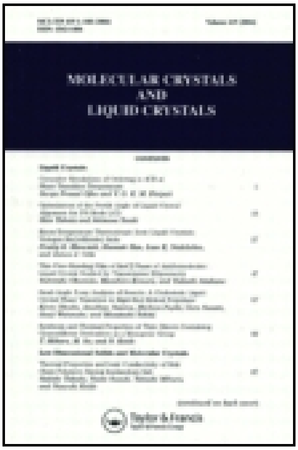

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Organic Transistor Integerated Circuits for Large-Area Sensors

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It is believed that skin sensitivity will be important for future robots working in our daily life for home-care and entertainment purposes. However, relatively little progress has been made in the field of pressure recognition compared to the areas of sight and voice recognition, mainly because good artificial "electronic skin" with a large area and mechanical flexibility is not yet available. The fabrication of a sensitive skin consisting of thousands of pressure sensors would require a flexible switching matrix that cannot be realized with present silicon-based electronics. Organic field-effect transistors can be used complimentary to such conventional electronics because organic circuits are inherently flexible and potentially ultra-low in cost even for large area. In this paper, we describe that integration of organic transistors and rubber pressure sensors provides an ideal solution to realize a practical artificial skin.

Keywords: flexible electronics; integrated circuits; large-area sensor; organic transistor; printed elctronics

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1. INTRODUCTION

Organic field-effect transistors (FETs) have many attractive attributes that are not possessed by silicon or other inorganic semiconductors. Organic transistors are mechanically flexible, lightweight, and thin. Furthermore, it is expected that organic transistor-based large-area circuits would be manufactured easily by ultralow cost processes such as printing technology and/or roll-to-roll process.

It has been recently reported by several groups that mobility for organic transistors with pentacene as channel layers exceeds $1\,cm^2/Vs$ Vs and on/off ratio goes far beyond 10^7 [1–5]. Both of those numbers are comparable to or somewhat larger than those of amorphous silicon.

Deposition of thin-film low-molecular weight organic semiconductors such as pentacene usually requires vacuum process, while there have been many efforts to manufacture plastic transistors by printing polymers [5,6]. Organic transistors fabricated by inkjet [5,6], microcontact printing [7] and other printing methods have been developed and reported.

As performance of organic transistors has been improved recently, various kinds of applications have been proposed and some of them get very close to practical use. Particularly, radio-frequency (rf) identification tags [8,9] and displays [7,10] have been driving applications of organic transistors and intensively investigated. However, mobility of organic transistors is by two or three orders of magnitude lower than that of silicon and, therefore, speed of organic transistor-based circuits is much slower than that of silicon. In order to realize circuits for high-frequency wireless tags and/or video-rate displays, further improvement of device performance, patricianly higher mobility, is crucial.

In contrast, our group has proposed large-area electronics as one of the promising applications of organic transistors [11–13]. Recently we have developed electronic artificial skins for robots with integrating organic transistor active matrix and pressure sensors. This new class of application does not require high speed such as wireless tags or displays. Furthermore, it enjoys many advantages of organic transistors, namely, large-area processability, flexibility, low-cost feature.

In this paper, we review the recent progresses of organic transistors for sensor applications, especially large-area pressure sensors or electronic skins. Then, we describe the future prospects of large-area electronics and remaining issues.

2. LARGE-AREA PRESSURE SENSORS

The manufactured large-area pressure sensors are mechanically flexible as shown in Figure 1 and therefore can be wrap around fine

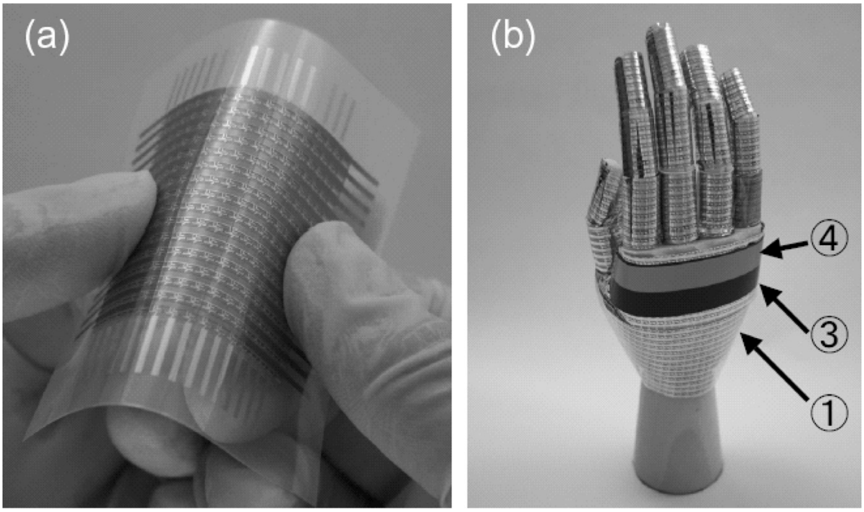

FIGURE 1 A flexible, large-area pressure sensor: (a) organic transistor active matrix is formed on a plastic film and integrated with pressure sensitive rubber, (b) an image of electronic artificial skin attached on the robot surface. A plastic film with organic transistors (1), a pressure sensitive rubber sheet (3), a plastic film with top electrodes (4) are laminated together to form a large-area pressure sensor. An intermediate layer (2) is not seen.

cylindrical bars like robot fingers. Sense of touch for robots is much behind sense of sight and hearing. This is mainly because a flexible, large-area pressure sensor matrix has not been manufactured with reasonable costs. There are flexible pressure sensors made of polymers or rubbers. With increasing the number of the sensor matrix, however, the problems associated with wiring cannot be overlooked, which makes it impossible to increase the density or the total number of sensors comparable to that of human skins.

In the present scheme, we have overcome the above problem by introducing organic transistor integrated circuits as flexible active matrix to read out pressure images, or distribution of pressure. As a result, we have successfully developed the large-area, flexible pressure sensors with the number of pressure sensors exceeding 1,000.

As shown in Figure 2, the device is manufactured with laminating four different functional films, namely, (1) a base plastic film with organic transistors, (2) a film with interconnection layer, (3) a pressure sensitive rubber sheet, and (4) a film suspending copper electrodes for power supply. One sensor cell (sensel) consists of one organic transistor and one pressure sensor. We have made 16×16 or 32×32 sensel matrix. The periodicity is 2.54 mm, which corresponds to 10 dots per inch (dpi).

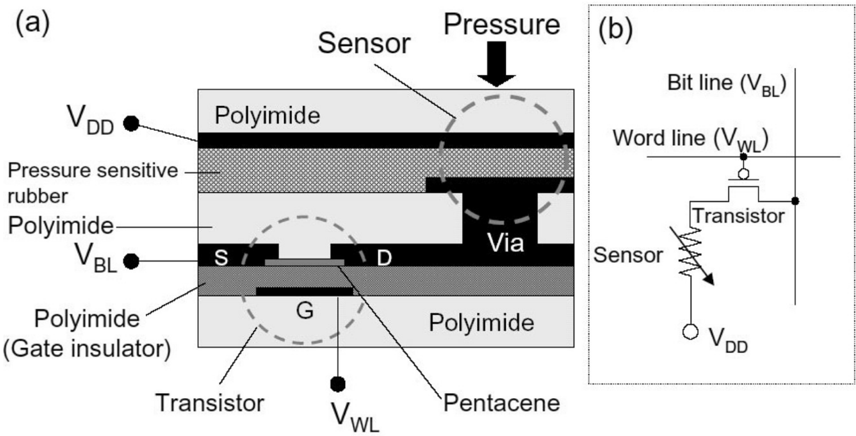

FIGURE 2 Integration of organic transistors with pressure sensitive rubber sheets: (a) A cross sectional view of the device structure, and (b) a circuit diagram of one sensor cell. The device is formed by laminating four different functional films. The pressure sensors are made with sandwiching a pressure sensitive rubber sheet between two electrodes. The one of those two electrodes is connected to the transistors through via holes. The source, drain, gate electrodes, and supply voltage are denoted as S, D, G, and V_{DD}, respectively.

Here we describe the manufacturing process flow. The base film is polyethylenenaphthalate (PEN) or polyimide with thickness of 50–125 µm. First, gate electrodes consisting of 5 nm thick chromium and 100 nm thick gold are deposited in the vacuum system. Then, polyimide precursors are spin-coated on the base film with gate electrodes and cured at 180°C. Although polyimide is usually cured at temperature above 300°C, the present material can be cured at 180°C. This curing temperature is compatible with the process with PEN films, which are low in cost and have quite low moisture absorption and water vapor permeability.

The channel layer is 50 nm thick pentacene deposited in the vacuum sublimation system at ambient substrate temperature with fine metal masks. After deposition of pentacene thin film, 30 nm thick gold layers are deposited as source and drain though fine metal masks.

The channel length L and width W of the transistors are 100 µm and 1.9 mm, respectively. The bare transistors without sensors show mobility of 0.5 cm^2/Vs and on/off ratio of 10^6.

The plastic film with interconnection layers denoted by (2) in Figure 1 can be made by the following process, which is similar to that to manufacture flexible circuit boards. Firstly, plastic films coated by copper foils are processed by numerical controlled (NC) drilling machine to make via holes. Then plating is employed to make interconnections between top and bottom sides though via holes. Finally, the copper layers are patterned by conventional photolithography and etching. Gold plating is occasionally employed to improve electronic interconnections.

The pressure sensitive rubber, denoted by (3) in Figure 1, is a 0.5 mm thick silicone sheet containing graphite particles as conductors. With application of pressure on the rubber sheet, as indicated by the arrow in Figure 2, spacing between graphite particles changes, resulting in big changes of resistance in the wide range from a few kΩ to insulator.

The copper electrodes for power supply are suspended by polyimide film denoted by (4) in Figure 1. Those copper electrodes are not patterned.

As shown in Figure 2, the pressure sensors are formed with sandwiching pressure sensitive rubber (3) between two electrodes and connected to the transistors though via holes (2). Voltage bias V_{DD} is connected to the transistor when pressure is applied to the sensors, enabling the detecting distribution of pressure.

3. ORGANIC TRANSISTOR-BASED INTEGRATED CIRCUITS

In order to read out pressure images from the sensor matrix, integrated circuits such as decoders and selectors are needed. We have also manufactured those integrated circuits with organic transistors and characterized the electronic performance of the system.

Figure 3 shows circuit diagram of electronic artificial skin system. Integrated circuits are formed by organic transistors with pentacene channel layer, which shows p-type conduction and consist of sensor matrix, column selector, and row decoder. The manufacturing process flow of sensor matrix has been described in the above and other circuits are processed by the similar flow.

The manufacturing process of selectors and decoders requires transistor–transistor interconnections with wiring gate electrodes and source/drain electrodes. To realize those interconnections, some spots of polyimide gate dielectric layers, uniformly coated on the base film, are removed by a CO_2 laser-drilling machine. The diameter of laser via holes is 90 μm. Although laser processes are widely used in the manufacture of flexible printed circuits, the present study is the first demonstration, to the best of our knowledge, to exploit this laser via technique for organic transistor integrated circuits.

Compared with conventional photolithography, laser drilling is a dry process and keep the surface of polyimide gate dielectric layer

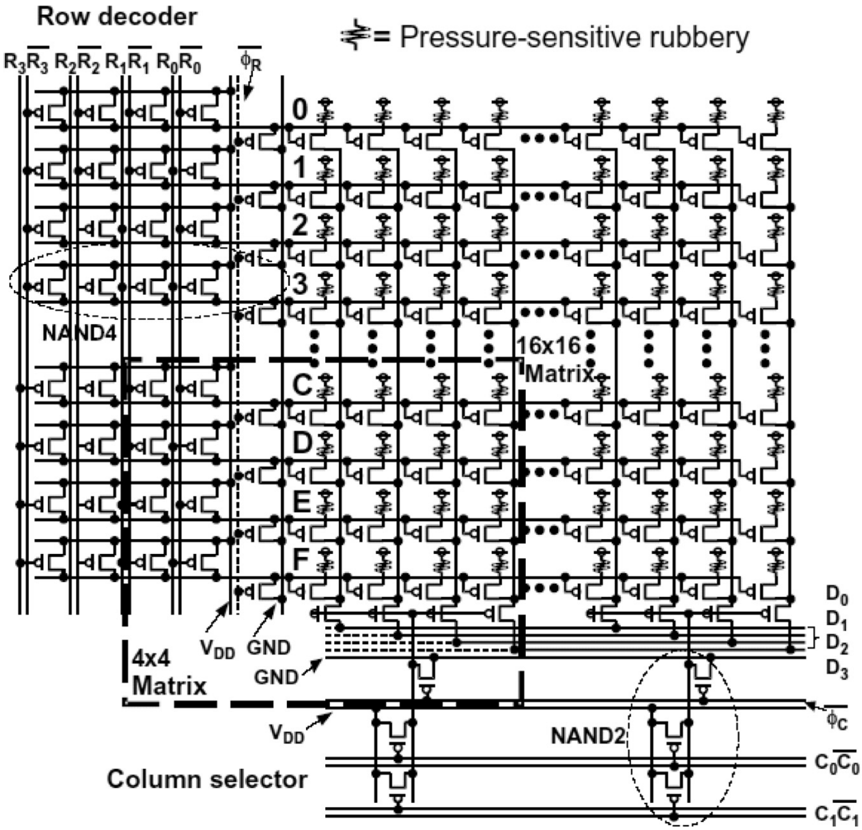

FIGURE 3 The circuit diagram of the electronic artificial skins consisting of 16×16 access transistor matrix, column selector, and row decoder. The manufactured transistor with pentacene channel layer shows p-type conduction. R0-R3 are row addresses, C0-C1 are column addresses, the bar indicates the reverse signal, ϕR-bar and ϕC-bar are activation signals of row decoder and column selector, respectively. D0-D3 are bit out. 0–4 and C-F are column addresses. GND is the ground, while V_{DD} is the power supply.

away from water, etching solution, or other solvent, which often degrade the surface of polyimide. We have confirmed that the transistor with laser via shows the identical electronic performance with that without laser via.

The sensor matrix, column selector, and row decoder are first manufactured on separate films and then assembled together with silver pastes and connecting tapes made of PEN films with gold stripes with 0.1 inch spacing. In this way, the circuits are manufactured by physically "cut and paste" procedure. The sensor matrix consisting of 16×16 sensor cells has assembling electrodes with 0.1 inch spacing to glue with connecting tapes. Figure 3 shows 16×16 sensor matrix. When the smaller sensor matrix, for example 4×4 matrix, is needed, we can make it by physically cutting the large matrix. Furthermore, if the non-rectangular shape of sensors is needed, we can also make it by cutting as far as the shape is convex. Such mask-less process scheme should make it possible to reduce the manufacturing costs drastically.

Figure 4 shows the waveforms of artificial skins. When pressure is applied to some areas of the sensor matrix, pressure rubber of those parts becomes conductive and sensor cells pull bit lines up to the supply voltage. In case of supply voltage of 40 V, the delay from activation to bit-out is 23 ms, from which the total time needed scan the whole 16×16 takes about 1 s. The delay for read out depends on supply

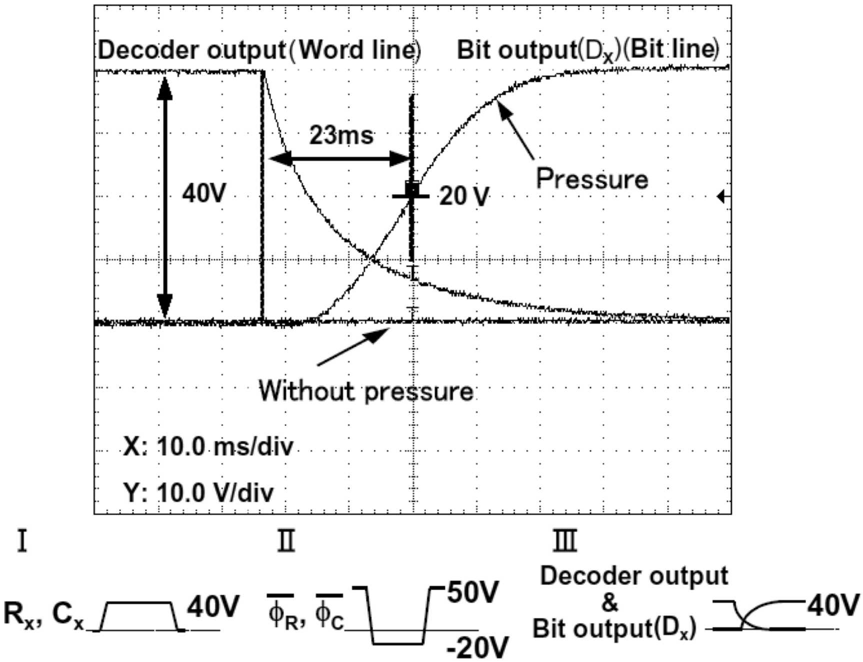

FIGURE 4 A measured waveform of electronic artificial skin. When pressure is applied to the sensor matrix, the pressure-sensitive rubber becomes conductive and bit line is pulled up to the supply voltage: (I) the input signals of column and row addresses, (II) the activation signal of the row decoder and column selector, (III) the measured waveform. The decoder output (word line) and bit output (bit line).

voltage: If the voltage is 100 V, the delay is estimated to be the half. It is also shown by the simulation that the scan speed can be enhanced by one order of magnitude easily if the parasitic capacitance is suppressed with reducing the channel length and/or width of wiring of decoders and selectors.

If we consider the reasonable form of the practical artificial skin system, it is most likely that the pressure data read out from organic integrated circuits would be transferred to silicon chips. In this sense, some readers may want to claim that it is not necessary to build decoder or selector with organic transistors. The denser and the larger-area integrated circuits, however, require the more complicated packaging and fine wiring, which cannot be easily achieved by silicon with reasonable costs. Thus our opinion is that it is very important to realize functionality of memories and processors as well as selectors and decoders with organic transistors.

4. FUTURE PROSPECTS OF LARGE-AREA ELECTRONICS

It is undoubted that one of the most important directions for future electronics is ambient intelligence or wireless sensor network. We believe that large-area features of organic transistors would be suitable to realize large-area sensors that detect physical or chemical information distributed for large area.

We are confident that large-area pressure sensors should find many applications beyond robotics, for example, security, homecare, entertainment, sports and more. When pressure sensitive carpet spread on a floor in a house, it should work a good security system that distinguishes family members from a stranger just from the analysis of footprints. Furthermore, a tactile bed should diagnose physical conditions instantly. A new class of applications requiring large-area detections is increasing its importance in the ubiquitous electronics in the next generations, while silicon devices get smaller and smaller.

It is not trivial for organic transistors to compete with silicon from the point of the cost per functions. However, organic transistors are really strong if the applications require low-cost features for large area. Therefore, organic transistors should fit well with large-area electronics.

Furthermore, organic transistors are expected to play an important role in the new area of information technology. Indeed, when we obtained many two-dimensional pressure data obtained from large-area pressure sensors, the analysis of those data should make it possible to recognize whether the material is textured or smooth. Thus we expect that large-area electronics based on organic transistors would open up a new field of information technology.

5. REMAINING ISSUES

We describe remaining issues of organic transistors from the viewpoint of large area electronics. First, stability and reliability are the central concerns for organic transistors. The devices measured in the present study are not encapsulated and the pentacene channel layer is exposed to the ambient air. The transistors are functional after the operation over a couple of days, but the degradation of transistor characteristic, namely reduction of saturation current and/or threshold voltage shift, is observed. The degradation may be induced by oxygen and/or moisture like electroluminescent (EL) devices and therefore can be suppressed drastically by appropriate encapsulation.

Some applications requiring mechanical flexibility such as electronic skins also need flexible substrates with low gas permeability, although plastic films have usually high gas penetration. Thus it is one of the urgent problems to develop flexible base films with low gas permeability.

The second issue is reduction of operation voltage. The present device requires 40 V as power supply, but it is favorable for electronic skin application to have much lower voltage. Lowering operation voltage can be achieved by reducing device dimensions. Although the channel length of the present transistors is 100 μm, the transistor with top contact geometry with channel length of 20 μm has been reported by 3 M. The thinning gate dielectric layers and/or those with the higher gate dielectric constant are very effective to lower the operation voltage. The thickness of polyimide gate dielectric layer is presently 900 nm, which should be decreased less than a few hundreds nm.

6. CONCLUSIONS

We have introduced, in this paper, large-area sensors as one of the promising applications of organic transistors. In particular, we have demonstrated large-area pressure sensors with integrating organic transistors matrix with pressure-sensitive rubber sheet. The new sensors will be useful for variety of applications such as regeneration medicine, new security system, and intelligent transportation system (ITS) beyond robot skins.

Furthermore, organic transistors are indispensable to realize ambient electronics. We expect the multiplier effect to use organic transistors as a complementary function to silicon.

The present study makes fully use of technical knowledge in the field of flexible printed circuits (FPC). Laser via process, plating, and lamination approaches, whose reliability and throughputs have been appreciated in mass-production lines of FPC, are used as a manufacturing process of organic transistor integrated circuits. Organic transistors should be manufactured by such low-cost and reliable process.

We hope that remaining issues related to stability, operation voltage, speed, power consumption will be solved in the future and organic transistors will be pushed to the practical use.

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