A Large-Area, Flexible, and Lightweight Sheet Image Scanner Integrated with Organic Field-Effect Transistors and Organic Photodiodes

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Abstract

A large-area, flexible, and lightweight *sheet image scanner* has been successfully manufactured on a plastic film, for the first time, integrating high-quality organic transistors and organic photodetectors. Since this area-type image-capturing device does not require any optics or any mechanical scanning devices, it is innovatively light to carry, shock-resistant and potentially inexpensive to manufacture.

Introduction

In order to realize pleasant mobile electronics, it is more desirable that electronic devices would be lightweight, thin, and shock-resistant, although such functionalities can't be easily achieved by the present silicon-based electronic materials plus mechanical components. Organic semiconductor-based electronics [1-6] can compensate the drawbacks of inorganic materials since organic devices are manufactured on plastic films at low (ambient) temperature and, therefore, inherently mechanically flexible, lightweight, and very thin, which are suitable for human-friendly mobile electronics.

In this paper, we report in detail a large-area, flexible, and lightweight *sheet image scanner* on a plastic film, for the first time, integrating high-quality organic field-effect transistors (FETs) and organic photodiodes. Organic photodetectors distinguish between black and white from the difference of reflectivity between black and white parts on paper. The effective sensing area of the integrated device is 2 inches; the resolution is 36 dots per inch (dpi), and the total number of sensor cells is 5,184. The pentacene FETs with top contact geometry have channel length of 18 μm, and mobility of 0.7 cm^2/Vs. Furthermore, we have successfully captured images of characters using a 250-dpi-photodiode matrix without organic transistors. The total thickness and the weight of the whole device are 0.4 mm and 1 g, respectively.

Device manufacturing process

As may be seen in Fig. 1, the integrated device formed on a plastic film is mechanically flexible, very thin, and lightweight. The device structure is schematically illustrated in Fig. 2 along with chemical structure of each layer. Organic FET matrix and photodiode matrix have been manufactured separately on different plastic films in clean room (class 100-1,000) and then laminated with each other with silver paste patterned by ultrafine printing technique. The chip pictures and a circuit diagram of the core part are shown in Fig. 3 and 4, respectively.

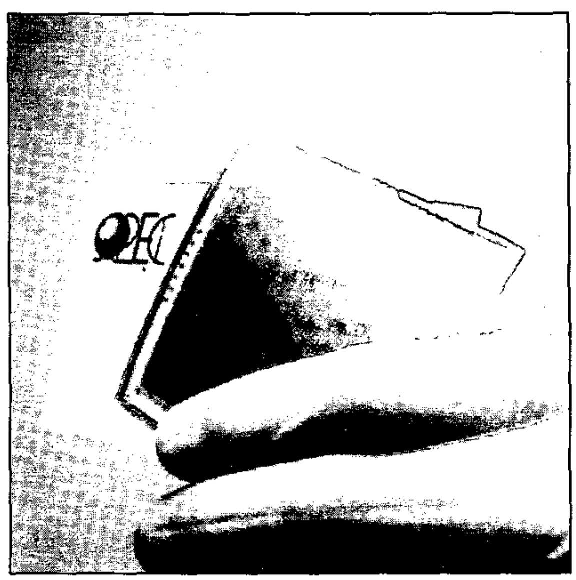

Fig. 1: An image of the manufactured large-area, flexible, and lightweight *sheet image scanner* consisting of organic transistors and organic photodiodes, which is placed on a business card under ambient light for capturing image.

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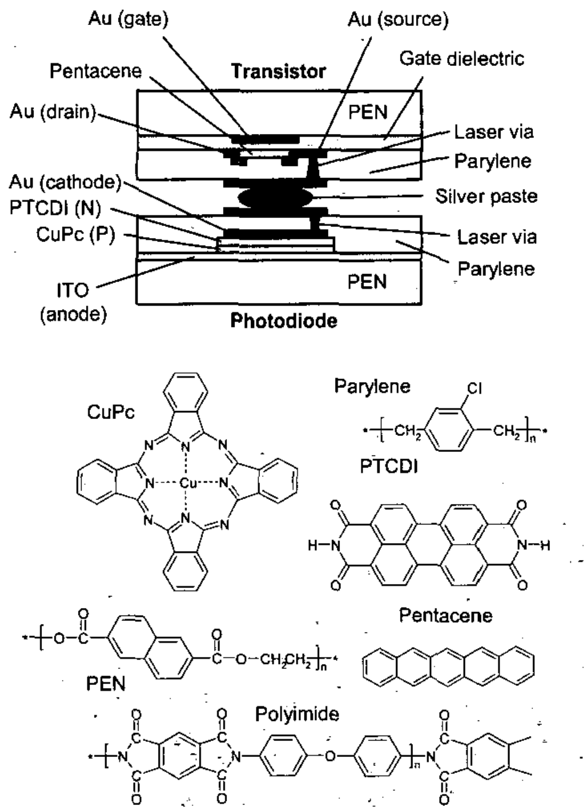


Fig. 2: The cross-sectional view of the device structure is schematically shown. Organic transistor matrix and organic photodiode matrix are separately manufactured on different PEN films and then laminated with each other with silver paste patented by ultra fine printing technique. The chemical structure of each layer is also shown.

A. Organic FETs

A 72x72 (~5,184) matrix of pentacene FETs with top-contact geometry is manufactured with ultrafine shadow mask (Athene corporation). The base film (substrate) is a transparent poly(ethylene naphthalate) (PEN) film (Teonex Q65, Teijin Dupont Films) with a thickness of 125 μm. The surface of the base film is coated with a 150-nm-thick gold layer with a 5-nm-thick chromium adhesion layer in the vacuum evaporator with shadow masks. Then, polyimide precursors (Kemitite CT4112A, Kyocera Chemical) are spin-coated and cured at 180°C to form 630-nm-thick gate dielectric layers. A 50 nm thick pentacene is deposited to form a channel layer, and a 60-nm-thick gold layer is evaporated through shadow masks to form the source and drain electrodes of the transistors. The channel length L and width W are 18 μm and 400 μm, respectively. The periodicity is 700 μm, which corresponds to resolution of 36 dpi.

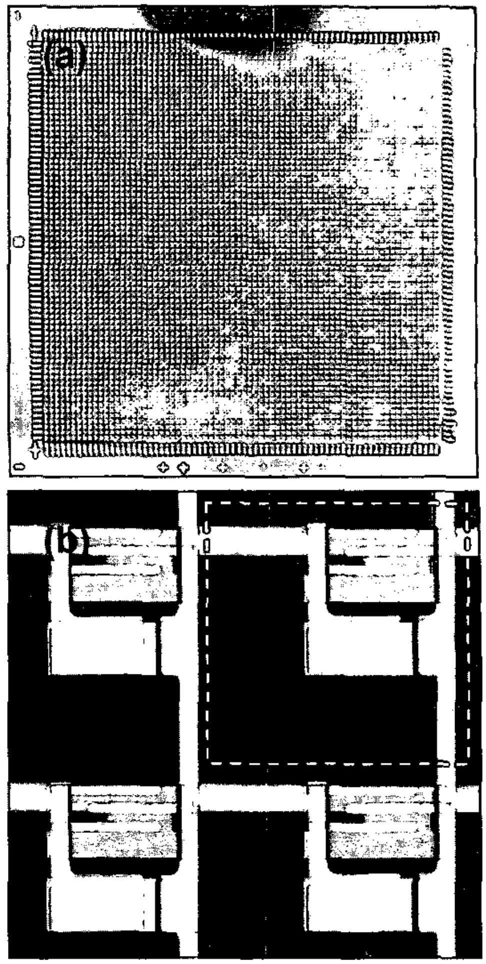


Fig. 3: The chip pictures. (a) The integrated device consisting of 72x72 sensor cells. The resolution is 36 dpi. Scale bar is 1cm. (b) The magnified image of organic transistor matrix manufactured on a PEN film before laminating with a film with photodiode matrix. The white dashed square indicates the one unit sensor cell, whose area is 700x700 μm^2.

B. Organic photodiodes

The base film of photodiodes is an ITO-coated PEN film with resistivity of 95 Ω/□. A 30 nm thick p-type semiconductor of copper phthalocyanine (CuPc) and a 50 nm thick 3,4,9,10-perylene-tetracarboxylic-diimide (PTCDI) are deposited in vacuum sublimation system and 150 nm thick gold is deposited as cathode electrodes. The size of cathode electrodes and periodicity of photodiodes used to integrate with organic transistors are 450x450 μm^2 and 700x700 μm^2, respectively, but the smaller photodiodes are also fabricated for comparison.

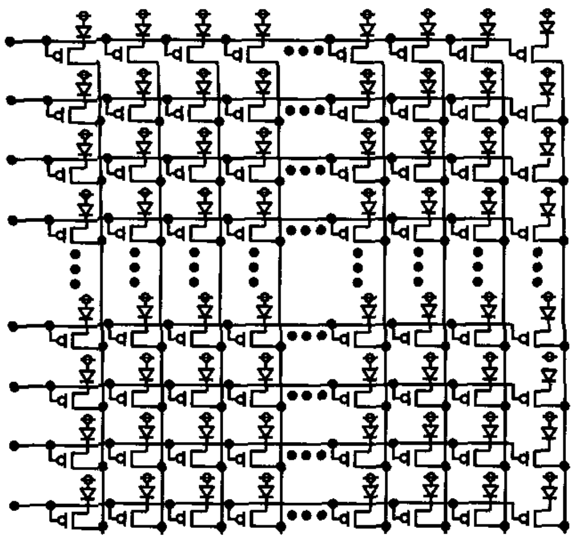


Fig. 4: A circuit diagram of the core part of the sheet image scanner. Each sensor cell consists of one transistor and one photodiode. The vertical lines and the horizontal lines are bit lines and word lines, respectively. The ITO anode electrodes of organic photodiodes are connected to power supply V_{DD}.

C. Integration of organic FETs and photodiodes

Both films with organic FETs and photodiodes are transferred to the vacuum chamber without exposing to air after manufacturing process and uniformly coated by 2 μm poly-monochloro-para-xylylene (parylene) passivation layer. Spots of parylene on electrodes are removed by a CO_2-laser drilling machine for electronic interconnections. Then those films are laminated with each other with silver paste patterned by ultrafine printing technology.

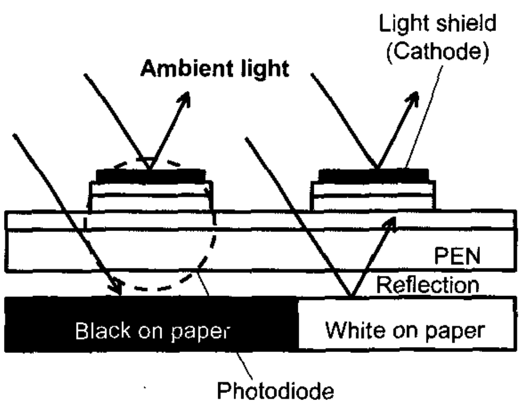


Fig. 5: Image capturing with photodiode matrix sheet in the reflection geometry. Organic photodiodes distinguish between black and white from the difference of reflectivity between black and white parts on paper. The present image-capturing device requires no optics or no mechanical scanning devices.

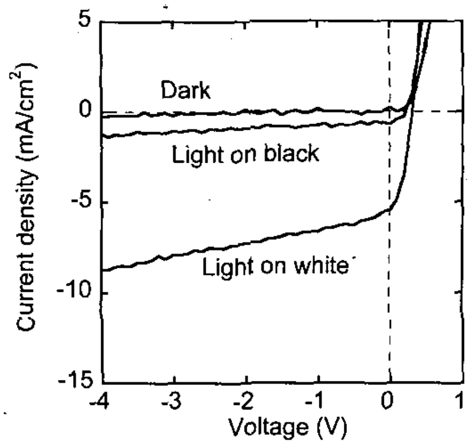


Fig. 6: IV characteristics of a 36 dpi-photodiode without light, with light on black and white regions are measured without transistors.

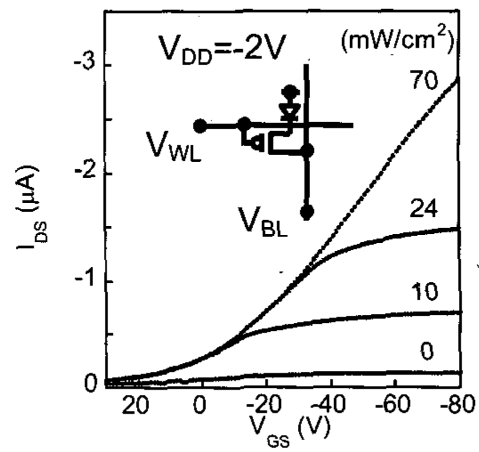


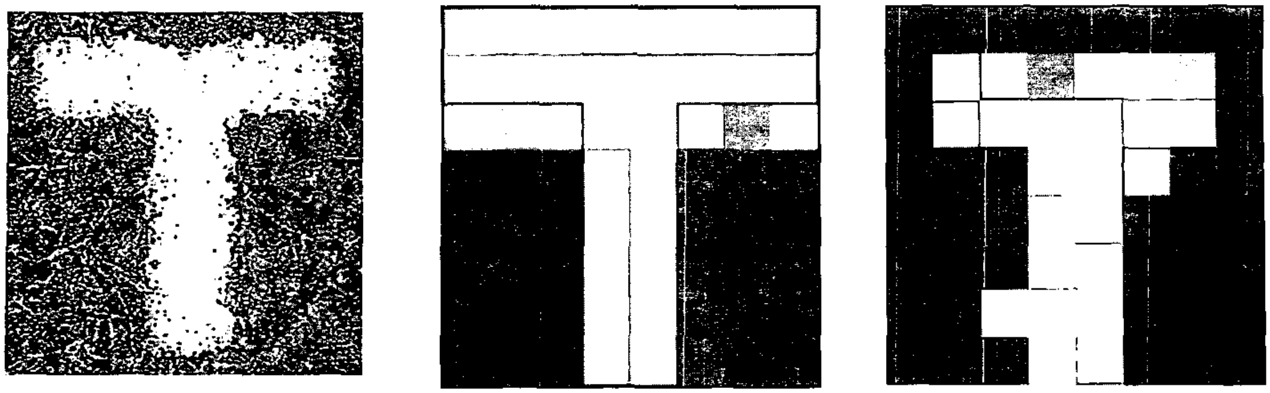
Fig. 7: I_{DS} vs V_{GS} under various intensities of light for one sensor cell of the 36-dpi integrated device. The power supply V_{DD} is −2 V.

Device characteristics

The individual organic transistors, photodiodes, and the integrated device are characterized under ambient environment with adequate device sealing or under nitrogen environment without sealing.

A. Organic FETs

The manufactured organic transistors show p-type conduction. The measured mobility is as high as 0.7 cm²/Vs. All the device failure is due to gate leakage. The initial yield strongly depends on the thickness of polyimide gate dielectric layers and exceeds 99% when it is 630 nm.



(a) An optical microscope **(b) A commercial scanner (250 dpi)** **(c) The present scheme (250 dpi)**

Fig. 8: A white capital letter of T prepared by a laser printer (a) was placed onto the 250-dpi organic photodetector matrix without organic transistors. Photocurrent of each detector is measured under light (80 mW/cm^2). The mapping of normalized photocurrents (c) is compared with an image (b) taken by a commercial scanner with 250 dpi. Dark regions in (c) contains three sensor cells which were not functional. The size of each image is 0.8x0.8 mm^2.

B. Organic photodiodes

The manufactured organic photodiodes are measured under illumination of a halogen lump with different light intensities. The density of photocurrent with reverse bias of – 4V is proportional to the light intensity. The reduction of device dimensions is crucial to increase spatial resolution of image scanners. We have prepared photodiodes with various sizes of gold cathode electrodes from 1x1 mm^2 to 50x50 μm^2 and measured the photocurrent density under illumination of light (70 mW/cm^2). We have found that the device dimensions can be reduced down to 50x50 μm^2 with reduction of photocurrent density by only 25%, which is sufficient to achieve spatial resolution of 250 dpi. The present device distinguishes between black and white in the reflection geometry, as shown in Fig. 5. One of the organic photodetectors is positioned on a sheet of white paper that has a black region printed by a laser printer. Figure 6 shows that IV curves measured on white and black parts; photocurrent ratio of 8:1 is obtained at voltage bias of – 4V.

C. Integrated device

One of the sensor cells consisting of one transistor and one photodetector is measured under illumination of various intensities of light. Figure 7 shows typical I-V characteristics of the sensor cell.

D. Imaging

We have prepared the 250-dpi 10x10 organic photodiode matrix without organic transistors. The effective sensing area of each sensor cell is 50x50 μm^2, while periodicity is 100 μm. We have positioned a sheet of paper with a white capital letter of T prepared by a laser printer onto the photodiode matrix and measured photocurrent of each detector with light illumination (80 mW/cm^2). The mapping of photocurrents is shown in Fig. 8 (c) and compared with the image (b) taken by a commercial scanner. The similar experiment was possible for integrated device with 36 dpi. Although the resolution of the present manufacturing process is limited by the diameter of laser via holes, the higher resolution would be feasible with an ultraviolet laser machine.

Acknowledgments

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