Integration of Organic Field-Effect Transistors and Rubbery Pressure Sensors for Artificial Skin Applications

Takao Someya
Quantum Phase Electronics Center, School of Engineering, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
Phone: +81-3-5841-6820, Fax: +81-3-5841-6834, Email: someya@ap.t.u-tokyo.ac.jp

Takayasu Sakurai
Center of Collaborative Research, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo, Japan
Phone: +81-3-5452-6251, Fax: +81-3-5452-6252, Email: tsakurai@iis.u-tokyo.ac.jp

Abstract

A large-area pressure sensor matrix has been fabricated on a plastic sheet for the first time, integrating high-quality organic field-effect transistors and rubbery pressure sensors. This pressure sensor demonstrates the feasibility of applying the organic transistor technology to flexible area-sensors, which opens up new applications of organic FET's including artificial skins.

Introduction

Sensing of a touch is important for robots of the next generation, but little progress has been made in the area of pressure recognition compared with recognition of sight and voice. This is mainly because a machine has not yet obtained a good artificial skin, which must be large in area and flexible mechanically to fit for any shape. Integration of organic transistors and rubbery pressure sensors, both of which can be produced by low-cost processing technology like large-area printing technology [1-4], will provide an ideal solution to realize a practical artificial skin, whose feasibility has been demonstrated in this paper.

Integration of organic transistor and sensor

As shown in Fig. 1, the integrated device formed on a plastic film is mechanically flexible and can be applied to a robot surface. The device structure is illustrated in Fig. 4.

First, glass resin (GR150, Techneglas) was spin-coated on a 50-μm thick polyimide film (Capton, Toray-Dupont) with an 8-μm thick copper film, which works as a gate electrode, and cured at 120 °C for 2hr. Then, the film of pentacene (Alrdich) is deposited on these films at ambient substrate temperature by vacuum sublimation at the pressure of 7×10^{-5} Pa. The nominal thickness of the pentacene layer is 30 nm. The chemical structures of pentacene and glass resin are shown in Fig. 4.

After deposition of pentacene channel layers, gold is deposited in a vacuum evaporation system through metal masks to form source and drain electrodes, which complete organic transistor structures of top contact geometry. Metal masks are made of stainless steel with conventional photolithography and etching. The resolution of patterns in metal masks are typically 50 or 100 μm.

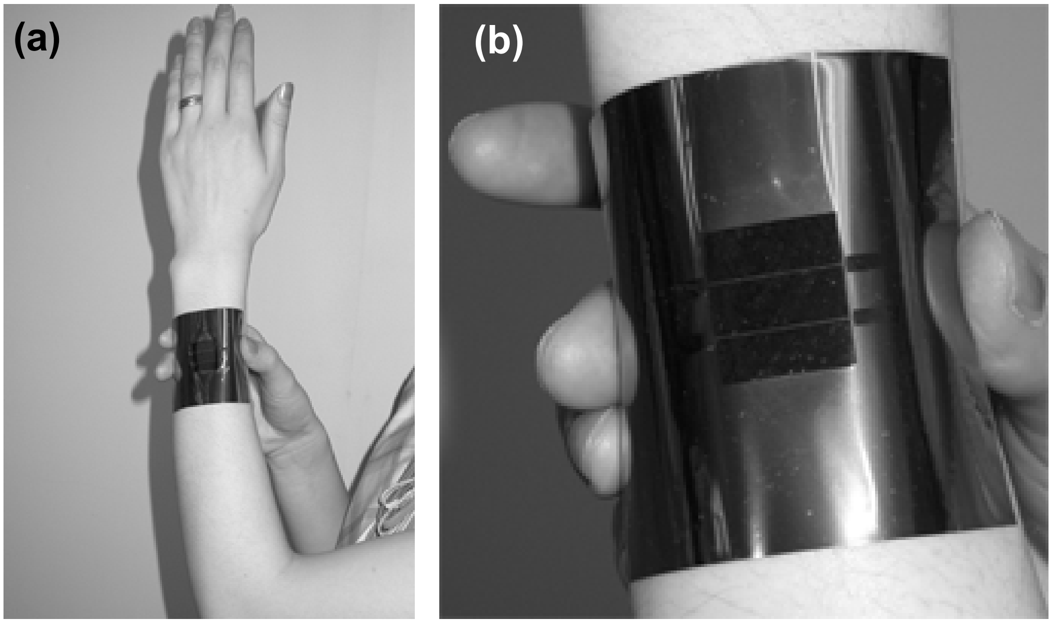

Figure 1: A large-area pressure sensor matrix has been successfully realized on a plastic sheet for the first time by integrating organic transistors and a conductive rubber. This flexible area sensor can be printed over large area and, thus, is potentially very low in production cost. This is a new class of applications for organic transistors, which provides an ideal solution of artificial skins.

0-7803-7873-3/03/$17.00 (c) 2003 IEEE

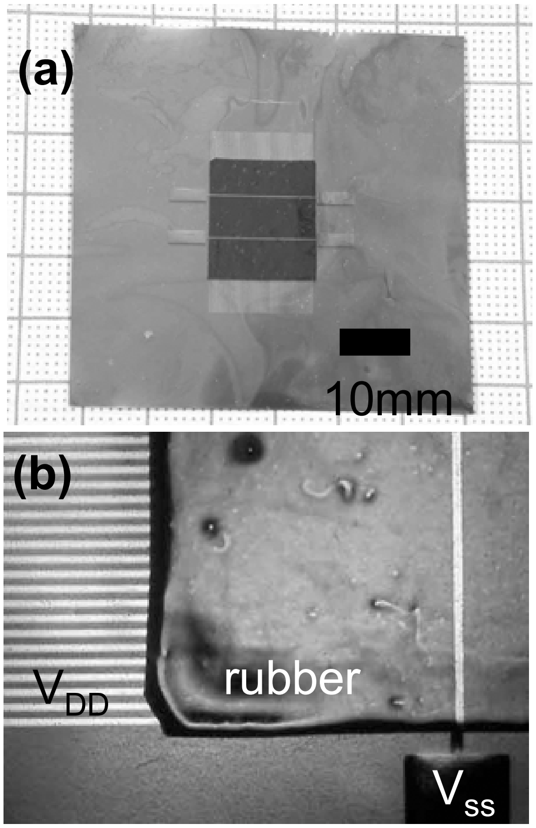

Figure 2: (a) A picture of the whole artificial and (b) a microphotograph of the part of the electrodes (V_{SS} and V_{DD}) and the pressure sensitive rubber.

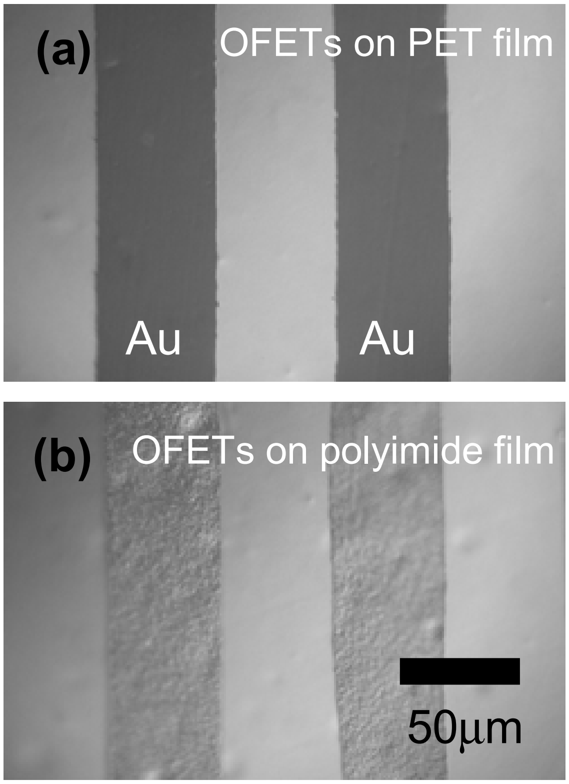

Figure 3: Microphotograph of organic transistors formed on (a) a PET/ITO film and (b) a polyimide/copper film. The insulator is of glass resin spun onto a plastic sheet and electrodes are made of gold.

Other substrates considered in the experiments are an indium-tin-oxide (ITO)-coated poly(ethylene terephthalate) (PET) film and heavily-doped silicon capped with 300-nm thick SiO_2 layer. In these substrates, ITO or SiO_2 layer works as gate electrodes.

The thickness of a PET film and that of a polyimide film is 75 µm and 50 µm, respectively. The thickness of an ITO layer and a copper layer is 200 nm and 8 µm, respectively.

The measured mobility of the manufactured p-type organic transistor is typically as high as 0.2 cm^2/Vs and the on/off ratio exceeds 10^5.

Figure 3 (a) and (b) show optical microscopic images of organic transistors formed on a PET/ITO film and a polyimide/copper film, respectively. The surface of a polyimide/copper film is rough. Since polyimide/copper films are originally made for application to flexible circuit boards, the rough surface is prepared intentionally by the supplier so that the adhesion between layers may be enhanced.

For this reason, electronic performance of the device on a PET film is better than that on a polyimide film. As shown in Fig. 5 (a), we monitored I_{DS} as a function of V_{DS}. A gate voltage V_{GS} is changed from 0 to –40V with a step of –10V.

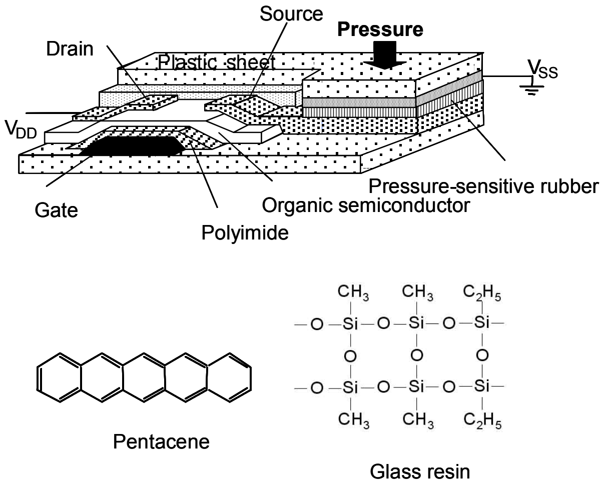

Figure 4: Schematic illustration of the device structure. An organic semiconductor is pentacene, a gate dielectric is glass resin, and S/D are gold. The chemical structures of pentacene and glass resin are also shown.

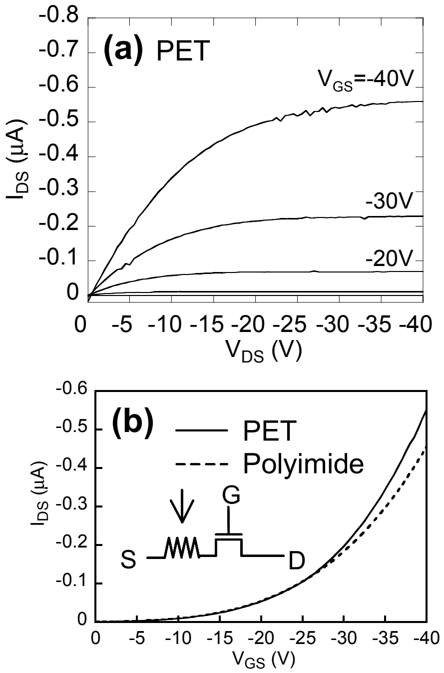

Figure 5: (a) I-V characteristics of integrated devices when pressure is applied. (b) The devices on PET and polyimide films are shown in solid and dash lines, respectively.

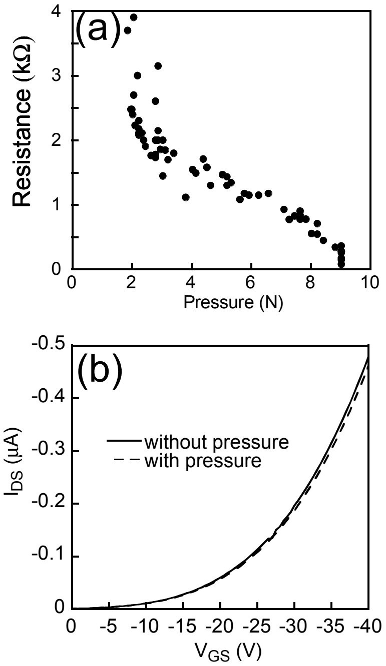

Figure 6: (a) Characteristics of pressure sensors before integration. The resistance was measured for a rubber whose effective area is 100μm x 100μm. (b) FET characteristics of only organic transistor parts before integration. The performance was not affected by pressure up to 10N.

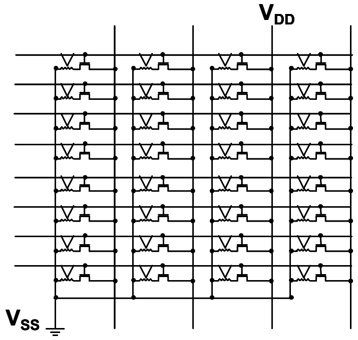

Figure 7: Circuit diagram of the sensor array. Resistance with arrow indicates a pressure sensor.

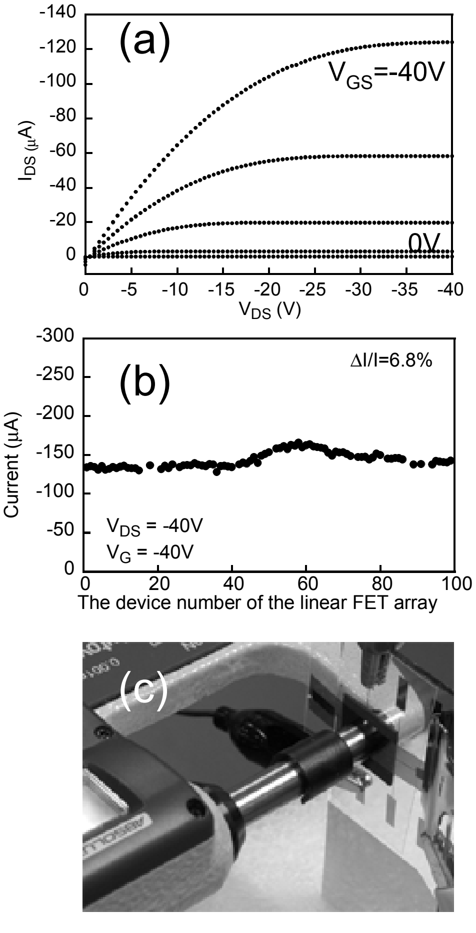

Figure 8: (a) I-V characteristic of pentacene FET's used in a pressure sensor linear array on silicon substrate. (b) Saturated currents of hundred transistors are plotted as a function of the device number. (c) The experimental setup for applying pressure.

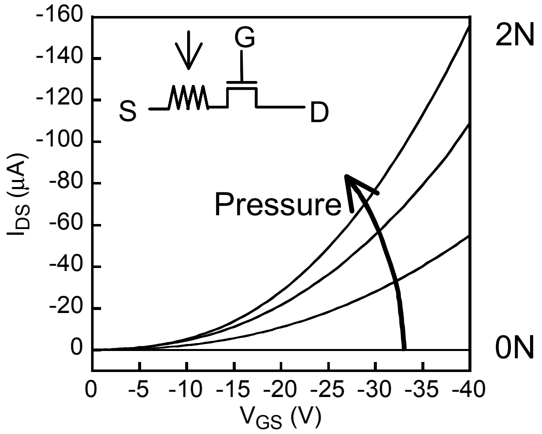

Figure 9: I-V characteristics of one cell of integrated devices with application of difference pressure.

For all electronic measurements, we used a semiconductor parameter analyzer (Agilent, 4156C) connected to a microprobe station (Micronics Japan, Co. Ltd., 706f).

Fig 5 (b) shows V_{GS} dependence of I_{DS} for I_{DS}= -40V. The solid line is of the device on a PET film, while the dash line is of the device on a polyimide film.

Then, pressure sensors are made out of pressure-sensitive conductive rubbery sheets sandwiched between two 100-μm width metal lines that cross at right angle. One of the metal lines is connected to an organic transistor, while the other line, suspended by a plastic firm, is connected to the ground. The pressure-sensitive sheet is 0.5-mm thick silicone rubber containing graphite.

Figure 6 (a) shows the resistance dependence on the pressure applied on the rubbery sensor before the integration. The current flows at the intersections of the two metal lines whose effective area is 100 μm square. In contrast, the performance of the organic transistor did not change by the pressure as shown in Fig. 6 (b).

Sensor array

The schematic diagram of the core part of the area sensor is shown in Fig. 7. Figure 8 (a) shows I-V characteristics of an organic transistor fabricated on silicon substrate, which is used for the measurement below. In order to fabricate a sensor array, it is important to minimize the performance variation of transistors over locations. Figure 8 (b) shows the measured drain current distribution of hundred transistors. Yield of the hundred transistors is 100% and the current variation is less than 6.8 % over 35 mm.

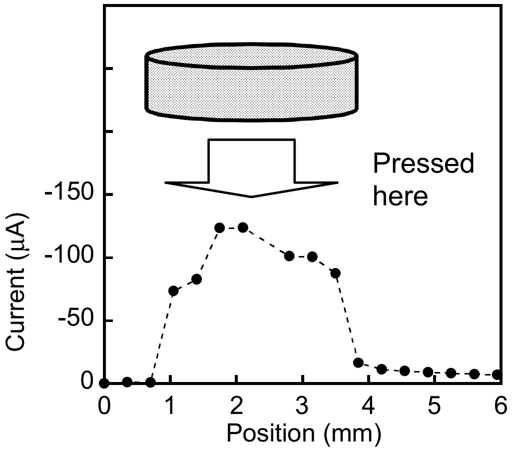

Figure 10: When a small cylinder was pressed on the sensor array, current increased at those positions where the pressure was applied, demonstrating the feasibility of the pressure area-sensor.

Figure 9 shows a measured change in the drain current dependence as a function of applied pressure to the sensor. The current increases with increasing pressure, but saturates when the pressure exceeds 2N. Then, we go on to press the fabricated sensor array with a tip of a cylindrical bar whose diameter is about 3 mm. Figure 10 shows that position dependence of the drain current with V_{DS}=–40V and V_{GS}= –40V. Note that the current increases at the position where the pressure is applied, demonstrating the feasibility of the artificial skin based on the low-cost organic transistor technology. The pitch of the fabricated pressure sensor is 0.35 mm, which is sufficient for most of the artificial skin applications, but if higher density is required, the density can be increased by a factor of ten.

Acknowledgements

The authors would like to thank H. Kawaguchi and T. Kobayashi for useful discussion, and S. Iba, Y. Kato, H. Shinaoka, and R. Teramoto for their assistance of measurements.

References

(1) J. A. Rogers, et al., *PNAS USA* 98, 4835 (2001).
(2) W. Fix, A. Ullmann, J. Ficker, and W. Clemens, *Appl. Phys. Lett.* 81, 1735- (2002).
(3) G. H. Gelinck, T. C. T. Geuns, and D. M. de Leeuw, *Appl. Phys. Lett.* 77, 1487 (2000).
(4) H. Sirringhaus et al., *Science* 290, 2123 (2000).