A Flexible, Lightweight *Braille Sheet Display* with Plastic Actuators Driven by An Organic Field-Effect Transistor Active Matrix

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Abstract

A flexible, shock-resistant, and lightweight *Braille sheet display* has been successfully manufactured on a plastic film by integrating a plastic sheet actuator array with a high-quality organic transistor active matrix. This is the first demonstration, to the best of our knowledge, to integrate *plastic MEMS (microelectromechanical systems) actuators* with organic transistor active matrices, which opens up new versatile possibilities for flexible, large-area electronic applications including tactile displays.

Introduction

An organic field-effect transistor (FET) [1-6] belongs to a new class of electronics that can be fabricated directly on plastic films at ambient temperatures; therefore it is mechanically flexible, lightweight, very thin, shock-resistant, and easy to transport. However, such functions cannot be achieved easily by the present silicon-based electronic materials.

In this paper, we present a detailed report on a flexible, shock-resistant, and lightweight *Braille sheet display* that is

Fig. 1: Images of a *Braille sheet display*. An image of the world's first pocket *Braille sheet display*. It was successfully manufactured on a plastic film by integrating the active matrix of high-quality organic transistors with a plastic sheet actuator array based on a perfluorinated polymer electrolyte membrane. The device is mechanically flexible, very thin, and lightweight.

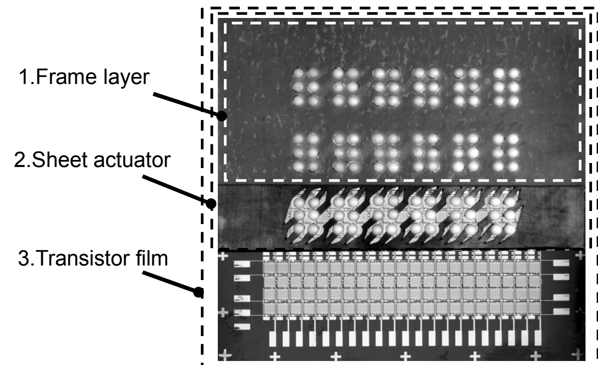

Fig. 2: Images of a *Braille sheet display*. A picture of the device assembly. Some components are intentionally removed to show the inner structures. A transistor film, sheet actuator, and frame covered by a rubber-like surface are laminated together.

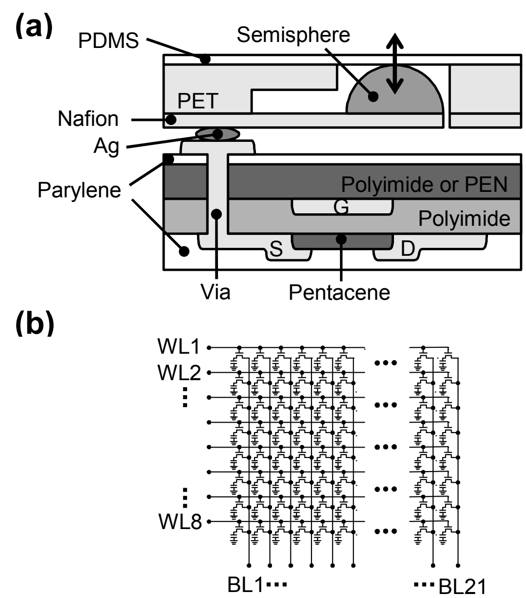

Fig. 3: The design. (a) A schematic cross-sectional view of the device structure is shown. An organic transistor active matrix is laminated with an array of actuators using a silver paste patterned by a microdispenser. (b) Circuit diagram of the core part of the *Braille sheet display*. Each cell consists of a transistor and a rectangular actuator. The vertical and the horizontal lines represent bit and word lines, respectively.

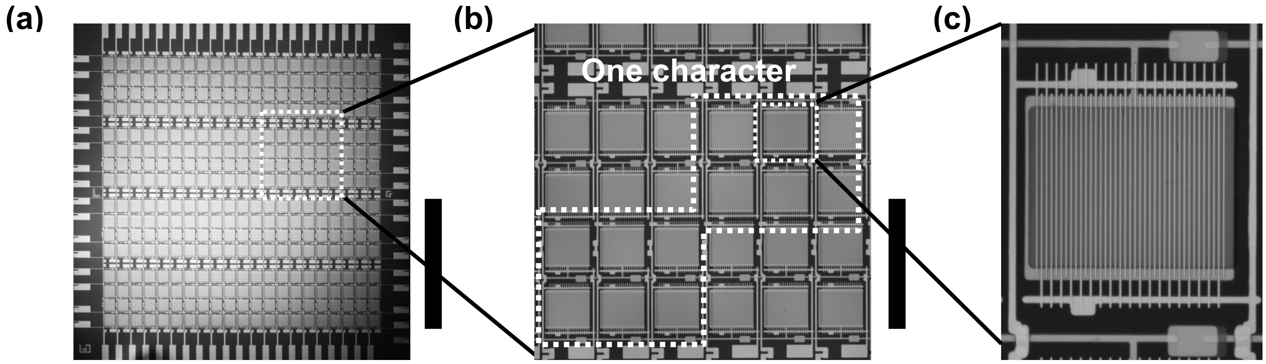

Fig. 4: The organic transistor active matrix in the chip. (a) A complete view of the organic transistor active matrix sheet, which switches 12 × 12 Braille dots. The scale is 2 cm. (b) Magnified image of an active matrix. The dotted line indicates an area of transistors that are required for switching a Braille character consisting of 3 × 2 dots. The scale is 5 mm. (c) A further magnified image of an organic transistor. The channel length and width are 20 μm and 49 mm, respectively. The scale is 1 mm.

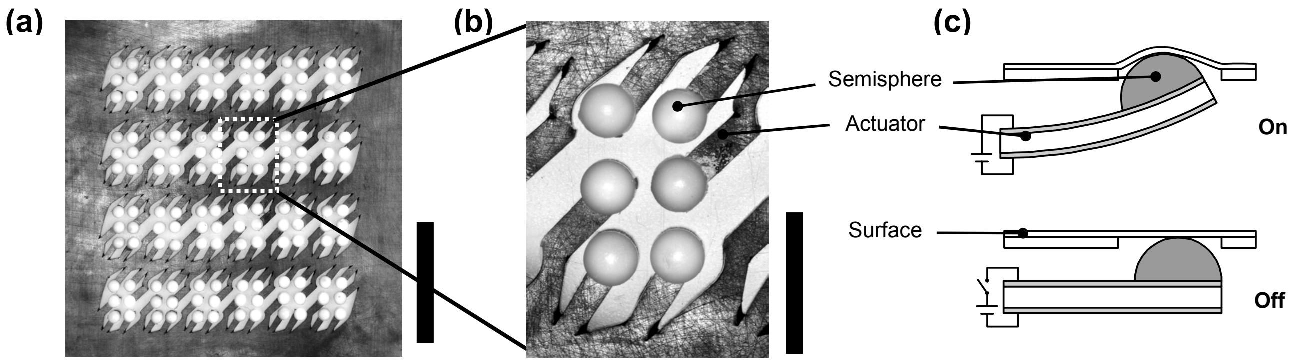

Fig. 5: Plastic actuator array. (a) Picture of a 12 × 12 array of rectangular actuators composed of a perfluorinated polymer electrolyte membrane (Nafion), which is processed by a cutting machine. The scale is 2 cm. (b) One character is displayed by a 3 × 2 array of rectangular actuators (4 mm in length and 1 mm in width), which are designed to be placed alternately. A semisphere of radius 0.9 mm is attached to each actuator, which bends and lifts the semisphere. The scale is 4 mm. (c) Principle of Braille motion.

fabricated on a plastic film for the first time, by integrating high-quality organic FETs with plastic MEMS actuators. An array of rectangular plastic actuators is processed from a perfluorinated polymer electrolyte membrane. A small semisphere that projects upwards from the rubber-like surface of the display is attached to the tip of each rectangular actuator. The effective display size is 4×4 cm^2. Each character consists of 3 × 2 Braille dots, and the total number of dots is 144; thus, 24 characters or 6 characters × 4 lines can be displayed. Pentacene FETs with top contact geometry have a channel length of 20 μm and a mobility of 1 cm^2/Vs. The Braille dots on one line are driven for 0.9 s. The total thickness and weight of the entire device are 1 mm and 5.3 g, respectively. The present scheme will enable people with visual impairments to carry the *Braille sheet display* in their pockets, and read Braille e-books at any time.

Device manufacturing process

As shown in Fig. 1 and Fig. 2, the integrated device formed on a plastic film is mechanically flexible, very thin, and lightweight. The device structure is schematically illustrated in Fig. 3(a). A plastic film with an organic FET active matrix is manufactured in a clean room and then laminated with an array of rectangular plastic actuators. The circuit diagram of the core part of the chip is shown in Fig. 3 (b).

A. Organic FET active matrixes

A matrix of pentacene FETs with top contact geometry is manufactured with an ultrafine shadow mask that has a spatial resolution of 20 μm, as shown in Fig. 4. The base film (substrate) is a poly(ethylene naphthalate) (PEN) film or a polyimide film. Its surface is coated with a 50-nm-thick gold layer and a 5-nm-thick chromium adhesion layer in a vacuum evaporator along with the shadow masks. Next, the polyimide precursors are spin-coated and cured at 180 °C to form 240-nm-thick gate dielectric layers. A 50-nm-thick pentacene layer is deposited to form a channel layer, and a 50-nm-thick gold layer is evaporated through the shadow asks to form the source and drain electrodes of the transistors. The channel length L and width W are 20 μm and 49 mm, respectively. The fabricated film is subsequently transferred to a vacuum chamber without exposure to air, and it is uniformly coated with an 8-μm-thick poly-chloro-para-xylylene (parylene) passivation layer. Via interconnections are made using a CO_2 laser.

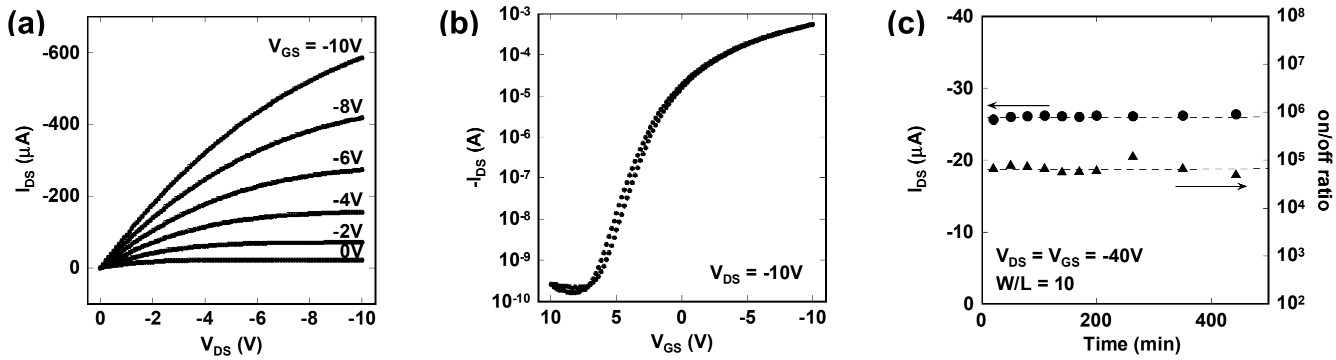

Fig. 6: Organic FETs. (a) A plot of I_{DS} vs V_{DS} of the organic transistors measured by varying the gate bias V_{GS} from 0 V to –10 V with a step of –2 V. (b) The transfer curve measured at V_{DS} = –10 V. The mobility is evaluated to be 1 cm^2/Vs. The on/off ratio exceeds 10^6 if the off current is defined as the minimum current at positive voltage bias. (c) I_{DS} in the saturation regime of the organic transistors and on/off ratio with a parylene passivation layer directly immersed in deionized water. The device exhibits no significant degradation over 400 min.

B. Plastic actuator array:

A 300-μm-thick perfluorinated polymer electrolyte membrane (Nafion, NE-1110, Dupont), which is chemically plated with gold, is used as a sheet-type soft actuator. In order to enhance displacement, high-frequency response, and actuator force, the electrolyte membrane was immersed in a LiCl solution to replace the H^+ cations in the membrane to Li^+. As shown in Fig. 5 (a) and (b), the electrolyte membrane is processed using a numerical controlled (NC) cutting machine to achieve a 12 × 12 array of rectangular actuators, whose length is 4 mm and width is 1 mm. A semisphere of radius 0.9 mm is attached to each rectangular actuator, which bends and lifts a semisphere up by approximately 0.3 mm with the application of voltage stimuli. The principle of Braille motion is shown in Fig. 5 (c).

C. Integration of FETs and actuators

The transistor film is laminated with a plastic actuator array using a silver paste patterned by a microdispenser. These laminated electronic components were finally packed inside a plastic frame. The surface is covered by a 10-μm-thick polydimethylsilane (PDMS) layer coated with a lubricating fluoride to reduce friction between human fingers and the rubber surface.

Device characteristics

We characterized organic transistors, stand-alone rectangular plastic actuators, and integrated devices using a semiconductor parameter analyzer.

A. Organic FETs

Figure 6 (a) and (b) show typical characteristics of the manufactured p-type organic transistor. The measured mobility is as high as 1 cm^2/Vs. The on/off ratio exceeds 10^6 if the off current is defined as the minimum current for a positive voltage bias. Figure 6 (c) shows the electric stability of the organic transistors with a parylene passivation layer directly immersed in deionized water. From the figure, it can be concluded that it is feasible to integrate the present organic FETs with a soft actuator operating in a wet environment. Indeed, this will be proven experimentally later.

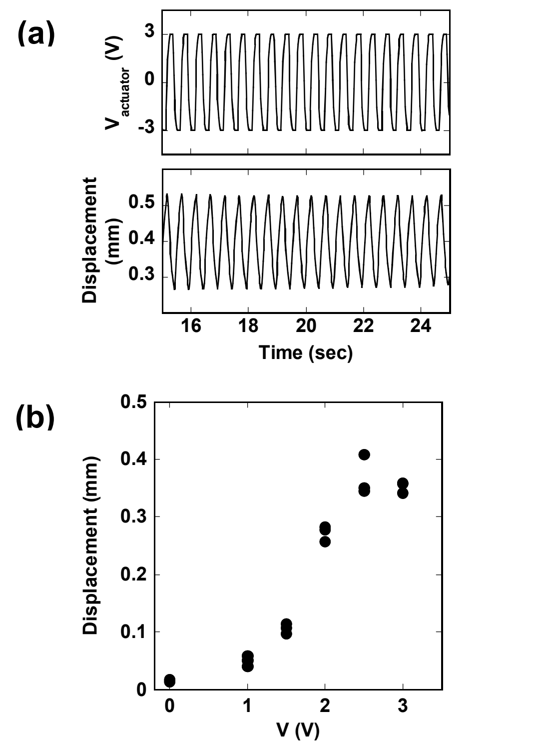

Fig. 7: Stand-alone plastic sheet actuators. (a) We characterized a stand-alone rectangular actuator of dimensions 4 × 1 mm^2. When a series of rectangular waves of amplitude 3V is input, the frequency response of the actuators extends up to 2 Hz. The voltage between two electrodes of an actuator is shown. (b) The displacement is plotted as a function of the input voltage.

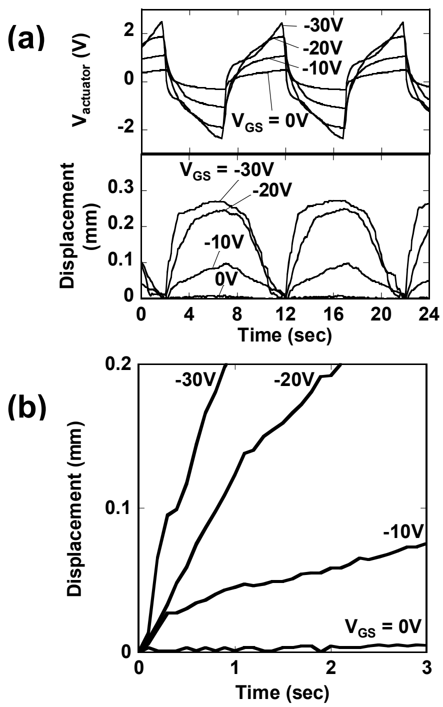

Fig. 8: Braille cells. (a) The displacement of a Braille cell consisting of a transistor and an actuator is measured as a function of time by inputting the rectangular waves. The voltage between two electrodes of an actuator is also measured. (b) Initial rise retraced from (a). The rise time required to displace a surface dot from 0 to 0.2 mm becomes 0.9 s at –30 V.

B. Stand-alone plastic sheet actuators

We characterized a stand-alone rectangular actuator of dimensions 4 × 1 mm^2. When a series of rectangular waves of amplitude 3 V is input, the frequency response of the actuators extends up to 2 Hz, as shown in Fig. 7 (a). The displacement is plotted as a function of the input voltage in Fig. 7 (b). In terms of the high-frequency response (~2 Hz), low operation voltage (~3 V), and large force (~1 gf), as demonstrated in those experiments, a perfluorinated polymer possesses suitable electronic properties for its use as a sheet actuator that is compatible with organic transistors.

The present actuators can be driven in wet as well as dry environments; however, those in wet environment exhibit slightly better electric and mechanical performance.

C. Braille cells

As shown in Fig. 8 (a), the displacement of a Braille cell consisting of a transistor and an actuator, which is implemented in the frame, is measured as a function of time by inputting rectangular waves of variable voltage amplitudes. Figure 8 (b) shows the initial rise, which is retraced from (a) and presented with a different magnification of the horizontal axis. With an increase in the gate voltage, the rise time required to displace a surface dot from 0 to 0.2 mm is reduced drastically, and it becomes 0.9 s at –30 V. The velocity is limited by magnitude of I_{DS} and therefore a larger mobility and/or W/L is rather effective in enhancing the operation speed.

D. Display operation

Figure 9 shows the characters “l” and “w” on the Braille display in the American Braille style. Magnified pictures of the activated and the inactivated cells are also shown.

Acknowledgements

This study is partially supported by IT program, TOKUTEI (15073204), MEXT, NEDO, MPHPT, and CREST, JST. The authors thank Kyocera Chemical Corporation for the high-purity polyimide precursors.

References

[1] H. Hagen, et. al., IEDM 15.2 (2004). [2] C-C. Kuo, et. al., IEDM 15.3 (2003). [3] I. Kymissis, et al., IEDM 15.4 (2004). [4] A. Wang, et. al., IEDM 15.5 (2003). [5] T. Someya, et. al., IEDM 15.1, 580 (2004); H. Kawaguchi, et. al., ISSCC, 365 (2005); T. Someya, et. al., IEEE Trans. Electron Devices (the issue of November 2005). [6] T. Someya, et. al., IEDM, 203 (2003); PNAS 101, 9966 (2004); PNAS 102 (35) (2005); ISSCC, 288 (2004); H. Kawaguchi, et. al., IEEE JSSC 40, 177 (2005); Y. Kato, et. al., APL 84, 3789 (2004).

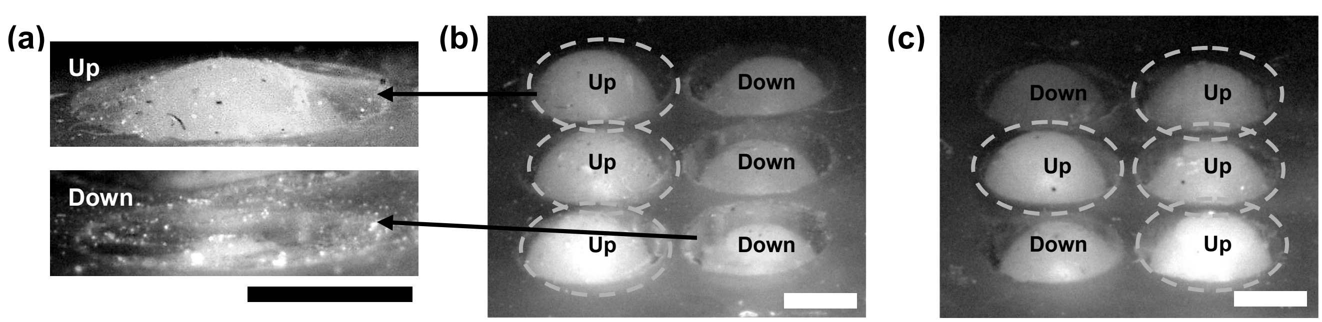

Fig. 9: Display operation. Pictures of the *Braille sheet display* showing the characters “l” and “w” in the American Braille style. Magnified pictures of the activated and inactivated cells are also shown. The scale bar is 1 mm.