

Supplementary Material (ESI) for Lab on a Chip
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Supporting Information for
Thin, Lightweight, Foldable Thermochromic Displays on Paper

Adam C. Siegel, Scott T. Phillips, Benjamin Wiley, and George M. Whitesides

Department of Chemistry and Chemical Biology, Harvard University

12 Oxford St., Cambridge, MA, U.S.A.

Fabricating the Display. We designed patterns of electrically conductive pathways on a computer using a layout editor (Clewint, WieWeb Inc.) and produced stencils from the patterns in plastic transparency film (thickness = 100 μm , Clear Choice Inc.) using a computer-controlled laser engraver (VersaLaser VLS3.50, Universal Laser Systems Inc.) (Figure 1A-B). The laser engraver produced stencils with apertures as small as 100 μm , and the time from designing the pathways to producing a stencil (22 cm \times 28 cm) was <10 min.

As an alternative to using the laser engraver, we also ordered Mylar and stainless steel stencils from a commercial vendor (Stencils Unlimited LLC, Lake Oswego, OR) based upon the design. The time from designing the pathways to receiving the finished stencil was <24 hrs.

We affixed the stencil to a paper substrate (3R11205 glossy 32 lb photo paper, Xerox Inc.) by applying a thin coating of spray-adhesive (3M Spray Mount, 3M Inc.) to one side of the stencil, and by pressing the stencil firmly to the paper. We used glossy paper because it has a very low surface roughness, which makes it easier to pattern electrically conductive pathways on the surface.^[28]

We deposited 100% Sn metal through the stencil and on the surface of the paper by e-beam evaporation (Temicsal Inc.). Using this method of deposition, it was possible to pattern layers of Sn and other metals (Zn, In, Ag, Au) up to 2 μm thick. It also was possible to sputter deposit metal (e.g., Ag, Au) with thicknesses up to 1 μm on paper using a desktop sputtering system (208HR, Cressington Inc.). Sputter-deposition requires a lower vacuum and less time than evaporation (\sim 75 mTorr and \sim 15 min/deposition vs. 20 μTorr and \sim 3 hr/deposition for evaporation) and may be less expensive for bulk applications. We chose evaporation in these experiments because it produces thicker metallic pathways than produced by sputtering with less variance in resistance, and it can be performed using inexpensive metals (e.g., Sn, Zn).

It also was possible to pattern electrically conductive wires without the use of specialized equipment (e.g., evaporators or sputter deposition systems) using spray-deposition of nickel and conductive carbon inks. The Ni spray (applied using an aerosol container from MG Chemicals Inc.) consists of conductive Ni flakes suspended in an acrylic base. Applying the spray to a substrate and curing at room temp (15 min) produced an electrically conductive surface (surface resistance = $\sim 0.7 \Omega/\text{square}$). We also purchased electrically conductive carbon ink (Graphite Conductive Adhesive 112, EMS Inc) consisting of 34% graphite particles in acrylic. Spray depositing a 1:1 mixture of carbon ink and ethyl alcohol using an airbrush (Model 200 Portable Airbrush System, Badger Co.) and curing at room temp (15 min) produced an electrically conductive surface (surface resistance = $\sim 10 \Omega/\text{square}$). Spray-deposition of metal is inexpensive and can be applied at room temperature without electricity or specialized equipment, however, the technique gives features with poorer resolution and substantially lower conductivity than features produced using evaporation or sputter-deposition, and it produces a brittle coating that tends to fracture when stressed.^[21] After evaporation, we peeled the stencils away from the paper substrate, which left behind metallic wires on the surface of the paper.

We produced a solution of thermochromic ink by mixing 35 g of Leuco Dye Powder #43 (9 wt%, Color Change Inc.), 40 mL of butanone (59 wt%), 100 mL of pentyl acetate (25 wt%), and 30 g of poly(methyl methacrylate) (PMMA, MW = 2000, 7.4 wt%). We coated the opposite, un-patterned surface of the paper (the “front side” of the display) with a layer of the leuco dye by spray-depositing the ink on the paper using a handheld airbrush (Model 200 Portable Airbrush System, Badger Co.), and by allowing the ink to dry (~ 15 min). This action produced a thin, smooth layer of leuco dye (thickness = $\sim 100 \mu\text{m}$) on the front side of the display. We cured the thermochromic ink by heating the paper to $80 \text{ }^\circ\text{C}$ for 5 seconds on a hotplate, followed by

cooling to room temperature (25 °C). This curing step is needed to ensure a consistent transition from opaque to transparent in the context of the display. Without this curing step, the unheated leuco dye remains a darker shade of grey than the leuco dye that is heated after activating the display.

Description of the electronic circuit used to power the display. We used a voltage-controlled current source to drive the display with currents ranging from 0–100 mA with resulting bias voltages of 0–10 V (Figure S1). We formed electrical connections between the circuit and the display by attaching flat alligator clips (BU-34, Mueller Inc.) to metal pads patterned on the surface of the paper.

Building the multi-color display. We (i) printed colored ink on the front side of a sheet of paper using a LaserJet printer (Phaser 6250, Tektronix, Inc.); (ii) patterned metal on the back side of the paper to form three discrete heating elements, each located directly opposite a designated section of the colored paper; and (iii) spray-deposited thermochromic ink on the front side of the paper to cover the colored regions.

Building a seven-segment display. The methods we describe in this article can be used to fabricate common displays like seven-segment numerical displays (Figure S2). The display comprises seven distinct, individually addressable wires (heating elements) patterned on paper and covering a 4 cm × 4 cm area. Applying current to the terminals activates the display and generates visible numbers: 0 through 9.

Figure S1. Schematic diagram of the circuit used to power the display.

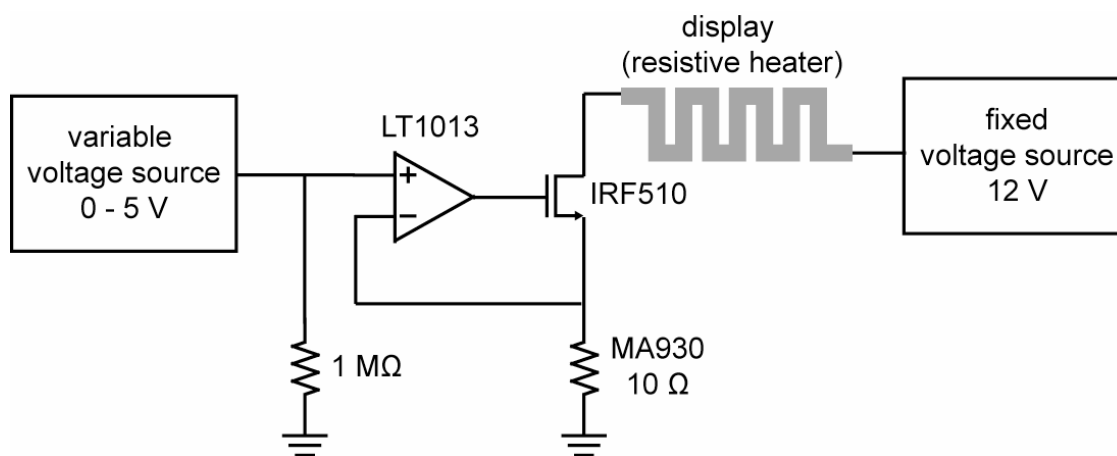


Figure S2. A seven-segment numerical display. The top images show the back side (left) and front side of the display, and an inactivated display (right). We used an LED seven-segment display driver to supply electrical current to several discrete elements at one time, and to generate the numbers 0–9.

