Supporting Information for

Foldable Printed Circuit Boards on Paper Substrates

Adam C. Siegel, Scott T. Phillips, Michael Dickey, Nanshu Lu, Zhigang Suo,

and George M. Whitesides

Department of Chemistry and Chemical Biology, Harvard University

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

Materials

We used a variety of paper and fiber-based substrates of various thickness, weight, price, and surface roughness to build circuits (Table S1). In general, substrates with low surface roughness also had the lowest surface resistivity, making them the most suitable for forming conductive pathways by evaporation or sputter-deposition.

We studied a variety of metals with differing electrical conductivity, mechanical property, melting point, and price for producing electrically conductive pathways on paper (Table S2). We used the ratio of electrical conductivity to hardness as a metric for ranking metals to fliter those that have both high conductivity and high ductility (low hardness). Tin and zinc were chosen as good metals for evaporation because of their high ratio of electrical conductivity to cost, their low melting temperatures (and thus ease in depositing thick layers), their relative ductility, their resistance to corrosion, and their low toxicity. Prices of metals represent the price/kg as of July 18, 2008 (London Metal Exchange: http://www.lme.co.uk).

Depositing metal on paper substrates

We designed patterns of metallic pathways on a computer using a layout editor (Clewin, WieWeb Inc.) and produced stencils from the patterns in plastic transparency film (thickness = 100 µm, Grafix Inc., Cleveland, OH) using a computer-controlled laser engraver (VersaLaser VLS3.50, Universal Laser Systems Inc.). The laser engraver produced stencils with apertures as small as 50 µm, and the time from designing the pathways to producing a stencil (22 cm × 28 cm) was <10 min.

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 bonded stencils to the paper by applying a thin coat of aerosol-based adhesive (3M spray mount, 3M Inc.) to one side of the stencil, and by pressing the stencil against the surface of the paper. The adhesive was chosen because it was strong enough to achieve conformal contact between the stencil and the paper, but weak enough to allow for removal of the stencil after the metal deposition.

We deposited metal on the paper/fabric substrates by (i) evaporating conductive metal through the stencil, (ii) sputter-depositing conductive metal through the stencil, or (iii) spraying conductive ink through the stencil (Figures 1, S1). For evaporation, a Temicsal e-beam evaporator was used to deposit metal layers up to 3 µm thick. For sputter deposition, a Cressington 208HR bench-top sputter coater was used to deposit metal layers up to 1 µm thick. For spray deposition, we held an aerosol can of conductive Ni ink (Super Shield Spray Coating, MG Chemicals, Inc.) approximately 40 cm away from the paper, and sprayed the ink through the stencil on the paper until the entire surface was coated with the ink. A single application deposited uniform metal layers ~50 µm thick; applying multiple coats produced layers up to 300 µm thick. Spray deposition is by far the least expensive method; a can of Ni spray coating, for example, costs $24 retail (volume = 355 mL) and contains sufficient material to coat a 10,000 cm^2 surface area.[46]

Examination of metal films using scanning electron microscopy

We used field emission scanning electron microscope (FESEM) Supra55VP (Carl Zeiss Inc.) to examine 1.5 µm thick Sn layers evaporated on Xerox Glossy Photo Paper at magnification (Figure S2). Bending the film positively (+180º) resulted in tensile rupture and delamination of the Sn film (Figure S2b); bending the film negatively (-180º) resulted in compression and extrusion of the Sn film (Figure S2c).

Bonding electronic components to paper

We prepared a commercially available two-part conductive adhesive (Circuit Specialists Inc.) by mixing equal volumes of the parts in a Petri dish. Immediately after mixing, we: (i) applied the adhesive to the metallic pathways using a syringe needle, and (ii) bonded discrete electronic components (e.g., integrated circuits, resistors, capacitors, transistors, diodes, mechanical switches, and batteries, all from Digikey Inc.) to the metallic pathways by pressing the terminals of the electronic component on the adhesive. The epoxy cured in <15 min, and formed permanent electrical connections between the components and the conductive pathways on the paper substrate.

Measuring electrical properties of paper circuits

We used a 2400 SourceMeter, Keithley Inc. to measure resistance of metallic wires patterned on paper. We used flat-tipped alligator tips (Pomona, Inc.) to connect the multimeter to the wires patterned on the paper circuit. Surface conductivity measurements were taken using a four-point probing station (Signatone Inc.).

Table S1. Representative substrates for fiber-based electronic circuits.

Table S1

Fiber-based substrate	Thickness (μm)	Weight (g/m^2)	Bulk price (US$/$m^2$)	RMS surface roughness (μm)	Surface resistivity 100% Sn metal 1 μm thick (Ω·sq.)
Xerox 32 Lb. Glossy Photo Paper	100	117.0	0.60	0.44	0.107
Staples Glossy Brochure Paper	200	193.0	4.00	0.72	0.176
Double Tack Adhesive Paper	130	158.0	10.00	1.70	0.160
Canson Glassline Waxed Paper	40	41.2	0.70	2.10	0.114
Yasutomo Origami Paper	70	67.2	1.00	2.40	0.230
Dupont Tyvek Fabric	120	48.8	1.00	2.70	0.322
Unprinted Newspaper	70	43.9	0.06	2.90	0.379
Staples Matte Brochure Paper	200	179.0	2.00	3.60	2.330
Wausau 24 lb. Copy Paper	140	107.0	0.70	3.60	0.183
Hammermill 20 lb. Copy Paper	100	79.2	0.10	4.20	0.289
Whatman Grade 1 Filter Paper	180	86.4	0.10	5.50	0.706
Brown Packing Paper	150	74.2	0.30	6.80	0.348
Scott Paper Towel	100	37.9	0.10	7.30	1.740
Non-Woven Polyester Fabric	100	67.6	2.00	20.00	2.860

Table S2. Properties of representative metals.

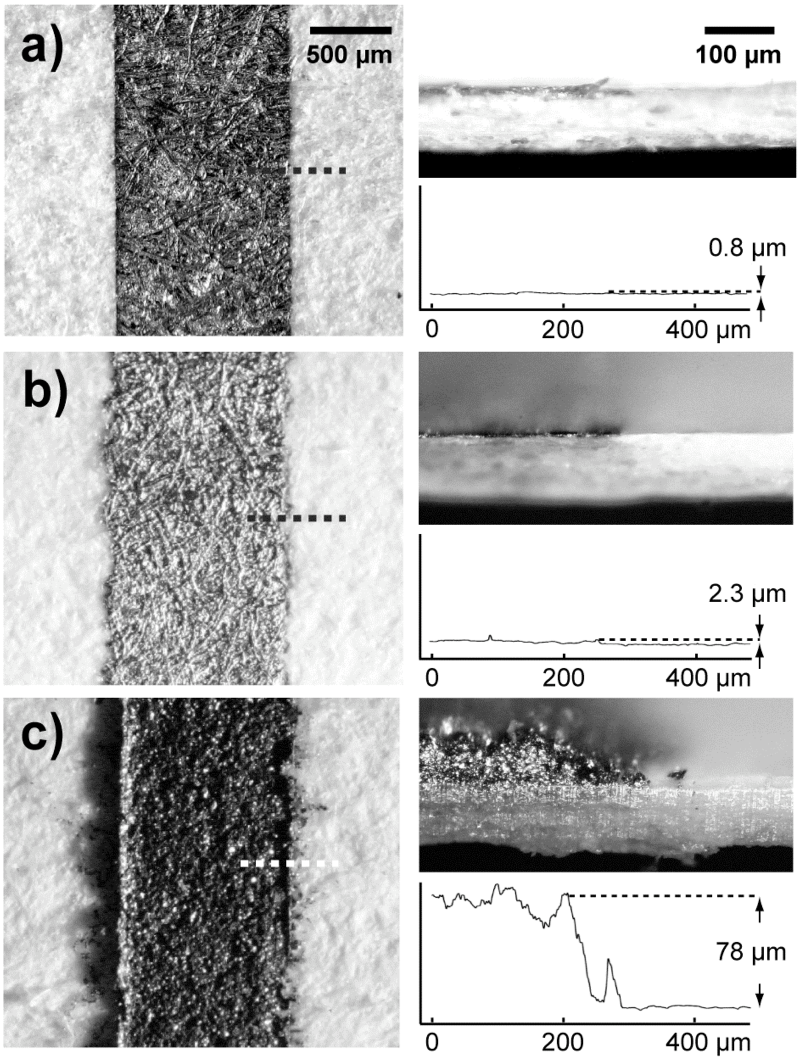
Table S2

Metal	Electrical Conductivity (10^6·S/m)	Brinell Hardness (MPa)	Young's Modulus (GPa)	Crystal Structure	Bulk Price (US$/kg)	Melting Point (°C)	Conductivity / price (kS·kg/m·US$)
Al	38.0	250.0	70	FCC	3.10	660.3	12,000.00
Zn	17.0	410.0	108	Hexagonal	1.80	419.3	9,400.00
Cu	60.0	870.0	119	FCC	8.30	1,085.0	7,200.00
Pb	4.8	38.0	16	FCC	1.90	327.5	2,500.00
Ni	14.0	700.0	200	FCC	20.00	1,455.0	700.00
Sb	2.9	290.0	55	Rhomb	5.60	630.6	520.00
Sn	8.7	51.0	50	Tetragonal	24.00	231.9	380.00
Ti	2.3	720.0	116	Hexagonal	9.60	1,668.0	240.00
Ag	63.0	25.0	83	FCC	640.00	961.8	98.00
Bi	1.0	94.0	32	Rhomb	31.00	271.5	32.00
In	12.0	8.8	11	Tetragonal	710.00	156.6	17.00
Au	45.0	38.0	78	FCC	31,000.00	1,064.0	1.50
Pt	9.5	390.0	168	FCC	59,000.00	1,768.3	0.16

FCC = Face-Centered Cubic, Rhomb = Rhombohedral

Figure S1. Deposition of metal on paper by different methods. Images show top view (left), cross-sectional view (top right), and cross-sectional profile (bottom right) for: a) sputter-deposition of 100% Ag metal (thickness = 0.8 μm); b) evaporation of 100% Sn metal (thickness = 2.3 μm); c) spray-deposition of nickel print (average thickness = 78.6 μm). Hammermill 20 lb copy paper was used as the substrate for all samples. Cross-sectional profiles were measured using a Dektak 8 surface profilometer (Veeco Inc.). The dashed lines have a length of 500 μm and indicate the direction in which the profile was measured. Cross-sectional photographs and profiles were obtained at close but different locations from the same sample; hence, the images do not match perfectly.

Figure S1



a)
500 µm
100 µm
0.8 µm
0
200
400 µm
b)
2.3 µm
0
200
400 µm
c)
78 µm
0
200
400 µm

Figure S2. SEM images of Sn deposited on paper. a) Top view image of 1.5 μm thick Sn layer showing cluster formation. b) Top-view images of the metal layer from a) after bending +180º and back (obtuse folding); c) Top-view images of the metal layer from a) after bending -180º and back (acute folding). In both b) and c), the left image shows the center of the wire; the right image shows the edge of the wire, where it borders the bare paper substrate underneath.

Figure S2