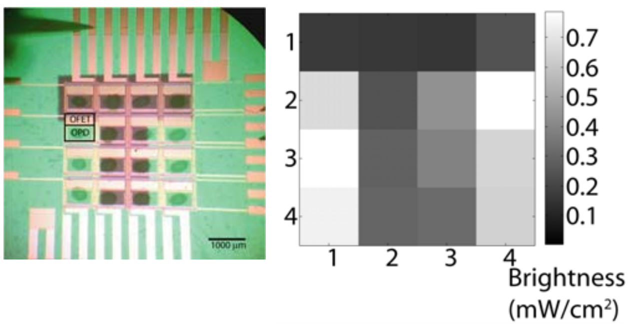

Figure 6. Photodetection results from series connected array with printed photodetector. A mask is used to gerate the pattern on the photodetectors.

2.2 Locally Amplified Strain Sensing

Sensing of mechanical stimuli is an interesting application for large area electronics. Crystalline silicon devices, which are expensive per unit area, are not economical for direct interfacing with macroscopic systems. Thin film semiconductor devices, however, are well suited for these applications. Using thin film devices compatible with large area processing it is possible to fabricate sensors that match the size of the target mechanical stimulus.

Organic field effect transistors (OFETs) are particularly interesting in this arena because of their compatibility with highly compliant polymer substrates. Several sensors for mechanical stimuli have been developed using organic field effect transistors, including pressure [7] and strain [8] sensors.

We have developed a strain sensor based on the piezoelectric and pyroelectric polymer polyvinylidene diflouride (PVDF) which is locally buffered by an organic field effect transistor. Traditional PVDF sensors have been used in a number of strain measuring applications, including structural health monitoring, turbulence detection, pulse and respiration detection, and traffic detection.

As the number of sensing elements, area, and degree of interconnect overlap increases, the parasitic capacitance between the actuated PVDF element and the detection point also increases. This capacitance shares the generated charge with the piezoelectric element, decreasing the measurable voltage and signal-to-noise ratio.

One strategy to overcoming the decrease in measurable charge is to place an OFET-based transimpedance amplifier near the piezoelectric material at each sensing element [] []. This amplifier would convert the charge signal to a current signal, and given enough time, the current source can charge even large parasitic capacitances between the point of charge generation and the sensing node. A single transistor or slightly more complicated circuit can be used for this purpose.

An additional challenge when working with PVDF is the low Curie temperature of the material. Exposure to temperatures exceeding 85C for an extended period of time recrystallizes the material into a paraelectric phase and destroys its piezoelectric character. Fortunately, OFETs can be fabricated at temperatures well under the Curie temperature of PVDF, allowing amplifier fabrication directly on the polymer sheet.

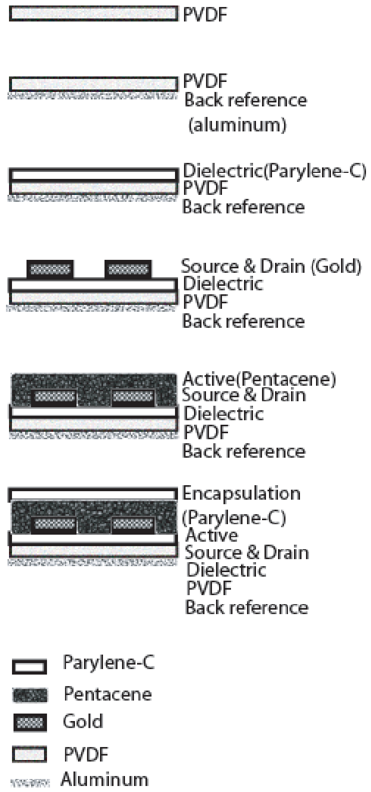

Figure 7: The process flow for the locally amplified piezoelectric sensor

The fabrication process is summarized in Fig. 7. Oriented and poled PVDF sheet is cleaned and coated with a reference electrode and a layer of parylene-C. The source/drain layer is then photolithographically defined, followed by the organic semiconductor pentacene. After final encapsulation the device is tested. The results from a typical actuation are shown in Fig. 8.

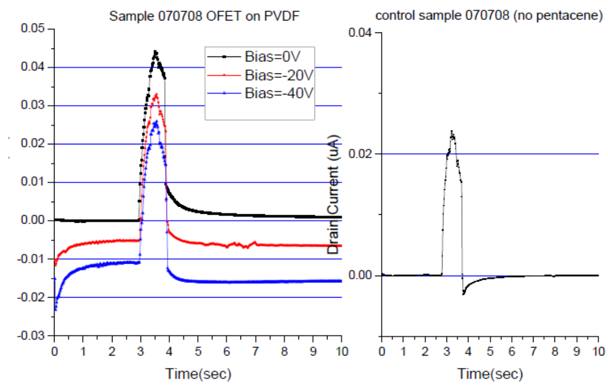

Figure 8. Typical actuation of a directly coupled PVDF/OFET stack. The pulse is capacitave coupling of OVDF into the reference and drain electrodes. Once this transient passes, however, the strain can be

determined by analyzing the change in effective gate voltage through the change in drain current.

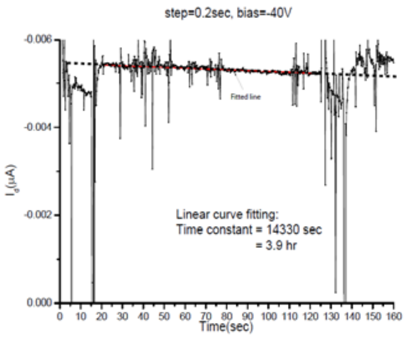

Figure 9. Charge retention in the PVDF/OFET stack. The charge retention characteristic of the PVDF/OFET stack. The projected decay rate has a time constant of approximately 4h.

There are several advantages of this architecture, which has no metallic gate, over coupling a PVDF element to a traditional gated OFET either on the PVDF substrate or attached using a hybrid process. Because there is no charge spreading or metallic gate electrode, there is no loading on the signal due to source/drain overlap capacitance. The charge retention time can also be very long. Because charge is locally stored at the parylene/PVDF interface, the retained charge does not leak out through the weakest point as typically occurs with a metal gate. Fig. 9 shows the charge retention in an actuated strain sensor unit—the discharge time constant is projected to be almost 4 hours. Figure 10 shows a strain map produced by laminating the sensor to a 0.8mm thick PVC credit card blank and flexing the system.

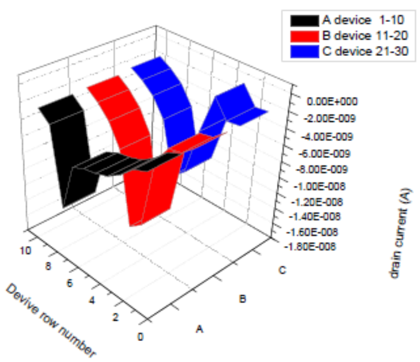

Figure 10. A strain map of a flexed PVC sheet produced by a set of the locally amplified PVDF/OFET strucures.

4. Summary

Organic field effect transistors can couple with a variety of sensing devices for large area sensing applications. With proper layout and design, it is possible to make a range of systems with unique sensing functionalities unattainable with conventional devices.

6. Acknowlegements

The photodetector work was mainly performed by Ivan Nausieda and Kevin Ryu, both at the Microsystems Technology Laboratory at the Massachusetts Institute of Technology. The strain sensor was developed by Yu-Jen Hsu, and Zhang Jia, both at Columbia University. This work was partially supported by the National Science Foundation award ECCS-0644656, by the Nanoscale Science and Engineering Initiative of the National Science Foundation under NSF Award Number CHE-0641523, and by the New York State Office of Science, Technology, and Academic Research (NYSTAR).

References

[1] H. Kawaguchi, S. Iba, Y. Kato, T. Sekitani, T. Someya, and T. Sakurai, "A 3-D-stack organic sheet-type scanner with double-wordline and double-bitline structure," *Ieee Sensors Journal,* vol. 6, pp. 1209-1217, Oct 2006.

[2] E. K. Panagiotis, C. G. Neil, S. Henning, H. F. Richard, C. B. James, S. Robert, C. Mariano, A. Tiziano, D. C. B. Donal, and N. Jenny, "X-ray stability and response of polymeric photodiodes for imaging applications." vol. 92: AIP, 2008, p. 023304.

[3] Z. D. Popovic and A. M. Hor, "Photoconductivity Studies of Titanyl Phthalocyanine," *Molecular Crystals and Liquid Crystals,* vol. 230, pp. 75-80, 1993.

[4] I. Kymissis, C. G. Sodini, A. I. Akinwande, and V. Bulovic, "An organic semiconductor based process for photodetecting applications," in *Electron Devices Meeting, 2004. IEDM Technical Digest. IEEE International*, 2004, pp. 377-380.

[5] I. Nausieda, K. Ryu, I. Kymissis, A. I. T. Akinwande, V. Bulovic, and C. G. Sodini, "An organic active-matrix imager," *Ieee Transactions on Electron Devices,* vol. 55, pp. 527-532, Feb 2008.

[6] I. Kymissis, A. I. Akinwande, and V. Bulovic, "A lithographic process for integrated organic field-effect transistors," *Display Technology, Journal of,* vol. 1, pp. 289-294, 2005.

[7] Y. Noguchi, T. Sekitani, and T. Someya, "Organic-transistor-based flexible pressure sensors using ink-jet-printed electrodes and gate dielectric layers," *Applied Physics Letters,* vol. 89, pp. -, Dec 18 2006.

[8] J. Soyoun and T. Jackson, "Organic semiconductor strain sensors," in *Device Research Conference Digest, 2005. DRC '05. 63rd*, 2005, pp. 149-150.