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Flexible electronic structures

Abstract

A flexible electronic structure includes a flexible substrate comprising an electrically conductive top substrate layer and an opposing electrically conductive bottom substrate layer and a component. The component can include a component substrate non-native to the flexible substrate having a component substrate top side and an opposing component substrate bottom side, a planar component top electrode disposed on the component substrate top side and electrically connected to the electrically conductive top substrate layer thereby defining a planar electrical contact, and a planar component bottom electrode disposed on the component substrate bottom side and electrically connected to the electrically conductive bottom substrate layer thereby defining a planar electrical contact. The component can be disposed between the electrically conductive top substrate layer and the electrically conductive bottom substrate layer.

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Background/Summary

PRIORITY APPLICATION (1) The present application claims the benefit of U.S. Provisional Patent Application No. 63/339,951, filed on May 9, 2022, the disclosure of which is hereby incorporated by reference in its entirety.

TECHNICAL FIELD

(1) The present disclosure relates generally to flexible electronic structures comprising integrated circuits on a flexible substrate.

BACKGROUND

(2) Flexible electronic systems are useful for a variety of applications in which the electronic system is integrated into flexible materials or structures, such as clothing, paper, bandages, including wearable and some medical devices. Integrated circuits can be disposed on flexible substrates, for example polymer substrates. Flexible printable circuits can be a part of flexible electronics in which electronic components are mounted on a flexible substrate and electrically connected with wires formed on the flexible substrate. Flexible substrates can include polyethylene naphthalate, polyethylene terephthalate, polyimide, polyether ether ketone, or generally polyester films or flexible glass.

(3) Some flexible electronic systems include active electronic components, such as transistors. The transistors can be made in relatively rigid crystalline semiconductor materials mounted on and non-native to a flexible substrate or can themselves be relatively flexible and formed on and native to the flexible substrate, for example organic electronics.

(4) Flexible electronic systems can be subject to extreme mechanical stress as the flexible substrate is flexed. Wires formed on the flexible substrate can crack as can electrical connections between wires on the flexible substrate and any relatively rigid electronic materials, such as relatively rigid crystalline semiconductor materials. In particular, the joint between a wire on a flexible substrate and any rigid structure is subject to exception mechanical stress as the flexible substrate is flexed.

(5) There remains a need, therefore, for mechanically robust systems, devices, circuits, and structures in flexible systems.

SUMMARY

(6) The present disclosure provides, inter alia, mechanically robust systems, devices, circuits, and structures useful in flexible systems.

(7) According to embodiments of the present disclosure, a flexible electronic structure comprises a flexible substrate comprising an electrically conductive top substrate layer and an opposing electrically conductive bottom substrate layer and a component. The component can comprise a component substrate non-native to (e.g., separate and independent from) the flexible substrate having a component substrate top side and an opposing component substrate bottom side, a planar component top electrode disposed on the component substrate top side and electrically connected to the electrically conductive top substrate layer thereby defining a planar electrical contact, and a planar component bottom electrode disposed on the component substrate bottom side and electrically connected to the electrically conductive bottom substrate layer thereby defining a planar electrical contact. The component can be disposed between (e.g., at least partly or entirely between) the electrically conductive top substrate layer and the electrically conductive bottom substrate layer. The flexible substrate can be a power-generating substrate and the electrically conductive top substrate layer, and the electrically conductive bottom substrate layer can be or comprise triboelectric layers. In some embodiments, the electrically conductive top substrate layer and the electrically conductive bottom substrate layer are a triboelectric power-generating pair.

(8) In some embodiments, the electrically conductive top substrate layer comprises an electrically conductive top substrate conductive layer and a top substrate power-generating layer. The top substrate conductive layer can be on a side of the top substrate power-generating layer opposite the component. The top substrate power-generating layer is on a side of the top substrate conductive layer opposite the component. In some embodiments, the electrically conductive bottom substrate layer comprises an electrically conductive bottom substrate conductive layer and a bottom substrate power-generating layer. The bottom substrate conductive layer can be on a side of the bottom substrate power-generating layer opposite the component. The bottom substrate power-generating

layer can be on a side of the bottom substrate conductive layer opposite the component.
(9) In some embodiments, the flexible substrate comprises a spacer between the electrically conductive top substrate layer and the electrically conductive bottom substrate layer. The spacer can comprise holes where no spacer material is present.
(10) According to some embodiments, the component is relatively rigid compared to the flexible substrate. The component substrate can comprise a crystalline semiconductor substrate.
(11) In some embodiments, the component has a thickness no greater than one hundred microns (e.g., no greater than fifty microns, no greater than twenty microns, no greater than ten microns, no greater than five microns, or no greater than two microns). An area of the component top electrode can have an area that is no less than 50% (e.g., no less than 60%, no less than 70%, no less than 80%, no less than 90% or no less than 100%) of an area of the component substrate top side. In some embodiments, an area of the component bottom electrode has an area that is no less than 50% (e.g., no less than 60%, no less than 70%, no less than 80%, no less than 90% or no less than 100%) of an area of the component substrate bottom side.
(12) The component can be an electronic or optoelectronic component and can comprise a light-emitting diode. The light-emitting diode can comprise at least a portion of a broken or separated LED tether as a consequence of micro-transfer printing.
(13) In some embodiments, the electrically conductive top substrate layer is transparent or comprises transparent openings through which the light-emitting diode can emit light or wherein the electrically conductive bottom substrate layer is transparent or comprises openings through which the light-emitting diode can emit light.
(14) According to embodiments of the present disclosure, the flexible electronic structure comprises a plurality of components disposed between (e.g., at least partly or entirely between) the electrically conductive top substrate layer and the electrically conductive bottom substrate layer and wherein the components are electrically connected in parallel. The flexible electronic structure can be a banknote, can be comprised in a portion of a banknote, or can be laminated on a banknote. The component can comprise at least a portion of a broken or separated component tether.
(15) Some embodiments of the present disclosure comprise a power generator electrically connected to the electrically conductive top substrate layer and the electrically conductive bottom substrate layer. The power generator can be disposed on the electrically conductive top substrate layer or on the electrically conductive bottom substrate layer. The power generator can be disposed between (e.g., at least partly or entirely between) the electrically conductive top substrate layer and the electrically conductive bottom substrate layer and is electrically connected to the electrically conductive top substrate layer and to the electrically conductive bottom substrate layer defining planar electrical contacts.
(16) Some embodiments of the present disclosure comprise multiple components electrically connected in parallel, multiple power generators electrically connected in parallel, or both. The multiple components or the multiple power generators can be electrically connected in parallel to the electrically conductive top substrate layer and the electrically conductive bottom substrate layer.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) The foregoing and other objects, aspects, features, and advantages of the present disclosure will become more apparent and better understood by referring to the following description taken in conjunction with the accompanying drawings, in which:
(2) FIG. **1** is a cross section of a flexible electronic structure comprising a component and a flexible substrate according to illustrative embodiments of the present disclosure;

(3) FIG. **2** is a cross section of a flexible electronic comprising a component and a flexible substrate with a spacer according to illustrative embodiments of the present disclosure;
(4) FIG. **3**A is a plan view of a flexible electronic structure comprising a component and a flexible substrate with a spacer having holes according to illustrative embodiments of the present disclosure;
(5) FIG. **3**B is a cross section of a flexible electronic structure comprising a component and a flexible substrate with a spacer having holes taken across cross section line A of FIG. **3**A according to illustrative embodiments of the present disclosure;
(6) FIG. **4**A is a cross section of a flexible electronic structure comprising a component and a flexible substrate with electrically conductive and power-generating layers according to illustrative embodiments of the present disclosure;
(7) FIG. **4**B is a cross section of a flexible electronic structure comprising a component and a flexible substrate with opaque electrically conductive layers with holes and power-generating layers according to illustrative embodiments of the present disclosure;
(8) FIG. **5**A is a cross section of a flexible electronic structure comprising a component and a flexible substrate with a spacer according to illustrative embodiments of the present disclosure;
(9) FIG. **5**B is a cross section of a flexible electronic structure comprising a component with light-emitting diodes (LEDs) and a flexible substrate with a spacer and opaque component electrodes with holes through which LEDs can emit light according to illustrative embodiments of the present disclosure;
(10) FIG. **5**C is a cross section of a flexible electronic structure comprising a component with light-emitting diodes (LEDs) and a flexible substrate with a spacer and transparent electrodes through which the LEDs can emit light according to illustrative embodiments of the present disclosure;
(11) FIG. **6**A is a plan view of a flexible electronic structure comprising a component and a flexible substrate with a spacer having holes and electrically conductive layers adjacent to the spacer according to illustrative embodiments of the present disclosure;
(12) FIG. **6**B is a cross section of a flexible electronic structure comprising a component and a flexible substrate with a spacer having holes and electrically conductive layers adjacent to the spacer taken across cross section line A of FIG. **6**A according to illustrative embodiments of the present disclosure;
(13) FIG. **7** is a plan view of a flexible electronic structure comprising multiple components and a flexible substrate according to illustrative embodiments of the present disclosure;
(14) FIG. **8** is a cross section of a flexible electronic structure laminated to a document substrate with a laminated strip under pressure from a finger according to illustrative embodiments of the present disclosure;
(15) FIG. **9** is a plan view of a flexible electronic structure comprising a component with cracked component electrode connections and a flexible substrate according to illustrative embodiments of the present disclosure;
(16) FIG. **10**A is a cross section of a component according to illustrative embodiments of the present disclosure;
(17) FIG. **10**B is a cross section of a component comprising a vertical LED according to illustrative embodiments of the present disclosure;
(18) FIG. **10**C is a cross section of a component comprising a horizontal LED according to illustrative embodiments of the present disclosure;
(19) FIG. **10**D is a cross section of a component comprising a horizontal LED and a hole for light emission through an opaque component top electrode according to illustrative embodiments of the present disclosure;
(20) FIG. **11**A is a cross section of a flexible electronic structure with a power generator disposed on a flexible substrate according to illustrative embodiments of the present disclosure;
(21) FIG. **11**B is a cross section of a flexible electronic structure with a power generator disposed

between electrically conductive top substrate layer and electrically conductive bottom substrate layer according to illustrative embodiments of the present disclosure;
(22) FIG. **12**A is a cross section of a flexible electrical structure comprising a power generator and a component with top and bottom substrate conductor layers;
(23) FIG. **12**B is a cross section of a flexible electrical structure comprising a power generator and a component with top and bottom substrate conductor layers and top and bottom power-generating layers; and
(24) FIG. **12**C is a plan view of a flexible electronic structure comprising multiple components and power generators and a flexible substrate according to illustrative embodiments of the present disclosure.
(25) Features and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements. The figures are not necessarily drawn to scale. The vertical scale of the Figures can be exaggerated to clarify the illustrated structures.
DETAILED DESCRIPTION OF CERTAIN EMBODIMENTS
(26) Embodiments of the present disclosure provide mechanically robust flexible electronic and optoelectronic structures, systems, devices, and circuits useful in flexible electronic systems and applications. Some embodiments are useful in authenticating secure documents, such as banknotes, passports, other secure government documents, labels, and private financial instruments such as paper certificates, bond notes, and the like.
(27) According to some embodiments of the present disclosure and as illustrated in FIG. **1**, a flexible electronic structure **90** comprises a flexible substrate **10** comprising an electrically conductive top substrate layer **10**T on a top side of flexible substrate **10** and an opposing electrically conductive bottom substrate layer **10**B on a bottom side of flexible substrate **10**. A component **20** has a component substrate **22** non-native to (e.g., separate and independent from) flexible substrate **10** having a component substrate top side **22**T and an opposing component substrate bottom side **22**B. A component top electrode **24**T is disposed on component substrate top side **22**T and electrically connected to electrically conductive top substrate layer **10**T to define a planar electrical contact (a planar contact between two surfaces providing an electrical connection). A component bottom electrode **24**B is disposed on component substrate bottom side **22**B and electrically connected to electrically conductive bottom substrate layer **10**B to define a planar electrical contact. Component **20** is disposed between (e.g., at least partly or entirely between) electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B, for example on electrically conductive bottom substrate layer **10**B and under electrically conductive top substrate layer **10**T. Component **20** can be disposed on electrically conductive bottom substrate layer **10**B, for example by printing (e.g., by disposing with a pick-and-place tool or by micro-transfer printing), and electrically conductive top substrate layer **10**T can be laminated on component **20** and electrically conductive bottom substrate layer **10**B.
(28) In some embodiments, printed flexible electronic structure **90** is a banknote, can be comprised in a portion of a banknote, or is disposed on a banknote, for example laminated on a banknote. Printed flexible electronic structure **90** can be comprised in a secure document, such as a passport or other secure government document, a label, or a private financial instrument such as a paper certificate, bond note, and the like.
(29) In general, for clarity in the Figures the vertical axis is greatly exaggerated with respect to the horizontal axis. For example, flexible substrate **10** can have dimensions of 20 cm in length and 12 cm in width and component **20** can have a length or width of a millimeter or less. Similarly, flexible substrate **10** can have a thickness of one hundred microns and component **20** can have a thickness no greater than fifty, twenty, ten, for five microns.

(30) Component substrate **22** can be an integrated circuit such as a silicon circuit and can comprise electronic circuitry. Component **20** can comprise a light-emitting diode disposed on component substrate **22** and controlled by the silicon circuit and can be relatively rigid compared to flexible substrate **10**. Circuits in component substrate **22** can be electrically connected to component top electrode **24**T and to component bottom electrode **24**B. In some embodiments, a light-emitting diode (LED) disposed on component substrate **22** can be electrically connected to component top electrode **24**T and to component bottom electrode **24**B either directly or through a circuit. The electronic circuitry can cause the LED to emit light, thereby demonstrating that the printed flexible device is genuine. In some embodiments, component substrate **22** is a semiconductor substrate, e.g., a crystalline semiconductor wafer or substrate; in some embodiments component substrate **22** is a dielectric substrate such as glass, for example flexible glass (that can be less flexible than flexible substrate **10**), a polymer such as polyimide (that can be less flexible than flexible substrate **10**), or a rigid substrate such as silicon dioxide or silicon nitride. Flexible substrate **10** can comprise any combination of cloth, paper, cardboard, or polymers, for example polymer-coated or infused paper or cloth. Embodiments of the disclosure are not limited by specific materials in flexible substrate **10** or component **20**.

(31) A planar electrical contact is an electrical contact that extends over an area between two electrically conductive surfaces, for example between electrically conductive top substrate layer **10**T and component top electrode **24**T or between electrically conductive bottom substrate layer **10**B and component bottom electrode **24**B. Most conventional electrical contacts are substantially one-dimensional wires that are edge contacts extending from or over a single edge or single side of an integrated circuit, for example from an integrated circuit to an electrical substrate such as a printed circuit board. A substantially one-dimensional wire has a length that is much greater than its width, thickness, or cross section, for example having a width that is a few microns and an aspect ratio of width to length that is no less than ten, twenty, fifty, one hundred, five hundred, or one thousand. In contrast, a planar or area electrical contact on a substrate surface extends up to or is adjacent to all sides or edges of component substrate top side **22**T or component substrate bottom side **22**B of component substrate **22**. The planar or area electrical contact can be substantially two dimensional and has a thickness that is much less than its length and a thickness that is much less than its width. In some embodiments, a planar contact has a thickness no greater than five, two, or one micron and an aspect ratio of length to width of substantially one, or no greater than ten, no greater than five, no greater than two, or no greater than 1.5, or no greater than one. A planar contact can extend over substantially all of component substrate top side **22**T or component substrate bottom side **22**B, or extend over no less than 30%, (e.g., no less than 90%, 80%, 70%, 60%, 50%, or 40%) of component substrate top side **22**T or component substrate bottom side **22**B. Accordingly and in some embodiments of the present disclosure, component top and bottom electrodes **24**T, **24**B do not extend over a side or edge of component substrate **22** and electrically conductive top and bottom substrate layers **10**T, **10**B extend over more than one side or edge of component substrate **22**, for example two sides or edges of component substrate **22**, three sides or edges of component substrate **22**, four sides or edges of component substrate **22**, or all sides of or edges of component substrate **22**. Component top and bottom electrodes **24**T, **24**B can be portions of conductive planes as can electrically conductive top and bottom substrate layers **10**T, **10**B when flexible substrate **10** is not flexed. A planar electrical contact can have a length or width no less than ten μm (e.g., a length or width no less than twenty μm, a length or width no less than fifty μm, a length or width no less than one hundred μm, a length or width no less than two hundred μm, or a length or width no less than five hundred μm). A planar electrical contact can have an area that is no less than ten μm by ten μm or that is no less than one hundred μm.sup.2 (e.g., no less than twenty μm by twenty μm or that is no less than four hundred μm.sup.2, no less than fifty μm by fifty μm or that is no less than 2500 μm.sup.2, no less than one hundred μm by one hundred μm or that is no less than ten thousand μm.sup.2), no less than two hundred μm by two hundred μm or

that is no less than forty thousand μm.sup.2, no less than five hundred μm by five hundred μm or that is no less than 250,000 μm.sup.2, or no less than one mm by one mm or that is no less than one mm.sup.2).

(32) Component top and bottom electrodes **24**T, **24**B can be electrically conductive films disposed on component substrate **22**, for example a metal film (e.g., aluminum, gold, silver, tin, copper, or other metals or metal alloys), a conductive oxide, or an electrically conductive polymer film, for example polythiophene. In some embodiments, one or both of component top and bottom electrodes **24**T, **24**B is transparent, for example transmitting 50%, 60%, 70%, 80%, 90%, or 95% or more of incident visible light. In some embodiments, one or both of component top and bottom electrodes **24**T, **24**B is opaque for example transmitting less than 50%, 40%, 30%, 20%, 100%, or 5% of incident visible light. Where one or both component top or bottom electrodes **24**T, **24**B is opaque, it can comprise holes **34** (e.g., transparent openings) through which light is transmitted or a transparent fill **32** material, such as a resin or epoxy. Despite the presence of holes **34** through component top or bottom electrodes **24**T, **24**B, component top or bottom electrodes **24**T, **24**B can be contiguous so that an electrical charge supplied to any portion of component top or bottom electrodes **24**T, **24**B can flow to any or every other portion of component top or bottom electrodes **24**T, **24**B.

(33) In operation, electrical power is generated either with flexible substrate **10** or a structure disposed on or in flexible substrate **10**. The electrical power is electrically conducted through electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B. Electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B can be or comprise electrodes (e.g., positive and negative electrodes) that conduct electrical current to component **20**. Component **20** responds to the conducted electrical current to operate, for example component **20** can comprise one or more light-emitting diodes that emit light in response to the electrical current conducted by electrically conductive top substrate layer **10**T through a top planar electrical contact defined by component top electrode **24**T, to component **20**, and then through a bottom planar electrical contact defined by component bottom electrode **24**B to electrically conductive bottom substrate layer **10**B to complete the circuit. Alternatively, electrical current can be conducted in the opposite direction.

(34) As illustrated in FIG. **1**, component **20** is disposed between electrically conductive top and bottom substrate layers **10**T and **10**B (also referred to as top and bottom substrate layers **10**T and **10**B), for example by disposing component **20** onto electrically conductive bottom substrate layer **10**B and laminating electrically conductive top substrate layer **10**T onto electrically conductive bottom substrate layer **10**B and component **20**. In some embodiments and as shown in FIG. **2**, flexible substrate **10** comprises a spacer **30** (e.g., a spacing layer) disposed between top and bottom substrate layers **10**T, **10**B to separate top substrate layer **10**T from bottom substrate layer **10**B. Component **20** can be disposed on or in spacer **30**. Spacer **30** can be a flexible polymer but cannot prevent component top electrode **24**T from electrically contacting top substrate layer **10**T and component bottom electrode **24**B from electrically contacting bottom substrate layer **10**B. Such a spacer **30** can provide a flatter and more appealing surface to flexible electronic circuit **90**. Spacer **30** can be a polymer or paper layer having a thickness the same as or comparable to a thickness of component **20**.

(35) In some embodiments of the present disclosure, flexible substrate **10** can be a power-generating substrate, for example top substrate layer **10**T and bottom substrate layer **10**B are or comprise triboelectric layers comprising triboelectric materials such as polymers such as PTFE, FEP, PDMS, and Kapton with or without additives that are responsive to pressing, pinching, or any form of mechanical pressure or motion to separate charge on each of the triboelectric layers. Thus, top substrate layer **10**T can comprise different materials from bottom substrate layer **10**B, e.g., top substrate layer **10**T and bottom substrate layer **10**B can comprise positive and negative triboelectric materials, respectively, or vice versa. Such polymer triboelectric materials can be elastic materials

that regain their shape after compression from mechanical pressure so that they can repeatedly separate charges in response to the mechanical pressure.

(36) In some embodiments of the present disclosure, spacer **30** can prevent or inhibit top substrate layer **10**T and bottom substrate layer **10**B from contacting or sliding along each other, diminishing the tribo-electric effect between top and bottom substrate layers **10**T, **10**B. To overcome or mitigate any such inhibition, spacer **30** can comprise holes **34** so that top substrate layer **10**T and bottom substrate layer **10**B can touch or closely approach each other through holes **34**, as shown in FIGS. **3**A and **3**B. As shown in the plan view of FIG. **3**A and the corresponding cross section across cross section line A of FIG. **3**A shown in FIG. **3**B, holes **34** are shown as relatively small, but in practice, a significant percentage of the area of spacer **30** (e.g., a majority of the area) can comprise holes **34** so that top substrate layer **10**T and bottom substrate layer **10**B can contact ample, adequate, and significant area responsive to mechanical pressure or motion to separate charges in the tribo-electric layers. (FIGS. **3**A and **3**B are not relatively to scale.)

(37) In some embodiments, the triboelectric materials are less electrically conductive than can be desired so that each of top substrate layer **10**T and bottom substrate layer **10**B can comprise multiple layers or sub-layers to facilitate charge conduction from an area of pressure or relative motion on flexible substrate **10** to component **20**. In some embodiments and as shown in FIGS. **4**A and **4**B, top substrate layer **10**T comprises an electrically conductive top substrate conductor layer **14**T and a top substrate power-generating layer **12**T. Similarly, bottom substrate layer **10**B comprises an electrically conductive bottom substrate conductor layer **14**B and a bottom substrate power-generating layer **12**B. Top and bottom substrate power-generating layers **12**T, **12**B together separate charges in response to mechanical pressure or motion and the separated charges are electrically conducted by the top and bottom substrate conductor layer **14**T, **14**B, respectively, through the planar contacts defined by component top and bottom electrodes **24**T, **24**B and thence to component substrate **22** (integrated circuit **22**).

(38) As shown in FIGS. **4**A and **4**B, top substrate conductor layer **14**T is on a side of the top substrate power-generating layer **12**T opposite component **20**. Pressure P can force top and bottom substrate power-generating layers **12**T, **12**B together, compressing them to separate charges that are conducted to component **20** with top and bottom substrate conductor layers **14**T, **14**B.

(39) In some embodiments of the present disclosure and as shown in FIG. **4**A, top or bottom substrate conductor layers **14**T, **14**B and component top or bottom electrodes **24**T, **24**B can be transparent. In some embodiments of the present disclosure, top or bottom substrate conductor layers **14**T, **14**B and component top or bottom electrodes **24**T, **24**B can be opaque. Where the layers are opaque and it is desirable to emit light through at least some of the layers, holes **34** with or without transparent fill **32** can be provided in top or bottom substrate conductor layers **14**T, **14**B and component top or bottom electrodes **24**T, **24**B so that light can transmit through the layers, as shown in FIG. **4**B. Transparent fill **32** can be, for example a flexible or rigid transparent polymer. Holes **34** in the layers can be aligned and, despite the presence of holes **34**, top and bottom substrate conductor layers **14**T, **14**B and component top and bottom electrodes **24**T, **24**B can each be electrically contiguous and form a single electrical contact and conductor (e.g., holes **34** do not extend completely from one side of top or bottom substrate conductor layers **14**T, **14**B or component top or bottom electrodes **24**T, **24**B to another side.

(40) As shown in FIGS. **5**A-**5**C, spacer **30** separates top and bottom substrate power-generating layers **12**T, **12**B. Spacer **30** can comprise holes **34** enabling compression and contact between top and bottom substrate power-generating layers **12**T, **12**B. Top and bottom substrate power-generating layers **12**T, **12**B are absent directly above and below component **20** to enable electrical contact between top and bottom substrate conductor layers **14**T, **14**B and component top and bottom electrodes **24**T, **24**B, respectively. As shown in FIG. **5**A and corresponding to FIG. **4**A, top or bottom substrate conductor layers **14**T, **14**B and component top or bottom electrodes **24**T, **24**B can be transparent or opaque.

(41) Where the layers are opaque and it is desirable to emit light through at least some of the layers, for example with light-emitting diodes (LEDs) **40**, holes **34** with or without transparent fill **32** can be provided in top or bottom substrate conductor layers **14**T, **14**B and component top or bottom electrodes **24**T, **24**B so that light can transmit through the layers, as shown in FIG. **5**B. As shown in FIG. **5**C, component **20** can comprise an LED **40** that receives power from top and bottom substrate layers **10**T, **10**B to emit light **80** through transparent top or bottom substrate conductor layers **14**T, **14**B or component top or bottom electrodes **24**T, **24**B.

(42) More generally, electrically conductive top substrate layer **10**T can be transparent or comprise transparent openings (e.g., holes **34**) through which light-emitting diode **40** can emit light **80** or the electrically conductive bottom substrate layer **10**B is transparent or comprises openings (e.g., holes **34**) through which light-emitting diode **40** can emit light **80**. Holes **34** in the layers can be aligned and, despite the presence of holes **34**, top and bottom substrate conductor layers **14**T, **14**B and component top and bottom electrodes **24**T, **24**B can each be electrically contiguous and form a single electrical contact and conductor.

(43) FIGS. **6**A and **6**B illustrate embodiments in which flexible substrate **10** comprises a spacer **30** between electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B. Top substrate layer **10**T comprises a top substrate power-generating layer **12**T and top substrate conductive layer **14**T. Bottom substrate layer **10**B comprises a bottom substrate power-generating layer **12**B and bottom substrate conductive layer **14**B. Top and bottom substrate conductor layers **14**T, **14**B are adjacent to spacer **30** and between spacer **30** and top and bottom substrate power-generating layers **12**T, **12**B, respectively. Holes **34** can be disposed in top and bottom substrate conductor layers **14**T, **14**B and spacer **30** to enable top and bottom substrate power-generating layers **12**T, **12**B to generate charges in response to pressure in holes **34** on top and bottom substrate power-generating layers **12**T, **12**B.

(44) FIG. **7** is a plan view of a flexible electronic structure **90** comprising multiple components **20** disposed under corresponding holes **34** or transparent fill **32** in top substrate conductor layer **14**T. The detail illustrates a planar electrical contact defined by top substrate conductor layer **14**T over component top electrode **24**T over LED **40** over component substrate **22**. Component top electrode **24**T covers most of component substrate **22** and top substrate conductor layer **14**T covers all of component substrate **22** and all of component top electrode **24**T.

(45) FIG. **8** is a cross section illustrating a flexible electronic structure **90** with flexible substrate **10**, spacer **30** with holes **34** and multiple components **20** disposed on or a part of a banknote **60** (or other paper or document, for example secure documents such as government documents or financial instruments). Components **20** are effectively electrically connected in parallel and can respond to a common electrical current provided through top and bottom substrate layers **10**T, **10**B. A laminated strip **62** (for example a transparent polymer strip) can be laminated on or over flexible electronic structure **90** to protect flexible electronic structure **90** from environmental contamination, such as liquids or gases and to provide further mechanical protection. FIG. **8** illustrates a finger providing pressure P on flexible electronic structure **90** to generate charges in flexible substrate **10** that are electrically conducted to electronically operate component **20**, for example to emit light from component **20**.

(46) A planar electrical contact provides advantages over conventional electrical wire contacts because it can be more robust and less likely to fail under mechanical stress as flexible substrate **10** is flexed. As flexible substrate **10** flexes, there is no single stress point, unlike wire contacts that are substantially connected at a point of the wire contact between a relatively less flexible integrated circuit package and a more flexible substrate. As shown in FIG. **9**, even if a portion of the planar contact cracks **50**, electricity can still flow around cracks **50** in a vertical direction orthogonal to the plane of the planar contact and horizontally around cracks **50**. Thus, in some embodiments, an area of component top electrode **24**T has an area that is no less than 50% (e.g., no less than 60%, no less than 70%, no less than 80%, no less than 90% or no less than 100% of the area of the component

substrate top side **22**T. Similarly, an area of component bottom electrode **24**B has an area that is no less than 50% (e.g., no less than 60%, no less than 70%, no less than 80%, no less than 90% or no less than 100% of the area of the component substrate bottom side **22**B. Moreover, in some embodiments an area of top substrate layer **10**T can be in electrical contact with substantially all of the area of component top electrode **24**T and an area of bottom substrate layer **10**B can be in electrical contact with substantially all of the area of component bottom electrode **24**B. In order to prevent any electricity from flowing through the planar contact (e.g., between electrically conductive top substrate layer **10**T and component top electrode **24**T or between electrically conductive bottom substrate layer **10**B and component bottom electrode **24**B), an entire layer of conductors comprising the planar electrical contact would have to be ripped off. Given that the planar electrical contact can be laminated and then covered with a protective layer, separating the two layers of electrical conductors can be quite difficult. Thus, planar electrical contacts in embodiments of the present disclosure can be robust and maintain an electrical connection when mechanically stressed.

(47) FIGS. **10**A-**10**D illustrate various embodiments of component **20**. As shown in FIG. **10**A, a conductor (electrode) **28** electrically connects a contact pad **72** of integrated circuit **22** insulated by dielectric structures **26** to component top electrode **24**T. A conductor (electrode) **28** also electrically connects a contact pad **72** of integrated circuit **22** to component bottom electrode **24**B through a through-silicon via (TSV) **29**. FIG. **10**B illustrates component **20** comprising a vertical LED **40** on integrated circuit **22**. Conductor **28** electrically connects to transparent or opaque component bottom electrode **24**B through TSV **29** and LED **40** electrically connects to transparent component top electrode **24**T to emit light **80** through transparent component top electrode **24**T in response to electrical current. FIG. **10**C illustrates component **20** comprising a horizontal LED **40** electrically connected to conductors **28** on integrated circuit **22**. Conductors **28** electrically connect to transparent component top electrode **24**T and to component bottom electrode **24**B through TSV **29** to emit light **80** through transparent component top electrode **24**T in response to electrical current. FIGS. **10**A-**10**C use transparent component top electrodes **24**T (for example polythiophene, indium tin oxide, or aluminum zinc oxide). FIG. **10**D illustrates component **20** comprising a horizontal LED electrically connected to conductors **28** on integrated circuit **22**. Conductors **28** electrically connect to component top electrode **24**T and to component bottom electrode **24**B through TSV **29** to emit light **80** in response to electrical current. Component top electrode **24**T is not transparent, for example comprising a metal coating and hole **34** (or transparent fill **32**) is provided for light **80** emitted by LED **40**.

(48) In some embodiments of the present disclosure, flexible substrate **10** generates electrical power, for example in response to mechanical stimulus such as pressing, squeezing, pinching, or other mechanical motion for example with a finger, fingers, or stylus. In some embodiments, electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B of flexible substrate **10** conduct electricity from a power generator **70**, as shown in FIGS. **11**A and **11**B. A power generator **70** can comprise, for example, one or more photovoltaic or piezoelectric, or both photovoltaic and piezoelectric, power generating materials and/or one or more photovoltaic or piezoelectric, or both photovoltaic and piezoelectric, circuits. In some embodiments, power generator **70** is disposed on flexible substrate **10** and electrically connected, for example with contact pads **72** to electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B of flexible substrate **10**, as shown in FIG. **11**A. In some embodiments, power generator **70** is disposed between (e.g., at least partly or entirely between) electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B of flexible substrate **10**, as shown in FIG. **11**B, can comprise a component substrate **22**, and component top and bottom electrodes **24**T, **24**B electrically connected to electrically conductive top substrate layer **10**T and electrically conductive bottom substrate layer **10**B, respectively, thereby defining planar electrical contacts. Thus, power generator **70** can be a type of component and the

structures and methods discussed with respect to component **20** can be applied to power generator **70**. Contact pads **72** can also be contact pads for generator **70**. Multiple power generators **70** and components **20** can be provided in flexible electronic structure **90** and can be electrically connected in parallel.

(49) FIG. **12**A illustrates a flexible electrical structure **90** with spacer **30** and power generator **70** disposed between (e.g., at least partly or entirely between) top and bottom substrate layers **10**T, **10**B that are top substrate conductor layer **14**T and bottom substrate layer **10**B can comprise bottom substrate power-generating layer **12**B and bottom substrate conductor layer **14**B, respectively. When power generator **70** produces electrical power, the electrical current can be conducted with top substrate conductor layer **14**T and bottom substrate conductor layer **14**B to component **20**.

(50) FIG. **12**B illustrates a flexible electrical structure **90** corresponding to FIGS. **5**A-**5**C with spacer **30** and power generator **70** disposed between top and bottom substrate layers **10**T, **10**B. Top substrate layer **10**T can comprise top substrate power-generating layer **12**T and top substrate conductor layer **14**T and bottom substrate layer **10**B can comprise bottom substrate power-generating layer **12**B and bottom substrate conductor layer **14**B. When power generator **70** produces electrical power, the electrical current can be conducted with top substrate conductor layer **14**T and bottom substrate conductor layer **14**B to component **20**. In some embodiments, therefore, flexible electrical structure can generate power with both top and bottom power-generating layers **12**T, **12**B and with power generator **70**. Power generator **70** can be oriented to provide current with matching charges as top and bottom power-generating layers **12**T, **12**B.

(51) Embodiments of the present disclosure can comprise multiple power generators **70** and components **20** electrically connected in parallel with top and bottom substrate layers, as shown in FIG. **12**C, with or without top and bottom power-generating layers **12**T, **12**B and holes **34** and in any of the configurations as described above.

(52) Embodiments of the present disclosure can be constructed by disposing components **20** and generators **70**, if included, onto bottom substrate layer **10**B, for example by pick-and-place methods or micro-transfer printing and laminating top substrate layer **10**T onto bottom substrate layer **10**B and components **20** and generators **70** to form flexible electronic structure **90**.

(53) Embodiments of the present disclosure can be constructed by laminating bottom substrate power-generating layer **12**B onto bottom substrate conductor layer **14**B, disposing components **20** and generators **70**, if included, onto bottom substrate power-generating layer **12**B, for example by pick-and-place methods or micro-transfer printing, laminating top substrate power-generating layer **12**T onto bottom substrate conductor layer **14**B and components **20** and generators **70**, and then laminating top substrate conductor layer **14**T over top substrate power-generating layer **12**T to form flexible electronic structure **90**.

(54) Embodiments of the present disclosure can be constructed by laminating bottom substrate conductor layer **14**B onto bottom substrate power-generating layer **12**B, disposing components **20** and generators **70**, if included, onto bottom substrate conductor layer **14**B, for example by pick-and-place methods or micro-transfer printing, laminating top substrate conductor layer **14**T onto bottom substrate power-generating layer **12**B and components **20** and generators **70**, and then laminating top substrate power-generating layer **12**T over top substrate conductor layer **14**T to form flexible electronic structure **90**.

(55) In some embodiments, any multiple layers of bottom substrate layer **10**B or top substrate layer **10**T can be first constructed (e.g., by lamination) to form bottom substrate layer **10**B or top substrate layer **10**T and then the top and bottom substrate layers **10**T, **10**B combined with components **20** and generators **70**, if present, to provide flexible electronic structure **90**.

(56) Component **20** can be a micro-component with one or more dimensions no greater than one mm. According to some embodiments of the present disclosure, component **20** can be micro-transfer printed from a component source wafer onto electrically conductive bottom substrate layer

10B and can comprise a broken (e.g., fractured) or separated component tether **21** in consequence of micro-transfer printing. Similarly, LED **40** can be micro-transfer printed from an LED source wafer onto component substrate **22** and can comprise a broken (e.g., fractured) or separated LED tether **41** in consequence of micro-transfer printing. In some embodiments, either or both component **20** and LED **40** are disposed onto bottom substrate layer **10**B using pick-and-place techniques.

(57) According to embodiments of the present disclosure, any one or combination of component **20**, LED **40**, and power generator **70** can be a microscopic structure with external dimensions less than two mm in length or width and a thickness no greater than 500 μm. For example, in some embodiments, component **20**, LED **40**, or power generator **70** can be a microscopic structure with external dimensions less than two mm in length or width (e.g., no greater than 1 mm, no greater than five hundred μm, no greater than three hundred μm, no greater than two hundred μm, no greater than one hundred μm, no greater than fifty μm, no greater than twenty μm, no greater than ten μm, or no greater than five μm) and a thickness no greater than five hundred μm (e.g., no greater than two hundred μm, no greater than one hundred μm, no greater than fifty μm, no greater than twenty μm, no greater than ten μm, no greater than five μm, or no greater than two μm).

(58) Component **20**, power generator **70**, or LED **40** can be any structure useful in combination with flexible substrate **10**, for example an active or passive electronic device. Component **20** can be an electrically responsive device and power generator **70** can be an electrically generating device such as a micro-electromechanical device. Component **20** or power generator **70** can be an electronic component **20**, an optoelectronic component **20**, can comprise electronic circuits or light-emitting devices such as light-emitting diodes **40**, or can comprise any one or more of: piezoelectric material, photovoltaic material, and semiconductor material. Component **20**, power generator **70**, or LED **40** can comprise any one or more of a combination of a conductive metals (e.g., metals or electrically conductive polymers), dielectric materials, such as inorganic oxides (e.g., silicon oxide), nitrides (e.g., silicon nitride), or organic materials such as photoresists, resins, or epoxies. Component **20**, power generator **70**, or LED **40** can be constructed using photolithographic methods and materials known in the art. Component **20**, power generator **70**, or LED **40** can be coated or encapsulated, for example with an organic (e.g., a resin) or inorganic (e.g., an oxide or nitride) dielectric.

(59) Reference is made in the present description to examples of micro-transfer printing (e.g., using a stamp with stamp posts) when describing certain examples of disposing LEDs **40**, components **20**, or power generators **70**. Similar other embodiments are expressly contemplated using other transfer or printing devices. For example, in some embodiments, a transfer device that is a vacuum-based or electrostatic transfer device can be used. A vacuum-based or electrostatic transfer device can comprise a plurality of transfer posts, each transfer post being constructed and arranged to pick up a single device (similarly to stamp posts in a stamp).

(60) According to some embodiments, micro-transfer printing can include any method of transferring component **20**, power generator **70**, or LED **40** from corresponding source wafers to flexible substrate **10** or component **20** by contacting them with a patterned or unpatterned stamp surface of a stamp to transfer them from their source wafer, transferring the stamp and contacted component **20**, power generator **70**, or LED **40** to flexible substrate **10** or component **20**, and contacting them to a surface of flexible substrate **10** or component **20**. Component **20**, power generator **70**, or LED **40** can be adhered to the stamp or flexible substrate **10** or component **20** by, for example, van der Waals forces, electrostatic forces, magnetic forces, chemical forces, adhesives, or any combination of the above, including separation-rate-dependent adhesion, for example kinetic control of viscoelastic stamp materials such as can be found in elastomeric transfer devices such as a PDMS stamp.

(61) Any one or all of component **20**, power generator **70**, or LED **40** can be unpackaged dice (each an unpackaged die) transferred directly from a native source wafer on or in which they are

constructed to flexible substrate **10** or component **20**.

(62) In certain embodiments, flexible substrate **10** is or comprises a member selected from the group consisting of polymer (e.g., plastic, polyimide, PEN, or PET), resin, metal foil, or flexible glass. In certain embodiments, flexible substrate **10** has a thickness from 5 μm to 20 mm (e.g., 5 to 10 μm, 10 to 50 μm, 50 to 100 μm, 100 to 200 μm, 200 to 500 μm, 500 μm to 0.5 mm, 0.5 to 1 mm, 1 mm to 5 mm, 5 mm to 10 mm, or 10 mm to 20 mm).

(63) Examples of micro-transfer printing processes suitable for disposing components onto target substrates are described in *Inorganic light-emitting diode displays using micro-transfer printing* (Journal of the Society for Information Display, 2017, DOI #10.1002/jsid.610, 1071-0922/17/2510-0610, pages 589-609), U.S. Pat. No. 8,722,458 entitled Optical Systems Fabricated by Printing-Based Assembly, U.S. patent application Ser. No. 15/461,703 entitled Pressure-Activated Electrical Interconnection by Micro-Transfer Printing, U.S. Pat. No. 8,889,485 entitled Methods for Surface Attachment of Flipped Active Components, U.S. patent application Ser. No. 14/822,864 entitled Chiplets with Connection Posts, U.S. patent application Ser. No. 14/743,788 entitled Micro-Assembled LED Displays and Lighting Elements, and U.S. patent application Ser. No. 15/373,865, entitled Micro-Transfer Printable LED Component, the disclosure of each of which is incorporated herein by reference in its entirety. Examples of micro-transfer printed acoustic wave filter devices are described in U.S. patent application Ser. No. 15/047,250, entitled Micro-Transfer Printed Acoustic Wave Filter Device, the disclosure of which is incorporated herein by reference in its entirety.

(64) For a discussion of various micro-transfer printing techniques, see also U.S. Pat. Nos. 7,622,367 and 8,506,867, each of which is hereby incorporated by reference in its entirety. Micro-transfer printing using compound micro-assembly structures and methods can also be used in certain embodiments, for example, as described in U.S. patent application Ser. No. 14/822,868, filed Aug. 10, 2015, entitled Compound Micro-Assembly Strategies and Devices, which is hereby also incorporated by reference in its entirety. In some embodiments, any one or more of components **20** or power generators **70** is a compound micro-assembled structure (e.g., a compound micro-assembled macro-system).

(65) As is understood by those skilled in the art, the terms “over” and “under” and “top” and “bottom” are relative terms and can be interchanged in reference to different orientations of the layers, elements, and substrates included in various embodiments of the present disclosure. Furthermore, a first layer or first element “on” a second layer or second element, respectively, is a relative orientation of the first layer or first element to the second layer or second element, respectively, that does not preclude additional layers being disposed therebetween. For example, a first layer on a second layer, in some implementations, means a first layer directly on and in contact with a second layer. In other implementations, a first layer on a second layer includes a first layer and a second layer with another layer therebetween (e.g., and in mutual contact).

(66) Throughout the description, where apparatus and systems are described as having, including, or comprising specific elements, or where processes and methods are described as having, including, or comprising specific steps, it is contemplated that, additionally, there are apparatus and systems of the disclosed technology that consist essentially of, or consist of, the recited elements, and that there are processes and methods according to the disclosed technology that consist essentially of, or consist of, the recited processing steps.

(67) It should be understood that the order of steps or order for performing certain action is immaterial so long as the disclosed technology remains operable. Moreover, two or more steps or actions in some circumstances can be conducted simultaneously.

(68) Having described certain implementations of embodiments, it will now become apparent to one of skill in the art that other implementations incorporating the concepts of the disclosure may be used. The disclosure has been described in detail with particular reference to certain embodiments thereof, but it will be understood that variations and modifications can be effected

within the spirit and scope of the following claims.

PARTS LIST

(69) A cross section line P pressure **10** flexible substrate **10**B electrically conductive bottom substrate layer/bottom substrate layer **10**T electrically conductive top substrate layer/top substrate layer **12**B bottom substrate power-generating layer **12**T top substrate power-generating layer **14**B bottom substrate conductor layer **14**T top substrate conductor layer **20** component **21** component tether **22** component substrate/integrated circuit **22**B component substrate bottom side **22**T component substrate top side **24**B component bottom electrode **24**T component top electrode **26** dielectric structure **28** conductor **29** through silicon via (TSV) **30** spacer **32** transparent fill **34** hole/transparent opening **40** light-emitting diode (LED) **41** LED tether **50** cracks **60** paper/document/banknote **62** laminated strip **70** power generator **72** contact pad **80** light **90** flexible electronic structure

Claims

1. A flexible electronic structure, comprising: a flexible substrate comprising an electrically conductive top substrate layer and an opposing electrically conductive bottom substrate layer; and a component, comprising: a component substrate non-native to the flexible substrate having a component substrate top side and an opposing component substrate bottom side; a planar component top electrode disposed on the component substrate top side and electrically connected to the electrically conductive top substrate layer thereby defining a planar electrical contact; and a planar component bottom electrode disposed on the component substrate bottom side and electrically connected to the electrically conductive bottom substrate layer thereby defining a planar electrical contact, wherein the component is disposed between the electrically conductive top substrate layer and the electrically conductive bottom substrate layer, and wherein the flexible substrate is a power-generating substrate.
2. The flexible electronic structure of claim 1, wherein the electrically conductive top substrate layer and the electrically conductive bottom substrate layer are or comprise triboelectric layers.
3. The flexible electronic structure of claim 2, wherein the electrically conductive top substrate layer comprises an electrically conductive top substrate conductive layer and a top substrate power-generating layer.
4. The flexible electronic structure of claim 3, wherein the top substrate conductive layer is on a side of the top substrate power-generating layer opposite the component.
5. The flexible electronic structure of claim 3, wherein the top substrate power-generating layer is on a side of the top substrate conductive layer opposite the component.
6. The flexible electronic structure of claim 2, wherein the electrically conductive bottom substrate layer comprises an electrically conductive bottom substrate conductive layer and a bottom substrate power-generating layer.
7. The flexible electronic structure of claim 6, wherein the bottom substrate conductive layer is on a side of the bottom substrate power-generating layer opposite the component.
8. The flexible electronic structure of claim 6, wherein the bottom substrate power-generating layer is on a side of the bottom substrate conductive layer opposite the component.
9. The flexible electronic structure of claim 1, wherein the flexible substrate comprises a spacer between the electrically conductive top substrate layer and the electrically conductive bottom substrate layer.
10. The flexible electronic structure of claim 9, wherein the spacer comprises holes where no spacer material is present.
11. The flexible electronic structure of claim 1, wherein the electrically conductive top substrate layer and the electrically conductive bottom substrate layer are a triboelectric power-generating pair.

12. The flexible electronic structure of claim 1, wherein the component is relatively rigid compared to the flexible substrate.
13. The flexible electronic structure of claim 1, wherein the component substrate comprises a crystalline semiconductor substrate.
14. The flexible electronic structure of claim 1, wherein the component has a thickness no greater than one hundred microns.
15. The flexible electronic structure of claim 1, wherein an area of the component top electrode has an area that is no less than 50% of an area of the component substrate top side.
16. The flexible electronic structure of claim 1, wherein an area of the component bottom electrode has an area that is no less than 50% of an area of the component substrate bottom side.
17. The flexible electronic structure of claim 1, wherein the component is an electronic or optoelectronic component.
18. The flexible electronic structure of claim 17, wherein the component comprises a light-emitting diode.
19. The flexible electronic structure of claim 18, wherein (i) the electrically conductive top substrate layer is transparent or comprises transparent openings through which the light-emitting diode can emit light, (ii) the electrically conductive bottom substrate layer is transparent or comprises openings through which the light-emitting diode can emit light, or (iii) both (i) and (ii).