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Printed skin-like large-area flexible sensors and actuators

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Abstract

In ambient electronics in the next generation, multiple electronic objects are scattered on walls, ceilings or in imaginative locations and interact each other to enhance safety, security and convenience. For implementation of many electronic objects in our daily life, large-area sheet-type flexible devices are expected to play an important role. In this paper, we review recent progress and future prospects of printed skin-like large-area flexible sensors and actuators. Moreover, the issues and the future prospect of flexible devices such as printed plastic MEMS devices and organic transistors will be addressed from the view point of ambient electronics.

Keywords: flexible electronics; printed electronics; organic electronics

1. Introduction

Organic thin film transistors (TFTs) and their integrated circuits (1-4) have attracted considerable attention because 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; therefore, they are mechanically flexible and potentially inexpensive to manufacture. Recent studies organic transistors are based on two major applications. The first application includes flexible displays, such as paper-like displays 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 RFIDs on packages.

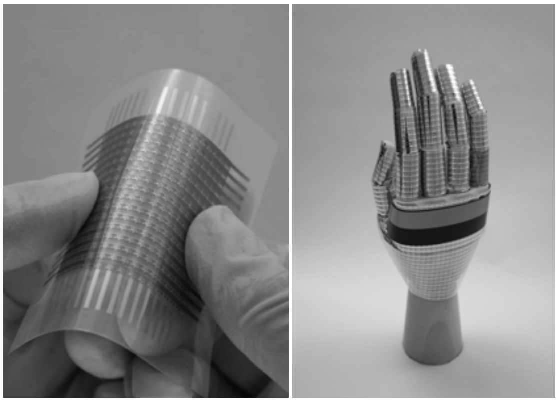

Fig. 1: A picture of an electronic artificial skin (E-skin), a large-area, flexible pressure sensor.

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As the third application, we propose and demonstrate flexible, large-area pressure sensors and actuators in which the active matrices of organic transistors and other 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-based flexible, large-area sensors and actuators.

2. E-skins

The first application of large-area sensors is a flexible pressure sensor, which is suitable for electronic artificial skin (Fig. 1), which will be used in next-generation robots. Although the mobility of organic semiconductors 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.

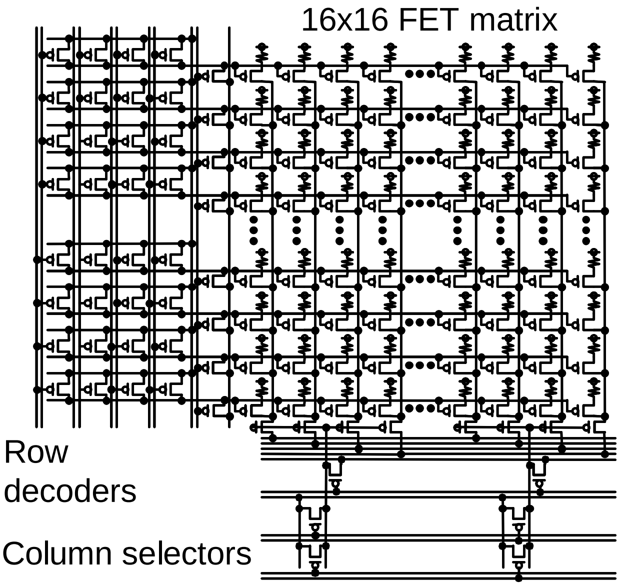

Fig. 2: A circuit diagram of an artificial skin system. A 16 × 16 organic transistor active matrix, a row decoder and a column selector are manufactured on plastic films separately and them assembled to make integrated circuits for data readout.

Figure 2 shows a circuit diagram of an artificial skin system. A 16 × 16 active matrix of organic transistors, row decoder, and 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 (6,7).

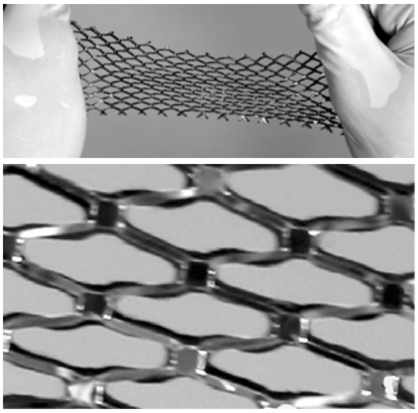

Fig.3: A plastic film with organic transistors and pressure sensitive rubber is processed mechanically to form a unique net-shaped structure, which makes a film device extendable by 25%.

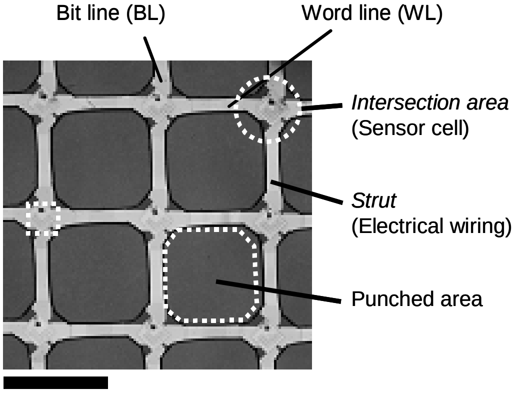

Fig. 4: A picture of the 3×3 sensor cells. Scale is 4 mm.

3. Net-shaped E-skins

Human skins perform 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. 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% (Fig. 3). The net-shaped pressure sensor matrix (Fig. 4) was attached to the surface of an egg and pressure images were successfully obtained in this configuration (7).

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.5).

4. Rubber-like stretchable ICs

We have developed elastic conductors using single-walled carbon nanotubes (SWNTs) as a conducting dopant. SWNTs (8) were uniformly dispersed as chemically stable dopants in a vinylidene fluoride-hexafluoropropylene copolymer matrix by using an ionic liquid of 1-butyl-3-methylimidazolium bis(trifluoromethanesulfonyl)imide (9), and manufactured SWNT composite films. The measured value of conductivity is as high as 57 S/cm. Such high conductivity is achieved because the content of SWNTs in the conductor can be increased up to 20 wt% without sacrificing mechanical flexibility and softness. The SWNT elastic conductor can be stretched to approximately 134% of its original size without significant mechanical damage.

We have also successfully fabricated rubber-like stretchable integrated circuits (ICs). The abovementioned elastic conductors are integrated with organic transistors, which are fabricated by state-of-the-art printing processes, and are then used as wirings in large-area stretchable ICs. These ICs, which have a high electronic performance, can be stretched by up to 80% without any degradation in their mechanical or electronic properties (Fig. 6). This is an important step in the development of ICs that can be used on freely curved surfaces and in smart surfaces. Subsequently, it will be possible to develop an intelligent surface that will be able to interact with people, objects, and the environment in new ways (10).

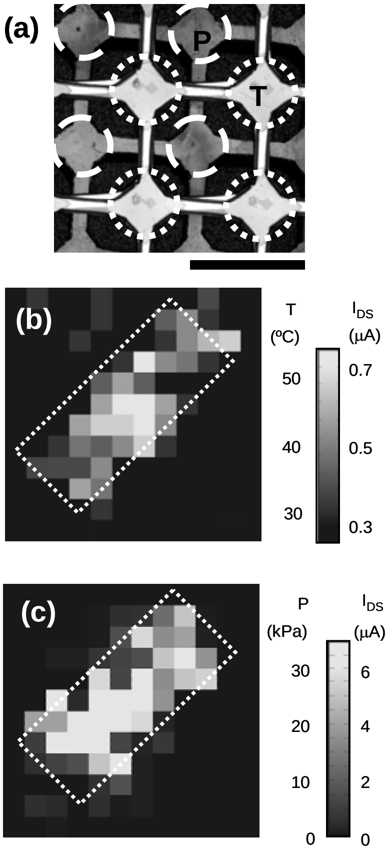

Fig.5: (a) A possible implementation of thermal and pressure sensor films. The pressure and thermal sensors are represented by P and T, respectively. Scale is 4 mm. (b) The spatial distribution of temperature that is converted from the temperature-dependent current in the thermal sensor network. A copper block whose temperature is maintained at 50 °C is positioned diagonally which is indicated by the dotted line. (c) Simultaneously, the spatial distribution of pressure is measured with the pressure sensor network.

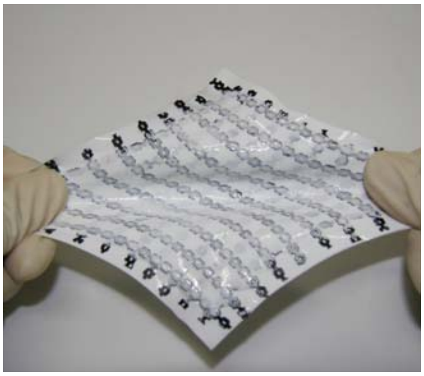

Fig.6: The stretchable active matrix did not exhibit any significant change in electronic performance even when it was stretched up to 80%

5. Power sheet

We demonstrated the first implementation of a large-area wireless power transmission system (12). The system realizes a low-cost sheet-type wireless power source of about 40 W. This is the first step toward building infrastructure for ubiquitous electronics where multiple electronic objects are scattered over desks, floors, walls, and ceilings and need to be powered. These objects may be mobile or located in the dark and therefore solar cells cannot be used to power them. On the other hand, the periodic replacement of the primary batteries could be tedious since there may be too many objects. The proposed wireless power transmission sheet may directly drive electronic objects and/or charge a rechargeable battery in the objects without a connector, thereby providing an easy-to-use and reliable power source.

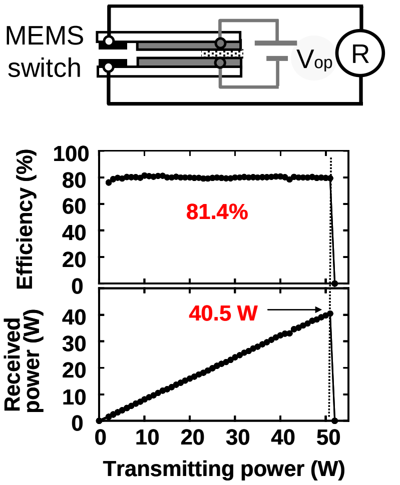

Fig. 7: The schematic structure of MEMS switch. Transmission efficiency and received power at receiver coils as a function of sending power.

The sheet-type large-area wireless power transmission system (Fig. 7) has been manufactured using organic transistors and MEMS switches. Although some existing systems have already used wireless power transmission, it has been difficult to transmit high-power to anywhere one likes over wire area. For example, weak power can be fed to IC cards relatively large area, while a fairly large power can be fed to electric tooth brushes at the exact mount position. The present method makes it possible to transmit high power to anywhere over large-area by “spatial subdivision”. In this way, the system selectively feeds power as high as 30 W to electronic objects placed upon it.

The position of an object is sensed by electromagnetic coupling, using an organic active transistor matrix. Power is fed to it inductively, by an array of copper coils driven by a printed plastic MEMS-switching matrix. Because the power transmission only occurs selectively when an object is sensed, net power-coupling efficiency is 81.4%. Power levels as high as 40.5 W have been transferred in this fashion. The 1-mm-thick flexible sheet weighs 50 g. It contains an 8 × 8 cell array comprising both position-sensing and power transmission units. The periodicity is 1 inch.

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