Design of Large Area Electronics with Organic Transistors

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Abstract— **Organic electronics is attracting a lot of attention for large-area pervasive electronics applications, because organic transistors can be fabricated using printing technologies on arbitrary substrates and this enables both high-throughput and low-cost production. In this paper, some examples of the large area electronics with the organic transistors including a wireless power transmission sheet and a communication sheet are presented. Challenges for future large area electronics are also described.**

I. Introduction

Organic electronics is attracting a lot of attention for large-area pervasive electronics applications, because organic transistors can be fabricated with printing technologies on arbitrary substrates, enabling both high-throughput and low-cost production. In this paper, some examples of large area electronics using organic transistors are shown. Section II describes the advantage of the organic electronics over silicon VLSI's and shows the reason why large area applications are suitable for organic transistors. Section III presents applications of large area electronics including a wireless power transmission sheet and a communication sheet. Section IV describes challenges for future large area electronics and some concluding remarks are given in Section V.

II. Large Area Electronics with Organic Transistors

In order to find the suitable applications of organic electronics, the advantages of this technology over conventional electronics should be clarified. Table I shows a comparison between our organic FETs (OFETs) and state-of-the-art 45-nm silicon MOSFETs. OFETs are flexible, because OFETs are fabricated on a film. Low voltage operation (3V) is possible already using organic CMOS technology. The gate delay of the OFETs, however, is 10^{10} times larger than that of the silicon MOSFETs, because the minimum gate lenght of OFETs is 440 times larger than that of the silicon MOSFETs and the on-current of OFETs is 1/300000 of that of the silicon MOSFETs (mostly due to the much lower mobility of organic semiconductors). The device lifetime of OFETs is several months, while that of the silicon MOSFETs is more than 10-years, because OFETs are chemically degraded by the oxygen and moisture in the atmosphere. The cost per area of OFETs is lower than that of the silicon MOSFETs, while the cost per transistor of OFETs is higher than that of the silicon MOSFETs. Therefore, large area electronics, which takes advantage of the flexibility and the low cost per area, is a good application of the OFETs. Intense research and development work is thus focusing on large area devices based on organic materials such as an organic electroluminescence (EL) displays, e-paper, organic EL lighting, organic solar cells, and human-size sensor and actuator devices.

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

	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
Lifetime	Months	Years

Fig. 1 shows the relation between conventional IT applications based on silicon VLSI and human interface applications using large area electronics. The IT applications such as computers and communications are supported by the conventional silicon VLSI's, because silicon MOSFETs are fast and the cost per transistor (=cost per function) is low. In contrast, human interface applications such as human interfaces and ambient intelligence can well be supported by large area electronics with OFETs, because OFETs are flexible and the

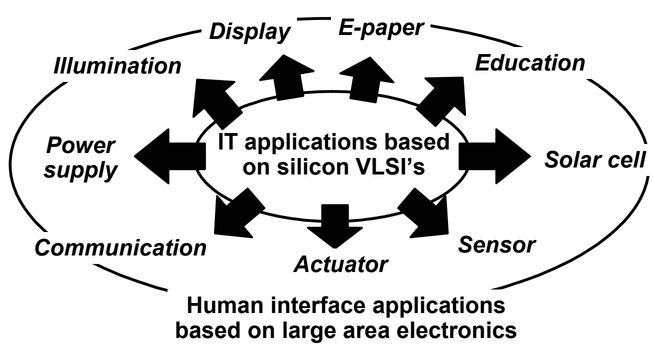

Fig.1 Relation between conventional IT applications using the silicon VLSI and human interface applications using large area electronics.

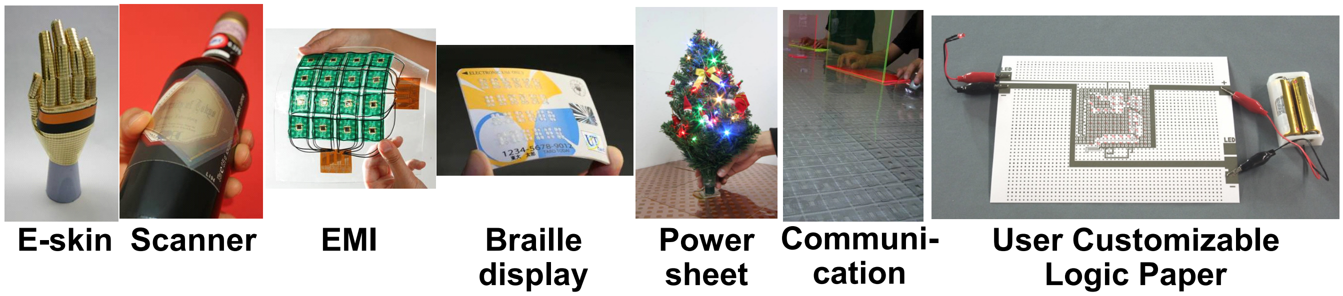

Fig.2 Examples of large area electronics applications. An E-skin is a sheet containing an array of pressures sensors and OFETs. A sheet scanner is a sheet integrating an array of photodetectors and OFETs. An EMI measurement sheet is a sheet supporting an array of silicon VLSI circuits and OFETs. A Braille display is a sheet integrating an array of plastic actuators and OFETs. A wireless power transmission sheet and a communication sheet combine on foil an array of coils, plastic MEMS switches, and OFETs. User Customizable Logic Paper can enable users to fabricate custom integrated circuits by printing interconnects with at-home ink-jet printers for the prototyping of large-area electronics and educational purposes.

cost per area is low. Thus silicon VLSI and OFETs are not competing technologies but more complement each other. By combining silicon VLSI's and OFETs, large area electronics has the potential to expand both the application field and the market size of electronic industry. Therefore, the development of the large area electronics which sophisticatedly combines silicon VLSI's and OFETs is strategically very important.

III. Applications of Large Area Electronics

A. Examples of Large Area Electronics Applications

Fig. 2 shows show examples of large area electronics applications. An E-skin [1-3] is a sheet containing an array of pressures sensors and OFETs. A sheet scanner [4-7] is a sheet integrating an array of photodetectors and OFETs. An EMI measurement sheet [8-9] is a sheet supporting an array of silicon VLSI circuits and OFETs. A Braille display [10-13] is a sheet integrating an array of plastic actuators and OFETs. A wireless power transmission sheet [14-15] and a communication sheet [16-19] combine on foil an array of coils, plastic MEMS switches, and OFETs. User Customizable Logic Paper (UCLP) [20] can enable users to fabricate custom integrated circuits by printing 200µm wide interconnects with at-home ink-jet printers for the prototyping of large-area electronics and educational purposes. The E-skin, the sheet scanner, and the EMI measurement sheet are examples of sensor applications. The Braille display is an actuator. The wireless power transmission sheet and the communication sheet are possible human-size IT applications and details are shown in the next section.

B. Ubiquitous Power Supply and Communications

In future ubiquitous electronics, also known as ambient intelligence, 1000 to 10000 electronic devices will be distributed around the user's environment and will contribute to security, promote healthcare and welfare, and provide entertainment and convenience. In the ubiquitous electronics environment, distributing power supply to the electronic devices and ensuring communication between them are serious problems. This is because battery replacement is not acceptable in this scenario and the power consumption for wireless communication between so many devices will be prohibitively high.

To solve these problems, both a wireless power transmission sheet and a communication sheet have been developed. These sheets are made with plastic MEMS switches and organic FET's as printable low-cost and large-area electronics can be embedded in furniture, walls and ceiling. These sheets detect the position of the electronic device placed nearby and provide the wireless power supply and low-power wireless communication.

a) Wireless Power Transmission Sheet

A pictorial view of the wireless power transmission sheet [14-15] is shown in Fig. 3. The developed power transmission sheet detects the position of the electronic devices on the sheet and delivers power as EM waves. The sheet is flexible, large area, and can be manufactured at low cost, because it is fabricated using a printing process on a polyimide film. The principle of the wireless power transmission is based on an array of transmission coils (TX-coil) made on the plastic sheet which are selectively driven by plastic MEMS switches and are coupled magnetically with a receiver coil (RX-coil) mounted on the power-receiving object. The typical problem of wireless power transmission using electromagnetic induction is the efficiency loss due to the displacement between the TX-coil

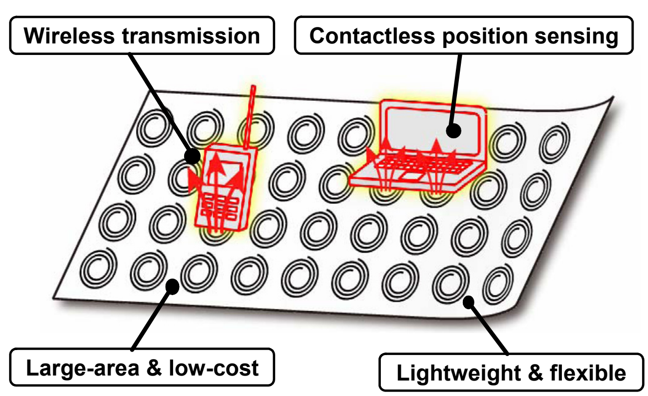

Fig.3 Overview of the developed wireless power transmission sheet.

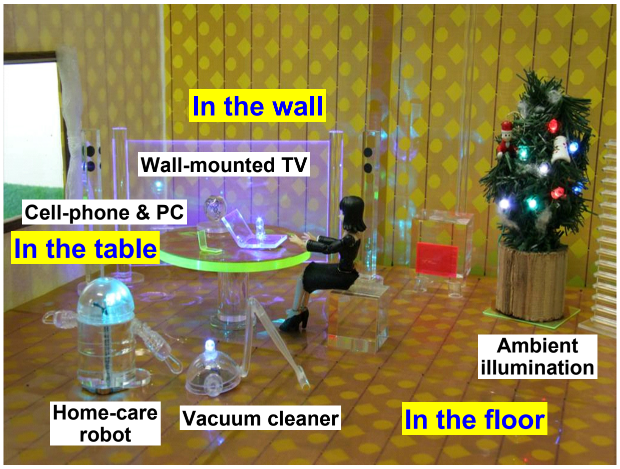

Fig.4 Expected applications of the wireless power transmission sheet.

and the RX-coil. The segmentation and selective activation of TX-coils introduced in this approach greatly reduce efficiency loss. Position detection of the receiving object is needed for the selective activation of TX-coils. This is achieved scanning through many TX-coils and measuring the antenna impedance of the TX-coil to detect if an RX-coil is placed nearby.

Fig. 4 shows a mock-up of expected applications of the wireless power transmission sheet. The sheet embedded in the walls delivers power wirelessly to a wall-mount TV. The sheet embedded in the table delivers power wirelessly to a cell phone and a laptop PC. The sheet embedded in the floor delivers power wirelessly to a moving home-care robot, a vacuum cleaner, and an ambient illumination. In this way the wireless power transmission sheet, an example of large area electronics made possible by OTFT technology, will enable ubiquitous electronics.

b) Communication Sheet

An overview of the communication sheet that our group developed [16-19] is shown in Fig. 5. By combining meter-scale wireline communication and micrometer-scale wireless capacitive-coupling communication, the communication sheet combines the mobility of wireless communication and the low-

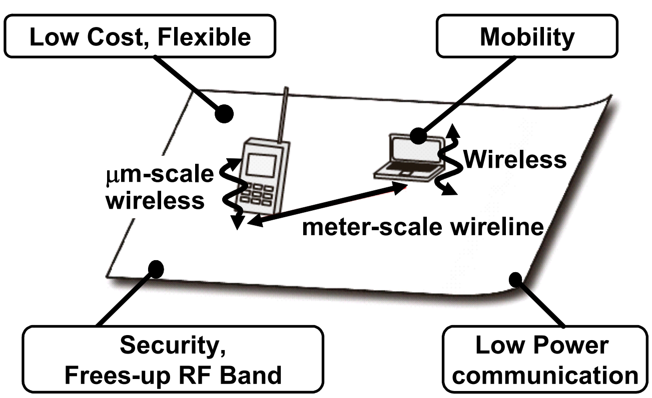

Fig.5 Overview of the developed communication sheet.

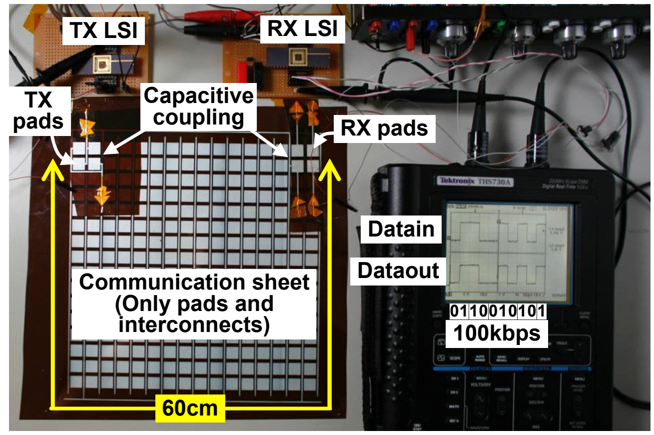

Fig.6 Measurement setup of the communication sheet. A 100-kb/s communication at 10.7μW was demonstrated at a distance of 60 cm.

power performance of wireline communication. The sheet enables multiple electronic objects scattered over tables, walls, and ceilings to communicate contactlessly with each other by establishing communication paths without cumbersome physical connections.

Fig. 6 shows a measurement setup of the communication sheet. The TX/RX Si chips are bonded to the TX/RX pads on the TX/RX sheet, and the pads are capacitively coupled to the communication sheet. In this measurement, to check the feasibility of the communication through the communication sheet, the MEMS switching matrices, the organic nonvolatile memory array, and the position-detection coil array are not included, and the communication route is laid out as a 60 cm hard-wired connection. A 100-kb/s communication at 10.7μW was demonstrated, which corresponds to 107 pJ/bit. The developed transceiver [17, 19] in 0.18-μm CMOS with a data-edge-signaling transmitter and DC power-free pulse detector contributes to the low power communication.

IV. Challenges for Future Large Area Electronics

Several challenges for the future large area electronics are itemized below.

- Improvements of organic device reliability are required.
- Variability of organic devices should be reduced.
- Faster operation speed of organic devices without increasing the manufacturing cost is required.
- Circuit and system-level design to solve the above issues.

The reliability of organic devices has been rapidly improved by the advancement in encapsulation technologies. Just as VLSI technologies have reduced the variability of silicon MOSFETs in past 40 years, the variability of organic devices will be reduced by the improvement of the manufacturing process. Faster operation speed of organic devices is required to extend the applications. The miniaturization of organic FETs is a straightforward approach to increase the speed. The increasing manufacturing cost with is miniaturization, however, should be avoided to maintain the low-cost advantage of organic devices. Improvements in process and device as well as circuit and system-level design are required to solve the reliability, variability, and low speed issues in organic devices.

V. SUMMARY

Large area electronics, which takes advantage of the flexibility and the low cost per area, is a good application of OFETs. By combining the silicon VLSI's and OFETs, large area electronics has the potential to expand both the application field of electronics and the total market of electronic industry. Therefore, the development of the large area electronics which sophisticatedly combines the silicon VLSI's and the OFETs is of great scientific and commercial interest.

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