Foldable Printed Circuit Boards on Paper Substrates

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This paper describes several low-cost methods for fabricating flexible electronic circuits on paper. The circuits comprise i) metallic wires (e.g., tin or zinc) that are deposited on the substrate by evaporation, sputtering, or airbrushing, and ii) discrete surface-mountable electronic components that are fastened with conductive adhesive directly to the wires. These electronic circuits—like conventional printed circuit boards—can be produced with electronic components that connect on both sides of the substrate. Unlike printed circuit boards made from fiberglass, ceramics, or polyimides, however, paper can be folded and creased (repeatedly), shaped to form three-dimensional structures, trimmed using scissors, used to wick fluids (e.g., for microfluidic applications) and disposed of by incineration. Paper-based electronic circuits are thin and lightweight; they should be useful for applications in consumer electronics and packaging, for disposable systems for uses in the military and homeland security, for applications in medical sensing or low-cost portable diagnostics, for paper-based microelectromechanical systems, and for applications involving textiles.

1. Introduction

1.1. Flexible Electronics

New applications for electronics require systems that can be fitted into non-planar forms, or can be folded and unfolded for packaging or storage.[1–3] Technologies based on organic materials,[4–7] reel-to-reel printed polymers,[8–11] inkjet-printed chemicals,[12–14] carbon nanotubes,[15–17] and thin-film semiconductors[18–20] have all contributed to the development of flexible electronics. Advances in these areas have generated new applications, including flexible displays,[21–24] flexible and conformal antenna arrays,[25,26] electronic solar cell arrays,[27,28] radio-frequency identification (RFID) tags,[29,30] flexible batteries,[31,32] electronic circuits fabricated in clothing,[33,34] and biomedical devices.[35,36]

While the electronics community has been developing methods for fabricating flexible semiconductor-based integrated circuit technologies (flexible ICs), there has been somewhat less focus on flexible printed circuit boards (flexible PCBs), which typically comprise components with relatively large conductive features (> 100 μm in lateral feature size). In these circuits—which are also called "chip-on-flex technologies"—low cost, speed of fabrication, amenability to high-volume manufacturing methods (e.g., reel-to-reel printing), and the ability to integrate multiple, discrete components into a functional system are the parameters of greatest importance.[37,38] Currently, most commercially available flexible PCBs are manufactured on plastic substrates using a silk-screen printing process that is similar to that used to produce rigid PCBs.[39] A typical one-sided flexible PCB comprises five layers: i) a base layer of polyimide (25 μm thick), ii) a layer of adhesive (25 μm thick), iii) a layer of copper (36 μm thick), iv) a second layer of adhesive (25 μm thick), and v) a cover layer of polyimide.

Although this method of manufacturing flexible electronic circuits is inexpensive and convenient when large quantities of circuits are required, it has several disadvantages: i) it produces circuits with limited flexibility (e.g., the radius of curvature of a flexible substrate with elements patterned on one side is typically 3–6× its thickness, or approximately 600 μm for a standard 140-μm thick circuit).[40] This low level of flexibility makes it difficult to fold or crease these circuits to form permanent three-dimensional shapes. ii) It is expensive for small-quantity production and prototyping; for example, 10 cm × 10 cm patterned flexible PCB prototypes typically cost ≈ $50–200/piece (single sided) and ≈ $100–250/piece (double-sided) in addition to up to a ≈ $1 000 tooling fee when purchased in small quantities (≈ 10 pieces) from commercial foundries.[41]

1.2. Advantages and New Capabilities of Paper-Based Flexible PCBs

Paper, as a substrate for fabricating flexible PCBs, offers a set of properties that are completely different from the properties of polyimide plastics used in conventional flexible PCB technology. Using paper, it is possible to fabricate flexible electronic

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circuits i) on materials that literally are *everywhere*; paper is ubiquitous in modern society—it is the material of choice for disposable cups, product packaging, envelopes, books and other documents, biodegradable materials, and so on; ii) that can be folded, unfolded, and creased for storage in small spaces or to form three-dimensional self-standing structures; iii) that are accessible quickly and at low cost on a typical chemical or electronics bench (e.g., for prototyping applications); iv) that can be trimmed with scissors or perforated for easy tearing; v) that are considerably thinner and lighter in weight than current circuit platforms (currently, the thinnest commercially available flexible PCBs are $\approx 140\,\mu$m thick; the technique described in this article allows us to produce a PCB that is $< 50\,\mu$m thick);[37,38] vi) that are porous or breathable and may be useful for applications in adhesive medical electrodes; vii) that can be combined with micro-portable analytical devices or paper-based microfluidics (μPADS) to analyze samples that wick in and fill microchannels.[42–44]

In this communication, we characterize several properties of paper-based electronic circuits, including i) the relationship between surface conductivity of the metallic wires and the surface roughness of the substrate; and ii) the mechanical stability of the wires as a function of the angle of crease, and of the number of cycles of creasing and unfolding (fatigue). We also demonstrate and prototype two functional applications: a battery-powered circuit that contains an LED (light-emitting diode) that flashes on/off with variable frequency, and a tamper-proof electronic security envelope.

2. Experimental Design

2.1. Choice of Substrate

Papers and other fiber-based materials are integral components of many of the materials with which we interact on a daily basis, and are available in almost limitless choices of composition, thicknesses, surface roughness, weight, strength, price, and wetting/wicking properties (see Table S1 in the Supporting Information for a list of papers that we studied). Because we were most interested in building circuits that would be easily adaptable to everyday products, we focused not on specialty papers, but rather on common papers that can be found in a typical office or stationary shop (e.g., printing paper, brochure paper, packaging paper, etc.).

2.2. Choice of Metal and Deposition Technique

Paper-based circuits that are flexible require the use of electrically conductive materials that also are flexible. Tin, zinc, silver, and indium are metals that are ductile and easily bent when deposited as thin films, while still maintaining electrical conductivity (see Table S2 in the Supporting Information for a list of metals and their properties on paper). In particular, the combination of high conductivity (electrical resistivity $= 115\,\mathrm{n}\Omega$ m and $59\,\mathrm{n}\Omega$ m at $25\,^\circ$C), resistance to corrosion, low toxicity, and low cost ($\approx$ \$24 per kg and $\approx$ \$2 per kg) of tin and zinc make these metals attractive for prototyping paper-based PCBs. The relatively low melting points ($232\,^\circ$C and $419\,^\circ$C, respectively) of these metals also make them easy to evaporate at low temperatures, and therefore, with low requirements for energy.

We used evaporation and sputter deposition to pattern metals on the surfaces of paper[45] (see Fig. S2a and b in the Supporting Information for cross-sectional images). Evaporation is applicable to a variety of metals, and deposits metal at rates of up to $50\,\mathrm{nm\,s^{-1}}$, but requires expensive equipment and a high vacuum ($> 20\,\mu$Torr). Sputter deposition, in contrast, can be performed using less expensive equipment and at a lower vacuum ($> 75\,000\,\mu$Torr), but deposits metals at a lower rate than evaporation (e.g., $1\,\mathrm{nm\,s^{-1}}$ for Au, with lower rates and higher energy requirements for other metals).

For rapid prototyping we also use spray deposition of nickel or silver (see Fig. S1c in the Supporting Information). The spray—which can be applied via an airbrush or an aerosol container—consists of metal (commonly Ni or Ag) flakes suspended in an acrylic base. Applying the spray to a substrate and curing at room temp (15 min) produces an electrically conductive surface; this surface has a sheet resistance $= 0.7\,\Omega$/square for Ni, $0.01\,\Omega$/square for Ag at $\approx 40\,\mu$m thickness, where sheet resistance R_s is defined as the resistance of a metal wire of identical width (w) and length (l) and uniform resistivity (ρ) and thickness (t), and is expressed as $R_s = \rho/t$.[46] Spray-deposition of metal is inexpensive and can be applied at room temperature without specialized equipment; these characteristics make it useful for testing a design before incurring the expense of evaporation or sputtering. The technique does have several disadvantages: it gives features with poorer resolution and lower conductivity than features produced using evaporation or sputter-deposition, it produces a brittle coating in which metal-containing film flakes from the substrate when bent, and (using Ni) it produces devices that are ferromagnetic, a property that may or may not be desirable in a specific application.

2.3. Choice of Adhesives for Electronic Components

Surface-mountable devices (SMDs) and other electronic components can be attached to paper substrates using commercially available conductive epoxies. Conductive epoxies are ideal for bonding to paper substrates because they can be applied and cured at room temperature, and require no flux (e.g., rosin-based chemicals used to free oxide during soldering; these liquids can wick in and damage the paper substrate).

3. Results

3.1. Patterning Electrically Conductive Wires on One Side of a Paper Substrate

3.1.1. Patterning Metal on Paper Substrates

We used a multi-step process to pattern wires on paper substrates (see Supporting Information for details). We generated a design for the conductive pathways using a computer, and obtained thin-film plastic stencils based on the design using a portable laser engraver

(≈ 10 min), or by ordering them directly from a commercial vendor (≈ 24 h). We then used an aerosol-based adhesive to attach the stencils to the paper, and deposited metal through the stencils and onto the paper by evaporation, sputter deposition, or spray deposition (Fig. 1). Peeling the stencils away from the paper left metallic pathways on the paper substrate in the pattern of the apertures of the stencil. E-beam and sputter deposition produced metal layers up to several micrometers thick, whereas spray deposition produced uniform metal layers 50–300-μm thick, depending on the number of coats. Spray deposition was by far the least expensive method for producing prototypes; a 355-mL can of nickel spray, for example, costs $24 (retail), contains sufficient material to coat an area up to 10 000 cm^2, and feature and gap resolutions down to ≈ 150 μm; for comparison, sputter deposition and evaporation produce wires with feature and gap resolutions down to ≈ 50 μm. Papers with rough surfaces (in which it was difficult to achieve conformal contact between the stencil and the paper) typically gave wires with poorer resolution than those produced on papers with smooth surfaces.

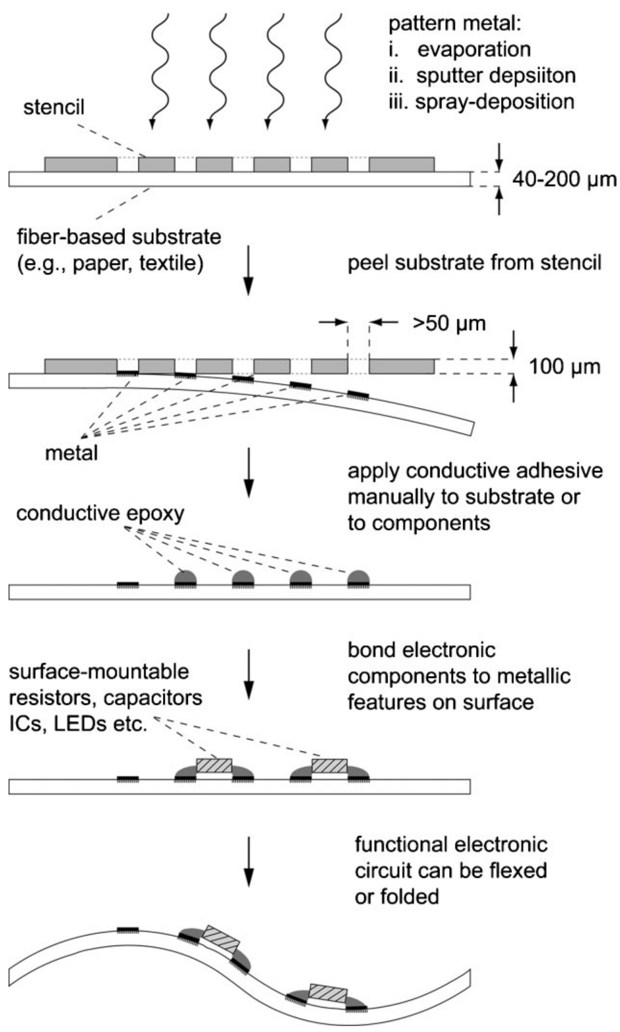

Figure 1. a) General scheme for fabricating flexible electronic circuits on fiber-based substrates. A photograph of an example circuit is shown in Figure 6a.

3.1.2. Physical Structure of Metal Wires on Paper

Evaporation, sputter deposition, and spray-deposition produced metal wires in which most of the applied metal adhered to the surface of the paper, with little metal penetrating into the paper itself (Fig. S1 in the Supporting Information). For papers with high porosity and/or surface roughness, we observed greater penetration of metal into the paper substrate, probably because gaps between fibers located at the outer regions of the paper allowed metal to attach to the inner fibers. Spray deposition also resulted in greater penetration of metal because the solvent promoted transport of particles into the paper. Spray deposition of Ni ink on Whatman 1 filter paper produced conductive wires that passed through the full thickness of the paper (data not shown).

3.1.3. Measuring the Conductivity of Metal on Paper versus Surface Roughness

We measured the surface resistivity (the inverse of the surface conductivity) of a 1.0-μm-thick layer of 100% Sn metal deposited on a variety of paper and fabric substrates—each with a different surface roughness—using a four-point probe (Fig. 2, and Table S1 in the Supporting Information). Metals patterned on papers and fabrics with low RMS surface roughness (e.g., < 1 μm) had lower surface resistivity than metals patterned with approximately the same thickness on papers and fabrics with high RMS surface roughness (e.g., > 5 μm); a mathematical fit of the data shows that the surface resistivity depends on the surface roughness exponentially. We believe this observation is due to an increase in the length of the conductive pathway from the non-uniform (rough) topography of the paper substrate. When we patterned thin layers of metal (e.g., ≈ 500-nm thick), we observed an increase in the dependence of the resistance of the paper on the surface roughness in comparison to thicker layers of metal (≥1 μm thick, data not shown), which we believe is caused by a reduction in the

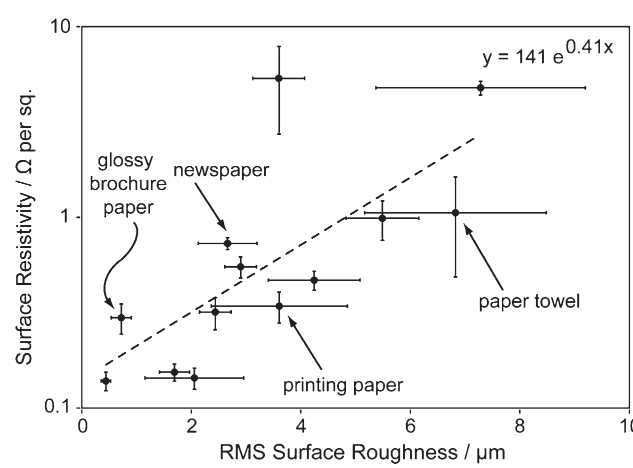

Figure 2. Surface resistivity of a layer of metal versus the surface roughness of the paper on which it is patterned. A list of the substrates used is given in Table S1 in the Supporting Information. Surface resistivity was measured using a four-point probe at 21 °C and 22% relative humidity. Values of surface roughness and resistivity describe the average of five measurements (resistivity) and three measurements (surface roughness). Error bars represent the standard deviation. The dashed line describes a mathematical fit of the dependence of surface resistivity on surface roughness.

overall number of electrically conductive connections created by patterning very thin layers of metal on a fibrous substrate with nonzero surface roughness.

3.1.4. Measuring the Mechanical/Electrical Fatigue of Wires versus Folding Angle

Paper-based circuits can be folded and still maintain function. We characterized the conductance of a 100% Sn wire (8 cm × 4 mm × 1.5 μm) prepared by evaporation on Xerox 32 lb Glossy Photo paper (thickness = 100 μm) as a function of the angle at which the paper was folded (Fig. 3a). We folded replica copies of the wire over machined Delrin manifolds with angles ranging from −180° (acute folding: a crease with metal on the inner surface) to +180° (obtuse folding: a crease with metal on the outer surface). The angles machined in the manifolds had a radius of curvature of ≈200 μm at their peak. In each instance, we measured the conductance of the wire using a multimeter while the paper was pressed against the manifold. The conductance through the wire decreased in proportion to the amount of the fold: folding the wires −90° led to a ≈5% decrease in conductance; folding the wires +90° led to a ≈11% decrease in conductance; folding the wires 180° in either direction led to a ≈15% decrease in conductance. This decrease in conductance results from fractures that form in the wire at the point of the fold (Fig. 3a inset).

3.1.5. Measuring the Mechanical/Electrical Fatigue of Wires versus Folding Iteration

Paper-based circuits maintain conductivity even after repetitive folding (Fig. 3b). We evaporated a 100% Sn wire (8 cm × 4 mm × 1.5 μm) on Xerox 32 lb Glossy Photo paper and measured the conductance of the wire as a function of the number of times we folded the sheet of paper, where one fold constituted folding the paper to a full crease (+180° or −180°) and back. The conductance of the wires decreased at a steady rate with each fold; the conductance of wires that we folded +180° (obtuse folding) decreased more rapidly than the conductance of wires that we folded −180° (acute folding). We observed full breakage (conductance = 0) in at least one of the samples starting at the sixth consecutive fold.

3.1.6. Analysis of the Failure of Metal Wires Folded on Paper Substrates

We used a field emission scanning electron microscope (FESEM) to study the microstructure and mode of failure of 1.5 μm thick tin wires evaporated on paper substrates subjected to folding (see Fig. S2 in the Supporting Information for images of the surface). The images showed that the as-deposited metal film grew in Volmer–Weber mode, and consisted of clusters with the size around 2 μm.[47] Similar patterns can be seen in both evaporated and sputtered Sn thin films, and are typically attributed to the high atomic mobility of Sn atoms.[48]

Bending a 1.5-μm-thick Sn film +180° (obtuse folding) and back produced a narrow band of the film with a width of ≈170 μm, which ruptured and delaminated from the paper substrate (Fig. S2b, the part of the film outside of the band remained intact). This delamination was caused by a deformation mismatch between the Sn film and its substrate; examination of the film edge showed that the most prominent cracks in the film aligned with the traces of greatest internal paper damage. These traces were found in the regions of the paper that were subjected to the maximum tensile strain.

Bending a 1.5-μm-thick Sn film −180° (acute folding) and back produced a 1.3 mm wide damaged area of the film, which was almost 10 times wider than the damaged area produced from obtuse bending (Fig. S2c, Supporting Information). The bending produced extrusion (outward buckling) of the Sn film, suggesting that the film had been subjected to extreme compression. Examination of the film edge showed that the film rupture was strongly correlated to the damage traces of the underlying paper.

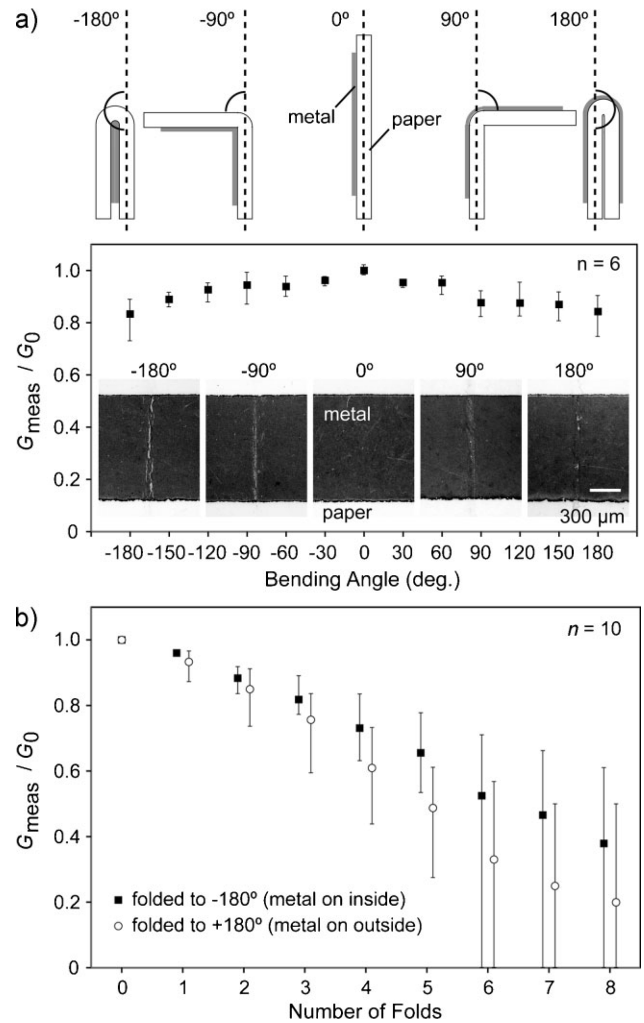

Figure 3. Flexibility of fiber-based electronic circuits. a) Schematic diagram of a metal wire patterned on paper and folded to various angles (top), and the ratio of measured conductivity (G_{meas}) to initial conductivity (G_0) of an evaporated tin wire on Xerox 32 lb glossy photo paper versus the angle to which the paper is folded (bottom); inset images show the wire at magnification folded −180, −90, 0, 90, and 180 degrees. b) The ratio of measured conductivity (G_{meas}) to initial conductivity (G_0) of an evaporated tin wire on Xerox 32 lb glossy photo paper versus folding iteration (fatigue). Error bars in all figures represent the full range of measurements; error in G_0 represents variance in values recorded from the multimeter.

Figure 3b shows that the measured conductivity of films bent acutely (−180°) is, on average, higher than those bent obtusely (+180°) after several iterations. We believe this observation results from the difference in the pattern of the fractures in films under compressive stress, and those under tensile stress. Acute bending produces multiple, small fractures in the metal film that are spread out over a larger area; these fractures do not individually span the width of the film, thus allowing conductivity around their edges. Obtuse bending, however, produces one or two large fractures; these fractures increase in size with each fold, decreasing conductivity through the metal wire to a greater degree than is observed in acute bending.

3.2. Patterning and Connecting Wires on Both Sides of a Paper Substrate

A useful characteristic in a printed circuit board technology is the ability to produce electrically conductive pathways on both sides of the substrate.[37,39] These "double-sided" PCBs allow electrically conductive wires to pass over and under other wires and allow for more freedom in the placement of electronic components. One of the challenges in building these two-layer circuits is in designing the "vias": electrically conductive elements that connect the wires on one side of the paper to those on the other side. We have developed two methods for producing vias in paper-based circuits: i) we pattern electrically conductive through-holes directly in the paper, and ii) we pattern electrically conductive tabs that fold around the edge of the paper to connect to the other side.

Vias to connect electronic components on opposite sides of a sheet of paper can be fabricated by patterning holes in the paper before evaporating metal (Fig. 4a). We generated holes in the paper by manually punching through it using a hole-puncher (diameter = 2 mm) purchased from an office-supply catalog, or by burning sharply defined holes in the paper (diameter = 200 μm) directly using a computer-controlled laser engraver. We then evaporated 100% Sn metal (thickness = 2 μm) through a stencil on both sides of the paper; this process coated both sides of the paper—and the interior walls of the hole—with metal, and generated electrical connection between the two sides of the paper. Using this technique, we fabricated an electrically conductive wire that transversed a sheet of paper through 70 vias in a crisscross pattern; an LED in this path illuminated (that is, there were no failures in 70 vias).

Metallic wires on opposite sides of a sheet of paper can also be connected by folding a conductive region of the paper out of the plane of the paper to bring it in contact with the other side (Fig. 4b). We produced electrically conductive pathways on both sides of a sheet of paper, and folded the paper over itself in a jellyroll configuration to bring the metal from one side of the paper in contact with the other; we sealed the metal regions together using conductive epoxy. This technique is not as scalable as the through-hole method of producing vias, but demonstrates the ability to fold paper to provide capabilities not available in conventional printed circuit-board technologies.

3.3. Insulating Paper-Based Circuits

Paper-based circuits can be electrically insulated and protected from water damage by applying a layer of clear acrylic or silicone-

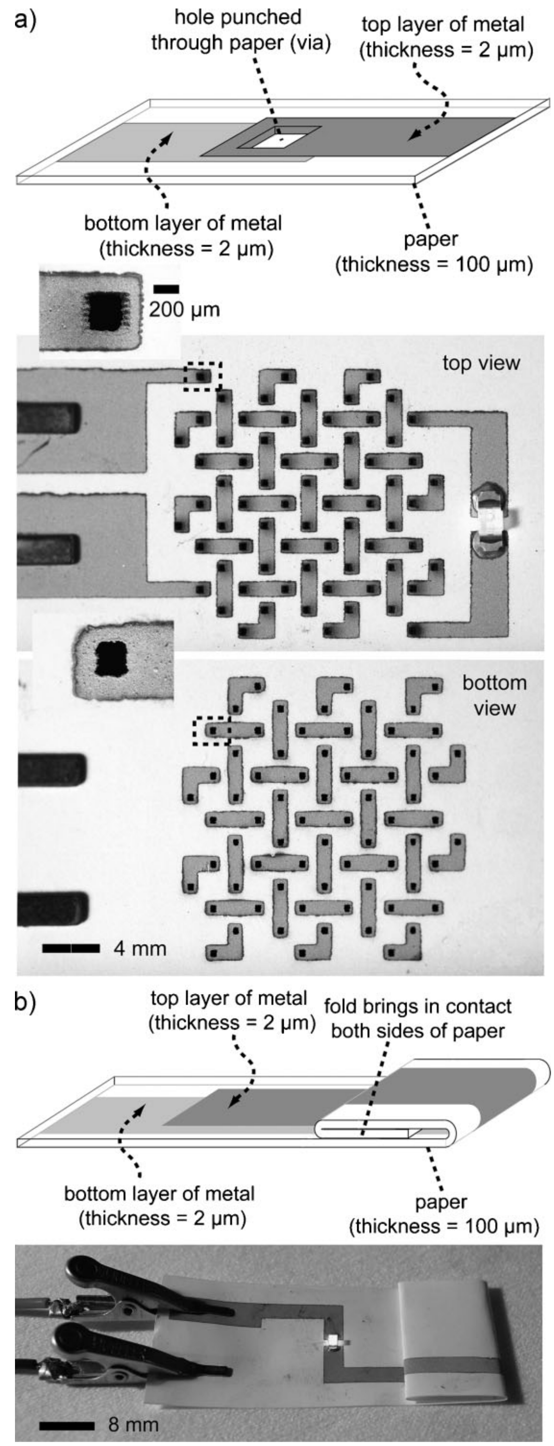

Figure 4. Connecting electrically conductive wires patterned on both sides of a sheet of paper. a) Schematic diagram of the through-hole method for connecting metal on both sides of a sheet of paper (above) and photographs of the top view (middle) and bottom view (below) of an electrically conductive pathway in a basketweave pattern, comprising 70 vias; the LED in the middle image is on, demonstrating conductivity of the wire. b) Schematic diagram of the folding method for connecting metal on both sides of a sheet of paper (above) and photograph of an electrically conductive pathway (below); the LED in the lower image is on, demonstrating conductivity of the wire.

based insulator following fabrication. Applying acrylic-based spray protectant (3M Inc.) and allowing it to dry (≈ 15 min) coated and electrically insulated both sides of the paper; it was also possible to coat the paper by dipping it in polydimethylsiloxane (PDMS) and curing in an oven (60 °C, 20 min). Applying the insulator increases the thickness of the paper (to 200 μm for acrylic and 500 μm for PDMS silicone) and increases the radius of curvature of the paper when folding, but does not affect electrical conductivity of wires or connections patterned on/in the paper.

3.4. Trimming and Disposing of Paper-Based Circuits

Paper-based circuits can be cut or trimmed easily using a pair of scissors or a razor blade (Fig. 5a). Perforating the paper using hand- or machine-based tools makes it possible to produce circuits that are easily torn by hand into pre-determined shapes. Patterning metal on certain fiber-based substrates (e.g., Tyvek) produces circuits that are difficult to tear by hand, but still can be cut with scissors or a razor blade.

Circuits patterned on burnable papers are disposable by incineration (Fig. 5b). We burned a circuit comprising tin wires patterned on Hammermill 20 lb printing paper using a flame from a match; the paper burned in approximately 3 s. This capability will, we believe, be useful in single-use medical supplies that contact biological fluids or tissues (e.g., analytical devices or bandages).

3.5. Topologically Complex Systems

Paper-based electronics can be used to produce a variety of functional circuits with complex shape in three dimensions. We designed and built a lightweight, battery-powered "paper airplane" with LED wing tips (Fig. 5c, top), and a circuit that takes the form of a self-standing origami "crane" with LED eyes that turn on/off (Fig. 5c, bottom). Each circuit comprised a metallic wire (100% In, thickness = 2 μm, width = 1 mm, length = 30–60 mm total) on Yasutomo origami paper, two surface-mountable LEDs, two resistors (67 Ω) and a watch battery (3.0 V). We bonded the LEDs, resistors, and battery to the circuit using a conductive adhesive (see Supporting Information).

3.6. Applications

Practical circuits comprising discrete electronic components are among the simplest applications of a printed circuit board technology. We fabricated a variable-frequency "flasher" circuit by bonding discrete electronic components to a paper substrate on which we had deposited a pattern of metallic pathways (Fig. 6a). The pathways (1–2 mm wide, 2 μm thick) were produced by evaporating a layer of 100% In through a stencil on the surface of Xerox 32 Lb. Glossy Photo Paper and then bonding electronic components to the circuit using a conductive adhesive (see Supporting Information). The circuit comprised a 3.1 V watch battery, two resistors (1 MΩ, 33 Ω), a capacitor (0.47 μF), a potentiometer (1 MΩ), a 555 timer integrated circuit, and an LED. The circuit could be turned on by folding a conductive region of the paper out of the plane of the circuit and bringing it in contact with the top (negative) surface of the battery (Fig. 6b and c). When on, the LED flashed at a fixed frequency that could be adjusted between 1–10 Hz using the potentiometer.

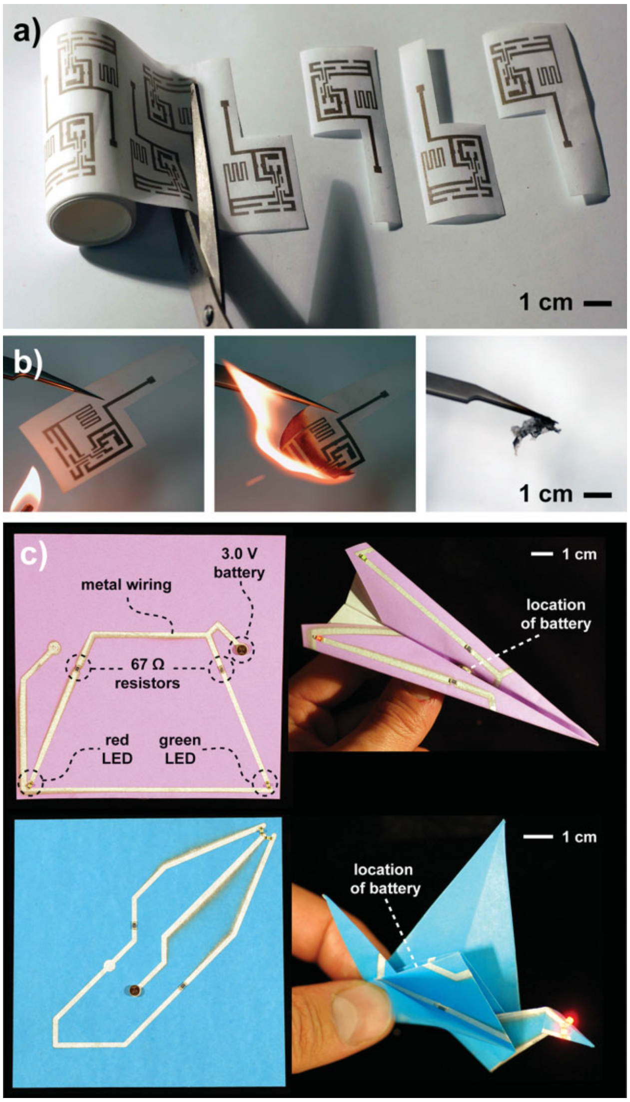

Figure 5. Properties of paper-based electronic circuits. a,b) Trimming and burning fiber-based electronic circuits; in (b), the paper circuit burned in 3 s. c) Topologically complex electronic circuits on paper demonstrating the ability to form foldable electronic circuits. (above) A paper airplane circuit shown unfolded (left) and folded (right) with battery-powered red/green LED wingtips. The circuit weighs < 1 g and glides like a typical paper airplane. (below) An origami "crane" shown unfolded (left) and folded (right) with battery-powered LED eyes. Electronic traces for both circuits comprised metallic wires (100% In, thickness = 2 μm, width = 1 mm, length = 30–60 mm total) patterned on Yasutomo origami paper substrates.

Paper-based electronic circuits can also be used to ensure security of envelopes and packages. We patterned an electrically conductive wire (100% Zn, thickness = 2 μm, width = 4 mm, total length = 96 cm) on the interior of a paper envelope (Fig. 6d). The envelope was folded and sealed using electrically conductive epoxy, which connected the wire patterned on the interior surface of the

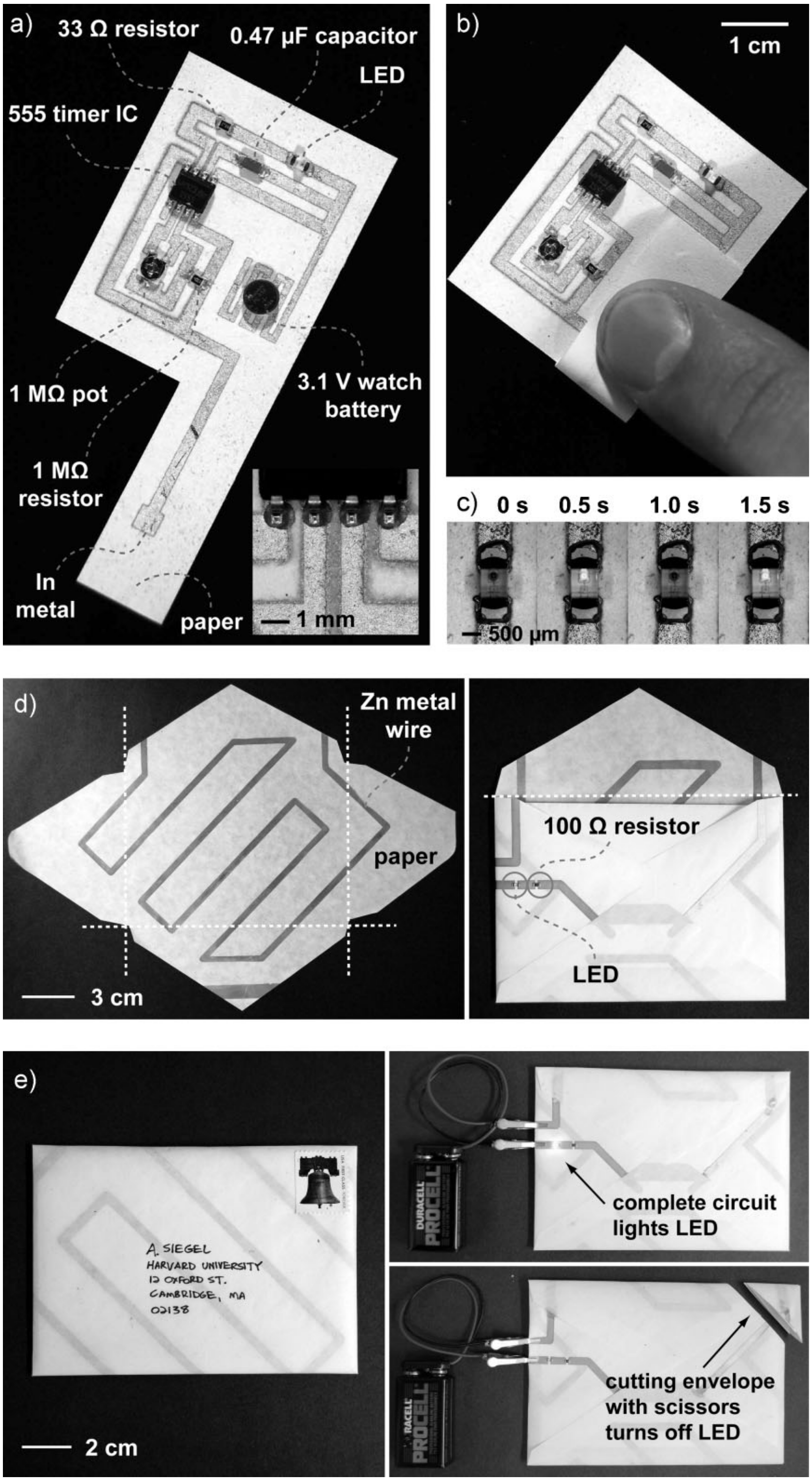

Figure 6. Applications of paper-based electronic circuits. a–c) A variable frequency "flasher" circuit fabricated on paper. d,e) A tamper-indicating "electronic envelope". Electrically conductive wires (100% Zn, width = 4 mm, height = 2 μm) are patterned on the interior surface of the envelope (Canson Glassline wax-coated paper). Dashed lines indicate the locations at which the envelope is creased. Passing current through an undamaged wire turns on an LED; tampering with the envelope (e.g., by cutting it with scissors) damages the wire and prevents the LED from turning on.

envelope to wires patterned on exterior surface. The wire was designed so that, when sealed, the conductivity of the wire could be tested using a simple LED circuit powered by a 9 V battery (Fig. 6e); the LED and resistor can be either located externally, or patterned on the envelope itself (as shown). Tampering with the envelope, either by prematurely opening the envelope or by cutting the envelope, led to an incomplete electrical circuit.

4. Conclusions

This article describes methods for producing simple electronic circuits on paper substrates. These substrates—which encompass a very broad range of materials, including paper, cellulose, polyimide, and nylon—are thin, lightweight, porous, inexpensive to manufacture, disposable, biodegradable, can be trimmed with scissors, and can be folded and creased into 3D structures that maintain their shape.

We believe these capabilities will make paper-based PCBs useful in a variety of applications including i) inexpensive, functional RFID (radio-frequency identification) tags (e.g., on the pages of books or clothing labels); ii) very low-cost reel-to-reel printed circuit boards for consumer electronics (e.g., for advertising or promotional use, such as cereal boxes); iii) three-dimensionally reconfigurable circuits that can be cut and folded to maintain shape, such as 3D antennas, 3D mechanical switches and relays, or paper-based microelectromechanical systems (MEMS); iv) medical sensing applications, such as porous electrodes that attach to the skin (e.g., for bandages, electrocardiography, electroencephalography, nerve conduction studies, or defibrillation); v) postal security, including the patterning of electronic circuits directly on envelopes and packaging; vi) electronic devices designed for disposal by incineration—such as those used in rockets—and explosives-based applications (e.g., fireworks); vii) lightweight circuits for air- or spacecraft applications; viii) low-cost, paper-based microfluidic diagnostics devices, in which an electronic interface is necessary to perform a function in, or record information from, the microchannel.

Paper-based circuits also have several limitations. Because the conductive wires in circuits formed in this manner are thin and reinforced only by the fiber-based substrate, repeated folding of the circuit causes fatigue in the metal and ultimate failure of the circuit. Similarly, the use of stencils and the need to achieve conformal contact between the stencils and the substrate can make it difficult to pattern features with dimensions less than the minimum feature size of the stencils ($\approx 50\,\mu$m for the laser engraving system we use), or to pattern features on highly fibrous papers, whose surface roughness is greater than the minimum feature size. In addition, because of the flammability of some paper- and fiber-based substrates, low-temperature techniques must be used (in most cases) to bond electronic components to the substrates.

PCBs on flexible, paper- and fabric-based substrates offer new opportunities for inexpensive, disposable, configurable circuit boards for portable applications where a circuit is required, but where the circuit may not be meant for continued use for months or years. These types of circuits may form the first step in the integration of electronics in materials that are present in all areas of modern society.

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