Large-Area and Flexible Sensors with Organic Transistors

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***Abstract*—Organic transistor circuits are attracting a lot of attention for large-area and flexible electronics applications, such as sensors for human interface applications, because organic transistors can be fabricated with printable/printed technology on arbitrary substrates, which enables low-cost production and high mechanical flexibility. In this paper, recent progresses of large-area and flexible sensors with organic transistors are reviewed.**

I. INTRODUCTION

Organic transistor circuits have been drawing attentions for large-area and flexible electronics applications. Table I summarize a comparison between our organic FETs (OFETs) and state-of-the-art 45-nm Si MOSFETs [1]. OFETs are much slower than Si MOSFETs, whereas OFETs have the following two advantages; 1) OFETs are mechanically flexible, since OFETs are fabricated with printable/printed technology on a film, such as a polyimide film and a polyethylene naphthalate (PEN) film, and 2) the cost per area of OFET is lower than that of Si MOSFETs. Therefore, large area and flexible electronics applications are suitable for OFETs. Sensors for human interface applications are one of the promising candidates, since large area and flexibility are extremely important for human interfaces. In this paper, some examples of large area and flexible sensors with organic transistors are shown.

II. LARGE AREA AND FLEXIBLE SENSORS WITH ORGANIC ELECTRONICS

In this section, recent progresses of large-area and flexible sensors with organic transistors are briefly reviewed.

A. *Electronic Artificial Skin (E-skin)*

The importance of pressure sensing is increasing in applications such as area sensor networks and robots for the next generation. We developed a large area and flexible pressure-sensor array, called E-skin [2-4], as shown in Fig. 1.

Fig.2 shows the developed E-skin system consisting of 16 x 16 sensor cell matrix, row decoders and column selectors glued with connecting tapes. Each sensor cell consists of a pressure sensor and an OFET for selecting the sensor cell as shown in the inset of Fig. 2. The OFETs are stacked with the pressure sensors. The pressure sensors are made of pressure-sensitive conductive rubbery sheets sandwiched between a copper-coated polyimide film (electrode sheet in Fig. 2) and another polyimide film with via holes (through-hole sheet in Fig. 2). The measured pressure dependence of current flowing through the sensor cell is also shown in the inset of Fig. 2. When the sensor is pushed by a rectangular object, only the corresponding part of the pressure-sensitive rubber turns on and the corresponding cells pull the bit lines (BLs). The size of the sensor cell is 2.54 x 2.54 mm^2.

Table I. Comparison between organic FETs (OFETs) developed in our group and state-of-the-art 45-nm Si MOSFETs [1].

	OFETs	Si MOSFETs
Minimum gate length	20 µm	45 nm
Mechanical flexibility	Flexible	Very limited
Normalized ON current	3 nA / µm @ 3 V	1 mA / µm @ 1 V
Gate delay	0.1 s @ 3 V	10 ps @ 1 V
Cost / area	Low	High
Cost / transistor	High	Low

Fig. 1. Implementation example of electronic artificial skin (E-skin), which is sheet containing array of pressure sensors and OFETs.

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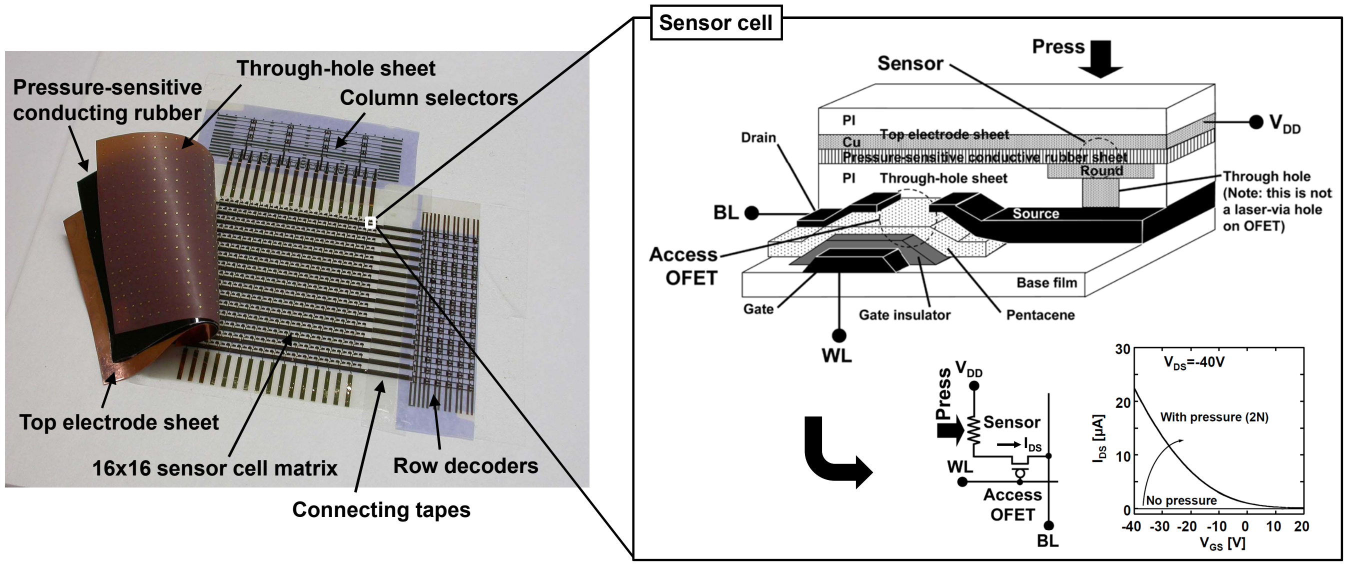

Fig. 2. Photograph of electronic artificial-skin (E-skin) system, and detailed structure of sensor cell.

Fig. 3. Sheet-type image scanner, which is sheet integrating array of photodetectors and OFETs.

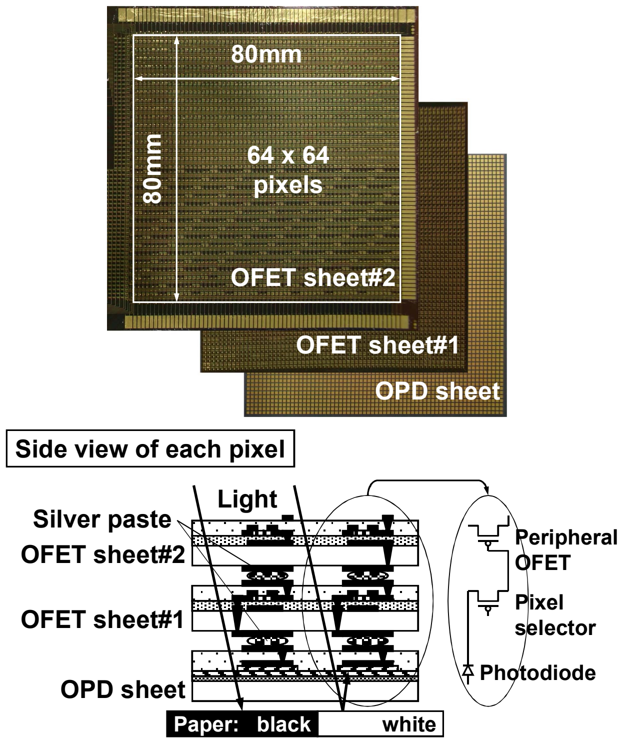

Fig. 4. Photograph of fabricated sheet-type image scanner system and device structure of each pixel.

In the developed E-skin, a scalable-circuit concept based on cut-and-paste programmability, which enables all of the circuits to be scalable in size, was proposed. This concept is preferable in terms of mask cost because there is no need to make new masks depending on the required sizes and shapes.

Using the E-skin system, a pressure image with resolution of 10 dpi was successfully taken. The system can be bent down to 5 mm in radius, which is sufficient to wrap around the surface of a round object like a robot as shown in Fig. 1.

B. *Sheet-Type Image Scanner*

Fig. 3 shows a sheet-type image scanner integrated with an OFET and organic photodiode (OPD) [5-8]. The sheet-type scanner can capture a black-and-white image on a paper without heavy mechanical components or optical lens.

Fig. 4 shows the photograph of the sheet-type scanner. The scanner contains 64 x 64 pixel arrays, which occupy 80 x 80 mm^2, and the structure of each pixel is also illustrated in Fig. 4. One OPD sheet and two OFET sheets are separately fabricated and glued together with silver paste. All base films are transparent PEN, through which light can pass. On the OPD sheet, the base film is covered with ITO as a common anode. CuPc is p-type semiconductor and PTCDI is n-type one, forming the OPD [9, 10]. The aperture (open-area ratio) is 45% of a total pixel area. The pixel size is 1.27 x 1.27 mm^2, which corresponds to 20 dpi. Three sheets are stacked as shown in Fig. 4 and the total thickness and weight are 0.4 mm and 1 g, respectively. The minimum bending radius is 30 mm.

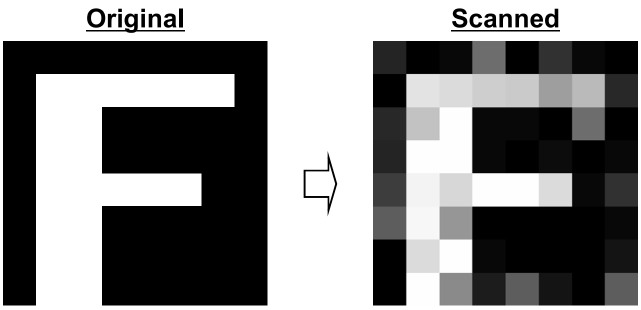

Fig. 5. Original image of "F" and image scanned by developed sheet-type image scanner.

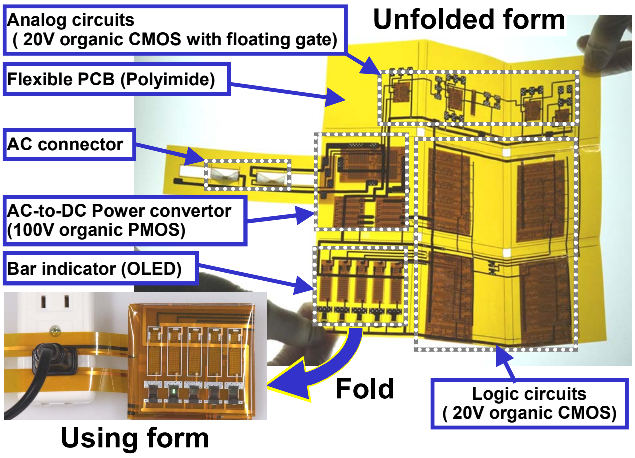

Fig. 6. Photograph of 100-V AC energy meter on flexible film.

Fig. 5 shows an example of scanned image using the developed sheet-type image scanner. The scanner is so thin and flexible that it can take an image of a round object such as a label on a wine bottle, as shown in Fig. 3, which is impossible for the conventional commercial scanners.

C. AC Energy Meter

A smart meter is essential for realizing the smart grid. In order to further reduce the energy loss in the power grid, an extremely fine-grain power monitoring system is desirable and it will require an enormous number of low-cost power meters. Since printable organic devices on flexible films have great potential to realize low-cost and flexible energy meters, we proposed a 100-V AC energy meter based on the system-on-a-film concept (SOF) [11, 12].

Fig. 6 shows a photograph of the proposed organic 100-V AC energy meter on a flexible film. Fig. 7 illustrates a block diagram of the energy meter. The key components of the energy meter include; 1) a rectifier composed of a 100-V organic pMOS, 2) analog circuits, such as operational amplifier, fabricated with 20-V organic CMOS transistors, 3) logic circuits composed of 20-V organic CMOS transistors for the frequency divider and the counter accumulating the measured power, 4) an organic LED (OLED) [13] bar indicator for

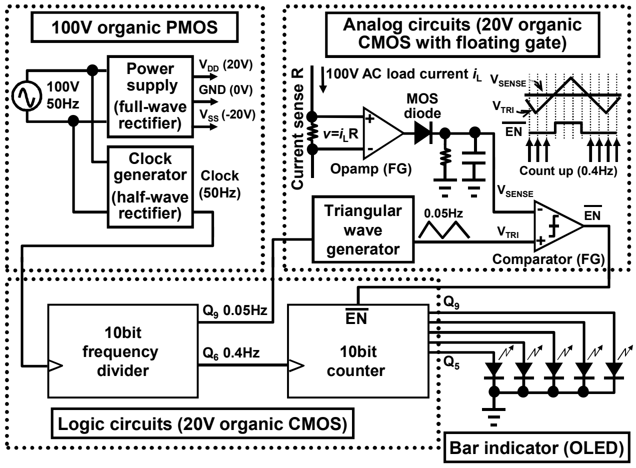

Fig. 7. Block diagram of energy meter.

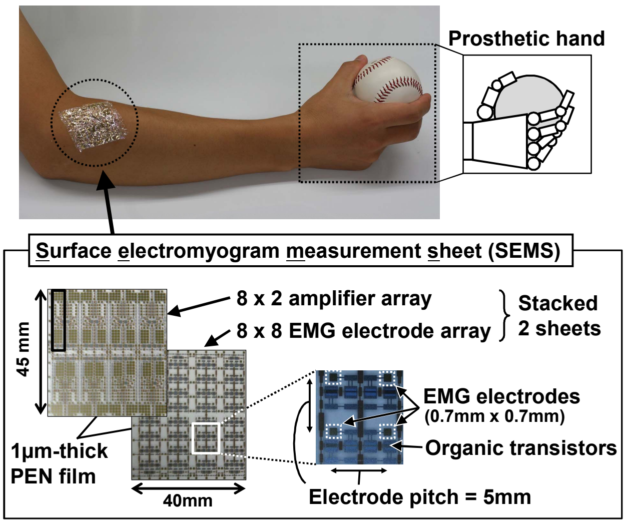

Fig. 8. Photograph of surface EMG measurement sheet.

displaying the measured energy, and 5) an AC connector inserted between the power plug and the AC outlet and discrete passive components (capacitors and resistors for circuit tuning) which are fully integrated on a 200 x 200 mm^2 flexible film. We name this type of system implementation an SoF. The energy meter based on the SoF is flexible and therefore can be installed to monitor each AC outlet simultaneously. The entire sheet of the film can be folded as shown in Fig. 6 and the total size of the proposed 100-V AC energy meter can be reduced to 70 x 70 mm^2.

D. Surface Electromyogram Measurement Sheet

A surface electromyogram (EMG), which measures a voltage waveform produced by skeletal muscles on a skin, is an important tool for applications detecting the human will of motion, such as for prosthetic hand control. In order to precisely control the hand, a multipoint EMG measurement is required [14, 15]. Conventional EMG measurements with passive electrodes, however, have the following two problems; 1) a long time measurement is annoying, and 2) the signal

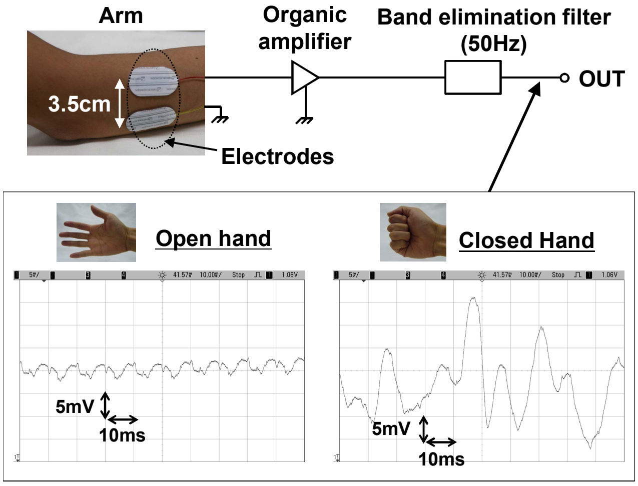

Fig. 9. Measured waveforms of the surface EMG with the organic amplifier.

integrity of EMG is degraded. To address these challenges, we developed a surface EMG measurement sheet (SEMS) [16].

Fig. 8 shows a photograph of the developed 45 x 40 mm^2 64-channel SEMS. In the SEMS, an 8 x 8 EMG electrode array sheet and an 8 x 2 amplifier array sheet with 2V organic transistors on a 1µm-thick ultra-flexible PEN film are stacked. The pitch of the EMG electrode is 0.7 mm and the area of the 8 x 8 EMG electrode array is 3.5 mm^2. Since the PEN film is ultra-flexible thanks to its thickness of 1µm and the distributed organic amplifiers improve the signal integrity of measured EMG signals, the developed SEMS enables a comfortable long-time measurement without signal integrity degradation.

In the developed SEMS, gain mismatch of the organic amplifier array is a problem. A post-fabrication tuning technique using inkjet-printed interconnects was proposed to reduce mismatch in organic circuits. Such technique is too costly and not practical in silicon VLSI technology, whereas it is feasible in printable/printed technology.

Fig. 9 shows the measured waveforms of the surface EMG with the organic amplifier. The difference between the waveforms with open and closed hands was clearly observed.

III. SUMMARY

In this paper, four examples of large area and flexible sensors with organic transistor, such as electronic artificial skin (E-skin), sheet-type image scanner, AC energy meter, and surface EMG measurement sheet, were explained. Organic transistors are suitable for such sensors for human interface applications, because human interface applications require high mechanical flexibility and large area, and organic transistors are able to meet the demand. Therefore, large area and flexible sensors are one of promising applications for organic electronics.

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