Self-Aligned, Roll-to-Roll-Compatible Manufacturing of Printed Conductors and Devices

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1. EXTENDED ABSTRACT

Applications for circuits and devices printed on flexible substrates abound, ranging from wearable diagnostic sensors to large area, roll-up displays. Continuous roll-to-roll (R2R) printing processes are attractive for manufacturing flexible electronics. However, two challenges typically arise in this pursuit: (1) creating small feature sizes, and (2) achieving registration of multiple functional layers. This presentation will cover our efforts to address these challenges using a new approach – Self-Aligned Capillarity-Assisted Lithography for Electronics (or SCALE) [1]. SCALE involves imprinting a multilevel open network of reservoirs, capillaries and device structures into a UV-curable coating deposited on a flexible substrate, delivering electronically functional inks into the reservoirs by inkjet printing, and using capillarity to selectively fill capillaries and device structures attached to the reservoirs. The single imprint step creates all the structural features needed in the devices and capillary flow creates self-aligned, multi-material devices. To-date we have used SCALE to create conductive networks [2-4], resistors [5,6], capacitors [5,7], diodes [8] and transistors [1,9,10], and we have demonstrated compatibility with R2R processing [2].

This talk will first focus on the creation of high-aspect ratio (height/width ≥ 1) conductors by SCALE [2-4], Figure 1. A key challenge for printed electronics generally is to produce narrow metal interconnects with low resistance and sharp, well-defined edges. We have been able to address this challenge using SCALE by first imprinting two-level, nested capillary channels connected to an ink reservoir (See Figure 1A). Ag ink is delivered to the reservoir by an ink jet nozzle and spontaneous capillary flow pulls the Ag ink into the narrow, deep capillary channels as shown in the figure. Annealing of the Ag ink is followed by electroless plating of bulk Cu metal into the capillary channels. The Ag layer acts as a seed for the Cu metal growth and the filling of the structure is controlled by the number and spacing of the deep channels. As shown in Figure 1, complete filling of the initial imprinted channel can be obtained, yielding extraordinarily large height/width aspect ratios. As shown in the comparison in Figures 1B and 1C, the two-level imprint offers the advantage of producing a conductor that is flush with the substrate surface. The completed Cu conductors exhibit conductivities that are within a factor of two of bulk values. Importantly, continuous Cu conductors many centimeters in length can be manufactured by judicious placement of ink reservoirs (1-2 cm apart). Key aspects of this conductor manufacturing process have been carried out with our roll-to-roll equipment (See Figure 2).

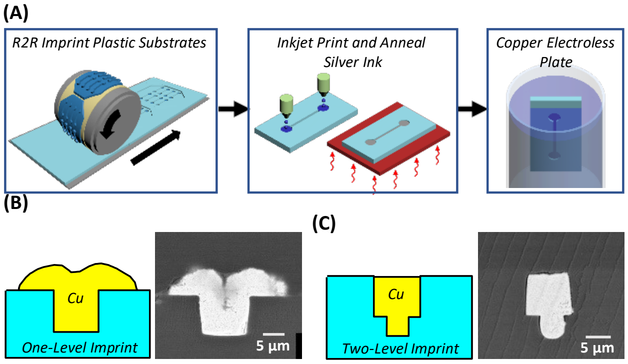

Figure 1: High aspect ratio embedded copper conductors by SCALE: (A) Fabrication sequence: R2R imprinting of substrates, inkjet printing and annealing of silver seed layer, and copper electroless plating; (B) Schematic diagram and cross-sectional SEM image of conductors fabricated in a one-level imprint with a 10 µm wide x 10 µm deep channel, (C) Schematic diagram and cross-sectional SEM image of conductors fabricated in a two-level imprint with a 10 µm wide x 10 µm deep main channel with a 5 µm wide x 5 µm deep inner channel. Silver seed layer is very thin and not shown in (B) and (C). (Adapted from [3] and [4]).

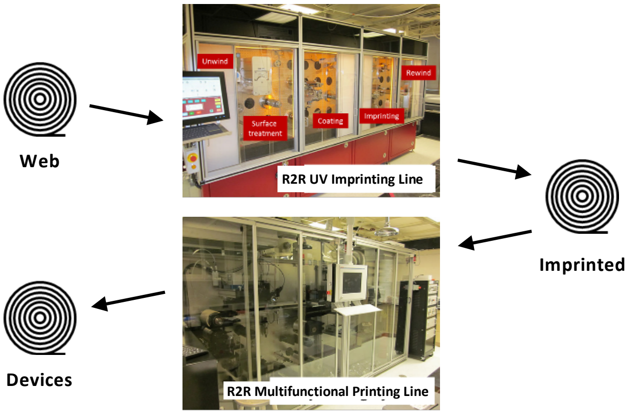

Figure 2: Two roll-to-roll lines at the University of Minnesota. The two key steps in SCALE are completed in sequence: UV imprinting followed by ink-jet printing.

The second half of the talk will demonstrate R2R-compatible, SCALE-based approaches to making discrete components, such as resistors, capacitors, and diodes. One approach to resistors leverages a recently discovered microfluidic diode structure to control ink flow in open capillaries [6]. The principle of the microfluidic diode involves a two-level junction joining a narrow, shallow capillary and a wide, deep capillary is fabricated by imprinting. Ink reservoirs connect to these two capillaries at either end. We find that ink delivered to the narrow capillary stops at the junction, whereas ink delivered to the wide capillary passes through the junction. Thus, there is one way flow through the two-tier junction and it thus serves a microfluidic diode. This structure can be used to advantage in the SCALE process when making devices. For example, resistors having precisely defined dimensions were made. Ag ink is first fed to the ink reservoirs on the left and right side of the device (not shown). The Ag ink flows toward the two-tier junction and is pinned at the junction. Subsequent delivery of resistive ink (e.g., carbon black or PEDOT:PSS) results in filling of the resistor device cavity and outward flow of the resistive material over the ends of the Ag electrodes. Good overlap between the resistive material and the Ag electrodes is obtained by taking advantage of the easy-flow direction of the microfluidic diode junctions. The end result is a very well-defined resistor structure with smooth, sharp features, and a resistance value that scales very clearly with length, as expected.

Ongoing work in our laboratories focuses on more complex device structures such as diodes and transistors that involve multiple layers of materials. If time permits, some of our recent progress in these areas will also be covered.

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