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(54) STRETCHABLE ELECTRONIC SYSTEMS WITH CONTAINMENT CHAMBERS

DEHNBARE ELEKTRONISCHE SYSTEME MIT SICHERHEITSBEHÄLTERN

SYSTÈMES ÉLECTRONIQUES ÉTIRABLES DOTÉS DE CHAMBRES DE CONFINEMENT

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- HU ET AL.: 'Stretchable Inorganic-Semiconductor Electronic Systems' 2011 ADV. MATER. vol. 23, 2011, pages 2933 - 2936, XP008180492

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Description**BACKGROUND OF INVENTION**

- 5 [0001] Since the first demonstration of a printed, all polymer transistor in 1994, a great deal of interest has been directed at a potential new class of electronic systems comprising flexible integrated electronic devices on plastic substrates. [Garnier, F., Hajlaoui, R., Yassar, A. and Srivastava, P., Science, Vol. 265, pgs 1684 - 1686] Recently, substantial research has been directed toward developing new solution processable materials for conductors, dielectrics and semiconductors for flexible plastic electronic devices. Progress in the field of flexible electronics, however, is not only driven by the development of new solution processable materials but also by new device component geometries, efficient device and device component processing methods and high resolution patterning techniques applicable to flexible electronic systems. It is expected that such materials, device configurations and fabrication methods will play an essential role in the rapidly emerging new class of flexible integrated electronic devices, systems and circuits.
- 10 [0002] Interest in the field of flexible electronics arises out of several important advantages provided by this technology. For example, the inherent flexibility of substrate materials allows them to be integrated into many shapes providing for a large number of useful device configurations not possible with brittle conventional silicon based electronic devices. In addition, the combination of solution processable component materials and flexible substrates enables fabrication by continuous, high speed, printing techniques capable of generating electronic devices over large substrate areas at low cost.
- 15 [0003] The design and fabrication of flexible electronic devices exhibiting good electronic performance, however, present a number of significant challenges. First, the well-developed methods of making conventional silicon based electronic devices are incompatible with most flexible materials. For example, traditional high quality inorganic semiconductor components, such as single crystalline silicon or germanium semiconductors, are typically processed by growing thin films at temperatures (> 1000 degrees Celsius) that significantly exceed the melting or decomposition temperatures of most plastic substrates. In addition, most inorganic semiconductors are not intrinsically soluble in convenient solvents that would allow for solution based processing and delivery. Further, although many amorphous silicon, organic or hybrid organic-inorganic semiconductors are compatible with incorporation into flexible substrates and can be processed at relatively low temperatures, these materials do not have electronic properties capable of providing integrated electronic devices capable of good electronic performance. For example, thin film transistors having semiconductor elements made of these materials exhibit field effect mobilities approximately three orders of magnitude less than complementary single crystalline silicon based devices. As a result of these limitations, flexible electronic devices are presently limited to specific applications not requiring high performance, such as use in switching elements for active matrix flat panel displays with non-emissive pixels and in light emitting diodes.
- 20 [0004] Flexible electronic circuitry is an active area of research in a number of fields including flexible displays, electro-active surfaces of arbitrary shapes such as electronic textiles and electronic skin. These circuits often are unable to sufficiently conform to their surroundings because of an inability of the conducting components to stretch in response to conformation changes. Accordingly, those flexible circuits are prone to damage and electronic degradation and can be unreliable under rigorous and/or repeated conformation change. Flexible circuits require stretchable and bendable interconnects that remain intact while cycling through stretching and relaxation.
- 25 [0005] Conductors that are capable of both bending and elasticity are generally made by embedding metal particles in an elastomer such as silicone. Those conductive rubbers are both mechanically elastic and electrically conductive. The drawbacks of a conductive rubber include high electrical resistivity and significant resistance changes under stretching, thereby resulting in overall poor interconnect performance and reliability.
- 30 [0006] Gray et al. discuss constructing elastomeric electronics using microfabricated tortuous wires encased in a silicone elastomer capable of linear strains up to 54% while maintaining conductivity. In that study, the wires are formed as a helical spring-shape. In contrast to straight-line wires that fractured at low strains (e.g., 2.4%), tortuous wires remained conductive at significantly higher strains (e.g., 27.2%). Such a wire geometry relies on the ability of wires to elongate by bending rather than stretching. That system suffers limitations in the ability to controllably and precisely pattern in different shapes and in additional planes, thereby limiting the ability to tailor systems to different strain and bending regimes.
- 35 [0007] Studies suggest that elastically stretchable metal interconnects experience an increase in resistance with mechanical strain. (Mandlik et al. 2006). Mandlik et al. attempt to minimize this resistance change by depositing metal film on pyramidal nanopatterned surfaces. That study, however, relies on the relief feature to generate microcracks that impart stretchability to thin metal lines. The microcracks facilitate metal elastic deformation by out of plane twisting and deformation. Those metal cracks, however, are not compatible with thick metal films, and instead are compatible with a rather narrow range of thin metal films (e.g., on the order of less than 30 nm) that are deposited on top of patterned elastomers.
- 40 [0008] One manner of imparting stretchability to metal interconnects is by prestraining (e.g., 15%-25%) the substrate

5 during conductor (e.g., metal) application, followed by spontaneous relief of the prestrain, thereby inducing a waviness to the metal conductor interconnects. (see, e.g., Lacour et al. (2003); (2005); (2004), Jones et al. (2004); Huck et al. (2000); Bowden et al. (1998)). Lacour et al. (2003) report by initially compressing gold stripes to generate spontaneously wrinkled gold stripes, electrical continuity is maintained under strains of up to 22% (compared to fracture strains of gold films on elastic substrates of a few per cent). That study, however, used comparatively thin layers of metal films (e.g., about 105 nm) and is relatively limited in that the system could potentially make electrical conductors that could be stretched by about 10%.

10 [0009] US Patent Nos. 7,557,367, 7,521,292, and 8,217,381 and US Patent Publication Nos. 2010/0002402, 2012/0157804, and 2011/0230747 describe flexible and/or stretchable electronic systems accessed by microfabrication pathways including printing-based techniques. The stretchable systems of these references include devices having distributed electronic device components interconnected via deformable electronic interconnects, optionally capable of elastic responses to large strain deformation. The systems of these references include electronic devices for applications including tissue mounted biomedical devices, solar energy and large area macroelectronic systems.

15 [0010] From the forgoing, it is apparent there is a need for electronic devices such as interconnects and other electronic components having improved stretchability, electrical properties and related processes for rapid and reliable manufacture of stretchable interconnects in a variety of different configurations. Progress in the field of flexible electronics is expected to play a critical role in a number of important emerging and established technologies. The success of these applications of flexible electronics technology depends strongly, however, on the continued development of new materials, device configurations and commercially feasible fabrication pathways for making integrated electronic circuits and devices 20 exhibiting good electronic, mechanical and optical properties in flexed, deformed and bent conformations. Particularly, high performance, mechanically extensible materials and device configurations are needed exhibiting useful electronic and mechanical properties in folded, stretched and/or contracted conformations.

25 [0011] US 2012/051005 teaches a stretchable electronic device. In one aspect, the device has a stretchable interconnection electrically connecting two electronic components. The stretchable interconnection includes an electrically conductive channel having a predetermined first geometry by which the channel is stretchable up to a given elastic limit and a first flexible supporting layer provided for supporting the electrically conductive channel and having a predetermined second geometry by which the first supporting layer is stretchable. The predetermined second geometry has a predetermined deviation from the predetermined first geometry chosen for restricting stretchability of the electrically conductive channel below its elastic limit.

30 [0012] US 2011/230747 A1 teaches implantable biomedical devices and methods of administering implantable biomedical devices, making implantable biomedical devices, and using implantable biomedical devices to actuate a target tissue or sense a parameter associated with the target tissue in a biological environment.

SUMMARY OF THE INVENTION

35 [0013] The present invention provides electronic systems according to independent claim 1 and a method of making electronic systems according to claim 26. Preferred embodiments are defined in the respective dependent claims. In the following parts of the description the terms "embodiment", "embodiment of the present invention" and "example according to embodiment" are used. Irrespective of these terms and expressions, only those examples that fall under 40 the scope of appended claims, namely as shown in figures 10A-71 and 102-103B, form part of the invention. Useful containment fluids for use in containment chambers of electronic devices of the invention include lubricants, electrolytes and/or electronically resistive fluids. In some embodiments, for example, electronic systems of the invention comprise one or more electronic devices and/or device components provided in a freestanding and/or tethered configuration that decouples, or otherwise mechanically isolates, forces originating upon deformation, stretching or compression of a 45 supporting substrate from the free standing or tethered device or device component, for example, so as to decrease the strain on the one or more electronic devices and/or device components caused by deformation, stretching or compression of the supporting substrate by a factor of 4 to 1000 times, and optionally greater than 10 times, relative to a comparable device having an equivalent device or device component provided in a configuration where it is directly bonded to the supporting substrate.

50 [0014] In an embodiment, for example, the present disclosure provides systems combining elastomeric materials, fluid packaging and devices or device components having a free standing or tethered geometry enabling useful mechanical, electronic and/or optical properties, for example, when provided in compressed, elongated, stretched and/or deformed configurations. Devices of the present disclosure are useful for a wide range of applications including power generation, communications, sensing, photovoltaics, displays, generation of electromagnetic radiation, medical devices, conformable electronics, large area electronics, wearable electronics, electronic paper, and the like.

55 [0015] In an aspect, for example, the present disclosure provides an electronic system comprising: (i) a substrate; (ii) an electronic device or device component supported by the substrate; wherein the electronic device or device component is free standing or tethered to the substrate; and (iii) a containment chamber at least partially enclosing the electronic

device or device component; wherein the containment chamber is at least partially filled with a containment fluid or a low modulus solid.

[0016] In an aspect, for example, the present disclosure provides an electronic system comprising: (i) an ultra low modulus layer; (ii) a substrate supported by the ultra low modulus layer; (iii) an electronic device or device component supported by the substrate; wherein the electronic device or device component is free standing or tethered to the substrate; and a containment chamber, comprising a plurality of side walls and a top wall, at least partially enclosing the electronic device or device component; wherein the containment chamber is at least partially filled with a containment fluid or a low modulus solid; wherein the substrate has a Young's modulus greater than a Young's modulus of the ultra low modulus layer and the top wall has a Young's modulus greater than a Young's modulus of the containment fluid or the low modulus solid such that a Young's modulus profile of the system spatially varies along an axis substantially perpendicular to the ultra low modulus layer.

[0017] In an embodiment, for example, the free standing or tethered configuration of the electronic device or device component at least partially decouples motion and/or deformation of the substrate from the electronic device or device component. In an embodiment, for example, the free standing or tethered configuration of the electronic device or device component at least partially decouples forces generated by elongation, compression or deformation of the substrate from the electronic device or device component.

[0018] In an embodiment, an ultra low modulus layer is provided on one surface of a substrate. For example, the ultra low modulus layer may improve adherence of the substrate to a surface. In an embodiment, the ultra low modulus layer may comprise ecoflex®. In an embodiment, the ultra low modulus layer has a Young's modulus less than or equal to 150 KPa, or less than or equal to 100 KPa, or less than or equal to 50 KPa. In an embodiment, the ultra low modulus layer has a Young's modulus selected from the range of 50 KPa to 150 Pa, or 50 KPa to 100 KPa.

[0019] An array of electronically interconnected devices is also described, where the device component layout on the substrate may be ordered, registered, random or arbitrary. A plurality of devices or device components may be enclosed within a single containment chamber and/or one or more devices or device components may be segregated into a compartmentalized or nested containment chamber. For example, a device or device component in a compartmentalized or nested containment chamber may be isolated from bulk devices or device components to perform a solitary function, e.g. to communicate with exterior devices and/or to communicate or otherwise interface with an external environment. A geometry of a device component layout of certain aspects of the present disclosure allows different components to communicate or interface with one another and/or allows device components to interface with an external environment, e.g. a tissue interface.

[0020] In an embodiment, the device of the present disclosure is characterized by an integrated electronic device and/or electronic circuit comprising a plurality of integrated device components, wherein the integrated electronic device and/or electronic circuit is provided as a free standing or tethered structure enclosed within a single containment chamber. Devices of this aspect may communicate with other devices (e.g. in a device array) or with an external environment via a range of systems including wired communication and/or power systems, optical communication systems, radio frequency systems, and/or electrical interconnects which connect the device or circuit provided within the containment chamber to devices or device components external to the containment chamber. In an embodiment, for example, a single freestanding or tethered integrated circuit or chip is provided in a single containment chamber.

[0021] In an embodiment, an electronic device or device component is provided on a receiving surface of a substrate or on an intermediate structure provided between the substrate and the electronic device or device component. As will be understood a wide range of intermediate structures may be used to support devices and device components of the present disclosure including functional device component structures (e.g. electrodes, electrical insulators, dielectric structures, semiconductor structures, etc.) and structural device component structures (e.g., thin film structures, low modulus solids, relief features, particles, pedestals, membranes, etc.).

[0022] In an embodiment, a containment chamber comprises one or more enclosing structures positioned to at least partially surround an exterior portion of an electronic device or device component, optionally entirely enclosing the device or device component. The one or more enclosing structures of the containment chamber may be operationally coupled to a supporting surface or an intermediate structure provided between the supporting surface and the one or more enclosing structures, for example via lamination, chemical bonding and/or use of adhesives. In an embodiment, the one or more enclosing structures of the containment chamber are not in physical contact with the electronic device or device component, and optionally for some embodiments all of the enclosing structures of the containment chamber are not in physical contact with the electronic device or device component. For example, the enclosing structures may comprise one or more chamber walls or barrier structures each positioned at least 1000 microns from a side of the electronic device or device component, optionally for some embodiments at least 100 microns from a side of the electronic device or device component and optionally for some embodiments at least 10 microns from a side of the electronic device or device component. In an embodiment, for example, a barrier structure or chamber wall is provided that constrains movement of the device or device component, for example, by physically impeding or otherwise blocking movement of the device or component. In an embodiment, for example, a barrier structure or chamber wall is provided that constrains

movement of the device or device component in a direction parallel to a surface of the substrate, e.g., a supporting surface of the substrate directly or indirectly supporting the device or device component, to less than or equal to 1000 microns, optionally for some embodiments less than or equal to 100 microns and optionally for some embodiments less than or equal to 10 microns. In an embodiment, for example, a barrier structure or chamber wall is provided that constrains

5 movement of the device or device component in a direction orthogonal to a surface of the substrate, e.g., a supporting surface of the substrate directly or indirectly supporting the device or device component, to less than or equal to 1000 microns, optionally for some embodiments less than or equal to 100 microns and optionally for some embodiments less than or equal to 10 microns. In an embodiment, for example, one or more of the enclosing structures of the containment chamber are in physical contact with the device or device component. In an embodiment, for example, one or more of
10 the enclosing structures of the containment chamber are not in physical contact with the device or device component, for example, when provided in an undeformed state.

[0023] In an embodiment, the containment chamber further comprises one or more recessed features provided in the substrate to accommodate the device or device component, for example, partially surrounding the electronic device or device component, where the one or more enclosing structures are provided to at least partially enclose the recessed
15 features. For example, the recessed features of the containment chamber may comprise one or more chamber walls or barrier structures each positioned at least 1000 microns from a side of the electronic device or device component, optionally for some embodiments at least 100 microns from a side of the electronic device or device component and optionally for some embodiments at least 10 microns from a side of the electronic device or device component. Typically,
20 at least a portion of the enclosing structures of the containment chamber is physically or chemically bonded (e.g., laminated, glued etc.) to the substrate or an intermediate structure provided between the substrate and the enclosing structure. For example, a flip chip bonder may be used to bond commercial off the shelf (COTS) chips and/or bare dies with anisotropic conductive film or solder bumper at the chip/metal interconnect interface. In some embodiments, COTS chips or bare die have a modulus from 10 GPa to 100 GPa, and a tensile rigidity from 0.01 GPa·mm² to 1000 GPa·mm².

[0024] In an embodiment, a barrier structure limits or otherwise restricts movement of a free standing or tethered
25 device or device component, for example limiting movement in a direction parallel and/or orthogonal to a supporting surface or receiving surface of a substrate. Exemplary barrier structures include but are not limited to corrals, relief features, embossed features, indentations or depressions, inner chamber walls of the containment chamber, the containment chamber itself, bumpers and the like. In an embodiment, barrier structures are positioned at least 1000 microns from a side of the electronic device or device component, optionally for some embodiments at least 100 microns from
30 a side of the electronic device or device component and optionally for some embodiments at least 10 microns from a side of the electronic device or device component. In an embodiment, barrier structures are positioned between 10 microns and 100 millimeters from a side of an electronic device or device component, or optionally between 100 microns and 5 millimeters from a side of an electronic device or device component, or optionally between 100 microns and 1 millimeter from a side of an electronic device or device component. In some embodiments, barrier structures have a
35 height, h, that is less than (e.g., 90% or less, optionally 60% or less) the full height of the containment chamber, such that a gap exists between the barrier structure and the top wall of the containment chamber. Alternatively, the present disclosure includes barrier structures that extend the entire height of a containment chamber. The height of a barrier structure is, however, at least sufficient to prevent a free standing device or device component from moving or otherwise extending over the barrier structure through a gap between the barrier structure and a top region of the containment
40 chamber.

[0025] In an embodiment, for example, the containment fluid or low modulus solid mitigates forces of friction acting
45 on the electronic device or device component, for example by functioning as a lubricant, for example to decrease the force of friction between moving surfaces of the device or device component. In some embodiments, for example, the containment fluid or low modulus solid decreases friction so as to prevent degradation or failure of the device or device component, for example, by decreasing friction generated by rubbing or other physical interactions of surfaces of the device or device components. In an embodiment, for example, the containment fluid or low modulus solid functions as a lubricant to decrease friction generated by physical interaction of an electrical interconnect with itself and/or other electrical interconnects or other components of a device. In an embodiment, the containment fluid or low modulus solid decreases the extent of friction between one or more devices or device components by more than a factor of 2, optionally
50 for some embodiments by more than a factor of 10 and optionally for some embodiments by more than a factor of 100, relative to a configuration not having the containment fluid present.

[0026] In an embodiment, the electronic device or device component is a free standing or tethered fully formed chip
55 or integrated circuit or a compound thereof. By utilizing the tethering, selective bonding and/or floating of the fluid containment strategy described herein, mechanical loads of the chips/integrated circuit to the elastomeric substrate are minimized. In an embodiment, the electronic device or device component is a single crystalline semiconductor structure or electronic device, such as a single crystalline inorganic semiconductor structure or electronic device including high purity inorganic single crystalline materials and/or doped inorganic single crystalline materials. In an embodiment, the electronic device or device component is a single crystalline semiconductor structure or device component, which may

be operationally connected to at least one additional device component or structure selected from the group consisting of a conducting structure, a dielectric structure, an electrode, a cathode, an anode, and an additional semiconductor structure. In an embodiment, for example, the device or device component comprises single crystalline silicon, germanium, III-V semiconductor (e.g., GaAs) or diamond. In an embodiment, for example, the device or device component comprises a piezoelectric material, such as a piezoelectric semiconductor material.

[0027] A single crystalline semiconductor electronic device or device component may, for example, comprise one or more electronic devices selected from the group consisting of a transistor, an electrochemical cell, a fuel cell, an integrated circuit, a solar cell, a laser, a light emitting diode, a nanoelectromechanical device, a microelectromechanical device, a photodiode, a P-N junction, a sensor, a memory device, an integrated circuit, a complementary logic circuit and arrays or combinations of these.

[0028] In an embodiment, the electronic device or device component has a thickness selected from the range of 10 nanometers to about 1000 microns, a width selected from the range of 100 nanometers to about 10 millimeter and a length selected from the range of 500 nanometers to about 10 millimeter. In an embodiment, the electronic device or device component has a thickness selected from the range of 10 nanometers to about 100 microns, a width selected from the range of 100 nanometers to about 1 millimeter and a length selected from the range of 1 micron to about 1 millimeter. In an embodiment, the electronic device or device component has a thickness selected from the range of 500 nanometers to about 1000 microns, a width selected from the range of 1 micron to about 1 millimeter and a length selected from the range of 1 micron to about 1 millimeter.

[0029] In an embodiment, an electronic system may further comprise one or more additional electronic devices or device components at least partially enclosed by a containment chamber or at least partially enclosed by one or more additional containment chambers. The present disclosure includes devices comprising an array of electronic devices or device components, optionally electrically interconnected with each other, provided in the same or a plurality of containment chambers. In an embodiment, for example, a device of the present disclosure includes 5 or more devices or device components provided in a containment chamber, optionally 20 or more devices or device components provided in a containment chamber, and optionally 100 or more devices or device components provided in a containment chamber.

[0030] In an embodiment, the electronic device or device component is an electrical interconnect, such as a stretchable electrical interconnect. For example, one or more stretchable electrical interconnects may be in electrical contact with an electronic device or device component, and at least a portion of the one or more stretchable electrical interconnects may be at least partially embedded in an enclosing structure of a containment chamber.

[0031] In an embodiment, an enclosing structure of a containment chamber, such as a chamber wall or barrier structure, has a Young's modulus selected from the range of 1 KPa to 1 GPa, or selected from the range of 1KPa to 100 MPa, or selected from the range of 100 KPa to 1 MPa, or selected from the range of 250 KPa to 750 KPa. In an embodiment, for example, an enclosing structure of a containment chamber, such as a chamber wall or barrier structure, has a Young's modulus that is less than or equal to 10MPa, optionally less than or equal to 1MPa, and, optionally less than or equal to 500KPa , optionally less than or equal to 200KPa. In an embodiment, an enclosing structure of a containment chamber, such as a chamber wall or barrier structure, has a flexural rigidity selected from the range of 10^{-13} N·m to 10^5 N·m, or selected from the range of 10^{-10} N·m to 10^3 N·m, or selected from the range of 10^{-5} N·m to 10 N·m. In an embodiment, an enclosing structure of a containment chamber has a permeability selected from the range of 1 fg·mm/m²·day to 1 g·mm/m²·day, or selected from the range of 1 ng·mm/m²·day to 0.5 g·mm/m²·day, or selected from the range of 1 mg·mm/m²·day to 0.1 g·mm/m²·day. In an embodiment, an enclosing structure of a containment chamber has a coefficient of thermal expansion selected from the range of 10^{-7} °C⁻¹ to 10^{-2} °C⁻¹, or selected from the range of 10^{-5} °C⁻¹ to 10^{-1} °C⁻¹, or selected from the range of 10^{-3} °C⁻¹ to 10 °C⁻¹.

[0032] In an embodiment, the containment chamber comprises a material that is not permeable to the containment fluid. For example, a wide range of polymers are useful for containment chambers of the present disclosure. For example, the containment chamber may comprise a soft material capable of being physically stretched, such as an elastomer. A wide range of polymers are useful for containment chambers of the present disclosure. In an embodiment, for example, the containment chamber comprises a material selected from the group consisting of polydimethylsiloxane (PDMS), ecoflex®, a silicone, a rubber, and a polymer. In an embodiment, PDMS base may be used without the addition of any curing agent.

[0033] In an embodiment, the containment chamber has a height selected from the range of 10 µm to 10 cm, or selected from the range of 100 µm to 5 cm, or selected from the range of 1 mm to 0.5 cm, or selected from the range of 5 mm to 50 mm. In an embodiment, for example, the containment chamber has a height that is greater than or equal to 10 µm, and optionally for some embodiments greater than or equal to 100 µm, and optionally for some embodiments greater than or equal to 1000 µm. In an embodiment, the containment chamber has lateral dimensions (e.g., length and width) selected from the range of 10 µm to 10 m, or selected from the range of 100 µm to 1 m, or selected from the range of 1 mm to 0.1 m, or selected from the range of 50 mm to 50 cm. In an embodiment, for example, the containment chamber has a lateral dimensions that are greater than or equal to 10 µm, and optionally for some embodiments greater than or equal to 100 µm, and optionally for some embodiments greater than or equal to 1000 µm. In an embodiment,

the containment chamber has a volume selected from the range of $1000 \mu\text{m}^3$ to 10 m^3 , or selected from the range of $1 \mu\text{m}^3$ to 1 m^3 , or selected from the range of 100 mm^3 to 100 cm^3 , or selected from the range of 10 mm^3 to 1 cm^3 . In an embodiment, for example, the containment chamber has a volume that is greater than or equal to $1000 \mu\text{m}^3$, and optionally for some embodiments greater than or equal to $1 \mu\text{m}^3$, and optionally for some embodiments greater than or equal to 100 mm^3 . In an embodiment, the containment chamber is structurally self-supporting.

[0034] In an embodiment, the containment chamber is formed of two thin sheets of elastomer sealed along an outer border to form a pouch. The fluid container may have a form factor or geometry selected from a 3D square, a 3D rectangle, a sphere, a prism, or an arbitrary form, depending on the layout of the electronic device or device component contained in the chamber.

[0035] In an embodiment, at least 50% of the volume of containment chamber is occupied by a containment fluid or low modulus solid, and optionally at least 90% of the volume of the containment chamber is occupied by a containment fluid or low modulus solid, and optionally at least 98% of the volume of the containment chamber is occupied by a containment fluid or low modulus solid. In an embodiment, the containment fluid occupies a percentage of the containment chamber selected from the range of 1% to 99.9%, or selected from the range of 1% to 99%, or selected from the range of 25% to 90%, or selected from the range of 50% to 90%, or selected from the range of 50% to 75%. In an embodiment, at least 0.1% of the volume of the containment chamber is occupied by an electronic device or device component. In an embodiment, the electronic device or device component occupies a percentage of the containment chamber selected from the range of 1% to 99%, or selected from the range of 2% to 50%, or selected from the range of 5% to 30%, or selected from the range of 5% to 15%. The containment fluid may, for example, be in physical contact with the electronic device or device component, for example, in physical contact with one or all external surfaces of the device or device component.

[0036] In an embodiment, the electronic device or device component is entirely immersed in the containment fluid or low modulus solid. Suitable containment fluids include but are not limited to functional fluids, such as liquids, colloids, gels, gases, lubricants, electrolytes, thermally functional fluids, fluids having a low viscosity, chemically inert fluids, fluids having a low ionic resistance, and fluids having a high ionic resistance (e.g., electrically insulating fluids). For example, suitable lubricants include oils (natural or synthetic) and uncured silicone elastomer precursors, such as a polydimethylsiloxane precursor. For example, suitable lubricants include silicones, halocarbons or fluorocarbons. Suitable electrolytes include non-aqueous lithium ion battery electrolytes, such as lithium salts, e.g. LiPF_6 , LiBF_4 or LiClO_4 in an organic solvent, such as ethylene carbonate, dimethyl carbonate, and diethyl carbonate. Suitable thermally functional fluids include heat transfer fluids, such as fluids having a finite heat transfer coefficient, in order to dissipate the heat generated from the electronic device components. In an embodiment, the containment fluid is a material selected from the group consisting of a prepolymer, a solvent, a nonaqueous electrolyte, a silicone, a natural oil, a synthetic oil, a polyolefin and a fluorocarbon. In an embodiment, one or more colloids may be added to the containment fluid to adjust the fluid's viscosity, optical properties, and/or electrical properties. In an embodiment, for example, the containment fluid is a thermally stable fluid.

[0037] In an embodiment, a containment fluid has a vapor pressure less than or equal to 760 Torr at 298 K. In an embodiment, a containment fluid has a viscosity selected from 0.1 cP to 10000 cP at 298 K, or selected from 10 cP to 500 cP at 298 K. In an embodiment, a containment fluid has an ionic resistance selected from $10^7 \text{ ohm}\cdot\text{cm}$ to infinity, or selected from $10^{10} \text{ ohm}\cdot\text{cm}$ to $10^{70} \text{ ohm}\cdot\text{cm}$. In an embodiment, a containment fluid has an electronic resistance selected from $10^7 \text{ ohm}\cdot\text{cm}$ to infinity, or selected from $10^{10} \text{ ohm}\cdot\text{cm}$ to $10^{70} \text{ ohm}\cdot\text{cm}$. In an embodiment, a containment fluid has a vapor pressure selected from 100 Pa to 1 MPa, or selected from 500 Pa to 1 kPa. In an embodiment, a containment fluid has a vapor pressure selected from $10^{-7} \text{ }^\circ\text{C}^{-1}$ to $10^{-1} \text{ }^\circ\text{C}^{-1}$, or selected from $10^{-5} \text{ }^\circ\text{C}^{-1}$ to $10^{-3} \text{ }^\circ\text{C}^{-1}$. In an embodiment, a containment fluid has a surface tension or wetting property, depending on the materials used for constructing the liquid chamber, such that the fluid should have a contact angle below 90°, e.g., selected from 1 dyne/cm to 70 dynes/cm. In an embodiment, a containment fluid has a high ionic conductivity, for example, so as to function as an electrolyte in an electrochemical system, such as an ionic conductivity greater than or equal to 0.001 S cm^{-1} , optionally greater than or equal to 0.01 S cm^{-1} , optionally greater than or equal to 0.005 S cm^{-1} .

[0038] Use of low modulus solids as containment materials addresses important design considerations, for example, by reducing or eliminating leakage of the containment material and/or drying of the containment chamber due to evaporation of the containment material. Other containment material properties that are important for the design of systems using containment chambers include, but are not limited to, viscosity, vapor pressure, porosity, elastic modulus, and temperature dependence of the elastic modulus. For example, the elastic modulus of a material typically decreases with increasing temperature, and some electronic systems with containment chambers may be operated in variable temperature environments (e.g., in unregulated environments, *in vivo*, in electronic systems that generate heat as a waste product, etc). In an embodiment, the low modulus solid is a material selected from the group consisting of a gel, a prepolymer, a silicone, a natural oil, a synthetic oil, a polyolefin or a fluorocarbon. In an embodiment, the low modulus solid has a Young's modulus less than or equal to 1 MPa, or less than or equal to 0.5 MPa, or less than or equal to 200 kPa. In an embodiment, the low modulus solid has a Young's modulus selected from the range of 2 kPa to 1 MPa, or

selected from the range of 2 KPa to 500 KPa, or selected from the range of 2 KPa to 200 KPa, or selected from the range of 2 KPa to 100 KPa, or selected from the range of 2 KPa to 50 KPa. In an embodiment, the low modulus solid has a Young's modulus that is lower than a Young's modulus of the substrate or the top wall of the containment chamber by a factor of 100, or by a factor of 10, or by a factor of 5, or by a factor of 2. In an embodiment, the low modulus solid has a Young's modulus that is lower than a Young's modulus of the substrate or the top wall of the containment chamber by a factor of 2 or more. In an embodiment, a low modulus solid is selected from the group consisting of silbione, exoflex®, solaris, PDMS and combinations of these. Silbione® RT Gel 4717 A&B (Bluestar Silicones USA, East Brunswick, NJ) is a biocompatible, two-component silicone elastomer that crosslinks at room temperature to produce an elastic and resistant gel. Solaris® is a low viscosity, clear and colorless liquid platinum cure silicone rubber distributed by Smooth-On, Inc., Easton, PA. In an embodiment, low modulus solid materials that are typically cured or crosslinked by mixing with a curing agent may be used in the absence of any curing agent.

[0039] In an embodiment, a level of containment fluid or low modulus solid within a containment chamber is monitored, adjusted or controlled through one or more microfluidic channels operationally connecting one or more containment chambers to a reservoir of containment fluid or low modulus solid.

[0040] In an embodiment, the electronic device or device component is a free standing structure supported by or in physical contact with the substrate. As used herein, free standing refers to a configuration wherein the device or device component is supported by, but not bonded to, a surface of the substrate or an intermediate substrate between the substrate and the device or device component. In an embodiment, for example, a free standing device or device component is capable of movement relative to a substrate surface, such as movement in a direction parallel and/or orthogonal to a substrate surface, such as a supporting or receiving surface of the substrate. A free standing structure may, however, undergo and/or participate in one or more associative interactions with the substrate or an intermediate structure provided between the substrate and the free standing structure, for example wherein the associative interaction is a dipole - dipole interaction or a Van der Waals interaction. In some embodiments, associative interactions between electronic devices or device components and a supporting layer or substrate may cause stiction. To reduce or eliminate stiction, in some embodiments, a supporting layer or substrate may be textured, microstructured or nanostructured to reduce the contact area between the electronic device or device component and the supporting layer or substrate.

[0041] In an embodiment, an electronic device or device component, such as a semiconductor device component, electrode and/or electrical interconnect, is a tethered structure supported by one or more tethering structures, such as relief features of a substrate or one or more relief features supported by the substrate. In an embodiment, for example, a tethered device or device component is capable of movement relative to a substrate surface, such as movement in a direction parallel and/or orthogonal to a substrate surface, such as a supporting or receiving surface of the substrate. In an embodiment, for example, a tethering structure, such as one or more relief features, is bonded to the substrate or an intermediate structure provided between the tethering structure and the substrate. In an embodiment, for example, a tethering structure, such as one or more relief features, is bonded to a portion, but not all, of a surface of the device or device component, such as 30% or less than the area of a bottom surface of the device or device component, optionally 10% or less than the area of a bottom surface of the device or device component, optionally 5% or less than the area of a bottom surface of the device or device component and optionally 1% or less than the area of a bottom surface of the device or device component. In an embodiment, for example, a tethering structure, such as one or more relief features, is bonded to a portion, but not all, of a surface of the device or device component, such as between 1% and 30% of the area of a bottom surface of the device or device component, optionally between 1% and 10% of the area of a bottom surface of the device or device component and optionally between 1% and 5% of the area of a bottom surface of the device or device component. Such embodiments having selective bonding between the tethering structure, such as one or more relief features, and some but not all of a surface of device or device component is particularly useful for achieving at least partial mechanical decoupling of the device or device component from motion and/or deformation of the substrate. The tethered geometry of some embodiments is useful for mechanically isolating the device component from the substrate, for example, providing mechanical isolation from movement and/or deformation of the substrate. In some embodiments, the tethered geometry of some embodiments is useful for holding the position of the device component, such as a semiconductor device component, electrode and/or electrical interconnect. In some embodiments, the tethered geometry is useful for preventing tangling of the device component, such as tangling of a semiconductor device component, electrode and/or electrical interconnect, for example, during or after stretching and release cycles.

[0042] In an embodiment, for example, an electronic device or device component is a tethered structure supported by array of 5 to 1000 relief features, and optionally for some examples an array of 5 to 100 relief features, and optionally for some examples an array of 5 to 20 relief features. In an embodiment, for example, an electronic device or device component is a tethered structure supported by at least 5 relief features, optionally for some embodiments supported by at least 10 relief features and optionally for some embodiments supported by at least 100 relief features. A wide range of tethering structures are useful in the present disclosure including one or more columns, pedestals, pillars, platforms, fingers, and the like. Tethering structures of the present disclosure may have a wide range of cross sectional shapes, such as circular, triangular, elliptical, rectangular, trapezoidal and any combination of these. In an embodiment, for

example, a tethering structure of the present disclosure extends a length along a direction orthogonal or substantially orthogonal (e.g. within 20 degrees of absolute orthogonal orientation) relative to the substrate surface.

[0043] For example, the one or more relief features may comprise a pedestal, or the one or more relief features may comprise an array of at least 10 pedestals, optionally for some embodiments an array of at least 20 pedestals, optionally for some embodiments an array of at least 100 pedestals, and optionally for some embodiments an array of at least 1000 pedestals. In an embodiment, the tethered structure is bonded to the one or more relief features comprising the tethering structure. In an embodiment, relief features of the tethering structure comprise an elastomer, PDMS, ecoflex®, or a silicone. In an embodiment, for example, the tether comprises a materials different than that of the device or device component.

[0044] In an embodiment, for example, each of the one or more relief structures of the tethering structure independently extends a length selected over the range of 100 nm to 1 mm and independently has one or more cross sectional physical dimensions selected over the range of 100 nm to 10 mm, and optionally for some embodiments a length selected over the range of 100 nm to 1000 microns and independently has one or more cross sectional physical dimensions selected over the range of 100 nm to 1000 microns, and optionally for some embodiments a length selected over the range of 1 micron to 1000 microns and independently has one or more cross sectional physical dimensions selected over the range of 1 micron to 1000 microns, and optionally for some embodiments a length selected over the range of 10 micron to 1000 microns and independently has one or more cross sectional physical dimensions selected over the range of 10 micron to 1000 microns.

[0045] In an embodiment, a substrate is a flexible substrate or a stretchable substrate, such as a polymer substrate. For example, a wide range of polymers are useful for substrates of the present disclosure. For example, the substrate may comprise one or more materials selected from the group consisting of an elastomer, PDMS, ecoflex®, spandex, adhesive bandages and silicone. Typically, the substrate has a Young's modulus selected from the range of 1 KPa to 100 MPa, or selected from the range of 10 KPa to 10 MPa, or selected from the range of 20 KPa to 1 MPa. In some embodiments, the substrate has a thickness selected from the range of 100 microns to 100 mm, or selected from the range of 100 microns to 50 mm, or selected from the range of 1 mm to 10 mm. In some embodiments, the substrate has a thickness less than or equal to 1000 mm, optionally less than or equal to 10 mm and optionally less than or equal to 1 mm. In some embodiments, a substrate may have spatially varying elastic properties within a plane of the substrate (e.g. shown by the coordinate axes of Fig. 70S), which may for example provide progressive elasticity and/or strain limiting behavior to prevent overstretching that could damage or break device components or connections. In an embodiment, a substrate may have an in-plane spatially varying Young's modulus that varies within a range of 1 KPa to 100 MPa, or within a range of 10 KPa to 10 MPa, or within a range of 20 KPa to 1 MPa.

[0046] In an embodiment, an electronic system may have spatially varying elastic properties out of the plane of the substrate (e.g. along an axis, such as axis N of Fig. 70N, that is substantially perpendicular to the plane of the substrate). In an embodiment, an electronic system may have an out-of-plane spatially varying Young's modulus that varies within a range of 1 KPa to 10 GPa.

[0047] In an embodiment, an electronic system comprises one or more electrical interconnects in electrical contact with an electronic device or device component. For example, the one or more electrical interconnects may establish electrical contact between the electronic device or device component and one or more additional electronic devices or device components. The electronic device or device component, the one or more additional electronic devices or device components and the one or more electrical interconnects may be provided in an island bridge geometry, where the electronic devices or device components comprise the islands and where the electrical interconnects comprise the bridges. The electronic device or device component, the one or more additional electronic devices or device components and the one or more electrical interconnects may be provided in a rigid island bridge geometry, where the electronic devices or device components comprise rigid islands and where the electrical interconnects comprise the flexible and/or stretchable bridges.

[0048] In an embodiment, an electronic system comprises an array of device components comprising rigid device islands, wherein the one or more electrical interconnects electrically connect adjacent rigid device islands. For example, at least one of the electrical interconnects may electrically connect a device component comprising a first rigid device island with a second device component comprising a second rigid device island. In an embodiment, an electronic system comprises a plurality of device components, where each of the rigid device islands corresponds to a device component. Generally, the physical dimension and geometry of the islands correspond to those of the electronic device or device component.

[0049] In an embodiment, one or more electrical interconnects may be a stretchable electrical interconnect configured to provide elasticity, bendability, or both to the electronic system. For example, at least a portion of the one or more stretchable electrical interconnects may have a bent, buckled, folded, curved or serpentine geometry. Further, at least a portion of the one or more stretchable electrical interconnects may have a geometry that is in plane, out of plane, or both in plane and out of plane, relative to a plane defined by a support surface of the substrate, which may be curved or substantially flat. In an embodiment, at least a portion of the one or more electrical interconnects has an in plane

serpentine geometry.

[0050] In an embodiment, an as-fabricated multilayer (polyimide(1.2 μm)/Cu(500 nm)/Au(100 nm)/polyimide(1.2 μm)/(Cu(600 nm)/polyimide(1.2 μm)/Al(600 nm)/polyimide(1.2 μm)) interconnect has an in-plane (or non-coplanar) serpentine geometry, or arc-shaped pop-up layout, with a lateral width of 50 μm - 100 μm . The Young's moduli of these materials are polyimide 2.5 GPa, Cu 120 GPa, Au 78 GPa, and Al 70 GPa.

[0051] In some embodiments, the free standing and/or tether device geometries of the present disclosure provide an efficient means of achieving mechanical isolation of the electronic device, or components thereof, from the substrate. This aspect of the present disclosure is beneficial, for example, for reducing the extent of strain on an electronic device component caused by movement or deformation of the substrate. In an embodiment, a free standing or tethered electronic device or device component, such as semiconductor device, chip, etc., is mechanically isolated from the substrate. For comparison, the strain level of a device without mechanical isolation is 4 to 1000 times larger than the strain level of a device that is free standing or tethered according to the present disclosure.

[0052] In an embodiment of a tethered configuration, a plurality of tethers (e.g., a pillar array) are used to support an electronic device, device component or interconnect. The number of tethers will vary depending on the number of devices or device components and the sophistication of the circuit layout. The function of the tethers is to substantially maintain the position of an electronic device or device component or interconnect to prevent physical or electrical interaction (e.g., tangling) during stretching and releasing. In an embodiment, a tether may be cylindrical, conical, rectangular, square, or irregularly shaped. Typically, the lateral dimensions of a tether range from 0.5 mm to 1 mm in diameter when used to support an electronic device or device component having lateral dimensions ranging from 1 mm to 10 mm. Thus, the rigid islands are bonded to tethers on a small portion of their overall area in a selective bonding configuration. In an embodiment, a tether has a height of about 100 μm , a Young's modulus of about 1 KPa to 1 GPa and a flexural rigidity of about 10^{-13} N·m to 10^5 N·m.

[0053] In an embodiment, tethers and the substrate are mounted in an etched Si wafer as a single, unitary piece and standard procedures are used to laminate multilayered metal serpentine interconnects onto the tether's surface by UV ozone activation and SiO_2 bonding.

[0054] In an embodiment, tethers are used to prevent drifting of the rigid device islands and stretchable interconnects are used to prevent entangling of the interconnects during repetitive stretching and releasing processes.

[0055] In an embodiment, devices or device components, such as COTS chips as received and after mechanical decapsulation, bare dies and in-house fabricated thin film sensors/devices, are embedded in enclosing structures of a containment chamber. In another embodiment, interconnects are embedded in enclosing structures (e.g. walls) of a containment chamber.

[0056] In an embodiment, interconnects are single or multilayered with vias, and conducting metal traces may be insulated, for example, by dielectric polymers, such as polyimide or parylene C or SU8.

[0057] In an embodiment, at least a portion of the one or more stretchable electrical interconnects comprises a plurality of electrically conductive structures each independently having a primary unit cell shape comprising a plurality of spatially offset and opposing segments, wherein the conductive structures are connected in a sequence characterized by a secondary shape comprising at least one pair of spatially offset and opposing regions formed from the sequence of electrically conductive structures, where the sequence of conductive structures is capable of undergoing deformation thereby providing stretchability of the stretchable electronic device. In an embodiment, at least a portion of the one or more electrical interconnects comprising the sequence of electrically conductive structures provides an overall self-similar geometry for the stretchable electrical interconnect. For example, the sequence of conductive structures may comprise a monolithic structure and/or the sequence of conductive structures may comprise a wire.

[0058] In an embodiment, the secondary shape is similar to the primary unit cell shape but has a different scale. For example, the secondary shape may be similar to the primary unit cell shape but at least 10 times larger than the primary unit cell shape, or at least 25 times larger than the primary unit cell shape, or at least 50 times larger than the primary unit cell shape.

[0059] In an embodiment, the sequence of electrically conductive structures is further characterized by a tertiary shape comprising at least one pair of spatially offset and opposing regions formed from a repeating series of the electrically conductive structures comprising the secondary shape.

[0060] In an embodiment, the spatially offset and opposing segments of the primary unit cell shape comprise convex and concave regions. For example, the unit cell shape may be a serpentine shape.

[0061] In an embodiment an electronic system comprises a transistor, an electrochemical cell, a fuel cell, an integrated circuit, a solar cell, a laser, a light emitting diode, a nanoelectromechanical device, a microelectromechanical device, a photodiode, a P-N junction, a sensor, a memory device, a complementary logic circuit or an array of any of these.

[0062] In an aspect, an electrochemical cell comprises: a substrate; a positive electrode forming part of a first electronic device component supported by the substrate; wherein the first electronic device component is free standing or tethered to the substrate; a negative electrode forming part of a second electronic device component supported by the substrate; wherein the second electronic device component is free standing or tethered to the substrate; and a containment chamber

at least partially enclosing the positive electrode, the negative electrode or both the positive electrode and the negative electrode; wherein the containment chamber is at least partially filled with an electrolyte fluid allowing for ionic transport between the positive electrode and the negative electrode. In the embodiment, an electrochemical cell further comprises one or more stretchable electrical interconnects in electrical contact with the positive electrode, the negative electrode or both the positive electrode and the negative electrode. For example, each of the one or more stretchable electrical interconnects may independently have a self-similar serpentine geometry. An array comprising a plurality of electronically interconnected electrochemical cells is also described.

[0063] In an aspect, a method of making an electronic system comprises: providing a substrate; providing an electronic device or device component that is free standing or tethered to the substrate in a containment chamber on the substrate such that the containment chamber at least partially encloses the electronic device or device component; and at least partially filling the containment chamber with a containment fluid or low modulus solid.

[0064] In an aspect, a method of using an electronic system comprises providing an electronic system comprising: a substrate; an electronic device or device component supported by the substrate; wherein the electronic device or device component is free standing or tethered to the substrate; and a containment chamber at least partially enclosing the electronic device or device component; wherein the containment chamber is at least partially filled with a containment fluid or low modulus solid; and applying an electric current to the electronic system.

[0065] Stretchable and flexible electronics having the configuration described herein may be used for a variety of device applications. The use of free floating interconnects in a fluid allows the interconnects to freely buckle and deform, which greatly increases the stretchability and flexibility of electronic devices in various fields of use. For example, a free floating interconnect may be used in a lithium ion battery having an array of active material islands connected by wavy interconnects. The islands may be firmly bonded on the substrate, while the wavy interconnects can freely buckle and deform. Stretchable interconnects may also be used in optical systems, such as light emitting diode and photo diode arrays formed as rigid island arrays. Rigid island sensor arrays be also be used to monitor temperature, hydration, pressure, strain and/or biological parameters. For example, by design specific functional circuits, electrophysiological parameters of humans and/or animals can be measured, such as skin temperature, electrocardiograms, electromyograms, electroencephalograms, electrooculograms.

[0066] The present disclosure also provides methods of making and using electronic systems including stretchable and/or deformable electronic devices and device arrays. These methods are explicitly intended to be commensurate in scope with the entirety of the description and may be practiced with all devices and embodiments disclosed herein.

[0067] Without wishing to be bound by any particular theory, there may be discussion herein of beliefs or understandings of underlying principles relating to the devices and methods disclosed herein. It is recognized that regardless of the ultimate correctness of any mechanistic explanation or hypothesis, an embodiment of the present disclosure can nonetheless be operative and useful.

[0068] In the following parts of the description the terms "embodiment", "embodiment of the present invention" and "example according to embodiment" are used. Irrespective of these terms and expressions, only those examples that fall under the scope of appended claims, namely as shown in figures 10A-71 and 102 -103B, form part of the invention

BRIEF DESCRIPTION OF THE DRAWINGS

[0069]

Figure 1. Aspects in battery layout and design, (a) Schematic illustration of a completed device, in a state of stretching and bending. (b) Exploded view layout of the various layers in the battery structure. (c) Illustration of 'self-similar' serpentine geometries used for the interconnects (black: 1st level serpentine; grey: 2nd level serpentine). (d) Optical images of the Al electrode pads and self-similar interconnects on Si wafer (left panel; top down view; ~4 unit cells), after transfer printing on a sheet of silicone (middle panel; top down view, in a bent geometry), and with moulded slurries of LiCoO₂ (right panel; top down view, in a bent geometry). (e) Optical images of the Cu electrode pads and self-similar interconnects on Si wafer (left panel; top down view; ~4 unit cells), after transfer printing on a sheet of silicone (middle panel; top down view, in a bent geometry), and with moulded slurries of Li₄Ti₅O₁₂ (right panel; top down view, in a bent geometry). Scale bars in d and e are 2 mm.

Figure 2. Experimental and computational studies of buckling physics in interconnects with self-similar serpentine layouts. Optical images and corresponding finite element analysis (FEA) of symmetric (left column) and anti-symmetric (middle column) deformation modes, for various levels of applied tensile strain (ϵ). The color in the FEA results represents the maximum principal strains of the metal layer. The scale bar is 2 mm. The right column shows the interconnect structures after releasing the applied strain.

Figure 3. Electrochemical and mechanical properties of the battery, (a) Galvanostatic charging and discharging

of the battery electrodes without (black) and with 300% uniaxial strain (red). **(b)** Capacity retention (squares) and coulombic efficiency (circles) over 20 cycles with a cutoff voltage of 2.5-1.6 V. **(c)** Output power as a function of applied biaxial strain. **(d)** Operation of a battery connected to a red LED while **(e)** biaxially stretched to 300%, **(f)** folded, **(g)** twisted, and **(h)** compliant when mounted on the human elbow.

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Figure 4. Stretchable system for wireless charging. **(a)** Circuit diagram. **(b)** Image of the integrated system with different components labeled. **(c)** Characterization of the wireless coil with an alternating voltage input at a frequency of 44.5 MHz (black) and the resulting direct voltage output (red), as indicated in **a**. **(d)** Charging voltage (orange) and current (blue) curves as a stretchable battery is charged with 3 V output from the wireless circuit. The scale bar in **b** is 1 cm.

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Figure 5. Illustration of the dimensions for the self-similar interconnect (copper layer).

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Figure 6. **(a)-(d)** Schematic illustration of the fabrication process, and images of the moulded **(e)** cathode and **(f)** anode slurry on water soluble tape.

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Figure 7. SEM image of a buckled Al foil (600 nm)/PI (1200 nm) bilayer on the surface of a sheet of ecoflex after releasing a prestrain of ~ 30%. This bilayer structure resembles the types of laminated Al/polymer packaging materials that are used in pouch cells, to block the permeation of water, air and solvent.

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Figure 8. Deformed configurations (FEA results) of the self-similar electrode for symmetric **(a)** and anti-symmetric **(b)** buckling modes under an applied strain of 50%, from different viewing angles (i.e., top, front, side, and three-dimensional (3D) views).

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Figure 9. The maximum value (ε_{max}) of the maximum principal strain in the metal layer of the self-similar interconnect as a function of the applied strain (ε_{appl}), together with the evolution of the deformations.

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Figure 10. The distribution of maximum principal strain in the metal layer when its maximum value reaches 1%: **(a)** the 2-order self-similar interconnect; and **(b)** the 1-order interconnect. The two structures have the same overall dimensions, and cross-sections.

Figure 11. The maximum value (ε_{max}) of the maximum principal strain in the metal layer of the interconnect as a function of the applied strain (ε_{appl}), for the self-similar and simple serpentine designs. The two interconnects have the same total length (l_{total}), span (L), amplitude (h), width (w), and thickness (t).

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Figure 12. Finite element analyses of the buckling profiles of a vertically aligned self-similar interconnect under compression, and its comparison with optical images from experiment. The color contours in the FEA results represent the distribution of maximum principal strain in the metal layer.

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Figure 13. The layout of Al and Cu pads **(a)**, and the dependences of fill factor on the size of a representative unit cell and the radius of the Al pad **(b)**. The offset distance **(d)** is set to be 0.5 mm in the model to avoid possible short circuits as the battery is stretched.

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Figure 14. Nyquist impedance plot for the pouch type stretchable battery from 1 MHz to 10 mHz with an a.c. perturbation amplitude of 10 mV.

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Figure 15. **(a)** Open circuit voltage decay curves and **(b)** leakage current curves for batteries in various configurations, measured at room temperature.

Figure 16. Capacity retention (squares) and coulombic efficiency (circles) over 20 cycles with a cutoff voltage of 2.5-1.6 V for coin cell geometries with exactly the same slurries and the capacitance matched cathode and anode geometries.

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Figure 17. Capacity retention curves with depth of discharge of 100% (circles curve, cut-off voltage of 1.60-2.50 V) and -75% (squares, cut-off voltage of 2.25-2.50 V).

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Figure 18. I-V curve of the commercial red light emitting diode, showing its turn on voltage at around 1.7 V.

Figure 19. (a) Schematic illustration of the layout of a wireless recharging system; (b) Calculated deformation and distribution of maximum principal strain under an applied strain of 32.3%, for a representative component of the wireless coil, with both the discrete diode and serpentine interconnect; (c) Calculated deformation and distribution of maximum principal strain under an applied strain of 32.6%, for a representative component of the wireless coil, with only the serpentine interconnect.

Figure 20. Calculated distribution of (a) maximum principal strain in the whole structure, and (b) substrate normal strain (ε_{33}) at the diode/substrate interface, when the system is stretched by 30% along the vertical direction.

Figure 21. The input and output electrical characteristics of the wireless charging systems. The Schottky diode rectifies the alternating voltage input from the functional generator (pink curve), to yield a rectified output (blue curve), which oscillates nominally from 0 V to 4.6 V. The parallel 1.7 nF capacitor integrates this oscillation to give a current source with a behavior closer to direct current (red curve). Increasing the capacitance (e.g. 17 nF) further smooths the current (black curve).

Figure 22. I-V curve of the wireless coil with the rectifying chip, showing its series resistance of about $2.3\text{ K}\Omega$.

Figure 23. (a) Input and output voltages (black) and currents (red) of the wireless coil 18 μm thick copper foil. (b) Optical micrographs of a 7 μm thick Cu coil at different levels of applied uniaxial strain. The scale bars are all 1 cm. (c) Finite element analysis of stretching of a segment of a serpentine coil with a thickness of 7 μm .

Figure 24. Comparison between the (a) measured current change and the (b) simulated result in the wireless coil charging circuit.

Figure 25. Exemplary overall fabrication flow chart for making some electronic systems, according to an embodiment of the present disclosure.

Figure 26. Illustration of silver epoxy scraping.

Figure 27. Illustration of liquid chamber fabrication, according to an embodiment of the present invention.

Figure 28. Illustration of a single battery according to an embodiment of the present invention.

Figure 29. Illustration an exemplary battery of the present disclosure undergoing -100% stretching.

Figure 30. ECG circuit with wireless power and telecommunication.

Figure 31. Exemplary ECG data.

Figure 32. Illustration of a circuit with selective bonding.

Figure 33. An array of Ecoflex pedestals.

Figure 34. Illustration of thin chips (<1 mm).

Figure 35. A circuit having a liquid chamber, according to an embodiment of the present disclosure.

Figure 36. Images demonstrating stretching of an electronic system.

Figure 37. Images demonstrating flexing of an electronic system.

Figure 38. Schematic diagrams illustrating interconnects at an interface.

Figure 39. Schematic diagrams illustrating system level mechanics-horizontal.

Figure 40. Schematic diagrams illustrating system level mechanics-vertical.

Figure 41. An advanced multifunctional circuit with liquid chamber.

Figure 42. Mechanically polished commercial off the shelf (COTS) chips.

Figure 43. List of example circuit functions.

Figure 44. Illustration of a multilayer - 1st.

Figure 45. Illustration of a multilayer - 2nd.

Figure 46. Illustration of a Multilayer - 3rd.

Figure 47. Illustration of the location of precise selective bonding (1).

Figure 48. Illustration of fabrication process of precise selective bonding (2).

Figure 49. Illustration of reduced sharp corners.

Figure 50. Illustration of self-similar interconnects.

Figure 51. Illustration of self-similar contact pads.

Figures 52. Exemplary basic fabrication scheme.

Figures 53. Exemplary basic fabrication scheme.

Figure 54. An example of a wireless power circuit.

Figure 55. Demonstration of wireless circuit stretching.

Figure 56. Exemplary ECG circuit.

Figure 57. Illustration of exemplary layout design considerations.

Figure 58. Illustration of exemplary layout design considerations.

Figure 59. Illustration of exemplary layout design considerations.

Figure 60. Illustration of exemplary fabricated interconnects.

Figure 61. Illustration of selective bonding using a fabrication process.

Figure 62. Illustration of device tethered components comprising stretchable electrical interconnects bonded to pedestals.

Figure 63. Illustration of chip depackaging.

Figure 64. Illustration of a fabricated device.

Figure 65. Illustration of stretching and flexing of an electronic device.

Figure 66. Exemplary mechanical analyses.

Figure 67. Illustration of strain distribution.

Figures 68. Schematic illustration of stretching simulations.

Figures 69. Schematic illustration of stretching simulations.

Figure 70. Schematic illustrations of multiple embodiments of electronic devices and/or device components within

containment chambers, according to multiple embodiments of the present invention.

Figure 71. Schematic illustration of an embodiment of an electronic device having device components that are selectively bonded (directly or indirectly) to a substrate, according to an embodiment of the present invention.

Figure 72. Schematic illustrations, scanning electron micrographs (SEMs) and pictures of a soft, stretchable electronic system that integrates strain-isolated device components and a free-floating interconnect network in a thin elastomeric microfluidic enclosure. (A) Exploded view schematic illustration of the key components of the system. (B) Illustration of the system after assembly, during initial stages of microfluidic injection using a syringe. (C) 3D FEA results, in exploded view format, that show the physics associated with equal-biaxial stretching of a small region of this system, as indicated by the red dash box in B. The colors indicate the maximum principal strains. The buckling physics of the free-floating serpentine interconnects and the strain isolation mechanics of the suspended chips represent the key features. (D) Angled view SEM of a region of the substrate showing a textured surface formed by sharp pyramidal features of surface relief, along with structures for local bonding of the device components (support post) and for avoiding entanglements in the interconnect network (barriers). (E) Angled view SEM of the same region in (D), after transfer printing the interconnect network (colorized yellow). (F) Angled view SEM of the region of (E) indicated by the red dashed box. (G) Image of a system designed for acquisition, filtering, amplification and radio transmission of EP signals measured from the skin. An integrated module for inductive power provides a wireless source of power. The colored dashed boxes and labels identify the various sub-systems. The grey dashed box around the periphery indicates, approximately, the location of bonding of the superstrate. Image of this system in a stretched (F) and a twisted (G) configuration.

Figure 73. Optical image of the non-coring needle, highlighting the inject pore on the side wall of the needle. This construction avoids removal of subject material during the injection process.

Figure 74. Thermogravimetric analysis of PDMS base fluid at elevated temperatures for prolonged time.

Figure 75. 3D-FEA results that illustrate the mechanics advantage of free-floating interconnects in comparison with fully bonded or embedded ones. (A) Initial configuration of one of the interconnects shown in Fig. 72C; (B) the strain distribution of the interconnect only with two ends bonded onto the top of the Ecoflex, when the applied strain reaches the corresponding elastic stretchability (167%) of the interconnect; (C) the strain distribution of the interconnect fully bonded onto the top of the Ecoflex, when the applied strain reaches its elastic stretchability (17%); (D) the strain distribution of the interconnect fully embedded in the middle of the Ecoflex, when the applied strain reaches its elastic stretchability (8%).

Figure 76. Characterization of the hierarchical substrate. (A) Optical image of a substrate with multiple levels of embossed relief. (B) SEM image of a small region of the substrate to illustrate its hierarchical structure.

Figure 77. X-ray side view image of a typical commercial chip with standard package design. The thickness of this chip can be reduced to 0.86 mm by grinding the excessive packaging epoxy away.

Figure 78. Optical images of the interface wetting behavior of the interconnects. Chips bonded on the interconnects (A) before and (B) after electroless Sn plating. These images clearly show that after Sn plating, the solder can wet the interconnector surfaces well and thus allow a robust bonding interface.

Figure 79. Layout design of the single ECG system, with labels for different parts of the device. The design of the transition region between the interconnectors and the chip bonding pads is also highlighted in the dashed purple box.

Figure 80. Comparison of mechanical performance of three different interconnect designs at the point of the periphery of the microfluidic enclosure. (A) Schematic illustration (left panel) of a self-similar serpentine interconnect across the interface, and the distribution of maximum principal strain (middle panel for horizontal stretching along the x direction; right panel for vertical stretching along the y direction) in the metal layer for 100% uniaxial stretching. (B) Schematic illustration (left panel) of a straight interconnect (length 1 mm) across the interface, and the distribution of maximum principal strain (middle panel for horizontal stretching; right panel for vertical stretching) in the metal layer for 100% uniaxial stretching. (C) Schematic illustration (left panel) of a straight interconnect (length 0.5 mm) across the interface, and the distribution of maximum principal strain (middle panel for horizontal stretching; right panel for vertical stretching) in the metal layer for 100% uniaxial stretching. The simulation shows that the optimized straight interconnect at the interface avoids fracture inducing strains even under 100% biaxial stretching, in agreement

with the FEA results, where the strain of interconnect remains well below the fracture limit (-5%).

Figure 81. Illustration of the fully integrated device. (A) Schematic illustration of a device in a slightly deformed configuration, and (B) optical image of an actual device in a similar state of deformation, with labels for different parts and modules in the circuit.

Figure 82. Schematic layout of the ECG system with the chip positions and chip types (Table 1) labeled. Black dots indicate the number 1 pin of each individual chip.

Figure 83. Computational and experimental studies of the physics of buckling in free-floating interconnect networks and of strain isolation in suspended chips, for a device capable of acquisition, filtering, amplification and radio transmission of EP signals measured from the skin, with inductive power supply. (A) System-level 3D FEA results for various magnitudes of equal-biaxial tensile strain. The color shows the maximum principle strains across each part of the system. The bottom panel illustrates a small region of the interconnect network. (B) Optical images of the device at equal-biaxial strains that correspond to those evaluated by 3D FEA. An additional image shows the system after release of the strain, to illustrate reversibility in the responses. The bottom panel provides a graph of the stress/strain responses measured by uniaxial testing for the case of a system with (black: in horizontal; blue: in vertical) and without (red: in horizontal; pink: in vertical) the chips and interconnect network. The results indicate nearly complete decoupling of the mechanics of the chips/interconnects from the substrate. (C) Images and 3D FEA results for a local region.

Figure 84. Experimental and computational studies of localized deformations in various self-similar serpentine interconnects within the ECG system, under biaxial stretching. (A) to (J) show optical images and corresponding FEA results for ten self-similar serpentine interconnects as the entire circuit is biaxially stretched from 0% to 50% and 100%. The color in the FEA results represents the maximum principal strains of the metal layer.

Figure 85. Dependence of the strain in the interconnect metal (at the material level) on the applied strain (at the system level). The maximum value (ε_{max}) of the principal strain in the metal layer of the interconnect network as a function of the biaxial applied strain (ε_{app}), together with illustrations of the evolution of the deformations.

Figure 86. Experimental and computational studies of buckling deformations across the entire circuits under uniaxial stretching along the horizontal direction. 3D-FEA results (A) and corresponding optical images (B) of the entire circuit when uniaxially stretched from 0% to 10%, 20%, 30% and 40%. The color in the FEA results represents the maximum principal strains in the metal layer.

Figure 87. Experimental and computational studies of localized deformations of self-similar serpentine interconnects with the circuits under uniaxial stretching along the horizontal direction. (A) to (E) show optical images and corresponding 3D-FEA results of five self-similar serpentine interconnects as the entire circuit is uniaxially stretched from 0% to 20% and 40%. The color in the FEA results represents the maximum principal strains of the metal layer.

Figure 88. Finite element simulations to illustrate the effects of rigid devices on the strain distribution across the soft substrate under biaxial stretching of $\varepsilon_{app}=20\%$. (A) The distribution of logarithmic strain in the substrate when the rigid devices are selectively bonded to the substrate (via small circular and rectangular pedestals). (B) The distribution of logarithmic strain in the substrate when the full regions of each device are bonded to the substrate.

Figure 89. Strain mapping at different levels of strain when all of the chips are fully bonded on the substrate. The strain localization can be clearly visualized under these chips.

Figure 90. Images and operational data from a device capable of measuring EP signals, filtering and amplifying them and then wirelessly transmitting the results, using inductive power supply. Optical images of the device on the forearm, with a pair of epidermal electrodes in self-similar serpentine mesh layouts (inset optical micrograph) for an undeformed state (A) and compressed and twisted state (B). (C) ECG acquired using a device mounted on the sternum. The graph on the right provides a detailed view that shows the expected QRS complex. (D) EOG acquired from the side of the left eye (green) and simultaneous measurement using a wired commercial device with commercial electrodes (blue) placed next to those of the wireless system. The right plot shows data during the time of two eye blinks. (E) EMG acquired using a device mounted over the left carpi radialis (green) and simultaneous measurement using a wired commercial device with commercial electrodes (blue) placed next to those of the wireless system. The data from the wireless device were inverted along the vertical axis, to facilitate comparison. The right plot shows

5 data corresponding to a single muscle contraction. (F) EEG acquired from the left forehead during mental math and rest (green), and simultaneous measurement using a wired commercial device with Au plated Ag electrodes and conductive gel (blue), mounted next to the wireless system. The large deflection represents the eyes closing as the subject shifts from mental math to resting, as shown in detail in the right plot. Data are plotted in arbitrary units, normalized and offset in the vertical direction to facilitate comparisons.

10 **Figure 91.** 3D-FEA of epidermal electrodes with self-similar serpentine mesh designs. (A) A traditional serpentine mesh design with a filling ratio of ~31%, and the strain distribution when the applied strain reaches the elastic stretchability (12.5%). (B) The self-similar serpentine mesh design with a filling ratio of ~31%, and the strain distribution when the applied strain reaches the elastic stretchability (25.0%). Both the top view and angled views of the deformed configurations are shown in the figure, indicating smaller wrinkling wavelength for the self-similar serpentine mesh design on the right.

15 **Figure 92.** Illustration of the experimental setup and measurement position on the human body. (A) Experimental setup to measure the ECG in a room designed to eliminate background electrical noise. (B) Different lamination positions on the human body for measuring the electrophysiological signals.

20 **Figure 93.** Comparison of the ECG signals from this work and commercial systems. (A) ECG data acquired using a device mounted on the sternum (green) and simultaneous measurement using a wired commercial device with commercial electrodes (blue) placed next to those of the wireless system. (B) The expanded graph provides a detailed view that shows the expected QRS complex. The data are plotted in arbitrary units, normalized and offset in the vertical direction to facilitate comparisons.

25 **Figure 94.** A time-frequency spectrogram of the EEG computed with wavelet decomposition. EEG data from Fig. 90F, in normalized arbitrary units were decomposed using a 20 cycle wavelet transform. During mental math, an increase in high-frequency activity between 12-40 Hz (Beta band) is observed that dissipates with rest. During rest, the data show a clear peak in the lower frequency delta band that is larger than that during math.

30 **Figure 95.** Images and operational data from a device capable of measuring EP signals, acceleration and temperature, filtering and amplifying them and transmitting the results in a time-multiplexed wireless mode. Exposed contact pads at the periphery provide points for integrating a separate power supply and a pair of epidermal electrodes for the electrical interface to the skin. (A) Optical image of a representative device. The colored dashed boxes and labels identify the various sub-systems. The grey dashed box around the periphery indicates, approximately, the location of bonding of the superstrate. (B) Image of the device on the skin, with a perspective view to show its overall thickness (~1 mm) with reference to a coin (US quarter). Image of the device in a twisted and stretched state (C) and a compressed state (D) induced by pinching the skin. (E) EMG acquired from above the left carpi radialis during periodic clinching and relaxing of the fist. The right panel provides an enlarged view of the EMG for a single clinching motion. (F) Acceleration profiles corresponding to walking, with the device mounted on the forearm. The data near the end of this timeframe corresponds to an intentional fall. (G) Temperature response to breathing warm air onto the device. The data shown in this figure used a small coin cell battery as a source of power.

35 **Figure 96.** The multifunctional sensor system with different parts and chip information (Table 3) labeled. Black dots indicate the number 1 pin of each individual chip.

40 **Figure 97.** Working principle of the multiplexer.

45 **Figure 98.** Design strategy for reducing the power consumption of the voltage controlled oscillator (VCO), by adding a pulse modulator. When the VCO duty cycle is reduced to 7%, the power consumption of the entire system is about 6 mW.

50 **Figure 99.** Releasable power supplies for the multifunctional system. (A) Optical image of the NFC module from the front and back sides, and associated chip information (Table 1). (B) Optical image of the front and back sides of a small coin cell battery module. Both of these modules can laminate onto the power supply contact pads of the multifunctional device, to provide power for operation.

55 **Figure 100.** Calibration curve for the temperature-frequency relationship in the multifunctional system.

Figure 101. Signal readouts from the multifunctional device when mounted on the forearm during periodic clinching

and relaxing of the fist. (A) Acceleration signal and (B) temperature signal before and after 9 min of clinching and relaxing. (C) The temperature measured before (left panel) and after (right panel) this exercise, as confirmed by the commercial IR camera.

Figure 102. Schematic of the stretchable design layout (a) and the serpentine interconnect (b) adopted in finite element analyses (FEA).

Figure 103. (A) Schematic of a design layout comprising a first low modulus material and a fluid or second low modulus material. (B) Schematic of a design layout comprising a fluid or low modulus solid filled containment chamber housing a solar cell soldered to two electronic devices or components on dielectric materials in contact with a substrate.

Figure 104. Photograph, and exploded view, of the device of Figure 103B.

DETAILED DESCRIPTION OF THE PRESENT DISCLOSURE

[0070] In general, the terms and phrases used herein have their art-recognized meaning, which can be found by reference to standard texts, journal references and contexts known to those skilled in the art. The following definitions are provided to clarify their specific use in the context of the present disclosure.

[0071] "Functional layer" refers to a layer that imparts some functionality to the device. For example, the functional layer may contain semiconductor components. Alternatively, the functional layer may comprise multiple layers, such as multiple semiconductor layers separated by support layers. The functional layer may comprise a plurality of patterned elements, such as interconnects running between or below electrodes or islands. The functional layer may be homogeneous or may have one or more properties or materials that are inhomogeneous. "Inhomogeneous property" refers to a physical parameter that can spatially vary, thereby effecting the position of the neutral mechanical plane within a multilayer device.

[0072] "Structural layer" refers to a layer that imparts structural functionality, for example by supporting and/or encapsulating and/or partitioning device components.

[0073] "Semiconductor" refers to any material that is an insulator at a very low temperature, but which has an appreciable electrical conductivity at a temperature of about 300 Kelvin. In the present description, use of the term semiconductor is intended to be consistent with use of this term in the art of microelectronics and electronic devices. Useful semiconductors include those comprising elemental semiconductors, such as silicon, germanium and diamond, and compound semiconductors, such as group IV compound semiconductors such as SiC and SiGe, group III-V semiconductors such as AlSb, AlAs, AlN, AIP, BN, BP, BAs, GaSb, GaAs, GaN, GaP, InSb, InAs, InN, and InP, group III-V ternary semiconductors such as $\text{Al}_x\text{Ga}_{1-x}\text{As}$, group II-VI semiconductors such as CsSe, CdS, CdTe, ZnO, ZnSe, ZnS, and ZnTe, group I-VII semiconductors such as CuCl, group IV - VI semiconductors such as PbS, PbTe, and SnS, layer semiconductors such as Pbl₂, MoS₂, and GaSe, and oxide semiconductors such as CuO and Cu₂O. The term semiconductor includes intrinsic semiconductors and extrinsic semiconductors that are doped with one or more selected materials, including semiconductors having p-type doping materials and n-type doping materials, to provide beneficial electronic properties useful for a given application or device. The term semiconductor includes composite materials comprising a mixture of semiconductors and/or dopants. Specific semiconductor materials useful for some embodiments include, but are not limited to, Si, Ge, Se, diamond, fullerenes, SiC, SiGe, SiO, SiO₂, SiN, AlSb, AlAs, AlIn, AIN, AIP, AIS, BN, BP, BAs, As₂S₃, GaSb, GaAs, GaN, GaP, GaSe, InSb, InAs, InN, InP, CsSe, CdS, CdSe, CdTe, Cd₃P₂, Cd₃As₂, Cd₃Sb₂, ZnO, ZnSe, ZnS, ZnTe, Zn₃P₂, Zn₃As₂, Zn₃Sb₂, ZnSiP₂, CuCl, PbS, PbSe, PbTe, FeO, FeS₂, NiO, EuO, EuS, PtSi, TiBr, CrBr₃, SnS, SnTe, Pbl₂, MoS₂, GaSe, CuO, Cu₂O, HgS, HgSe, HgTe, Hgl₂, MgS, MgSe, MgTe, Cas, CaSe, SrS, SrTe, BaS, BaSe, BaTe, SnO₂, TiO, TiO₂, Bi₂S₃, Bi₂O₃, Bi₂Te₃, Bil₃, UO₂, UO₃, AgGaS₂, PbMnTe, BaTiO₃, SrTiO₃, LiNbO₃, La₂CuO₄, La_{0.7}Ca_{0.3}MnO₃, CdZnTe, CdMnTe, CulnSe₂, copper indium gallium selenide (CIGS), HgCdTe, HgZnTe, HgZnSe, PbSnTe, Tl₂SnTe₅, Tl₂GeTe₅, AlGaAs, AlGaN, AlGaP, AlInAs, AlInSb, AlInP, AlInAsP, InGaAs, InGaP, InGaN, InAsSb, InGaSb, InMnAs, InGaAsP, InGaAsN, InAlAsN, GalnAsSb, GalnAsPb, and any combination of these. Porous silicon semiconductor materials are useful for aspects described herein. Impurities of semiconductor materials are atoms, elements, ions and/or molecules other than the semiconductor material(s) themselves or any dopants provided to the semiconductor material. Impurities are undesirable materials present in semiconductor materials which may negatively impact the electronic properties of semiconductor materials, and include but are not limited to oxygen, carbon, and metals including heavy metals. Heavy metal impurities include, but are not limited to, the group of elements between copper and lead on the periodic table, calcium, sodium, and all ions, compounds and/or complexes thereof.

[0074] A "semiconductor component" broadly refers to any semiconductor material, composition or structure, and expressly includes high quality single crystalline and polycrystalline semiconductors, semiconductor materials fabricated

via high temperature processing, doped semiconductor materials, inorganic semiconductors, and composite semiconductor materials.

[0075] A "component" is used broadly to refer to an individual part of a device. An "interconnect" is one example of a component, and refers to an electrically conducting structure capable of establishing an electrical connection with another component or between components. In particular, an interconnect may establish electrical contact between components that are separate. Depending on the desired device specifications, operation, and application, an interconnect is made from a suitable material. Suitable conductive materials include semiconductors.

[0076] Other components include, but are not limited to, thin film transistors (TFTs), transistors, electrodes, integrated circuits, circuit elements, control elements, microprocessors, transducers, islands, bridges and combinations thereof. Components may be connected to one or more contact pads as known in the art, such as by metal evaporation, wire bonding, and application of solids or conductive pastes, for example.

[0077] "Neutral mechanical plane" (NMP) refers to an imaginary plane existing in the lateral, b, and longitudinal, l, directions of a device. The NMP is less susceptible to bending stress than other planes of the device that lie at more extreme positions along the vertical, h, axis of the device and/or within more bendable layers of the device. Thus, the position of the NMP is determined by both the thickness of the device and the materials forming the layer(s) of the device.

[0078] "Coincident" refers to the relative position of two or more objects, planes or surfaces, for example a surface such as a neutral mechanical plane that is positioned within or is adjacent to a layer, such as a functional layer, substrate layer, or other layer. In an embodiment, a neutral mechanical plane is positioned to correspond to the most strain-sensitive layer or material within the layer.

[0079] "Proximate" refers to the relative position of two or more objects, planes or surfaces, for example a neutral mechanical plane that closely follows the position of a layer, such as a functional layer, substrate layer, or other layer while still providing desired conformability without an adverse impact on the strain-sensitive material physical properties. "Strain-sensitive" refers to a material that fractures or is otherwise impaired in response to a relatively low level of strain. In general, a layer having a high strain sensitivity, and consequently being prone to being the first layer to fracture, is located in the functional layer, such as a functional layer containing a relatively brittle semiconductor or other strain-sensitive device element. A neutral mechanical plane that is proximate to a layer need not be constrained within that layer, but may be positioned proximate or sufficiently near to provide a functional benefit of reducing the strain on the strain-sensitive device element.

[0080] "Unitary" refers to an object formed as a single piece or undivided whole.

[0081] The terms "direct and indirect" describe the actions or physical positions of one component relative to another component, or one device relative to another device. For example, a component that "directly" acts upon or touches another component does so without intervention from an intermediary. Contrarily, a component that "indirectly" acts upon or touches another component does so through an intermediary (e.g., a third component).

[0082] "Electronic device" generally refers to a device incorporating a plurality of components, and includes large area electronics, printed wire boards, integrated circuits, component arrays, electrophysiological and/or biological and/or chemical sensors, and physical sensors (e.g., temperature, acceleration, etc.).

[0083] "Sensing" refers to detecting the presence, absence, amount, magnitude or intensity of a physical and/or chemical property. Useful electronic device components for sensing include, but are not limited to electrode elements, chemical or biological sensor elements, pH sensors, accelerometers, temperature sensors and capacitive sensors.

[0084] "Island" refers to a relatively rigid component of an electronic device comprising a plurality of semiconductor components. "Bridge" refers to structures interconnecting two or more islands or one island to another component. The present disclosure includes electronic devices having bridge structures comprising electrical interconnects, such as stretchable electrical interconnects provided between and in electrical contact with semiconductor device components.

[0085] "Encapsulate" refers to the orientation of one structure such that it is at least partially, and in some cases completely, surrounded by one or more other structures. "Partially encapsulated" refers to the orientation of one structure such that it is partially surrounded by one or more other structures, for example, wherein 30%, or optionally 50% or optionally 90%, of the external surfaces of the structure is surrounded by one or more structures. "Completely encapsulated" refers to the orientation of one structure such that it is completely surrounded by one or more other structures.

[0086] "Contiguous" refers to materials or layers that are touching or connected throughout in an unbroken sequence. In one embodiment, a contiguous layer of a device has not been manipulated to remove a substantial portion (e.g., 10% or more) of the originally provided material or layer.

[0087] "Active circuit" and "active circuitry" refer to one or more components configured for performing a specific function. Useful active circuits include, but are not limited to, amplifier circuits, multiplexing circuits, current limiting circuits, integrated circuits, impedance matching circuits, wireless power harvesting circuits, wireless data transmission circuits, transistors and transistor arrays.

[0088] "Substrate" refers to a material, layer or other structure having a surface, such as a receiving surface or supporting surface, that is capable of supporting one or more components or electronic devices. A component that is "bonded" to the substrate refers to a component that is in physical contact with the substrate and unable to substantially move

relative to the substrate surface to which it is bonded. Unbonded components or portions of a component, in contrast, are capable of substantial movement relative to the substrate. In an embodiment, the present disclosure includes electronic devices having one or more free standing semiconductor device components supported by a substrate, optionally in physical contact with the substrate or in physical contact with one or more intermediate structures supported by the substrate. In an embodiment, the present disclosure includes electronic devices having one or more tethered semiconductor device components supported by, or optionally bonded to, one or more structures, such as a pedestal or array of pedestals, independently connecting the semiconductor device components to the substrate.

[0089] A "containment chamber" is a structure that encloses or encapsulates an electronic device or device component. In one embodiment, a containment chamber is shaped as a rectangular or square structure comprising a substrate or bottom wall, a lid or top wall, and a plurality of walls to support the top wall. In another embodiment, a containment chamber is shaped as a sphere, half sphere, pyramid, or an irregular three-dimensional structure. In an embodiment, a containment chamber is self-supporting, such that the containment chamber retains its shape when hollow or partially hollow. In an embodiment, the containment chamber is a fluid containment chamber. In an embodiment, a containment chamber is a low modulus solid containment chamber.

[0090] "Free standing" refers to a configuration wherein a device or device component is supported by, but not bonded to, a substrate or intermediate structure provided between the device or device component and the substrate. In an embodiment, for example, a substrate is able to move relative to a free standing device or component supported by the substrate. In an embodiment, for example, a free standing device or component is able to move relative to a substrate supporting the free standing device or component. In some embodiments, for example, a free standing configuration of a device or device component decouples movement and/or deformation of the substrate from the device or device component. In some embodiments, for example, a free standing configuration of a device or device component decouples forces generated by elongation, compression or deformation of the substrate from the device or device component. In some embodiments, a free standing device or component is characterized by undergoing an associative interaction with a substrate surface or intermediate structure provided thereon, such as a Van der Waals interaction, dipole-dipole interaction or other non-covalent associative interaction. In an embodiment, a free standing device or component is not covalently bonded to the supporting surface of a substrate.

[0091] "Tethered" refers to a configuration wherein a device or component is connected to a substrate via one or more tethering structures, such as a pedestal or array of pedestals. In an embodiment, for example, a substrate is able to move relative to a tethered device or component supported by the substrate. In an embodiment, for example, a tethered device or component is able to move relative to a substrate supporting the tethered device or component. In some embodiments, for example, a tethered configuration of a device or device component decouples movement and/or deformation of the substrate from the device or device component. In some embodiments, for example, a tethered configuration of a device or device component decouples forces generated by elongation, compression or deformation of the substrate from the device or device component. In some embodiments, less than 20%, optionally less than 5%, and optionally less than 1%, of the area of a bottom surface of a device or component is covalently bonded to the tethering structure connected to the substrate.

[0092] "Nanostructured surface" and "microstructured surface" refer to device surfaces having nanometer-sized and micrometer-sized relief features, respectively. The relief features extend a length, x , from a substantially contiguous plane of the device surface. Quantitative descriptors of a structured surface include surface roughness parameters, such as R_{\max} , R_a , and normalized roughness (R_a/R_{\max}), all of which may be measured by atomic force microscopy (AFM). R_{\max} is the maximum height between a highest peak to a lowest valley. R_a is the center-line-mean roughness, which is the average of an absolute value of a deviation from a center line of a roughness curve to the roughness curve. The surface of a substrate or layer is "substantially smooth", for the purposes of this disclosure, if the surface has an R_a value of 100 nm or less. If the surface has an R_a value greater than 100 nm, the surface is considered to be a "structured surface" for purposes of this disclosure.

[0093] "Dielectric" refers to a non-conducting or insulating material. In an embodiment, an inorganic dielectric comprises a dielectric material substantially free of carbon. Specific examples of inorganic dielectric materials include, but are not limited to, silicon nitride, silicon dioxide and non-conjugated polymers.

[0094] "Polymer" refers to a macromolecule composed of repeating structural units connected by covalent chemical bonds or the polymerization product of one or more monomers, often characterized by a high molecular weight. The term polymer includes homopolymers, or polymers consisting essentially of a single repeating monomer subunit. The term polymer also includes copolymers, or polymers consisting essentially of two or more monomer subunits, such as random, block, alternating, segmented, grafted, tapered and other copolymers. Useful polymers include organic polymers or inorganic polymers that may be in amorphous, semi-amorphous, crystalline or partially crystalline states. Crosslinked polymers having linked monomer chains are particularly useful for some applications. Polymers useable in the methods, devices and components include, but are not limited to, plastics, elastomers, thermoplastic elastomers, elastoplastics, thermoplastics and acrylates. Exemplary polymers include, but are not limited to, acetal polymers, biodegradable polymers, cellulosic polymers, fluoropolymers, nylons, polyacrylonitrile polymers, polyamide-imide polymers, polyimides,

polyarylates, polybenzimidazole, polybutylene, polycarbonate, polyesters, polyetherimide, polyethylene, polyethylene copolymers and modified polyethylenes, polyketones, poly(methyl methacrylate), polymethylpentene, polyphenylene oxides and polyphenylene sulfides, polyphthalamide, polypropylene, polyurethanes, styrenic resins, sulfone-based resins, vinyl-based resins, rubber (including natural rubber, styrene-butadiene, polybutadiene, neoprene, ethylene-propylene, butyl, nitrile, silicones), acrylic, nylon, polycarbonate, polyester, polyethylene, polypropylene, polystyrene, polyvinyl chloride, polyolefin or any combinations of these.

[0095] "Elastomeric stamp" and "elastomeric transfer device" are used interchangeably and refer to an elastomeric material having a surface that can receive as well as transfer a material. Exemplary elastomeric transfer devices include stamps, molds and masks. The transfer device affects and/or facilitates material transfer from a donor material to a receiver material.

[0096] "Elastomer" refers to a polymeric material which can be stretched or deformed and returned to its original shape without substantial permanent deformation. Elastomers commonly undergo substantially elastic deformations. Useful elastomers include those comprising polymers, copolymers, composite materials or mixtures of polymers and copolymers. Elastomeric layer refers to a layer comprising at least one elastomer. Elastomeric layers may also include dopants and other non-elastomeric materials. Useful elastomers include, but are not limited to, thermoplastic elastomers, styrenic materials, olefinic materials, polyolefin, polyurethane thermoplastic elastomers, polyamides, synthetic rubbers, PDMS, polybutadiene, polyisobutylene, poly(styrene-butadiene-styrene), polyurethanes, polychloroprene and silicones. In some embodiments, an elastomeric stamp comprises an elastomer. Exemplary elastomers include, but are not limited to silicon containing polymers such as polysiloxanes including poly(dimethyl siloxane) (i.e. PDMS and h-PDMS), poly(methyl siloxane), partially alkylated poly(methyl siloxane), poly(alkyl methyl siloxane) and poly(phenyl methyl siloxane), silicon modified elastomers, thermoplastic elastomers, styrenic materials, olefinic materials, polyolefin, polyurethane thermoplastic elastomers, polyamides, synthetic rubbers, polyisobutylene, poly(styrene-butadienestyrene), polyurethanes, polychloroprene and silicones. In an embodiment, a polymer is an elastomer.

[0097] "Conformable" refers to a device, material or substrate which has a bending stiffness that is sufficiently low to allow the device, material or substrate to adopt any desired contour profile, for example a contour profile allowing for conformal contact with a surface having a pattern of relief features.

[0098] "Conformal contact" refers to contact established between a device and a receiving surface. In one aspect, conformal contact involves a macroscopic adaptation of one or more surfaces (e.g., contact surfaces) of a device to the overall shape of a surface. In another aspect, conformal contact involves a microscopic adaptation of one or more surfaces (e.g., contact surfaces) of a device to a surface resulting in an intimate contact substantially free of voids. In an embodiment, conformal contact involves adaptation of a contact surface(s) of the device to a receiving surface(s) such that intimate contact is achieved, for example, wherein less than 20% of the surface area of a contact surface of the device does not physically contact the receiving surface, or optionally less than 10% of a contact surface of the device does not physically contact the receiving surface, or optionally less than 5% of a contact surface of the device does not physically contact the receiving surface.

[0099] "Young's modulus" is a mechanical property of a material, device or layer which refers to the ratio of stress to strain for a given substance. Young's modulus may be provided by the expression:

$$40 \quad E = \frac{(\text{stress})}{(\text{strain})} = \left(\frac{L_0}{\Delta L} \right) \left(\frac{F}{A} \right), \quad (\text{I})$$

where E is Young's modulus, L_0 is the equilibrium length, ΔL is the length change under the applied stress, F is the force applied, and A is the area over which the force is applied. Young's modulus may also be expressed in terms of Lame constants via the equation:

$$50 \quad E = \frac{\mu(3\lambda + 2\mu)}{\lambda + \mu}, \quad (\text{II})$$

where λ and μ are Lame constants. High Young's modulus (or "high modulus") and low Young's modulus (or "low modulus") are relative descriptors of the magnitude of Young's modulus in a given material, layer or device. In some embodiments, a high Young's modulus is larger than a low Young's modulus, preferably about 10 times larger for some applications, more preferably about 100 times larger for other applications, and even more preferably about 1000 times larger for yet other applications. In an embodiment, a low modulus layer has a Young's modulus less than 100 MPa, optionally less than 10 MPa, and optionally a Young's modulus selected from the range of 0.1 MPa to 50 MPa. In an

embodiment, a high modulus layer has a Young's modulus greater than 100 MPa, optionally greater than 10 GPa, and optionally a Young's modulus selected from the range of 1 GPa to 100 GPa.

[0100] "Inhomogeneous Young's modulus" refers to a material having a Young's modulus that spatially varies (e.g., changes with surface location). A material having an inhomogeneous Young's modulus may optionally be described in terms of a "bulk" or "average" Young's modulus for the entire material.

[0101] "Low modulus" refers to materials having a Young's modulus less than or equal to 1 MPa, less than or equal to 0.5 MPa, or less than or equal to 200 KPa. A low modulus material may have a Young's modulus selected from the range of 1 MPa to 1 KPa, or 0.5 MPa to 1 KPa, or 200 KPa to 1 KPa, 100 KPa to 1 KPa, or 50 KPa to 1 KPa.

[0102] "Ultra low modulus" refers to materials having a Young's modulus less than or equal to 150 KPa, less than or equal to 100 KPa or less than or equal to 50 KPa.

[0103] "Bending stiffness" is a mechanical property of a material, device or layer describing the resistance of the material, device or layer to an applied bending moment. Generally, bending stiffness is defined as the product of the modulus and area moment of inertia of the material, device or layer. A material having an inhomogeneous bending stiffness may optionally be described in terms of a "bulk" or "average" bending stiffness for the entire layer of material.

Example 1: Stretchable batteries with self-similar serpentine interconnects and integrated wireless recharging systems

[0104] An important trend in electronics involves the development of materials, mechanical designs and manufacturing strategies that enable the use of unconventional substrates, such as polymer films, metal foils, paper sheets or rubber slabs. The last possibility is particularly challenging because the systems must accommodate not only bending but also stretching, sometimes to high levels of strain (>100%). Although several approaches are available for the electronics, a persistent difficulty is in energy storage devices and power supplies that have similar mechanical properties, to allow their co-integration with the electronics. In this Example, we provide a set of materials and design concepts for a rechargeable lithium ion battery technology that exploits thin, low modulus, silicone elastomers as substrates, with a segmented design of the active materials, and unusual 'self-similar' interconnect structures. The result enables reversible levels of stretchability up to 300%, while maintaining capacity densities of ~1.1 mAh/cm². Stretchable wireless power transmission systems provide means to charge these types of batteries, without direct physical contact.

[0105] Development of classes of electronic and optoelectronic technologies that offer elastic responses to large strain (>>1%) deformations has accelerated in recent years¹⁻⁶. Combinations of materials, device layouts, mechanics designs and manufacturing approaches are now beginning to emerge for realistic applications in areas ranging from wearable photovoltaics⁷ to 'epidermal' health/wellness monitors⁸, to sensitive robotic skins⁹⁻¹¹, to soft surgical tools¹² and electronic 'eyeball' imaging devices¹³. In many cases, stretchability represents a key, enabling characteristic. For many of these and other uses, a critical need lies in energy storage devices with similar physical properties, to allow for direct and natural integration with the electronics¹⁴. Many important storage devices have been developed with flexible characteristics, including supercapacitors¹⁵⁻¹⁷ and batteries^{17,18}. Here, sufficiently thin geometrical forms lead to flexibility, by virtue of bending induced strains (typically to values of ~1% or less) that decrease linearly with thickness, for a given bend radius. Stretchability, on the other hand, represents a more challenging type of mechanics, in which the systems must accommodate large strain deformation (>>1%), typically of arbitrary form, including not only bending, but also twisting, stretching, compressing and others, and thickness is typically not a critical factor. Stretchable supercapacitors using buckled thin films of CNTs¹⁹ or CNT-soaked fibrous textiles²⁰, and stretchable non-rechargeable zinc carbon batteries based on conductive fabrics^{21,22} represent two examples. Although these technologies each have attractive features, none offers multiple capabilities in recharging with high storage capacity, stretching to large levels of deformation (>100%), or establishing wireless electrical interfaces to external power supplies. The materials and integration schemes provided in this example achieve these characteristics in a type of lithium ion battery that exploits segmented layouts and deformable electrical interconnects in specialized, 'self-similar' geometries. The resulting devices offer biaxial stretchability up to strains of 300%, with capacity densities of ~1.1 mAh/cm², and little loss in capacity for up to 20 cycles of recharging. The designs also allow integration of stretchable, inductive coils to enable charging through external supplies without the need for physical connections. This set of attributes satisfies requirements for many applications that are being contemplated for stretchable electronics.

Results

[0106] Battery design. The devices of this example exploit pouch cells in which arrays of small-scale storage components are connected by conducting frameworks with extraordinary stretchable characteristics. A schematic illustration of the system, an exploded view of the multilayer construction of a unit cell, and a representation of the 'self-similar' interconnect geometries appear in Fig. 1a,b,c, and Fig. 5 in Supplementary Information (SI). The current collectors consist of photolithographically patterned circular disks of aluminum (600 nm) and copper (600 nm). Layers of polyimide (PI; 1.2 µm) encapsulate interconnecting traces between these disks in a way that places the metals close to the neutral

mechanical plane (Fig. 1d and 1e, left panel). Thin (0.25 mm), low modulus (60 KPa) sheets of silicone elastomer form top and bottom substrates that support these structures (Fig. 1d and 1e, middle panel) and other components of the batteries. The overall construct consists of a square array of 100 electrode disks, electrically connected in parallel. Molded pads of slurries based on LiCoO₂ and Li₄Ti₅O₁₂ serve as active materials at the cathode and anode^{23,24}, respectively (Fig. 1d and 1e, right panel, and Fig. 6). The two sheets laminate together in a way that involves spatial offsets between the active materials to avoid electrical shortage between them and to eliminate the need for a separator. A spacer, made of the same silicone elastomer and applied around the periphery of the system, prevents direct contact of the top and bottom sheets. A gel electrolyte injected into the gap provides media for ionic transport. Thin encapsulating layers of an acryloxy perfluoropolyether elastomer bonded to the outer surfaces help to prevent moisture from diffusing into the battery and solvents in the gel from leaking out²⁵. Long term operation requires more sophisticated packages consisting, for example, of buckled bilayer sheets of aluminum/polyimide that bond to the outer surfaces of the battery (Fig. 7). The materials and fabrication details appear in the Methods section.

[0107] The devices must accommodate two competing design goals: (1) achieving high areal capacity, which requires large coverage of the active regions, and (2) affording high mechanical stretchability, which requires large distances between these regions. Strategic features of relief on the elastomer substrates provide a partial solution to this challenge, as demonstrated recently in photovoltaic modules^{26,27}. A disadvantage is that levels of stretchability beyond ~30% can be difficult to achieve without sacrificing coverage. Here, we take a different, but complementary, approach in which the focus is on deformable interconnects with advanced designs. In particular, we introduce layouts that use 'self-similar' structures of wires in serpentine configurations to offer, simultaneously, high system-level stretchability, and low inter-connect resistances. A conventional serpentine consists of circular arcs connected by straight lines. 'Self-similar' designs follow from iteratively applying this basic geometry, beginning with a unit cell as illustrated schematically in the red box of Fig. 1c. Here, reducing the scale of the cell, and then connecting multiple copies of it in a fashion that reproduces the layout of the original cell geometry corresponds to one iteration. The yellow line in Fig. 1c represents a 2nd order serpentine geometry, created in this fashion. Although higher orders can be designed and implemented easily, the 2nd order construct satisfies requirements for the applications considered here, as described in the detailed experimental and theoretical study below.

[0108] Mechanical characteristics of the 'self-similar' interconnects. Three-dimensional (3D) finite element analysis (FEA) (SI text) and experimental measurements illustrate the essential mechanics. Test samples fabricated for this purpose consist of freestanding, multilayer traces, with materials and multilayer stack designs (PI (1.2 μm) / Cu (0.6 μm) / PI (1.2 μm)) that match those used in the batteries, between circular pads that bond to posts molded onto underlying elastomer substrates. The self-similar geometry leads to hierarchical buckling physics that ensure ultra-low strains in the materials, even under extreme stretching^{3,28}. For the entire range of tensile strains examined, from 0% to 300%, the configurations predicted by FEA agree remarkably well with optical images collected during the experiments, as shown in Fig. 2. Both symmetric and anti-symmetric buckling modes exist (see Fig. 8 for detailed illustrations of the two modes). The trace consists of three columns of serpentine wires connected by two horizontal straight lines. We refer to the construct that corresponds to the 'short' wavelength serpentine within each column as the 1st level; the 2nd level corresponds to the large-scale serpentine shape, with 'long' wavelength. For the symmetric buckling mode (Fig. 8(a)), the left and right columns undergo mainly an overall bending deformation along the vertical direction, resulting in the collective upward motion of the entire middle column of serpentine wires. In this sense, the out-of-plane displacement is symmetric with respect to the center line ($x=0$) in the "Front view" of Fig. 8(a). For the anti-symmetric buckling mode (Fig. 8(b)), the serpentines in the left and right columns mainly undergo an overall twisting deformation along the vertical direction. Here, the two ends of the middle serpentine move in opposite directions (i.e. one moves up, and the other moves down). In this case, the out-of-plane displacement is anti-symmetric with respect to the center line ($x=0$) in the "Front view" of Fig. 8(b). The critical buckling strains obtained by FEA for the symmetric (0.078%) and anti-symmetric (0.087%) modes are much lower than those (>0.172%) for all other buckling modes. This result is consistent with experimental observation of only these two modes. In both cases, the physics associated with stretching involves a mechanism of "ordered unraveling", which begins at the 2nd level, at a well-defined, critical buckling strain, -0.08% for the example investigated here. Next, the 2nd level gradually "unravels" via bending and twisting as the applied strain increases from 0.08% to -150%, during which there is essentially no further deformation in the 1st level. The motions in the 1st level start when the 2nd level is almost fully extended, corresponding to an applied strain of -150% in this case. As the "unraveling" of the 1st level serpentine approaches its end, the strain in the materials begins to increase rapidly, thereby defining the practical limit in stretchability.

[0109] For applied strains below this limit, the deformation mechanisms of ordered unraveling processes ensure low levels of strain in the materials (Fig. 9). For a representative failure strain of 1% for copper, FEA predicts a stretchability of 321%, which is in good agreement with the experimental observations (300% < $\varepsilon_{stretchability}$ < 350%). (Simulations suggest that the copper reaches its failure point before the PI.) For reversible behavior (i.e., the interconnects return to their initial configuration after release), the maximum material strain must be less than the yield strain. For a representative yield strain of 0.3% for copper, FEA suggests reversibility for applied strains up to -168%. This value is lower than

experimental observations, where reversibility occurs even for strains of between 200% and 250% (Fig. 2). The likely explanation for this discrepancy is that yield occurs first in only small portions of the interconnect (e.g., one element in the FEA). In this case, the effects on reversibility might not be easily observed in experiments.

[0110] These levels of stretchability (>300%) and reversibility (>200%) significantly exceed those of previous reports in stretchable batteries and/or battery electrodes; they are also greater than those of any other reports of stretchable interconnects that use lithographically defined patterns of conventional metals. The importance of the self-similar designs can be assessed through comparisons of stretchability to otherwise similar, but conventional serpentine structures: the former exhibits a stretching range of 321%, while the latter is 134%, determined by FEA (Fig. 10). Furthermore, even for the same total length (l_{total}), span (L), amplitude (h), and cross section (width w and thickness t), the self-similar design again outperforms the conventional serpentine, both in stretchability (809% vs 682 %) and reversibility (528% vs 284%) (Fig. 11). We note that in all cases of uniaxial stretching, the Poisson effect leads to compression in the orthogonal direction. The buckling profiles in these regions have behaviors that are consistent with FEA (Fig. 12).

[0111] **Electrochemical and mechanical behavior of the battery.** After choosing a set of dimensions that offers excellent system level stretchability, with good areal capacity density, and modest interconnect resistance, we observed the best electrical performance for layouts in which the diameters of the disks for the cathode and anode are 2.20 mm and 1.58 mm, respectively, and the offset distances are 0.51 mm. This configuration corresponds to an areal coverage of 33% for the cathode, 17% for the anode, and 50% for the entire battery (in the undeformed configuration) (Fig. 13). The interconnects have thicknesses of 600 nm and widths of 50 μm . For these parameters, the resistance between adjacent disks is 24 Ω , and that between the connection lead and the most distant disk is 45 Ω . The leads for external connection are thin and narrow to avoid strain at the interface, and facilitate connection to flexible (but not stretchable) cables that connect to external characterization equipment. The gel electrolyte combines the flow properties of viscous liquids with the cohesive properties of a solid, thereby allowing it to accommodate large strains while maintaining ionic conduction pathways.

[0112] Electrochemical properties of the battery electrodes without and with 300% uniaxial strain appear in Fig. 3a. The results show two well defined plateaus at around 2.35 V corresponding to potentials of $\text{Co}^{3+}/\text{4+}$ and $\text{Ti}^{4+}/\text{3+}$ redox couples²⁹. The thickness of the LiCoO_2 (specific capacity 145 mAh/g) at each unit is -120 μm , corresponding to a mass of -95 mg, and thus areal capacity density of 1.1 mAh/cm² at a charge/discharge rate of C/2. The mass of $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (specific capacity 160 mAh/g) is -90 mg, which corresponds to 5%-10% more anode capacity than cathode³⁰. Slurry disks with thicknesses larger than those described here yield improved areal capacity density, but with reduced rate capability due to the concentration polarization in the disks^{31,32}. The output resistance of the battery is -70 Ω (Fig. 14), and the leakage current is 1-10 μA . The leakage current arises from three main sources: (i) the reverse biased Schottky diode, (ii) internal ohmic self-discharge between the slurry disks at the anode and cathode and (iii) Faradaic effects, including shuttle reactions associated with impurities in the slurry materials, residual oxygen and/or moisture. Experimental results presented in the SI and Fig. 15 show that use of separators and enhanced packaging schemes can reduce the capacity loss from 161 $\mu\text{A}\cdot\text{h}$ to 23 $\mu\text{A}\cdot\text{h}$ in 44 hours. Figure 3b shows the coulombic efficiency (red) and cycling performance (black) of the encapsulated battery. The coulombic efficiency rises from -60% for the first cycle to over 90% after three cycles. The initial loss can be attributed to the formation cycle, during which a solid-electrolyte-interphase forms, and lithium is consumed in side reactions with impurities in the electrolyte. The gradually degrading capacity retention results rather from the cycle fade (Fig. 16) but more likely from the calendar fade due to some combination of reaction with residual water in the packaging materials, moisture penetration, and electrical discontinuity of slurry particles that detach from the disks (which are not hot-pressed), and can be sometimes observed in the electrolyte gel. Varying the depth of discharge from 100% to 75% did not have a significant effect on the degradation characteristics (Fig. 17). Further increasing the baking temperature and optimizing the composition of the slurries, such as increasing the binder ratio, could reduce the latter behaviors. Improved conditions for device assembly could reduce effects of the former. Figure 3c shows the output power of the battery, when connected to a resistor (2020 Ω), during biaxial stretching and releasing. The slight decrease in output power with strain likely results from increased internal resistances that arise from the significantly increased separations between slurry disks with strains at these large levels. The battery provides sufficient power to operate commercial light emitting diodes (LEDs), with turn on voltages of 1.7 V (Fig. 18), as shown in Fig. 3d. The battery could be stretched for up to 300% (Fig. 3e), folded (Fig. 3f), twisted (Fig. 3g), and compliant when mounted on human skin (Fig. 3h) without noticeable dimming of the LED. Furthermore, FEA demonstrates that the effective modulus (66.8 KPa) of the full composite structure of the battery is only slightly higher than the modulus (60.0 KPa) of substrate materials (Ecoflex). As a result, the battery is not only stretchable but also exceptionally soft and compliant. The modulus is, in fact, lower than that of the human epidermis (140-600 KPa)⁸, thereby offering the potential for integration onto the skin and biological tissues, without significant mechanical loading.

[0113] **Stretchable wireless charging system for the battery.** In many practical cases such as embedded devices, the ability to charge the battery without establishing physical connections to external supplies can be valuable. Even in systems where the charging terminals are accessible, such as in skin-mounted devices, there is value in wireless charging, simply because the process of establishing physical contacts can be mechanically destructive to thin, stretch-

able devices (or to the underlying soft tissue). Approaches that involve physical contact also have the danger of electrical shock to surrounding materials (e.g. the skin itself). The versatility of the materials and designs enable integration of wireless power transmission systems, monolithically with the battery itself. The design and an actual device appear in Figs. 4a, b, respectively. A secondary coil couples the electromagnetic flux from a primary coil, and a Schottky diode provides rectification. The Schottky diode (packaged in epoxy, with a modulus of -4.0 GPa) has a modulus of more than 4 orders of magnitude larger than that of the substrate (made of Ecoflex, modulus -60 KPa), but its size (length 0.62 mm, width 0.32 mm, and height 0.31 mm) is only a few percent (-2%) of the overall size (-30 mm x -20 mm) of the wireless system. As a result, the influence on the overall stretchability is still negligible, as demonstrated by finite element simulations shown in Figs. 19 and 20. The capacitor smooths oscillations in the output voltages; its small size and thickness enable natural integration into the overall system. Larger capacitors can smooth the oscillations to an even greater extent (Fig. 21). The coil and rectifier add a series resistance of 2.3 k Ω (Fig. 22), which functions as a parallel resistance with the secondary coil, shunting away current from the battery. The resistance of the serpentine secondary coil is 1.92 k Ω /m; a coil with similar overall geometry but without the serpentine shape is calculated to be 1.22 k Ω /m. Improving the efficiency of the charging system can be achieved by increasing the width and thickness of the wires, but at the expense of reduced stretchability and increased modulus. Specific application requirements will define the right tradeoffs. In this case, the output power from the primary coil was 187 mW. With a working distance of 1 mm between the primary and secondary coil, the power received on the secondary coil is 9.2 mW, corresponding to an efficiency of 4.9%. The power coupling efficiency of the wireless charging system depends strongly on the resistance of the serpentine receiver coil. Increasing the thickness to 7 μ m and using copper improves the efficiency from 4.9% to 17.2%. At this thickness, the coil retains stretchability to strains of 25%. Data and images appear in the SI. The capacitor has a capacitance of 1.7 nF, in a structure that uses a 1.2 μ m thick layer of polyimide as the dielectric, with a layer of thiol molecules on the bottom Au electrodes to enhance adhesion. Figure 4c shows the input and output of this wireless power transmission device. An input voltage at a frequency of 44.5 MHz matches the self-resonant frequency of the secondary coil, which is dependent on the coil area, number of turns, distance between each turn, and wire resistance. For a peak-to-peak input voltage of 9.1 V (Fig. 4c black curve), the DC output voltage is 3.0 V (Fig. 4c red curve). The charging curves of a small scale battery using the wireless coil appear in Fig. 4d. The battery voltage (Fig. 4d orange curve) rises to 2.5 V in about 6 mins. The charging current in the circuit (Fig. 4d blue curve) decreases from 0.5 mA to below 0.2 mA. We used a partial differential equation to model the charging circuit, and a numerical program to calculate the charging current curve. Simulation of this process agrees well with the experimental data (SI text and Fig. 20).

30 Discussion

[0114] The materials and schemes described in this example provide routes to energy storage devices and wireless charging systems with forms and properties that are attractive for powering stretchable electronic and optoelectronic devices. The slurry materials themselves are deployed in ways (a soft lithographic type casting process) that allow natural integration with unusual materials (low modulus silicone rubber sheets, embossed with surface relief). The stretchable interconnects exploit a 'self-similar' design that offers unique, 'spring within a spring' mechanics. The consequence is a level of stretchability that is more than 4x larger than previous reports, even while, at the same time, enabling coverages of active materials as high as 50%. The combination of these two aspects, together with comprehensive and experimentally validated models of the underlying mechanics, leads to a technology, i.e. a stretchable, rechargeable battery, which offers much different characteristics than anything that has been previously possible. As an additional advance, we introduce integrated stretchable, wireless charging systems that offer physical properties similar to those of the batteries.

[0115] The slurry chemistries, separator materials, and stretchable, air-impermeable packaging materials can be selected to provide high device performance. The self-similar serpentine interconnect structure possesses a geometry of space filling curve, and a buckling physics of ordered unraveling. This type of interconnect structure has immediate, and general utility, suitable for any class of stretchable technology that combines hard and soft materials. The topology-level interconnect geometry simultaneously provides for large mechanical stretchability and low electrical resistance. Wireless power transfer efficiency can be improved by reducing the coil input resistance, maximizing the mutual inductance between the primary and secondary coils, and increasing the self-resonant frequency of the coils. Regulation circuits may be incorporated to avoid over-charging the battery.

Methods

[0116] Fabrication of electrodes and mechanical testing of self-similar interconnects: Sequential spin casting defined a bilayer of poly(methyl methacrylate) (PMMA 495 A2, 3000 rpm for 30 s, baked on a hotplate at 180°C for 2 mins) and then a layer of polyimide (PI, from poly(pyromellitic dianhydride-co-4,4'-oxydianiline) amic acid solution; 4000 rpm for 30 s, baked on a hotplate at 150 °C for 4 mins and then in a vacuum oven at 10 mT and 250 °C for 1 h) on a silicon

wafer. The cathode and anodes consisted of 600 nm thick layers of Al or Cu, respectively, deposited by electron beam evaporation onto the PI. Photolithography (AZ5214E) and etching (Type A aluminum etchant on hotplate at 50 °C for 2 min; Type CE-100 copper etchant at room temperature for 10 s; Transene Company) defined patterns in these metals. After removing the residual photoresist, spin coating formed an additional layer of PI over the entire structure. Next, photolithography (AZ 4620, 2000 rpm for 30 s, baked at 110 °C for 4 mins) and oxygen plasma etching (300 mT, 20 sccm O₂, 200 W for 10 mins) patterned the layers of PI in a geometry matched to the metal traces.

[0117] Immersion in hot acetone partially removed the underlying PMMA layer, thereby allowing the entire structure to be retrieved from the silicon wafer onto the surface of a piece of water soluble tape (3M, Inc.). Electron beam evaporation of Ti (5 nm) / SiO₂ (50 nm) through a shadow mask formed backside coatings aligned to the metal disks³³. Thin (250 µm) silicone substrates (Ecoflex, Smooth-On, Inc., Easton, PA) were prepared by mixing the two components in a 1:1 weight ratio, spin-casting (300 rpm for 30 s) the resulting material into a petri dish and then partially curing it (30 mins at room temperature). Next, spin-casting (3000 rpm for 30 s) an allyl amide functional perfluorinated ether (DuPont), and then curing it under ultraviolet (UV) light for 30 mins formed a top encapsulation layer. The other side of the Ecoflex substrate was surface-activated under UV light for 5 mins. Laminating the electrode structures onto this surface led to strong bonding, upon contact³⁴. The water soluble tape was removed by immersing the substrate in tap water for overnight. As a final step, the electrodes were dipped in 1 mM HCl to remove oxides from the surfaces of the metals.

[0118] Mechanical testing of the self-similar interconnects was performed with a customized uniaxial stretcher. To ensure that the interconnects were decoupled from the substrate, each disk was mounted on top of a post (250 mm in height) molded into the silicone substrate. Images and video of the deformed interconnects were collected with a digital single-lens reflex camera.

[0119] Patterned moulding of slurries and their integration with current collecting electrodes: Photolithography (AZ 4620, 7-8 µm thick) and inductively coupled plasma reactive ion etching (ICP RIE) defined arrays of cylindrical wells on the surface of a silicon wafer. The conditions were chosen to yield sloped sidewalls, which are important for effective transfer of the slurries, as described subsequently. Washing with acetone removed the photoresist. A layer of polytetrafluoroethylene (-200 nm) conformally deposited using the ICP RIE tool served as a coating to prevent adhesion. The slurry materials consisted of lithium cobalt oxide or lithium titanium oxide, acetylene black, and polyvinylidene fluoride, mixed in a weight ratio of 8:1:1 in a solvent of N-methyl-2-pyrrolidone (NMP) for the cathode and anode, respectively. The mixture was stirred for overnight, and then mechanically scraped across the etched surface of the silicon wafer. The cylindrical wells, filled with slurry in this manner, were baked on a hotplate at 90 °C for overnight, and then retrieved onto the surface of a piece of water soluble tape. The baking conditions were selected carefully to enable retrieval of the slurry with high yield. Registering the tape to the metal electrodes ensured that the molded slurry aligned to the metal disks. Immersion in tap water for overnight dissolved the tape. Baking the substrates at 170 °C for overnight in a vacuum oven removed the moisture and improved the strength of bonding between the slurry and the metal.

[0120] Assembly and electrochemical testing of the battery: Anisotropic conductive films, hot pressed onto the metal electrodes, served as points for external electrical connection. Application of Sylgard Prime Coat (Dow Corning, Inc.) to the periphery of the substrates prepared them for bonding. A thin silicone spacer layer (500 µm thick) at the periphery prevented direct contact as the two sheets were laminated together. A lateral spatial offset prevented electrical shorting between the active regions. The edges were sealed with an additional application of Ecoflex followed by baking on a hotplate (90 °C for 2 h). The gel electrolyte consisted of a mixture of 100 g lithium perchlorate, 500 ml ethylene carbonate, 500 ml dimethylcarbonate, and 10 g polyethylene oxide (4 × 106 g/mol), prepared in an argon filled glovebox as a homogenous gel. This material was injected into the battery using a syringe through an edge.

[0121] A BioLogic VMP3 electrochemical station with a cutoff voltage of 2.5-1.6 V at room temperature was used to charge and discharge the as-fabricated and stretched battery electrodes, and to evaluate cycling behavior of the full, integrated battery. Areal capacity density was calculated based on the active region. The output power was monitored with the battery connected to a 2020 Ω resistor, using an ammeter. Values of current were recorded as a function of strain applied to the battery.

[0122] Fabrication and testing of the wireless coil: A silicon wafer, coated with layers of PMMA and PI using steps described previously, served as a substrate for deposition of Cr (5 nm) / Au (500 nm) by electron beam evaporation. Photolithography (AZ 5214E) and etching (Transene Company) defined patterns in the geometry of the bottom electrode of the capacitor and associated contact lines. Removing the photoresist with acetone, and then immersing the substrate in a 1 mM poly(ethylene glycol) methyl ether thiol solution in isopropanol for 15 mins served to enhance the adhesion and coverage of a second layer of PI spin-cast (4000 rpm 30 s) and cured (on hotplate at 150 °C for 4 mins and then in vacuum oven at 250 °C for 1 h) on the electrodes. This layer of PI served as the dielectric for the capacitor. Photolithography (AZ 4620, 2000 rpm for 30 s, baked at 110 °C for 4 mins) defined a mask for etching vias through the PI layer, as points of connection between the coil and the bottom electrode of the capacitor. After immersion in acetone to remove the photoresist, sputter deposition formed a conformal layer of Cu (600 nm) over the entire surface, including the sidewalls. Photolithography (AZ 5214E) and etching defined the coil and the other top electrode of the capacitor. After removing the resist, a third spin-cast layer of PI formed a coating on the Cu electrodes. An oxygen plasma etching through the

three PI layers in a patterned geometry defined the final device layout. Release by immersion in hot acetone partially removed the underlying PMMA, to enable the release of the entire structure onto water soluble tape. Deposition of Ti (5 nm) / SiO₂ (50 nm) and lamination onto the UV activated surface of an ecoflex substrate led to strong bonding. After the water soluble tape was removed, a Schottky diode chip (Digikey BAT 62-02LS E6327) was bonded between the coil and the capacitor using silver epoxy. The forward input resistance is -500 Ω, and the rectification ratio is ~1×104 at a bias voltage of ±1 V³⁵.

[0123] High frequency alternating current signals were generated by a KEITHLEY 3390 50 MHz arbitrary waveform generator. The input and output characterization of the wireless coil were performed using an Agilent infiniium DSO8104A oscilloscope (1 GHz, 4 channels). The wireless charging voltage and current to the battery were monitored using a BioLogic VMP3 electrochemical station.

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[0124]

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SUPPLEMENTARY INFORMATION

- 55 **Fabrication of a stretchable encapsulating layer, consisting of a buckled sheet of Al/PI on a silicone substrate**
- [0125]** The first step involved fabrication of a trilayer of PMMA/PI/Al on a silicon substrate, using procedures similar to those employed for the Al battery electrodes. Photolithography with AZ5214E and wet etching the Al defined the

lateral dimensions of the PI/Al sheet. Next, oxygen plasma etching (300 mT, 20 sccm O₂, 200 W for 5 mins) removed the PI layer in the exposed regions. Immersion in hot acetone partially removed the underlying PMMA layer, thereby allowing the entire structure to be retrieved from the silicon wafer onto the surface of a piece of water soluble tape (3M, Inc.). Electron beam evaporation of Ti (5 nm) / SiO₂ (50 nm) formed backside coatings. On a separate substrate, 500 µm thick silicone sheets (Ecoflex, Smooth-On, Inc., Easton, PA) were prepared, then removed and prestrained biaxially to a level of -30% and then fixed by lamination onto a glass slide. The silicone surface was activated by exposure to UV-induced ozone for 5 mins. Laminating the PI/Al bilayer onto this surface led to strong bonding, upon contact. The water soluble tape was removed by immersing the substrate in tap water for overnight. Peeling the entire assembly away from the glass slide released the prestrain, and led to an expected pattern of buckling. In this configuration, the overall system can be stretched to strains as large as those equal to the prestrain.

Mechanical analyses of "island-bridge" self-similar electrode structures: FEA

[0126] Full three-dimensional (3D) FEA is adopted to analyze the postbuckling behaviors of "island-bridge" self-similar electrode structures under stretching and compression. Due to the structural periodicity of the electrode, a representative unit cell was studied, and its detailed geometry is shown in Fig. 5. The circular island of the electrode is mounted on a post (height 250 µm) molded on the surface of a silicone substrate (ecoflex; thickness 500 µm). The metal interconnect (thickness 0.6 µm), is encased, top and bottom, by a thin layer of polyimide (PI, thickness 1.2 µm for each layer). The elastic modulus (E) and Poisson's ratio (v) are $E_{\text{ecoflex}}=0.06 \text{ MPa}$ and $v_{\text{ecoflex}}=0.49$ for ecoflex; $E_{Cu}=119 \text{ GPa}$ and $v_{Cu}=0.34$ for copper; $E_{Al}=70 \text{ GPa}$ and $v_{Al}=0.35$ for aluminum; and $E_{PI}=2.5 \text{ GPa}$ and $v_{PI}=0.34$ for PI. Eight-node 3D solid elements and four-node shell elements were used for the ecoflex and self-similar electrode, respectively, and refined meshes were adopted to ensure the accuracy. The evolution of deformed configurations with applied strains are obtained from FEA for both stretching and compression, as shown in Fig. 2 and Fig. 12, respectively. Good agreement between FEA and experiment results can be found. Here, we take the case of copper as a demonstration of the buckling profiles. The results for the aluminium layer are similar. For the comparison of stretchability and reversibility between self-similar and serpentine interconnects (Fig. 11), the key geometrical parameters are kept the same, including the total length ($l_{\text{total}}=16.77 \text{ mm}$), span ($L=1.6 \text{ mm}$), amplitude ($h=0.4 \text{ mm}$), width ($w=30 \text{ µm}$), and thickness ($t=3.0 \text{ µm}$). The aluminum interconnect (thickness 0.6 µm) is encased by two thin layers of polyimide (thickness 1.2 µm for each layer). Fig. 11 demonstrates that over the entire range of stretching from 0% to -800%, the strain level of the self-similar interconnect is always lower than the serpentine one. The stretchability (809%) and reversibility (528%) of the self-similar design, are higher than those ($\varepsilon_{\text{stretchability}}=682\%$, $\varepsilon_{\text{reversibility}}=284\%$) of the simple serpentine design.

Battery leakage current analysis

[0127] The leakage current arises from three sources. The first source is current through the reverse biased Schottky diode. This current is -0.2 µA, and is relatively constant throughout the lifetime of the battery. Schottky diodes with smaller reverse current are available; such devices can reduce this contribution to the leakage.

[0128] The second source is the internal ohmic self-discharge current between the slurry disks at the anode and cathode. This contribution arises from finite electronic conductivity of the electrolyte and any parasitic physical contacts between the slurry disks at the cathode and anode. These losses can be dramatically reduced by electrolyte materials with enhanced purity and implementing separators. New experiments reveal the latter effects quantitatively. Fig. 15a and b show the voltage decay and leakage current curves for otherwise similar batteries with and without a commercial separator (Celgard). This component reduces the capacity loss from 161 µA·h to 88 µA·h in 44 hours.

[0129] The third source is from current produced by Faradaic effects, including shuttle reactions associated with impurities in the slurry materials, residual oxygen and/or moisture. Improving the air-impermeability of the packaging materials can reduce currents that arise from such reactions. New experiments show that sealing the battery in an Al pouch (which can be configured in a wrinkled configuration to allow stretching) reduces the capacity loss from 161 µA·h to 62 µA·h. Combining the separator and the Al pouch packaging, suppresses the capacity loss to 23 µA·h. Fig. 15 summarizes all of these findings.

50

Discrete Schottky diode stretching behavior analysis

[0130] From a practical standpoint, we observe no significant constraints on the overall mechanical properties of the integrated system, due to the comparatively small size of the diode. In particular, although the Schottky diode, which is encapsulated in epoxy which has a modulus of -4.0 GPa, is effectively more than 4 orders of magnitude larger than that of substrate (made of Ecoflex, with a modulus of -60 KPa), its dimensions (length 0.62 mm, width 0.32 mm, and height 0.31 mm) represent only a few percent (~2%) of the overall size (~30 mm × ~20 mm) of the wireless system. Experimentally, we observe that the system is robust to stretching up to -30% and beyond.

[0131] To study these effects quantitatively, we carried out full, three dimensional finite element simulations that examine the influence of the diode on the stretchability of the coil in the integrated system, as in Fig. 19a. Results in Fig. 19b and 19c, indicate that: (1) The decrease in stretchability is modest, from 32.6% to 32.3%, when the diode is included and (2) The strain in the diode (i.e. the epoxy) is very small (< 0.15%, much smaller than the strain needed to induce fracture), even when the overall system is stretched by 32.3%.

[0132] The normal interface strain is also important. Fig. 20a shows the distributions of maximum principal strains in a large Ecoflex substrate with a diode mounted in its center, for stretching to 30%. Fig. 20b illustrates the distribution of the substrate normal strain at the diode/substrate interface. The normal interface strain in this case is negative, corresponding to compressive strain at the interface. This outcome, which is consistent with theoretical predictions based on energy release rates at an interface crack, minimizes the propensity for delamination.

Coil resistance effect on the wireless power transfer efficiency

[0133] The coil resistance/quality factor is a critical parameter that dictates the efficiency. In additional experiments to illustrate the effects, we replaced the 600 nm thick gold serpentine coils with otherwise similar ones fabricated with copper at increased thicknesses. The results show that coils formed using a 7 μm thick copper film (Dupont) have total resistances of 185 Ω , and generate a received power of 30.8 mW with an input power of 179 mW (at a distance of 1 mm, similar to the previously reported results). The corresponding efficiency is 17.2%, which represents more than a factor of three improvement over the original, gold coils (4.9%). Further reducing the coil resistance to 38 Ω by using 18 μm thick copper foil (MTI Corp.) improves the received power to 36.2 mW, and the efficiency to 20.2%. See Fig. 23a.

[0134] These increases in thickness, and therefore power transfer efficiencies, lead to changes in the essential mechanics associated with stretching. In particular, as the thickness increases, the stretchability decreases. The coil with thickness of 7 μm offers a good balance between efficiency and mechanical deformability, with ability to accommodate strains of -25%. Images at various levels of strain appear in Fig. 23b, which agree well with the finite element analysis results in terms of both the maximum uniaxial strain and the geometry of the coil serpentines (Fig. 23c).

Modeling of the charging current in the wireless power transmission circuit

[0135] The charging circuit can be described using the model below:

$$U_0 = U(t) + L \frac{dI(t)}{dt} + I(t)R \quad (1)$$

[0136] Here U_0 is the charging source of 3 volts voltage. L and R are the associated inductance and the resistance of the circuit. $U(t)$ is the time dependent readout of the voltmeter and $I(t)$ is the time dependent readout of an ammeter.

[0137] A program has been developed to simulate the I-V curve based on the partial differential equation (1). The simulated time dependent current $I_s(t)$ based on $U(t)$ is compared with measured $i(t)$, and the results are shown in Fig. 20.

[0138] The program used to simulate the current:

```
#include<iostream.h>
#include<stdio.h>
#include<stdlib.h>
#include<math.h>
#include<time.h>
#define tim 3500
#define start 265
float curre[tim];
float nihe[tim];
float test[tim];
float voll[tim];
FILE *fp;
int main()
int i,j,k;
{
55   fp=fopen("Cur.txt","r");
   for(i=0;i<tim;i++)
      fscanf(fp,"%f",&curre[i]);
   {
```

```

        curre[i]=-curre[i];
        cout<<curre[i]<<endl;
    }
fclose(fp);
5   fp=fopen("Vol.txt" , "r");
for(i=0;i<tim;i++)
{
    fscanf(fp,"%f",&voll[i]);
    cout<<voll[i]<<endl;
}
10  fclose(fp);
double coef1;
double coef2;
coef2=curre[1]/(voll[1]-voll[0]);
cout<<coef2<<endl;
test[0]=curre[0] ;
test[start]=curre[start];
double coef1th;
double maxh=1000000000;
double coef2th;
for(coef2=0;coef2<0.04; coef2=coef2+0.0001)
20
{
    cout<<coef2<<endl;
    for(coef1=0.94; coef1<=0.96; coef1=coef1+0.0001)
    {
        // cout<<coef1<<endl;
        fbr(i=start+1 ;i<tim;i++)
    {
        test[i]=coef1*test[i-1]+(3-(voll[i]+voll[i-1])*0.5)*coef2;
    }
    double poi=0;
    for(i=start;i<tim;i++)
30
    {
        poi+=(test[i] -curre[i])*(test[i]-curre [i]);
        if(poi<maxh)
        {
            coef1th=coef1;
            coef2th=coef2;
            maxh=poi;
            for(int j=0;j<tim;j++)
            {
                nihe[j]=test[j];
            }
        }
    }
}
40
}
cout<<coef1th<<endl;
cout<<coef2th<<endl;
45   cout<<maxh<<endl;
fp=fopen("nihe.txt","w");
for(i=0;i<tim;i++)
{
    fprintf(fp, "%f", -nihe[i]);
    fprintf(fp, "\n");
50
}
fclose(fp);
fp=fopen("canshu.txt", "w");
fprintf(fp, "%f", coef1th);
fprintf(fp, "\n");
55   fprintf(fp, "%f", coef2th);
    fprintf(fp, "\n");
fclose(fp);
return(1);

```

{}

Example 2: Device Geometries and Materials Strategies for Stretchable Electronic Systems.

- 5 [0139] Figures 25 and 27 provide example fabrication process flow diagrams for making some electronic systems of the invention. Figure 25 provides an overall fabrication flow chart. Figure 26 illustrates silver epoxy scraping for making the electrical contact between the serpentine interconnects and COTS chips. Figure 27 illustrates liquid chamber fabrication. The cavity or pouch is formed by laminating a thin piece of elastomer sheet on top of the substrate, and sealing at the surrounding periphery is achieved under heat and pressure with the uncured elastomer as glue. Fluid is injected
10 into the as-formed cavity by injection through the cavity side edge with a syringe.
- [0140] Figure 28 illustrates a single battery of the present disclosure. Figure 29 illustrates a battery undergoing -100% uniaxial stretching.
- 15 [0141] Figure 30 provides an ECG circuit with wireless power and telecommunication. Figure 31 provides an example of ECG data on wired oscilloscope, and on frequency counter by wireless telecommunication, where the data fidelity is very high, and the QRS complexes can be clearly distinguished.
- 20 [0142] Figure 32 illustrates a stretchable format of the circuit in Figure 30, where the red circles indicate places with selective bonding to the substrate. Figure 33 shows an array of Ecoflex pedestals mounted into etched Si wafer or patterned thick SU8. Figure 34 illustrates the same circuit as Figure 32 but with a thinner version of COTS chips (<1 mm). Figure 35 shows the circuit in Figure 34 but with a liquid chamber, where a bubble is intentionally left behind to indicate the presence of fluid. Figure 36 provides images demonstrating stretching. Figure 37 provides images demonstrating flexing at a radius of around 2 cm.
- 25 [0143] Figure 38 provides mechanical simulations illustrating the strain distribution in different geometries of the interconnects under a fully encapsulated case at the liquid chamber interface.
- 26 [0144] Figure 39 provides schematic diagrams illustrating system level strain distribution in the interconnects between the stiff islands-horizontal. Figure 40 provides schematic diagrams illustrating system level strain distribution in the interconnects between the stiff islands-vertical.
- 30 [0145] Figure 41 shows the overall layout of a multifunctional circuit with liquid chamber. The basic functions of this circuit include: wireless radiofrequency power harvesting, two-terminal electrophysiological sensors (electrocardiogram, electromyogram, electroencephalogram, and electrooculogram), temperature sensor, acceleration sensor, and wireless data transmission. Figure 42 shows mechanically polished commercial off the shelf (COTS) chips with the electrical functionality intact and a thickness below 0.5 mm. Figure 43 provides a list of example circuit functions.
- 35 [0146] Figure 44 illustrates a multilayer - 1st data transmission lines, Figure 45 illustrates a multilayer - 2nd power delivery lines and Figure 46 illustrates a multilayer - 3rd ground lines. At the cross points of these lines, they are insulated from each other by polymer, such as polyimide, parylene C, or SU8.
- 40 [0147] Figure 47 illustrates the locations of precise selective bonding of the islands and the interconnects (1). Figure 48 illustrates the fabrication processes to achieve precise selective bonding (2). Figure 49 illustrates reduced sharp corners to increase the robustness of the interconnects. Figure 50 illustrates the hybrid usage of self-similar interconnects and conventional serpentine interconnects (1). Figure 51 illustrates self-similar interconnects of the contact pads to the skin (2).
- 45 [0148] Figures 52 and 53 illustrate an example of basic fabrication schemes, similar to Figures 25 and 26.
- [0149] Figure 54 provides an example of a wireless power circuit using a resonant inductive coil. Figure 55 demonstrates wireless circuit stretching uniaxially to 100%.
- [0150] Figure 56 illustrates an example ECG circuit similar to the circuit in Figure 30.
- 50 [0151] Figures 57, 58 and 59 illustrate examples of layout, selective bonding location under each rigid island, and interconnect geometry design considerations. Figure 60 illustrates examples of fabricated interconnects with three layers of metals for data, power, and ground lines, respectively. These metal layers are separated by polyimide, in this case. The contact pads in the metal layers to the COTS chips are exposed.
- 55 [0152] Figure 61 illustrates selective bonding using an unconventional fabrication process, along with optical microscope images showing the parts with selective bonding. Figure 62 illustrates scanning electron microscope images with tethered device components comprising stretchable electrical interconnects bonded to pedestals. As shown, the interconnects are selectively bonded to the substrate at discrete locations, such that 5% or less of the surface area of a device component is in physical contact a tether, or 2% or less of the surface area of a device component is in physical contact with a tether, or 1% or less of the surface area of a device component is in physical contact with a tether. Tethering through selective bonding of interconnects and/or other device components at one or more positions may be used to reduce or prevent entanglement of interconnects, device components and/or devices.
- [0153] Figure 63 illustrates chip depackaging by purely mechanical polishing and acid etching by hot fuming nitric acid.
- [0154] Figure 64 shows a fabricated multifunctional device with liquid chamber on a bent cylindrical surface with COTS chips as received and mechanically polished. Figure 65 illustrates stretching and flexing of the device in Figure 64.

Figure 66 shows example mechanical analyses of the multilayered interconnects. Figure 67 shows strain distribution in the multilayered interconnects under vertical uniaxial strain of 30%. Figures 68 and 69 schematically illustrate stretching simulation video.

5 Example 3: Electronic Systems Having Fluid Containment

[0155] Electronic devices having fluid containment will now be described with reference to the figures, where reference numerals used to describe Figure 70 show the same features in multiple embodiments, multiple items within a figure may not be labeled, and the figures may not be drawn to scale.

10 [0156] Figures 70A and 70L show side plan views of inventive systems **102** comprising a substrate **100** with one or more electronic devices or device components **110A**, **110B**, **110C** supported by a surface **105** of the substrate. In the inventive embodiments shown, devices or device components **110A**, **110B**, **110C** are free standing and a containment chamber **135** is formed by a plurality of enclosing structures, such as a top wall **135B** and side walls **135A**, **135C**. The containment chamber **135** at least partially surrounds the devices/components **110A**, **110B**, **110C** within a void space **130** of the chamber that is at least partially filled with a containment fluid **140**. In the embodiment of Figure 70A, the devices/components **110A**, **110B** are connected to one another by an electrical interconnect **120**.

15 [0157] Figures 70B and 70M show embodiments similar to those of Figures 70A and 70L except that containment chamber **135** is formed in part by a bottom wall **135D** in addition to top wall **135B** and side walls **135A**, **135C**. In this embodiment, devices/components **110A**, **110B**, **110C** and containment fluid **140** do not contact substrate **100**. Instead, the devices/components **110A**, **110B**, **110C** are free standing on bottom wall **135D**.

20 [0158] Figure 70C shows an embodiment where a containment chamber **135** contains an interior wall **135E** that forms multiple void spaces **150**, **160**. In the embodiment shown, devices/components **110A** and **110B** are located in separate void spaces **150**, **160**, but they are in electrical contact through electrical interconnect **120**, which is embedded within interior wall **135E**. A containment fluid **140** at least partially fills each void space **150**, **160**.

25 [0159] Figure 70D shows an embodiment of a system **102** comprising multiple void spaces **150**, **160** formed by a containment chamber **135** having a top wall **135B**, a bottom wall **135D**, side walls **135A**, **135C** and an interior wall **135E**. A containment fluid **140** at least partially fills each void space **150**, **160**. The devices or device components are located in separate void spaces **150**, **160**, but are connected to one another by electrical interconnect **120**, which is embedded within interior wall **135E**. The entire system is supported by a substrate **100**.

30 [0160] Figures 70E and 70N show embodiments of a system **102** comprising one or more devices or device components **110A**, **110B**, **110D** that are tethered to a substrate **100** by a relief feature **170A**, **170B**, **170D**. For example, in some embodiments, the relief feature **170A**, **170B**, **170D** may be a pedestal. In the embodiment of Figure 70E, devices/components **110A**, **110B** are connected to one another by an electrical interconnect **120**, which may be a stretchable or serpentine electrical interconnect. Devices/components **110A**, **110B**, **110D**, relief features **170A**, **170B**, **170D** and optionally electrical interconnect **120** are enclosed within a void space **130** of a containment chamber **135** formed by a top wall **135B** and side walls **135A**, **135C** that are laminated to substrate **100**. Void space **130** is at least partially filled with a containment fluid **140**.

35 [0161] Figure 70F shows an embodiment where devices or device components **110A**, **110B**, which are each tethered to a substrate **100** by a relief feature **170A**, **170B**, are located in separate void spaces **150**, **160** of a containment chamber **135** formed by a top wall **135B**, side walls **135A**, **135C**, and an interior wall **135E**. The tethered devices/components are connected to one another by an electrical interconnect **120** that passes through interior wall **135E**.

40 [0162] Figure 70G shows an embodiment comprising an array of relief features supporting each device or device component **110A**, **110B**. For example, device/component **110A** is supported by relief features **170A1**, **170A2** and **170A3**, and device/component **110B** is supported by relief features **170B1**, **170B2** and **170B3**. In this embodiment, containment fluid **140** is able to infiltrate between relief features **170A1-A3** and **170B1-B3**.

45 [0163] Figure 70H shows an embodiment of a system **102** comprising devices or device components **110A**, **110B** each supported by an array of relief features **170A1-A3** and **170B1-B3**, where each device/component **110A**, **110B** is disposed in an independent void space **150**, **160** of a containment chamber **135** formed by a top wall **135B**, side walls **135A**, **135C** and an interior wall **135E**. In the embodiment shown, containment chamber **135** is laminated to the surface **105** of substrate **100**, but alternate embodiments could include a bottom wall **135D** (not shown) of a containment chamber.

50 [0164] Figures 70I1 and 70I2 show the result of stretching substrate **100**. Figure 70I1 shows a system **102** without any external force on the system. Figure 70I2 shows a force in the direction of arrow **A** on substrate **100**. The applied force pulls the point of relief feature **170B** bound to the substrate in the direction of arrow **A**. The tethered geometry of device/component **110B** involving relief feature **170B** functions to decouple motion and/or deformation of the substrate from device/component **110B**. Containment fluid **140** within void space **130** of containment chamber **135** buffers device/component **110B**.

55 [0165] Figures 70J1 and 70J2 show the result of contracting a substrate **100** of a system **102**. Figure 70J1 shows system **102** without any external force on the system. Figure 70J2 shows forces in the directions of arrows **B1** and **B2**

such that substrate **100** is being contracted or squeezed. The applied forces moves the bonding points of relief features **170B** and **170A** with the substrate in the directions of arrows **B1** and **B2**, respectively. The tethered geometry of devices/components **110B** and **110A** involving relief features **170B** and **170A** functions to decouple motion and/or deformation of the substrate from device/components **110B** and **110A**.

[0166] Figure 70K shows a top plan view of an embodiment of a system **102** comprising a stretchable serpentine electrical interconnect **120** connecting devices or device components **110A, 110B**. The system further includes a containment chamber **135** having a void **130** that is at least partially filled with a containment fluid **140**. The containment chamber **135** may include a top wall (not shown) and/or a bottom wall (not shown). The entire system is supported by a substrate **100**.

[0167] Figure 70O shows a top plan view of an embodiment of an exemplary system **102** comprising a stretchable serpentine electrical interconnect **120** connecting devices or device components **110A, 110B**. The system further includes a containment chamber **135** having a void **130** that is at least partially filled with a containment fluid **140**. The containment chamber **135** may include a top wall (not shown) and/or a bottom wall (not shown). The entire system is supported by a substrate **100**. The embodiment shown in Figure 70O also includes barrier structures **700**, in the form of corrals, which limit movement of a free standing device or device component. Corrals **700** are unitary structures having a height, **h**, that is less than the full height of containment chamber **135** and having an opening for interconnect **120** to access device or device component **110A, 110B**. Figure 70P shows a similar embodiment, where the barrier structures are formed as a plurality of bumpers **710** including side walls **710(1)**, back walls **710(2)** and front walls **710(3)**. Each bumper **710** is positioned substantially parallel to an edge of a device or device component, and although bumper **710** is shorter than the edge of the device or device component it sufficiently long to constrain movement of the device or device component without preventing movement of containment fluid **140**. Two front walls **710(3)** form an opening for interconnect **120** to access device or device component **110A, 110B**. Figure 70Q shows a side plan view of the embodiment of Figure 70P, wherein free standing devices or device components **110A, 110B** are laterally constrained by bumpers **710** having widths, **w**, less than a corresponding edge of device or device component **110A, 110B**, and heights, **h**, at least sufficient to prevent device or device component **110A, 110B** from moving vertically and escaping through a gap, **g**, between a bumper **710** and top wall **135B** of containment chamber **135**.

[0168] Figure 70R shows a top plan view of an embodiment of a system **102** comprising a plurality of stretchable serpentine electrical interconnects **120** connecting devices or device components **110A-110D**. The system further includes a containment chamber **135** having a void **130** that is at least partially filled with a containment fluid (not shown). The containment chamber **135** may include a top wall (not shown) and/or a bottom wall (not shown). The entire system is supported by a substrate **100** comprising discrete areas **800** of higher elastic modulus material than other portions of the substrate. In an embodiment, the higher modulus areas may be localized under or near devices or device components **110A-110D** to minimize strain at the junction of interconnect **120** and device or device component **110A-110D**. In an embodiment, the substrate may be formed from alternating higher modulus areas and lower modulus areas (e.g., formed by discrete strips of material). The areas of higher modulus material may be provided by replacing the substrate materials with a higher modulus material, incorporating a higher modulus material (e.g., a mesh or glass wool) into the substrate material at discrete locations, layering a higher modulus material with the substrate material at discrete locations, thickening the substrate material at discrete locations, and other techniques known to those of skill in the art.

[0169] Figure 70S shows a top plan view of an embodiment of a system **102** comprising a plurality of stretchable serpentine electrical interconnects **120** connecting devices or device components **110A-110D**. The system further includes a containment chamber **135** having a void **130** that is at least partially filled with a containment fluid (not shown). The containment chamber **135** may include a top wall (not shown) and/or a bottom wall (not shown). The entire system is supported by a substrate **100** having a continuously varying elastic modulus (schematically represented by cross-hatching), where the elastic modulus is spatially varying within the plane of the substrate. In an embodiment, the elastic modulus of the substrate may spatially vary according to a continuous or smooth linear, parabolic or sinusoidal function. In an embodiment, the elastic modulus of the substrate may spatially vary from one edge or corner of the substrate to an opposite edge or corner of the substrate, or from a center of the substrate to an outer perimeter of the substrate, or according to a set frequency or pattern. A smooth or continuous spatial variation may be provided by incorporating a spatially varying concentration of higher modulus material (e.g., a mesh or glass wool) into the substrate, spatially varying substrate thickness (e.g., by molding or reductive processing), and other techniques known to those of skill in the art.

[0170] Figure 71 shows a top plan view of an embodiment of an exemplary system **770** comprising stretchable serpentine electrical interconnects **120** connecting devices or device components **110**, which may be free floating or tethered and optionally may be constrained within a barrier structure (not shown). The system further includes a containment chamber **135** having a void **130** that is at least partially filled with a containment fluid **140**. The containment chamber **135** may include a top wall (not shown) and/or a bottom wall (not shown). The entire system is supported by a substrate **100**. To reduce or prevent tangling, interconnects **120** are selectively bonded to the bottom wall or substrate **100** by a bonding pad **750**, which may be a pedestal, adhesive bead, or other material for anchoring a device or device component to a bottom wall or substrate **100**.

Example 4: Soft Systems of Sensors. Circuits and Radios for the Skin

[0171] When mounted on the skin, modern sensors, circuits, radios and power supply systems have the potential to provide clinical-quality health monitoring capabilities for continuous use, beyond the confines of traditional hospital or laboratory facilities. The most well-developed component technologies are, however, broadly available only in hard, planar formats. As a result, existing options in system design are unable to effectively accommodate integration with the soft, textured, curvilinear and time-dynamic surfaces of the skin. Here, we present combined strategies in materials, microfluidic systems, structural designs and mechanics theory for low modulus, stretchable systems that incorporate assemblies of high modulus, rigid, state-of-the-art functional elements. The outcome is a thin, conformable device technology that can softly laminate onto the surface of the skin, to enable advanced, multifunctional operation for physiological monitoring in a wireless mode. The versatility of these ideas and their compatibility with other approaches to flexible/stretchable electronics suggest a foundation for rapid progress in wearable devices that exploit intimate integration with the human body.

[0172] Successful development and deployment of electronic systems with precision capabilities in continuous physiological monitoring, intervention and therapy could have many important consequences, ranging from enhanced safety in sports to improved cost structures and outcomes in advanced health-care. Multi-modal, non-invasive access to the body can be accomplished through electrical/optical/fluidic interfaces established transcutaneously. Conventional hard electronic components and sensors adhere to the skin by use of straps, pins or tapes, thereby constraining natural motions in ways that cause discomfort, frustrate robust adhesion and prevent stable biotic/abiotic interfaces. 'Skin-like' devices, sometimes referred to as 'epidermal' electronic systems (1, 2), avoid these limitations by adopting thicknesses (3-5), moduli, levels of elastic stretchability and other basic physical properties that match those of the skin itself, to allow a soft, compliant type of integration. These ideal characteristics can be achieved even in components that incorporate established, high-performance semiconductor materials such as silicon, which are themselves hard and brittle (1, 6, 7). The required specialized, ultrathin device geometries can, however, create engineering impediments to quick design iterations and fast development. Alternative approaches that use soft active materials (3, 4, 8-13) and/or liquid metals (14-16) are valuable for certain sensors and individual components, but they cannot presently support the entire range of functions needed for practical applications nor are they immediately compatible with established methods for micro-fabrication and device integration. Here, we demonstrate ideas for compliant, skin-mounted systems that can incorporate not only these and other recently explored materials and devices but also commercial, chip-scale components, including integrated circuits, radio frequency hardware, microelectromechanical structures, physical/chemical sensors and power sources. Interconnected collections of such chips that float in thin microfluidic enclosures defined by elastomeric membranes offer soft, low modulus mechanics at the system level. Here, the influence of the high modulus components on the overall mechanics is negligible, even when they are present at high areal coverage. Such mechanical properties are qualitatively different from those achievable with solid constructs explored previously (17-20). The resulting systems can laminate softly and non-invasively onto the skin, to define highly functional interfaces with the ability to combine unusual devices with standard parts. These concepts enable rapid prototyping of broad classes of sophisticated bio-integrated electronic devices, as illustrated here through systems that offer wirelessly powered operation, precision measurement of biopotentials, acceleration and/or temperature, with radio frequency (RF) data transmission.

[0173] The layout involves a matrix of microfluidic spaces designed to decouple the mechanics of the constituent devices and associated interconnect network from a thin, elastomeric enclosure that simultaneously provides a supporting surface (i.e. substrate) and an encapsulation layer (i.e. superstrate). Each component bonds to the bottom surface of this enclosure selectively at small, localized cylindrical features of relief (i.e. support posts) molded onto the thin elastomer substrate. Except for these posts, the devices are suspended in the surrounding fluid and, as a result, are mechanically isolated. A free-floating network of interconnects in thin, serpentine shapes and multilayer, neutral mechanical plane layouts joins the devices into circuit architectures that provide system-level function. Figure 72A presents an exploded view schematic illustration of an integrated device capable of wireless acquisition, filtering, amplification and RF transmission of electrophysiological (EP) data, for precision measurement of electrocardiograms (ECGs), electromyograms (EMGs), electrooculograms (EOGs) and electroencephalograms (EEGs).

[0174] Bonding the superstrate and substrate at their edges defines a microfluidic structure that is filled, in a second step, with a dielectric fluid using an injection needle (Fig. 72B). The elastomer self-seals after removal of the needle (Fig. 73); additional elastomer can be added to enhance the robustness of this seal. Selection criteria for the fluid include (1) wettability toward the electronic components and the substrate/superstrate, to facilitate the filling process, (2) large volume resistivity ($>1\times10^{14}$ Ohm*cm) to eliminate electrical crosstalk, (3) high dielectric strength (>10 kV/mm) to avoid electrical breakdown, (4) moderate viscosity (~5 Pa·s) to enhance impact resistance, (5) good thermal stability (weight loss $< 0.1\%$ at 100 °C for 4 hours (Fig. 74) to allow reliable long-term operation, (7) low loss RF properties and small dielectric constant (<3), to minimize influence on RF operation, (8) low reactivity and chemical stability, to avoid corrosion or other forms of chemical degradation, (9) hydrophobic character, to expel moisture from the package and (10) optical transparency to enable rapid inspection of the components. Although many materials can be considered, the devices

reported here use a soft, silicone elastomer (Ecoflex, Smooth-On, Inc., Easton, PA) for the substrate/superstrate, and a high molecular weight silicone oligomer (Sylgard 184, without curing agent) for the fluid.

[0175] The free-floating interconnects can buckle, twist and deform, both in and out of the plane, with little constraint, in response to externally imposed deformations of the entire system. Likewise, the fluidic-based strain isolation strategy allows large-range motions of the substrate/superstrate with minimal coupling to the device components. This physics is apparent from the three dimensional (3D) finite element analysis (FEA) results of Fig. 72C. The ability of the interconnects to move freely increases their range of stretchability, relative to designs that involve bonding to or embedding in solid or porous elastomers (17-23). For the case of an interconnect shown in Fig. 72C, this increase in stretchability corresponds to a factor of -10 and -20 when compared to the case of bonding or embedding, respectively (Fig. 75). The maximum principal strain in the interconnect metal (in Fig. 72C) is less than -0.2% for a biaxial stretch of 50% for the entire system. The support posts lead to differences in strains between the hard components and the elastomer immediately below that can be as large as -64%, absolute, for the same level (50%) of biaxial stretch.

[0176] A dense array of sharp, pyramidal features molded onto the superstrate/substrate prevent non-specific adhesion to the interconnects and the devices, to allow low friction, lubricated relative motions. This relief, as well as that associated with a support post to allow strain isolation of component chips and a physical barrier to prevent entanglement of adjacent interconnects, appear in the cross sectional scanning electron microscope (SEM) image of Fig. 72D and Fig. 76. Figure 72, E and F, show the same region after integration of the interconnect network by transfer printing, including a magnified view. Crossovers in the interconnect network can be accommodated either with interlayer dielectrics or chip-scale crossovers. All chips (all <1 mm in thickness, achieved by mechanical grinding (Fig. 77)) bond, electrically and mechanically, to this network via a low temperature solder (Sn₄₂Bi₅₈) applied by screen printing to metallized (electrolessly deposited Sn (Fig. 78)) regions of integrated pads with matching contacts. Adhesion to the substrate (thickness ~0.4 mm) occurs selectively only at the locations of the supporting posts (~1 mm diameter). These pads incorporate tapered shapes at joints with the interconnects, to minimize stress concentrations (Fig. 79). Wide, straight traces (Fig. 80) pass through opposite edges of the microfluidic enclosure (microfluidic thickness ~1 mm; superstrate thickness ~0.1 mm), and terminate at external contact pads that provide locations for lamination of epidermal electrodes (Fig. 81), as interfaces to the skin. The completed system (Fig. 72G) includes modules for (1) wireless power supply by resonant inductive energy transfer, (2) low-noise amplification and filtering of EP signals and (3) frequency-modulated (FM) RF transmission of measured data. Table 1 and Fig. 82 summarize the components and the design rationale. The images in Fig. 72, H and I, show the ability of the device to stretch (shown here to -30% uniaxial strain) and twist (shown here to -75 degrees), respectively. Detailed information on the materials and fabrication procedures are provided in the Supplementary Information section.

Table 1. Chip information of the ECG system.

Device number	Type	Value	Manufacturer part number
0	Jumper	0 Ω	CRCWD603000020EAHP
1	Operational amplifier	N/A	AD627BRZ-R7
3	Voltage controlled oscillator	N/A	MAX275DEU4+
4	Resistor	249 Ω	PAT0603E249CBST1
10	Resistor	10K Ω	ERJ-3EKF1002V
13	Resistor	200K Ω	RG1506N-204-W-T1
18	Multilayer antenna	N/A	7488810245
101	Inductor	10 μH	2TT103C
105	Capacitor	10 μF	C1608X5R1A105K
107	Capacitor	0.1 μF	C0603C104J4RACTU

[0177] Mechanical behaviors at the system level are critically important to overall design. Figure 83 summarizes systematic computational and experimental studies of the device in Fig. 72, without the superstrate membrane to facilitate imaging. 3D finite element analysis (FEA) results (Fig. 83A) and experimental pictures (Fig. 83B) reveal the configurations of the chips and interconnects at various levels of equal-biaxial stretch. The good agreement observed here validates the models and establishes their utility as design tools for optimizing the layouts of the chips and the shapes of the interconnects. In particular, for any choice of system geometry, the computed results allow rapid identification of locations of (1) high principle strains, (2) entanglements in the interconnects and (3) collisions between the chips. An iterative

process that involves coupled considerations in circuit and mechanics design, with 3D-FEA modeling as a guide, allows optimization of all relevant parameters (including positions of molded barriers) for a desired device size, degree of stretchability and effective modulus. The system shown here results from several iterations in the layouts of the chips and the geometries of the self-similar serpentine shapes that form the aperiodic interconnection network. Attention to the hierarchical mechanics of in- and out-of-plane bending and twisting in the serpentines and their dependence on geometry is paramount, subject to constraints set by requirements on their electrical properties. Figure 83C and Fig. 84 show the subtle effects that can occur. An example of one of the many modifications introduced with guidance from theory is a small bonding site added at the midpoint of the long interconnect at the base edge, to ensure reversibility in its mechanics and to avoid entanglements (Fig. 79). The final design offers an effective modulus, at the system level, that is only slightly larger (by 3-5%) than the intrinsic value associated with the bare elastomeric substrate (Table 2). In fact, uniaxial testing of the substrate with and without the chips, interconnect network and surrounding fluid reveal almost identical stress/strain responses, as shown in the bottom frame of Fig. 83B. This outcome is notable, considering the large differences between the moduli of the electronic materials (-100 GPa) and the elastomers (-180 kPa).

Table 2. Computational model for the effective Young's modulus. The moduli for the experimental data are determined by using linear fits of the stress-strain curve in the range of [0%, 50%].

FEA	Experiment	Modulus (x)	Modulus (y)
With chip	172.06 kPa	193.80 kPa	176.88 kPa
Without chip	166.41 kPa	185.15 kPa	166.41 kPa
Increased percentage	3.4%	4.7%	2.9%
Average	3.2%		5.5%

[0178] In addition to a low modulus, the system offers a large range of stretchability. For example, 100% equal-biaxial strain induces maximum principle strains of only -2% in the active materials (Cu of the interconnects), as highlighted by a segment of the interconnect network shown in the bottom frame of Fig. 83A. The maximum biaxial stretchability predicted by 3D-FEA is -125%, limited by localized fracture of the Cu (failure strain -5%) in the interconnect network, consistent with experimental observation (~100%). Reversible, elastic behaviors can be obtained (yield strain of Cu -0.3%) for biaxial strains of -49% (Fig. 85), even with the high (~46%) cumulative areal coverage of chips in this device layout. Practical limits in uniaxial stretching are -40%, defined by collisions of adjacent chips caused by orthogonal contractions that arise from the Poisson effect (Figs. 86 and 87). In all cases, deformations in the substrate show no evidence of constraints in motion associated with the chips or the interconnect network, as illustrated by the uniform separations between fiducial dots (Cr, 100 nm thick) deposited in a square array on the back surface of the substrate, visible in the images of Fig. 83. For quantitative analysis, see Fig. 88. This low modulus (-180 kPa, as soft as the skin (1)), isotropic stretchable response follows uniquely from the microfluidic strain-isolation approaches introduced here. Such properties are critically important for soft, reliable, non-invasive integration of state-of-the-art, commercially available electronic components onto the skin. Analogous systems that do not exploit strain isolation of the chips show highly non-uniform deformations in the substrate (Fig. 89); those that replace the microfluidics with solid elastomer show an elastic stretchability of only 6%, and local effective moduli that vary from values comparable to those of the chips themselves (>100 GPa) to the elastomer constrained by the bonded interconnects (-250 kPa). Such characteristics are poorly matched to requirements for mounting on the skin.

[0179] Figure 90, A and B, shows a completed device (~1.7×1.8 cm²), including a pair of epidermal electrodes (each ~0.8×1 cm², in filamentary, self-similar serpentine mesh designs; Fig. 91), laminated onto the skin of the forearm, in undeformed and deformed states, respectively. Here, low interface stresses associated with the low effective modulus of the device enable robust adhesion to the skin through van der Waals forces alone, facilitated by an ultralow modulus thin elastomer coating on the bottom surface of the substrate. Alternating voltage (10 V_{p-p} at 150 kHz) applied to a primary coil in proximity (within mm's) to the device activates it by creating direct current output from the inductive power module, which consists of an LC oscillator, a Schottky diode rectifier and an integration capacitor (10 μF). The total power consumption is -35 mW, which lies with a range accessible to near field communication (NFC) capabilities present in many modern cellular phones. An instrumentation amplifier provides a gain of up to 800. Capacitors remove high

frequency and DC components of EP signals collected by the epidermal working and reference electrodes, with a floating ground. A voltage controlled RF oscillator transforms the amplified data into an FM RF signal at -2.4 GHz that passes out of the device through a compact three dimensional antenna. A separate patch antenna, RF amplifier and frequency counter can receive the transmitted RF reliably at a distance of up to 1 m (Fig. 92), when operated in a room designed to eliminate background electrical noise. Laminating the device across the sternum with the electrodes in bi-lateral fourth intercostal spaces enables collection of ECG. Representative measurements, with clearly identifiable QRS complexes, appear in Fig. 90C. The fidelity of this system is similar to that of conventional commercial hardware (Brain Vision V-Amp) with wired connections. Results for ECG measured from standard adhesive electrodes placed next to the epidermal electrodes (with a nearby ground electrode on a distal position on the left forearm) are shown in Fig. 93.

[0180] Figure 90D presents corresponding EOG recorded at positions superior and inferior to the left eye (and slightly lateral from the left outer canthus) as the subject blinks once per second. Similar levels of agreement occur in EMG and EEG, where the commercial system used a pair of Au plated Ag electrodes held against the head with adhesive stickers and conductive electrode gel, and a nearby ground electrode. EMG measured from the proximal left forearm over the flexor carpi radialis muscle during hand clenches appears in Fig. 90E, and Fig. 90F shows EEG measured on the forehead, with commercial electrodes placed inferior to the hairline at position Fpz referenced to a lateral electrode at location AF7. The epidermal electrodes were directly inferior, parallel, and the same distance apart. Here, the subject engaged in mental math (counting backwards by 7 from 200) for one minute, closed his eyes and remained at rest for another minute. EOG activity from the eyes closing separates the two tasks. The data reveal strong high-frequency activity during mental math, and strong low-frequency activity during rest (Fig. 94), as expected.

[0181] The core concepts in materials, mechanics and device integration have general applicability. A multi-modal measurement system, capable not only of EP sensing, but also of recording motion with a tri-axial accelerometer and temperature with a thermistor in a Wheatstone bridge configuration (Fig. 95A and Fig. 96) provides an example. This set of measurement capabilities is important for many applications, ranging from training in sports, to tracking in sleep apnea studies, to monitoring in neonatal care, to assessing cognitive state and awareness. A multiplexer switches sequentially among the outputs of the three sensor channels, to allow data transmission with a single voltage controlled oscillator. In particular, data from the EP, acceleration and temperature channels transmit for 18, 9 and 9 seconds, respectively, as determined by two oscillators that generate two bit control logic by tuning the ratio of their oscillation frequencies to 1:2 (Fig. 97). The device includes 31 component chips, and an interconnect network with 4 crossovers, with an overall size of 1.9x2.9 cm². Table 3 and Fig. 96 summarize the components and design rationale. A pulse width modulation oscillator periodically turns on and off the voltage controlled oscillator, for a duty cycle of -7% at a frequency of 1000 Hz (Fig. 98), to reduce the average power consumption from -40 mW (continuous operating mode) to -6.3 mW. This power level lies in a range that can be addressed not only with NFC, but also by small coin-cell batteries or, potentially, far field RF power transfer. A pair of contact pads enables integration of these or other options in power supply (Fig. 95A). Examples of inductive and battery power appear in Fig. 99. A combined circuit and mechanics iterative design process, similar to that described for the single-channel device, enables a high level of stretchability, and low effective modulus. As a consequence, the system (Fig. 95B) can naturally integrate with the skin, and remain adhered by van der Waals forces during twisting, stretching, and pinching (Fig. 95, C and D). Figure 95E shows an EMG recorded from the forearm during repeated clenching and releasing of the fist. The output of the accelerometer during walking and falling appears in Fig. 95F. The temperature responses induced by breathing onto the device (Fig. 95G) and by physical exercise are consistent with those observed using a commercial IR camera Figs. 100 and 101).

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Table 3. Chip information for the multifunctional system.

	Device number	Type	Value	Manufacturer part number
5	0	Jumper	0 Ω	CRCW06030000Z0EAHP
10	1	Operational amplifier	N/A	AD627BR2-R7
15	2	IC multiplexer	N/A	MAX4734EUB+
20	3	Voltage controlled oscillator	N/A	MAX2750EUA+
25	4	Resistor	249 Ω	PAT0603E2490BGT1
30	5	Temperature sensor	N/A	PT080501B500RP100
35	6	IC accelerometer	N/A	KXTH9-2083
40	9	IC oscillator	N/A	LTC6992IBS-2#TRMPBF
45	10	Resistor	10 kΩ	ERJ-3EKF1002V
50	11	Resistor	392 kΩ	ERJ-3EKF3923V
55	12	Resistor	215 kΩ	ERA-3AE82153V
60	13	Resistor	200 kΩ	RG1608N-204-W-T1
65	14	Resistor	1 MΩ	ERJ-3EKF1004V
70	15	Capacitor	0.1 μF	C0402C104K8R/ALTU
75	16	Resistor	549 Ω	ERA-3AE85490V
80	17	Resistor	18 kΩ	RG1608N-183-W-T1
85	18	Multilayer antenna	N/A	T488910345
90	19	Resistor	430 kΩ	1-1875417-0
95	20	Capacitor	82 pF	VJ0402D820JXXAJ
100	21	IC oscillator	N/A	LTC6991IBS-2#TRMPBF
105	22	Capacitor	4.7 μF	C1608X5R1A475K0.50

[0182] The ideas illustrated here provide versatile routes to integrated assemblies of sensors, circuits, radios and devices for power supply into systems that exhibit uniformly soft, elastic mechanical responses. These physical characteristics allow direct lamination onto the skin to yield advanced modes of operation in wearable electronic devices, with capabilities that complement and extend those of other approaches. Other embodiments might, for example, combine epidermal transistors for amplified, multiplexed addressing of signals from distributed arrays of soft sensors, with compact, stretchable collections of chip-scale components for data storage, processing and RF transmission. Such opportunities, taken together with progress in power efficient radios (24-26), wireless energy transfer (27-29) and functional microfluidics (14-16), suggest promising body-integrated electronics.

SUPPLEMENTARY INFORMATION

Materials and Methods

[0183] Design rationale for the circuits. For the inductive ECG system, Chip 105 (10 μF capacitor) is used to block the DC offset of the incoming ECG signal. Chip 107 (0.1 μF capacitor) and chip 13 (200 kΩ) form a high pass RC filter to remove low frequency noise from the incoming ECG signal. The instrumentation amplifier (AD627b, chip 1) amplifies the ECG signal by 800 times. Chip 107 (0.1 μF capacitor) and chip 10 (10 kΩ) form a low pass RC filter to remove high frequency noise from the amplified ECG signal. A voltage controlled oscillator (MAX2750, chip 3) generates high frequency signals that represent the ECG signal voltage. The output of this chip passes through a compact antenna (chip 18). The inductive power module is based on resonant inductive coupling: a 10 μH inductive coil (27T103C, chip 101) and 0.1uF capacitor (chip 107) forms a LC loop.

[0184] For the multifunctional device, the EP amplification subunit is similar to that of the ECG system. The acceleration sensing module consists of chip 6 (KXTH9) which converts acceleration to an analog voltage output. The temperature sensing module uses a bridge circuit to convert temperature to an analog voltage output. Chip 5 (PTS080501 B500RP100) is a RTD sensor. Chips 16 and 17 are paired resistors to form the bridge loop. In the multiplexing module, chip 21 (LTC6991) generates an oscillating signal that controls the multiplexer (MAX4734, chip 2), to switch between EP, tem-

perature and acceleration sensing. The wireless data transmission subunit is similar to that of the ECG system.

[0185] Molding structures of surface relief on the elastomeric device substrate. The process began with a piece of a clean (100) Si wafer, coated with a 100 nm thick Si_3N_4 film formed by plasma enhanced chemical vapor deposition (STS PECVD). Photolithography (AZ P4620, 3000 rpm, 30 s, soft bake at 110 °C for 3 min, 300 mJ/cm², 1:2 volume ratio of AZ 400K and DI water for 1 min) and reactive ion etching (RIE, 22.5 sccm CF₄, 40 mT, 150 W, 8 min) defined an array of circles (20 μm) in the Si_3N_4 . Wet chemical anisotropic etching of the silicon with KOH (100 ml 33% weight percent water solution, 20 ml isopropanol alcohol, 130 °C, 45 min, with strong magnetic stirring) generated an array of pyramidal shaped recessed regions on the surface of the wafer. After removing the remaining Si_3N_4 , a second photolithography step (AZ P4620) and inductively coupled plasma reactive ion etching process (ICP RIE, Bosch process) defined trenches (30 μm in depth) for the support posts for the chips. A third photolithography step (AZ P4620) and RIE process (STS ICP RIE, Bosch process) defined the trenches (100 μm in depth) for the isolation barriers. A layer of polytetrafluoroethylene (~200 nm) conformally deposited (STS ICP RIE) all exposed surfaces to minimize adhesion. Thin (300 μm) silicone substrates (Ecoflex, Smooth-On, Inc., Easton, PA) were prepared by mixing the two components of a commercial kit in a 1:1 weight ratio, spin-casting (300 rpm for 30 s) the resulting material onto the processed Si wafer and then curing into a solid form (2 hours at room temperature).

[0186] Fabrication of the interconnect network. The process began with spin casting of polydimethylsiloxane (PDMS, Sylgard 184), mixed at 10:1 ratio of base to curing agent, onto a clean glass slide at 3000 rpm for 30 s. After curing in an oven at 70 °C for 2 hours, the PDMS was exposed to oxygen plasma (20 sccm O₂, 300 mT, 200 W, 30 s). A 2.4 μm thick layer of polyimide (PI, from poly(pyromellitic dianhydride-co-4,4'-oxydianiline) amic acid solution was then applied by spin casting (2000 rpm for 60 s), baked on a hotplate at 150 °C for 4 mins and in a vacuum oven at 10 mT and 250 °C for 1 h. The interconnects and metal electrodes consisted of a 400 nm thick layer of Cu deposited by electron beam evaporation onto the PI. Photolithography (AZ P4620) and etching (CE-100 copper etchant, Transene Company) defined patterns in the Cu. Next, spin coating formed a second 2.4 μm thick layer of PI over the entire structure. A 50 nm thick layer of SiO₂ was then deposited using electron beam evaporation, to serve as an etching mask for the PI. Next, photolithography (AZ P4620), RIE etching (50 mT, 40 sccm CF₄, 100 W, 20 min), and oxygen plasma etching (20 sccm O₂, 300 mT, 200 W for 21 mins) patterned the layers of PI in a geometry matched to the metal traces. The residue SiO₂ mask was removed using buffered oxide etchant, and the overall circuit electrodes were immersed in electroless Sn plating solution (Transene Company) at 80 °C for -10 s. The Sn deposited only onto the exposed Cu surfaces, for the purpose of ensuring good wettability of the solder on the bonding pads. Finally, the circuit electrodes were retrieved using water soluble tape (3M, Inc.) for aligned transfer to the device substrate.

[0187] Assembly of the chip components. Electron beam evaporation of Ti (5 nm) / SiO₂ (50 nm) on the pads (mounting sites for the chips) of the interconnect network formed backside coatings (30). A shadow mask made of PI (Stencilunlimited corp.) with patterns matched to the support posts, was aligned and laminated onto the molded silicone substrate. The substrate was then activated by exposure to ultraviolet induced ozone for 5 mins. Aligning and laminating the interconnect network onto this surface led to irreversible strong bonding upon contact, only at the locations of the support posts. After aging for 10 mins, the water soluble tape was removed by immersion in tap water for 1 hour. Another shadow mask, the same as the one for electroless Sn plating, was then aligned and laminated onto the electrodes to selectively expose the contact pads for the pin contacts associated with each of the component chips. A Sn₄₂Bi₅₈ alloy solder paste (Chip Quik Inc. SMDLTFP250T3) was screen printed onto the contact pads. A combined lapping and polishing process with tripod polisher was used for thinning of the thickest chips, such that all chips had thicknesses <1 mm. The lapping process involved a fast back grinding step, followed by a polishing process to remove remaining rough surfaces. Each chip component was manually placed over the electrodes under an optical microscope. After all of the chips were in position, the solder paste was reflowed in an oven at -180 °C for 5 mins. Good solder joints appeared smooth and shiny, with complete wetting to the contact pads. A thin silicone superstrate (-100 μm thick) encapsulated the entire chip region of the device. The edges were sealed with an additional application of partially cured silicone followed by baking on a hotplate at 120 °C for 10 min. A liquid PDMS base (Sylgard 184, without the curing agent), injected into the capped cavity through an edge, covered all of the chips and interconnects via capillary force.

[0188] Mechanical testing and simulation of the devices. An array of metal dots (100 nm Cr, 0.4 mm for each dot, 1 mm pitch) was deposited through a polyimide shadow mask mounted on the back side of the relief substrate. After integrating the interconnect network and chips and adding a thin layer of PDMS base, equal-biaxial stretching was applied to the device using a customized stage. Strain was added/removed gradually and simultaneously in both directions. Images of the device at various stages of deformation were collected with a digital single-lens reflex camera from the backside of the device so that the metal dots were clearly visible. The Young's moduli of the devices with and without the chips and interconnect network were measured in orthogonal directions using an INSTRON MINI44. The strain-stress curves were averaged over at least three individual measurements. Mechanical simulation was performed using FEA techniques.

[0189] Full three-dimensional (3D) FEA was adopted to analyze the postbuckling behaviors of the entire device under uniaxial and biaxial stretching. The chips were selectively bonded to the silicone substrate (Ecoflex; thickness 0.5 mm)

via small circular (diameter 1 mm) and rectangular (0.5 mm by 1.0 mm) pedestals. Each of the metal interconnect (Cu, thickness 400 nm) lines, was encased, top and bottom, by a thin layer of polyimide (PI, thickness 2.4 μm for each layer). The elastic modulus (E) and Poisson's ratio (ν) are $E_{\text{Ecoflex}}=0.0623 \text{ MPa}$ and $\nu_{\text{Ecoflex}}=0.49$ for Ecoflex; $E_{\text{Cu}}=119 \text{ GPa}$ and $\nu_{\text{Cu}}=0.34$ for copper; and $E_{\text{PI}}=2.5 \text{ GPa}$ and $\nu_{\text{PI}}=0.34$ for PI. Eight-node 3D solid elements and four-node shell elements were used for the ecoflex and self-similar electrode, respectively, and refined meshes were adopted to ensure the accuracy. Linear buckling analyses were carried out to determine the critical buckling strain and lowest buckling mode for each interconnect, which were then implemented as initial geometric imperfections in the postbuckling simulation. The evolution of deformed configurations with applied strains were obtained from FEA for the entire device under both uniaxial and biaxial stretchings, as shown in Figs. 83, 84, 86, and 87. Good agreement between FEA and experiment results can be found.

[0190] Functional testing of the devices on human subjects. Prior to device integration, hairs were removed and the skin was cleaned using a mild abrasive and Scotch tape to exfoliate some of the stratum corneum and to remove sebaceous oils (31). Afterwards, the device was placed on the desired areas on the skin for recording of EP signals. For NFC powering, a high frequency alternating current source to the primary coil was generated using a KEITHLEY 3390 50 MHz arbitrary waveform generator. The input and output characteristics of the wireless coil were measured using an Agilent infiniium DSO8104A oscilloscope (1 GHz, 4 channels). The ECG data were received by a back end antenna, then filtered through a 2.2-2.7 GHz band pass filter (RF-lambda, RBPF2450, SN:12041902227), amplified by a 2.2-2.7 GHz low noise amplifier (ZQL-2700MLNW+), and read out by a frequency counter, where the frequency-modulated signals were processed and analyzed. For recordings with commercial equipment, we used a pair of Au/Ag ring electrodes, fixed with an adhesive sticker to the skin along with conductive electrode gel. A ground electrode was attached on a more proximal section of the right arm. The wireless system, placed directly adjacent to the electrodes used for measurement with the commercial system, utilized a floating ground. Recorded data were passed through band pass filters to remove line noise and other high frequency artifacts, as well as slow drifts in the signal. The mean voltage of each signal was subtracted to remove the DC offsets. The data were then normalized to their peak values, to facilitate comparisons.

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[0191]

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35 Example 5: Mechanics Modeling of Systems Using Containment With Low Modulus Solid Material

[0192] Fig. 102a shows a schematic of a design layout for achieving high stretchability of electronic systems encapsulated within containment chambers. In the embodiment shown, an electronic system comprises an electronic device or component **1000** encapsulated within a containment chamber formed by a substrate **1002** and a superstrate **1004**. The electronic device or component **1000** is supported by substrate **1002** and a first filler or low modulus solid **1006**. A second filler or low modulus solid **1008** contacts top and side surfaces of electronic device or component **1000**. In an embodiment, a thickness of the first filler is less than or equal to 1000 μm , or less than or equal to 500 μm , or less than or equal to 250 μm , or less than or equal to 100 μm . In an embodiment, the first and second fillers may be the same or different low modulus solid materials. In an embodiment, the Young's moduli of the first filler and the second filler may be the same or different. In an embodiment, more than two filler materials (e.g., 3, 4, 5, 6 filler materials) may be present (e.g., mixed or layered) within a containment chamber.

[0193] In an embodiment, electronic device or component **1000** may be completely bonded, partially bonded or tethered to the first filler. In an embodiment, electronic device or component **1000** is free-standing on the first filler.

[0194] In an embodiment, electronic device or component **1000** is tethered to substrate **1002** but at least partially supported by first filler **1006**. For example, in an embodiment, first filler **1006** naturally fills a space beneath an electronic device or component that is at least partially supported by a pedestal.

[0195] One important mechanics concept is isolation of the deformation of electronics from that of the substrate, which may be accomplished in some embodiments by filling soft materials between the electronics and substrate. We adopted full three-dimensional (3D) FEA to analyze the mechanical performance using different low modulus solid filling materials. We studied an electrical interconnect in the serpentine layout (as shown in Fig. 102b), with the ultrathin copper layer (0.3 μm) sandwiched by two polyimide (PI, 1.2 μm) layers. This interconnect is encapsulated in a soft elastomer (i.e., filler in Fig. 102a, with the thickness $t_{\text{Filler-1}}=100 \mu\text{m}$, $t_{\text{Filler-2}}=400 \mu\text{m}$) that is laminated onto a substrate (Ecoflex, 200 μm). The superstrate has negligible effect on the deformation of the electronics, and therefore, is not taken into account

in the FEA. The material parameters adopted in the FEA are shown in Table 4. Eight-node 3D solid elements were used for the substrate and filler, and four-node shell elements were used for the serpentine interconnect, with refined meshes to ensure accuracy.

[0196] The calculated elastic stretchabilities are summarized in Table 5 for various exemplary filler materials, with modulus values ranging from 0 to 1.0 MPa. The elastic stretchability increases as the Young's modulus of the filler material decreases. When ultra low modulus elastomers, such as silbione (Silbione® RT Gel 4717 A/B, Bluestar Silicones) and PDMS (1:50), are adopted, the predicted elastic stretchabilities (115.6% and 108.4%) are very close to the limit (120.0%) of a freestanding interconnect stretched from two ends (which is similar to the environment provided by fluidic systems). This set of simulations clearly shows the mechanical advantage of the stretchable design using low modulus solid fillers.

Table 4. Material parameters adopted in FEA

Materials	Cu	PI	Substrate	Filler
Young's Modulus (MPa)	119,000	2,500	0.06	0.0-1.0
Poisson ratio	0.34	0.34	0.49	0.49

Table 5. Elastic stretchability of the interconnect using different filler materials

Material	Fluid or Air	Silbione	PDMS (1:50)*	Ecoflex	Solaris	PDMS (1:20)	PDMS (1:10)
Modulus of filler (kPa)	0	3	20	60	170	500	1000
Elastic stretchability	120.0%	115.6%	108.4%	69.0%	39.3%	11.9%	8.0%

* PDMS ratios represent 1 part curing agent to 10/20/50 parts monomer or pure PDMS base.

Example 6: Fabrication of Systems Using Containment With Low Modulus Solid Material

[0197] In one embodiment, containment systems comprising a low modulus solid may be fabricated by bonding a superstrate and a substrate to form a cavity. The superstrate may, for example, comprise a plurality of side walls and a top wall. A low modulus solid, such as silbione, is then injected into the cavity using a needle, e.g., through an edge between the superstrate and substrate. Generally, the injection hole self-seals after removal of the needle, but additional elastomer can be added at the injection site to enhance the robustness of the seal.

[0198] In an alternate embodiment, containment systems comprising a low modulus solid may be fabricated by bonding a plurality of side walls to a substrate to form an open cavity. A low modulus solid is then added to the cavity via the opening. Lastly, a top wall is positioned on and sealed to the side walls to enclose the low modulus solid.

Example 7: Fabrication of Systems in Containment Chambers Filled with Fluids and/or Low Modulus Solid Materials

[0199] An interconnect having a self-similar structure is fabricated by conventional photolithography using PI (1.2 micron) coated Cu foil (5 micron). It is then picked up with water soluble tape and a Cr (5 nm)/SiO_x (60 nm) layer is deposited on it by e-beam evaporation. Finally, the interconnect is transferred onto a desired substrate and an individual solar cell, battery or other electronic device or component is attached to the interconnect with In-based solder.

[0200] In an embodiment, the substrate (e.g., Ecoflex) has a layer of low modulus solid (e.g., Silbione) on the surface of the substrate that receives the interconnect. In one method for forming this structure, Silbione is mixed in a 2:1 ratio of base to curing agent, then spin coated onto a 0.5 mm thick layer of Ecoflex and cured at room temperature for 2 days before the interconnects and other components are contacted with the low modulus solid. An Ecoflex superstrate or cap is bonded to the substrate, and a fluid or low modulus solid is injected into the cavity of the containment chamber.

[0201] In an embodiment, an interconnect is bonded directly to the substrate. In one method for forming this structure, the interconnect is transferred onto a 0.5 mm thick layer of Ecoflex. After assembly of the electronic device(s), the substrate is covered by a silicone cap and sealed with Ecoflex. After complete sealing, PDMS base is injected into the cap.

[0202] Figure 103A shows a schematic of a design layout comprising a first low modulus material and a fluid or second low modulus material. Figure 103B shows a schematic of a design layout comprising a fluid or low modulus solid filled containment chamber housing a solar cell soldered to two electronic devices or components on dielectric materials in contact with a substrate. Figure 104 is a photograph, and exploded view, of the device of Figure 103B.

STATEMENTS REGARDING INCORPORATION BY REFERENCE AND VARIATIONS

[0203] Thus, it should be understood that although the present invention has been specifically disclosed by preferred embodiments, exemplary embodiments and optional features, the present is solely limited by the scope of the appended claims.

Claims

- 10 1. An electronic system (102) comprising:
- i. a substrate (100);
 - ii. electronic devices or device components (110A, 110B) supported by said substrate (100); wherein said electronic devices or device components (110A, 110B) are free standing or tethered to said substrate (100);
 - 15 iii. a containment chamber (135) at least partially enclosing said electronic devices or device components (110A, 110B); wherein said containment chamber (135) is an elastomer at least partially filled with a containment fluid (140) or a low modulus solid; and an ultra low modulus layer; wherein the substrate (100) is supported by said ultra low modulus layer; wherein the containment chamber (135) comprises enclosing structures including a plurality of side walls (135A 135C) and a top wall (135B) at least partially enclosing said electronic devices or device components (110A, 110B); and wherein said substrate (100) has a Young's modulus greater than a Young's modulus of said ultra low modulus layer and said containment fluid (140) or said low modulus solid, wherein the containment chamber walls form a void space (130) at least partially filled with the containment fluid (140) or low modulus solid (140) such that the electronic devices or device components (110A, 110B) are at least partially immersed in the containment fluid (140) or low modulus solid; and adjacent electronic devices or device components (110A, 110B) of said electronic devices or device components are connected to one another by one or more electrical interconnects (120), and wherein said top wall (135B) has a Young's modulus greater than a Young's modulus of said containment fluid (140) or said low modulus solid such that a Young's modulus profile of the system (102) spatially varies along an axis substantially perpendicular to the ultra low modulus layer.
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 - 25
 - 30
 - 2. The system (102) of claim 1, wherein said ultra low modulus layer has a Young's modulus less than or equal to 150 KPa, or wherein said ultra low modulus layer has a Young's modulus selected from the range of 50 KPa to 150 Pa.
 - 3. The system (102) of claim 1, wherein said free standing or tethered configuration of said electronic devices or device components (110A, 110B) at least partially decouple motion or deformation of said substrate (100) from said electronic devices or device components (110A, 110B) or at least partially decouple forces generated by elongation, compression or deformation of said substrate (100) from said electronic devices or device components (110A, 110B).
 - 35
 - 4. The system (102) of claim 1, wherein said electronic devices or device components (110A, 110B) are provided on a receiving surface (105) of said substrate (100) or on an intermediate structure provided between said substrate (100) and said electronic devices or device components (110A, 110B).
 - 40
 - 5. The system (102) of claim 4, wherein said enclosing structures of said containment chamber (135) are operationally coupled to said receiving surface or an intermediate structure is provided between said receiving surface and said one or more enclosing structures, or wherein said enclosing structures comprise barrier structures each positioned at least 10 microns from a side of the electronic devices or device components (110A, 110B).
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 - 6. The system (102) of claim 4, wherein said containment chamber (135) further comprises one or more recessed features provided in said substrate (100) partially surrounding said electronic devices or device components (110A, 110B), wherein said enclosing structures are provided to enclose said recessed features, wherein said enclosing structures of said containment chamber (135) are positioned at least 10 microns from a side of said electronic devices or device components (110A, 110B).
 - 50
 - 7. The system (102) of claim 4, further comprising one or more stretchable electrical interconnects in electrical contact with said electronic devices or device components (110A, 110B).
 - 55
 - 8. The system (102) of claim 1, wherein at least 50% of the volume of said containment chamber (135) is occupied by said containment fluid (140), or wherein at least 0.1% of the volume of said containment chamber (135) is occupied

by said electronic devices or device components (110A, 110B), or wherein said containment chamber (135) is structurally self-supporting.

- 5 9. The system (102) of claim 1, wherein the containment chamber (135) is filled with the containment fluid (140), wherein said containment fluid (140) is in physical contact with said electronic devices or device components (110A, 110B), or wherein said electronic devices or device components (110A, 110B) are entirely immersed in said containment fluid (140), or wherein said containment fluid (140) is a material selected from the group consisting of a prepolymer, a solvent, a nonaqueous electrolyte, a silicone, a natural oil, a synthetic oil, a polyolefin and a fluorocarbon.
- 10 10. The system (102) of claim 1, wherein the containment chamber (135) is filled with the low modulus solid, wherein said low modulus solid is a gel, a prepolymer, a silicone, a silicone rubber, a natural oil, a synthetic oil, a polyolefin or a fluorocarbon, or
wherein said low modulus solid has a Young's modulus less than or equal to 200 KPa.
- 15 11. The system (102) of claim 1, wherein said electronic devices or device components (110A, 110B) are free standing structures supported by or in physical contact with said substrate (100) or said low modulus solid, wherein said free standing structure undergoes an associative interaction with said substrate (100) or an intermediate structure provided between said substrate (100) and said free standing structure; wherein said associative interaction is a dipole - dipole interaction or a Van der Waals interaction.
- 20 12. The system (102) of claim 1, wherein said electronic devices or device components (110A, 110B) are tethered structures supported by one or more relief features (170) of said substrate (100) or one or more relief features (170) supported by said substrate (100), wherein each of said one or more relief structures independently extend a length selected over the range of 100 nm to 1 mm and independently have one or more cross sectional physical dimensions selected over the range of 100 nm to 1 mm.
- 25 13. The system (102) of claim 1, wherein said electronic devices or device components (110A, 110B) comprise a single crystalline inorganic semiconductor structure or wherein said electronic devices or device components (110A, 110B) comprise a single crystalline inorganic semiconductor structure operationally connected to at least one additional device component or structure selected from the group consisting of a conducting structure, a dielectric structure, an electrode, a cathode, an anode, and an additional semiconductor structure, or wherein said electronic devices or device components (110A, 110B) have a thickness selected from the range of 10 nanometers to about 100 microns, a width selected from the range of 100 nanometers to about 1 millimeter and a length selected from the range of 1 micron to about 1 millimeter.
- 30 14. The system (102) of claim 1, wherein said electronic devices or device components (110A, 110B) comprise single crystalline semiconductor electronic devices, and wherein said single crystalline semiconductor electronic devices or device components (110A, 110B) comprise one or more electronic devices selected from the group consisting of a transistor, an electrochemical cell, a fuel cell, an integrated circuit, a solar cell, a laser, a light emitting diode, a nanoelectromechanical device, a microelectromechanical device, a photodiode, a P-N junction, a sensor, a memory device and a complementary logic circuit.
- 35 15. The system (102) of claim 1, wherein the containment chamber further contains an interior wall (135E) that separates said void space into two separate void spaces (150, 160), wherein said electronic devices or device components (110A, 110B) consist in two electronic devices or two device components and wherein one of said two electronic devices or device components is located in one of the two separate void spaces and the other of said two electronic devices or device components is located in the other of the two separate void spaces.
- 40 16. The system (102) of claim 1, wherein said substrate (100) is a flexible substrate or a stretchable substrate, or wherein said substrate (100) has a Young's modulus selected from the range of 20 KPa to 1 MPa.
- 45 17. The system (102) of claim 1, wherein said electrical interconnects (120) are individually connected to said substrate (100) at at least one point.
- 50 18. The system (102) of claim 1, wherein said one or more electrical interconnects (120) are stretchable electrical interconnects (120), wherein said one or more stretchable electrical interconnects (120) are configured to provide elasticity, bendability, or both of said electronic system,

or wherein at least a portion of said one or more stretchable electrical interconnects (120) has a bent, buckled, folded, curved or serpentine geometry.

5 **19.** The system (102) of claim 18. wherein at least a portion of said one or more stretchable electrical interconnects (120) has a geometry that is in plane, out of plane, or both in plane and out of plane, relative to a plane defined by a supporting surface of said substrate (100).

10 **20.** The system (102) of claim 19, wherein said supporting surface is curved or said supporting surface is substantially flat, or wherein at least a portion of said one or more electrical interconnects (120) has an in plane serpentine geometry.

15 **21.** The system (102) of claim 17, wherein at least one of said electrical interconnects (120) electrically connects said device components (110A, 110B) comprising a first rigid device island with a second device component (1000) comprising a second rigid device island.

20 **22.** The system (102) of claim 21, further comprising an array of said device components (110A, 110B) comprising rigid device islands, wherein said one or more electrical interconnects (120) electrically connect adjacent rigid device islands, wherein each of said rigid device islands corresponds to a device component (110A 110B).

25 **23.** The system (102) of claim 1, wherein said electronic devices or device components (110A, 110B) are free standing or tethered fully formed integrated circuits.

30 **24.** The system (102) of claim 1 comprising a transistor, an electrochemical cell, a fuel cell, an integrated circuit, a solar cell, a laser, a light emitting diode, a nanoelectromechanical device, a microelectromechanical device, a photodiode, a P-N junction, a sensor, a memory device, a complementary logic circuit or an array of any of these.

35 **25.** An array of electronically interconnected systems of claim 1.

40 **26.** A method of making an electronic system comprising:

30 providing an ultra-low modulus layer providing a substrate (100), wherein said substrate (100) is supported by said ultra-low modulus layer;

35 providing electronic devices or device components (110A, 110B) that are free standing or tethered to said substrate (100) in a containment chamber (135) on said substrate (100) such that said containment chamber (135) at least partially encloses said electronic devices or device components (110A, 110B); wherein said containment chamber (135) is an elastomer;

40 at least partially filling said containment chamber (135) with a containment fluid (140) or low modulus solid; and wherein the containment chamber (135) comprises enclosing structures including a plurality of side walls (135A, 135C) and a top wall (135B) at least partially enclosing said electronic devices or device components (110A, 110B);

45 and wherein said substrate (100) has a Young's modulus greater than a Young's modulus of said ultra low modulus layer and said top wall (135B) has a Young's modulus greater than a Young's modulus of said containment fluid (140) or said low modulus solid;

50 wherein the containment chamber (135) walls form a void space (130) at least partially filled with the containment fluid (140) or low modulus solid (140) such that the electronic device or device component (110A 110B) is at least partially immersed in the containment fluid (140) or low modulus solid; and

55 connecting adjacent electronic devices or device components (110A, 110B) of said electronic devices or device components to one another by an electrical interconnect (**120**), and wherein said top wall (135B) has a Young's modulus greater than a Young's modulus of said containment fluid (140) or said low modulus solid such that a Young's modulus profile of the system (102) spatially varies along an axis substantially perpendicular to the ultra low modulus layer.

Patentansprüche

55 **1.** Elektronisches System (102) umfassend:

i. ein Substrat (100);

ii. elektronische Vorrichtungen oder Vorrichtungskomponenten (110A, 110B), welche durch das Substrat (100)

getragen sind; wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) freistehend oder an das Substrat (100) angebunden sind;

iii. einen Sicherheitsbehälter (135), welcher zumindest teilweise die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) einschließt; wobei der Sicherheitsbehälter (135) ein Elastomer ist, welches zumindest teilweise mit einem Sicherheitsfluid (140) oder einem Feststoff mit niedrigem Modul gefüllt ist; und eine Schicht mit ultraniedrigem Modul; wobei das Substrat (100) von der Schicht mit ultraniedrigem Modul getragen ist; wobei der Sicherheitsbehälter (135) einschließende Strukturen umfasst mit einer Mehrzahl von Seitenwänden (135A, 135C) und eine obere Wand (135B), die zumindest teilweise die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) einschließen; und wobei das Substrat (100) einen Elastizitätsmodul aufweist, der größer ist als ein Elastizitätsmodul der Schicht mit ultraniedrigem Modul und dem Sicherheitsfluid (140) oder des Feststoffs mit niedrigem Modul, wobei die Wände des Sicherheitsbehälters einen Hohlraum (130) bilden, der zumindest teilweise mit dem Sicherheitsfluid (140) oder dem Feststoff mit niedrigem Modul (140) gefüllt ist, so dass die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) zumindest teilweise in das Sicherheitsfluid (140) oder den Feststoff mit niedrigem Modul eingetaucht sind, und benachbarte elektronische Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) durch eine oder mehrere elektrische Verbindungen (120) miteinander verbunden sind, und wobei die obere Wand (135B) einen Elastizitätsmodul aufweist, der größer ist als ein Elastizitätsmodul des Sicherheitsfluid (140) oder des Festkörpers mit niedrigem Modul, so dass ein Elastizitätsmodulprofil des Systems (102) räumlich entlang einer Achse variiert, die im Wesentlichen senkrecht zu der Schicht mit ultraniedrigem Modul verläuft.

2. System (102) nach Anspruch 1, wobei die Schicht mit ultraniedrigem Modul einen Elastizitätsmodul von weniger als oder gleich 150 KPa aufweist, oder wobei die Schicht mit ultraniedrigem Modul einen Elastizitätsmodul aufweist, der aus dem Bereich von 50 KPa bis 150 Pa.

3. System (102) nach Anspruch 1, wobei die freistehende oder angebundene elektronische Konfiguration der elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) zumindest teilweise die Bewegung oder Verformung des Substrats (100) von den elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) entkoppeln oder zumindest teilweise die durch Dehnung, Kompression oder Verformung des Substrats (100) erzeugten Kräfte von den elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) entkoppeln.

4. System (102) nach Anspruch 1, wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) auf einer Aufnahmefläche (105) des Substrats (100) oder auf einer Zwischenstruktur zwischen dem Substrat (100) und den elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) vorgesehen sind.

5. System (102) nach Anspruch 4, wobei umschließende Strukturen des Sicherheitsbehälters (135) mit der Aufnahmefläche wirkverbunden sind oder

eine Zwischenstruktur, die zwischen der Aufnahmefläche und der einen oder den mehreren umschließenden Strukturen vorgesehen ist,

oder wobei die einschließenden Strukturen Barrierstrukturen umfassen, die jeweils mindestens 10 Mikrometer von einer Seite der elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) entfernt angeordnet sind.

6. System (102) nach Anspruch 4, wobei der Sicherheitsbehälter (135) weiter ein oder mehrere vertiefte Merkmale umfasst, die in dem Substrat (100) vorgesehen sind und die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) teilweise umgeben, wobei die umschließenden Strukturen vorgesehen sind, um die vertieften Merkmale zu umschließen, wobei die umschließenden Strukturen des Sicherheitsbehälters (135) mindestens 10 Mikrometer von einer Seite der elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) entfernt angeordnet sind.

7. System (102) nach Anspruch 5, weiter umfassend eine oder mehrere dehbare elektrische Zwischenverbindungen, die in elektrischem Kontakt mit den elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) stehen.

8. System (102) nach Anspruch 1, wobei mindestens 50 % des Volumens des Sicherheitsbehälters (135) von dem Sicherheitsfluid (140) eingenommen wird, oder wobei mindestens 0,1 % des Volumens des Sicherheitsbehälters (135) von den elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) eingenommen wird, oder wobei der Sicherheitsbehälter (135) strukturell selbsttragend ist.

9. System (102) nach Anspruch 1, wobei der Sicherheitsbehälter (135) mit dem Sicherheitsfluid (140) gefüllt ist, wobei das Sicherheitsfluid (140) in physischem Kontakt mit den elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) steht, oder wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) vollständig in das Sicherheitsfluid (140) eingetaucht sind, oder
- 5 wobei das Sicherheitsfluid (140) ein Material ist, das aus der Gruppe ausgewählt ist, die aus einem Präpolymer, einem Lösungsmittel, einem nichtwässrigen Elektrolyten, einem Silikon, einem natürlichen Öl, einem synthetischen Öl, einem Polyolefin und einem Fluorkohlenstoff besteht.
- 10 10. System (102) nach Anspruch 1, wobei der Sicherheitsbehälter (135) mit dem Feststoff mit niedrigem Modul gefüllt ist, wobei der Feststoff mit niedrigem Modul ein Gel, ein Präpolymer, ein Silikon, ein Silikonkautschuk, ein natürliches Öl, ein synthetisches Öl, ein Polyolefin oder ein Fluorkohlenstoff ist, oder
- 15 wobei der Feststoff mit niedrigem Modul einen Elastizitätsmodul von höchstens 200 KPa aufweist.
- 15 11. System (102) nach Anspruch 1, wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) freistehende Strukturen sind, die von dem Substrat (100) oder dem Festkörper mit niedrigem Modul getragen werden oder mit diesem in physischem Kontakt steht, wobei die freistehende Struktur eine assoziative Wechselwirkung mit dem Substrat (100) oder einer Zwischenstruktur eingeht, die zwischen dem Substrat (100) und der freistehenden Struktur vorgesehen ist; wobei die assoziative Wechselwirkung eine Dipol-Dipol-Wechselwirkung oder eine Van-der-Waals-Wechselwirkung ist.
- 20 12. System (102) nach Anspruch 1, wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) angebundene Strukturen sind, die von einem oder mehreren Reliefmerkmalen (170) des Substrats (100) oder einem oder mehreren Reliefmerkmalen (170) getragen werden, die von dem Substrat (100) getragen werden, wobei jede der einen oder mehreren Reliefstrukturen sich unabhängig voneinander über eine Länge erstreckt, die im Bereich von 100 nm bis 1 mm ausgewählt ist, und unabhängig voneinander eine oder mehrere physikalische Querschnittsabmessungen aufweisen, die im Bereich von 100 nm bis 1 mm ausgewählt sind.
- 25 13. System (102) nach Anspruch 1, wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) eine einkristalline anorganische Halbleiterstruktur umfassen oder
- 30 wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) eine einkristalline anorganische Halbleiterstruktur umfassen, die mit mindestens einer zusätzlichen Vorrichtungskomponente oder Struktur verbunden sind, die aus der Gruppe ausgewählt ist, die aus einer leitenden Struktur, einer dielektrischen Struktur, einer Elektrode, einer Kathode, einer Anode und einer zusätzlichen Halbleiterstruktur besteht, oder wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) eine Dicke, ausgewählt aus dem Bereich von 10 Nanometern bis etwa 100 Mikrometern, eine Breite, ausgewählt aus dem Bereich von 100 Nanometern bis etwa 1 Millimeter, und eine Länge, ausgewählt aus dem Bereich von 1 Mikrometer bis etwa 1 Millimeter, aufweisen.
- 35 14. System (102) nach Anspruch 1, wobei die elektronischen Vorrichtungen oder die Vorrichtungskomponenten (110A, 110B) elektronische Einkristall-Halbleiter-Vorrichtungen umfassen, und wobei die elektronische Einkristall-Halbleiter-Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) eine oder mehrere elektronische Vorrichtungen umfassen, die aus der Gruppe ausgewählt sind umfassend einen Transistor, eine elektrochemische Zelle, eine Brennstoffzelle, einen integrierten Schaltkreis, eine Solarzelle, einen Laser, eine lichtemittierende Diode, eine naolektromechanische Vorrichtung, eine mikroelektromechanische Vorrichtung, eine Photodiode, einen P-N-Übergang, einen Sensor, eine Speichervorrichtung und eine komplementäre Logikschaltung.
- 40 15. System (102) nach Anspruch 1, wobei der Sicherheitsbehälter (135) weiter eine innere Wand (135E) umfasst, welche den Hohlraum in zwei separate Hohlräume (150, 160) aufteilt, wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) aus zwei elektronischen Vorrichtungen oder zwei Vorrichtungskomponenten bestehen und wobei eine der zwei elektronischen Vorrichtungen oder Vorrichtungskomponenten in einem der zwei separaten Hohlräume und die andere der zwei elektronischen Vorrichtung oder Vorrichtungskomponenten in dem anderen der zwei separaten Hohlräume angeordnet ist.
- 45 16. System (102) nach Anspruch 1, wobei das Substrat (100) ein flexibles Substrat oder ein dehnbares Substrat ist, oder wobei das Substrat (100) einen Elastizitätsmodul aufweist, der aus dem Bereich von 20 KPa bis 1 MPa ausgewählt ist.

17. System (102) nach Anspruch 1, wobei die elektrischen Verbindungen (120) an mindestens einem Punkt einzeln mit dem Substrat (100) verbunden sind.
- 5 18. System (102) nach Anspruch 1, wobei die eine oder die mehreren elektrischen Verbindungen (120) dehbare elektrische Verbindungen (120) sind, wobei die eine oder die mehreren dehbaren elektrischen Verbindungen (120) so konfiguriert sind, dass sie dem elektronischen System Elastizität, Biegbarkeit oder beides verleihen, oder wobei zumindest ein Teil der einen oder mehreren dehbaren elektrischen Verbindungen (120) eine gebogene, geknickte, gefaltete, gekrümmte oder serpentinenförmige Geometrie aufweist.
- 10 19. System (102) nach Anspruch 18, wobei mindestens ein Teil der einen oder mehreren dehbaren elektrischen Verbindungen (120) eine Geometrie aufweist, die in der Ebene, außerhalb der Ebene oder sowohl in der Ebene als auch außerhalb der Ebene relativ zu einer Ebene liegt, die durch eine Stützfläche des Substrats (100) definiert ist.
- 15 20. System (102) nach Anspruch 19, wobei die Stützfläche gekrümmmt oder die Stützfläche im Wesentlichen flach ist, oder wobei mindestens ein Teil der einen oder mehreren elektrischen Verbindungen (120) eine serpentinenförmige Geometrie in der Ebene aufweist.
- 20 21. System (102) nach Anspruch 17, wobei mindestens eine der elektrischen Verbindungen (120) die Vorrichtungskomponenten (110A, 110B), die eine erste starre Vorrichtungsinsel umfassen, elektrisch mit einer zweiten Vorrichtungskomponente (1000) verbindet, die eine zweite starre Vorrichtungsinsel umfasst.
- 25 22. System (102) nach Anspruch 21, weiter umfassend eine Anordnung der Vorrichtungskomponenten (110A, 110B), die starre Vorrichtungsinseln umfassen, wobei die eine oder die mehreren elektrischen Verbindungen (120) benachbarte starre Vorrichtungsinseln elektrisch verbinden, wobei jede der starren Vorrichtungsinseln einer Vorrichtungskomponente (110A 110B) entspricht.
- 30 23. System (102) nach Anspruch 1, wobei die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) freistehende oder angebundene, vollständig ausgebildete integrierte Schaltungen sind.
- 35 24. System (102) nach Anspruch 1, umfassend einen Transistor, eine elektrochemische Zelle, eine Brennstoffzelle, eine integrierte Schaltung, eine Solarzelle, einen Laser, eine Leuchtdiode, eine nanoelektromechanische Vorrichtung, eine mikroelektromechanische Vorrichtung, eine Fotodiode, einen P-N-Übergang, einen Sensor, eine Speichervorrichtung, eine komplementäre Logikschaltung oder eine Anordnung aus diesen.
- 40 25. Eine Anordnung von elektronisch miteinander verbundenen Systemen nach Anspruch 1.
- 45 26. Verfahren zur Herstellung eines elektronischen Systems umfassend:
- Bereitstellen einer Schicht mit ultraniedrigem Modul
Bereitstellen eines Substrats (100), wobei das Substrat (100) von der Schicht mit ultraniedrigem Modul getragen wird;
Bereitstellen elektronischer Vorrichtungen oder Vorrichtungskomponenten (110A, 110B), die freistehend oder mit dem Substrat (100) verbunden sind, in einem Sicherheitsbehälter (135) auf dem Substrat (100), so dass der Sicherheitsbehälter (135) die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) zumindest teilweise umschließt; wobei der Sicherheitsbehälter (135) ein Elastomer ist;
zumindest teilweises Füllen des Sicherheitsbehälters (135) mit einem Sicherheitsfluid (140) oder einem Feststoff mit niedrigem Modul; und
wobei der Sicherheitsbehälter (135) einschließende Strukturen mit einer Vielzahl von Seitenwänden (135A, 135C) und eine obere Wand (135B) umfasst, welche die elektronischen Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) zumindest teilweise einschließen; und wobei das Substrat (100) einen Elastizitätsmodul aufweist, der größer ist als ein Elastizitätsmodul der Schicht mit ultraniedrigem Modul, und wobei die obere Wand (135B) einen Elastizitätsmodul aufweist, der größer ist als ein Elastizitätsmodul des Sicherheitsfluids (140) oder des Feststoffs mit niedrigem Modul;
wobei die Wände des Sicherheitsbehälters (135) einen Hohlraum (130) bilden, der zumindest teilweise mit dem Sicherheitsfluid (140) oder dem Feststoff mit niedrigem Modul (140) gefüllt ist, so dass die elektronische Vorrichtung oder Vorrichtungskomponente (110A 110B) zumindest teilweise in das Sicherheitsfluid (140) oder den Feststoff mit niedrigem Modul eingetaucht ist; und
Verbinden benachbarter elektronischer Vorrichtungen oder Vorrichtungskomponenten (110A, 110B) der elek-

tronische Vorrichtungen oder Vorrichtungskomponenten miteinander durch eine elektrische Verbindung (120), und wobei die obere Wand (135B) einen Elastizitätsmodul aufweist, der größer ist als ein Elastizitätsmodul des Sicherheitsfluids (140) oder des Festkörpers mit niedrigem Modul, so dass ein Elastizitätsmodulprofil des Systems (102) räumlich entlang einer Achse variiert, die im Wesentlichen senkrecht zu der Schicht mit ultraniedrigem Modul ist.

Revendications

10 1. Système électronique (102) comprenant :

- i. un substrat (100) ;
- ii. des dispositifs électroniques ou des composants de dispositif (110A, 110B) portés par ledit substrat (100) ; lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) étant indépendants ou attachés audit substrat (100) ; et
- iii. une chambre de confinement (135) enfermant au moins partiellement lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) ; ladite chambre de confinement (135) étant un élastomère au moins partiellement rempli d'un fluide de confinement (140) ou d'un solide à faible module ; et une couche à très faible module ; le substrat (100) étant porté par ladite couche à très faible module ; la chambre de confinement (135) comprenant des structures d'enveloppe incluant une pluralité de parois latérales (135A, 135C) et une paroi supérieure (135B) enfermant au moins partiellement lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) ; et ledit substrat (100) ayant un module de Young supérieur à un module de Young de ladite couche à très faible module et dudit fluide de confinement (140) ou dudit solide à faible module, les parois de la chambre de confinement formant un espace vide (130) au moins partiellement rempli avec le fluide de confinement (140) ou le solide à faible module (140) de telle sorte que les dispositifs électroniques ou composants de dispositif (110A, 110B) sont au moins partiellement immergés dans le fluide de confinement (140) ou le solide à faible module ; et des dispositifs électroniques ou composants de dispositif adjacents (110A, 110B) parmi lesdits dispositifs électroniques ou composants de dispositif étant connectés les uns aux autres par une ou plusieurs interconnexions électriques (120), et ladite paroi supérieure (135B) ayant un module de Young supérieur à un module de Young dudit fluide de confinement (140) ou dudit solide à faible module de telle sorte qu'un profil de module de Young du système (102) varie spatialement le long d'un axe sensiblement perpendiculaire à la couche à très faible module.

2. Système (102) selon la revendication 1, dans lequel ladite couche à très faible module a un module de Young inférieur ou égal à 150 KPa, ou dans lequel ladite couche à très faible module a un module de Young choisi dans la plage allant de 50 KPa à 150 Pa.

3. Système (102) selon la revendication 1, dans lequel ladite configuration indépendante ou attachée desdits dispositifs électroniques ou composants de dispositif (110A, 110B) découple au moins partiellement un mouvement ou une déformation dudit substrat (100) vis-à-vis desdits dispositifs électroniques ou composants de dispositif (110A, 110B) ou découple au moins partiellement des forces générées par allongement, compression ou déformation dudit substrat (100) vis-à-vis desdits dispositifs électroniques ou composants de dispositif (110A, 110B).

4. Système (102) selon la revendication 1, dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) sont disposés sur une surface de réception (105) dudit substrat (100) ou sur une structure intermédiaire disposée entre ledit substrat (100) et lesdits dispositifs électroniques ou composants de dispositif (110A, 110B).

5. Système (102) selon la revendication 4, dans lequel lesdites structures d'enveloppe de ladite chambre de confinement (135) sont couplées de manière fonctionnelle à ladite surface de réception ou une structure intermédiaire est disposée entre ladite surface de réception et ladite ou lesdites structures d'enveloppe, ou dans lequel lesdites structures d'enveloppe comprennent des structures de barrière positionnées chacune à au moins 10 microns d'un côté des dispositifs électroniques ou composants de dispositif (110A, 110B).

6. Système (102) selon la revendication 4, dans lequel ladite chambre de confinement (135) comprend en outre un ou plusieurs éléments évidés prévus dans ledit substrat (100) entourant partiellement lesdits dispositifs électroniques ou composants de dispositif (110A, 110B), dans lequel lesdites structures d'enveloppe sont prévues pour entourer lesdits éléments évidés, dans lequel lesdites structures d'enveloppe de ladite chambre de confinement (135) sont positionnées à au moins 10 microns d'un côté desdits dispositifs électroniques ou composants de dispositif (110A,

110B).

7. Système (102) selon la revendication 4, comprenant en outre une ou plusieurs interconnexions électriques extensibles en contact électrique avec lesdits dispositifs électroniques ou composants de dispositif (110A, 110B).
- 5 8. Système (102) selon la revendication 1, dans lequel au moins 50 % du volume de ladite chambre de confinement (135) est occupé par ledit fluide de confinement (140), ou dans lequel au moins 0,1 % du volume de ladite chambre de confinement (135) est occupé par lesdits dispositifs électroniques ou composants de dispositif (110A, 110B), ou dans lequel ladite chambre de confinement (135) est structurellement autoportante.
- 10 9. Système (102) selon la revendication 1, dans lequel la chambre de confinement (135) est remplie avec le fluide de confinement (140), dans lequel ledit fluide de confinement (140) est en contact physique avec lesdits dispositifs électroniques ou composants de dispositif (110A, 110B), ou dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) sont entièrement immersés dans ledit fluide de confinement (140), ou dans lequel ledit fluide de confinement (140) est un matériau choisi parmi le groupe consistant en un prépolymère, un solvant, un électrolyte non aqueux, une silicone, une huile naturelle, une huile synthétique, une polyoléfine et un fluorocarbone.
- 15 10. Système (102) selon la revendication 1, dans lequel la chambre de confinement (135) est remplie avec le solide à faible module, dans lequel ledit solide à faible module est un gel, un prépolymère, une silicone, un caoutchouc de silicone, une huile naturelle, une huile synthétique, une polyoléfine ou un fluorocarbone, ou dans lequel ledit solide à faible module a un module de Young inférieur ou égal à 200 KPa.
- 20 11. Système (102) selon la revendication 1, dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) sont des structures indépendantes portées par ou en contact physique avec ledit substrat (100) ou ledit solide à faible module, dans lequel ladite structure indépendante subit une interaction associative avec ledit substrat (100) ou une structure intermédiaire disposée entre ledit substrat (100) et ladite structure indépendante ; et dans lequel ladite interaction associative est une interaction dipôle - dipôle ou une interaction de Van der Waals.
- 25 12. Système (102) selon la revendication 1, dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) sont des structures attachées portées par un ou plusieurs éléments en relief (170) dudit substrat (100) ou un ou plusieurs éléments en relief (170) portés par ledit substrat (100), et dans lequel chacune de ladite ou desdites structures en relief s'étend indépendamment sur une longueur sélectionnée dans la plage allant de 100 nm à 1 mm et a indépendamment une ou plusieurs dimensions physiques en section transversale sélectionnées dans la plage allant de 100 nm à 1 mm.
- 30 13. Système (102) selon la revendication 1, dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) comprennent une structure semi-conductrice inorganique monocristalline, ou dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) comprennent une structure semi-conductrice inorganique monocristalline reliée de manière fonctionnelle à au moins un composant de dispositif supplémentaire ou à au moins une structure sélectionnée parmi le groupe consistant en une structure conductrice, une structure diélectrique, une électrode, une cathode, une anode et une structure semi-conductrice supplémentaire, ou dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) ont une épaisseur choisie dans la plage allant de 10 nanomètres à environ 100 microns, une largeur choisie dans la plage allant de 100 nanomètres à environ 1 millimètre et une longueur choisie dans la plage allant de 1 micron à environ 1 millimètre.
- 35 14. Système (102) selon la revendication 1, dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) comprennent des dispositifs électroniques à semi-conducteur monocristallin, et dans lequel lesdits dispositifs électroniques ou composants de dispositif à semi-conducteur monocristallin (110A, 110B) comprennent un ou plusieurs dispositifs électroniques choisis parmi le groupe consistant en un transistor, une cellule électrochimique, une pile à combustible, un circuit intégré, une cellule solaire, un laser, une diode électroluminescente, un dispositif nanoélectromécanique, un dispositif microélectromécanique, une photodiode, une jonction P-N, un capteur, un dispositif de mémoire et un circuit logique complémentaire.
- 40 15. Système (102) selon la revendication 1, dans lequel la chambre de confinement contient en outre une paroi intérieure (135E) qui sépare ledit espace vide en deux espaces vides distincts (150, 160), dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) consistent en deux dispositifs électroniques ou en deux composants de dispositif, et dans lequel l'un desdits deux dispositifs électroniques ou composants de dispositif est

situé dans l'un des deux espaces vides distincts et l'autre desdits deux dispositifs électroniques ou composants de dispositif est situé dans l'autre des deux espaces vides distincts.

5 **16.** Système (102) selon la revendication 1, dans lequel ledit substrat (100) est un substrat flexible ou un substrat extensible, ou dans lequel ledit substrat (100) a un module de Young choisi dans la plage allant de 20 KPa à 1 MPa.

17. Système (102) selon la revendication 1, dans lequel lesdites interconnexions électriques (120) sont reliées individuellement audit substrat (100) en au moins un point.

10 **18.** Système (102) selon la revendication 1, dans lequel ladite ou lesdites interconnexions électriques (120) sont des interconnexions électriques extensibles (120), dans lequel ladite ou lesdites interconnexions électriques extensibles (120) sont configurées pour fournir une élasticité, un caractère pliable, ou les deux, audit système électronique, ou dans lequel au moins une partie de ladite ou desdites interconnexions électriques extensibles (120) a une géométrie courbée, bouclée, pliée, incurvée ou en serpentin.

15 **19.** Système (102) selon la revendication 18, dans lequel au moins une partie de ladite ou desdites interconnexions électriques extensibles (120) a une géométrie qui est dans le plan, hors du plan, ou à la fois dans le plan et hors du plan, par rapport à un plan défini par une surface de support dudit substrat (100).

20 **20.** Système (102) selon la revendication 19, dans lequel ladite surface de support est incurvée ou ladite surface de support est sensiblement plate, ou dans lequel au moins une partie de ladite ou desdites interconnexions électriques (120) a une géométrie en serpentin dans le plan.

25 **21.** Système (102) selon la revendication 17, dans lequel au moins l'une desdites interconnexions électriques (120) relie électriquement lesdits composants de dispositif (110a, 110B) comprenant un premier îlot de dispositif rigide à un second composant de dispositif (1000) comprenant un second îlot de dispositif rigide.

30 **22.** Système (102) selon la revendication 21, comprenant en outre un réseau desdits composants de dispositif (110a, 110B) comprenant des îlots de dispositif rigides, dans lequel ladite ou lesdites interconnexions électriques (120) relient électriquement des îlots de dispositif rigides adjacents, dans lequel chacun desdits îlots de dispositif rigides correspond à un composant de dispositif (110A, 110B).

35 **23.** Système (102) selon la revendication 1, dans lequel lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) sont des circuits intégrés entièrement formés indépendants ou attachés.

40 **24.** Système (102) selon la revendication 1, comprenant un transistor, une cellule électrochimique, une pile à combustible, un circuit intégré, une cellule solaire, un laser, une diode électroluminescente, un dispositif nanoélectromécanique, un dispositif microélectromécanique, une photodiode, une jonction P-N, un capteur, un dispositif de mémoire, un circuit logique complémentaire ou un réseau de l'un quelconque de ceux-ci.

45 **25.** Réseau de systèmes interconnectés électroniquement selon la revendication 1.

26. Procédé de fabrication d'un système électronique comprenant :

50 fournir une couche à très faible module ;
 fournir un substrat (100), dans lequel ledit substrat (100) est porté par ladite couche à très faible module ;
 fournir des dispositifs électroniques ou des composants de dispositif (110A, 110B) qui sont indépendants ou attachés audit substrat (100) dans une chambre de confinement (135) sur ledit substrat (100) de telle sorte que ladite chambre de confinement (135) enferme au moins partiellement lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) ; dans lequel ladite chambre de confinement (135) est un élastomère ;
 remplir au moins partiellement ladite chambre de confinement (135) avec un fluide de confinement (140) ou un solide à faible module ; et
 dans lequel ladite chambre de confinement (135) comprend des structures d'enveloppe comprenant une pluralité de parois latérales (135A, 135C) et une paroi supérieure (135B) enfermant au moins partiellement lesdits dispositifs électroniques ou composants de dispositif (110A, 110B) ; et dans lequel ledit substrat (100) a un module de Young supérieur à un module de Young de ladite couche à très faible module et ladite paroi supérieure (135B) a un module de Young supérieur à un module de Young dudit fluide de confinement (140) ou dudit solide à faible module ; dans lequel les parois de la chambre de confinement (135) forment un espace vide (130) au

EP 2 954 762 B1

moins partiellement rempli avec le fluide de confinement (140) ou le solide à faible module (140) de telle sorte que le dispositif électronique ou le composant de dispositif (110A, 110B) est au moins partiellement immergé dans le fluide de confinement (140) ou le solide à faible module ; et
5 relier des dispositifs électroniques ou composants de dispositif adjacents (110A, 110B) parmi lesdits dispositifs électroniques ou composants de dispositif les uns aux autres par une interconnexion électrique (120), et dans lequel ladite paroi supérieure (135B) a un module de Young supérieur à un module de Young dudit fluide de confinement (140) ou dudit solide à faible module de telle sorte qu'un profil de module de Young du système (102) varie spatialement le long d'un axe sensiblement perpendiculaire à la couche à très faible module.

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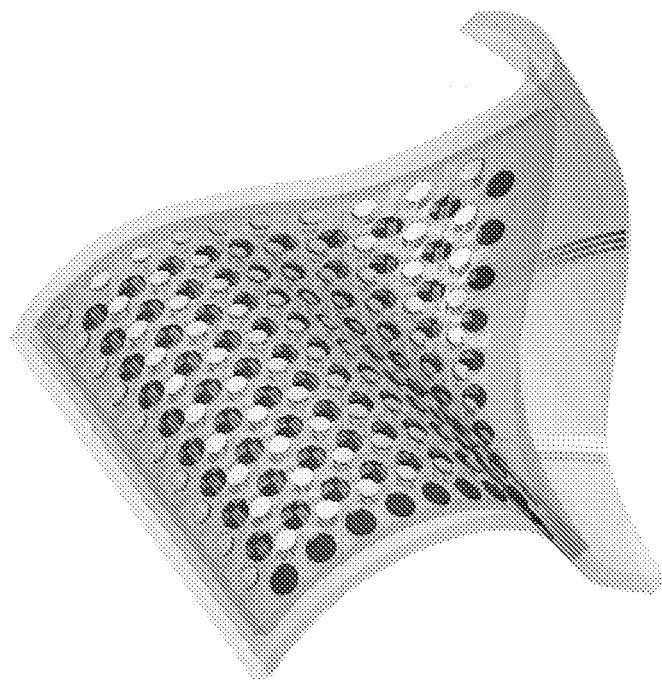


Figure 1A

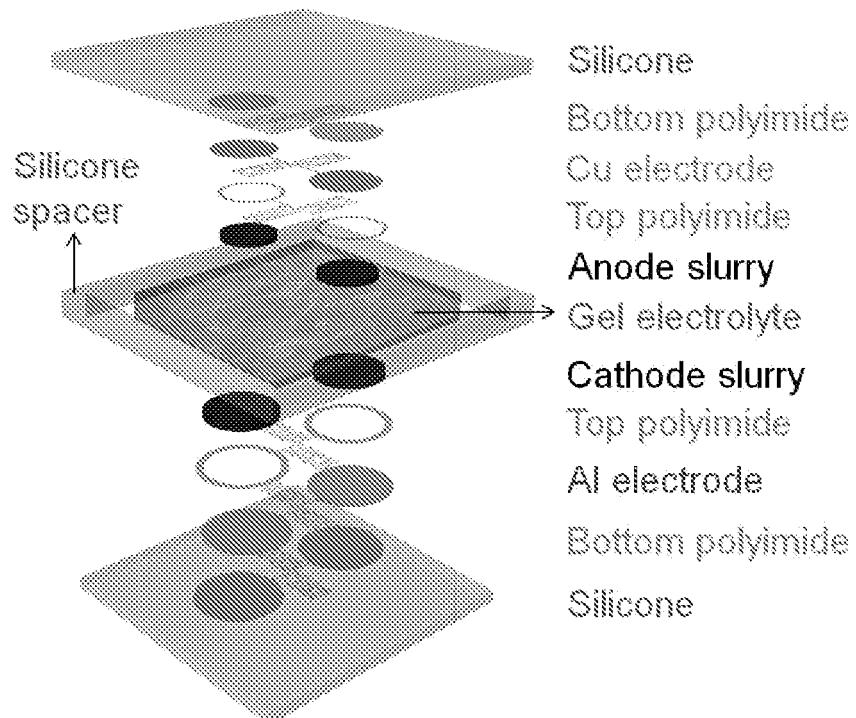


Figure 1B

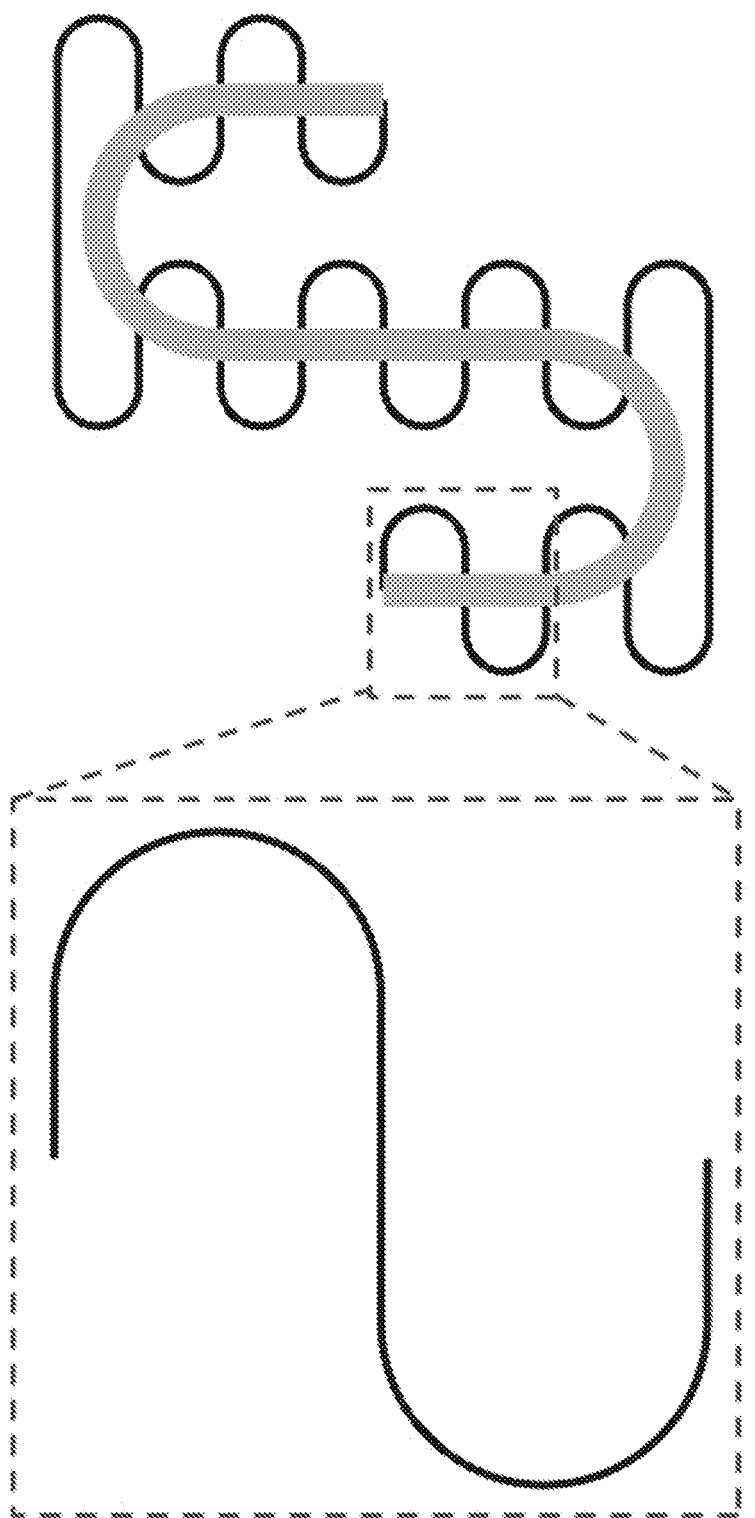


Figure 1C

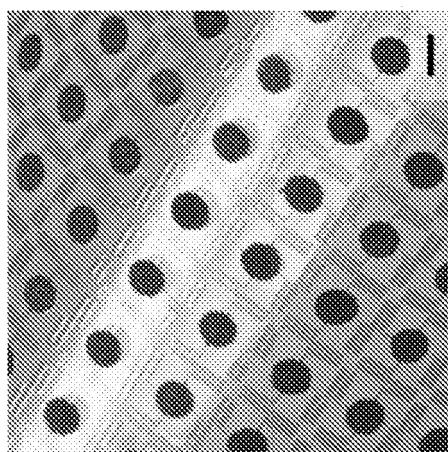
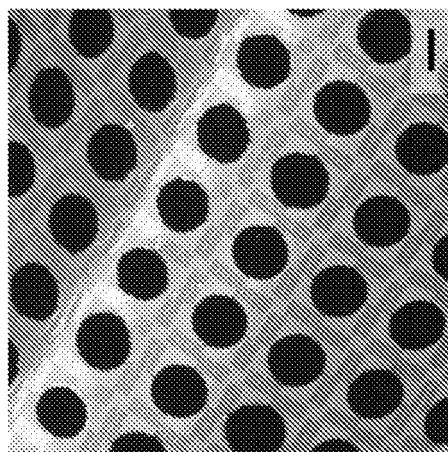


Figure 1D

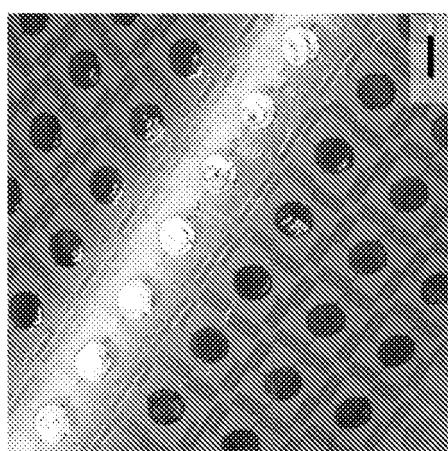
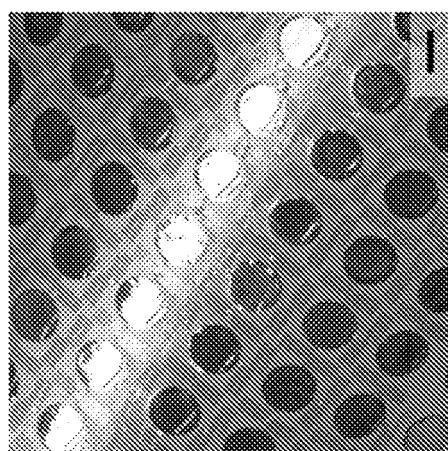
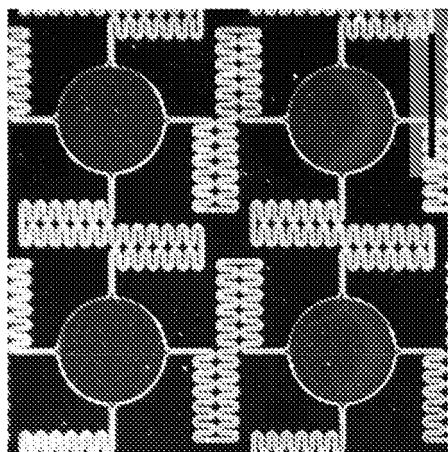
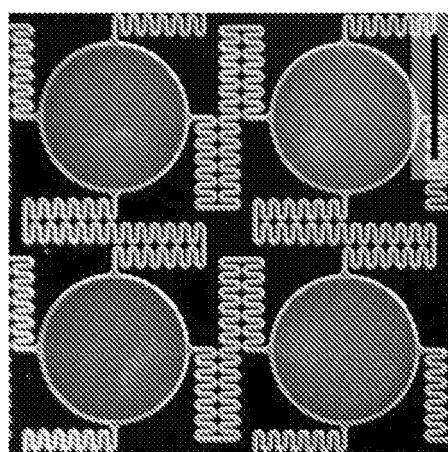


Figure 1E



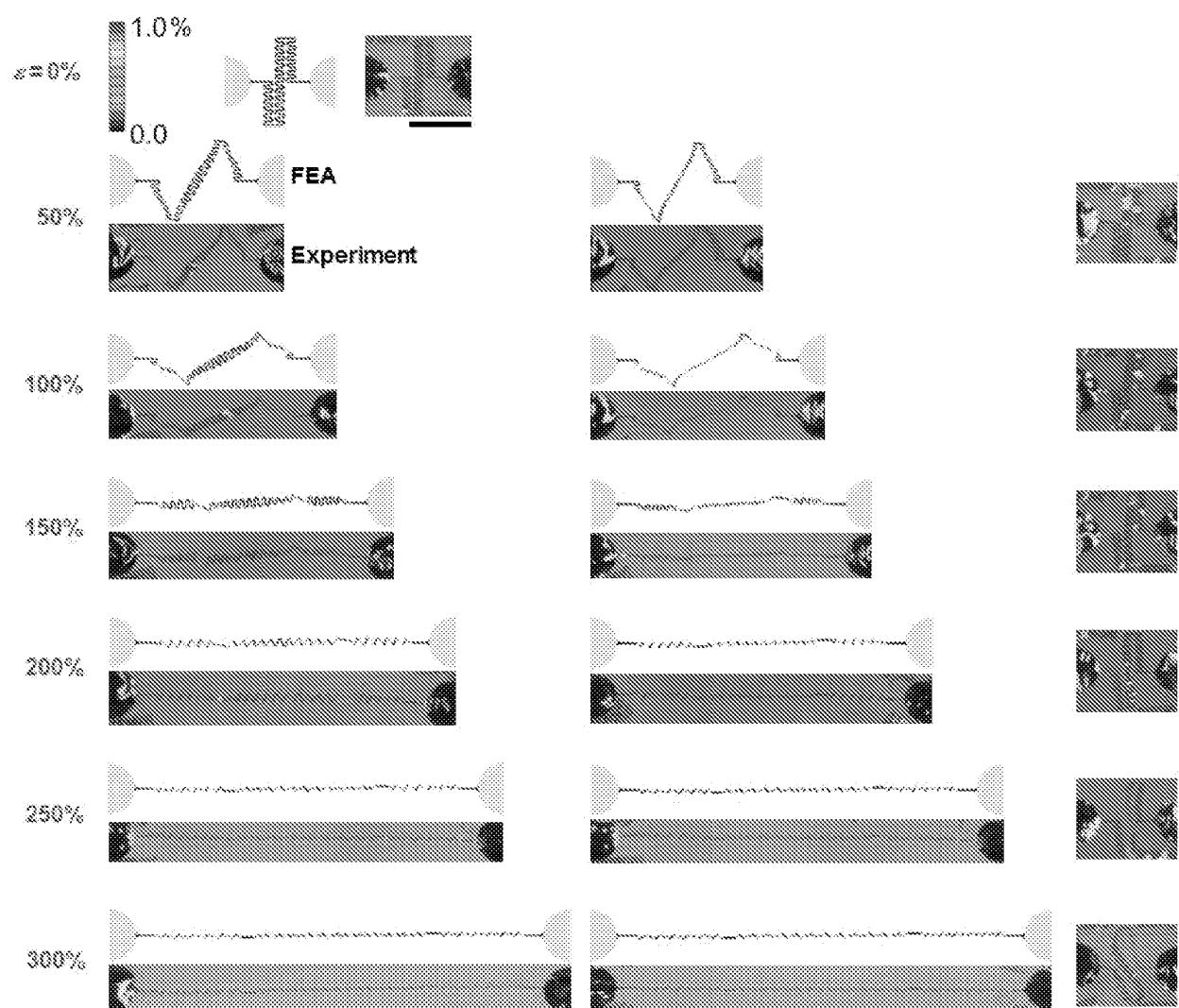
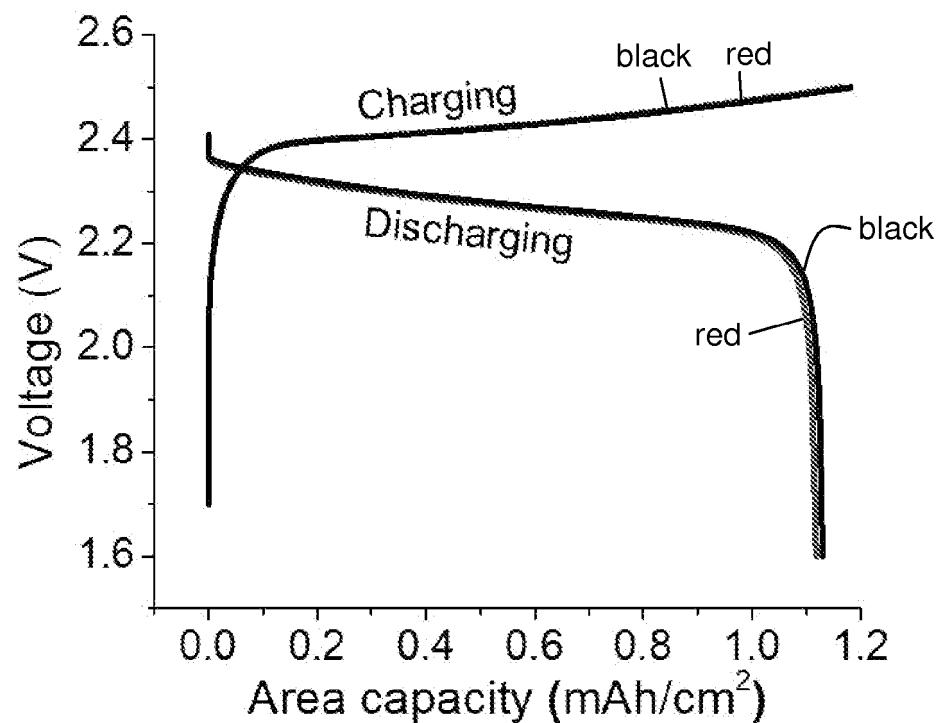
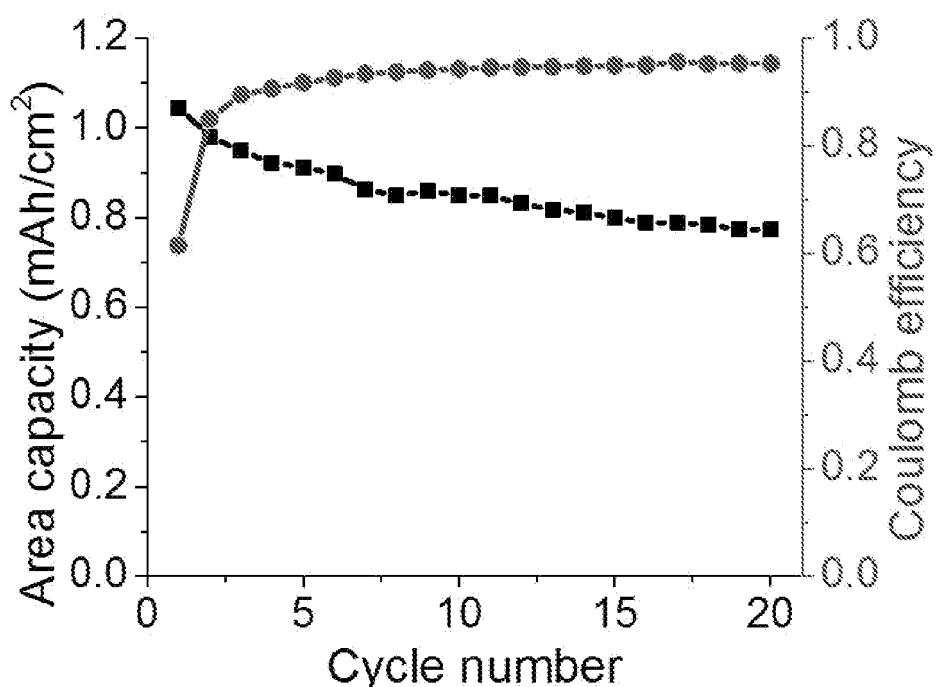


Figure 2

**Figure 3A****Figure 3B**

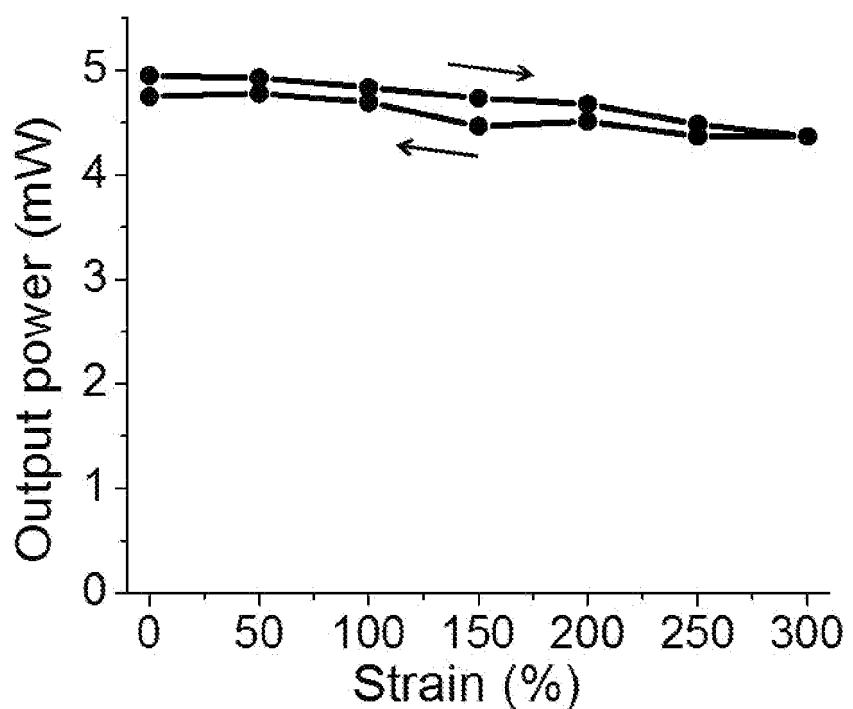


Figure 3C

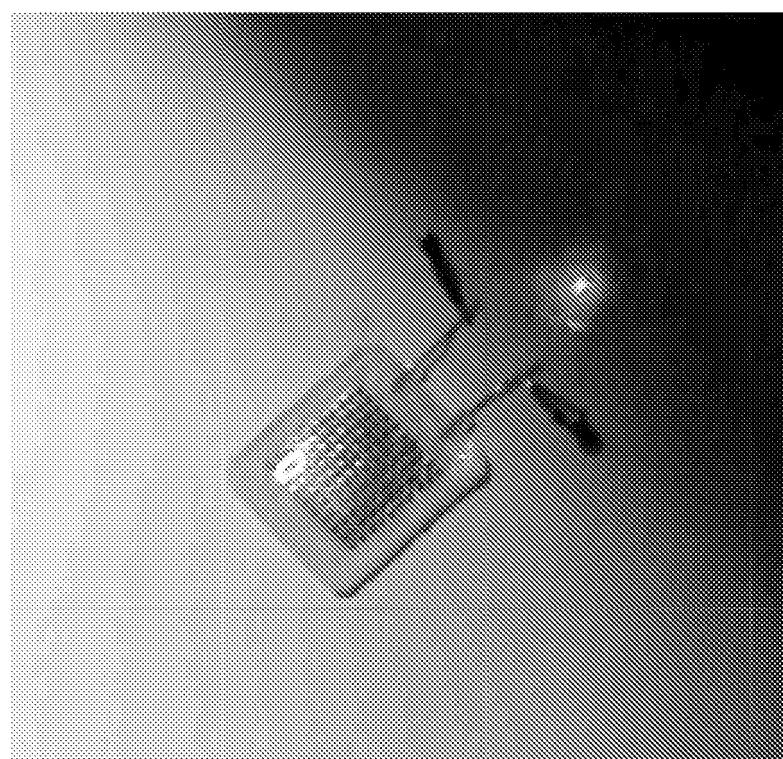


Figure 3D

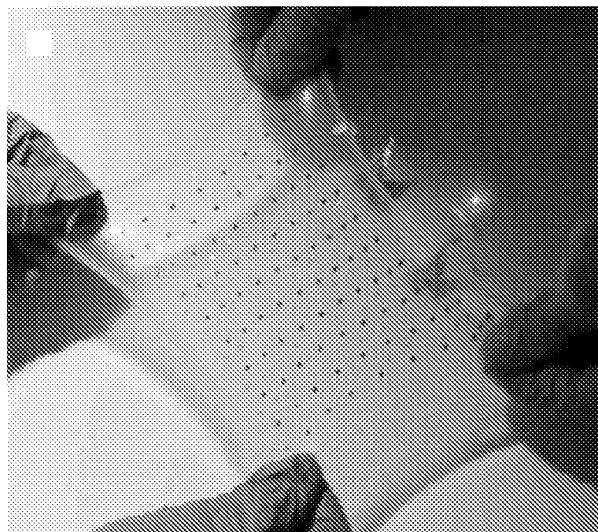


Figure 3E

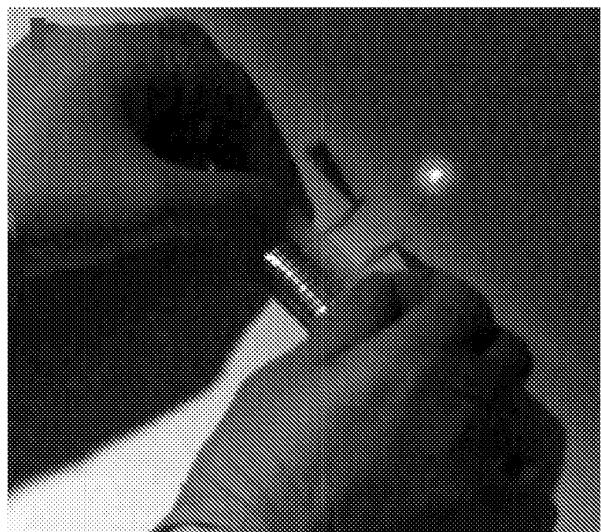


Figure 3F



Figure 3G

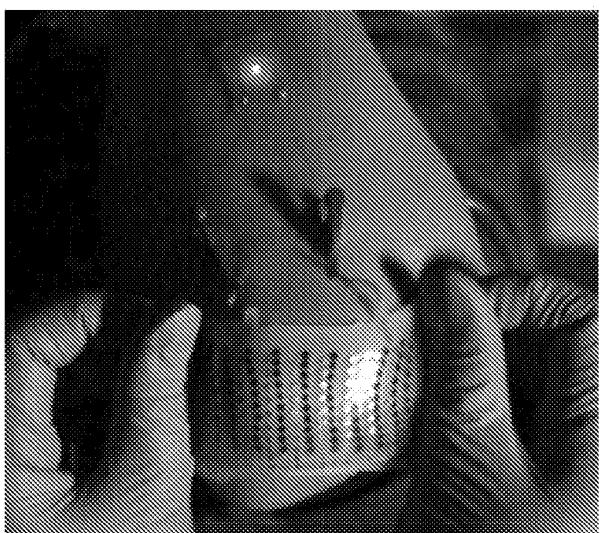


Figure 3H

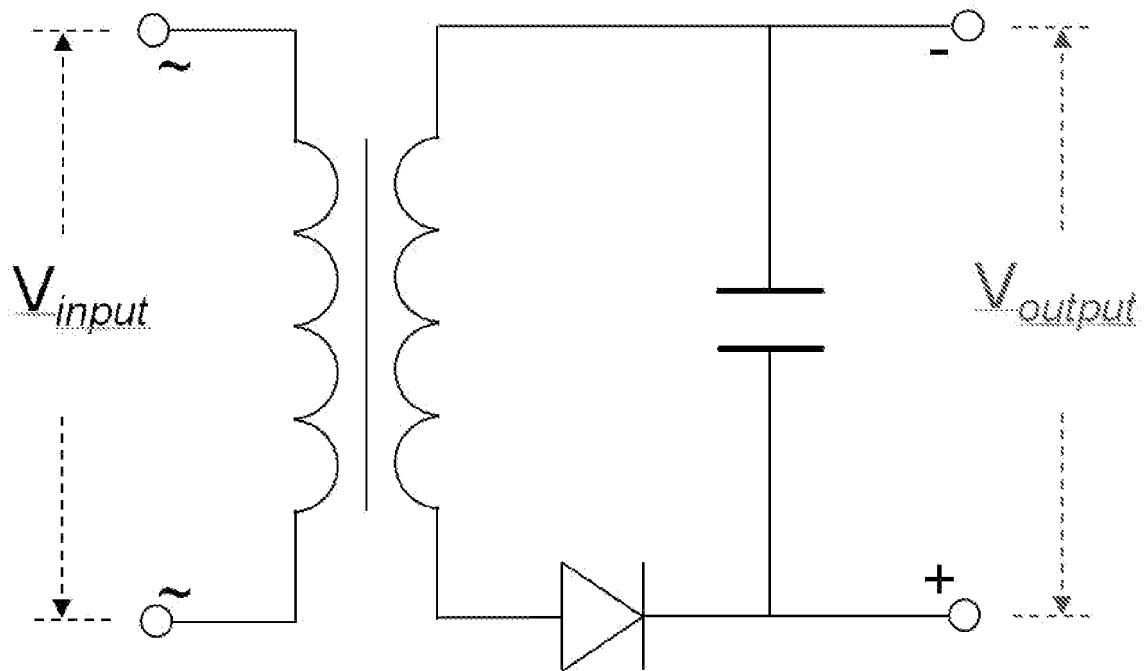


Figure 4A

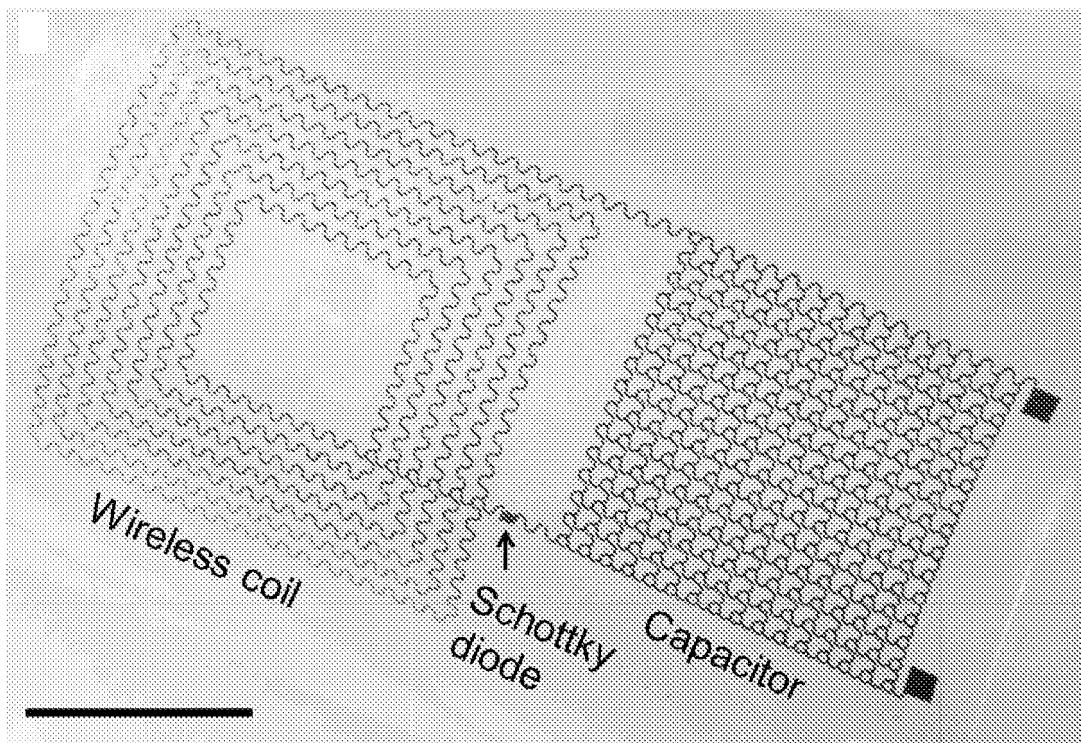


Figure 4B

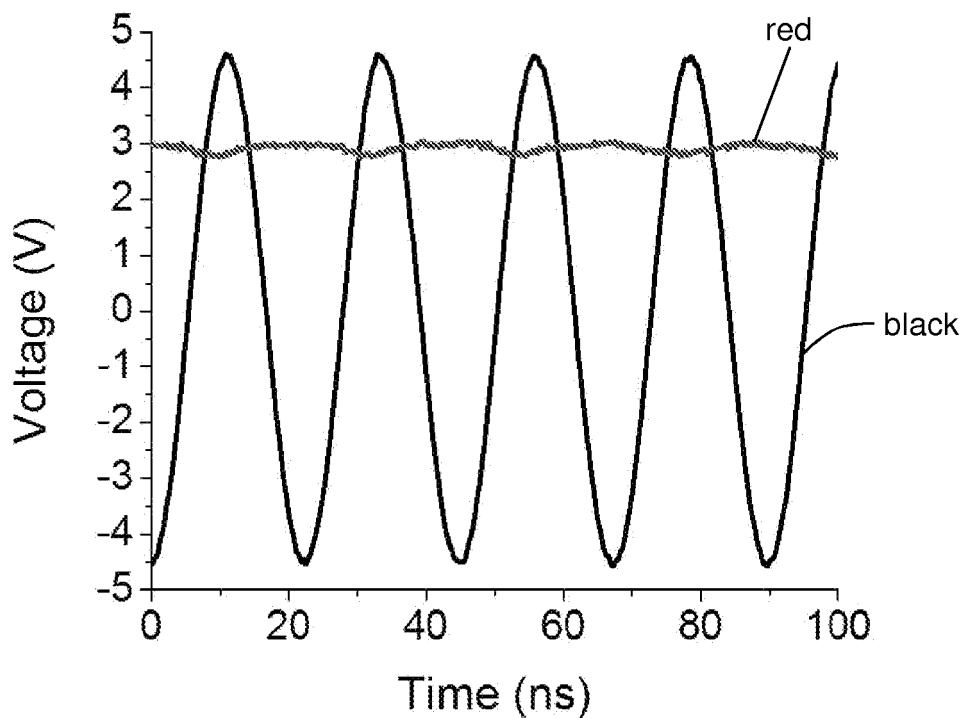


Figure 4C

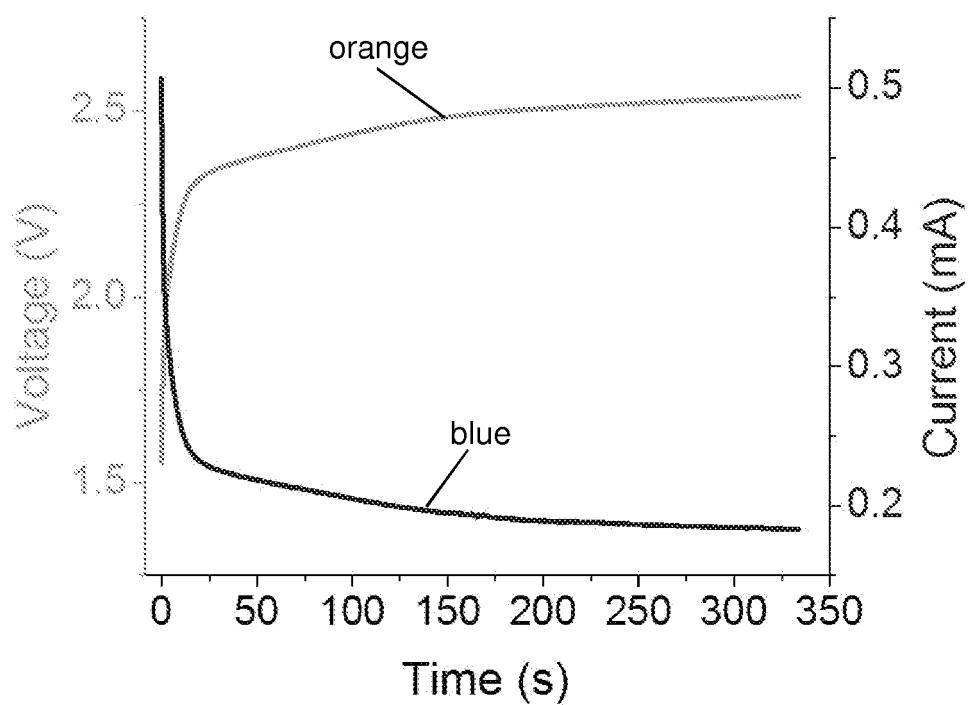


Figure 4D

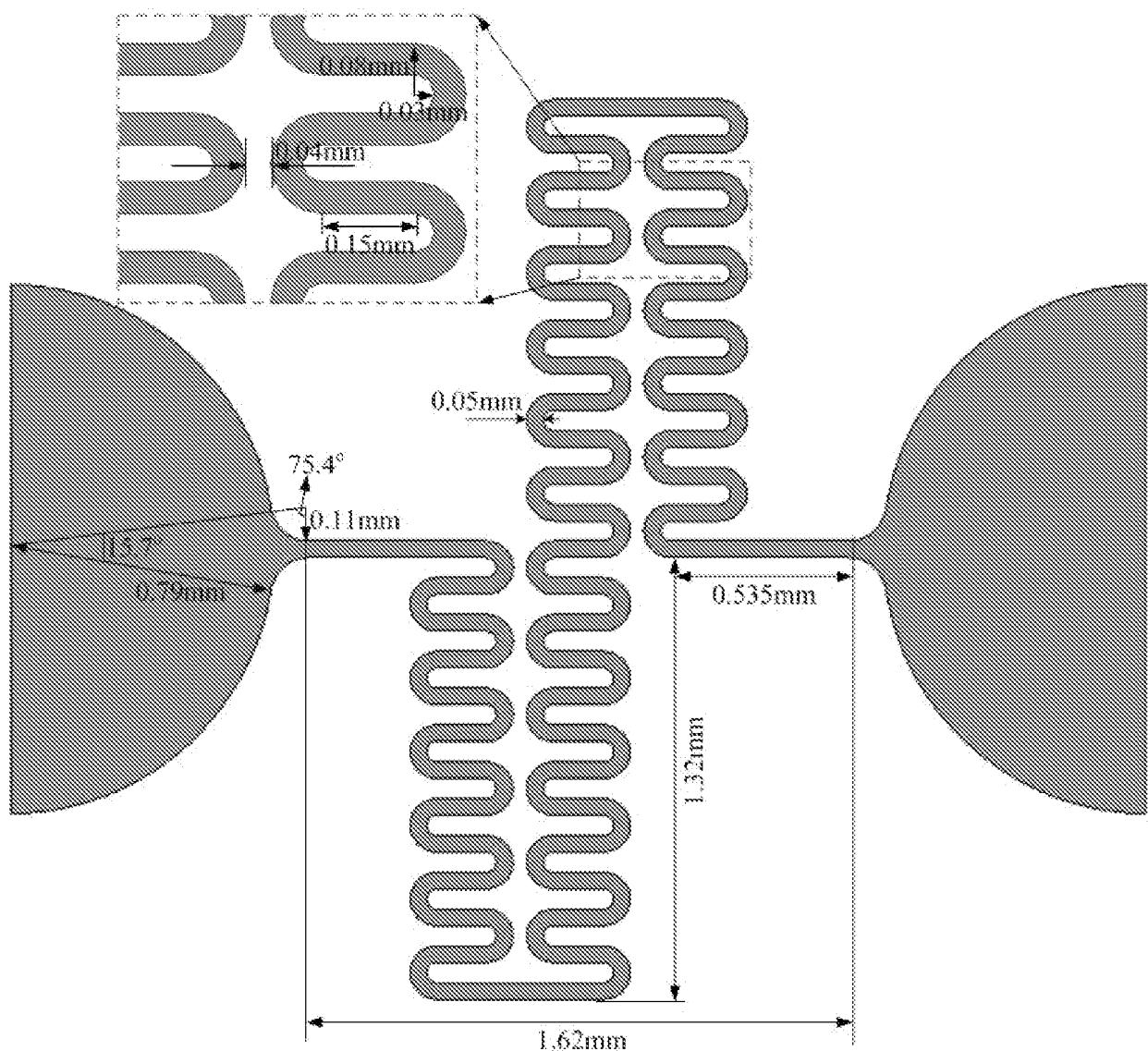


Figure 5

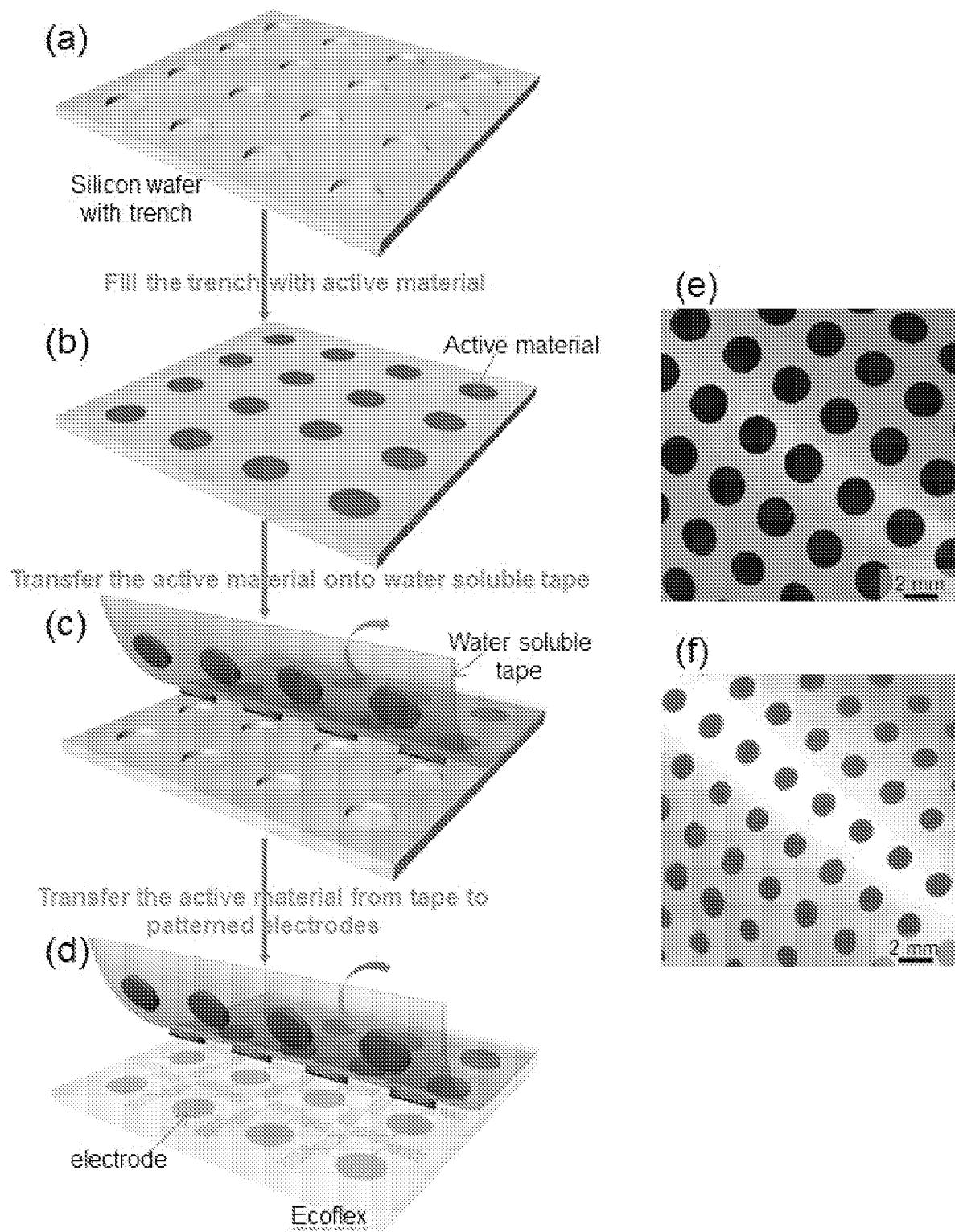


Figure 6

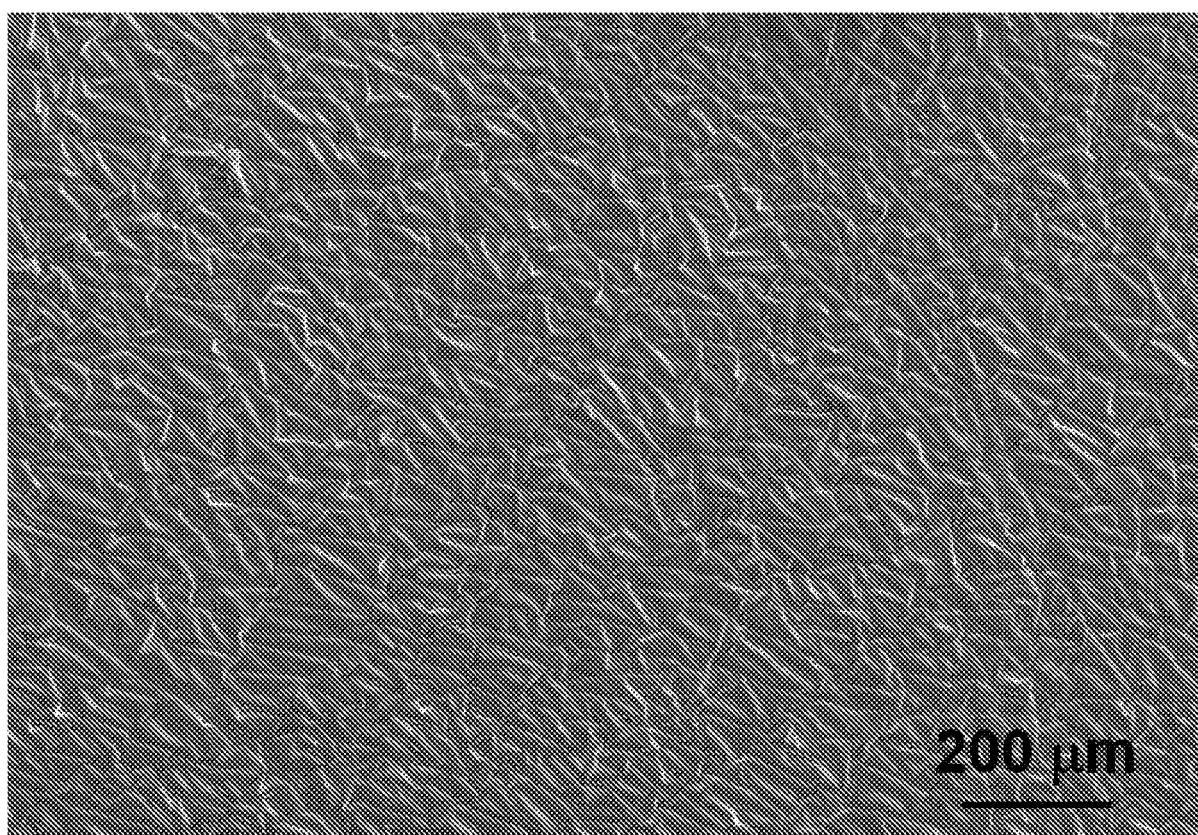
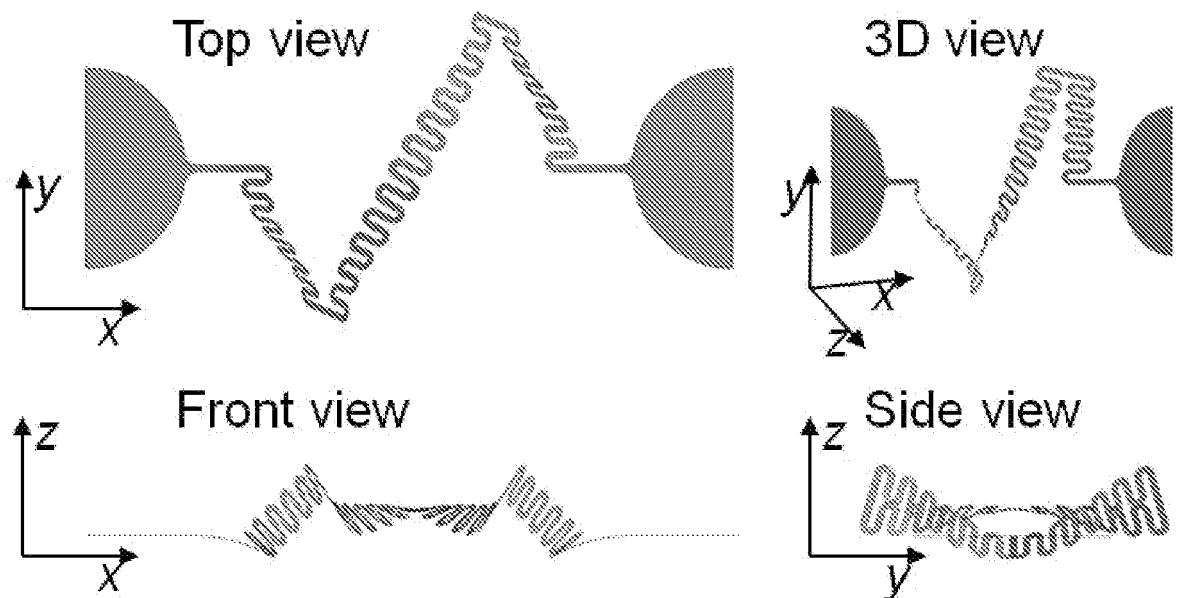


Figure 7

(a) Symmetric buckling mode



(b) Anti-symmetric buckling mode

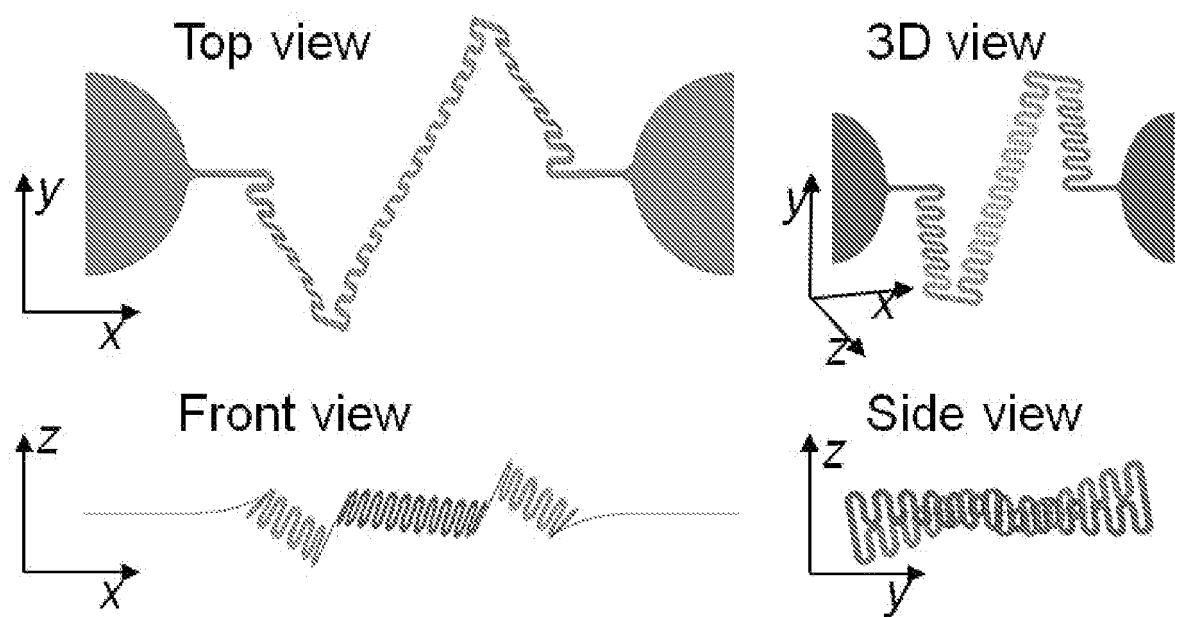
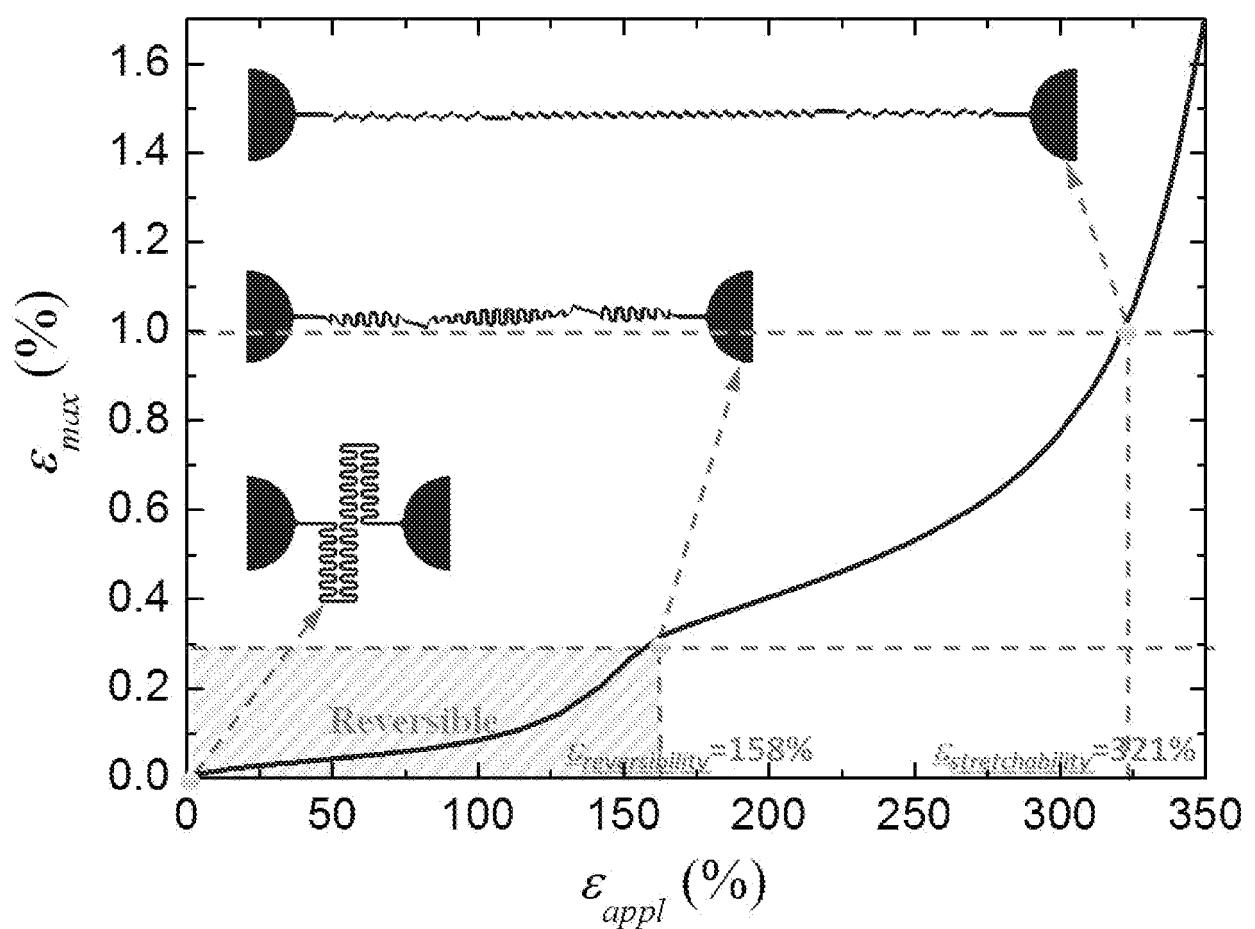


Figure 8

**Figure 9**

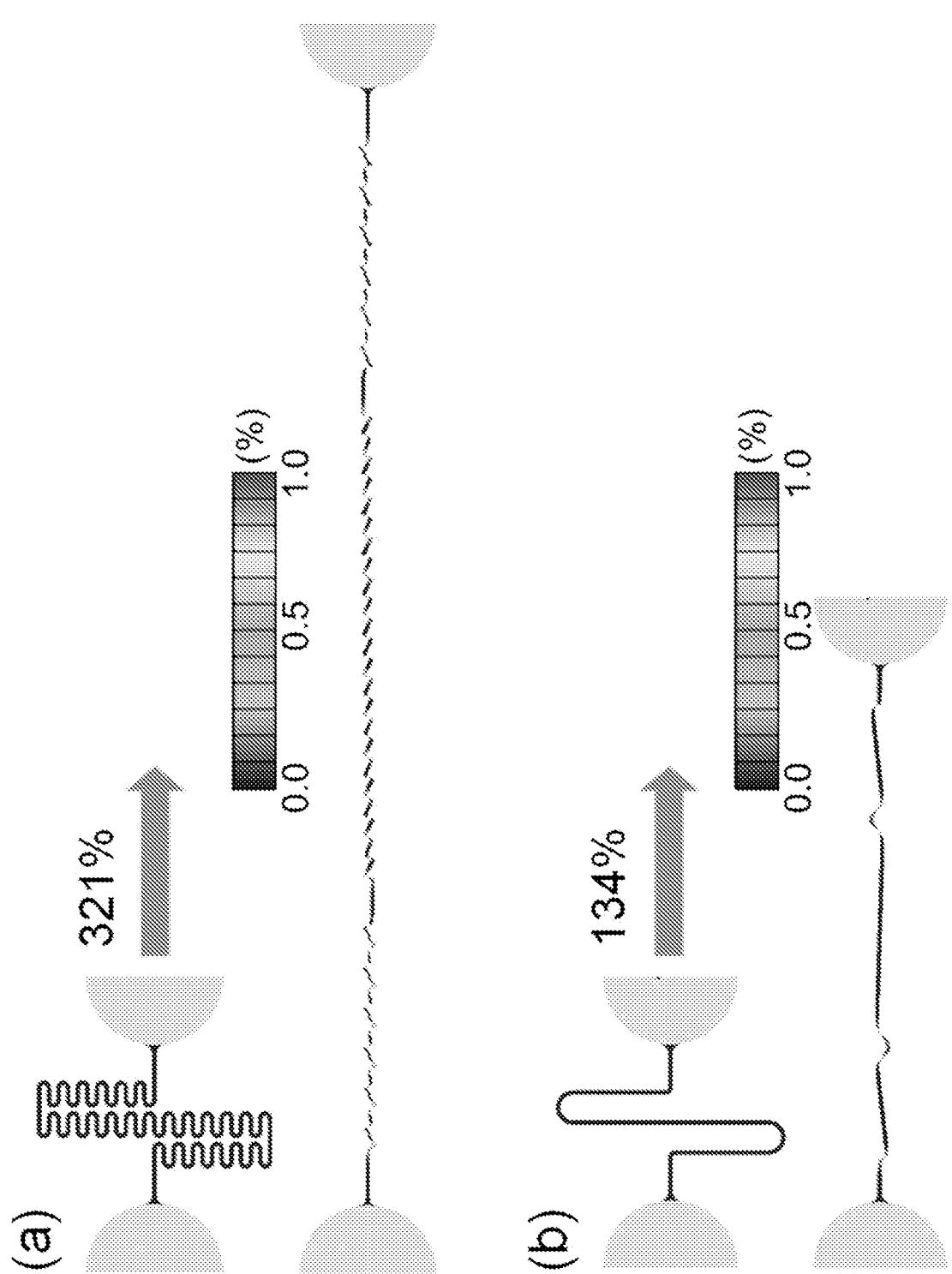
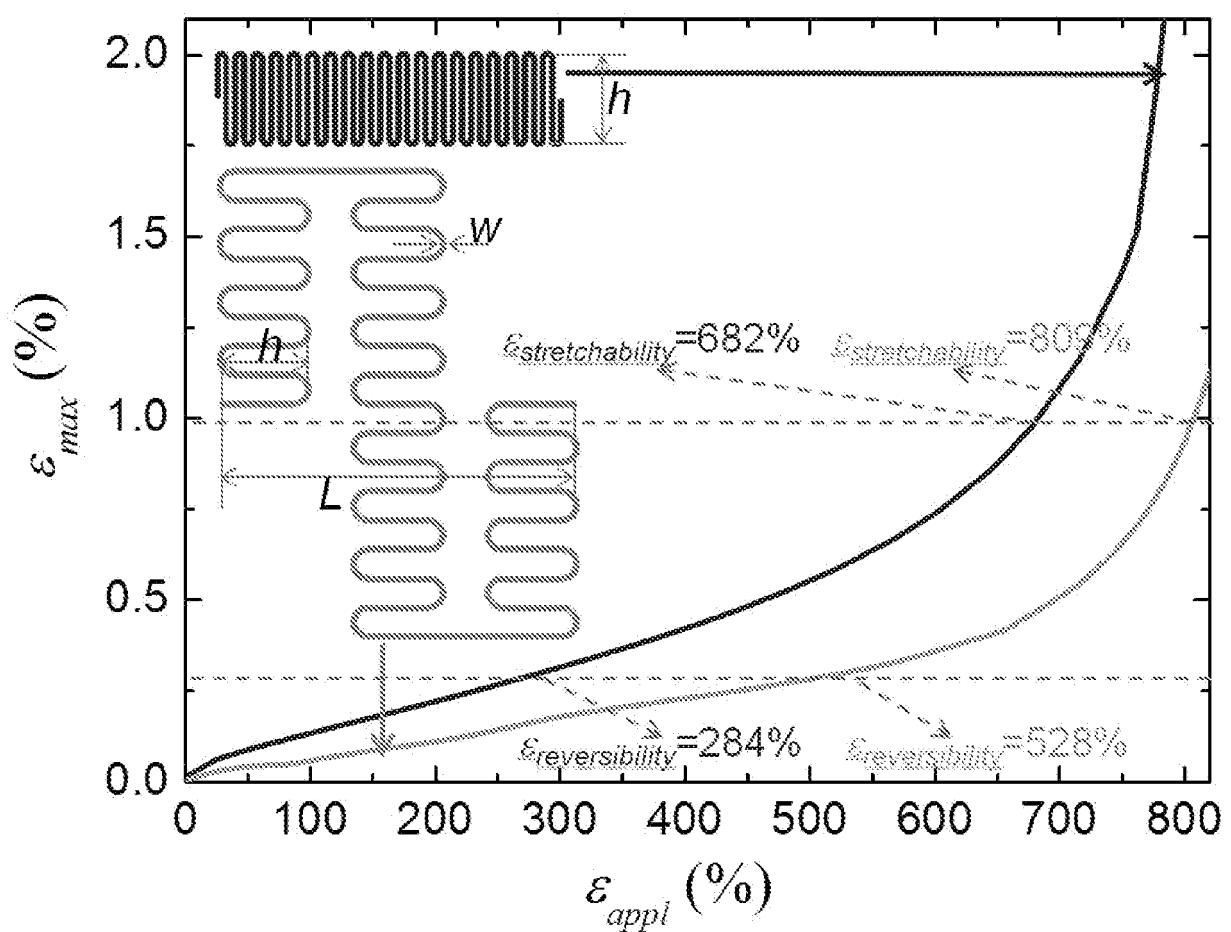


Figure 10

**Figure 11**

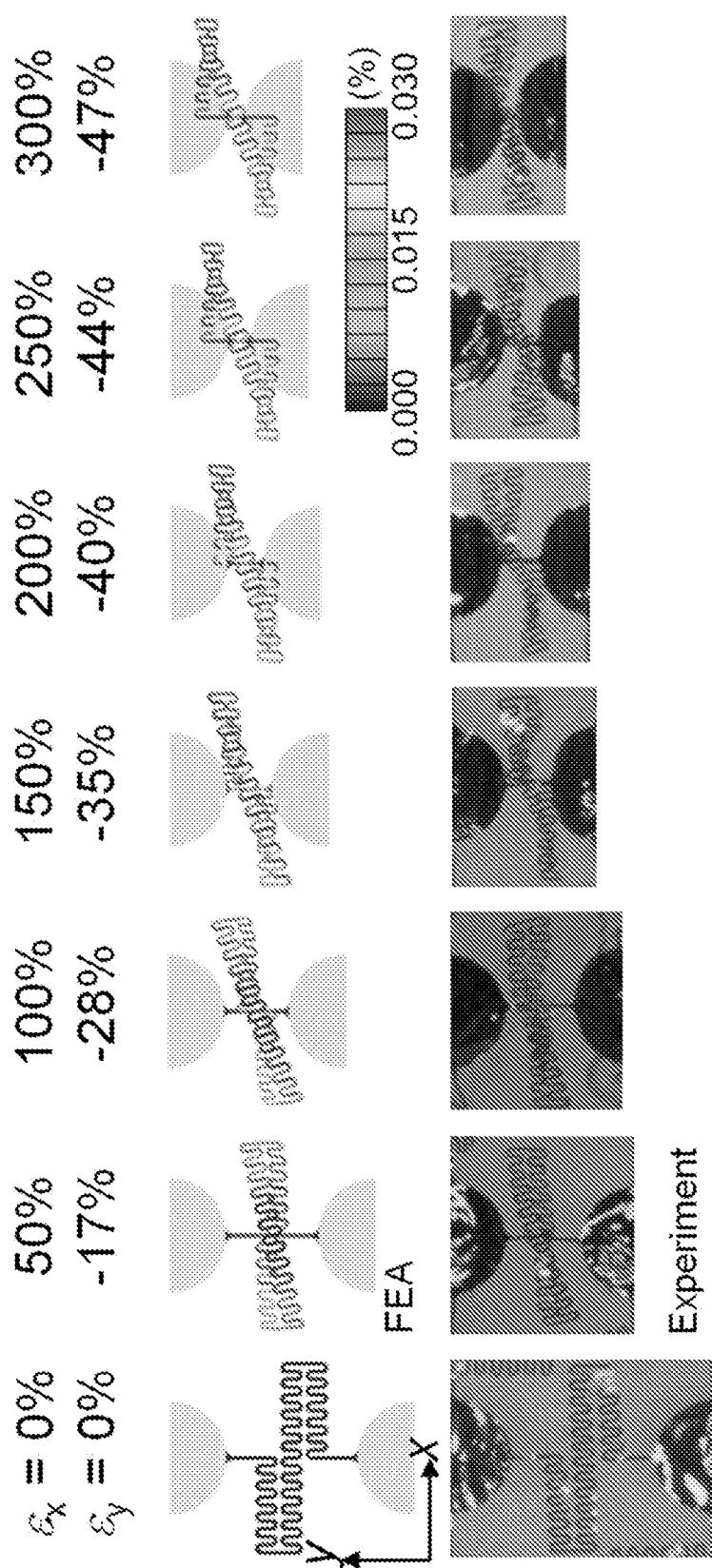
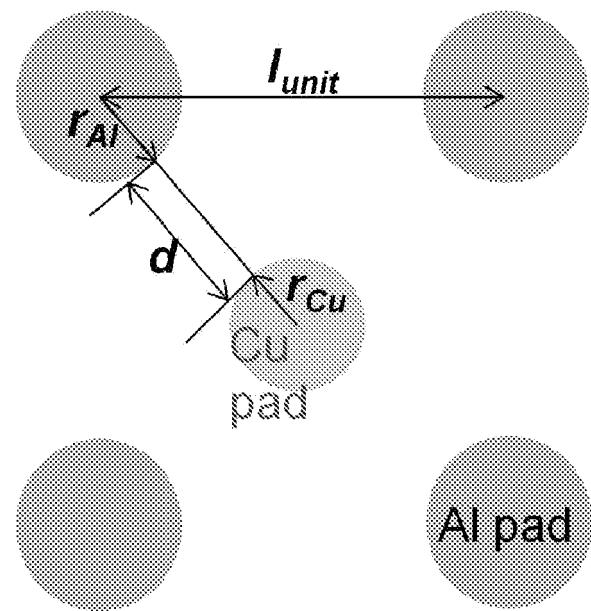
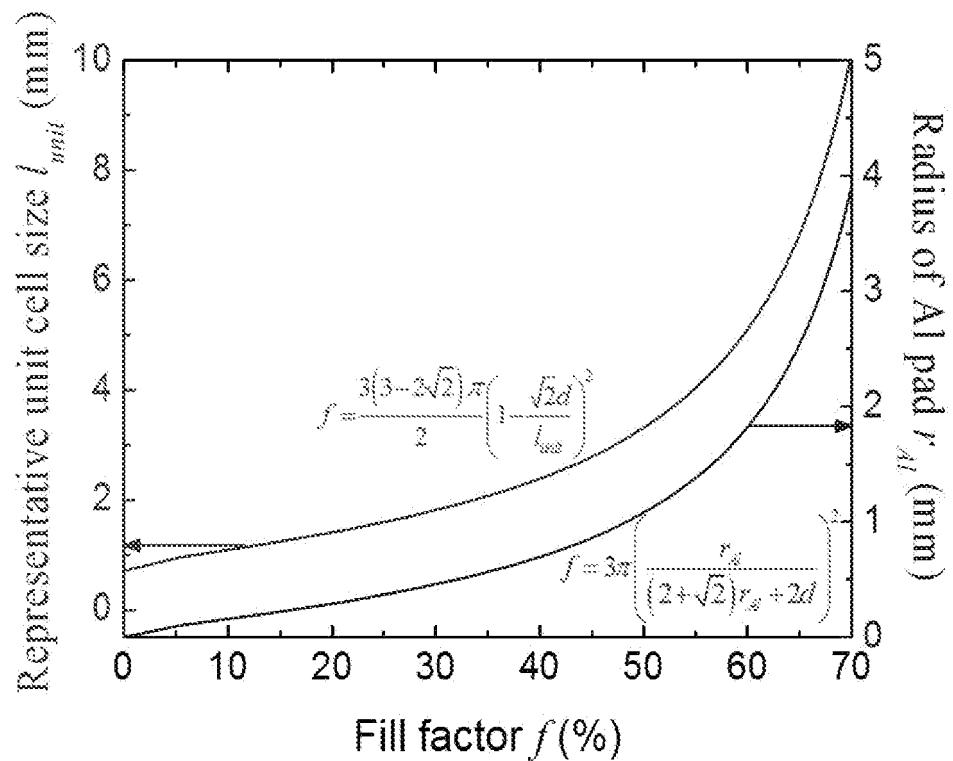


Figure 12

**Figure 13A****Figure 13B**

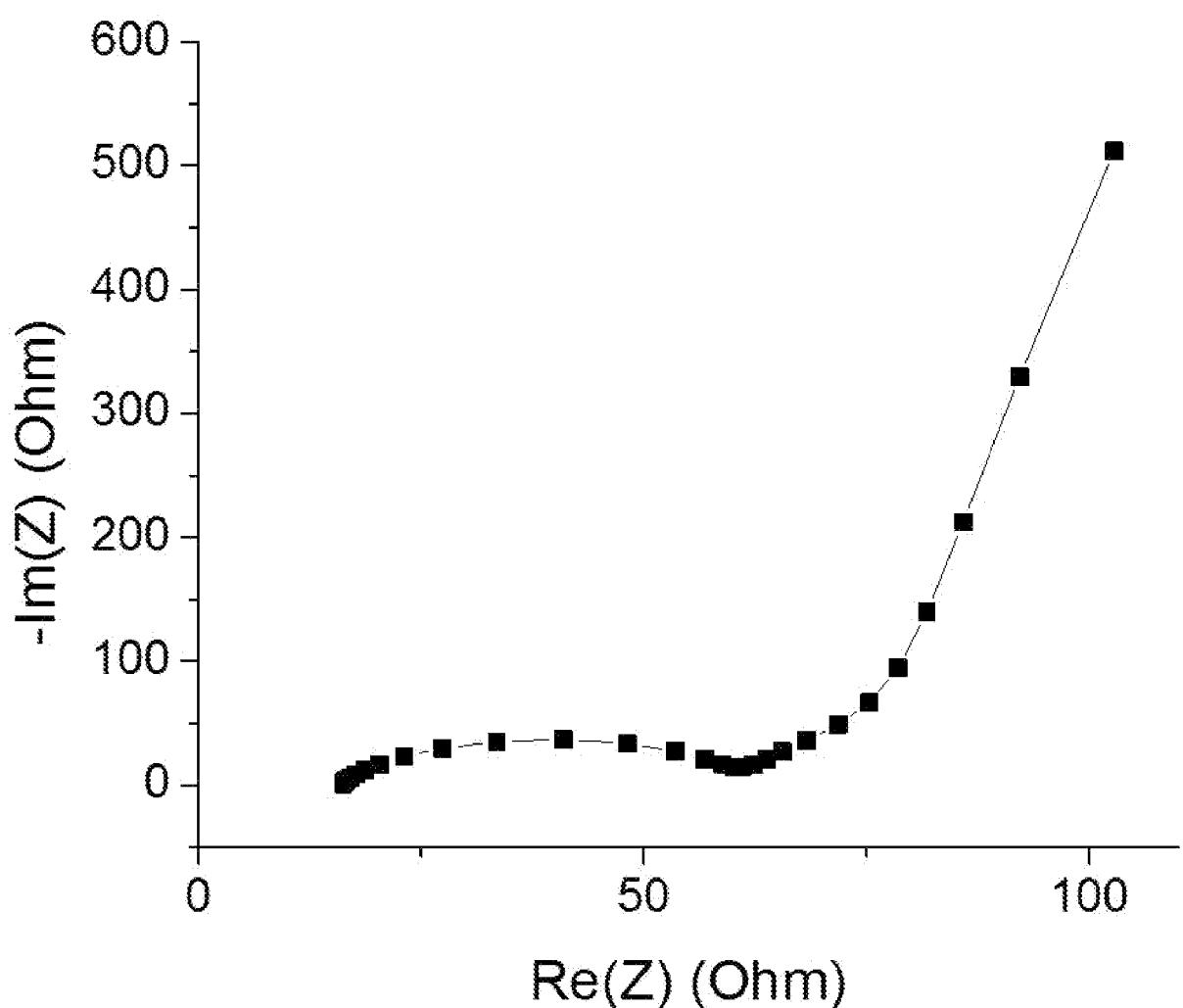
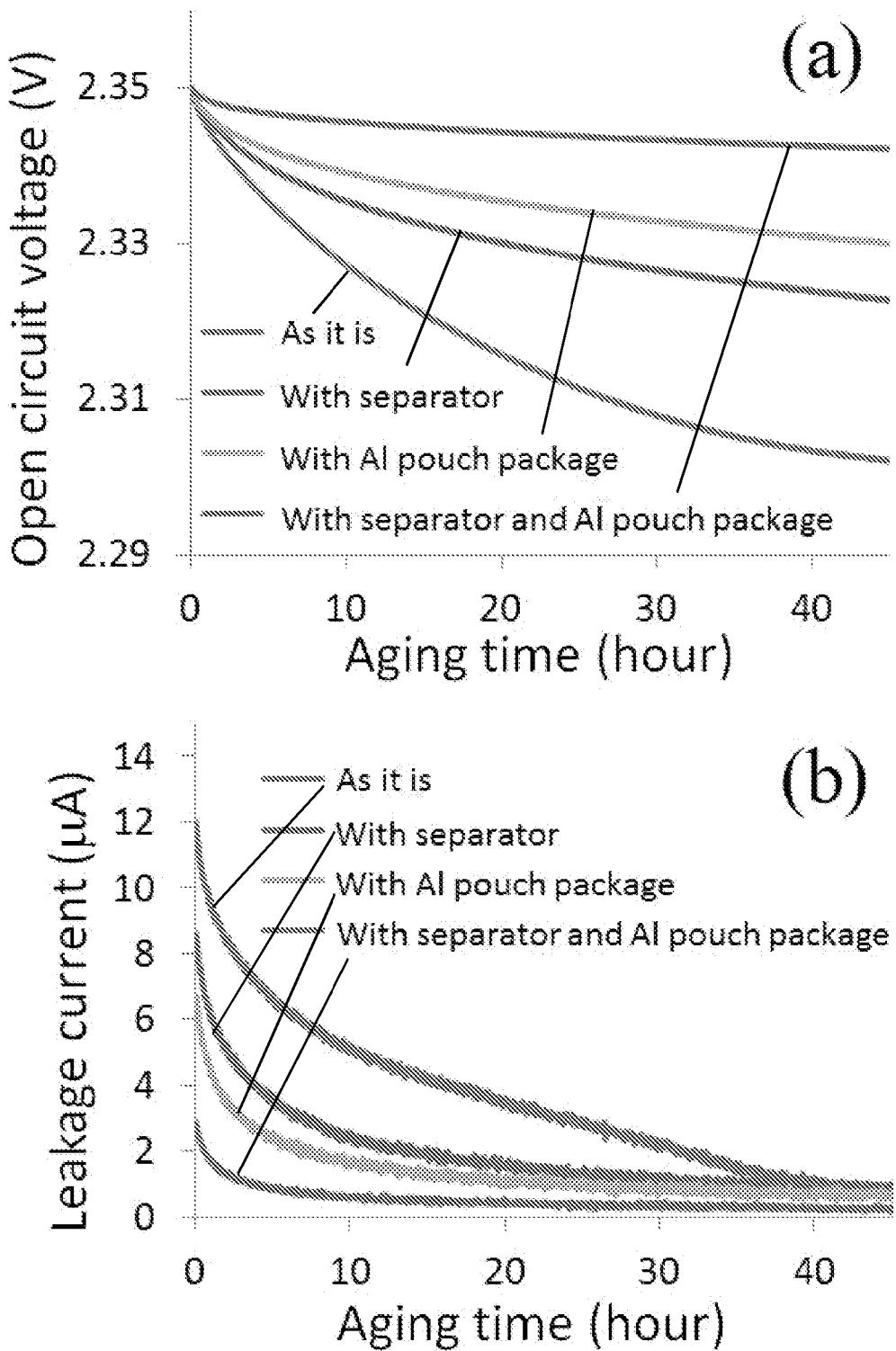
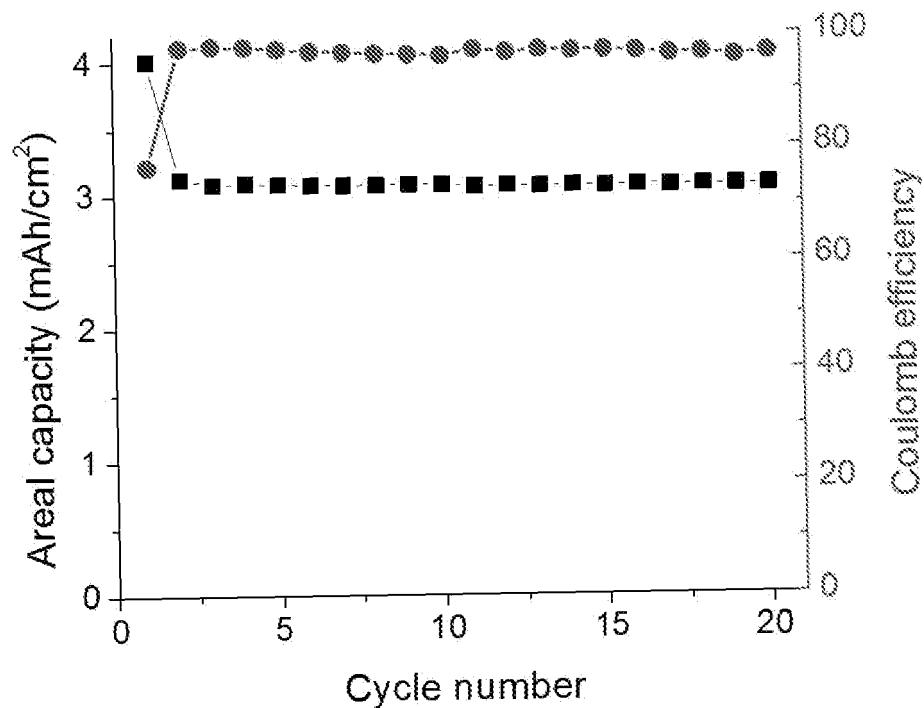
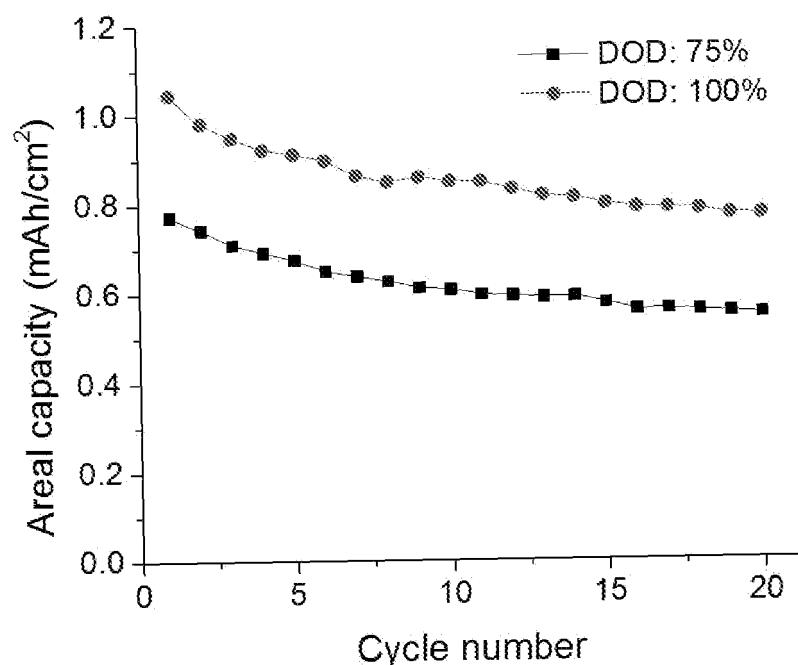


Figure 14

**Figure 15**

**Figure 16****Figure 17**

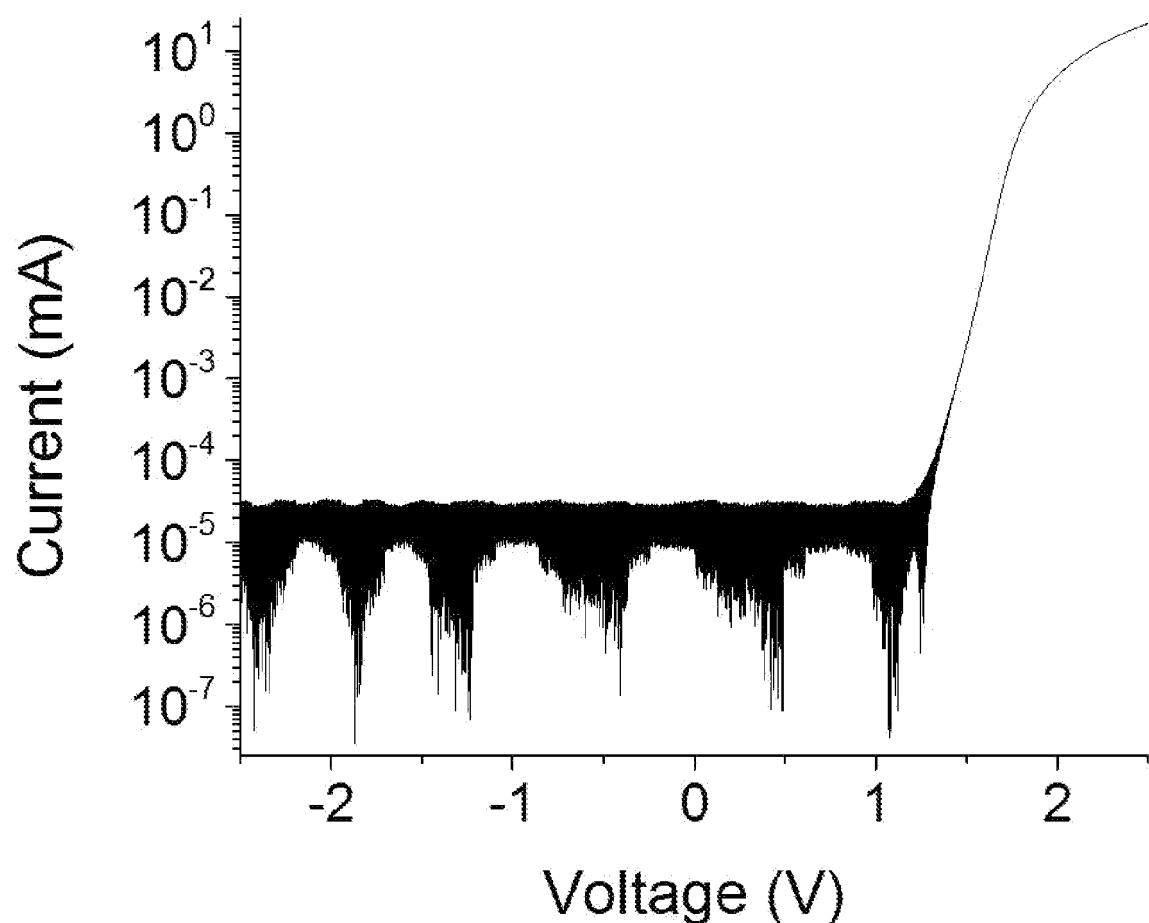


Figure 18

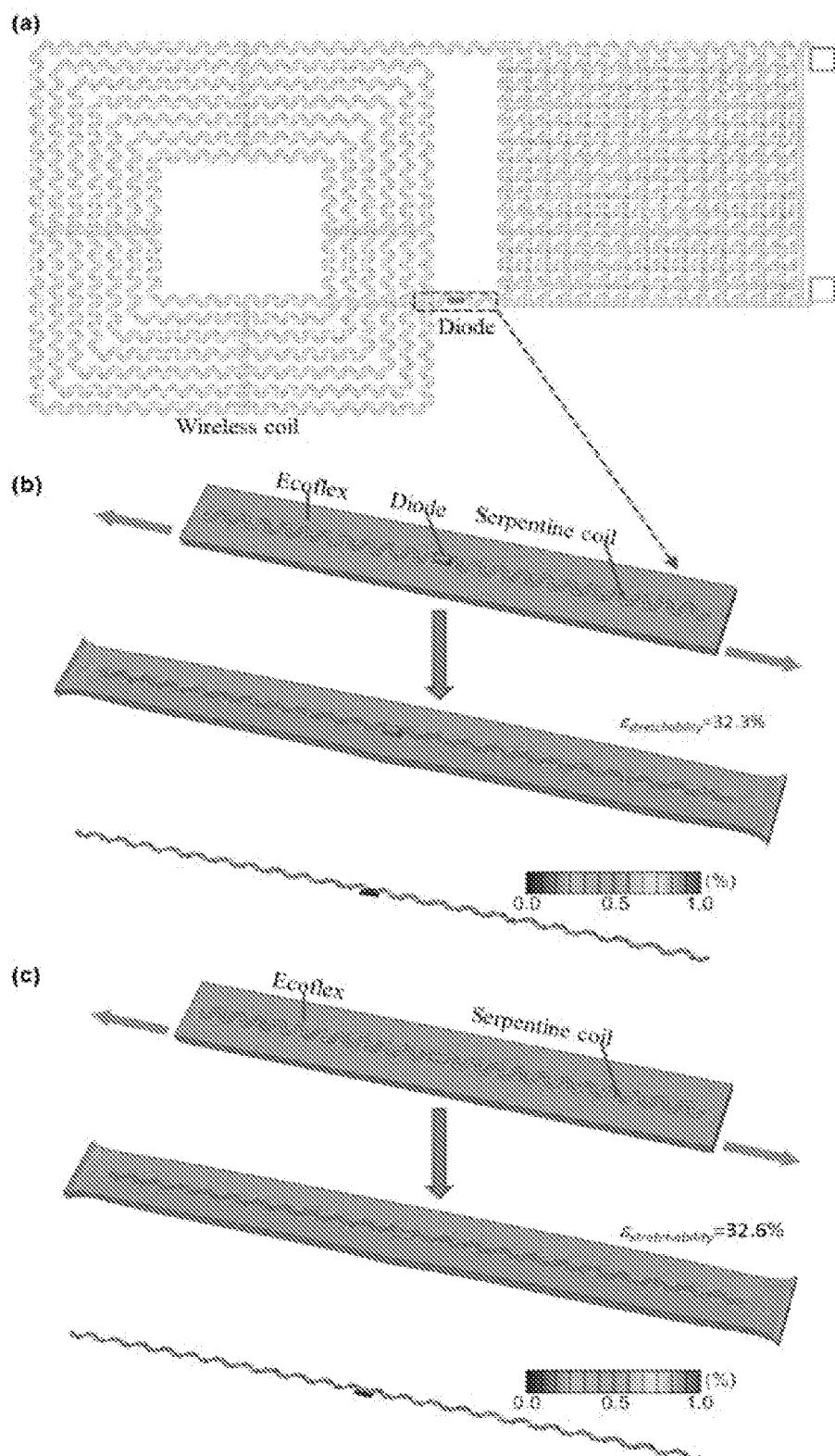


Figure 19

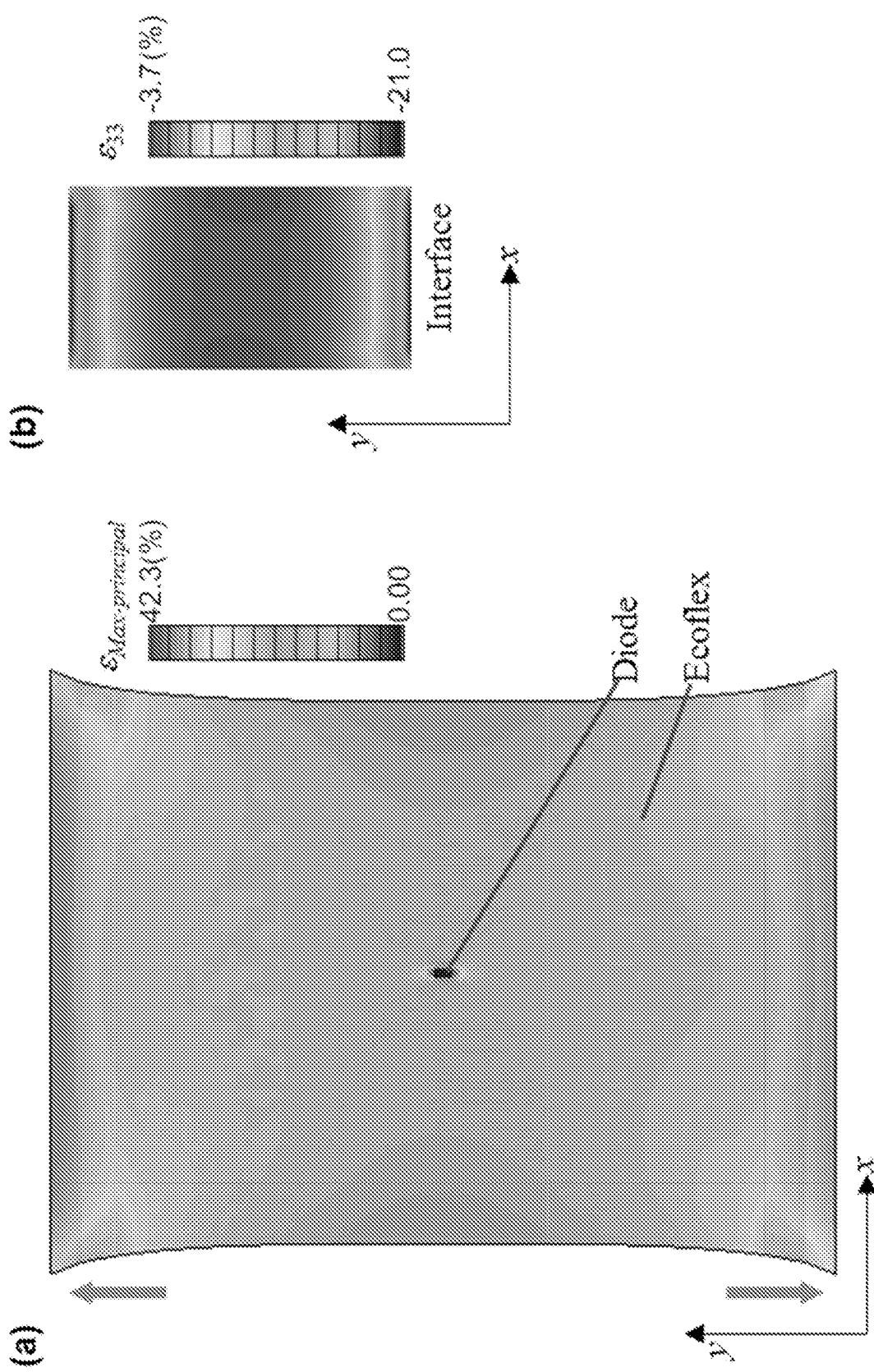


Figure 20

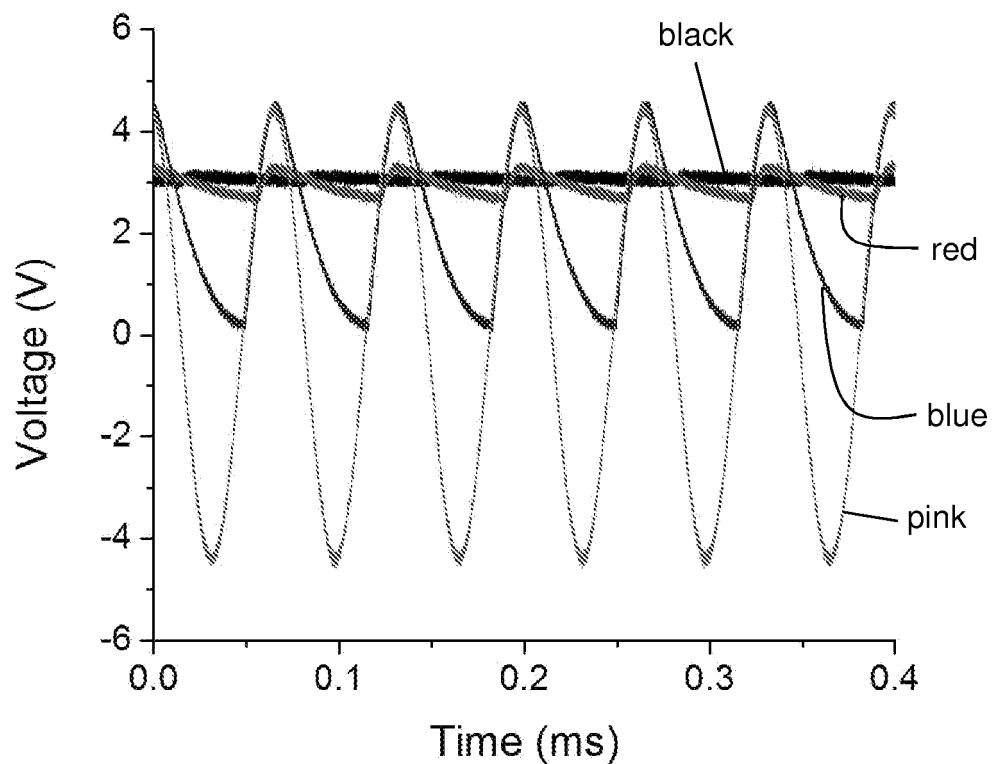


Figure 21

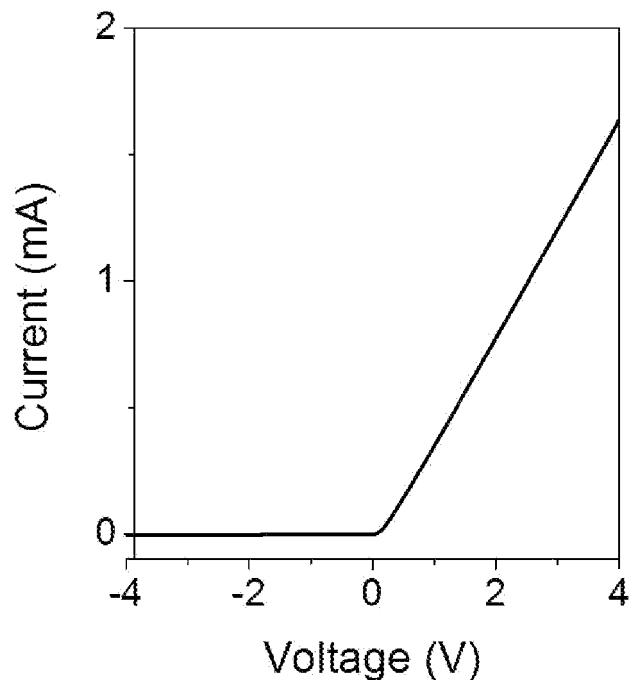


Figure 22

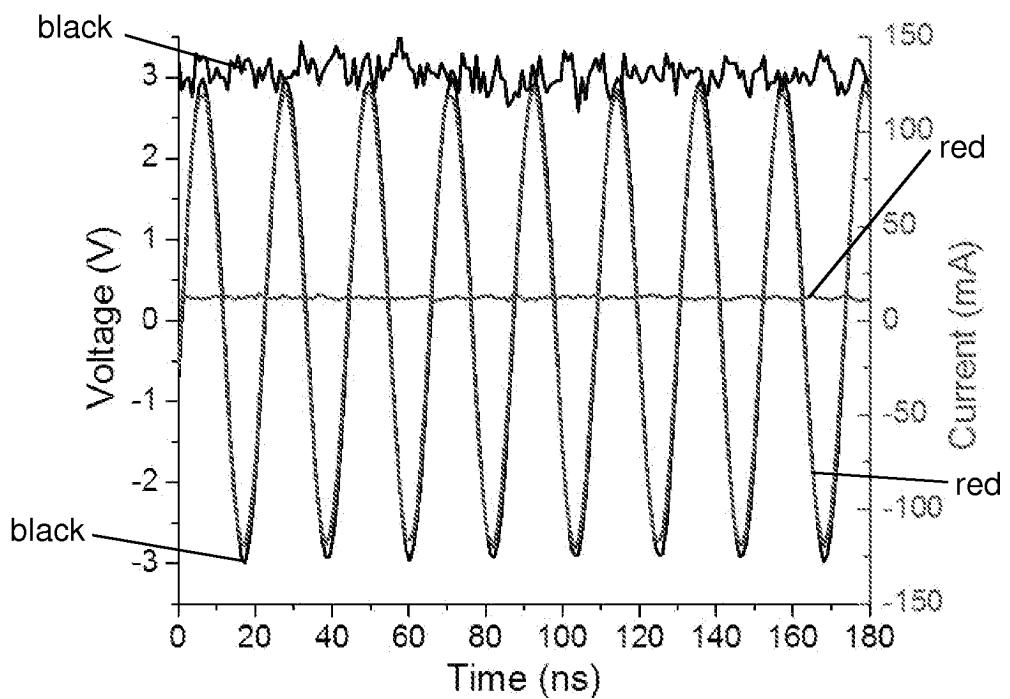


Figure 23A

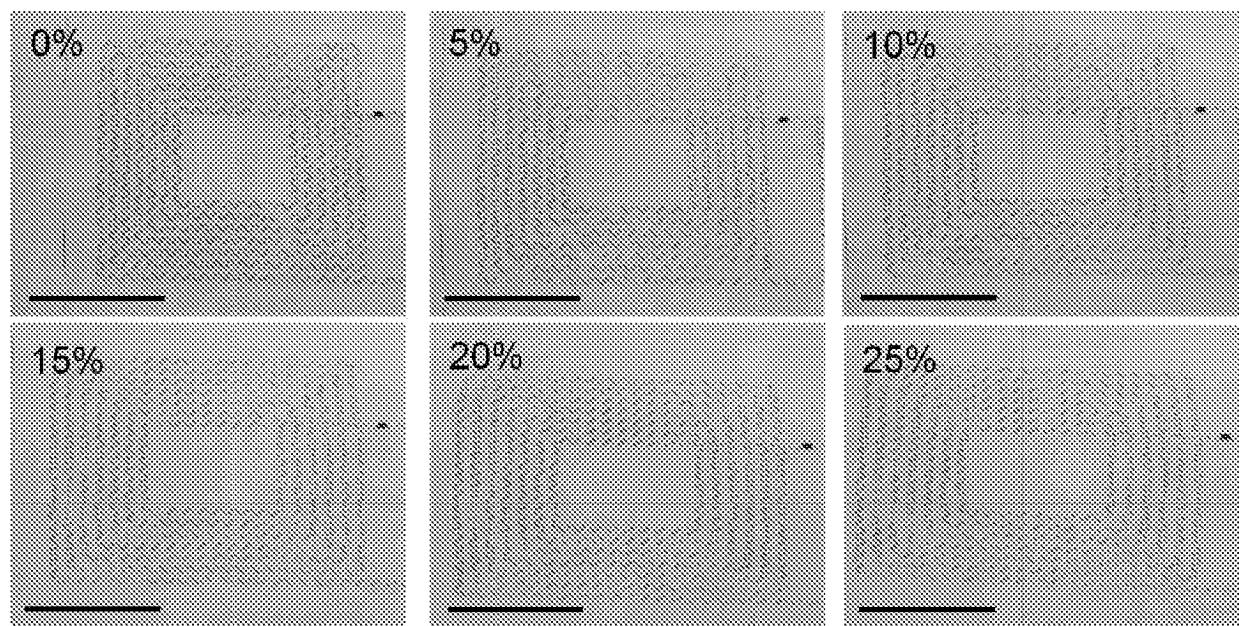


Figure 23B

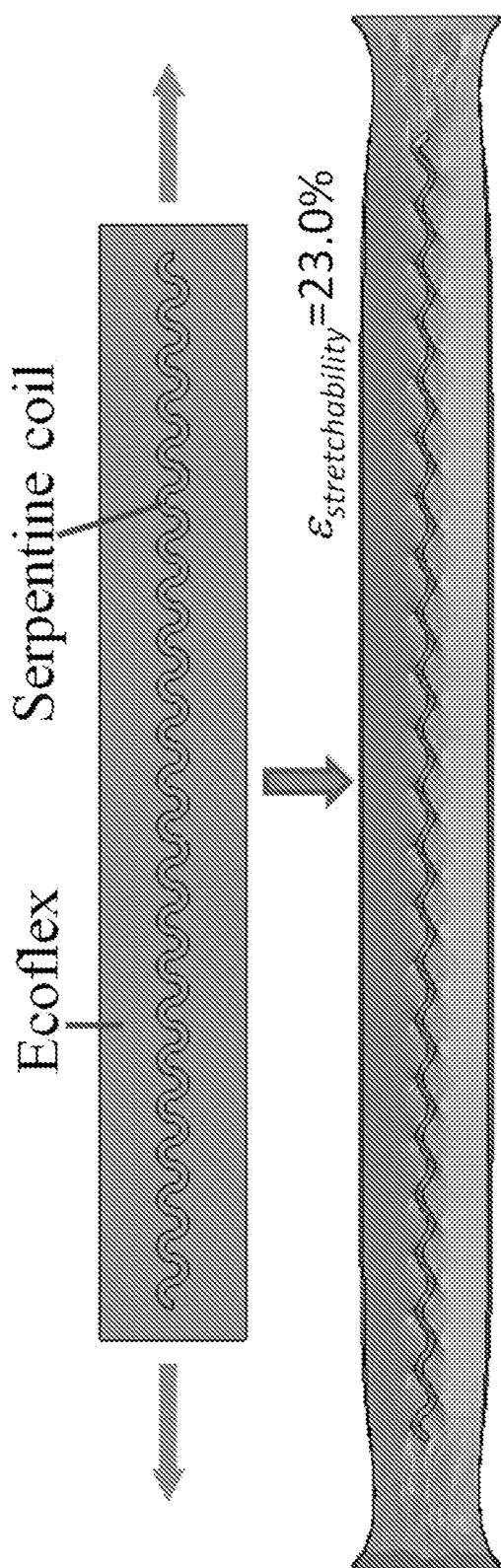


Figure 23C

Figure 24A

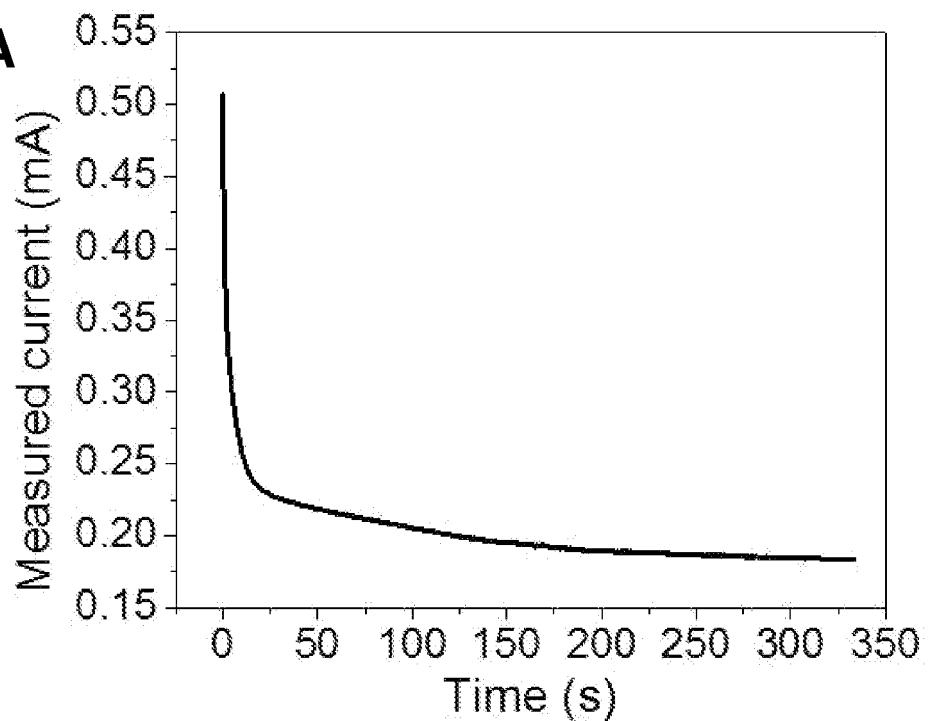
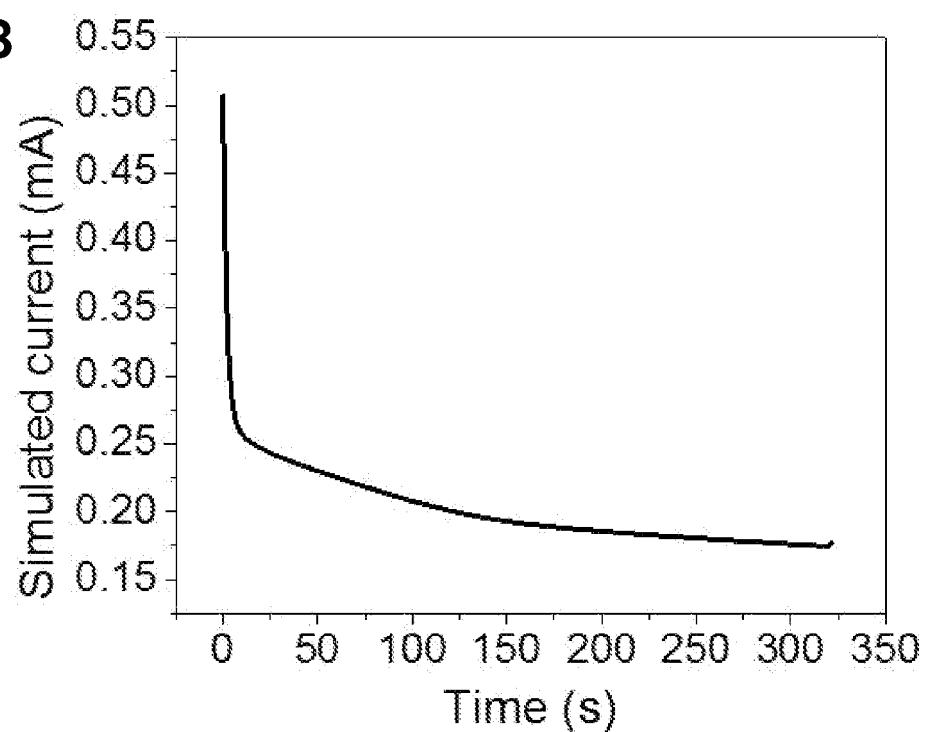


Figure 24B



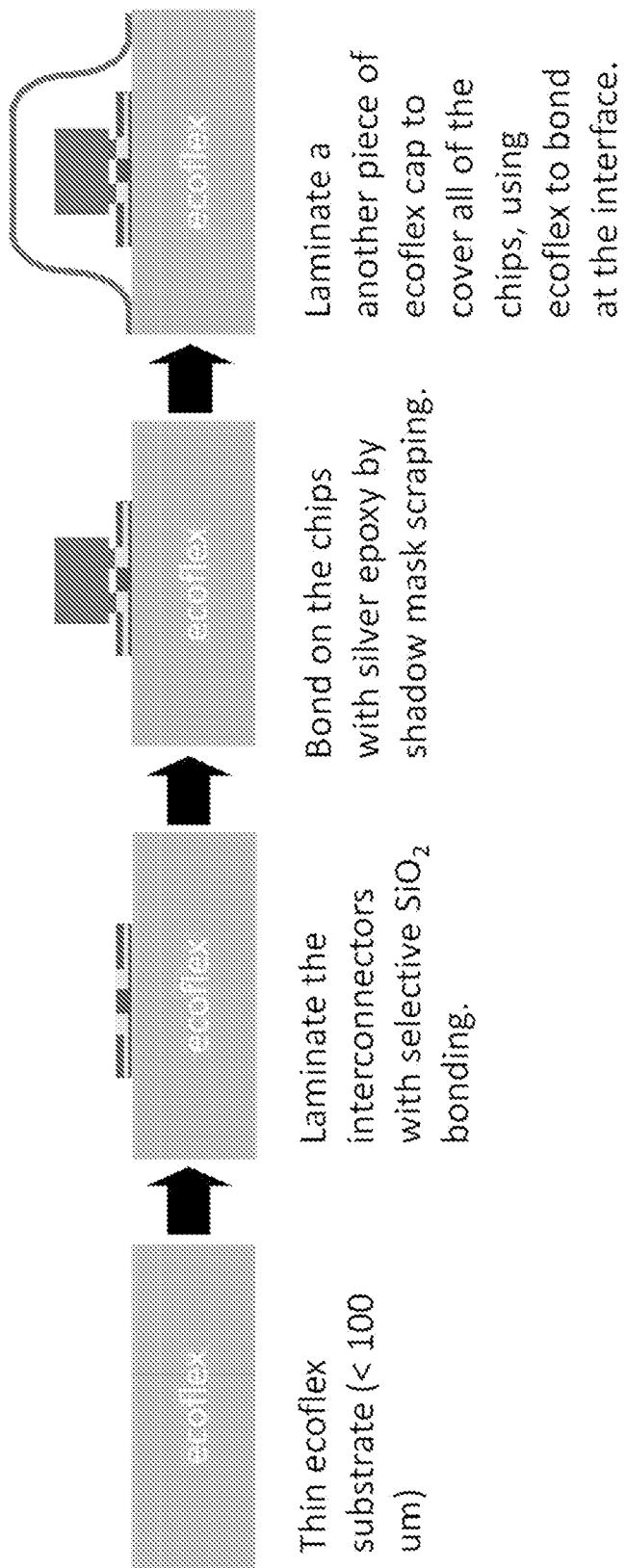


Figure 25

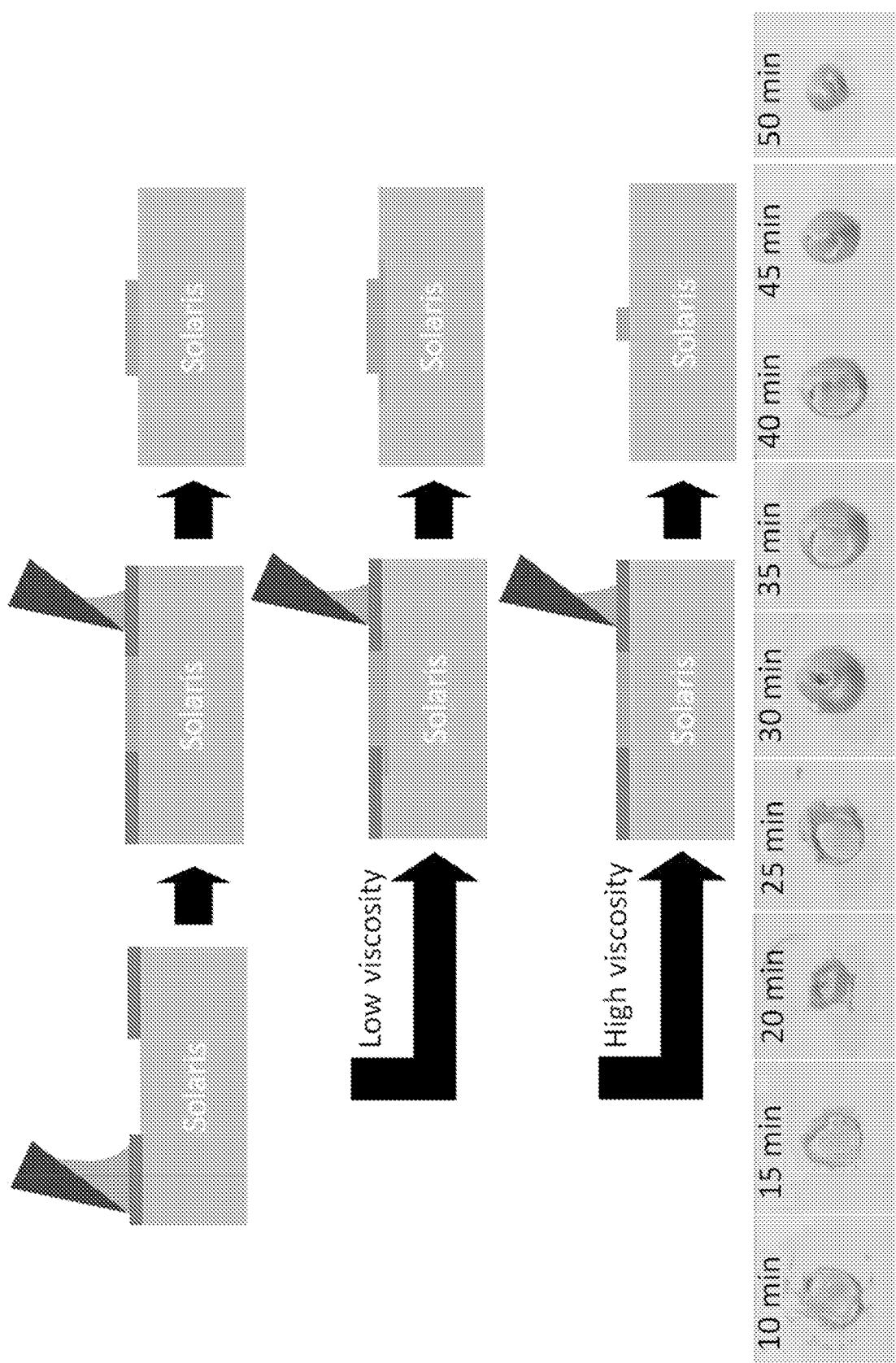


Figure 26

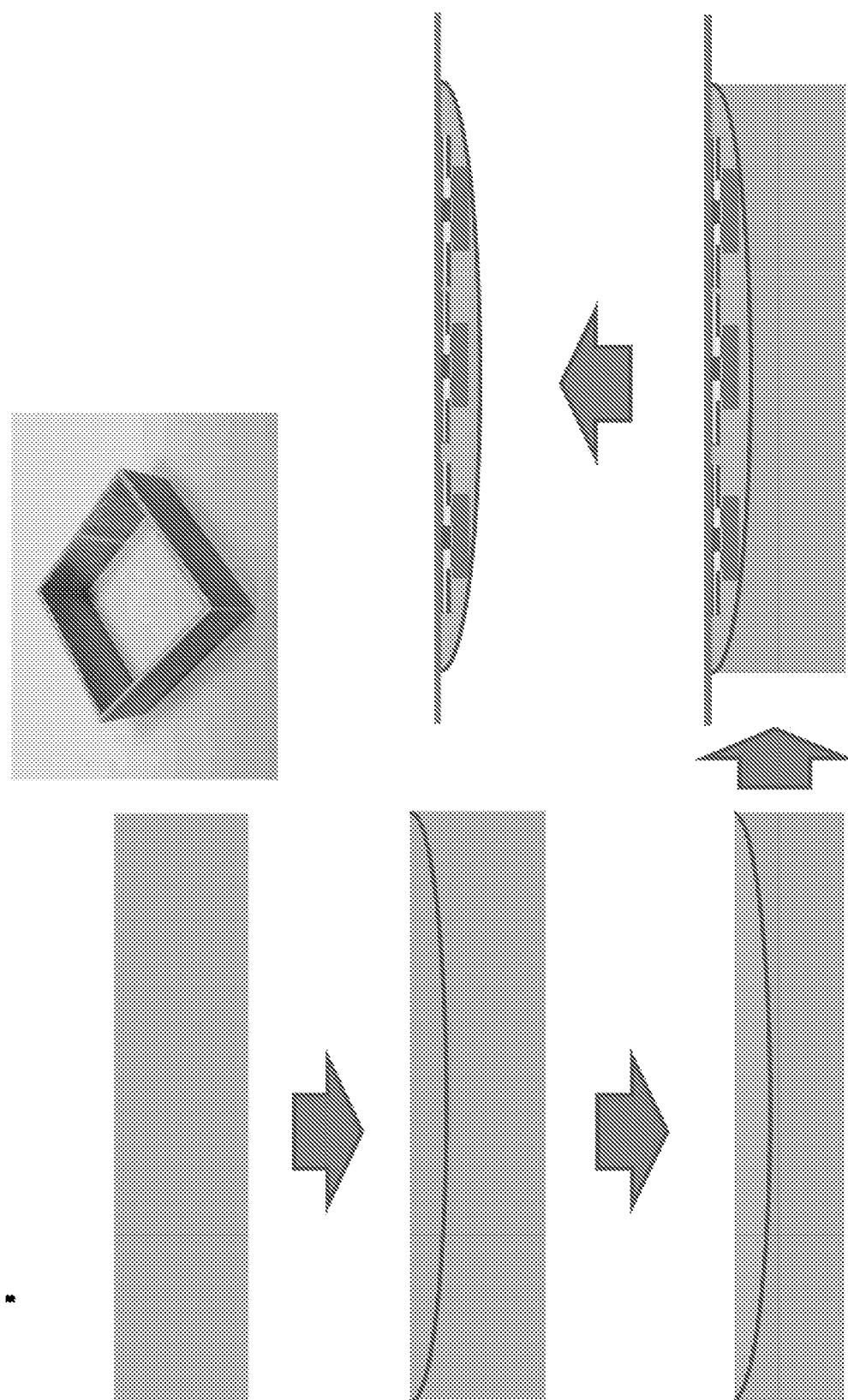


Figure 27

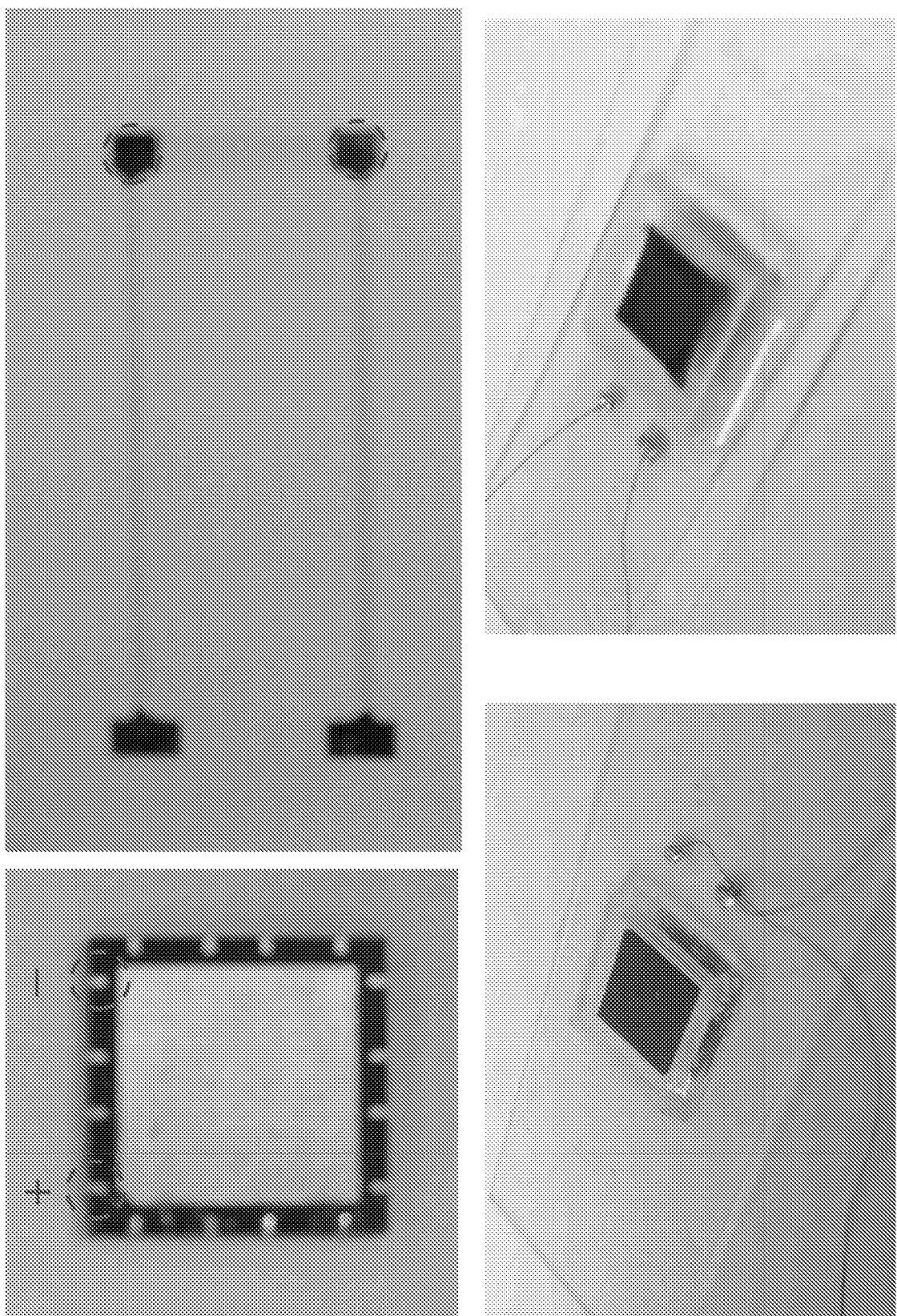
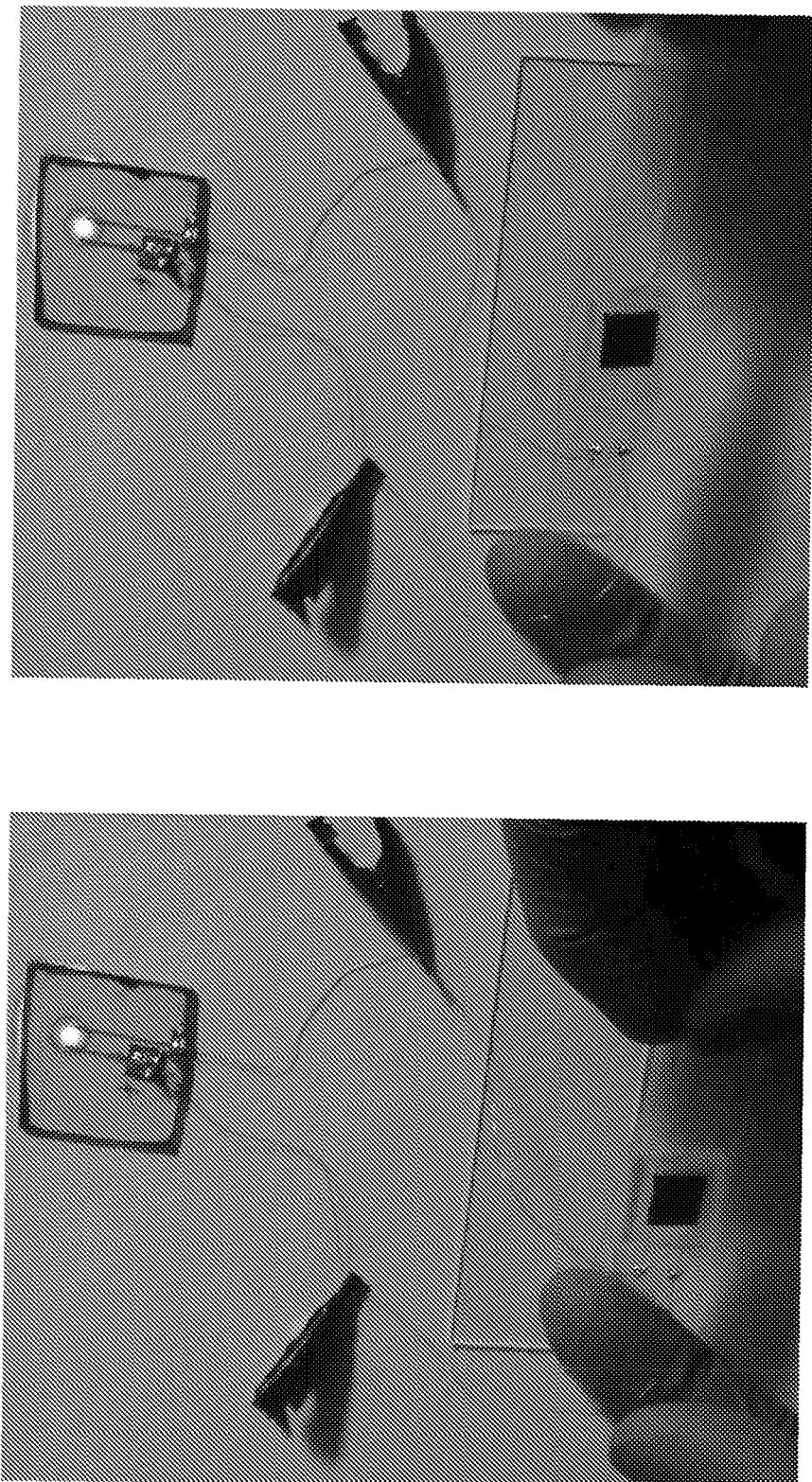


Figure 28



Battery chip in liquid chamber to power up a blue LED (a) before stretching and (b) under stretching. Stretchability limiting factor: bonded serpentines in the chamber wall.

Figure 29

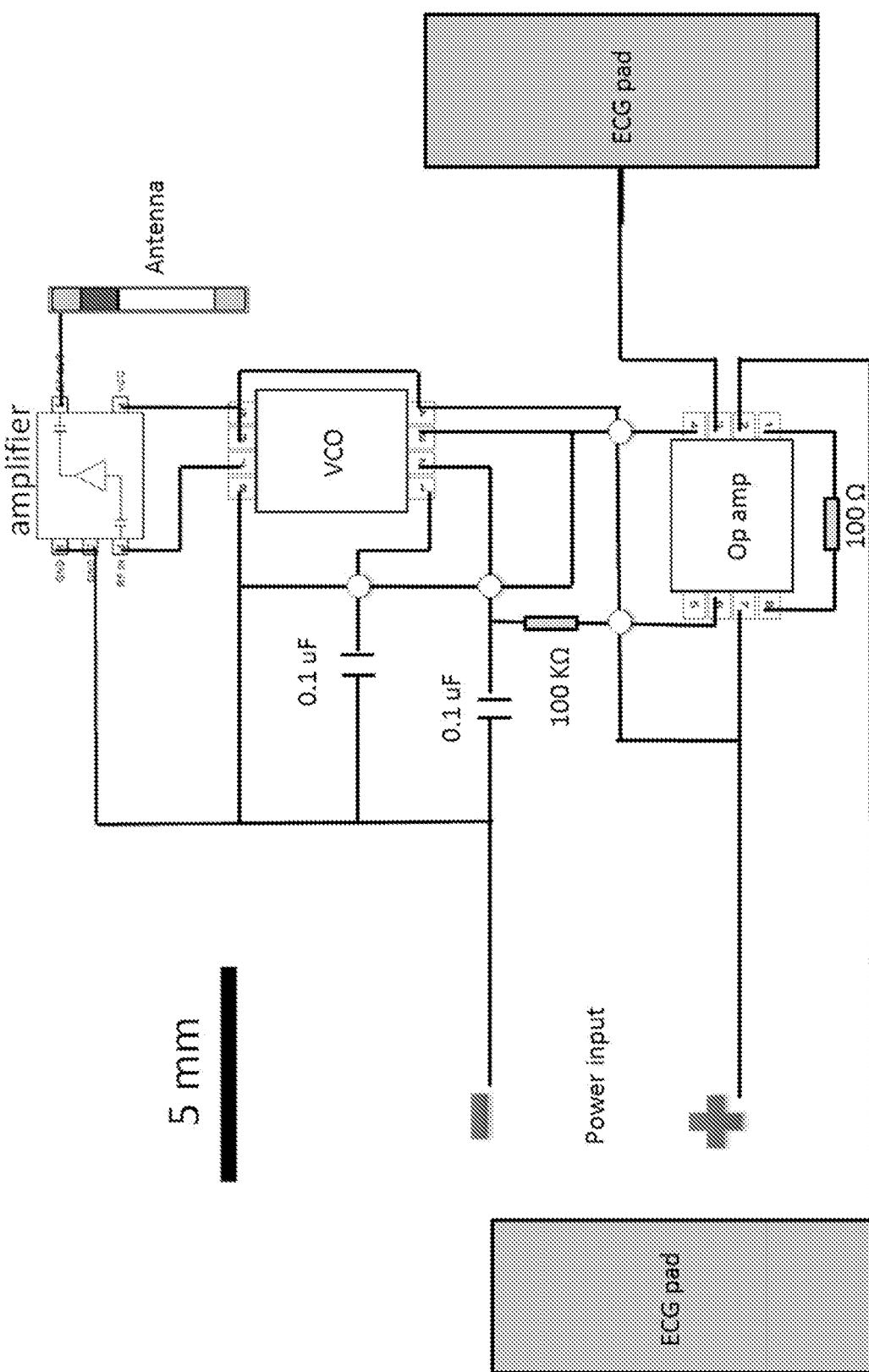


Figure 30

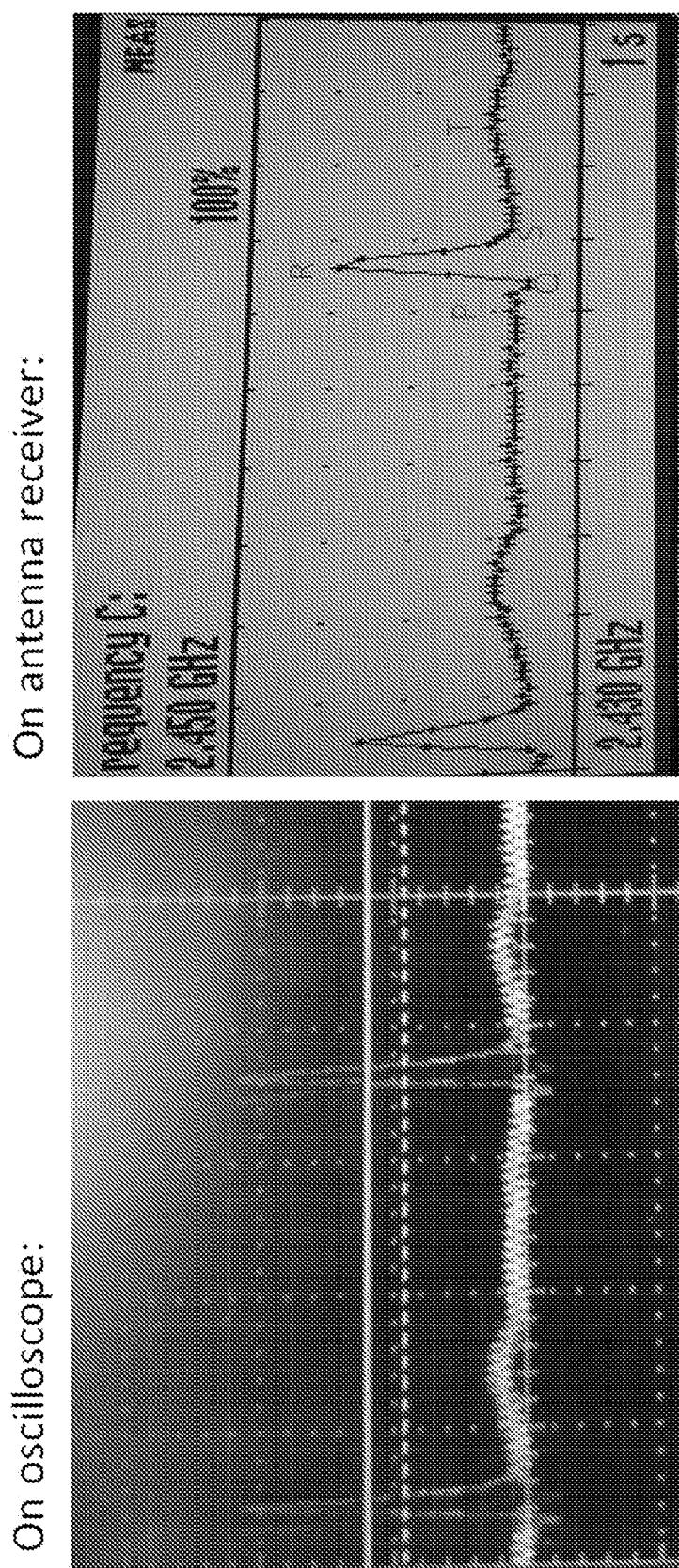


Figure 31

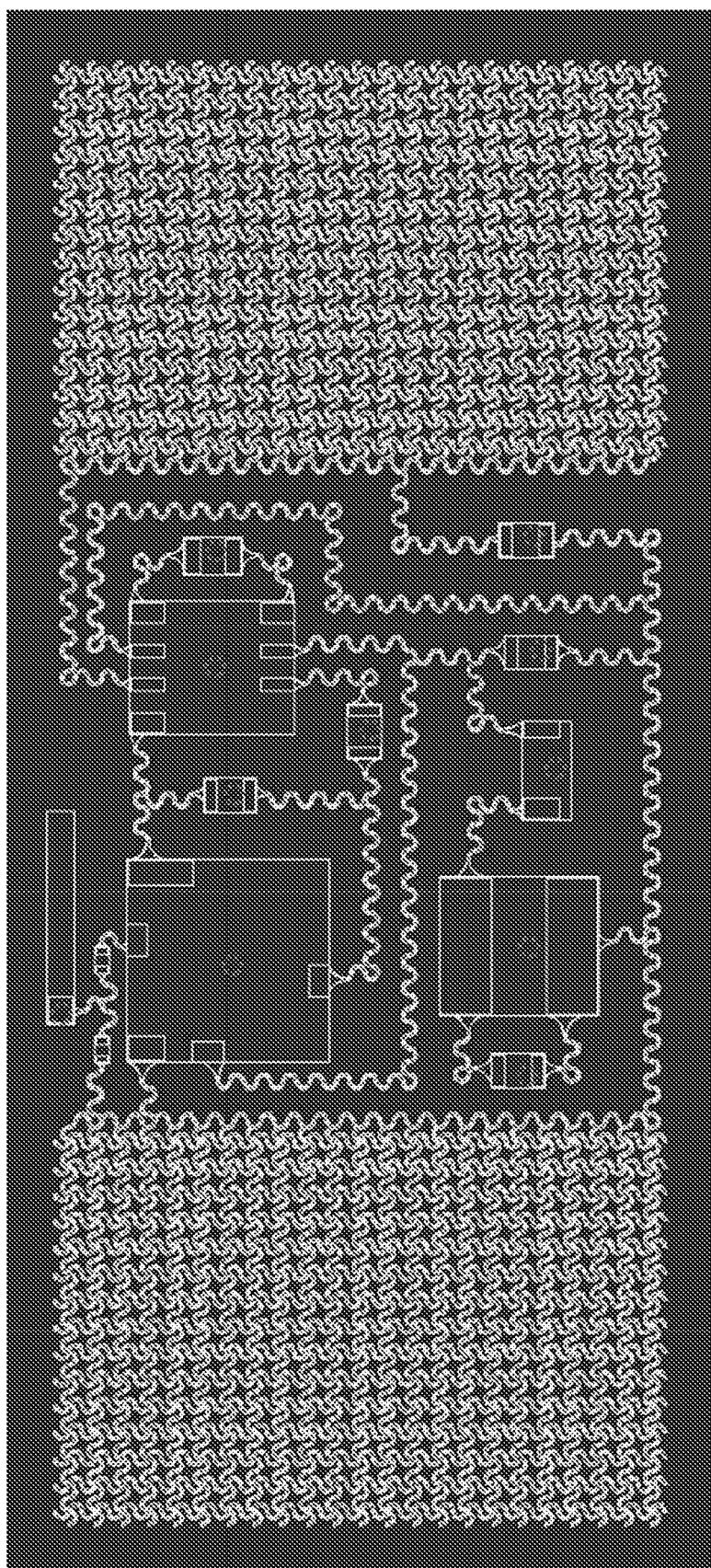
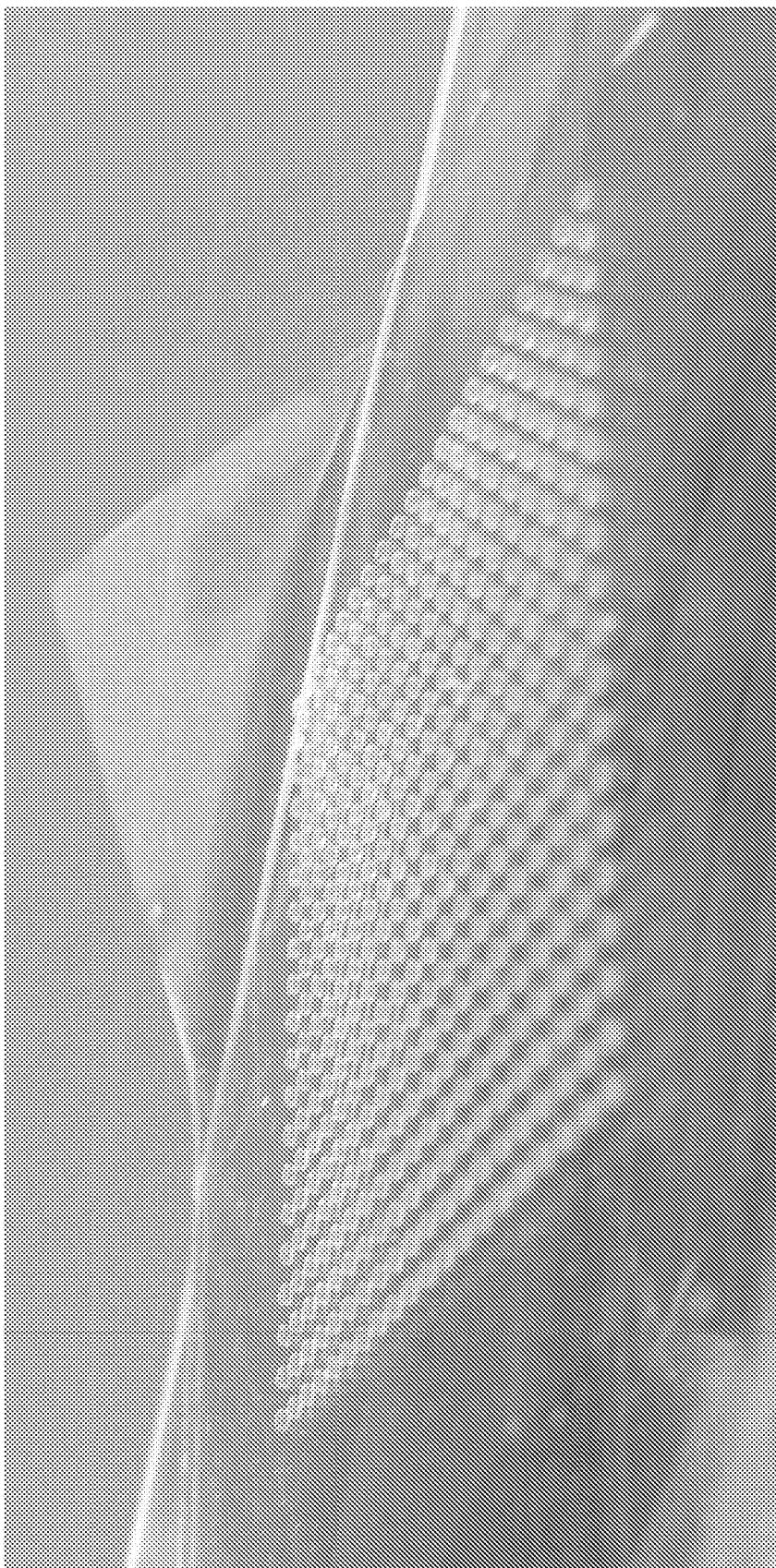


Figure 32



Under the chip to facilitate the interconnect to glide in the liquid chamber.

Figure 33

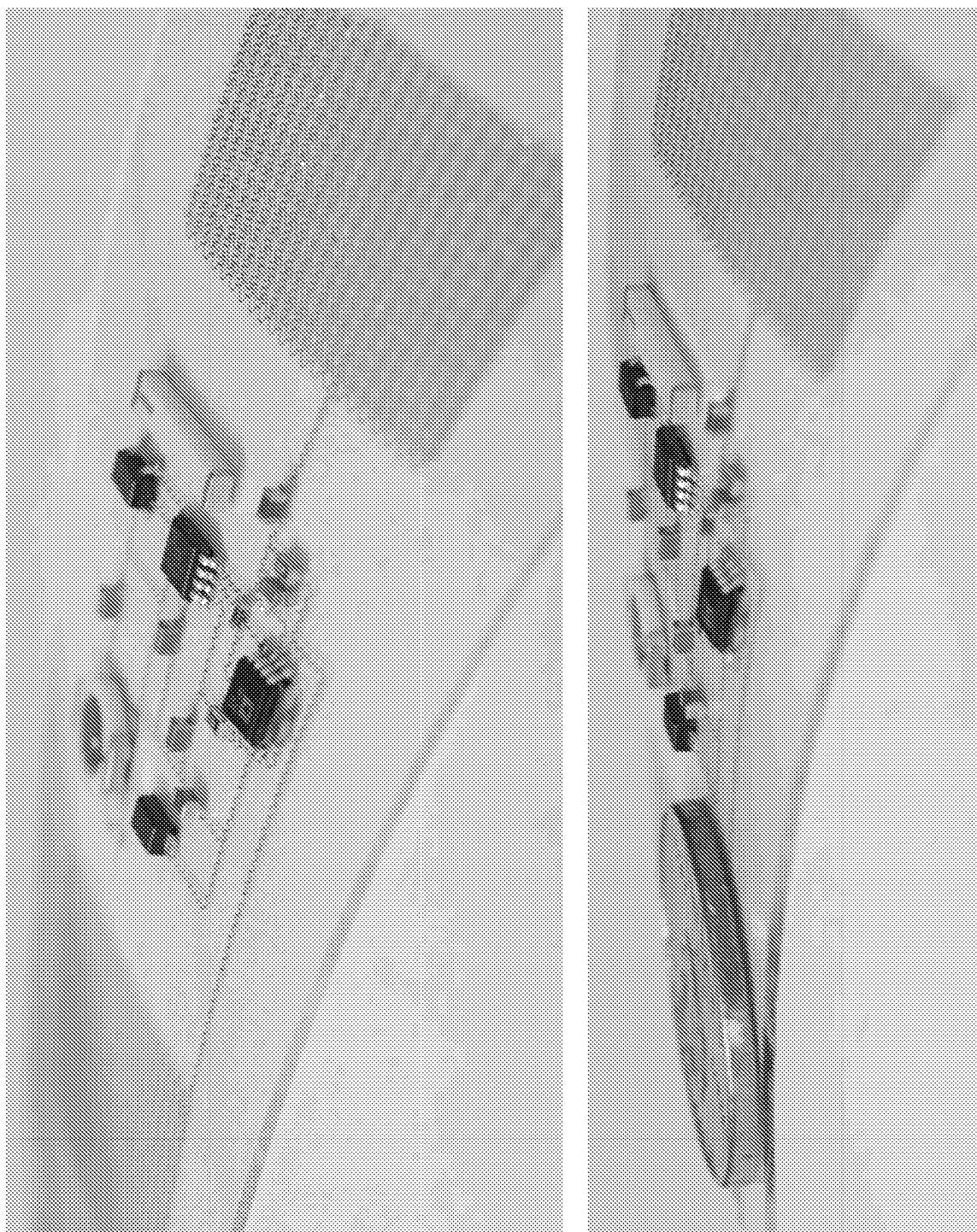


Figure 34

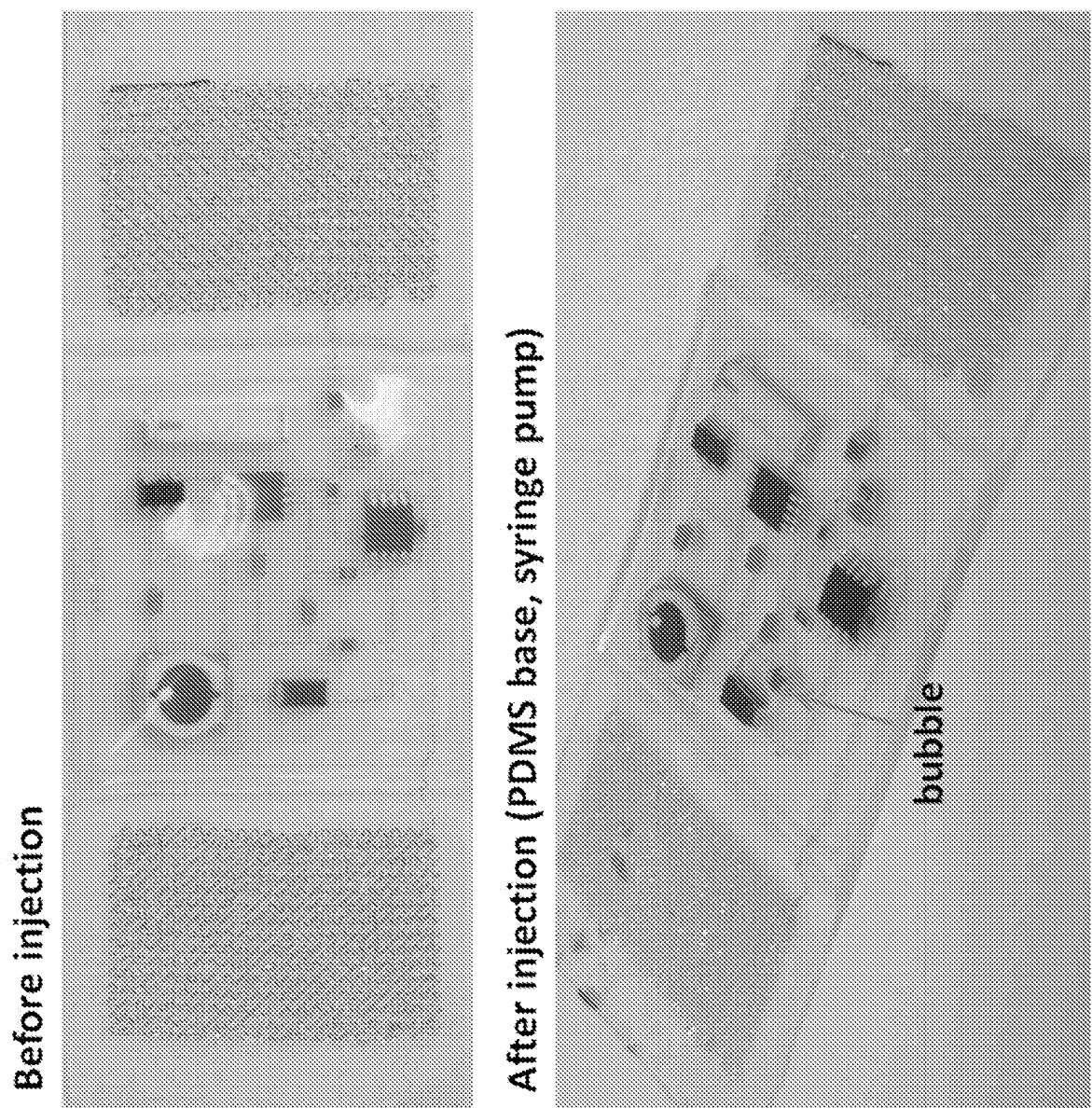


Figure 35

~ 50% uniaxial stretching:

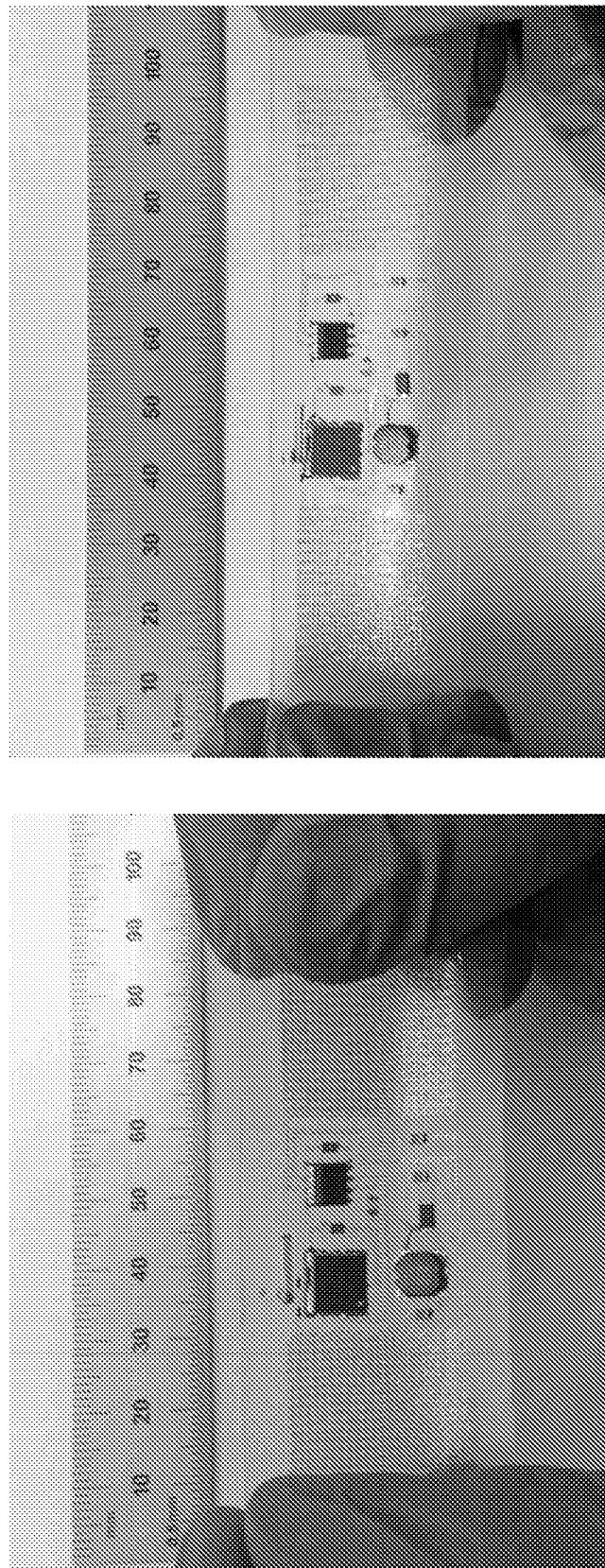


Figure 36

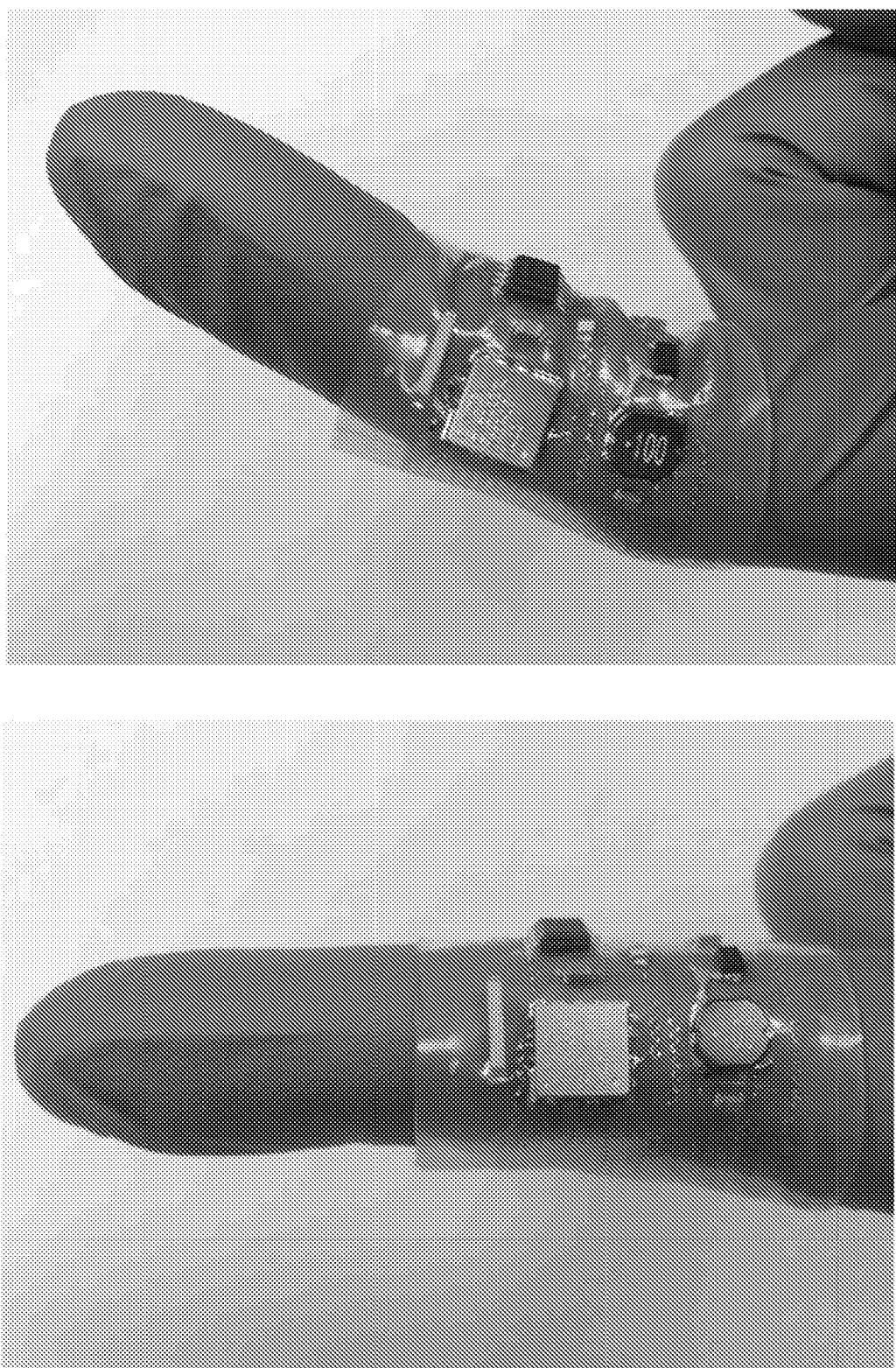


Figure 37

Circuit overall thickness: 2 mm

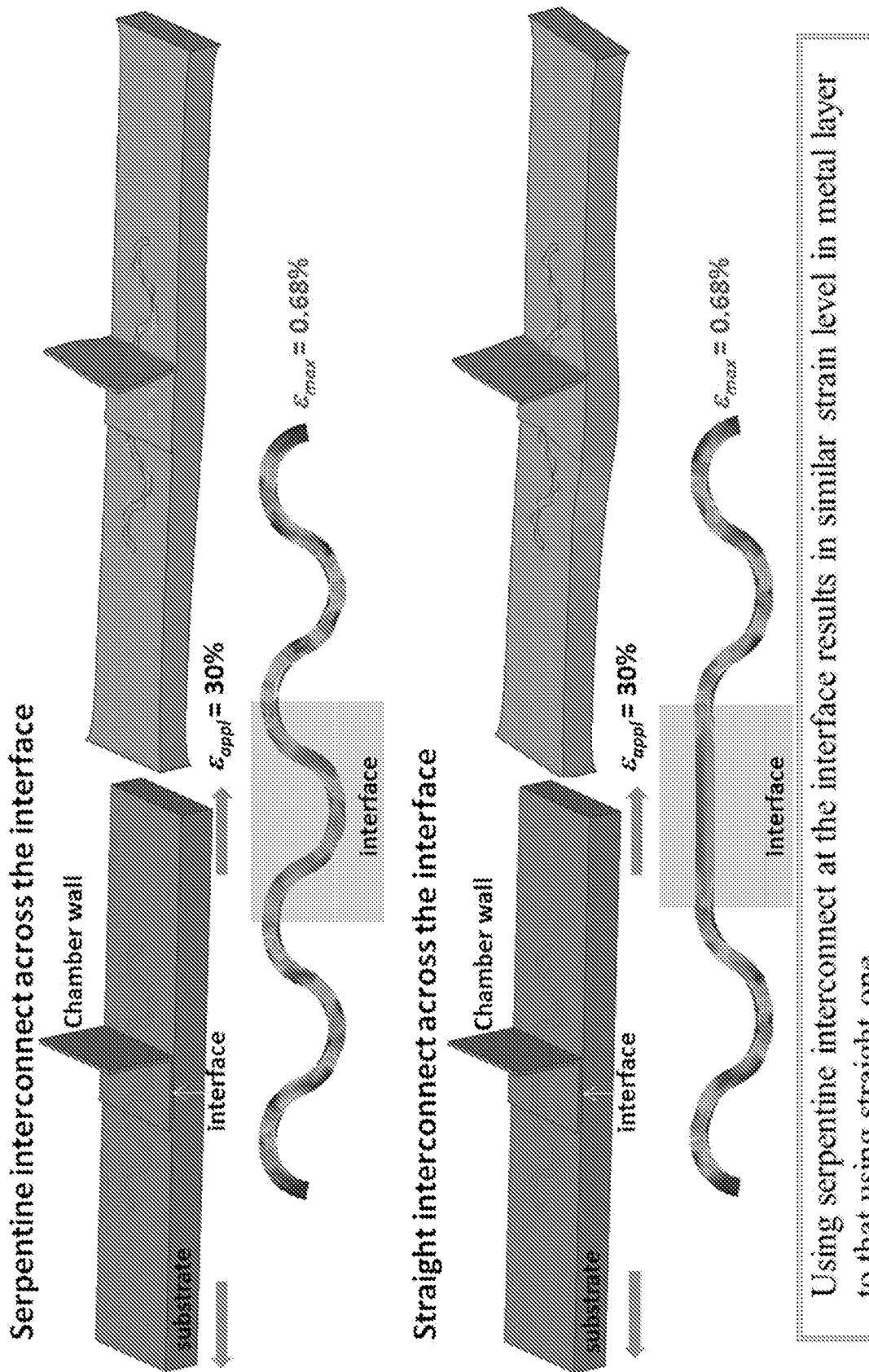


Figure 38

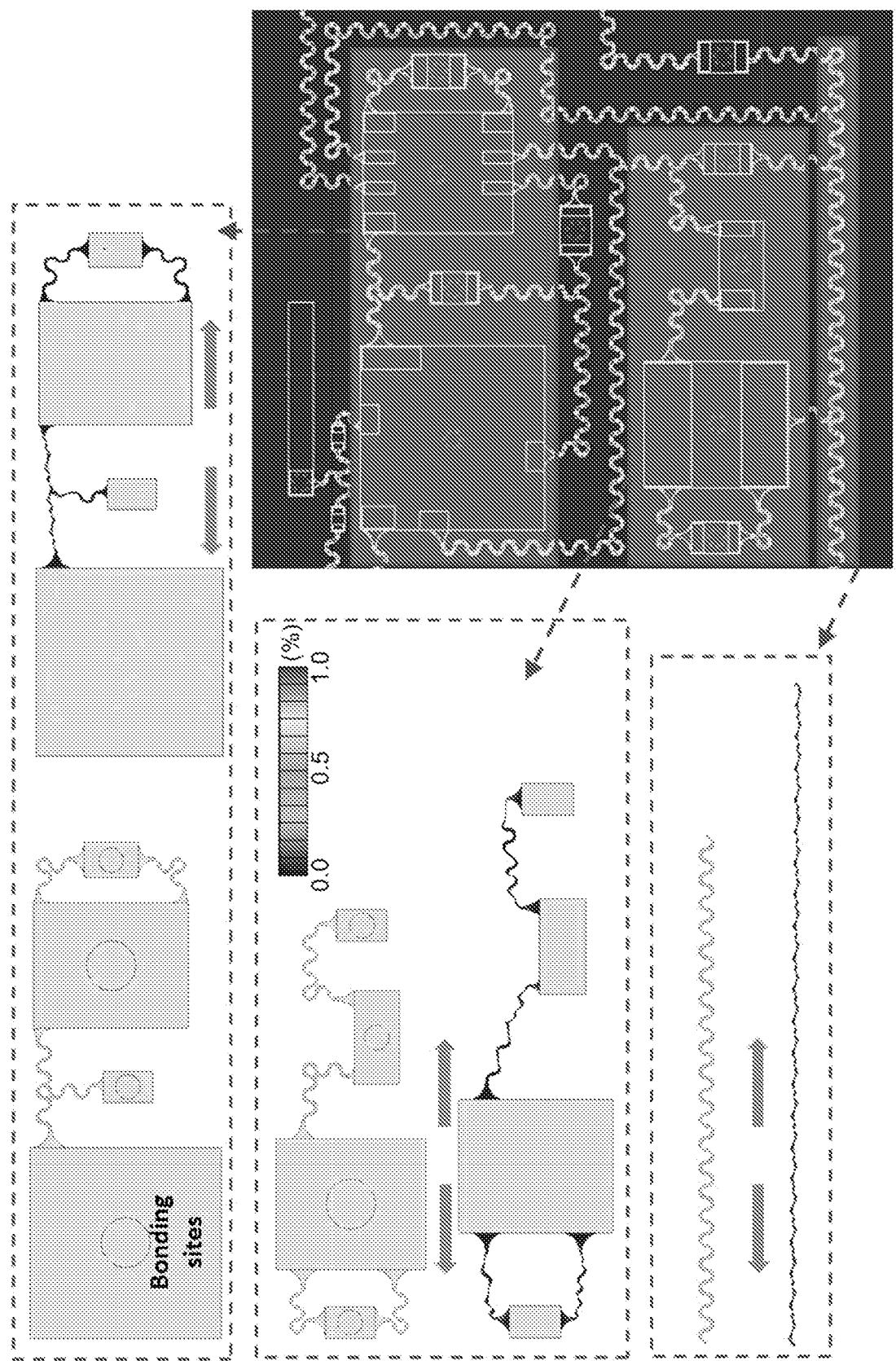


Figure 39

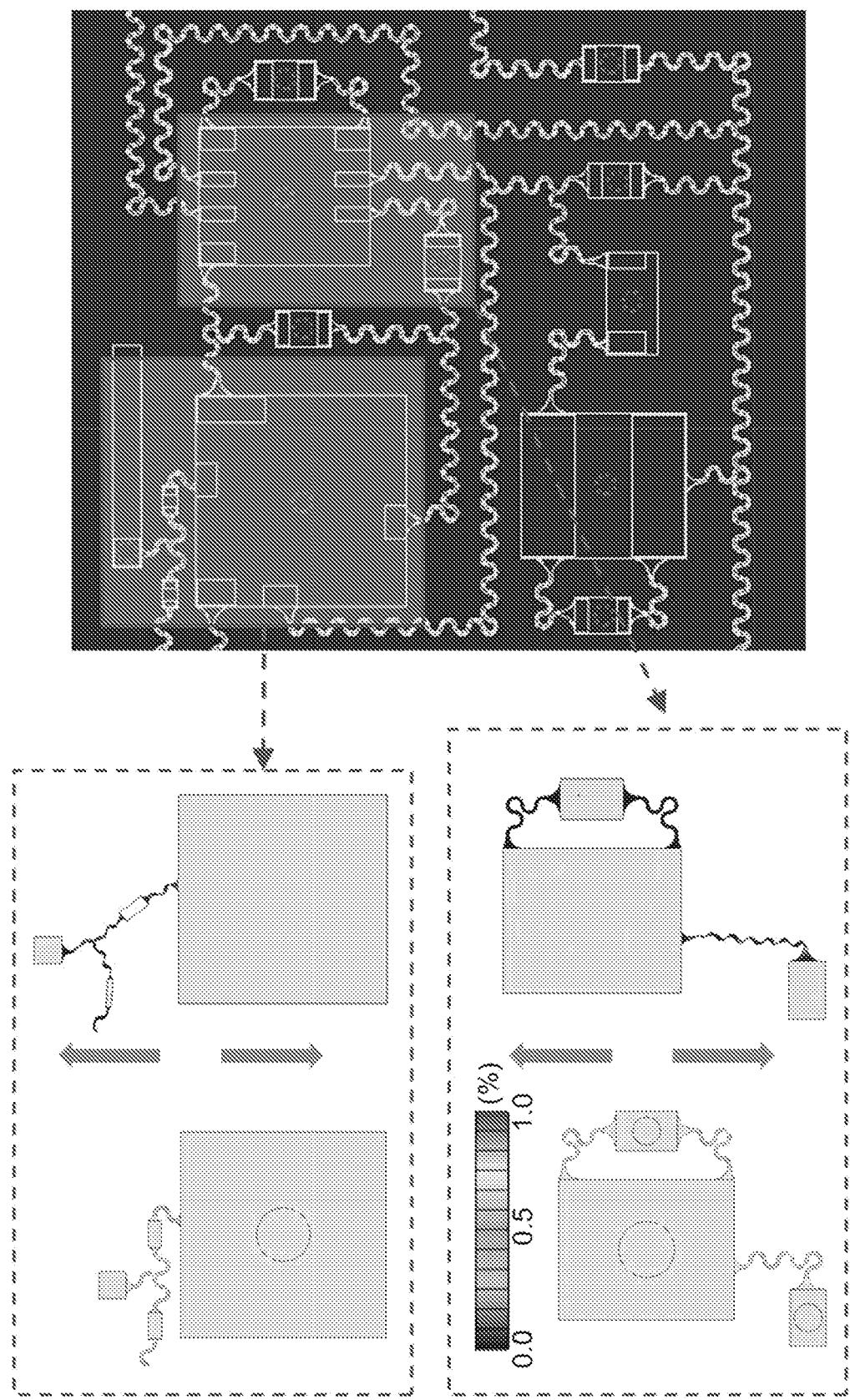


Figure 40

- Overall circuit thickness within 0.5 mm by mechanical decapsulation.
- Releasable contact pads
- Optimized stretchability (30%) vs wire resistance.
- Off centered selective bonding of the hard chips to accommodate the small gap between the chips.
- Selective bonding of the serpentine wires to avoid tangling.

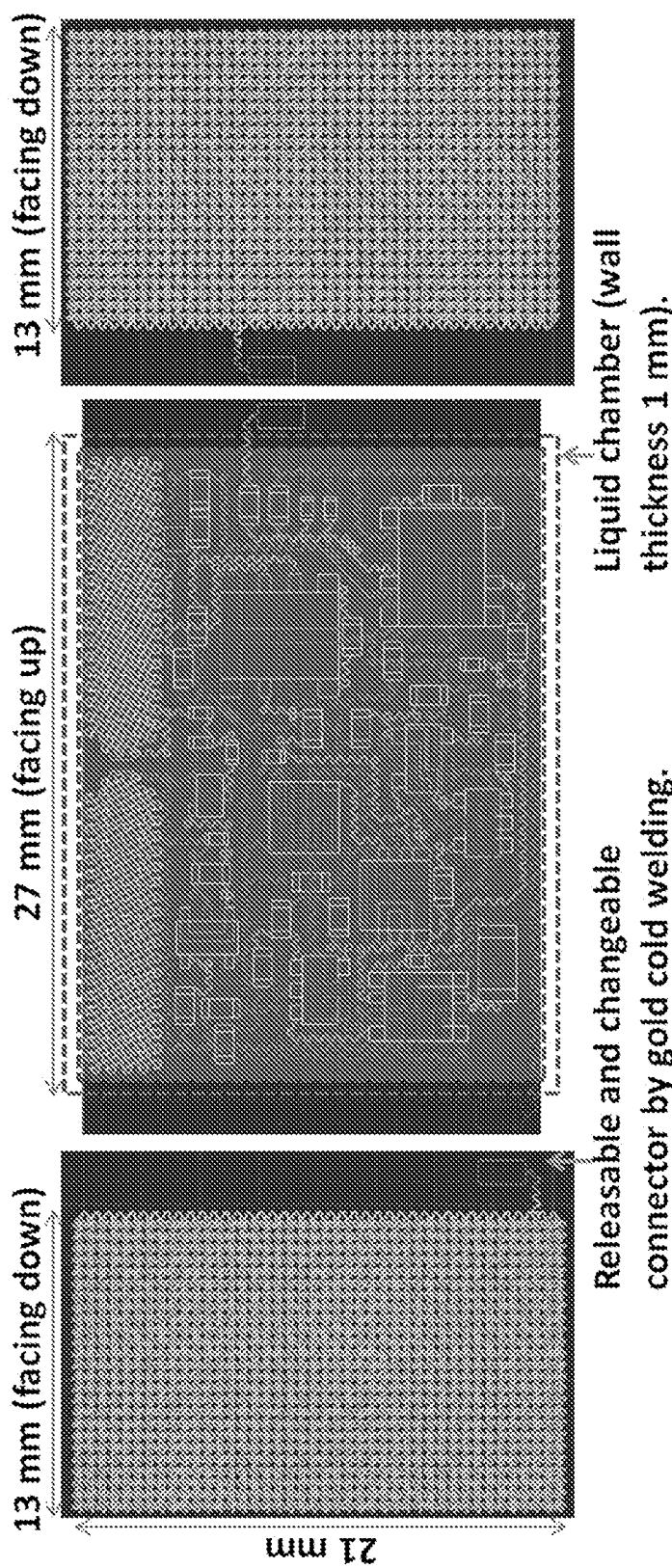


Figure 41

- Using tripod
- With reduced thickness

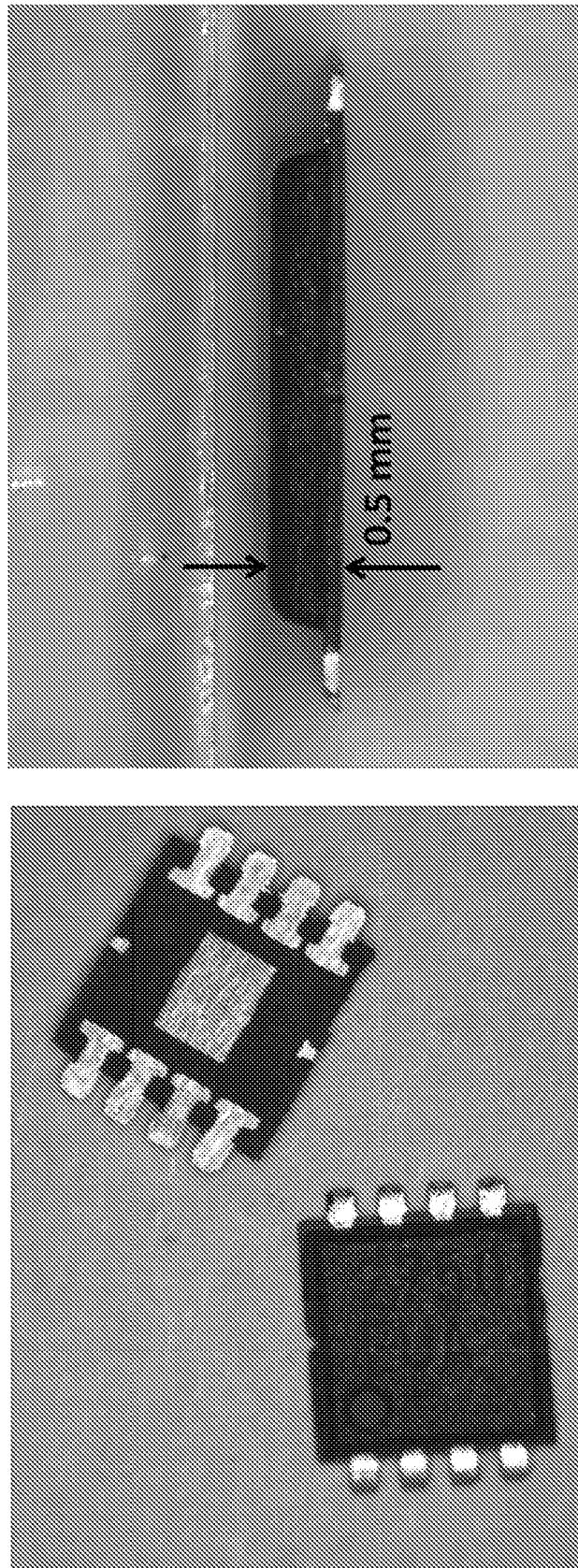


Figure 42

- Self-powered system with RF energy harvesting antenna.
- ECG/EMG/EEG and temperature multifunctional sensing capabilities.
- Wireless data transmission.

Figure 43

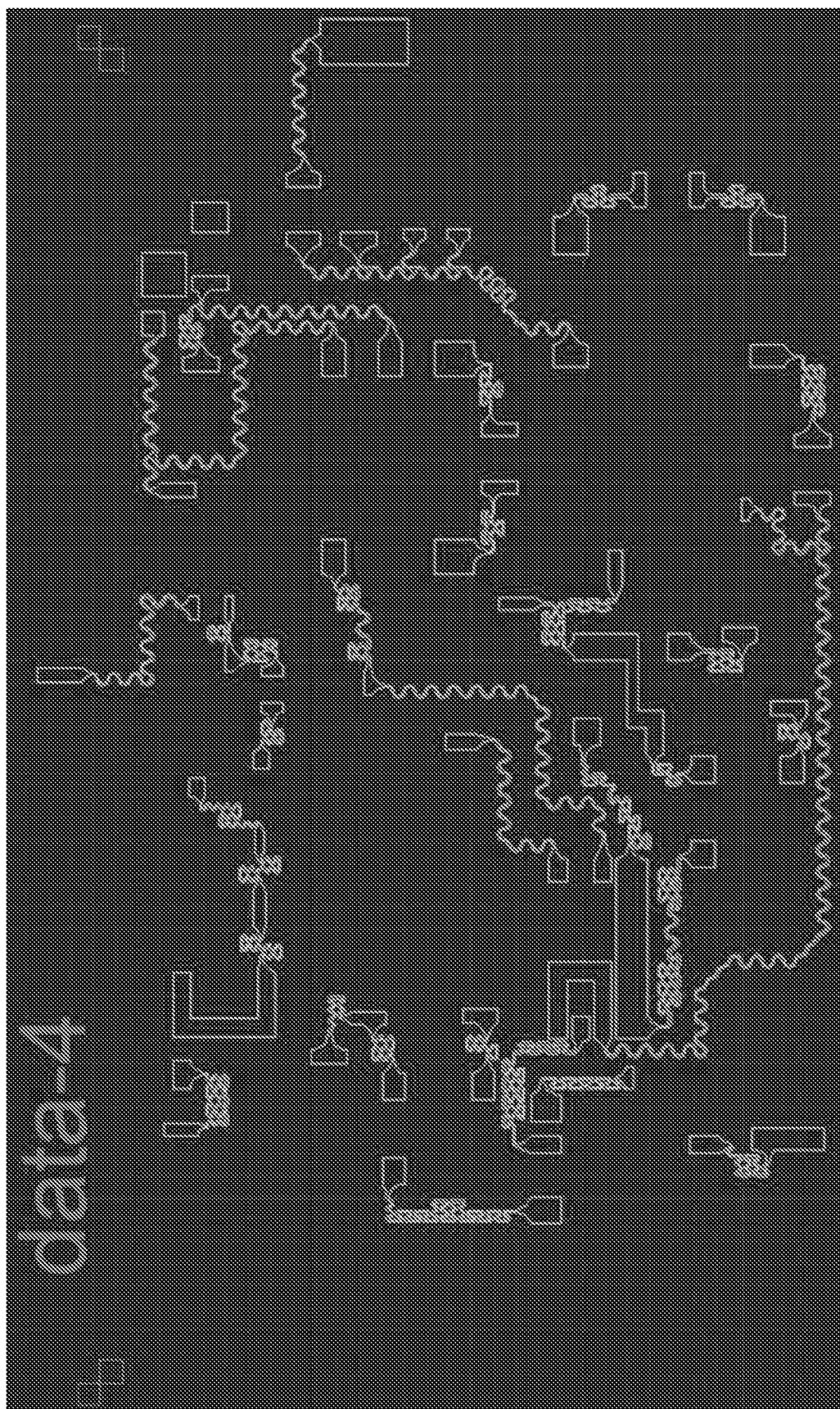


Figure 44

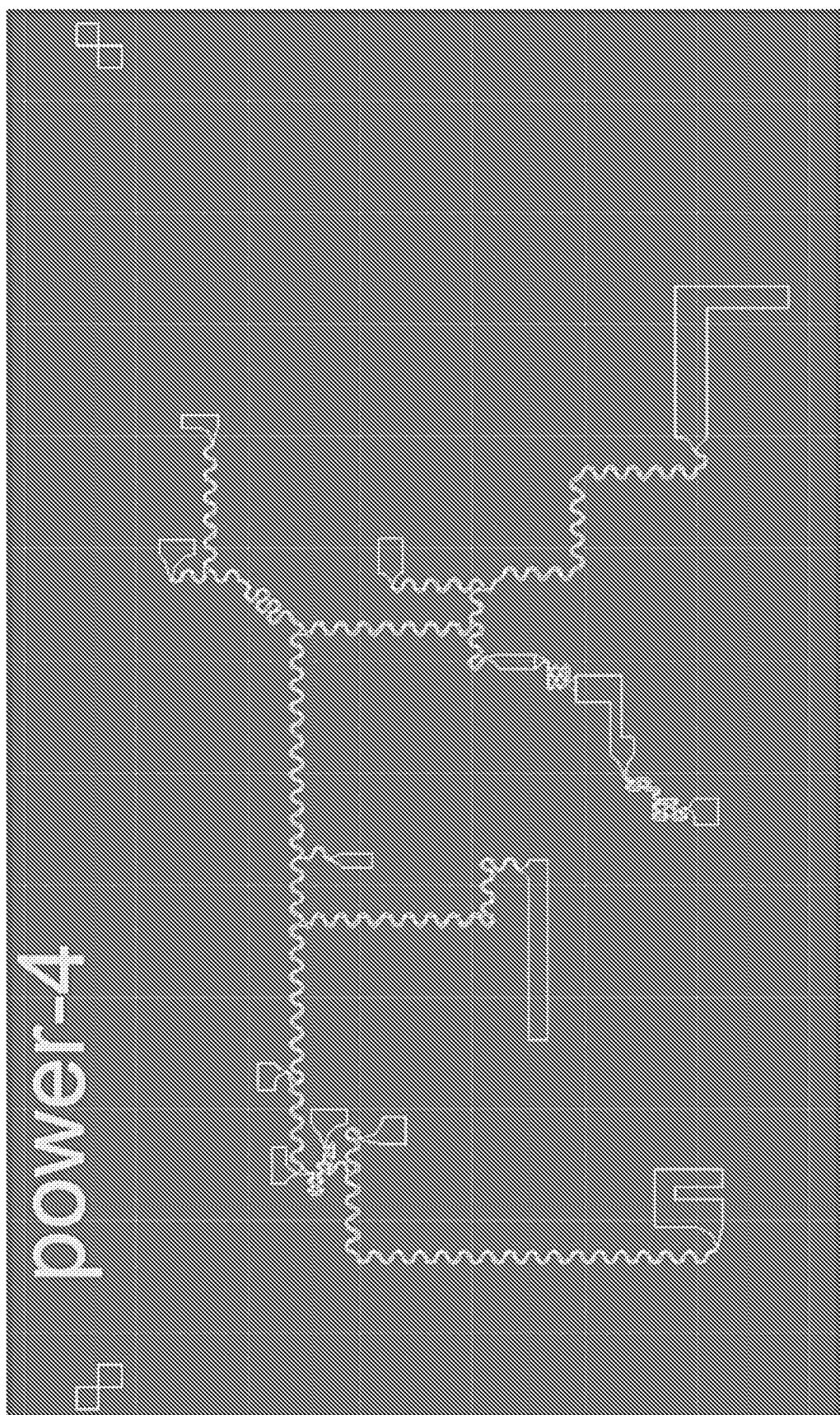


Figure 45

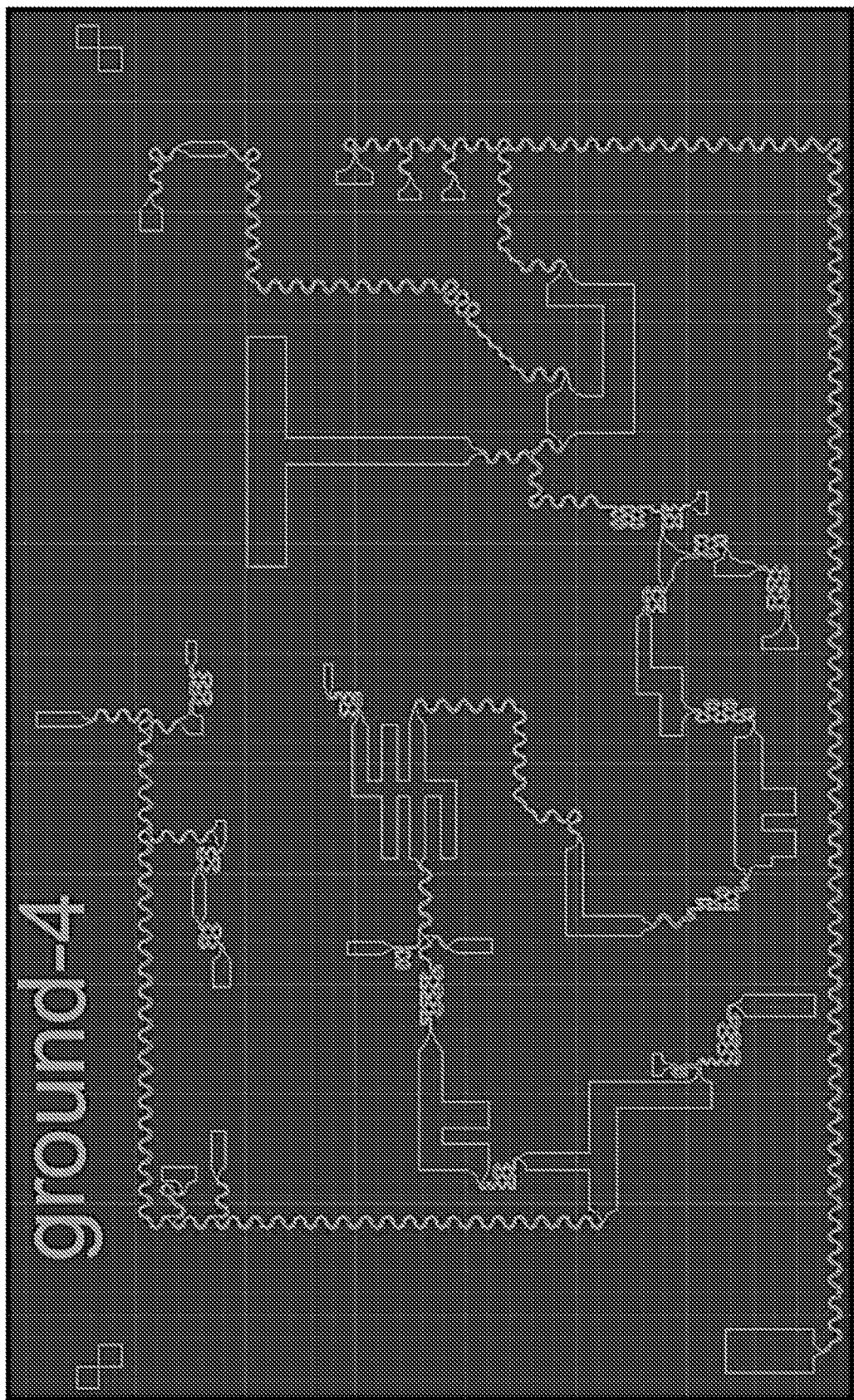


Figure 46

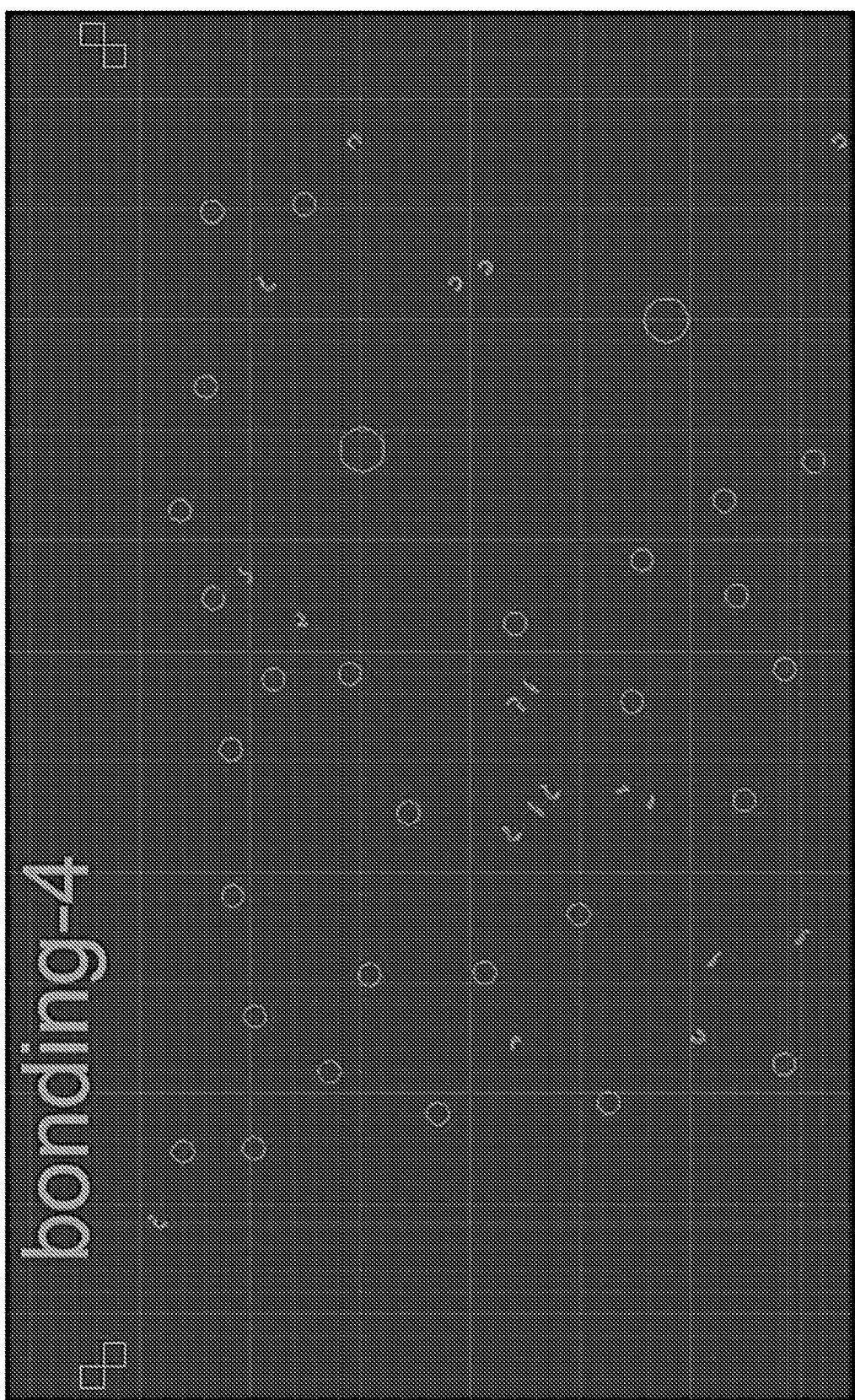
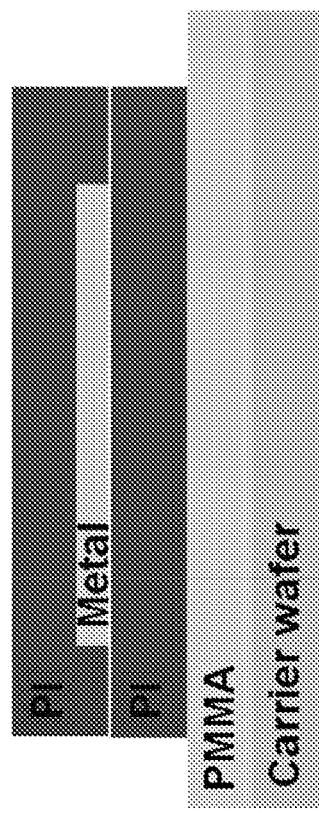


Figure 47

Conventional:



Modified:

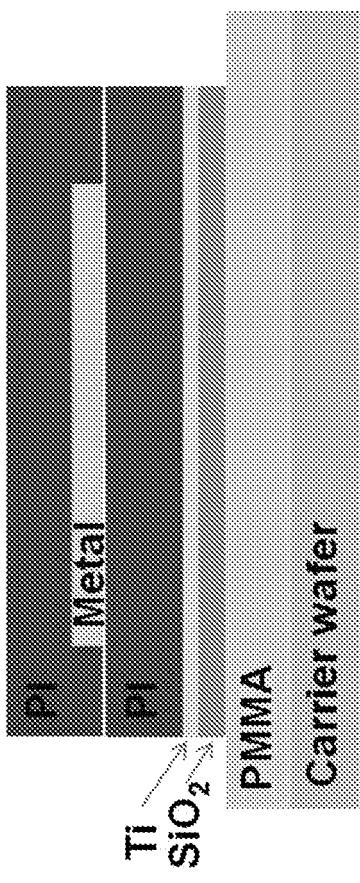


Figure 48

Replaced all of the sharp corners with rounded corners.

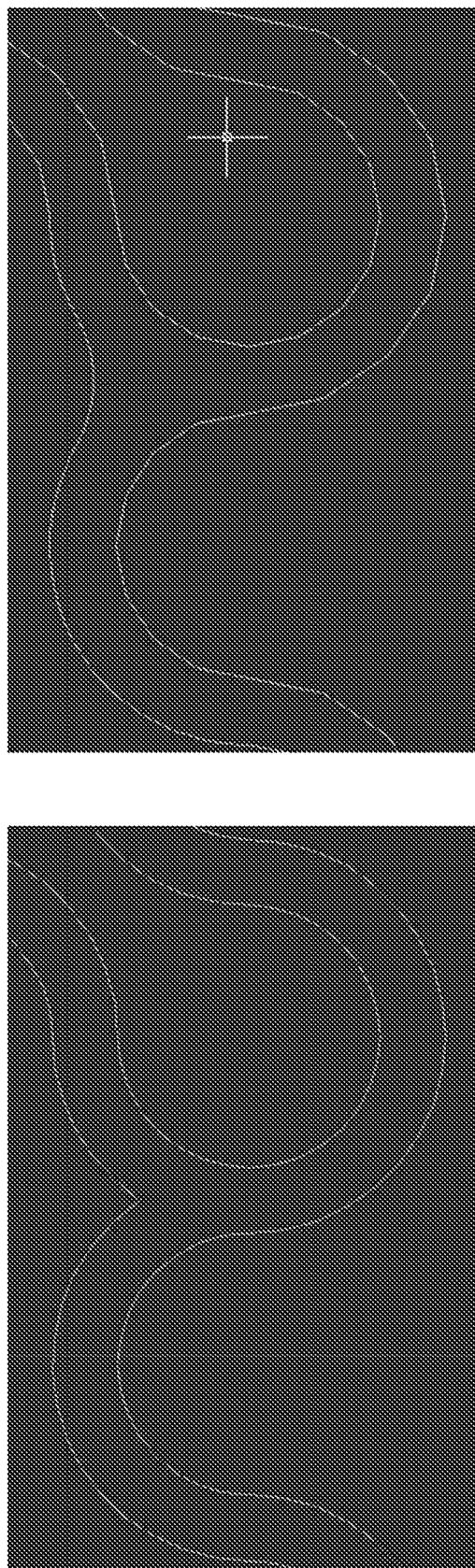


Figure 49

Hybridized conventional serpentine and self-similar interconnects:

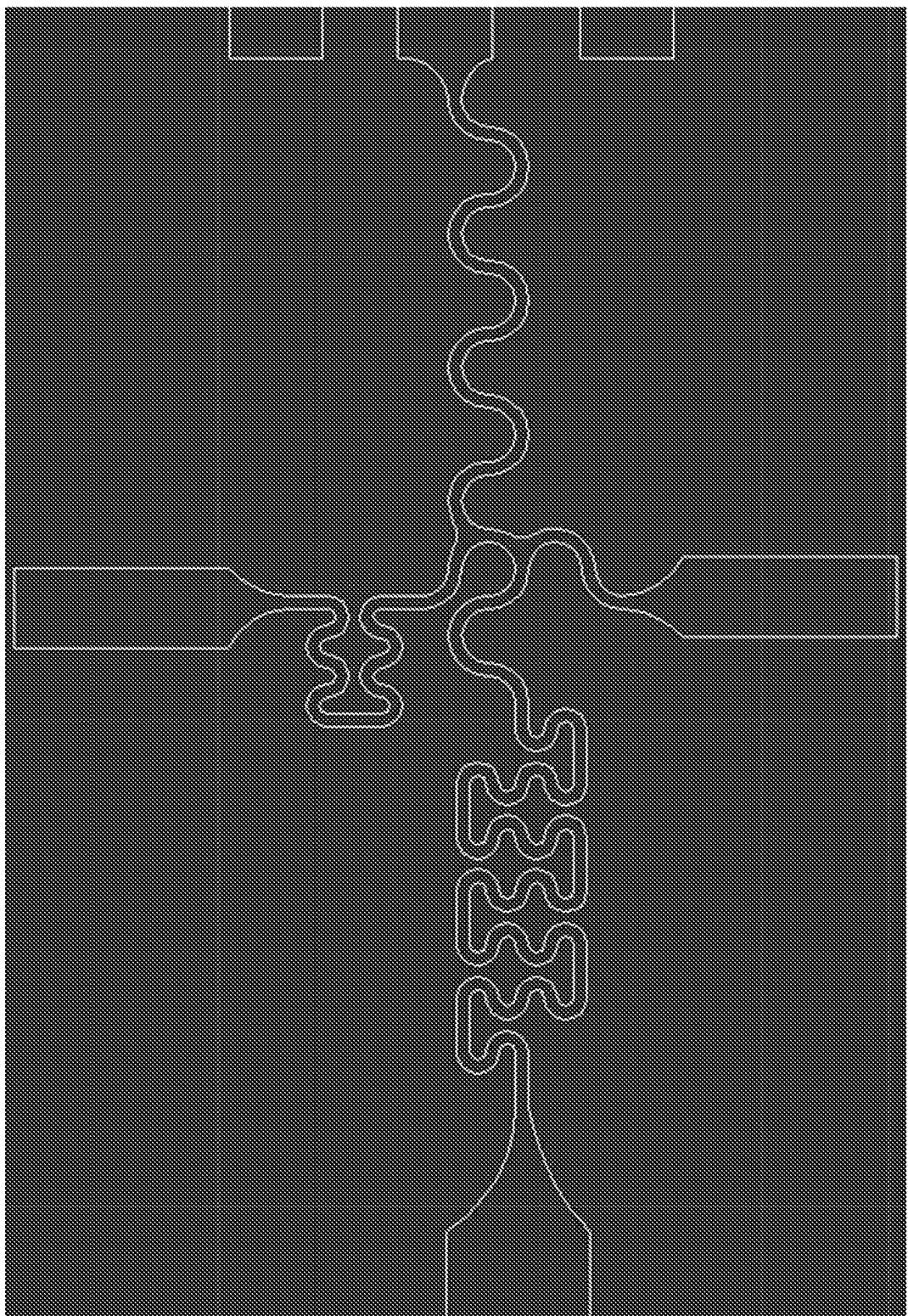


Figure 50

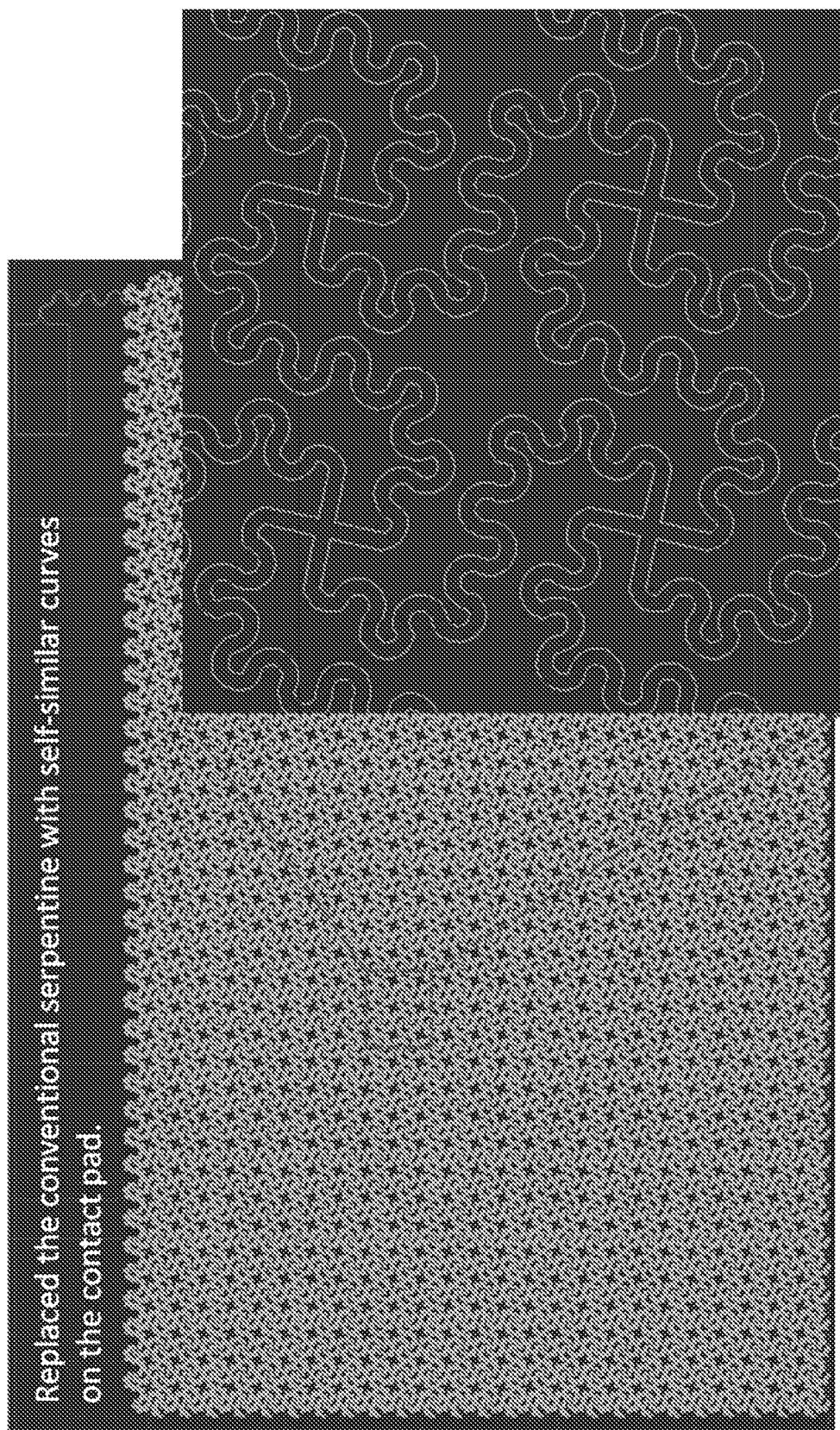
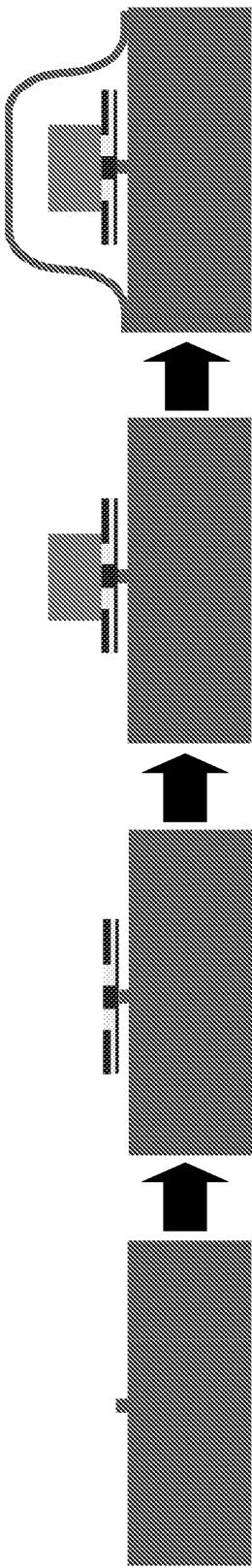


Figure 51

Basic fabrication scheme



Thin silicone substrate with pedestals.

Laminate the interconnectors with selective SiO₂ bonding on the back.

Bond the chips using conductive paste (or flip chip bonder?).

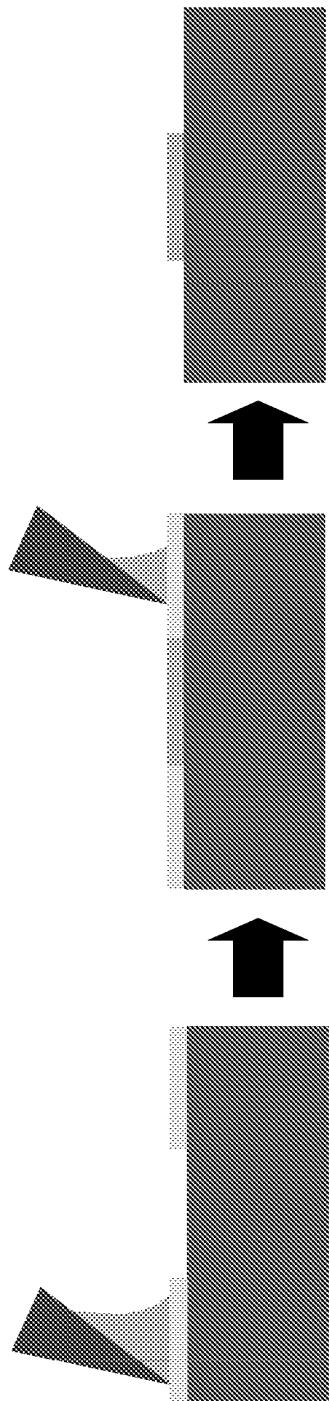
Laminate a top silicone cap to cover all of the chips, heat up to seal, and then inject liquid.

- **Pedestals provide a separation that seeds the cracking between the chip and the substrate.**

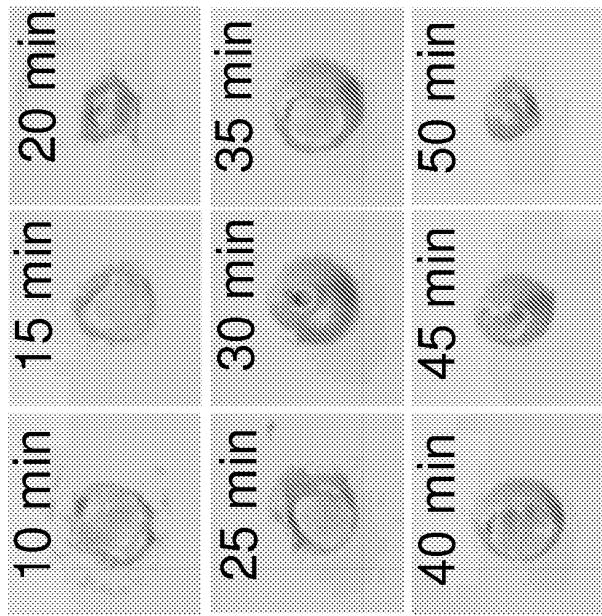
- Liquid chamber:
 1. As lubricant to facilitate the interfacial gliding
 2. As mechanical shock buffer

Figure 52

Conductive paste patterning



By scraping:



By ink-jet printing:

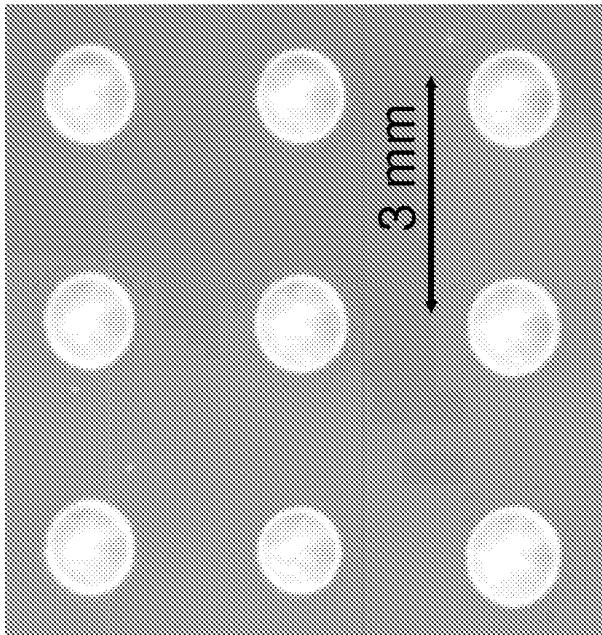
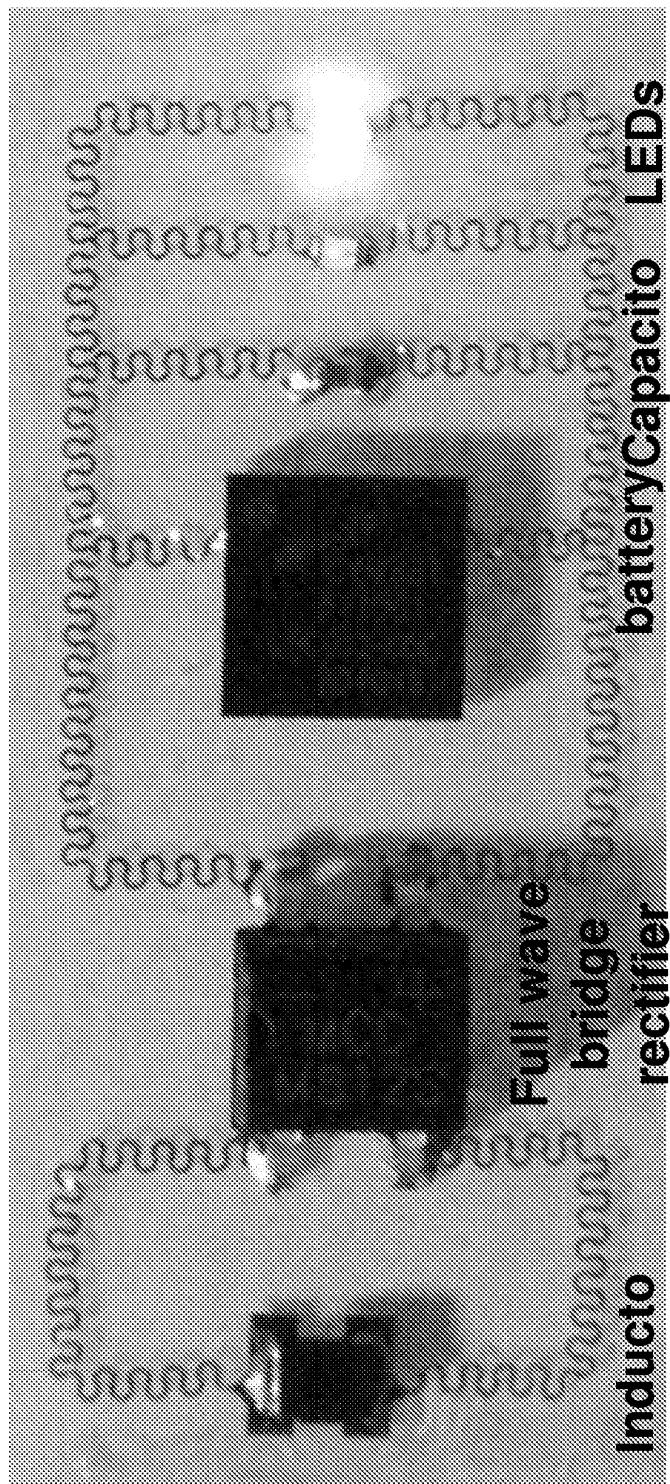


Figure 52

Wireless power circuit



- **Inductor:** resonant frequency ~ 48 MHz
 - Rectifier: Schottky diode based
- **Battery:** internal resistance ~ 2000 Ohm
 - LEDs: resistance ~ 10 Ohm
- **Capacitor:** to smooth out the fluctuation

Figure 54

Wireless circuit stretching

EP 2 954 762 B1

- Stretchability: ~100%
- Fully bonded wires

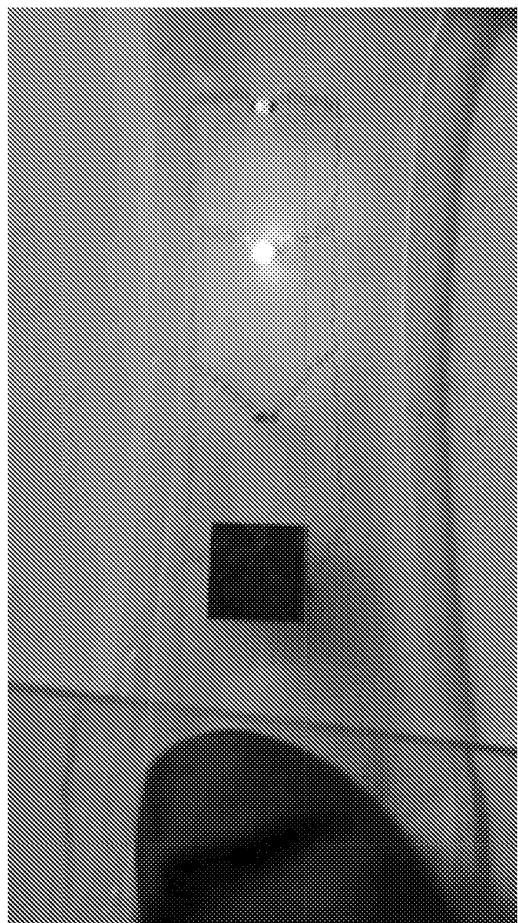


Figure 55

ECG circuit

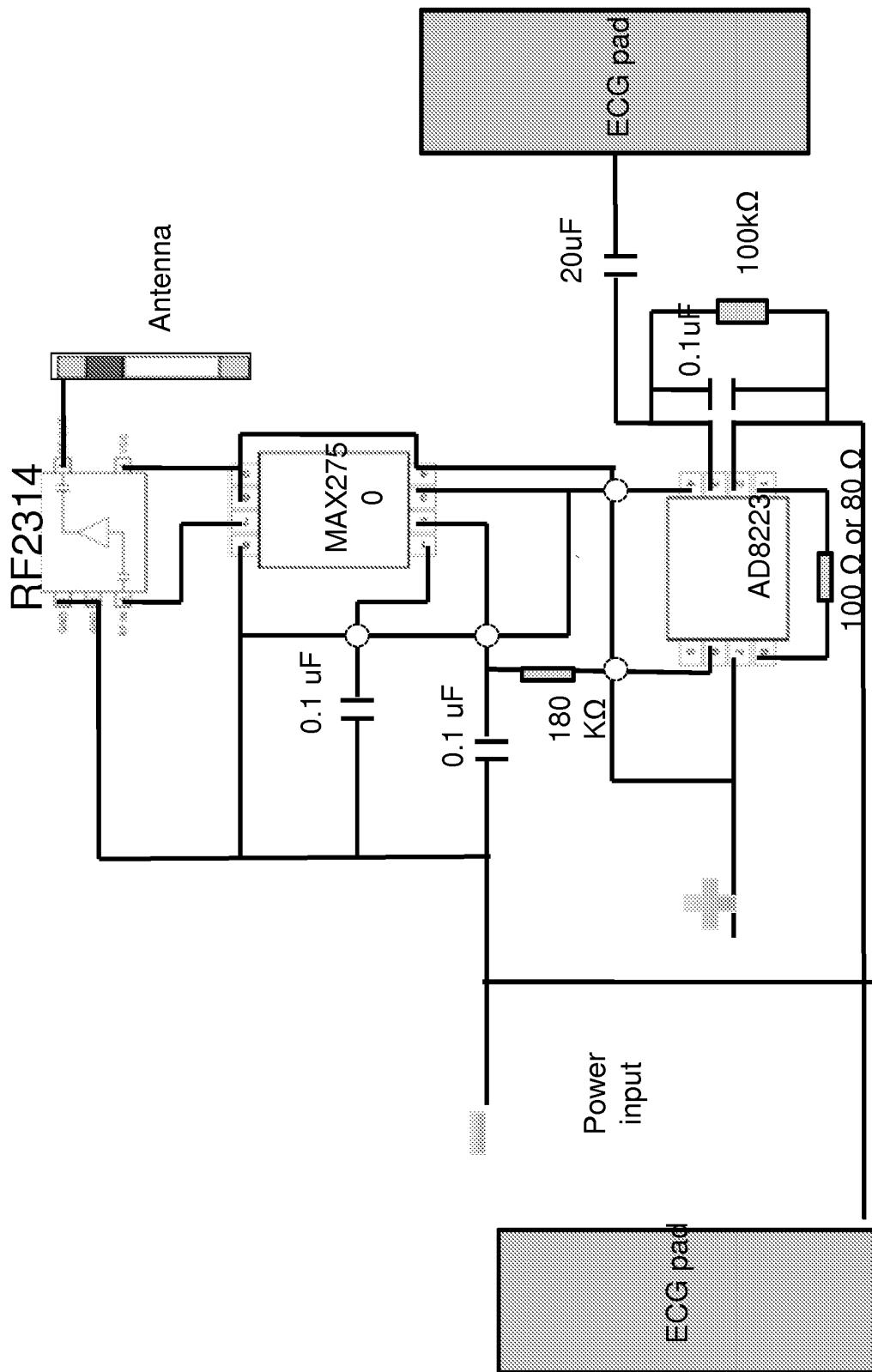
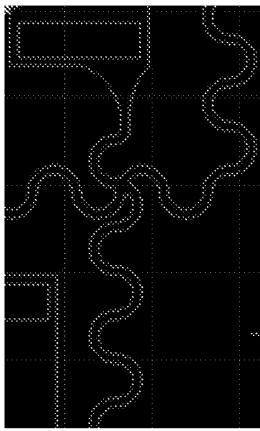


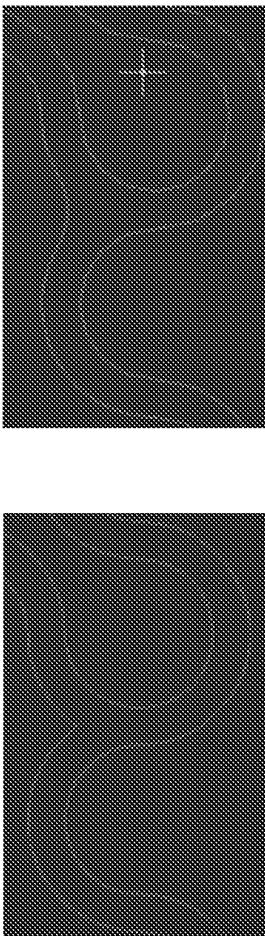
Figure 56

Layout design considerations (5)

1. Self-similar vs conventional serpentine.



2. Replaced all of the sharp corners with rounded corners.



3. Selective bonding
of the serpentine
wires to avoid
tangling.

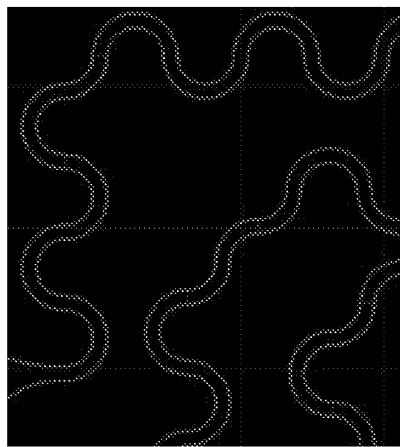


Figure 57

Layout design considerations (6)

**Off-centered bonding to accommodate the small gap between
the chips :**

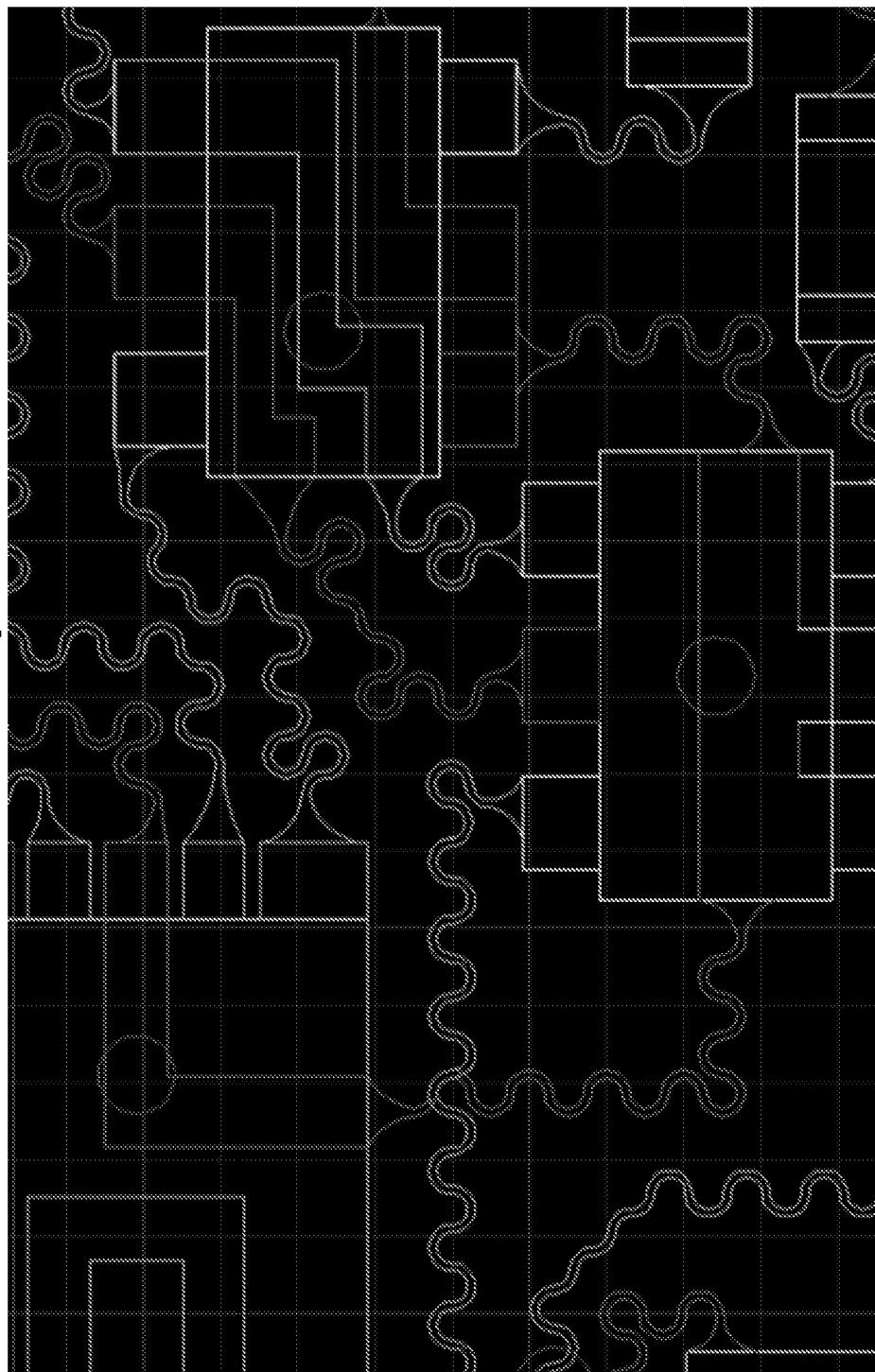


Figure 58

Layout design considerations (7)

Adjusted the chip size after depackaging:

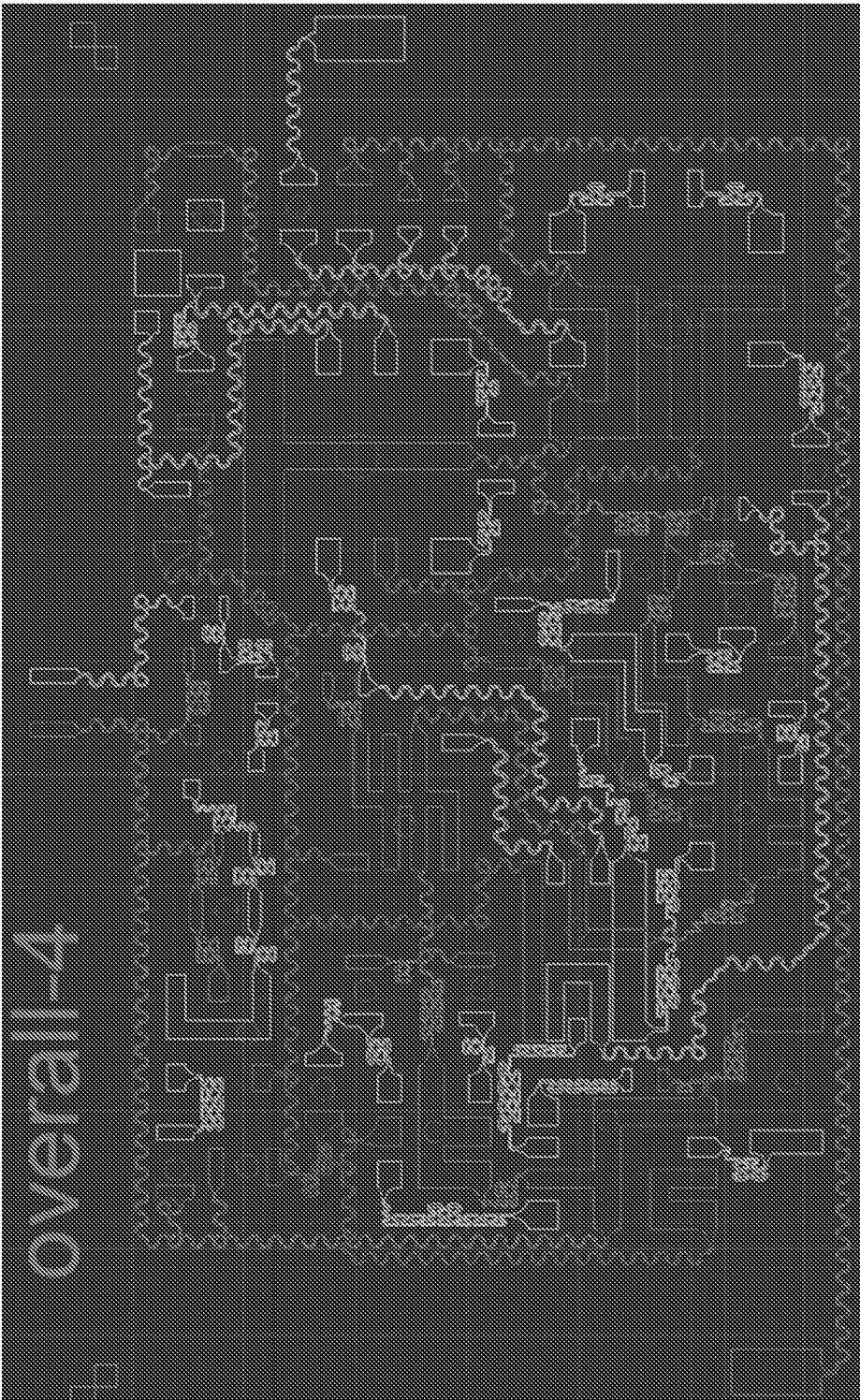


Figure 59

As fabricated interconnects

Layered structure:

- PI (1.2 µm)
- Data: Al (600 nm)
- PI (1.2 µm)
- Ground: Cu (600 nm)
- PI (1.2 µm)
- Power: Cu (500 nm)/Au (100 nm)
- PI (1.2 µm)

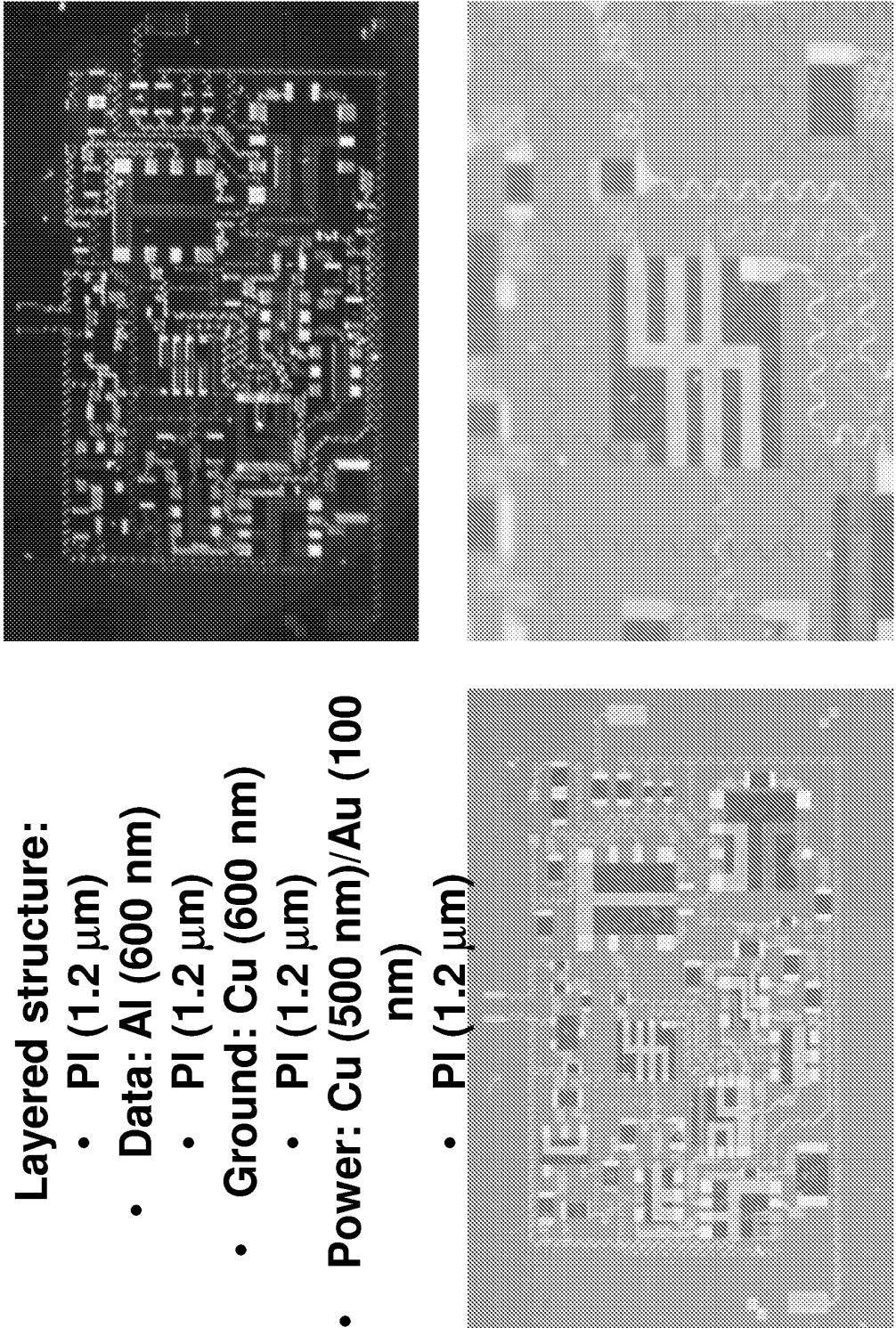
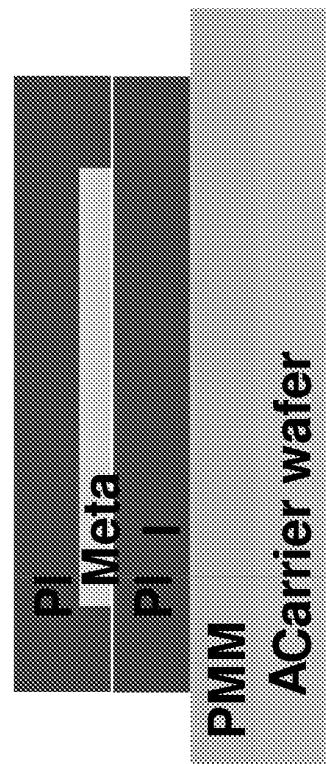


Figure 60

Selective bonding with new fabrication process

Conventional:



Modified:

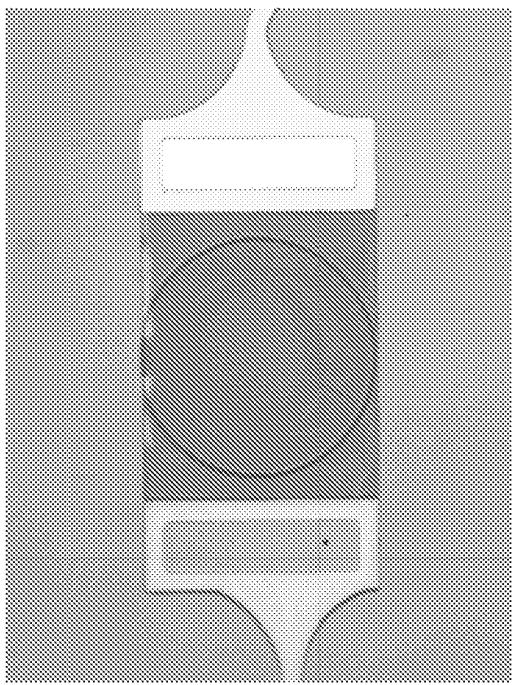
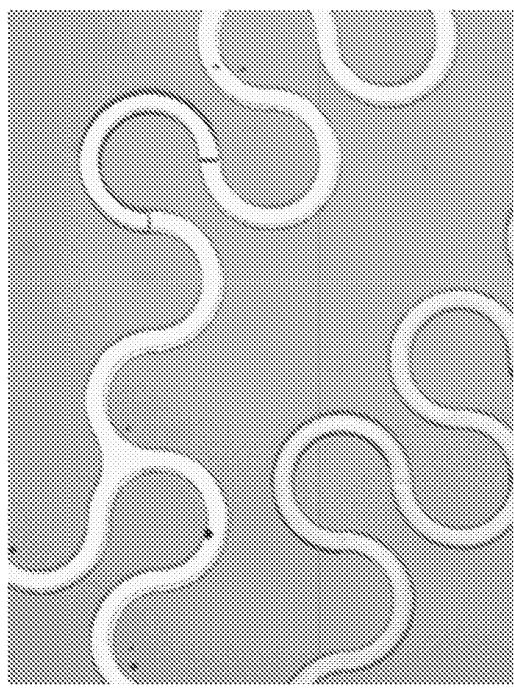
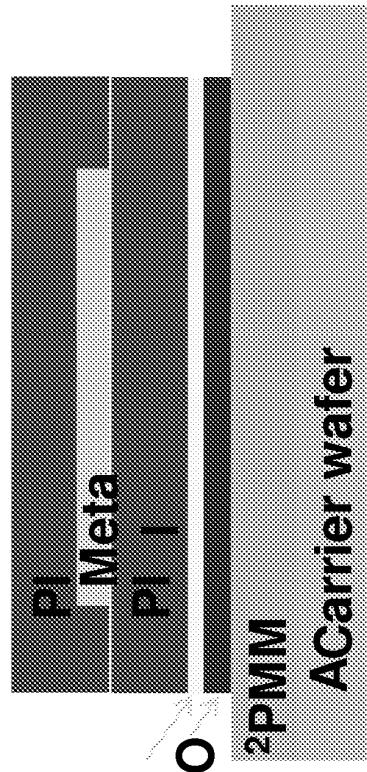
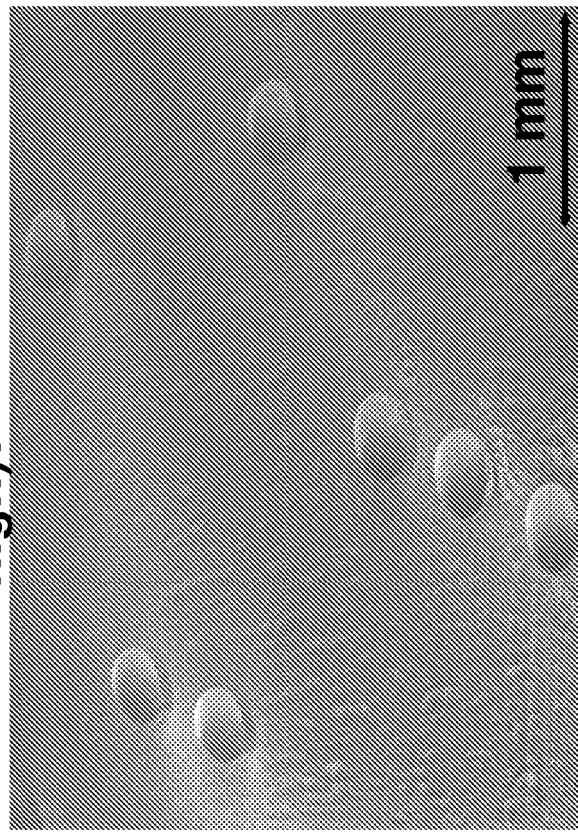


Figure 61

Pedestals and bonded interconnects

Pedestals (~100 μm high):



Interconnects selectively bonded on pedestals:

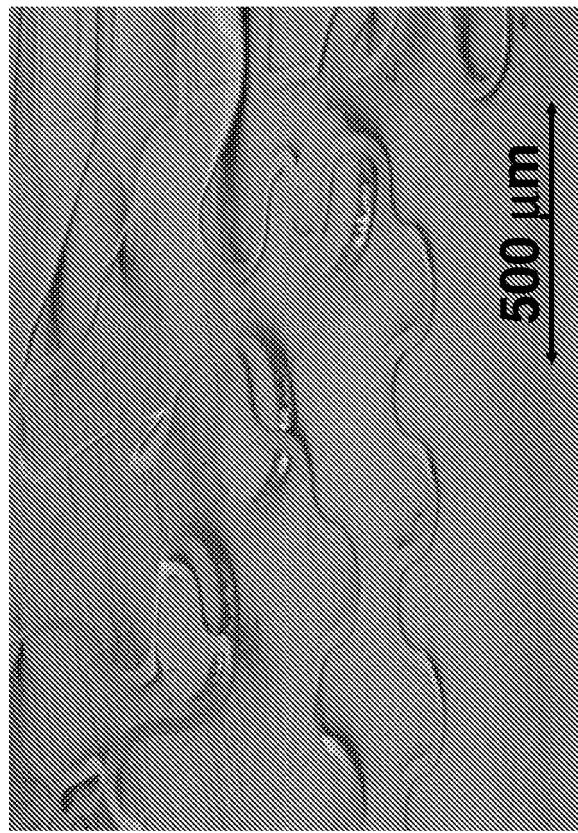
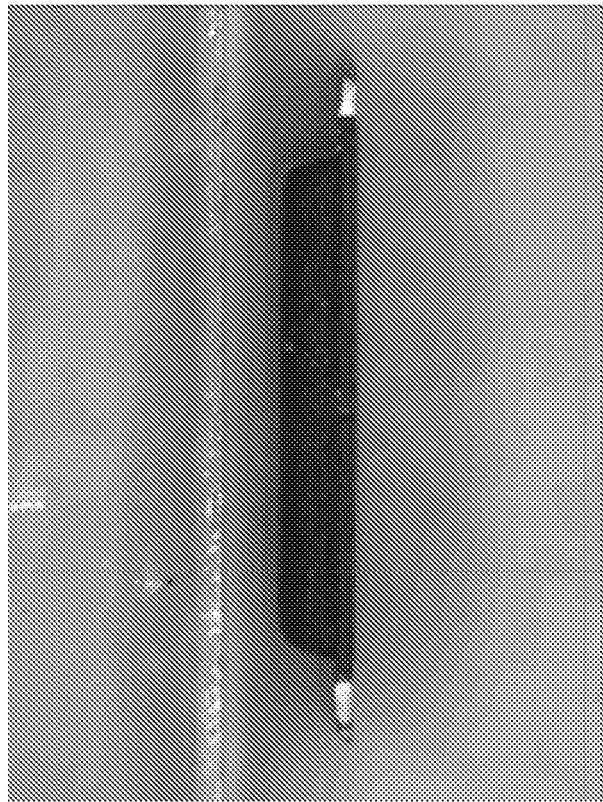


Figure 62

Chip depackaging

**Halfly depackaged by
mechanical polishing:**



**Fully depackaged by acid
etching:**

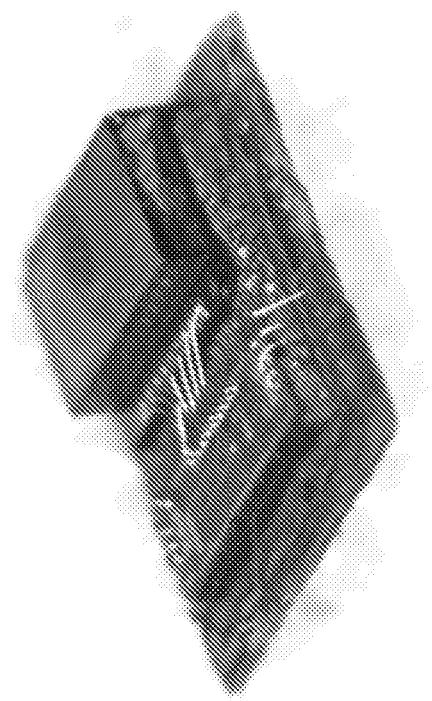


Figure 63

As fabricated device

Made of COTS chips (overall thickness ~3 mm):

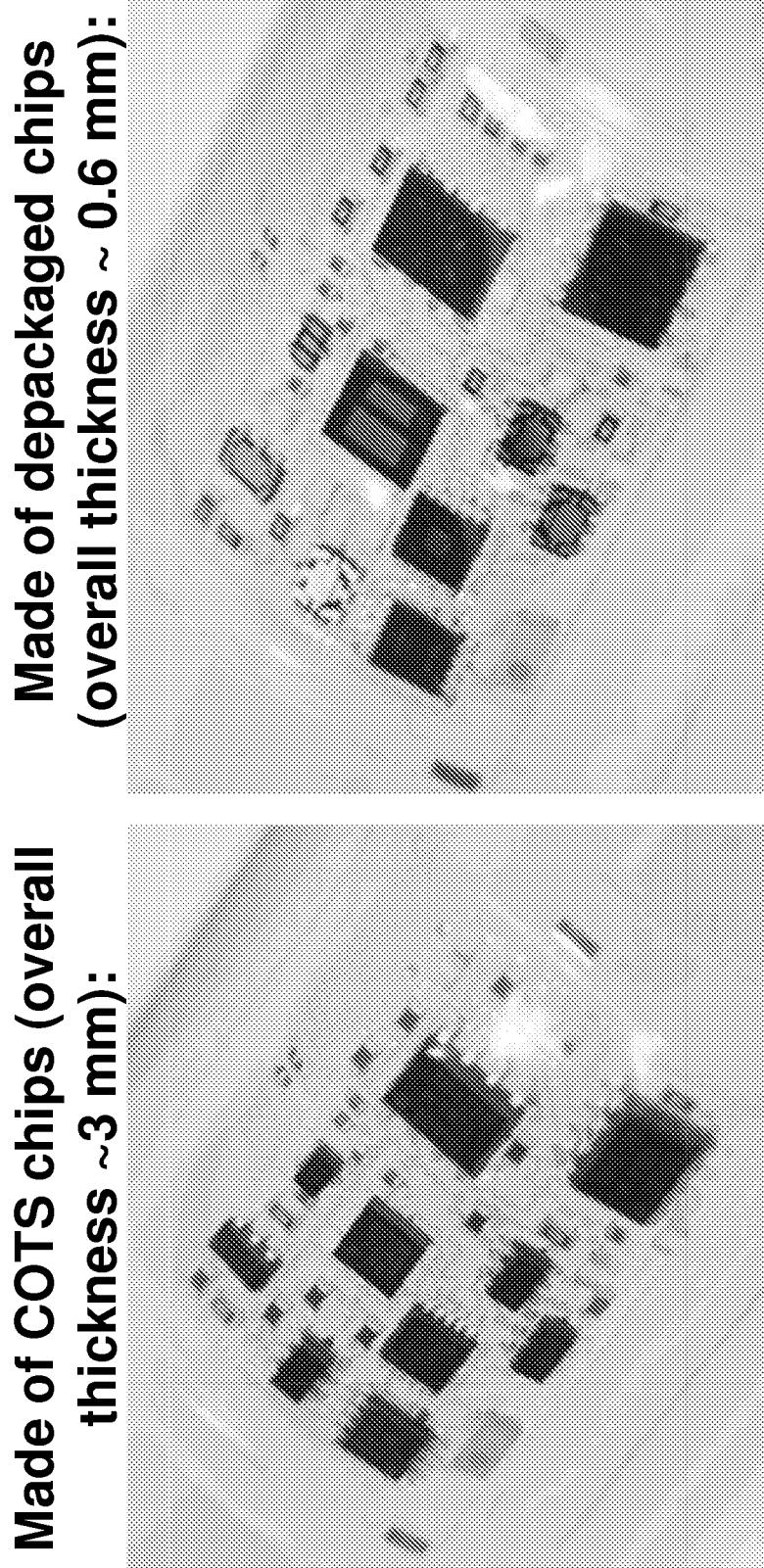
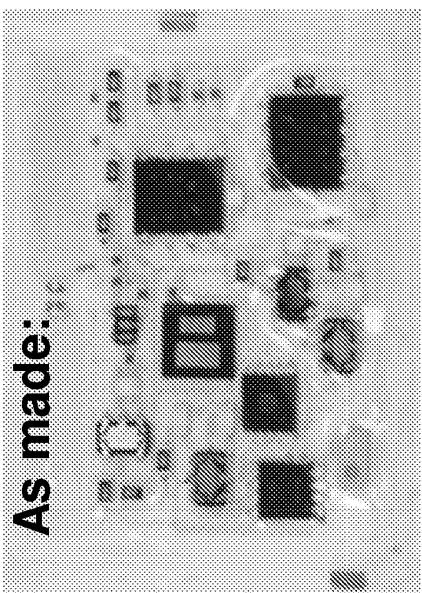
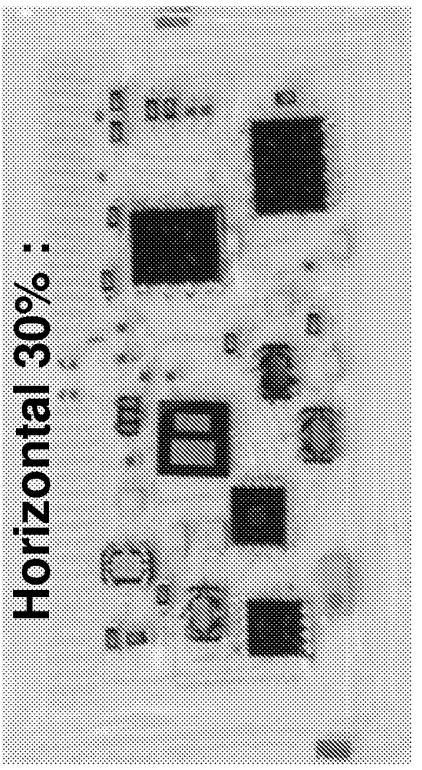


Figure 64

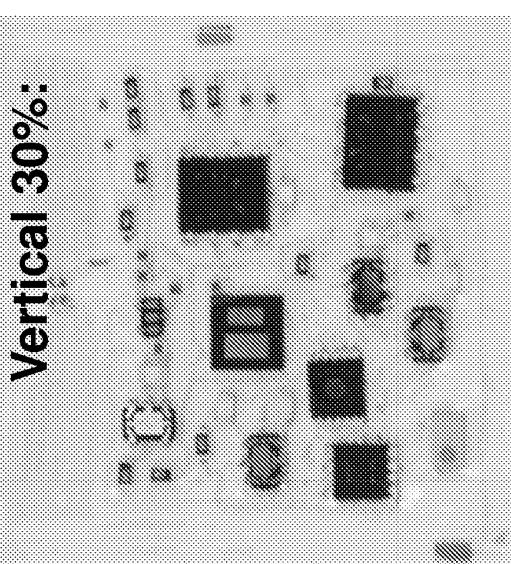
Device stretching and flexing



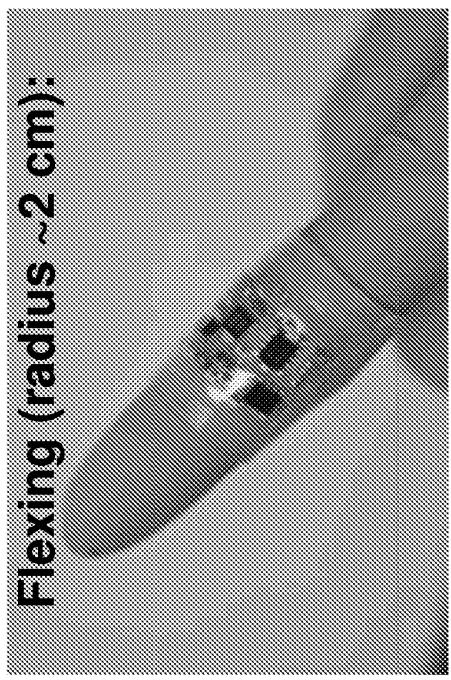
As made:



Horizontal 30% :



Vertical 30%:



Flexing (radius ~2 cm):

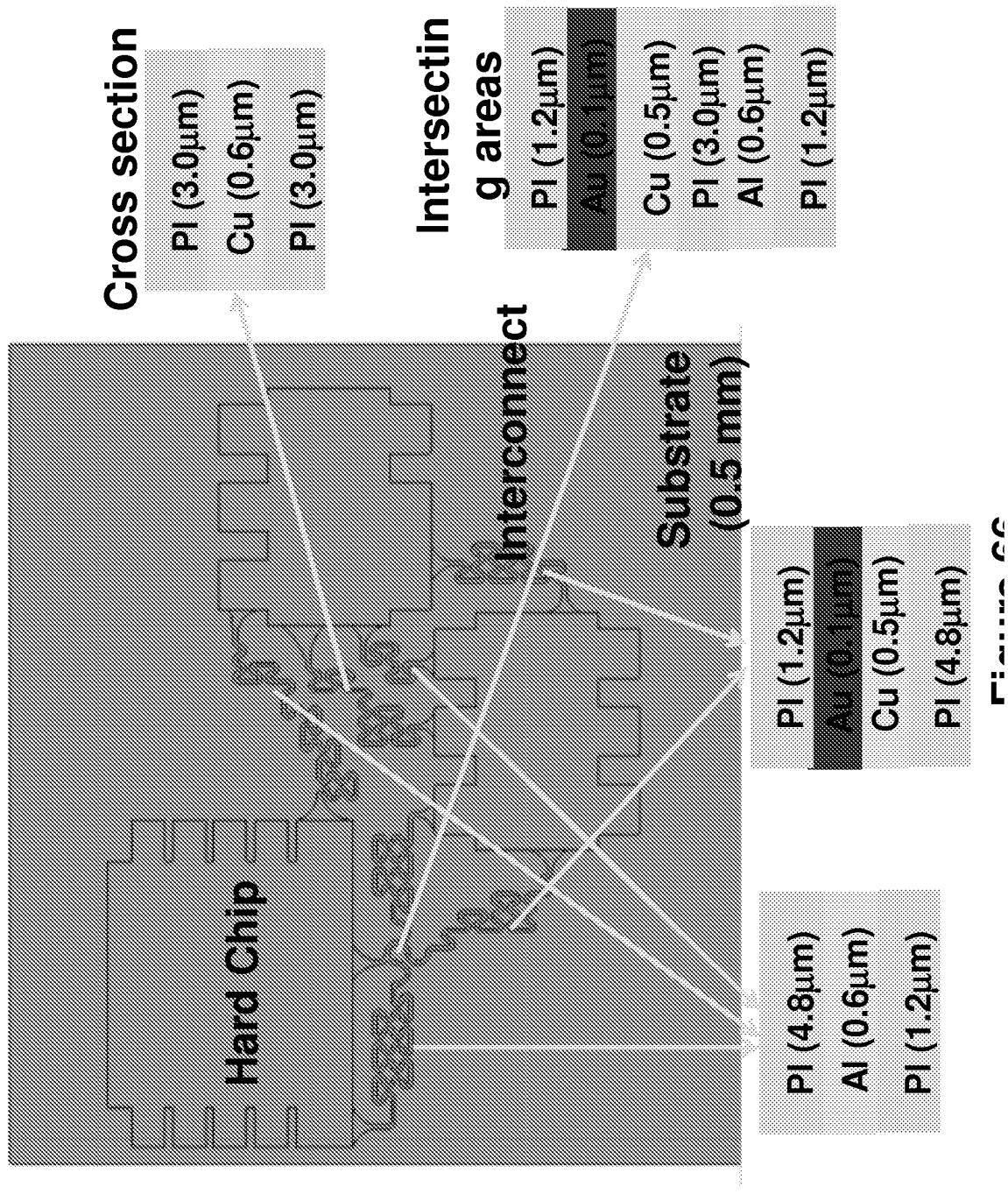
Chip rotation:

Small bonding area ($\sim 1 \text{ mm}^2$) and anisotropic strain distribution

Figure 65

Mechanics analyses (Y. Huang@Northwestern)

EP 2 954 762 B1



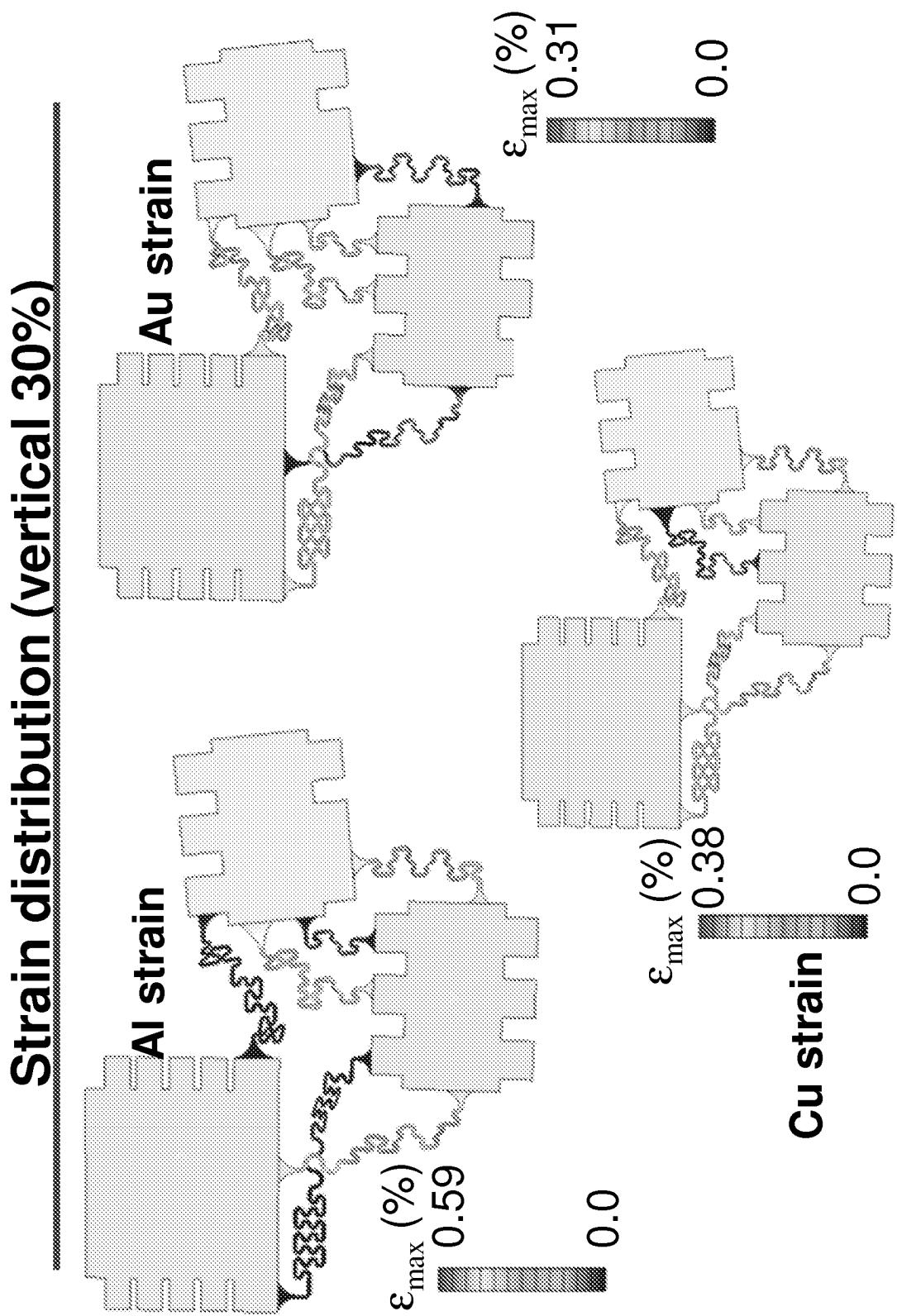


Figure 67

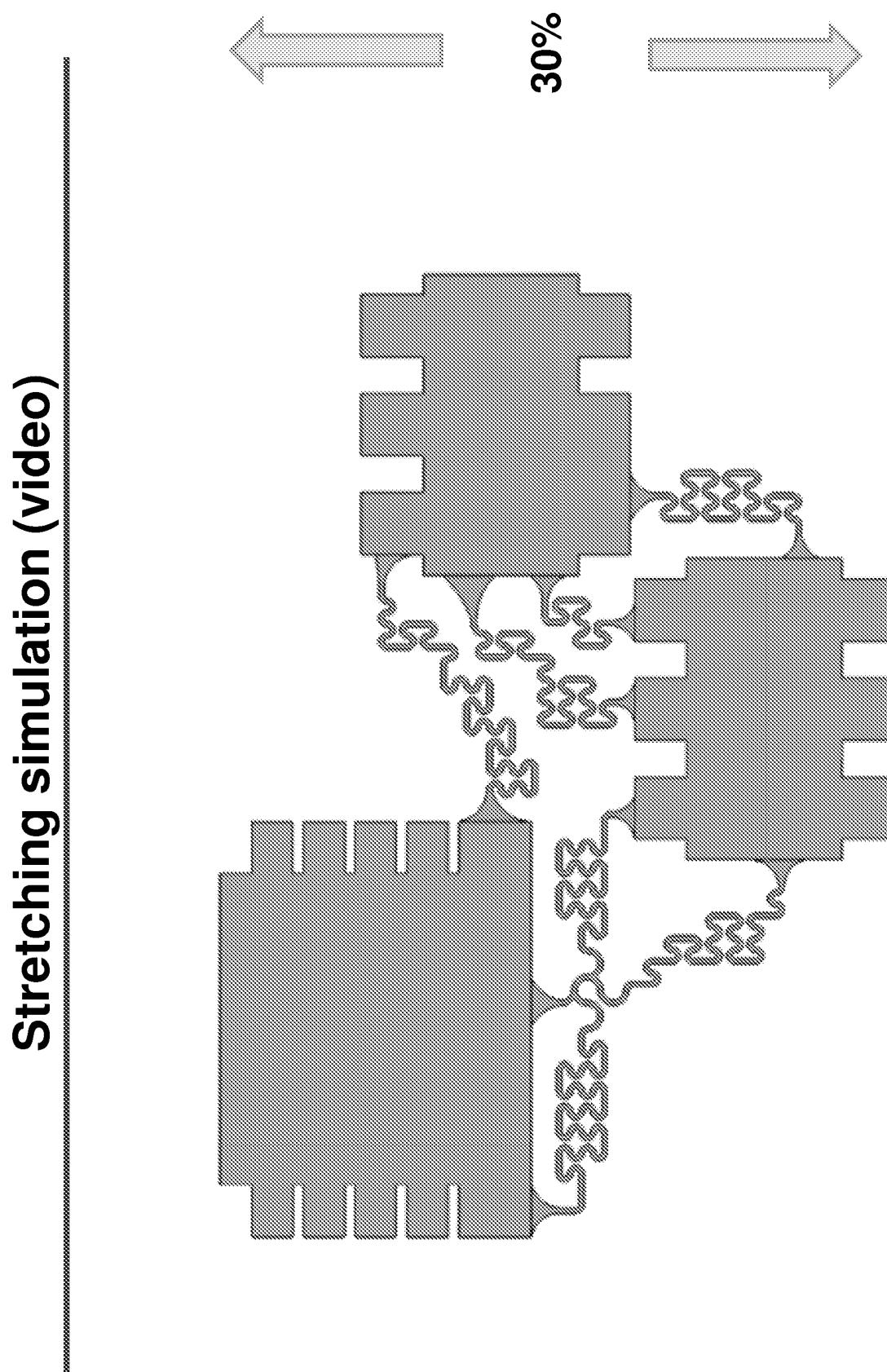


Figure 68

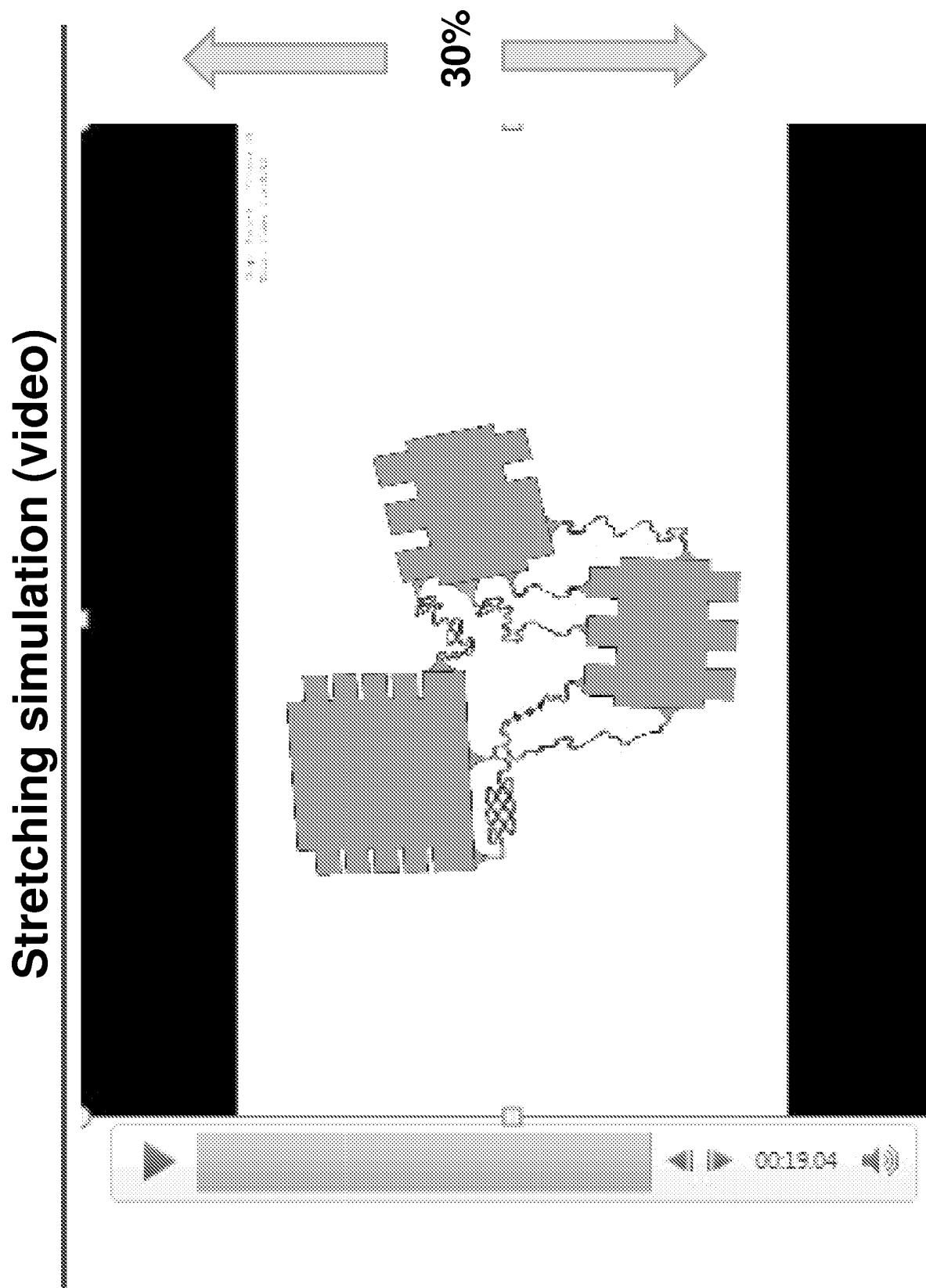


Figure 69

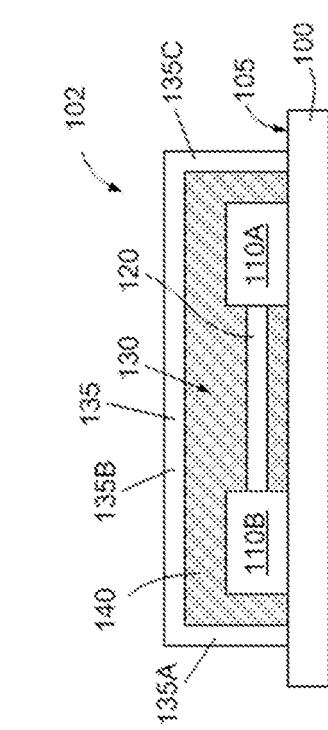


Figure 70A

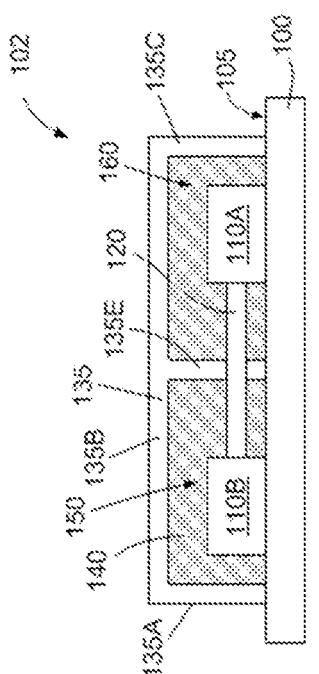


Figure 70C

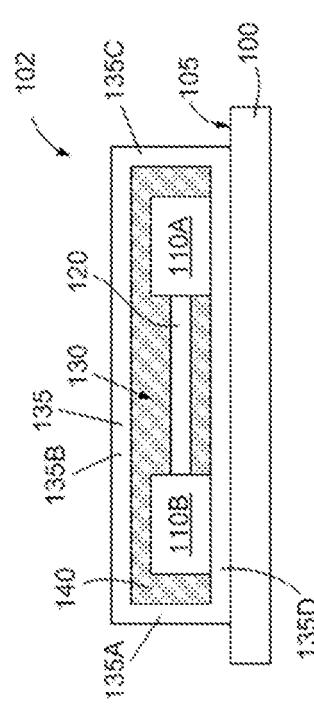


Figure 70B

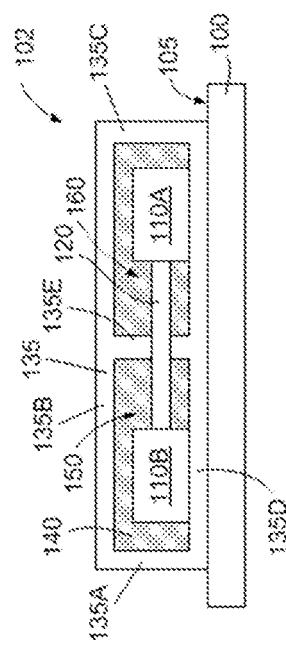


Figure 70D

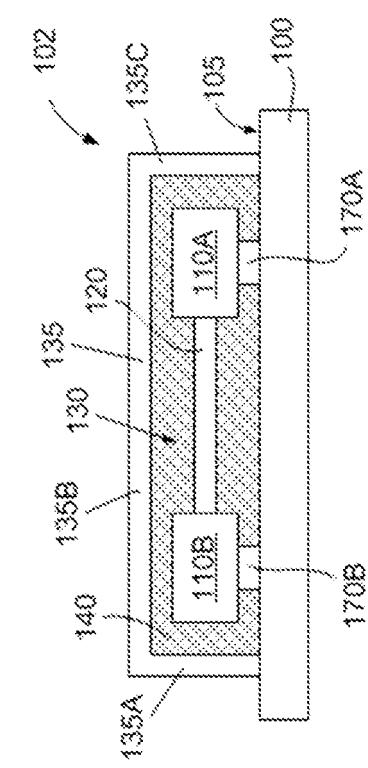


Figure 70E

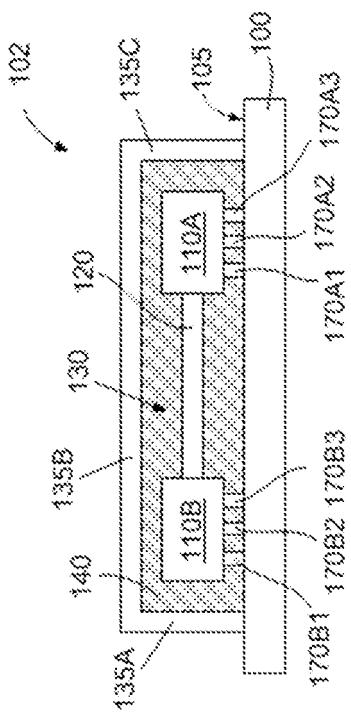


Figure 70G

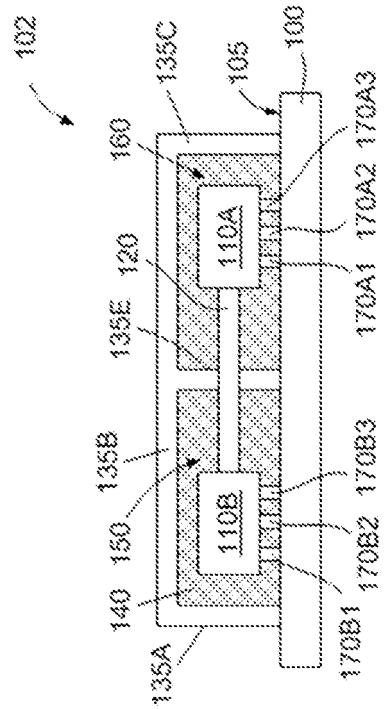


Figure 70H

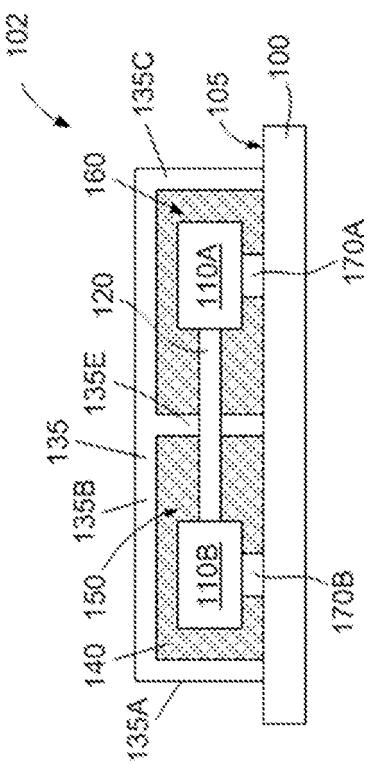


Figure 70F

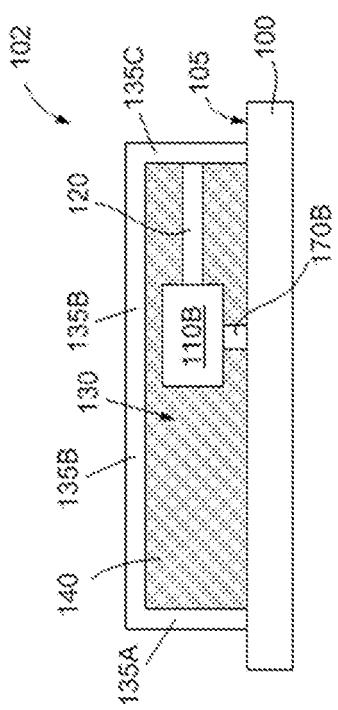


Figure 70I1

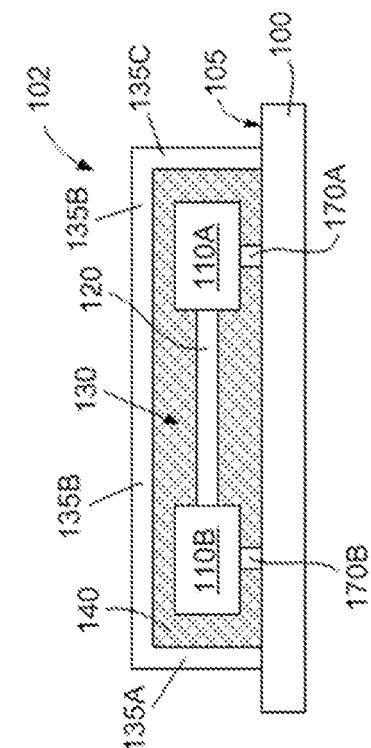


Figure 70J1

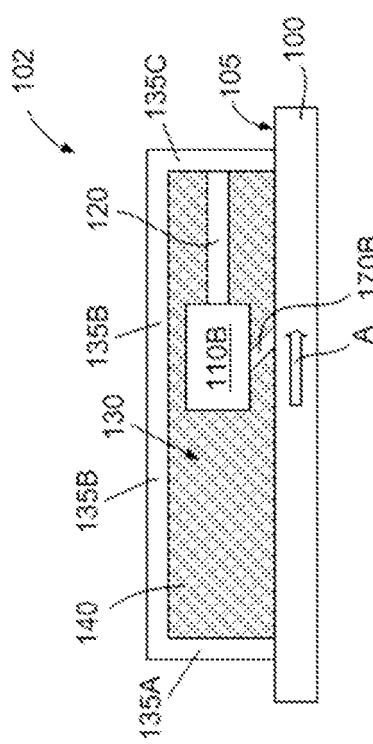


Figure 70I2

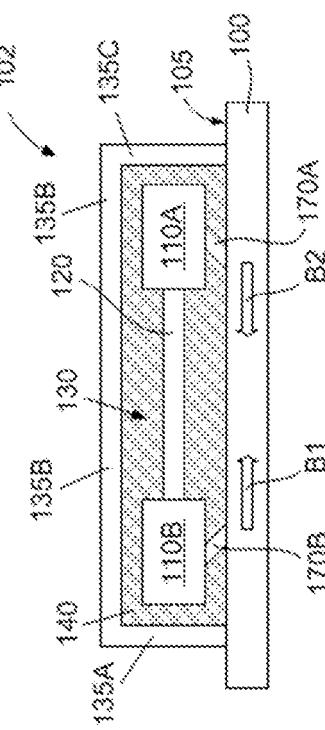


Figure 70J2

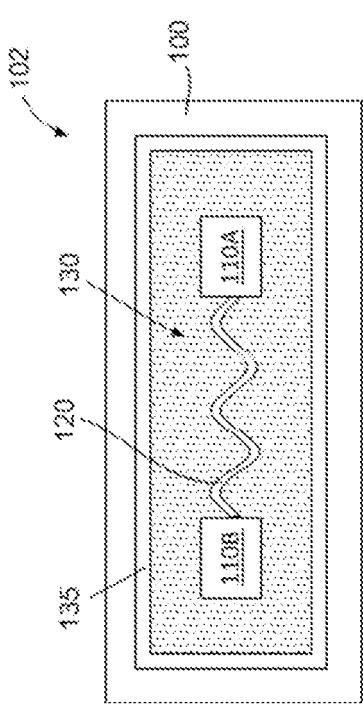


Figure 70K

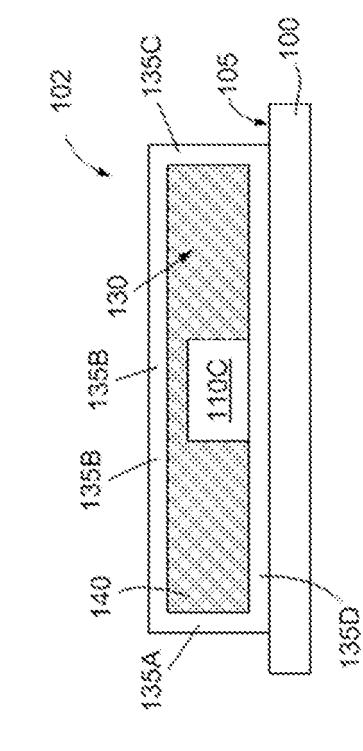


Figure 70M

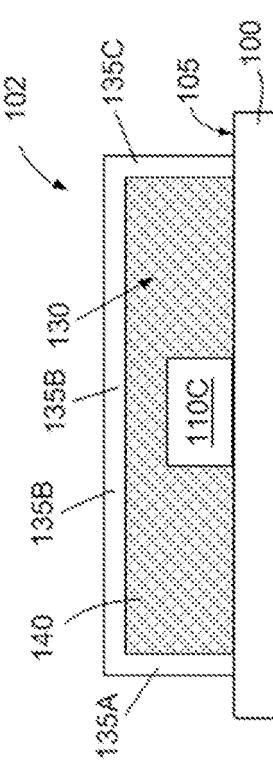


Figure 70L

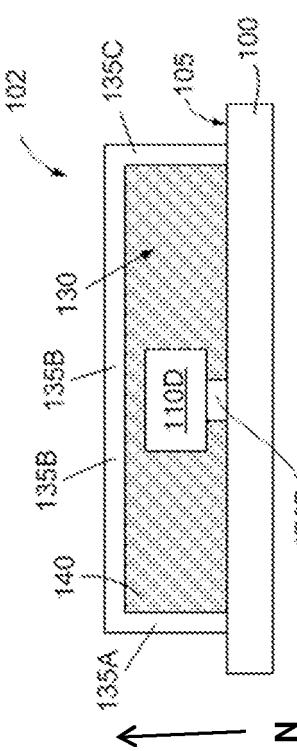


Figure 70N

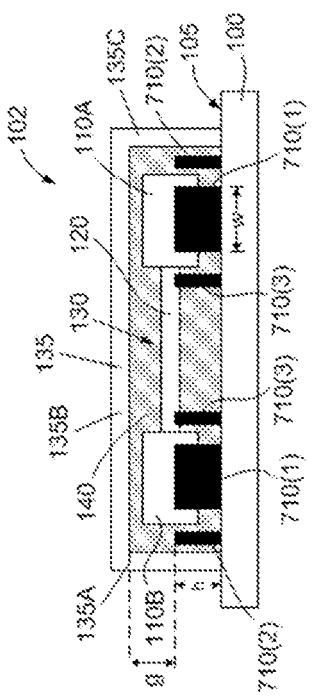


Figure 70Q

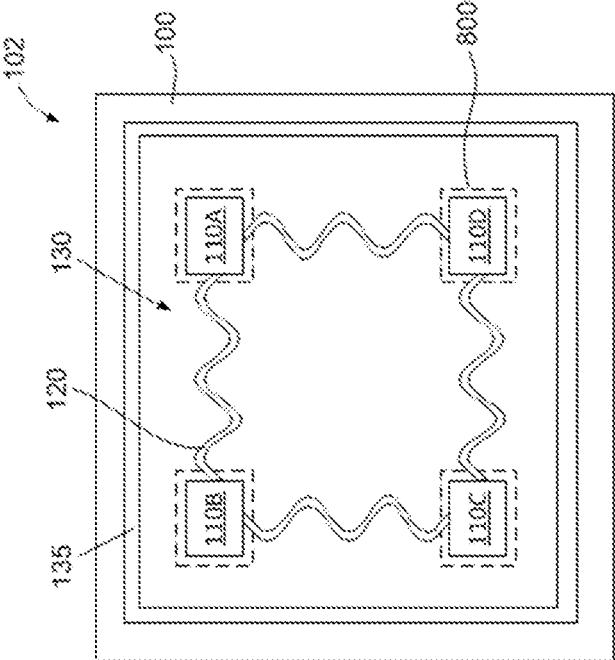


Figure 70R

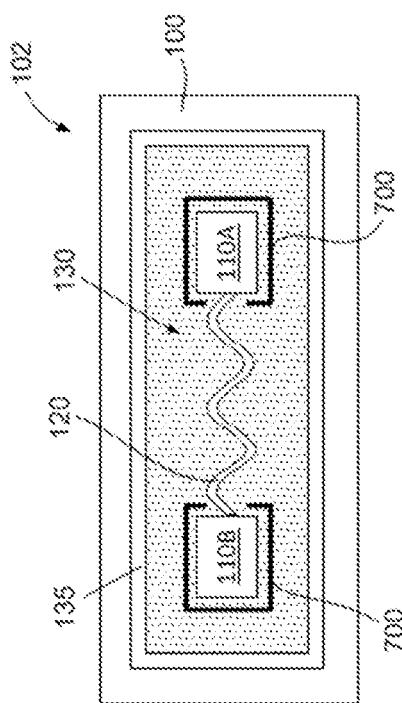


Figure 70O

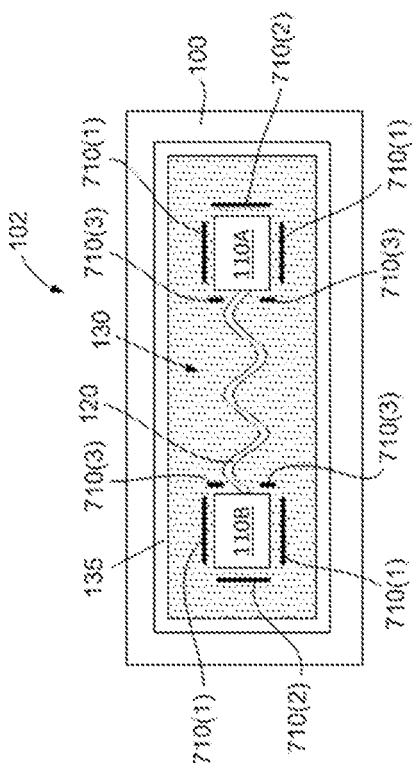


Figure 70P

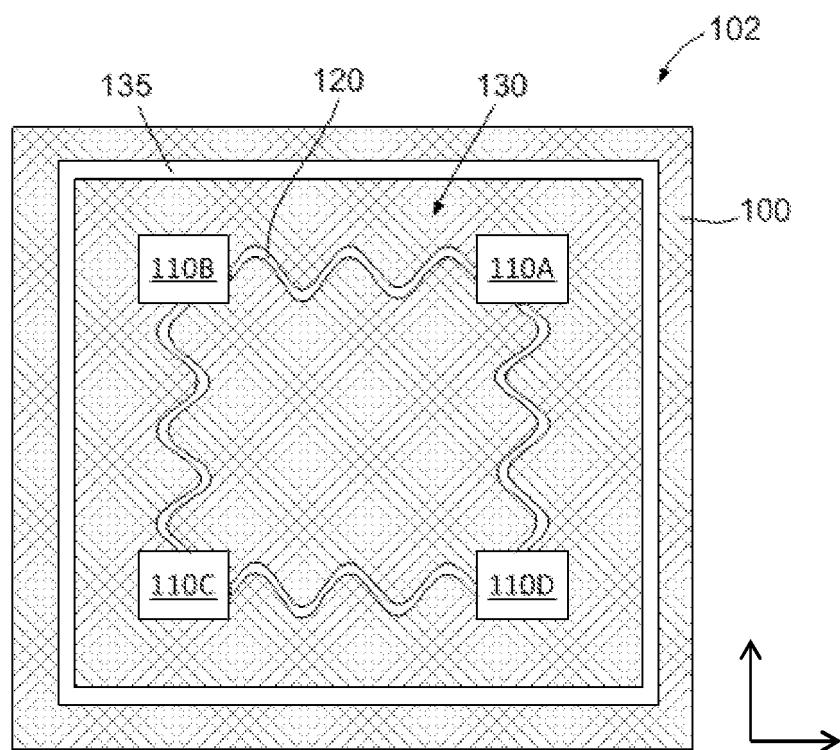


Figure 70S

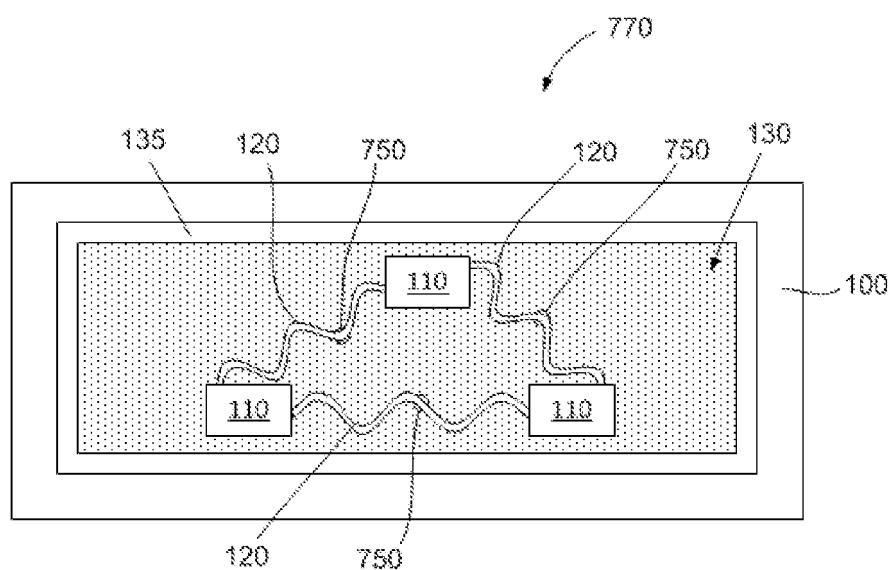


Figure 71

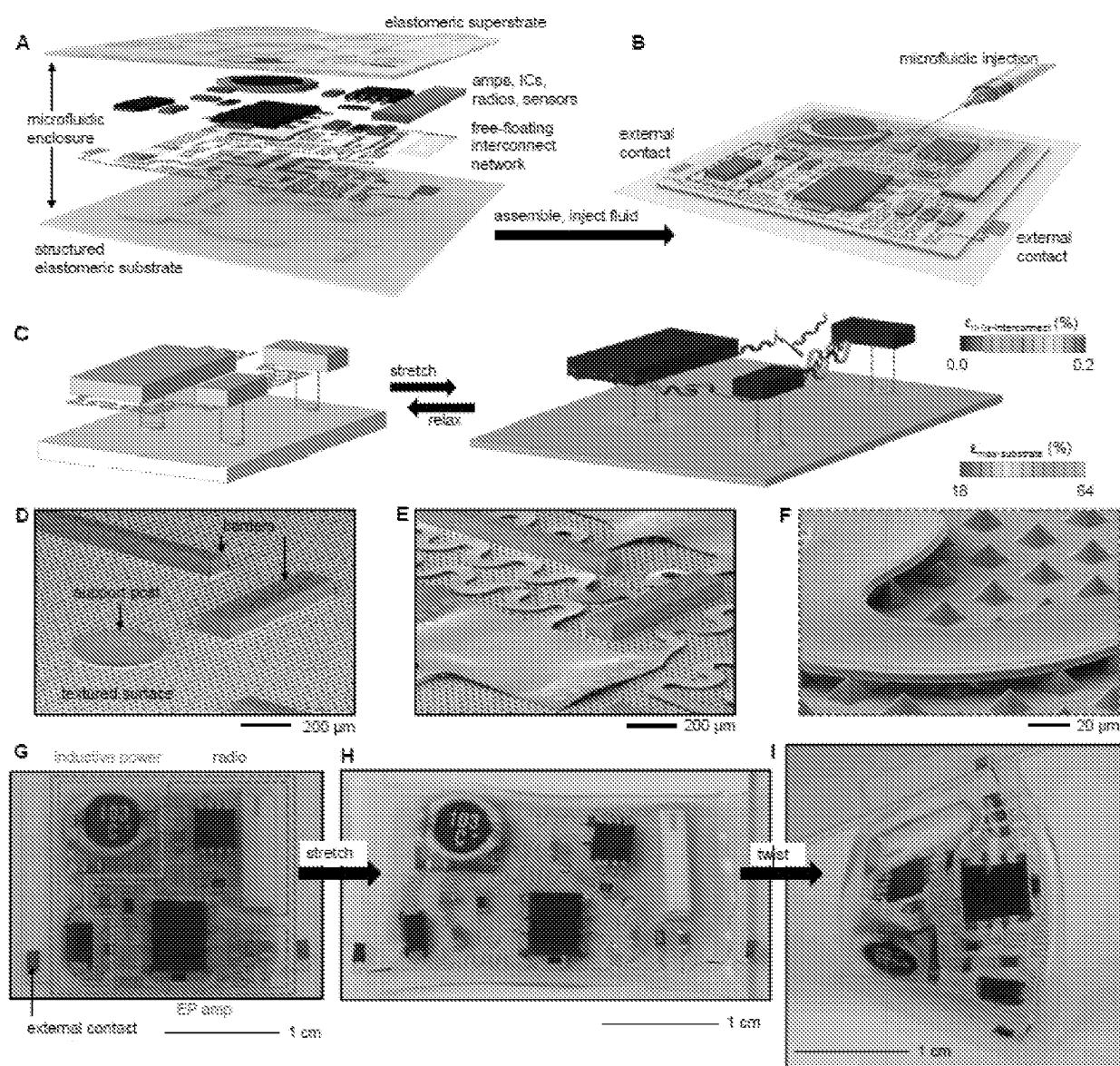


Figure 72

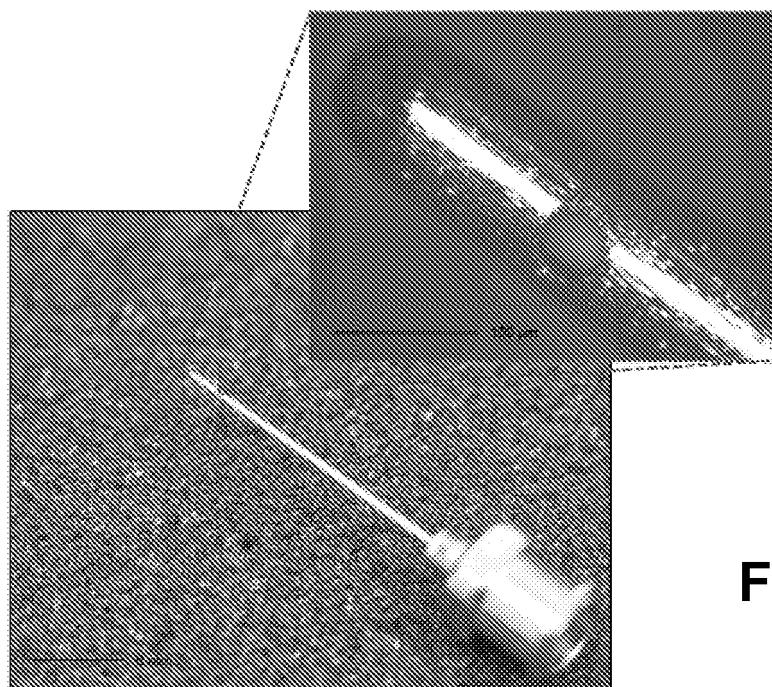


Figure 73

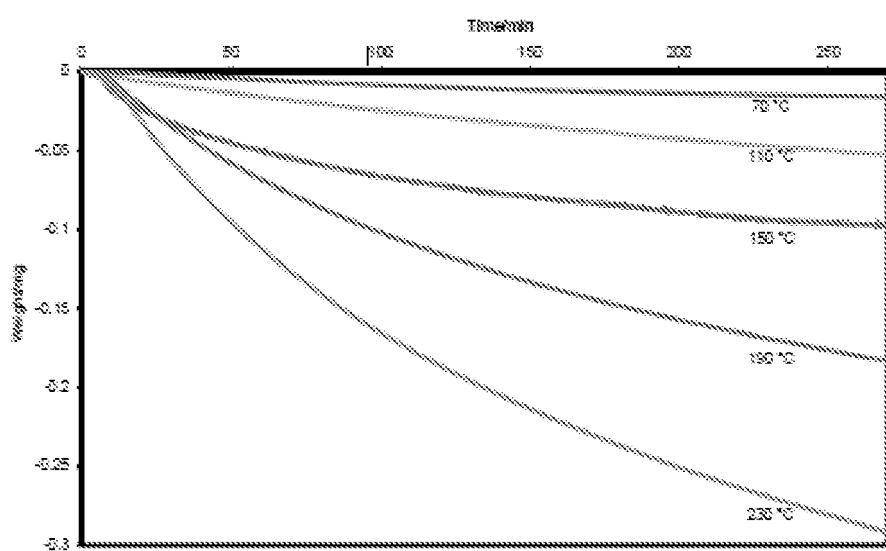
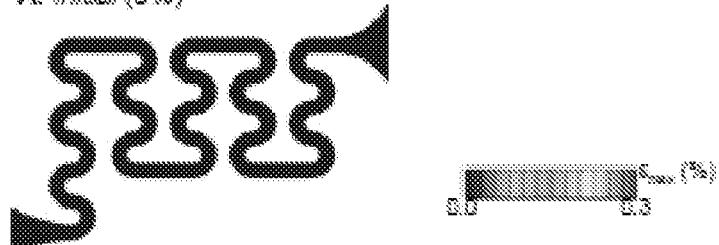


Figure 74

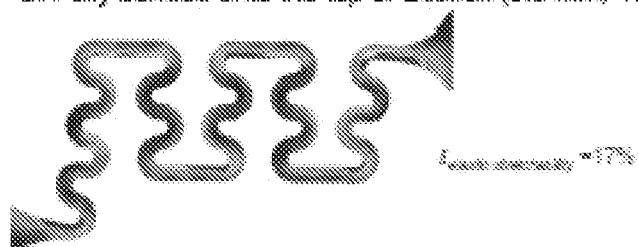
A. Initial (0%)



B. Bonded onto the top of Ecoflex at two ends, and the center part is freestanding
ε_{max} (0%) ~167%



C. Fully bonded onto the top of Ecoflex (0.5 mm, 166.42 kPa)
ε_{max} (0%) ~17%



D. Fully embedded in the middle of Ecoflex (1.0 mm, 166.42 kPa)
ε_{max} (0%) ~6%

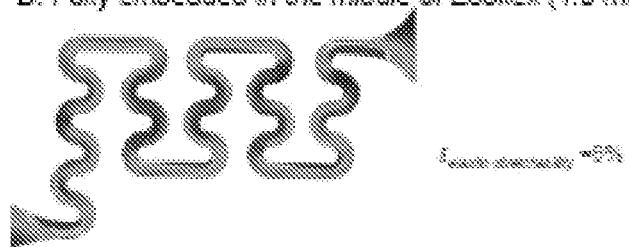


Figure 75

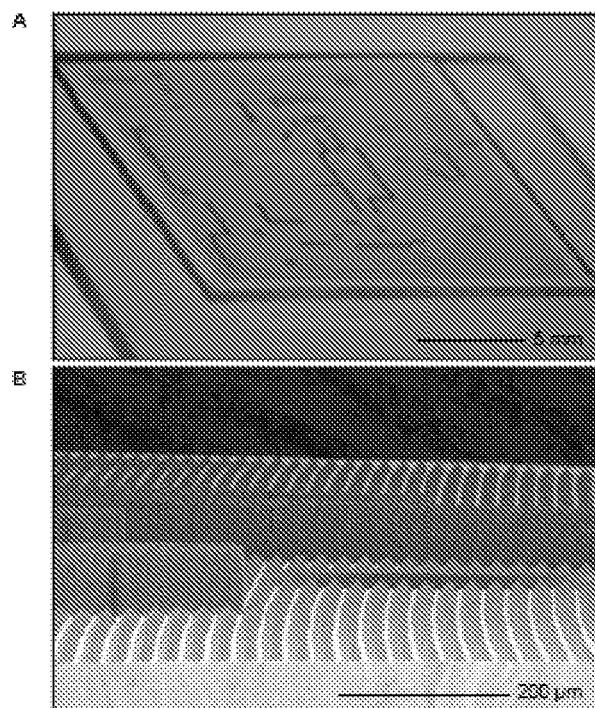


Figure 76

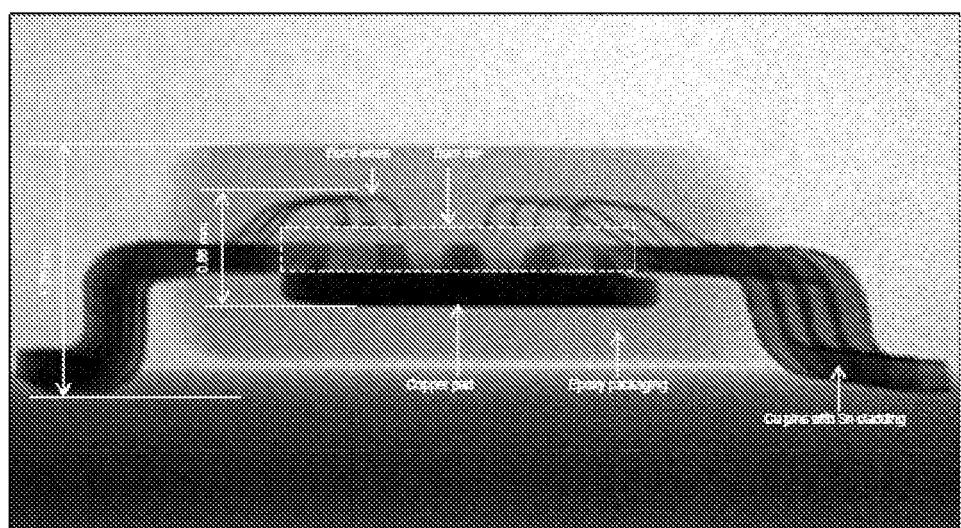


Figure 77

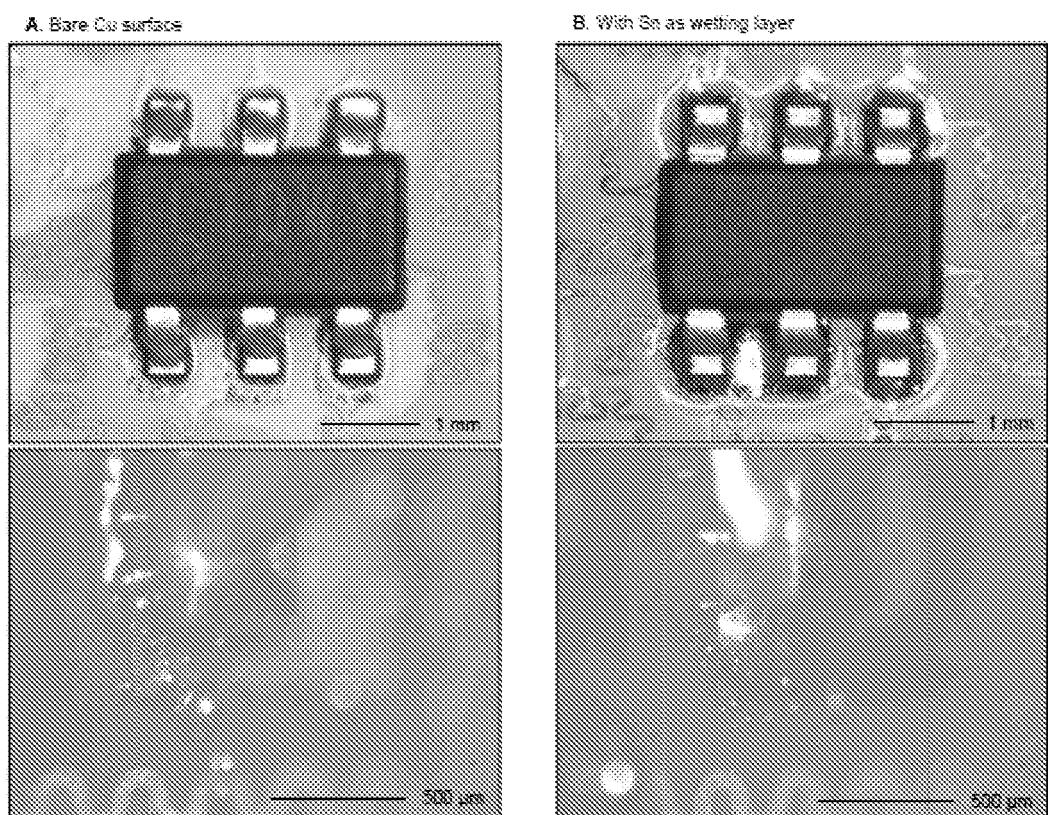
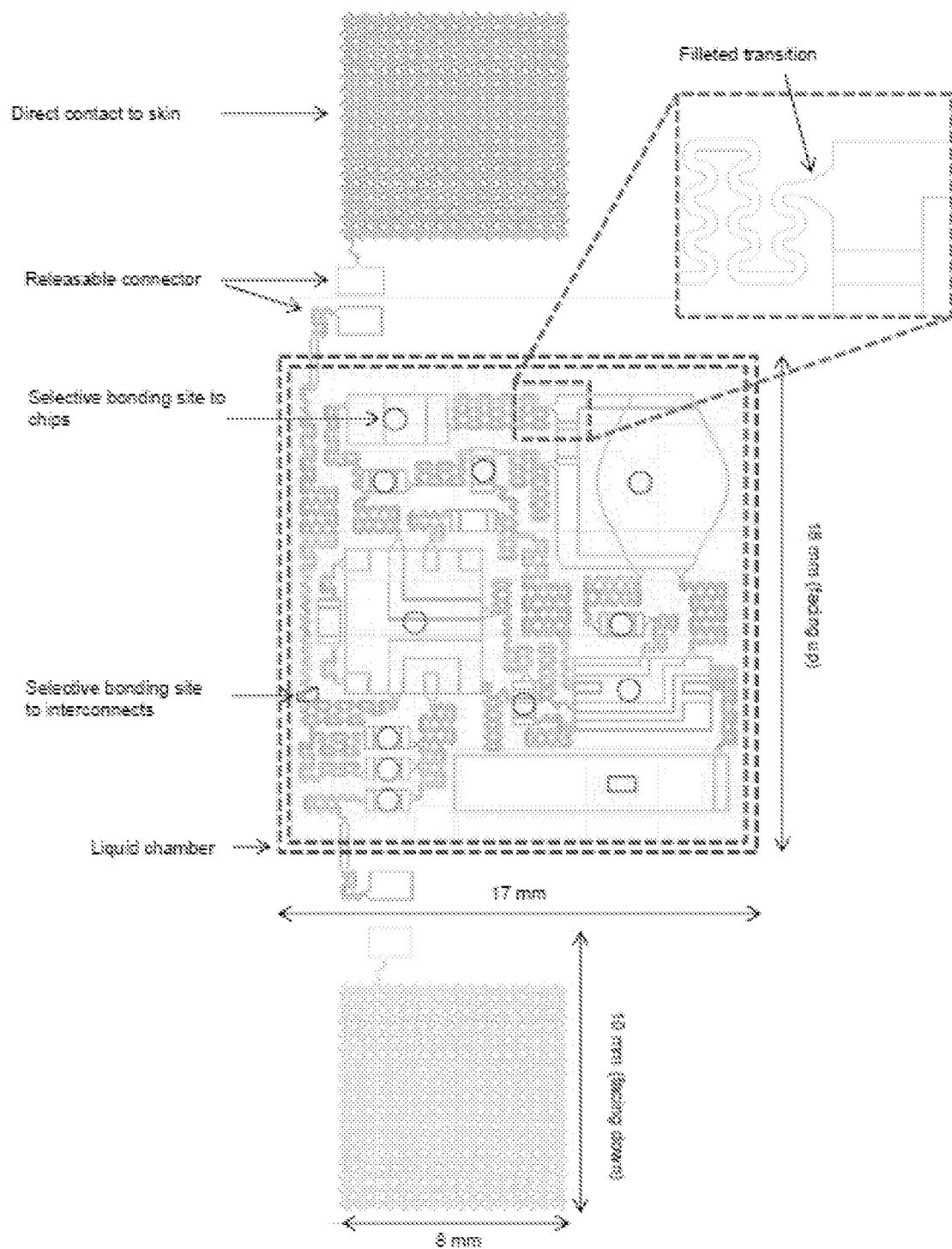


Figure 78

**Figure 79**

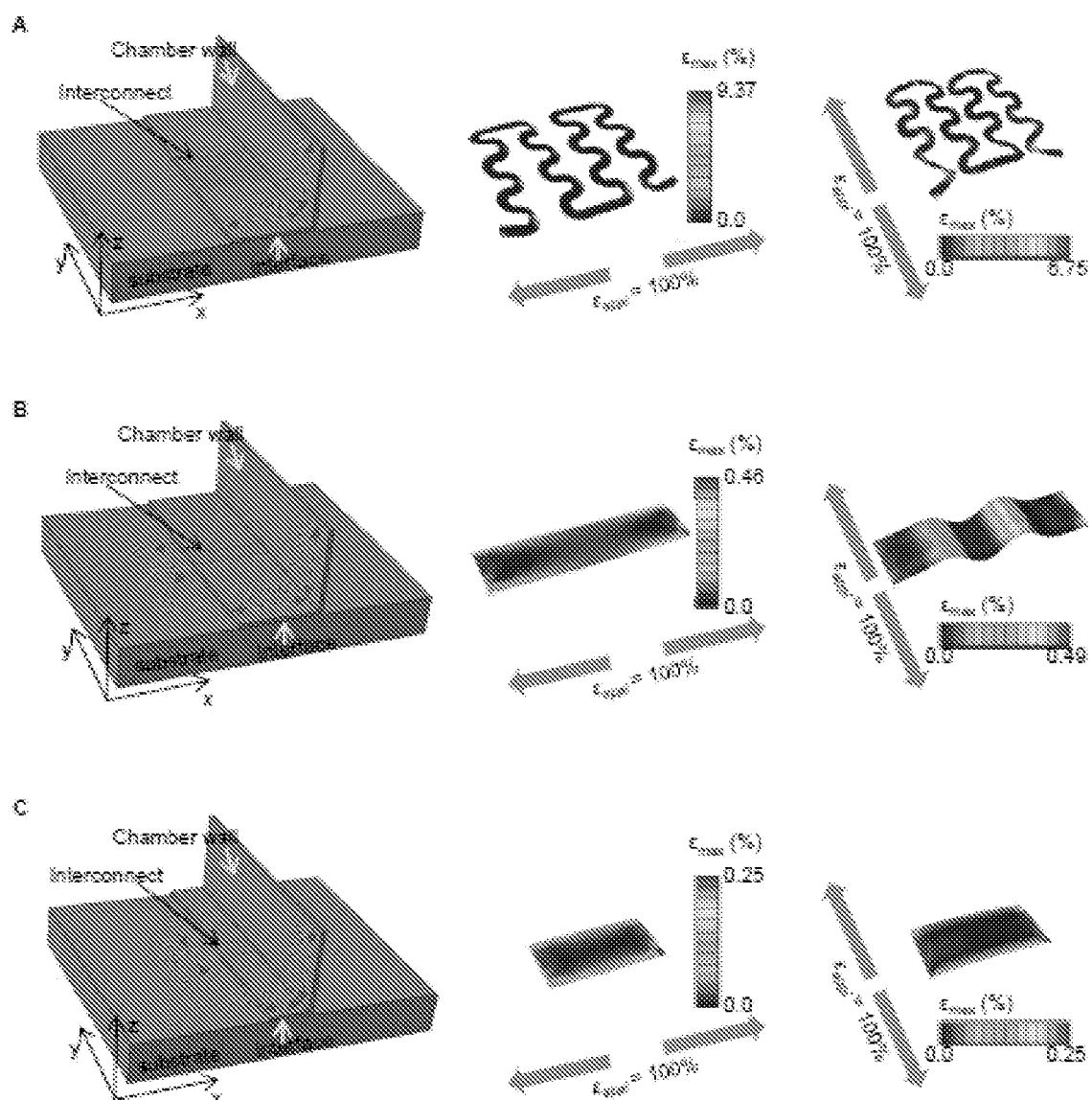


Figure 80

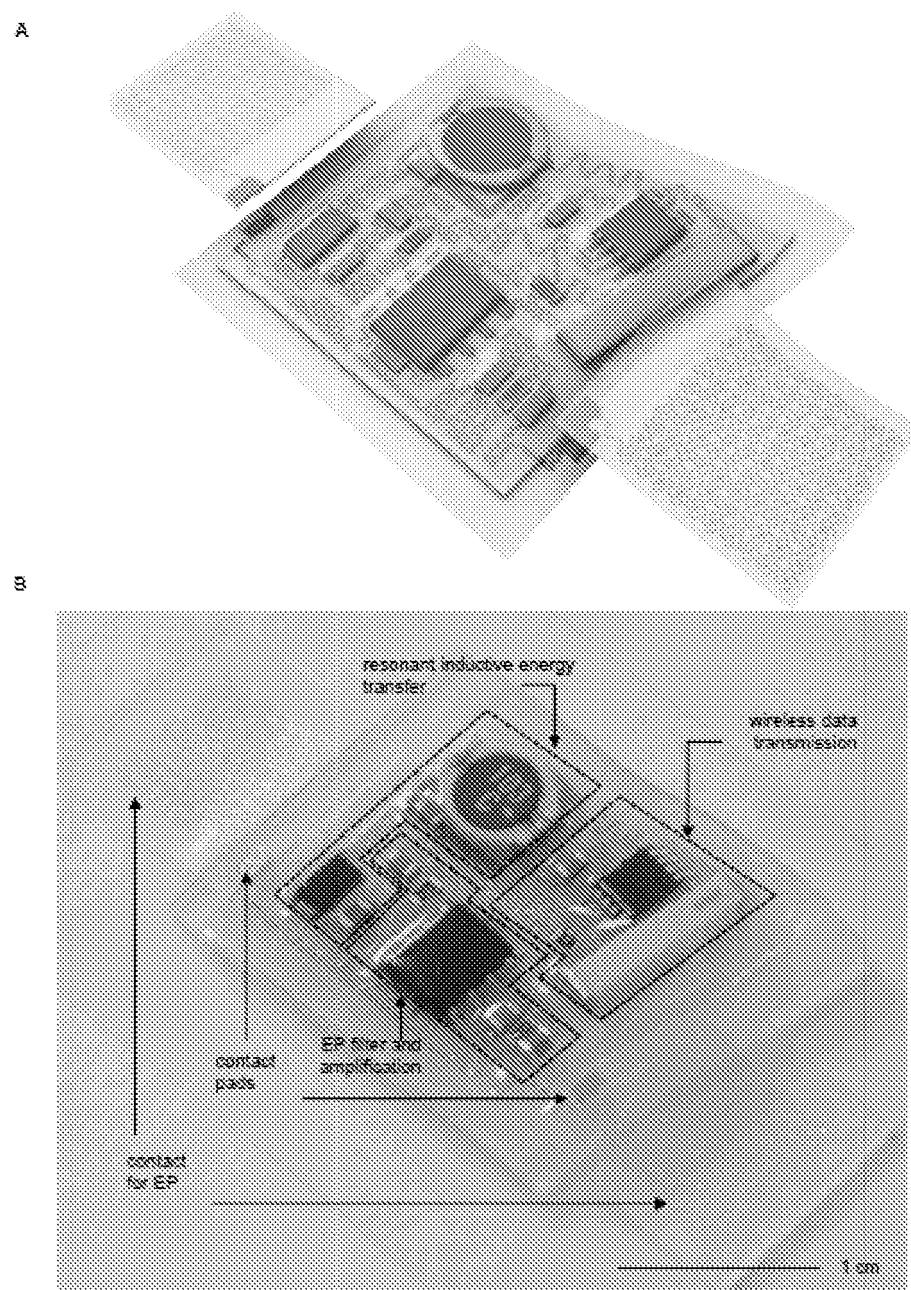


Figure 81

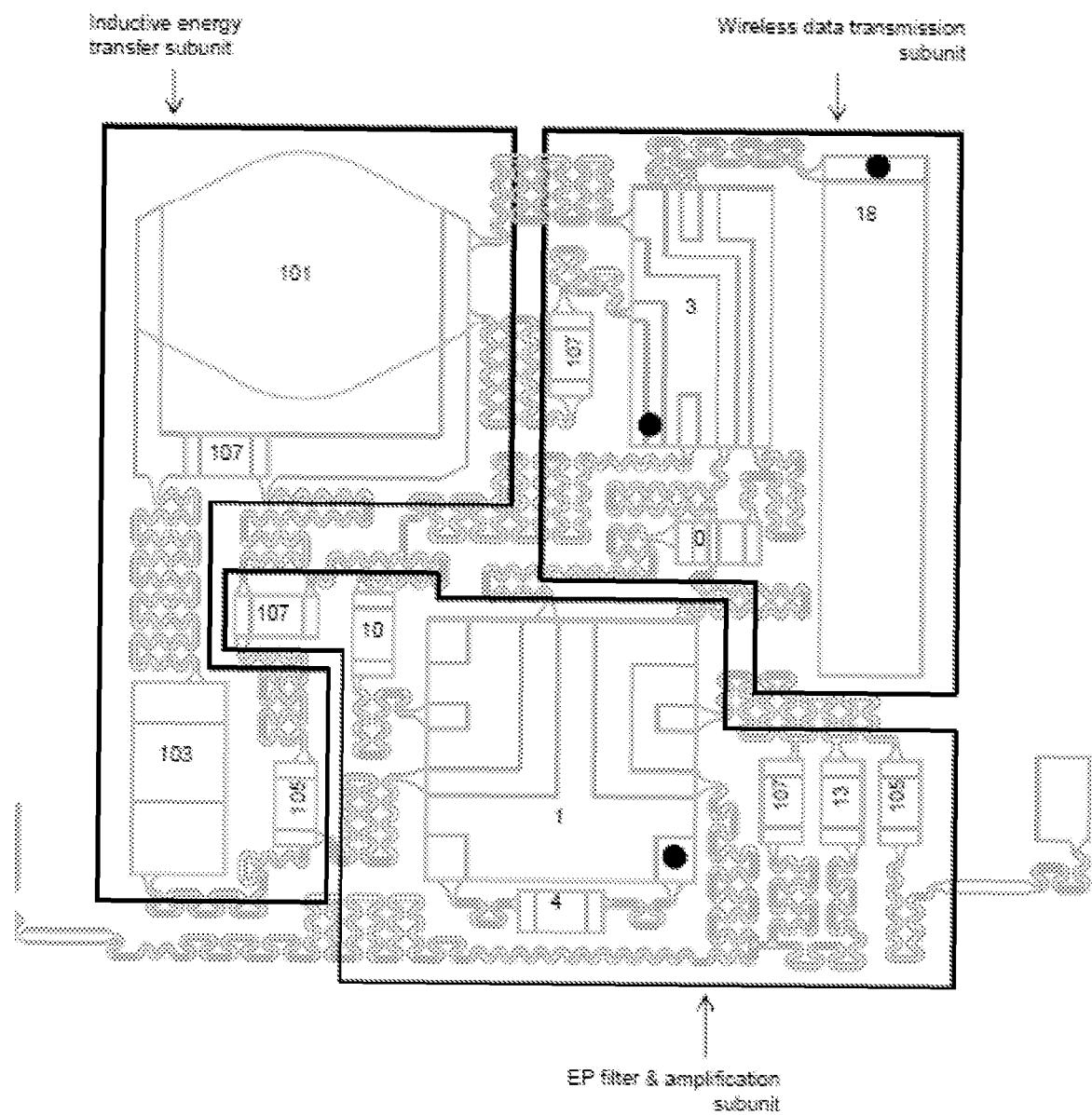
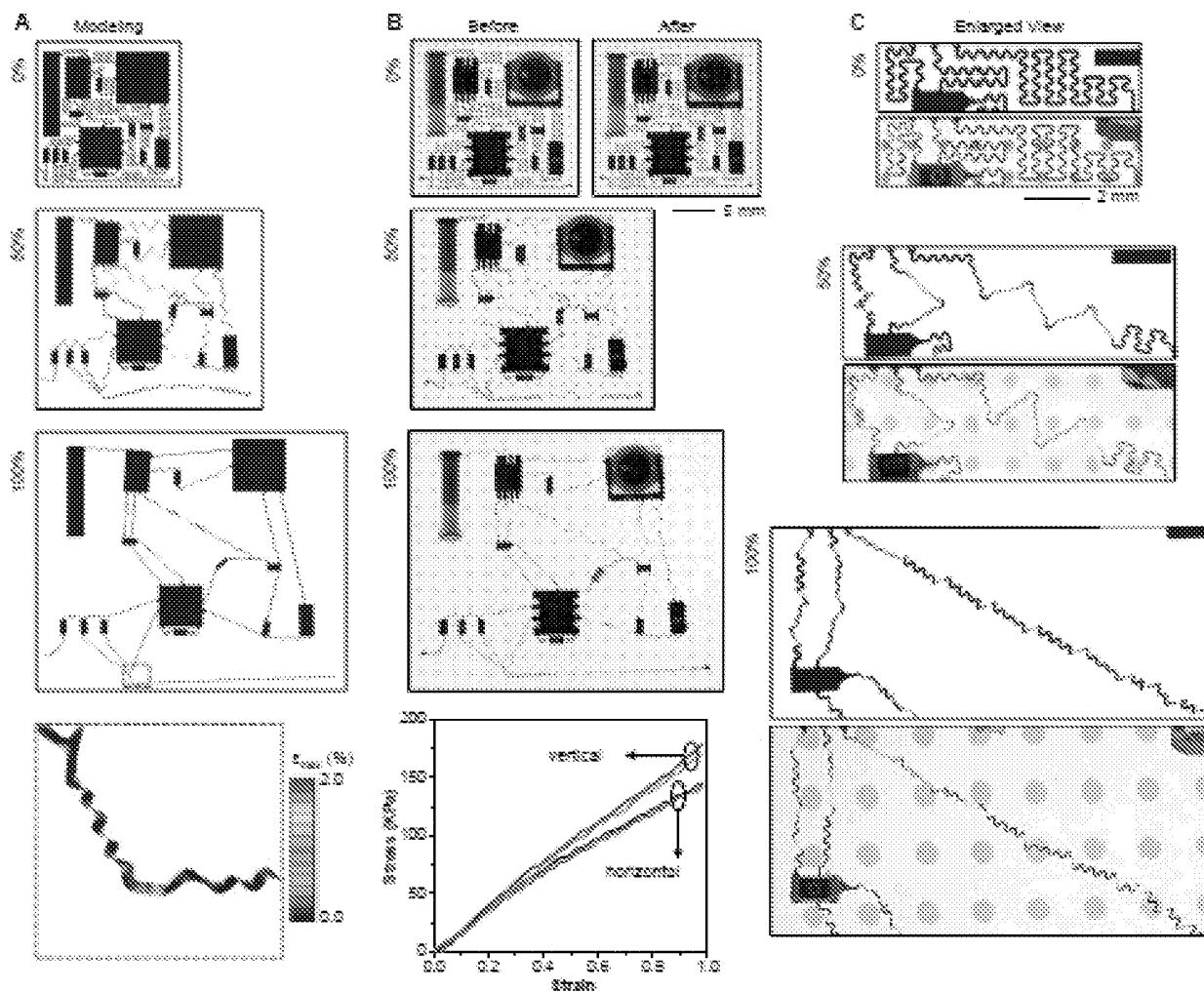
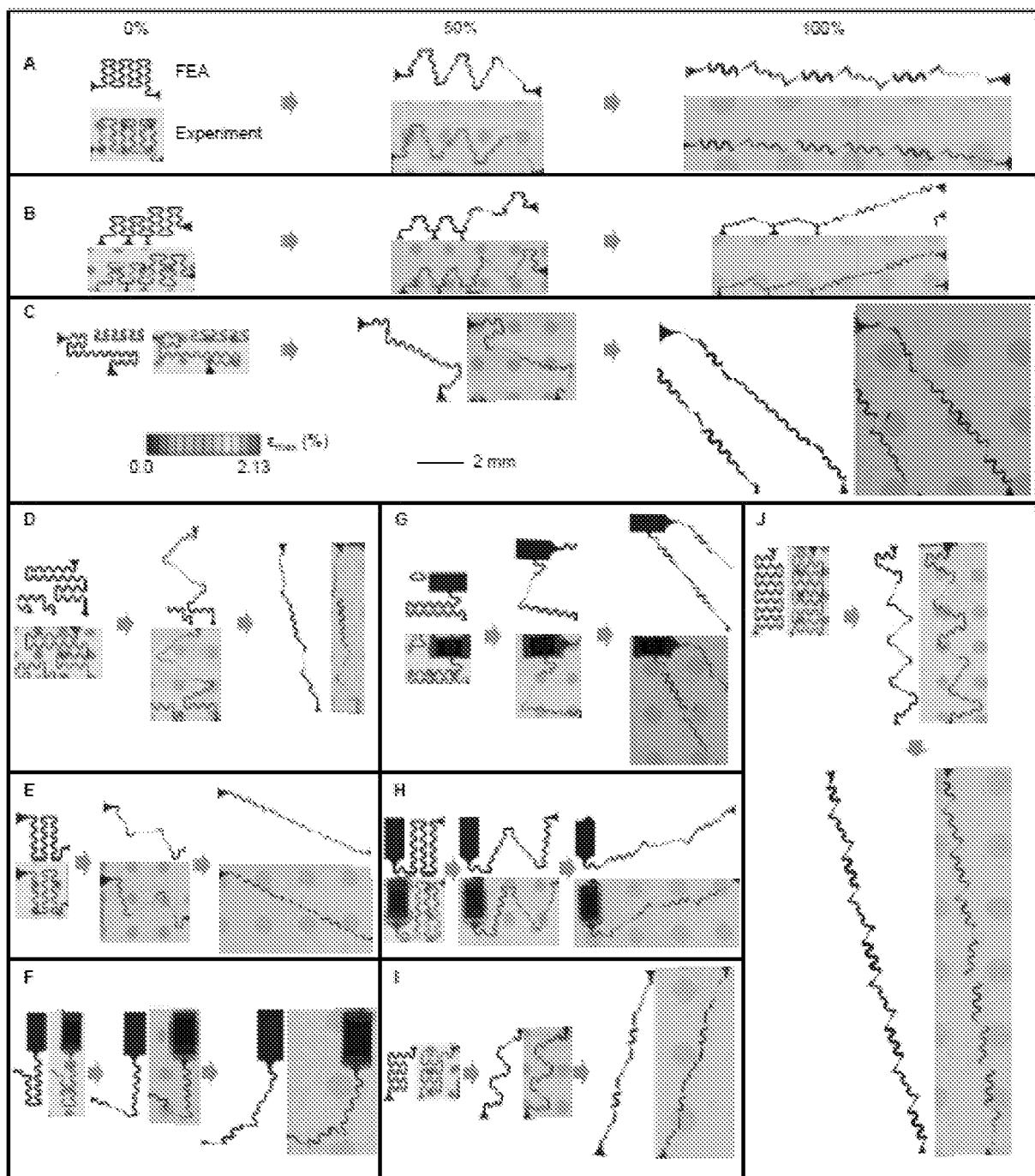


Figure 82

**Figure 83**

**Figure 84**

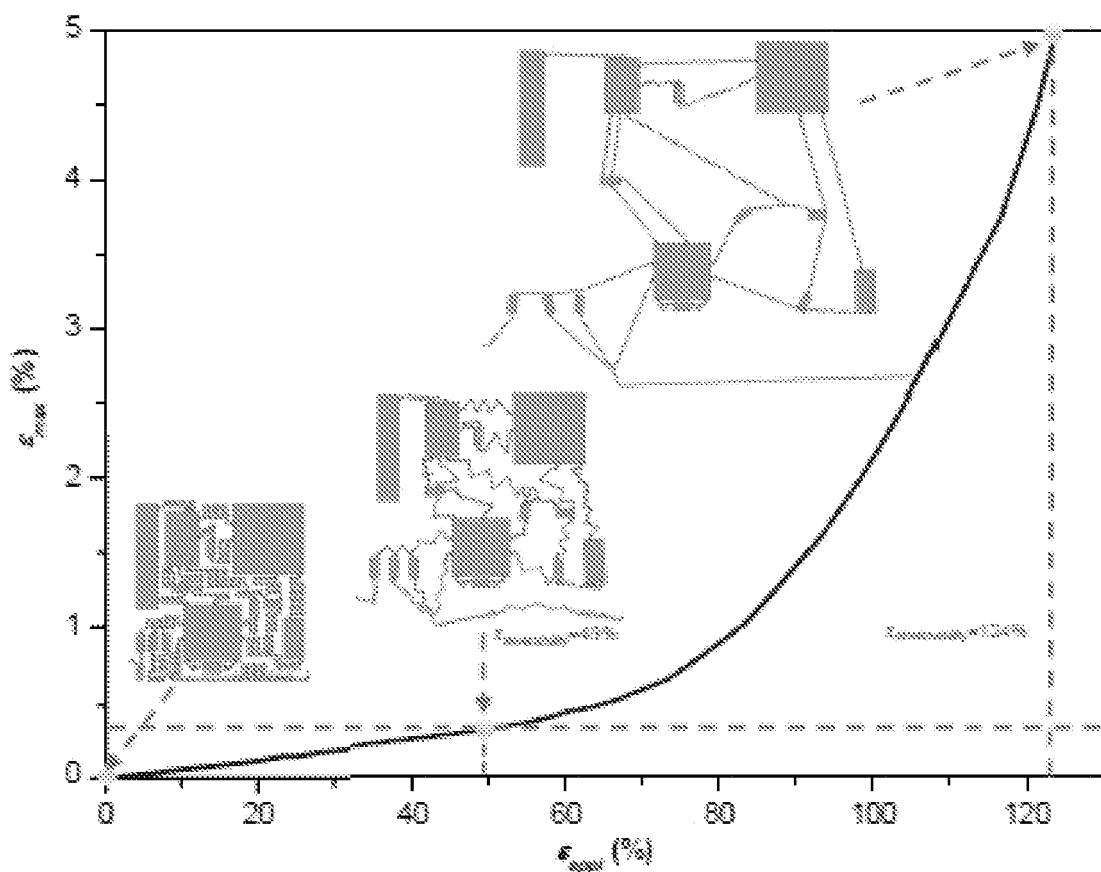


Figure 85

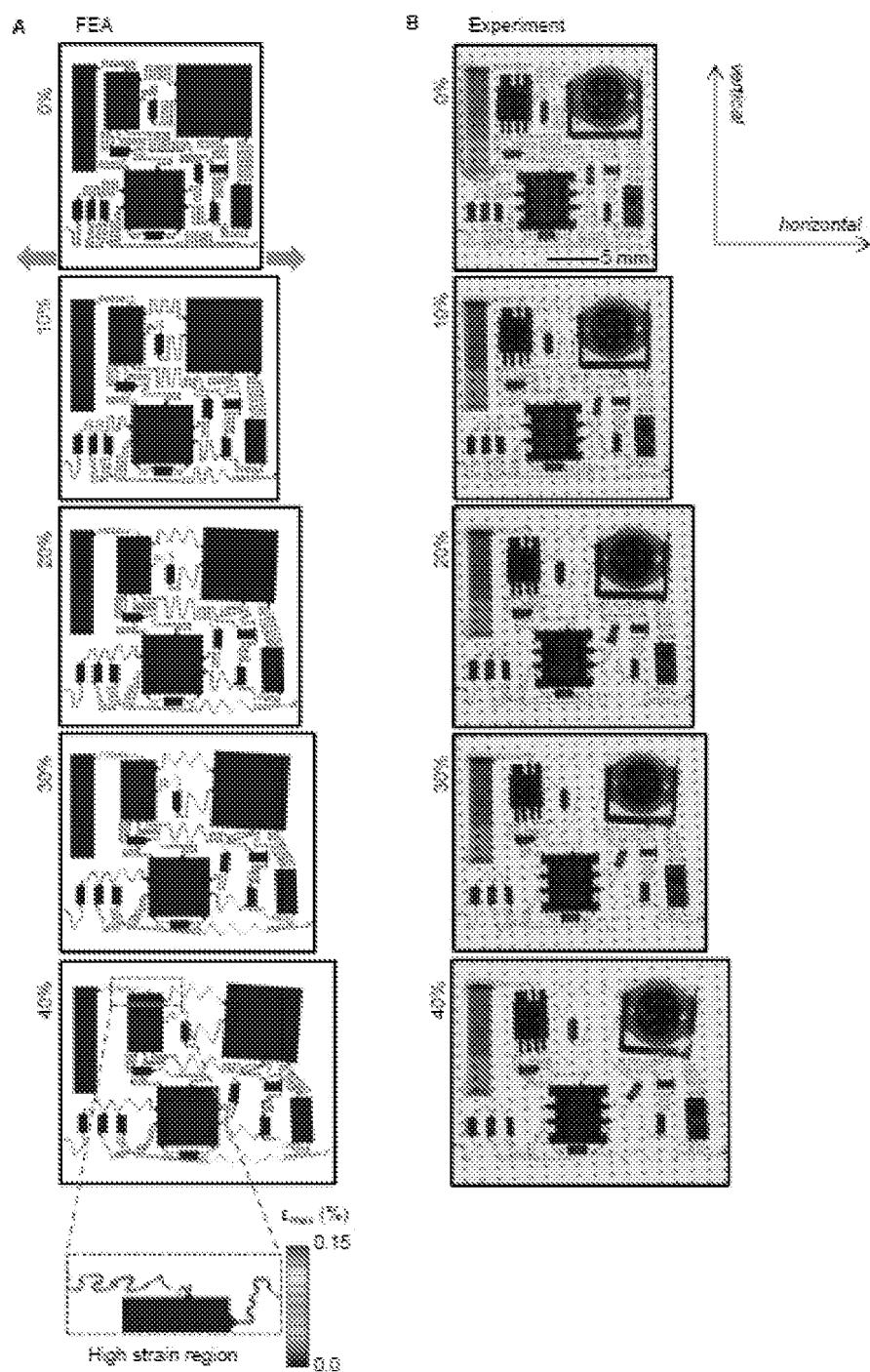


Figure 86

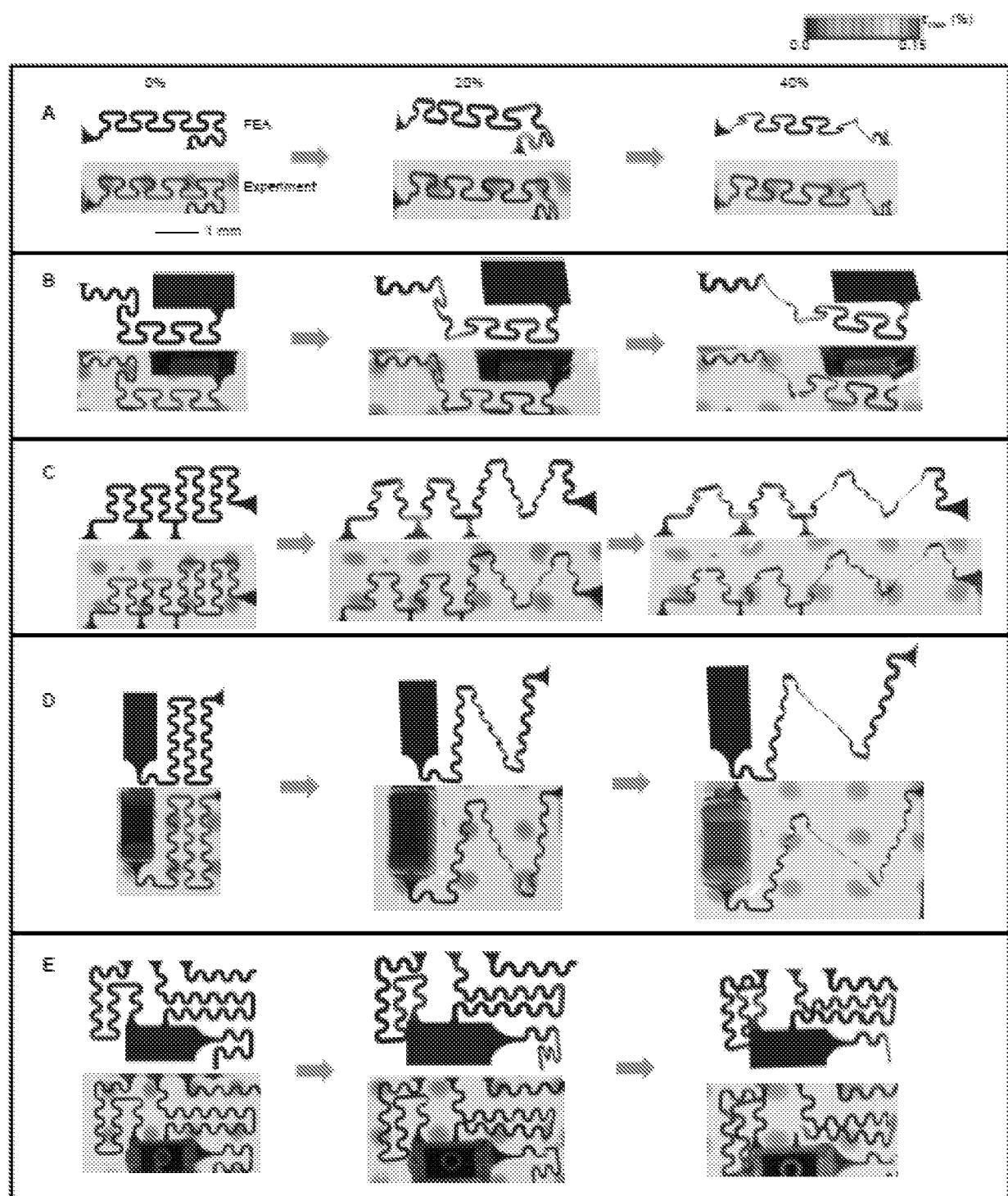


Figure 87

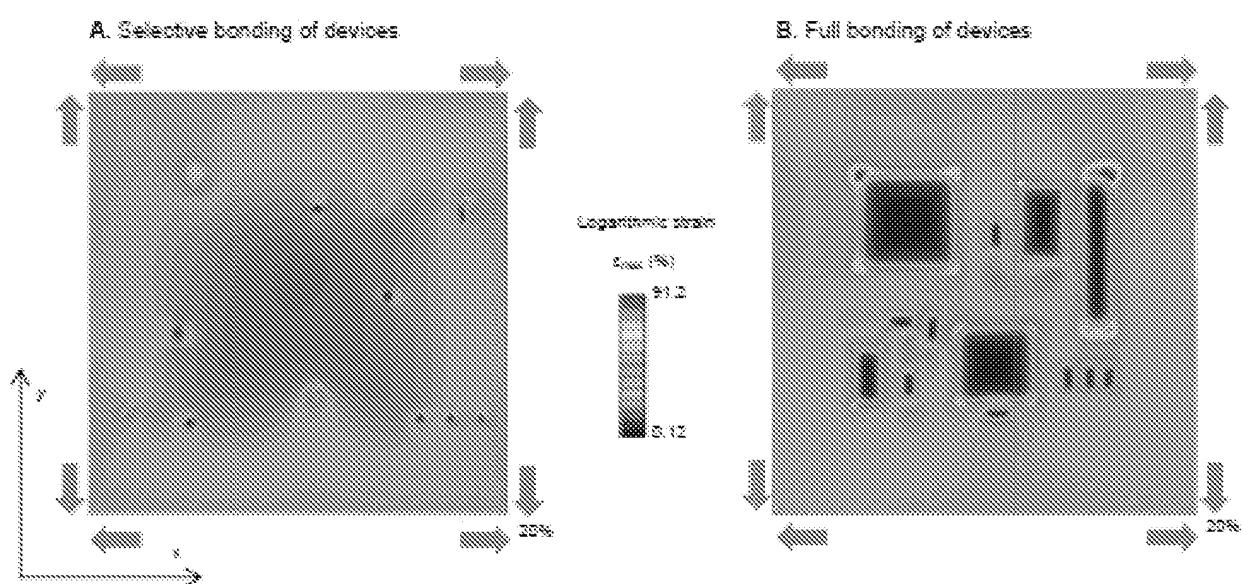


Figure 88

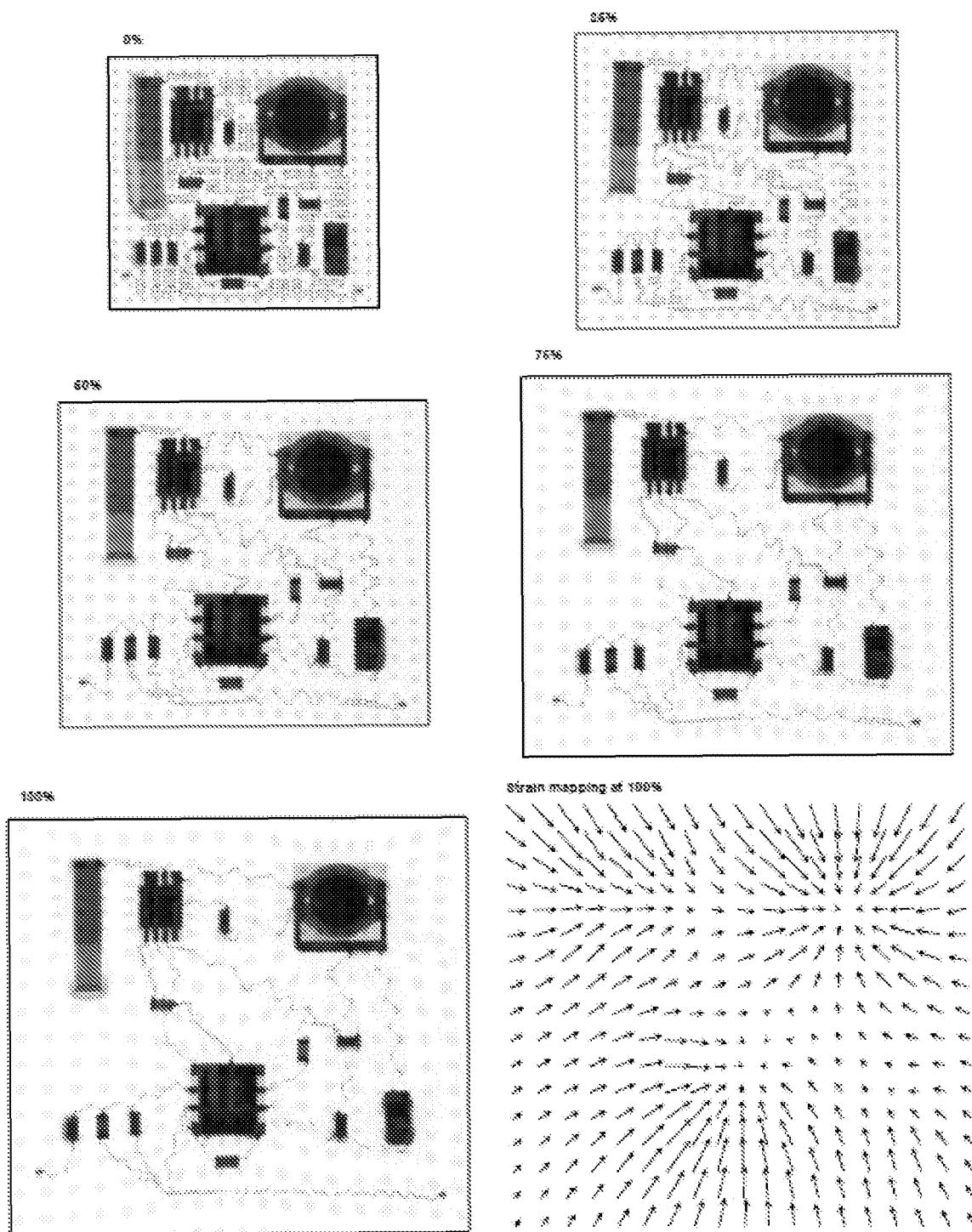
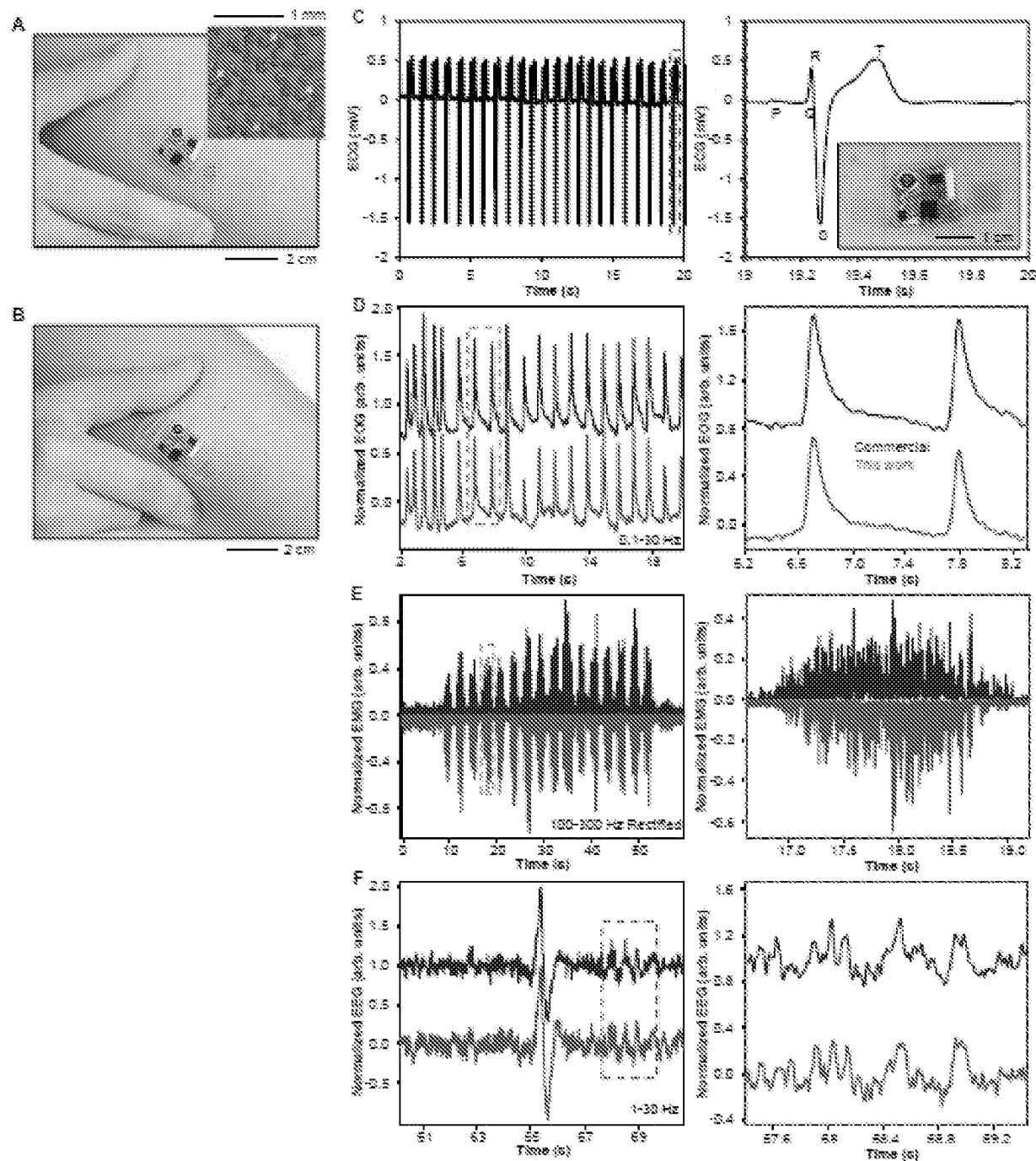


Figure 89

**Figure 90**

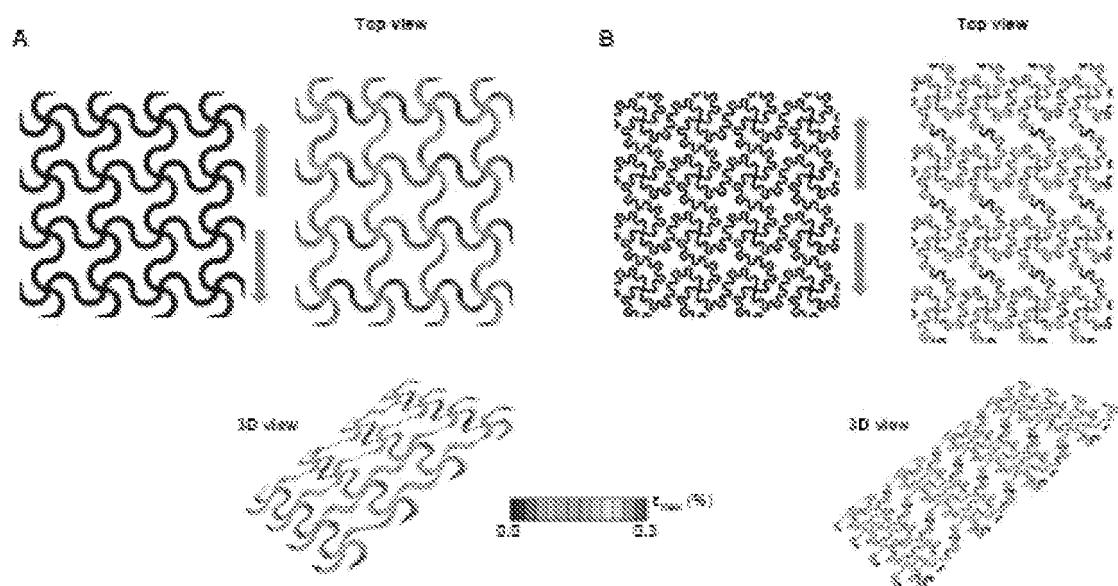


Figure 91

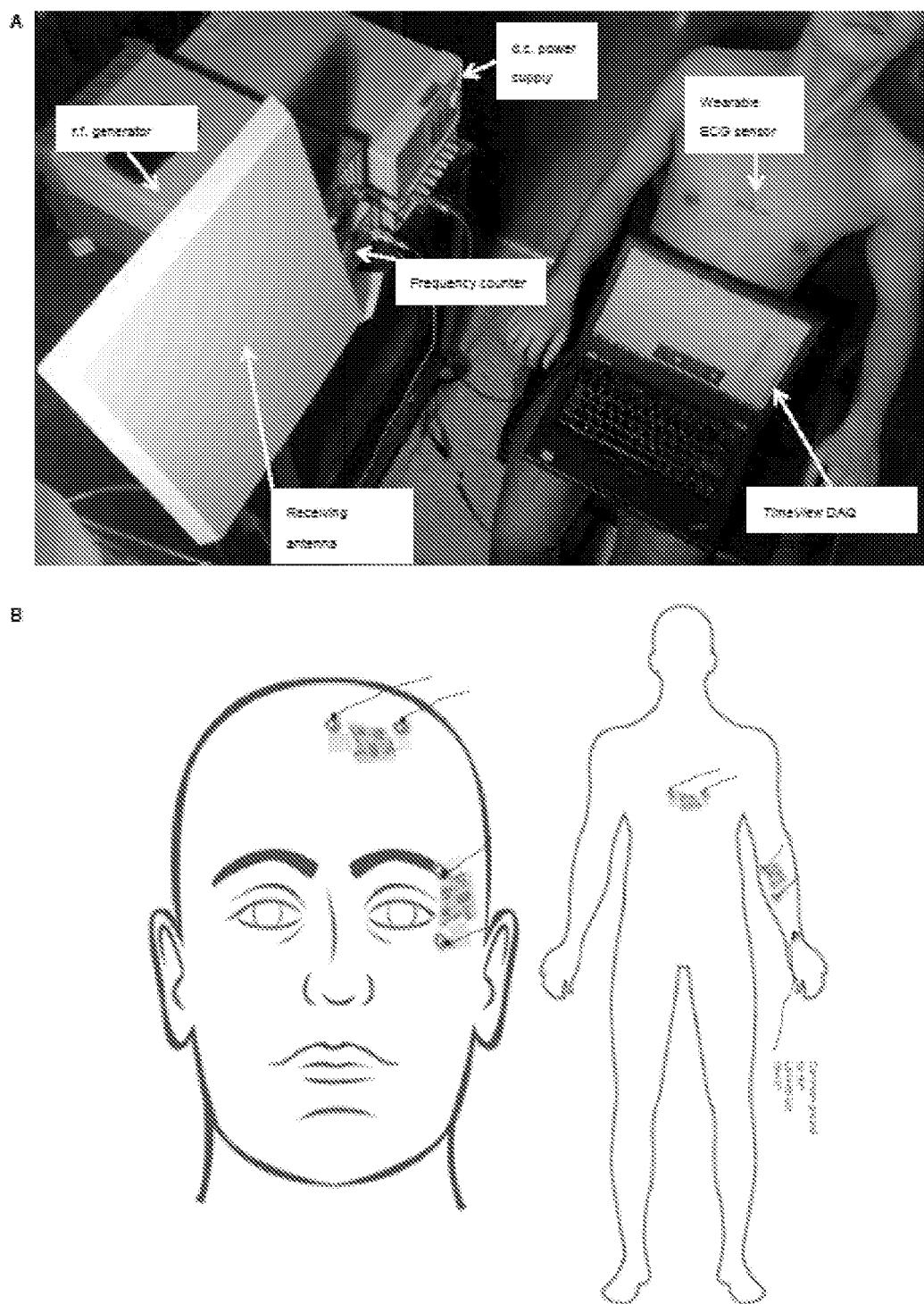
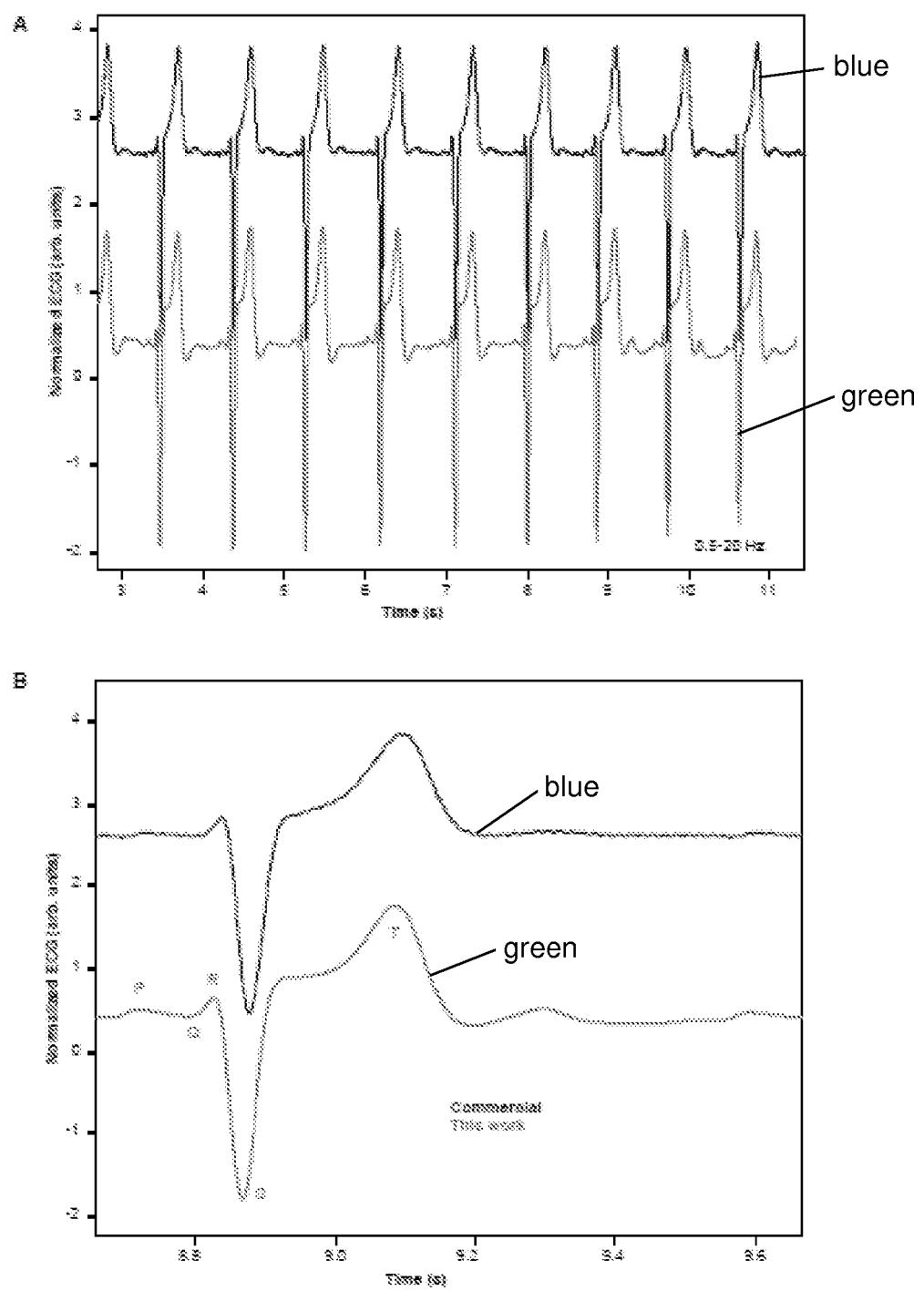


Figure 92

**Figure 93**

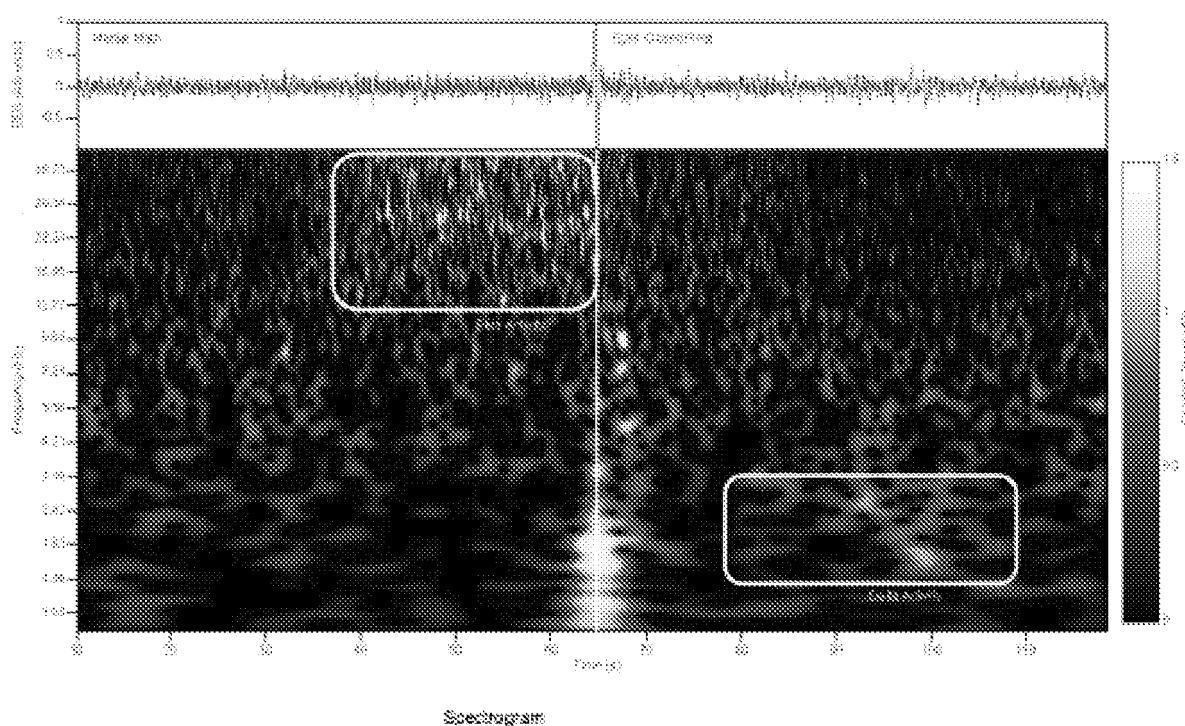
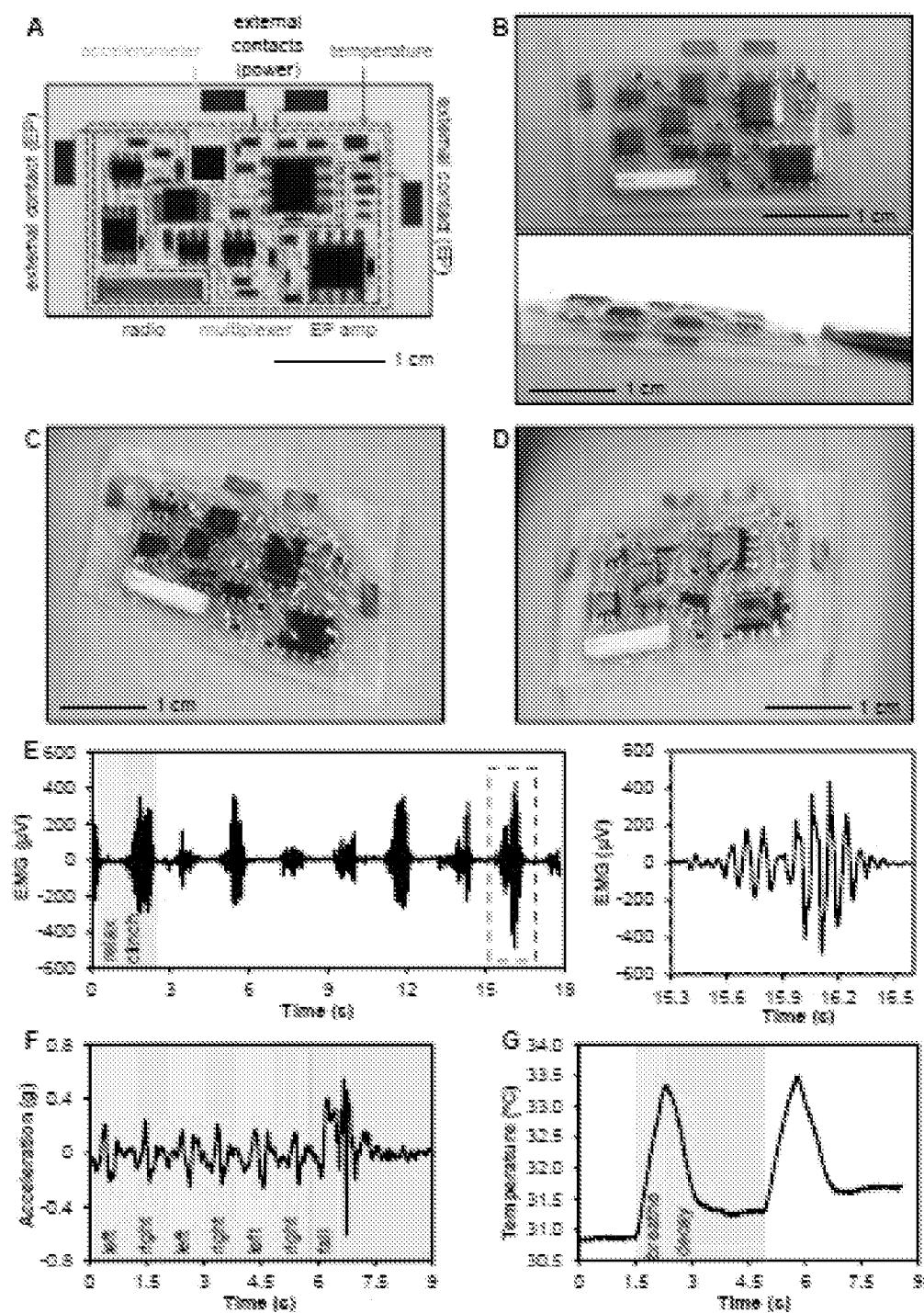


Figure 94

**Figure 95**

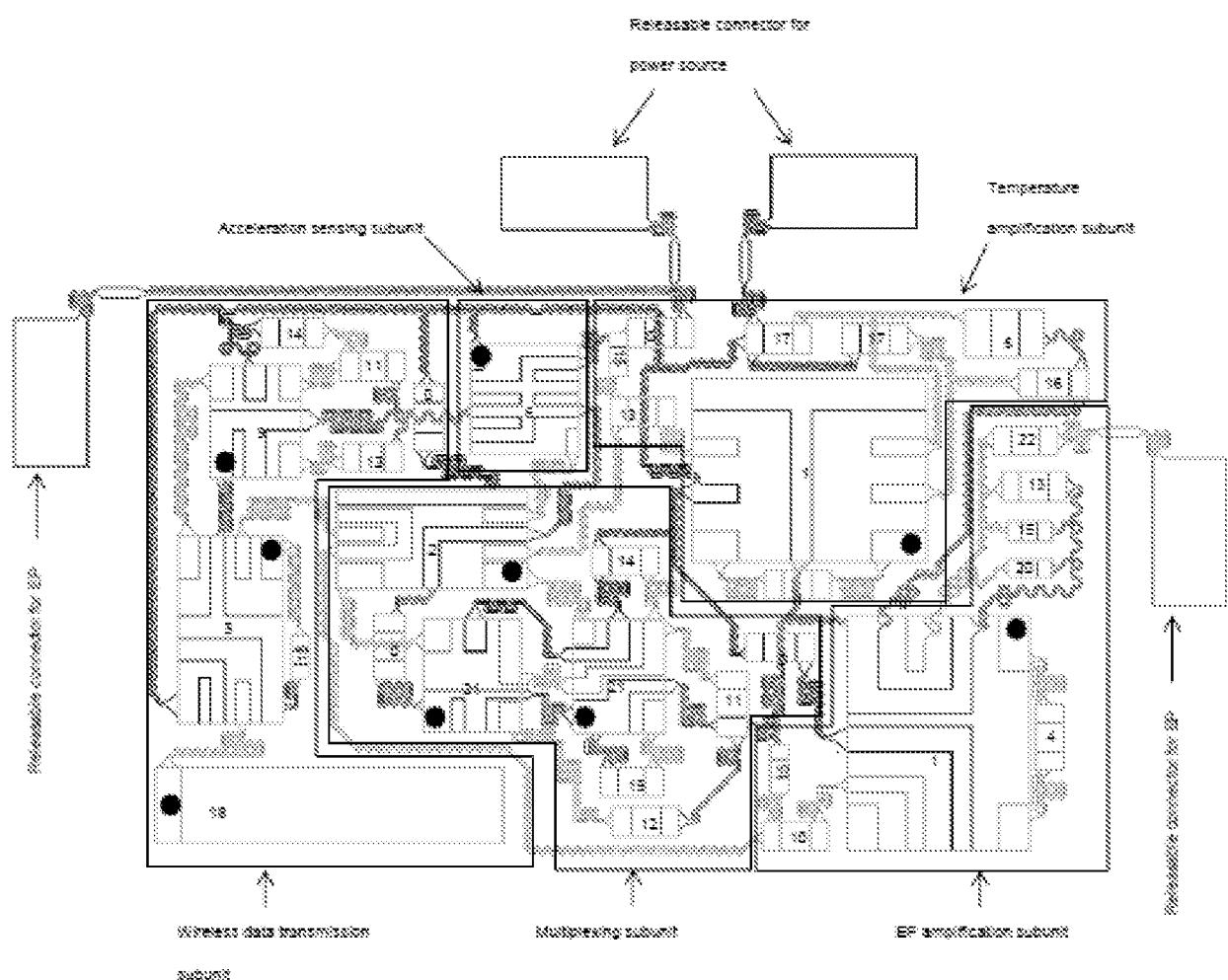
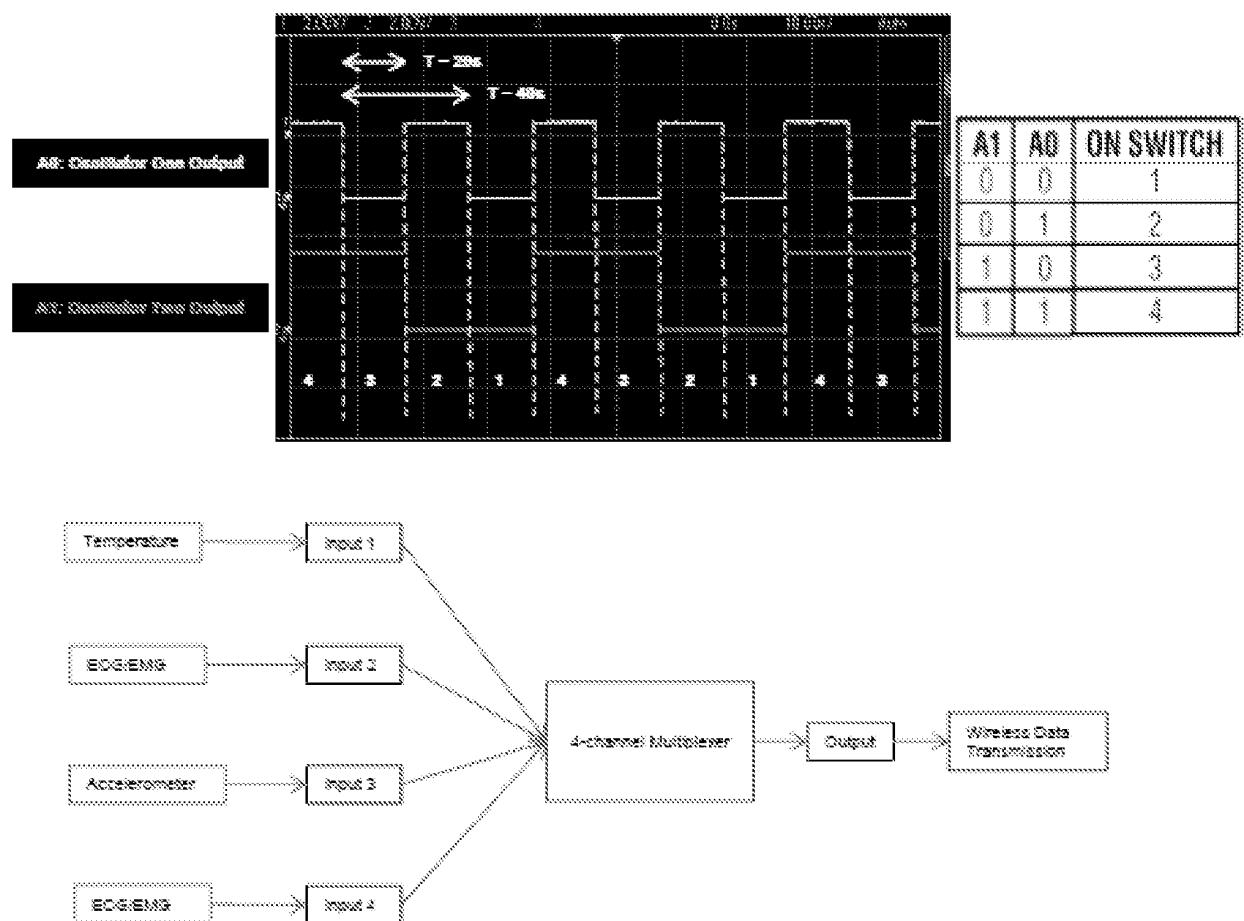


Figure 96

**Figure 97**

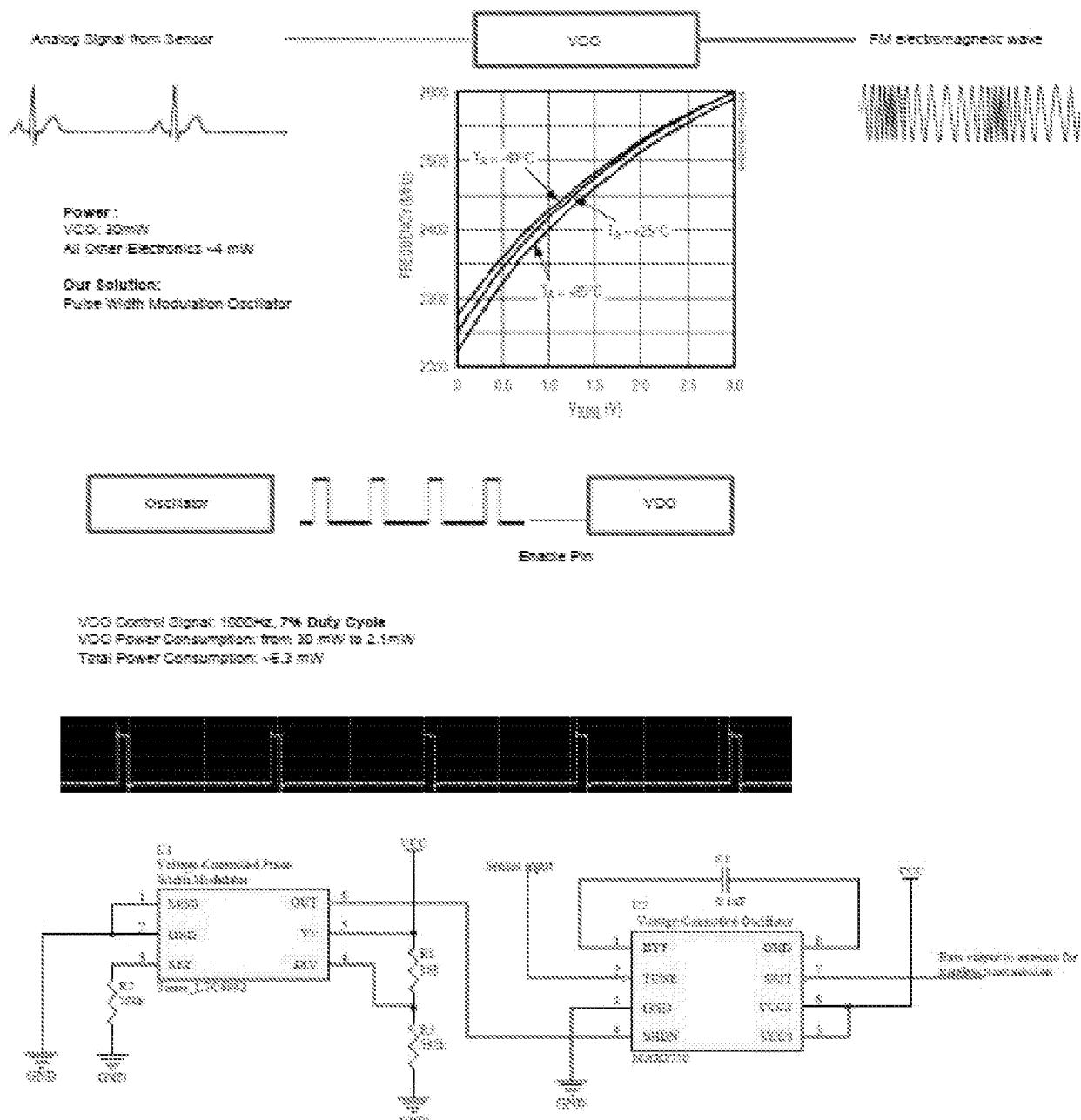
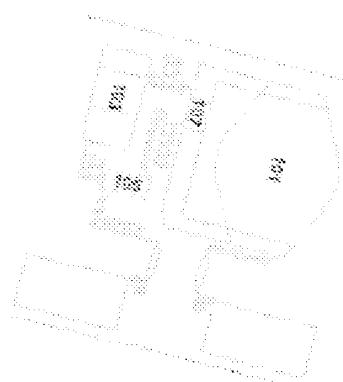
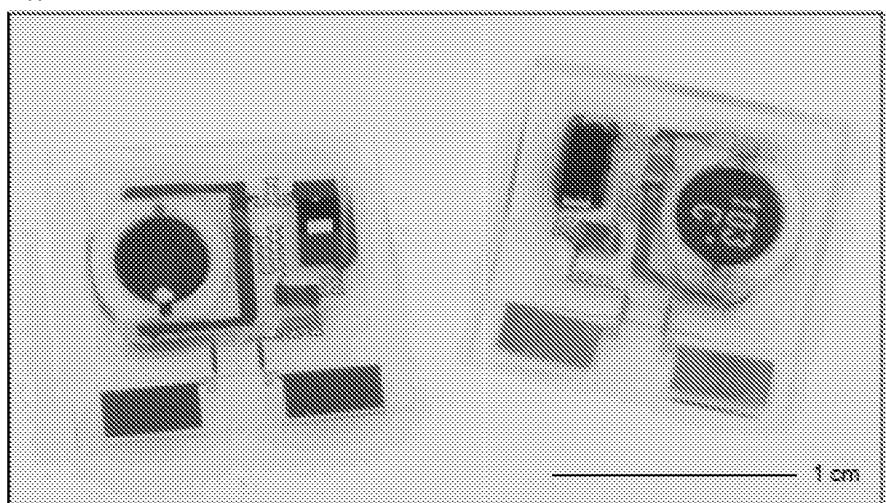


Figure 98

A



B

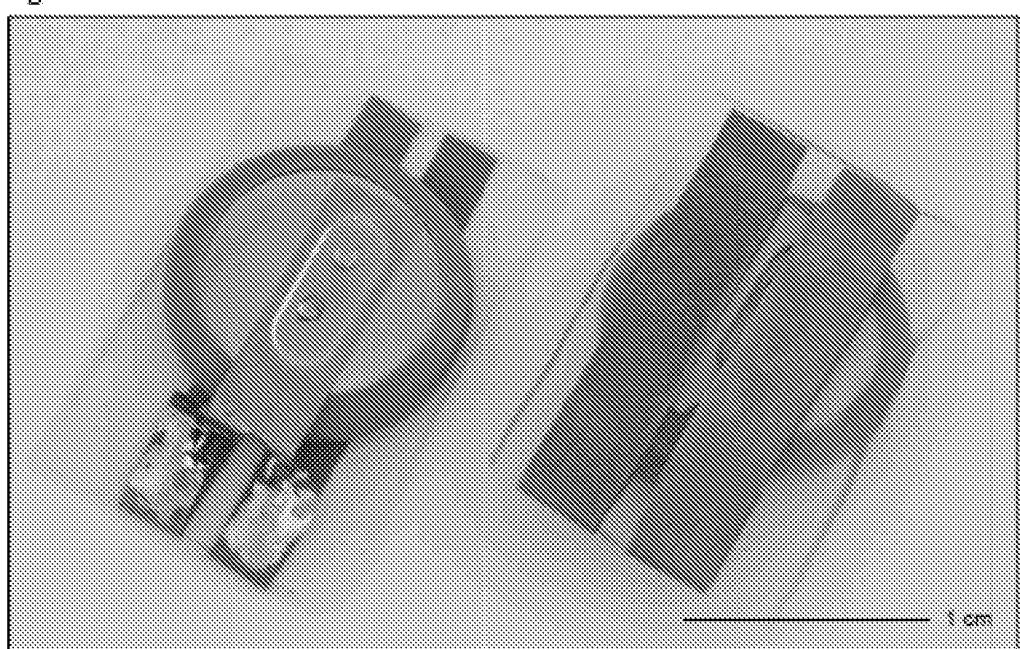


Figure 99

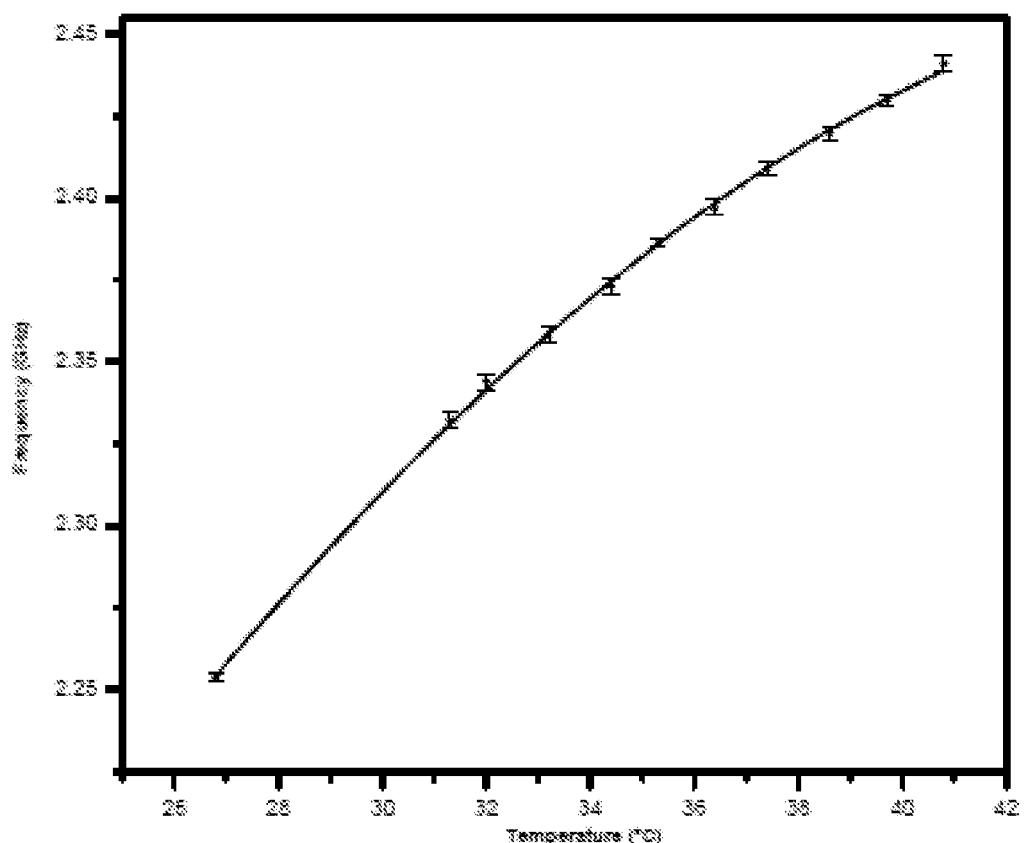


Figure 100

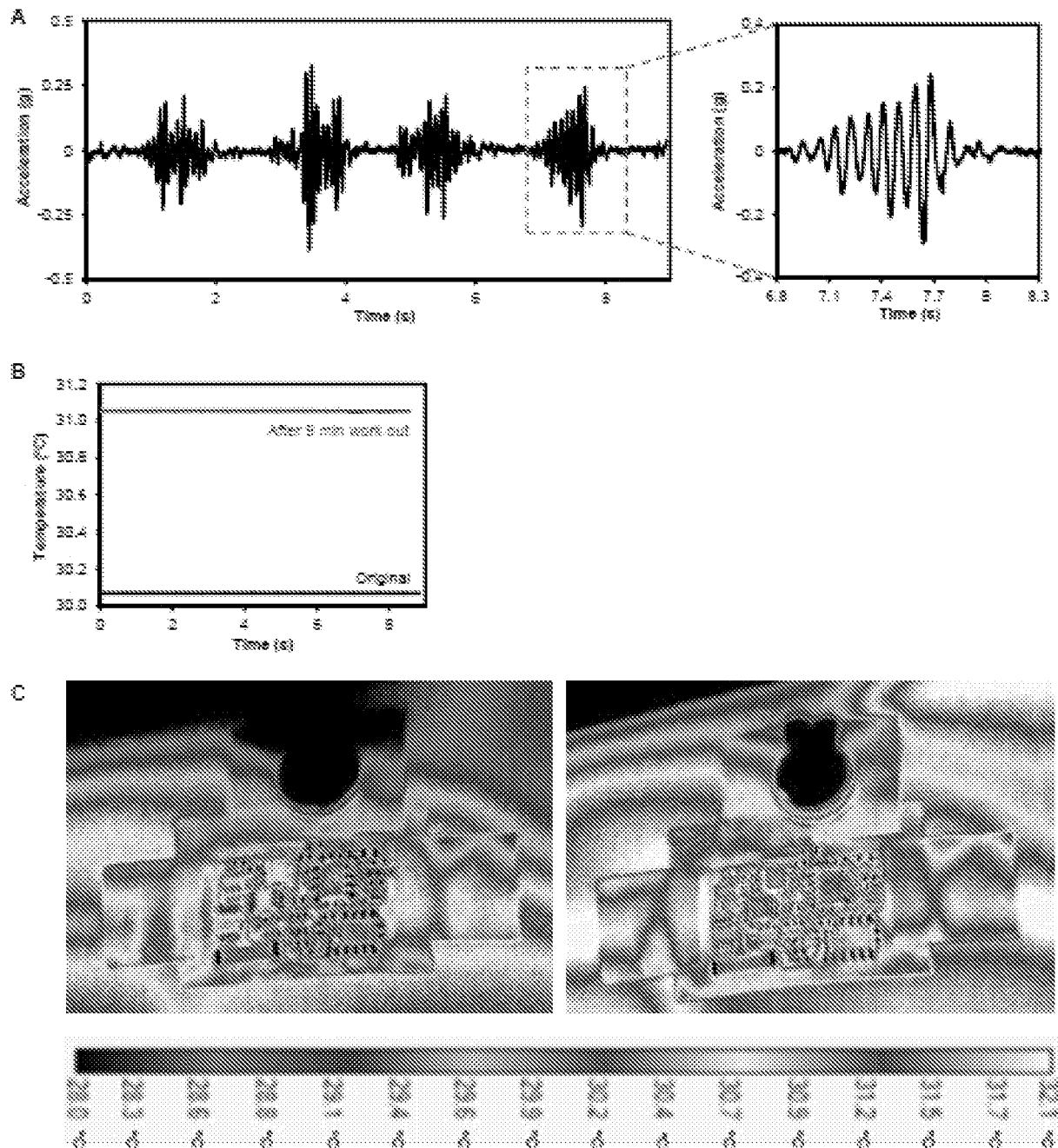


Figure 101

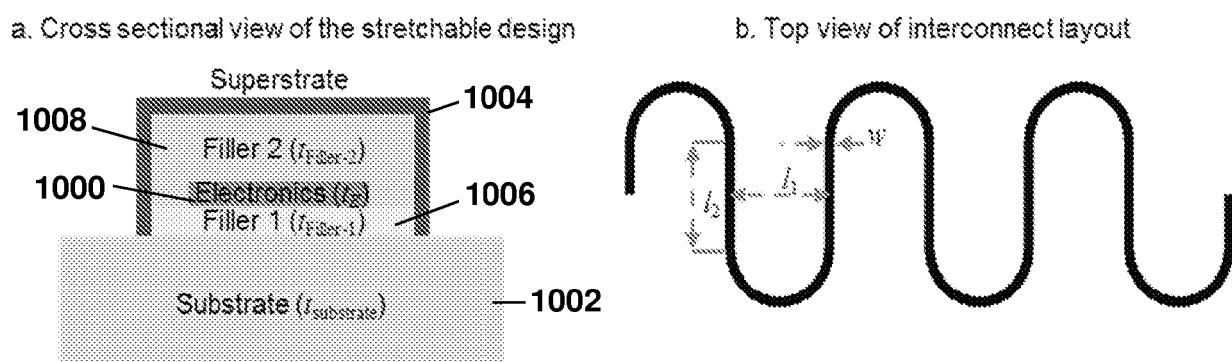


Figure 102

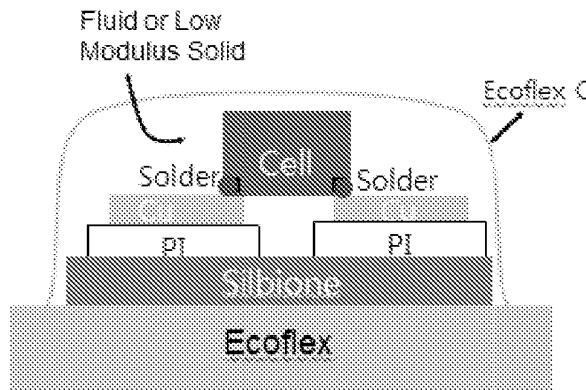


Figure 103A

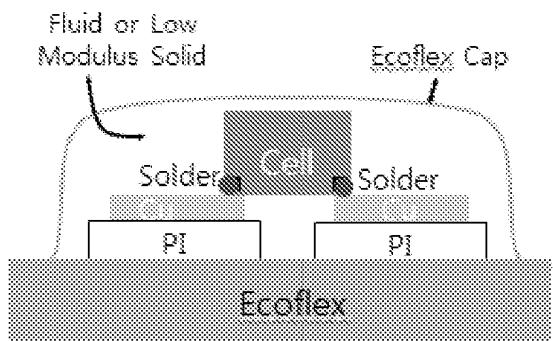


Figure 103B

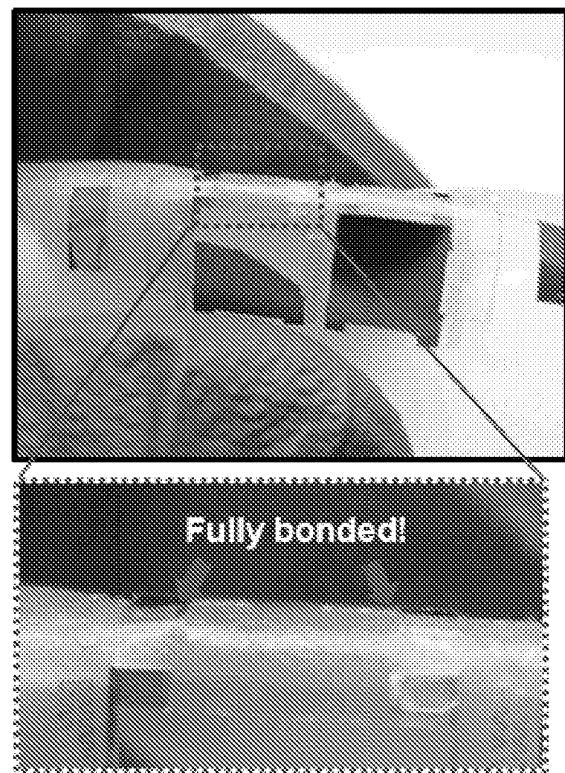


Figure 104

REFERENCES CITED IN THE DESCRIPTION

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