Large-Area Flexible Electronics with Organic Transistors

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***Abstract*—Organic transistors are promising candidates for realizing large-area flexible electronics such as smart displays, power transmission sheets, and electronic skin for robots. In this paper, recent progress of organic transistors and novel interconnects are briefly surveyed. Example applications of large-area flexible organic electronics in particular EMI measurement sheet and User Customizable Logic Paper (UCLP) are introduced.**

I. Introduction

With the advantages of flexibility, printable/printed technology, and low cost in the future, organic transistors are promising candidates for realizing large-area flexible electronics including smart displays, power transmission sheets, and electronic skin for robots. In this paper, recent progress of organic transistors, novel interconnects, and some examples of large-area flexible organic electronics are introduced. In Section II, resent progress of organic transistors and their circuit blocks are briefly surveyed. Section III introduces two novel stretchable/flexible interconnects. Section IV introduces some examples of large-area flexible organic electronics in particular EMI measurement sheet, User Customizable Logic Paper. Finally some conclusions are provided in Section V.

II. Recent progress of Organic Transitors

Organic PMOS transistors have been getting good yield and time dependent reliability, and therefore, highly integrated organic PMOS circuits were presented such as an 8-bit microprocessor [1] and a first-order delta-sigma ADC [2]. In terms of low-voltage operation, self assembled monolayer (SAM) [3] realized 1.5 to 3V operation enabling direct silicon-organic circuit interface [4] was presented. In terms of printed electronics, some printed CMOS circuits were presented [5]. This section introduces resent progress of organic transistors and their circuit blocks briefly.

A. An 8-bit Microprocessor on Plastic Foil

The improvement of yield of organic PMOS transistor realized an 8-bit organic microprocessor on a plastic foil for the first time [1]. The processor consists of only NAND gates and inverters in 5μm organic PMOS process, and operates with 6Hz clock at 10V V_{DD}. Numbers of transistors of the processor foil and an instruction code foil are 3381 and 612, respectively.

B. Fully Integrated ΔΣ ADC with OrganicPMOS Transistors

A continuous time ΔΣ ADC with 5μm organic PMOS transistors was presented [2]. It is a fully integrated organic ADC for the first time. In order to compensate V_{TH} mismatch of input differential pair transistors in an amplifier and improve the gain, the circuitry employs backgate biasing. Measured SNR and bandwidth are 26.5dB and 15.6Hz, respectively. Clock frequency is 500Hz at 15V V_{DD}. The circuit consists of 129 transistors.

C. Low-Voltage Organic CMOS Circuit

A low-voltage organic CMOS circuit using SAM gate oxide was presented [3]. A nanometer order gate oxide thickness with SAM realizes 1.5 to 3V operation which is around 10-time lower than that of conventional organic transistors. This improvement enables direct silicon-organic circuit interface.

D. Fully Printed Organic CMOS Circuit

A complete printed organic CMOS technology on a plastic foil was proposed [5]. The devices are fabricated by 5μm line/space resolution screen printing process and annealing at 100°C. Oscillation frequency of a 7-stage ring oscillator that consists of W/L=1000/20μm CMOS transistors varies from 70Hz at 40V to 16Hz at 20V. An NMOS differential amplifier was also provided in [5]. The maximum gain achieves 17 at 10V V_{DD}.

TABLE I. Summary of Recent Progress of Organic Transistors

	[1]	[2]	[3]	[5]
Key features	8-bit micro-processoer	Fully integrated ADC	Low-voltage operation	Fully printed
Transistor type	PMOS	PMOS	CMOS	CMOS
Gate length	5μm	5μm	5μm	20μm
Supply voltage	10V	15V	1.5 to 3V	10 to 40V
Number of transistors	3381	129	2	≈20

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III. Novel Flexble Interconnects

In order to realize flexible electronics, interconnects should also be stretchable or flexible. In this section, two novel flexible interconnects, stretchable Interconnects with carbon nanotubes (CNTs) and printed interconnects with at-home ink-jet printers, are introduced.

A. Stretchable Interconnects with Carbon Nanotubes

A rubberlike stretchable interconnection was presented [6]. The conductive material for the stretchable interconnects is CNTs. CNTs are an inherently stretchable material with a very low resistivity of 0.02μΩcm [6], however, CNTs should be disentangled prior to being combined with a rubberlike material. The process flow of the stretchable interconnects is shown in Fig. 1. Single-walled CNTs are used as a conductive material. An ionic liquid (1-butyl-3-methyl imidazoliumbis (trifluoromethanesulfonyl) imide, BMITFSI [6]) and CNTs are combined and ground to disentangle the CNTs. A rubberlike material, fluorinated copolymer, and CNT dispersed in gel are combined and stirred by sonication. The stretchable interconnects film is formed by air-drying. Fig. 2 demonstrates its stretchability. The flexible interconnects can be stretched by 40% thanks to the sliding CNTs embedded in the rubberlike material, fluorinated copolymer.

B. Printed Interconnects with At-Home Ink-Jet Printers

A number of ink-jet printed interconnects technologies

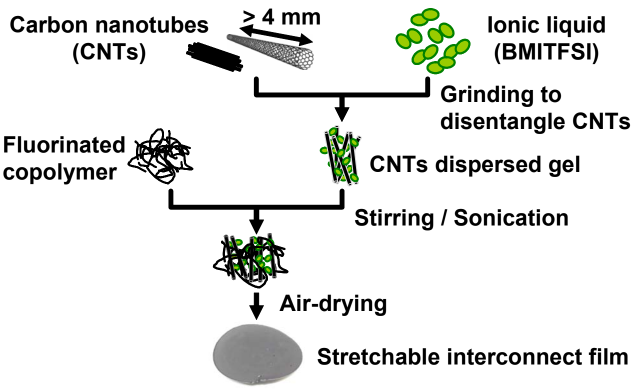

Fig. 1. Process flow of the stretchable interconnects.

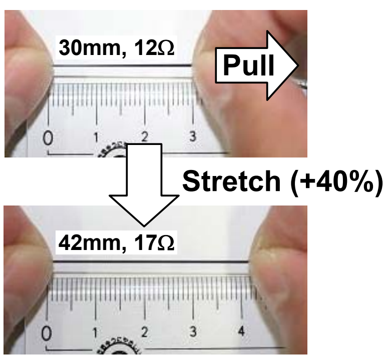

Fig. 2. Demonstration of stretchable interconnect.

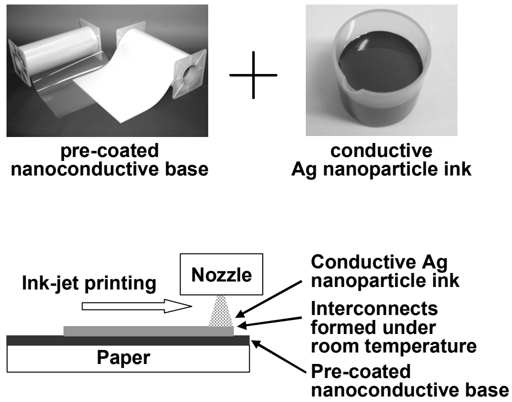

Fig. 3. Materials and process flow of the ink-jet printed interconnects.

have been developed to date. However, either a high temperature (130-150ºC) sintering or chemical process with organic solvent is required after the printing process, which causes damage to organic transistors. In contrast, recently proposed ink-jet printing technology [7] does not require such processes. The technology consists of pre-coated nanoconductive base and silver nanoparticle ink as shown in Fig. 3. The pre-coated nanoconductive base is a type of micro-porous layer made of Polyethylene, Polyvinyl alcohol, boracic acid, and other materials to absorb the solvent in the silver nanoparticle ink. Its thickness is around 40um. The ink includes 15% silver particles, alcohol, surface active agent, and dispersant. The diameter of silver nanoparticles in the ink is typically 20nm. The ink chemically reacts with the pre-coated nanoconductive base on the paper at room temperature, that is, a sintering-free process. This does not cause any damage to organic transistors. When the printed interconnect is stored in a laminated bag, the life time is five months or longer. In air, the resistance of the interconnects increases by 10% after the one month.

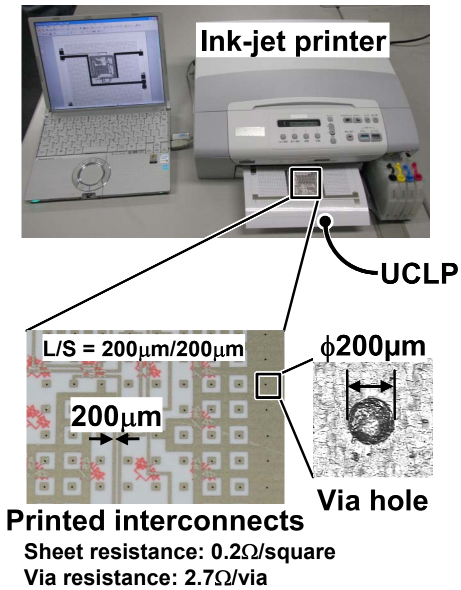

Fig. 4. Photograph of the printing process of the interconnects on UCLP using ink-jet printer, printed interconnects, and a via hole.

Fig. 4 shows a photograph of the printing process of the interconnects using an off-the-shelf ink-jet (piezo-jet) printer and printed interconnects and a via hole [8]. The thickness of the Ag interconnect is 1µm (typ.) and the measured sheet resistance is 0.2Ω/square (typ.). The via holes of 200µm in diameter are prefabricated by punching. The measured via resistance is 2.7Ω/via.

IV. LARGE-AREA FLEXIBLE ELECTRONICS WITH ORGANIC TRANSISTORS

This section introduces some examples of large-area flexible organic electronics such as EMI measurement sheet and User Customizable Logic Paper (UCLP).

A. A Stretchable EMI Measurement Sheet

Fig. 5 shows an example of an intrasystem EMC issue in a cell phone. EMI largely depends on the circuit board layout. Localizing either an EMI source or a critical wiring is difficult by simulation. EMI measurement is, therefore, important for the development of electronic systems. However, there is no method of measuring EMI on the surface of 3D structures. In the conventional method, a pencil-like magnetic field probe with X-Y scanning equipment and spectrum analyzers are used for the EMI measurement [9]. In the method, the surface of the electronic device should be scanned repeatedly with the probe. However, the scanning equipment can only move in a flat plane. In another conventional method, a measurement system with an integrated array of magnetic field loop antennas is used [10]. Although the method captures the distribution of a magnetic field, it is not applicable to 3D structures since the antenna array is implemented on a flat and rigid printed circuit board.

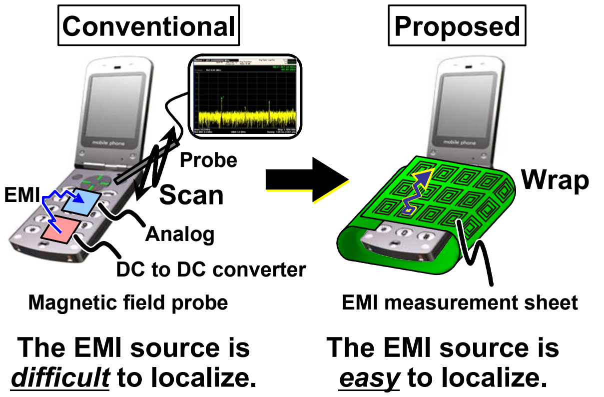

Fig. 5. Intrasystem EMC issue in a cell phone.

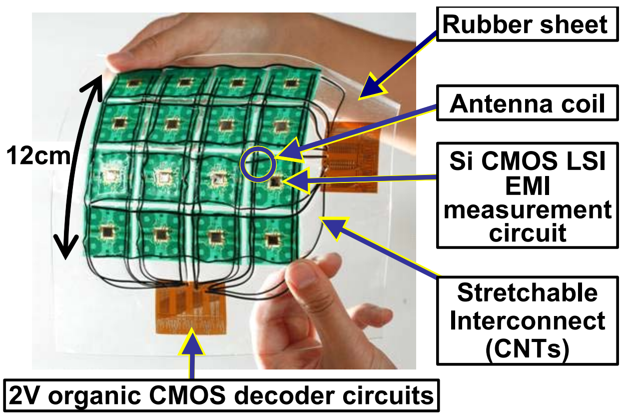

Fig. 6. Stretchable EMI measurement sheet.

To solve this problem, an EMI measurement sheet [4] was proposed, which enables the measurement of EMI distribution on the surface of 3D structures by wrapping the devices with a sheet like "*furoshiki*". Once EMI noise is roughly localized with the measurement sheet, one can easily scan EMI noise using the probe method for precise localization or better quantification of the EM field. The sheet can measure not only a magnetic field but also an electric field suitably by simply changing its antenna connection [4].

Fig. 6 shows a prototype of the stretchable EMI measurement sheet. Each printed circuit board (PCB) includes 2×2 antenna coils and a silicon EMI measurement LSI. The sheet consists of 4×4 PCB's, and therefore, 8×8 antennas are located in $12{\times}12cm^2$ area. The antennas and LSI's are controlled using 2V organic CMOS decoder and selector. Each module is electrically connected with a stretchable interconnect made of CNTs. The overall system is sealed with a rubber sheet made of silicone elastomer. The sheet is, therefore, flexible and stretchable. The sheet detects the total power of an electric field in the band up to 700MHz and that of a magnetic field up to 1GHz. The minimum detectable power of the electric and magnetic fields are -60 and -70dBm, respectively.

B. User Custamizable Logic Paper (UCLP)

UCLP is proposed for both prototyping of larger-area electronics and educational applications [8]. In particular, as shown in Fig. 7, learners can study and experience the operation of integrated circuits by fabricating custom integrated circuits, using at-home ink-jet printers to print conducting interconnects on paper that contains prefabricated arrays of organic transistors. The feasibility of UCLP is demonstrated with the newly proposed Sea-of Transmission-Gates (SOTG) of organic CMOS transistors, providing field customizability through the use of the printable electronics technology. UCLP is applicable to a wide range of products of printable electronics including flexible displays and electronic paper, as

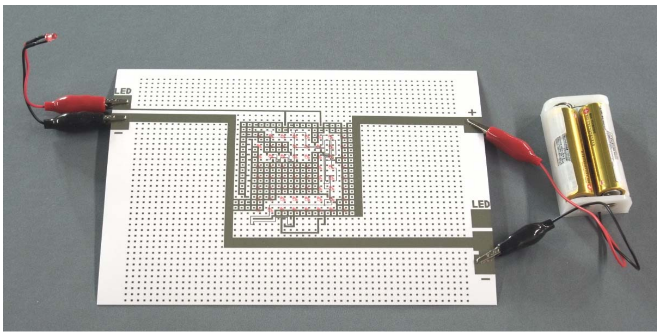

Fig. 7.User Customizable Logic Paper (UCLP) for educational purpose. Learners can study and experience operation of integrated circuits by fabricating custom integrated circuits, using at-home ink-jet printers to print conducting interconnects on paper that contains prefabricated arrays of organic transistors.

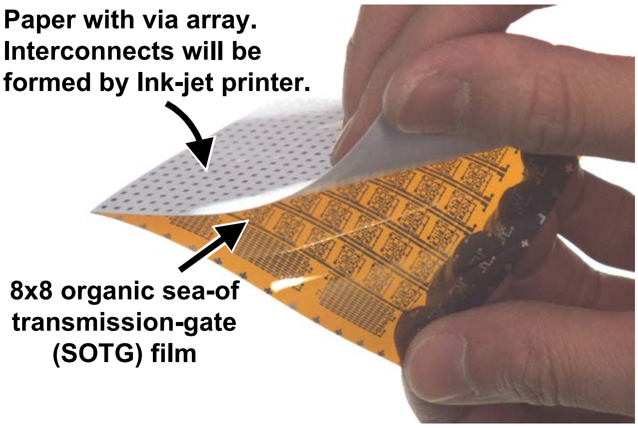

Fig. 8. Prototype of UCLP.

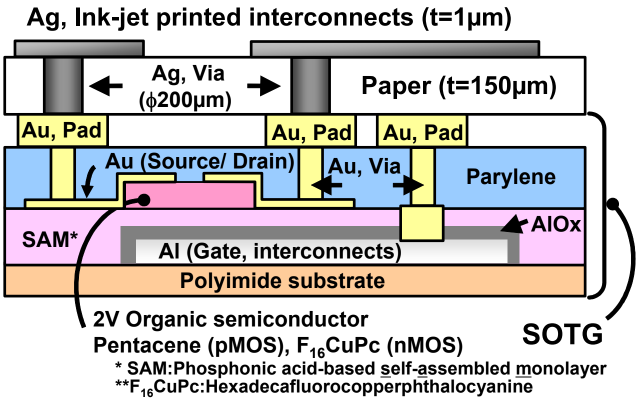

Fig. 9. Cross sectional view of UCLP.

well as for educational purposes. This technology provides a new means to add programmability for integrated circuits used in large-area electronics. Fig. 8 shows a prototype of UCLP [8]. In UCLP, paper that contains an array of vias and an organic SOTG film are stacked. Although it would be ideal to fabricate the whole UCLP including the organic transistors using ink-jet printers, this proves to be very difficult since both high temperature (130-150ºC) and an organic solvent are required to fabricate the organic transistors. Since high temperatures and organic solvents cannot be handled by ink-jet printers, in UCLP the organic transistors are prefabricated and the field customizability is provided by the printed interconnects.

Fig. 9 shows the cross sectional view of UCLP. The 2-V organic CMOS transistors [8] are fabricated on polyimide film. Organic semiconductors for NMOS and PMOS are F16CuPc and pentacene, respectively [8]. Self-assembled mono-layers (SAM) realize 2-V organic transistors, which are covered with a protective layer of parylene. Connection pads to the paper are formed with gold on top of this protective layer. The interconnects are ink-jet printed onto the paper by users.

V. Conclusions

In this paper, resent progress of organic transistors and their circuit blocks are briefly surveyed. Highly integrated circuit blocks such as microprocessors and ADC can be implemented with organic transistors. Low-voltage organic CMOS transistors enables direct silicon-organic circuit interface. Printed electronics can be fabricated at a low cost. The progress of organic transistors will realize large-area, flexible electronics with low-cost process in the near future.

Acknowledgment

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