Printed organic transistors for large-area electronics

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Abstract

We report the recent progress and future prospects of flexible, large-area sensors and actuator using organic thin-film transistors (TFTs). In particular, we describe printing technologies to manufacture electronic artificial skins (e-skins) for robots, sheet image scanners suitable for mobile applications, and Braille sheet display with plastic actuator arrays. We also present recent progress of reliability and stability issues.

1. Introduction

Organic thin film transistors (TFTs) and their integrated circuits have attracted considerable attention (1–6). Organic TFTs possess attributes that complement high-performance silicon-based LSI devices, which are expensive. Organic TFTs can be manufactured on plastic films at ambient temperatures or room temperature. Therefore, they are mechanically flexible and potentially inexpensive to manufacture. Recent studies on organic transistors are motivated mainly by two applications. The first application is a flexible display, such as a paper-like display or e-paper, in which electronic inks or other media are driven by matrices of organic transistors. The other is radio frequency identification (RFID) tags. The printable features of organic transistors should facilitate the implementation of RFID tags on packages.

As one of the new applications of organic TFTs, flexible, large-area pressure sensors and actuators are proposed and demonstrated: The active matrices of organic TFTs integrated circuits are used for data readout from area-type sensors or to drive large-area actuators. In this paper, we report the recent progress and future prospects of organic TFT active matrix technologies for flexible, large-area sensors and actuators. In particular, we describe printing technologies to manufacture electronic artificial skins (e-skins) for robots, sheet image scanners, and Braille sheet display. We present recent progress of reliability and stability issues of organic TFTs.

2. Electronic artificial skins (E-skins)

The first example of large-area sensors is a flexible pressure sensor (5). This new device is suitable for electronic artificial skins (Fig. 1), which will be used in next-generation robots. The mobility of pentacene TFTs is typically 1 cm^2/Vs. Although his number is approximately two or three orders of magnitude less than that of poly- and single-crystalline silicon, the slower speed is tolerable for most applications of large-area sensors. In particular, for the fabrication of E-skins, the integration of pressure sensors and organic peripheral electronics avoids the drawbacks of organic transistors, while taking advantage of their mechanical flexibility, large area, low cost, and relative ease of fabrication.

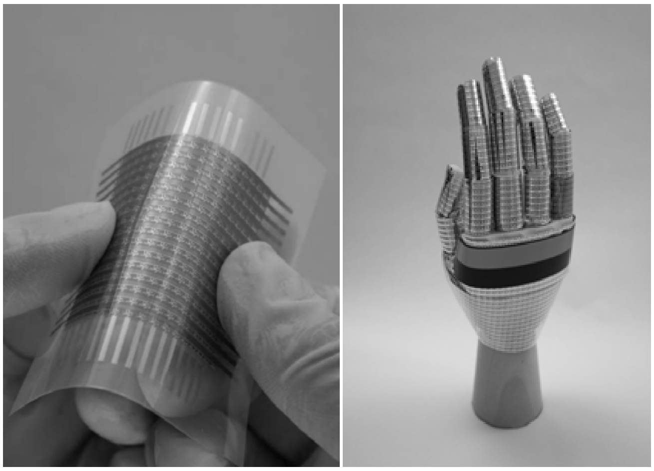

Fig. 1: A picture of an electronic artificial skin (E-skin) for a robot in the next generations. Organic transistors are used to read out pressure distributions. Since all the components except electrodes are made of soft materials and manufactured on a plastic film, it is lightweight, thin and mechanically flexible.

An artificial skin system that comprises of a 16 × 16 active matrix of organic transistors, a row decoder, and a column selector are assembled by a physical cut-and-paste procedure to develop integrated circuits for data readout. Three functional films — an interconnection layer, a pressure-sensitive rubber sheet, and a top electrode for power supply— are then laminated together with the organic ICs. Pressure images were obtained by a flexible active matrix of organic transistors whose mobility is as high as 1.4 cm^2/Vs. These sensors can be bent to a radius of 2 mm, which is sufficiently small for the fabrication of human-sized robot fingers.

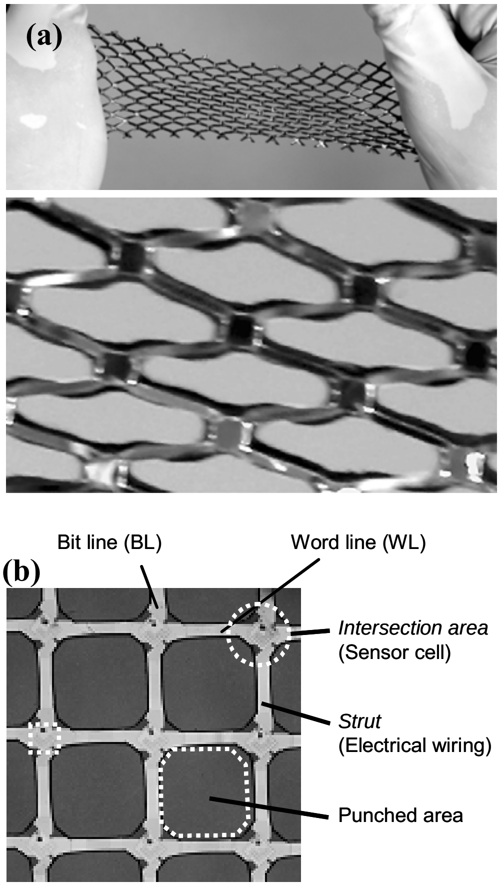

Fig. 2: (a) A plastic film with organic transistors and pressure sensitive rubber is processed mechanically to form a unique net-shaped structure, which makes a film device extendable by 25%. (b) A picture of the 3×3 sensor cells. Scale is 4 mm.

Human skin is more complex than transistor-based imitations demonstrated thus far. It performs certain functions including thermal sensing. Furthermore, without conformability, the application of E-skins to three-dimensional surfaces is impossible. Based on an organic semiconductor, we have developed conformable, flexible, wide-area networks of thermal and pressure sensors (Fig. 2). A plastic film with organic transistor-based electronic circuits was processed to form a net-shaped structure that allows the E-skin films to be stretched by 25%. The net-shaped pressure sensor matrix was attached to the surface of an egg and pressure images were successfully obtained in this configuration.

Moreover, a similar network of thermal sensors was developed using organic semiconductors. A possible implementation of both pressure and thermal sensors on various surfaces is presented. By using laminated sensor networks, the distributions of pressure and temperature are simultaneously obtained (Fig.3).

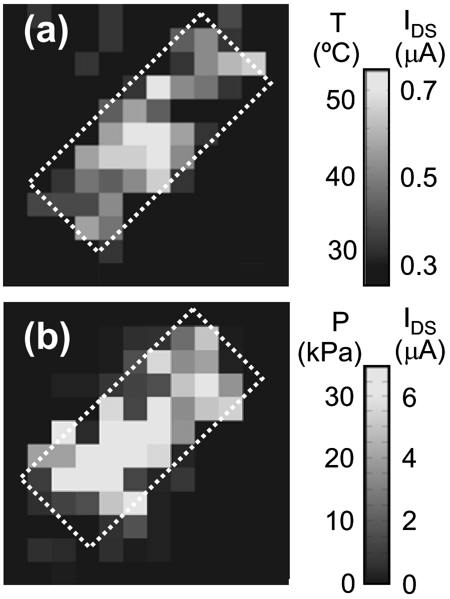

Fig. 3 (a) The spatial distribution of temperature that is converted from the temperature-dependent current in the thermal sensor network. A copper block (15×37 mm^2) whose temperature is maintained at 50 °C is positioned diagonally which is indicated by the dotted line. The sensing area is 44×44 mm^2. (b) Simultaneously, the spatial distribution of pressure is measured with the pressure sensor network.

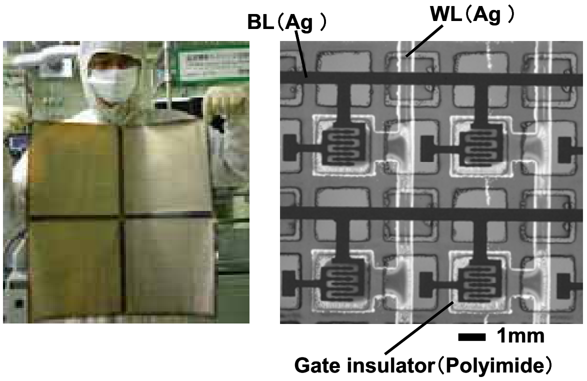

Fig. 4: A printed organic TFT active matrix for e-skin applicataions.

In order to develop low-cost manufacturing process, we have combined inkjet and screen printing systems and manufactured organic TFT active matrixes for e-skin applications (Fig.4).

3. Sheet image scanners

Another example of flexible, large-area sensors is a *sheet image scanner* (Fig. 5) that is fabricated on a plastic film and integrating organic field-effect transistors with organic photodiodes. The new sheet scanner does not require any mechanical or optical component such as focusing lenses. In the new design, a two-dimensional array of organic photodiodes coupled with organic transistors is used. Instead of a line-by-line mechanical scanning procedure, the signal of the photodiodes is read out by electrically probing the organic transistors. As a result, the device is thin, lightweight, and mechanically flexible.

Fig. 5: 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.

The effective sensing area is 5×5 cm^2 and the spatial resolution is 36 dots per inch (dpi). The total number of sensor cells is 5,184. The photodetectors can detect black and white tones by sensing the difference in reflected light from the dark and bright parts of an image.

The device structure is schematically illustrated in Fig. 6 along with chemical structure of each layer. Organic FET matrix and photodiode matrix have been manufactured separately on different plastic films in clean room and then laminated with each other with silver paste. The thin-film pentacene transistors have an 18 micrometers channel length and a 0.7 cm^2/Vs hole mobility. The base film of photodiodes is an ITO-coated PEN film with resistivity of 95 Ω/sq. A p-type semiconductor of copper phthalocyanine (CuPc) and an n-type semiconductor of 3,4,9,10-perylene-tetracarboxylic-diimide (PTCDI) are deposited in vacuum sublimation system and gold is deposited as cathode electrodes.

Both films with organic FETs and photodiodes are uniformly coated by 2 μm poly-monochloro-para-xylylene (parylene) passivation layer. Spots of parylene on electrodes are removed by a CO_2 laser for electronic interconnections. Then those films are laminated with each other with silver paste patterned by ultrafine printing technology.

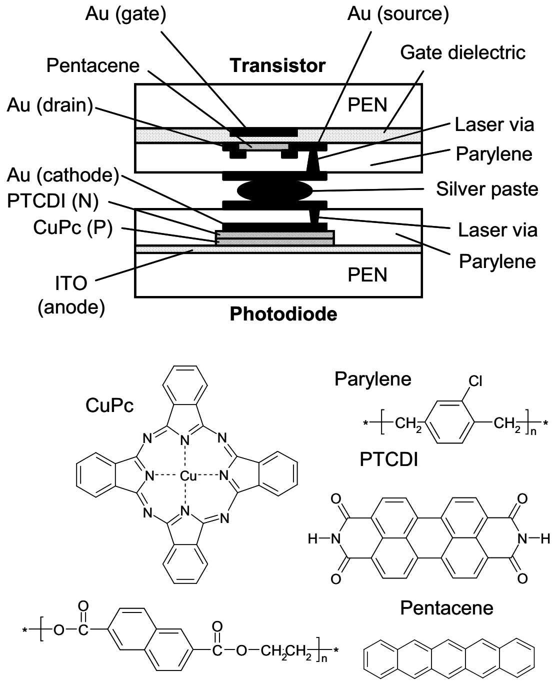

Fig. 6: The cross-sectional structure of a *sheet image scanner* is schematically shown along with chemical structure of each layer.

We have prepared the 8×8 organic photodiode matrix without organic transistors. The effective sensing area of each sensor cell is $50\times50\ \mu m^2$, while periodicity is 100 μm, which corresponds to 250 dpi. 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. 7.

The new scanner is thin, ultra-light-weight and flexible, is suitable for mobile electronics and could be easily carried in a pocket. Because it can be bended to cover entirely at once the bent page of an open book, it would be suitable for the recording of fragile, historically invaluable documents or other curved images such as labels of wine bottles.

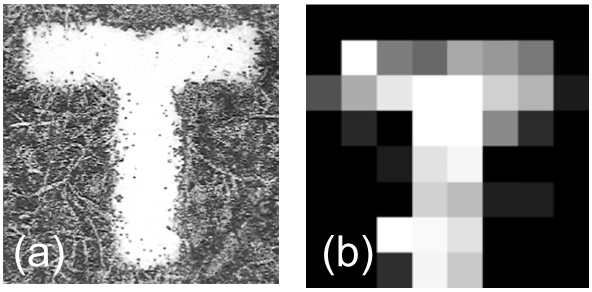

Fig. 7: Image capturing with photodiode matrix sheet in the reflection geometry. Organic photodiodes distinguish between black and white from the difference of reflectivity between black and white parts on paper. A white capital letter of T prepared by a laser printer (a) was placed onto the 250-dpi organic photodetector matrix without organic transistors. Photocurrent of each detector is measured under light (80 mW/cm^2). The mapping of normalized photocurrents is shown in (b). The size of each image is 0.8×0.8 mm^2.

4. Sheet-Type Braille Displays

Organic transistors are also suitable for applications to flexible, large-area actuators. We have fabricated a novel, flexible, lightweight *sheet-type Braille display* that is fabricated on a plastic film by integrating high-quality organic TFTs with plastic actuators (7). A small hemisphere that projects upwards from the rubber-like surface of the display is attached to the tip of each rectangular actuator (Fig. 8).

Fig. 8: An image of a pocket *Braille sheet display* that was manufactured on a plastic film by integrating the active matrix of organic TFTs with a plastic sheet actuator array. A semisphere is attached to each actuator, which bends and lifts the semisphere.

5. DC Bias Stress

We report organic TFTs that exhibit a very small degradation in performance under a continuous DC bias stress (8). When the pentacene TFTs are annealed at 140 ^{o}C for 12 h in a nitrogen environment, the change in I_{DS} is less than 1% even after the application of continuous DC voltage biases of $V_{DS} = V_{GS} = -40$ V for 9 days.

6. Acknowledgements

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5. References

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