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Programmable logic circuits for functional integrated smart plastic systems

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ABSTRACT

In this paper, we present a functional integrated plastic system. We have fabricated arrays of organic thin-film transistors (OTFTs) and printed electronic components driving an electrophoretic ink display up to 70 mm by 70 mm on a single flexible transparent plastic foil. Transistor arrays were quickly and reliably configured for different logic functions by an additional process step of inkjet printing conductive silver wires and poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) resistors between transistors or between logic blocks. Among the circuit functions and features demonstrated on the arrays are a 7-stage ring oscillator, a D-type flip-flop memory element, a 2:4 demultiplexer, a programmable array logic device (PAL), and printed wires and resistors. Touch input sensors were also printed, thus only external batteries were required for a complete electronic subsystem. The PAL featured 8 inputs, 8 outputs, 32 product terms, and had 1260 p-type polymer transistors in a 3-metal process using diode-load logic. To the best of our knowledge, this is the first time that a PAL concept with organic transistors has been demonstrated, and also the first time that organic transistors have been used as the control logic for a flexible display which have both been integrated on to a single plastic substrate. The versatility afforded by the additive inkjet printing process is well suited to organic programmable logic on plastic substrates, in effect, making flexible organic electronics more flexible.

1. Introduction

When the organic field effect transistor (OFET) was first fabricated in 1987 [1], the Intel 80386 was the established microprocessor of the day with a minimum channel length of 1.5 μm and 275,000 transistors in an area of 104 mm^2 [2]. 25 years later, the 2,600,000,000 transistors of the state-of-the-art 10-core Intel Xeon are accompanied by a minimum channel length of 32 nm in an area of 512 mm^2 [2]. Meanwhile, there have also been notable advances in the large scale integration of organic transistors. Recent publications have demonstrated circuit functions such as 8-bit, 64-bit and 128-bit radio frequency identification (RFID) tags [3–5], and 8-bit microprocessors with 3381 transistors at a channel length of 5 μm [6]. These achievements, roughly comparable to the Intel 4004 of 1971 [2], are expanding the current envelope of integrated organic transistor circuit designs while also demonstrating the benefits of organic transistor technology such as flexibility, low temperature fabrication, and solution processing.

In order to alleviate the often prohibitive time and expense of silicon chip design and fabrication, semi-cus-

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tom and programmable logic devices are often used instead of full custom multiple mask set designs. With semi-custom designs, a mask set for a generic array of transistors is used to partially fabricate the device, requiring only a final metal layer mask (or masks) which customises the function. In this way, the costs of the shared masks are spread over all applications and only the cost of the final customising mask is additional. Alternatively, for a programmable device, the entire mask set is made and the chip is fabricated but a customised function is then programmed in the final device. There are several ways to accomplish the programming such as Erasable Programmable Read Only Memory (EPROM), Electrically Erasable Programmable Read Only Memory (EEPROM), Static Random Access Memory (SRAM) or antifuse [7].

In this paper we show an approach to complex functions fabricated with organic electronics which uses a programmable array of organic thin-film transistors (OTFTs) and makes best use of an additive manufacturing step, in this case, inkjet printing. Inkjet printing offers the advantages of a maskless on-demand processing step which allows low-cost, quick and accurate placement of functional wires and components. Inkjet printing has been previously used to create a Print-Programmable Read-Only Memory (P^2ROM) for use as an instruction generator in a hybrid oxide-organic complementary microprocessor system [8]. We demonstrate two architectures of programmable arrays which can be customised by final printing steps. We also highlight the advantages of organic processing by integrating a simple, flexible display on to the same plastic foil substrate as the fabricated transistors and printed electronics, driven only by the array of organic transistors. Four different circuit designs are presented with these two different array architectures. The first programmable array architecture is an uncommitted transistor array whose devices can be connected with a single final level of inkjet printed wires and resistors to form logic functions. Three circuit designs on this first programmable array architecture highlight key building blocks necessary for more complex logic circuits, namely (i) a ring oscillator, (ii) a memory element, and (iii) a pass-code checker. The second programmable array architecture is a full-featured programmable array logic device (PAL) comparable with commercially available silicon simple programmable logic devices (SPLDs) featuring 8 inputs, 32 product terms, and 8 outputs with macrocells consisting of memory and selectable inverters. A single circuit design of a 2:4 demultiplexer driving an electrophoretic ink (E-Ink) display was demonstrated on this second programmable array architecture.

2. Experimental

To demonstrate functional integrated plastic systems (FIPS), 2 different programmable array architectures were designed and fabricated on separate plastic foils. Transistors with a channel length of 5 μm of the same construction as used in Plastic Logic's high yielding and uniform active matrix display manufacturing process [9,10] were designed as either an array of transistors or as logic blocks programmable by inkjet printing. To complete the integration of the foils, an E-Ink display supplied by E Ink Corporation and inkjet printed wires and resistors were added. Our work provides a first example of how an OTFT manufacturing process developed by Plastic Logic for display applications and optimised for high transistor yield and uniformity over large-area flexible substrates can be used for large-scale logic circuit integration.

2.1. Foil 1 programmable array architecture description

The first foil (FIPS1 - Fig. 1) consisted of a transistor array and a 4-shape E-Ink display. The transistor array was an 18 × 3 array of 54 transistors of 3 different widths with which a function could be implemented by inkjet printing a single layer interconnect pattern in conductive silver ink (Inktec TEC-IJ-050). Using our own custom software to interface between the computer aided design (CAD) system and the inkjet printer, we were able to reliably design and print interconnect patterns of up to 344 individually printed wires. Three of the circuits presented in this paper are examples of the speed and versatility of this method using this programmable array architecture; namely, a 7-stage ring oscillator, a flip-flop memory element, and a pass-code checking circuit with finger-touch sensors and different printed resistor values. All digital circuits have been designed using diode-load logic with p-type transistor devices [11].

The E-Ink display (Fig. 1) consisted of 4 geometric shapes; a circle, a triangle (not displayed), a square, and a pentagon. Each shape was able to be independently switched on (black) or off (white) by application of a voltage which was positive (on) or negative (off) with respect to a mid-rail common voltage.

2.2. Foil 2 programmable array architecture description

The second foil (FIPS2 – Fig. 2) greatly increased the sophistication of FIPS1 by incorporating a complete implementation of a PAL with a patterned graphic, directly driven E-Ink display of 100 μm resolution. The PAL was configured as a conventional AND-OR array with a fully programmable AND-array and fixed OR-array. The programming of the PAL was accomplished by accurate printing of conductive wires at a 250 μm pitch in a switch fabric between the functional blocks of the PAL (Fig. 3). In addition to the PAL of the FIPS2 foil, some pre-configured standard circuits were also incorporated. These were a 9-stage ring oscillator with divide-by-2 frequency dividers, and a 2:1 clock selector. (As yet, these additional components have not been incorporated into any circuit designs using the PAL.) There were a total of 1260 transistors on FIPS2.

The patterned graphic E-Ink display had 3 interleaving designs. These can be seen on Fig. 2 as a thin vines pattern, a broader swirls pattern, and the background pattern which includes neither the vines nor the swirls. As with FIPS1, each pattern can be independently switched on (black) or off (white).

2.3. Fabrication

The fabrication of the foils was performed jointly by Plastic Logic and the University of Cambridge. The