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(54) Title: METHOD FOR MANUFACTURING HYBRID SOFT-RIGID ELECTRONIC DEVICES

(57) Abstract: A method for manufacturing a hybrid soft-rigid electromechanical device comprising the steps of i) placing electronic components on a temporary substrate; ii) encapsulating said electronic components within a soft curable material and curing said soft curable material, thereby embedding said electronic components into a cured soft material; iii) removing said temporary substrate, thereby exposing a levelled surface comprising a cured soft material and electronic components; iv) forming at least one conductive path on said exposed levelled surface, and in direct contact with at least one of said electronic components; and v) encapsulating the resulting structure within a soft curable material and curing said soft curable material, thereby embedding said at least one conductive path into a cured soft material. Hybrid soft-rigid electromechanical device obtainable by the said method are also disclosed.



Method for manufacturing hybrid soft-rigid electronic devices**Technical Field**

[0001] The present invention belongs to the field of electro-mechanical devices. In particular, the present invention relates to a method of manufacturing hybrid (soft/rigid) multi-component electronic circuits and devices, as well as to hybrid (soft/rigid) multi-component electronic circuits and devices as manufactured according to the method.

Background Art

[0002] Molding of thermoset and thermoplastic materials (silicone, acrylonitrile butadiene styrene (ABS), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), styrene butadiene styrene (SBS), styrene ethylene butylene styrene (SEBS), polystyrene (PS) and the like) is commonly used to produce high volume products with tailored shape and surface finish. These materials have important functions in electronic systems, as can they provide the overall shape and mechanical structure of the product and/or form a protective layer as encapsulation. In current techniques, the electronic and mechanical components are manufactured separately and then assembled together in a final step, limiting the design possibilities.

[0003] Creating electronic circuits comprising stretchable electrical conductors, electrode arrays, paths, strips or the like together with rigid, commercially available electronic components and/or printed circuit boards, all embedded into a soft and stretchable matrix to create a monolithic structure, is a still challenging goal, especially with one of the most prevalent stretchable metallization techniques currently being explored: fluid conductors such as gallium-based liquid metal alloys. Typically, when manufacturing an electronic circuit, the conductor (copper on a PCB, for example) is patterned and then electronic components (LEDs, IMUs, passives, MCUs, batteries and the like) are soldered in place. When this approach is applied to liquid metal circuits, however, it has been noted that failure is very likely: in fact, placing rigid components on

top of an e.g. liquid metal trace results in the liquid being displaced and, eventually, flowing, with the further result of merging of neighbouring conductive traces.

[0004] There is therefore still a demand for methods for designing,
5 manufacturing and encapsulating electro-mechanical devices such as hybrid (soft/rigid) multi-component electronic circuits that are simple and efficient enough to be adapted for large-scale production and/or to any stretchable electrical conductors, arrays, paths and/or strips, including fluidic ones.

10 **Summary of the Invention**

[0005] Disclosed in the present application are examples of methods for manufacturing electro-mechanical devices (in particular monolithic) composed of electronic circuits within molded thermoset and thermoplastic materials. The methods as disclosed allow to merge rigid and flexible electronic components
15 and compliant interconnects within a structural, preferably soft, material via a hybrid (soft/rigid) multi-component structuring process.

[0006] Accordingly, disclosed in the present application is a method for manufacturing a hybrid soft-rigid electromechanical device comprising the steps of:

- 20 i) placing electronic components (at least one) on a temporary substrate;
- ii) encapsulating said electronic components within a soft curable material and curing said soft curable material, thereby embedding said electronic components into a cured soft material;
- iii) removing said temporary substrate, thereby exposing a levelled surface
25 comprising a cured soft material and electronic components;
- iv) forming at least one conductive path on said exposed levelled surface, in direct contact with at least one of said electronic components; and
- v) encapsulating the resulting structure within a soft curable material and curing said soft curable material, thereby embedding said at least one conductive path
30 into a cured soft material.

[0007] In one aspect as disclosed, the above-described step ii) comprises:

[0008] ii') connecting said temporary substrate to a first mold having a first receiving cavity;

[0009] ii'') placing a soft curable material into said first receiving cavity and curing said soft curable material, thereby embedding said electronic components into a cured soft material.

[0010] In one aspect as disclosed, the above-described step v) comprises:

v') connecting said first mold to a second mold having a second receiving cavity; and

v'') placing a soft curable material into said second receiving cavity and curing said soft curable material, thereby embedding said at least one conductive path into a cured soft material.

[0011] Further disclosed is a hybrid soft-rigid electromechanical device manufactured by performing a method according to the present disclosure.

In particular. According to the present invention, there is provided a method for manufacturing a hybrid soft-rigid electromechanical device comprising the steps of:

i) placing at least one electronic component on a temporary substrate;

ii) encapsulating said at least one electronic component within a first soft curable material and curing said first soft curable material, thereby embedding said at least one electronic component into a first cured soft material arising from curing said first soft curable material;

iii) removing said temporary substrate, thereby exposing a surface of said cured soft material and a surface of said at least one electronic component;

iv) forming at least one conductive path extending at least in part on said exposed surface, and being in direct contact with said at least one electronic component; and

v) encapsulating the resulting structure within a second soft curable material and curing said second soft curable material, thereby embedding said at least one conductive path and said at least one electronic

component into a second cured soft material arising from curing said second curable soft material.

According to an embodiment step ii) comprises:

5 ii') disposing a first mold having a first receiving cavity on said temporary substrate;

ii'') filling said first soft curable material into said first receiving cavity and curing said first soft curable material, thereby embedding said at least one electronic component into said first cured soft material arising from curing said first soft curable material.

10 According to an embodiment step v) comprises:

v') disposing on said first mold a second mold having a second receiving cavity; and

15 v'') filling said second soft curable material into said second receiving cavity of said second mold and curing said second soft curable material, thereby embedding said at least one conductive path and said at least one electronic component into said cured soft material arising from curing said second soft curable material.

According to an embodiment one or both of said first and second soft material and is a rubber material.

20 According to an embodiment the method comprises coating the temporary substrate with a removable adhesive layer before placing said at least one electronic component on said temporary substrate.

25 According to an embodiment said at least one conductive path is substantially composed of composite materials such a metallic and/or carbon-based inks and pastes, a solid metal conductive layer or film, liquid metals or alloy thereof as well as combinations thereof.

According to an embodiment said liquid metals or alloys thereof comprise one of gallium and a gallium-based alloy.

30 According to an embodiment at least one conductive path has a thickness comprised between 10 nm and 5 mm.

According to an embodiment said at least one electronic component and said at least one conductive path are operatively put in direct contact in a solder-free fashion.

According to an embodiment forming said at least one conductive path is performed by physical vapor deposition, chemical vapor deposition, spray, condensation, screen printing, inkjet printing as well as combinations thereof.

The present invention further relates to a hybrid soft-rigid electromechanical device manufactured by performing a method according to one of the above summarized embodiments and/or aspects.

[0012] Further embodiments of the present invention are defined by the appended claims.

[0013] In the following, the present inventions, along with objects, features and advantages thereof will be clarified by means of the following description of the embodiments of the present invention as depicted in the drawings. However, the present invention is not limited to the embodiments as described in the following and/or depicted in the drawings; to the contrary, the scope of the present invention is defined by the appended claims.

Brief description of drawings

[0014] In the Drawings:

[0015] In Figure 1 there are depicted method steps according to an embodiment of the present disclosure;

[0016] In Figure 2 there is depicted a general process flow diagram of a method according to an embodiment of the present method.

Detailed description of the Invention

[0017] The following disclosure relates to embodiment of the present invention as depicted in the drawings. It is however to be understood that the following disclosure is given for clarifying specific not limiting examples of embodiments of the present invention, the scope of which is defined by the appended claims, and that the terminology used in the following is for the purpose

of describing particular embodiments by way of example only and is not intended to be limiting of the claimed disclosure.

[0018] As used in the following and in the appended claims, the singular forms "a", "an" and "the" include plural referents unless the context clearly dictates otherwise. Also, the use of "or" means "and/or" unless stated otherwise. Similarly, "comprise", "comprises", "comprising", "include", "includes" and "including" are interchangeable and not intended to be limiting. It is to be further understood that where for the description of various embodiments use is made of the term "comprising", those skilled in the art will understand that in some specific instances, an embodiment can be alternatively described using language "consisting essentially of" or "consisting of."

[0019] Unless defined otherwise, technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Further, unless otherwise required by the context, singular terms shall include pluralities and plural terms shall include the singular. The methods and techniques of the present disclosure are generally performed according to conventional methods well known in the art and as described in various general and more specific references that are cited and discussed throughout the present specification unless otherwise indicated.

[0020] In the following, a simple and elegant solution is disclosed which allows to tackle and overcome the shortcomings and/or drawbacks affecting known manufacturing approaches to produce monolithic, hybrid soft-rigid electromechanical devices. In more detail, the following disclosure relates to a method for manufacturing devices such as, *inter alia*, touch sensors, strain sensors and the like, as well as devices such as biomedical implantable neural interfaces, said devices generally comprising three main elements: 1) rigid or semi-rigid electronic components such as printed circuit boards (PCBs), flexible circuit boards (FCBs), as well as individual packaged electronic components such as LEDs, IMUs, MCUs, batteries, transistors and the like; 2) electrical conductors such as electrical conductive strips, paths, lines, arrays or the like, preferably compliant, bendable and/or stretchable in nature; and 3) a soft, preferably

stretchable body made of a polymeric matrix embedding and encapsulating the entire system.

[0021] Generally speaking, the method of the invention comprises the following steps:

- 5 [0022] i) placing electronic components on a temporary substrate;
[0023] ii) encapsulating said electronic components within a soft curable material and curing said soft curable material, thereby embedding said electronic components into a cured soft material;
[0024] iii) removing said temporary substrate, thereby exposing a levelled
10 surface comprising a cured soft material and electronic components;
[0025] iv) forming at least one conductive path on said exposed levelled surface, and in direct contact with at least one of said electronic components; and
[0026] v) encapsulating the resulting structure within a soft curable material and curing said soft curable material, thereby embedding said at least one
15 conductive path into a cured soft material.

[0027] One consideration upon which the invention is based, and which represents the basis for a key technical inventive solution compared to known approaches in the field of soft and stretchable electronics, is the evidence that when liquid electrical conductors or interconnects are first patterned on a
20 substrate (e.g. a soft polymeric material) and then an electronic component is placed on top of said conductors or interconnect, there is a great potential for failure of the device due to fluid flow, thus shorting traces. To the contrary, if the component is placed first and the electrical interconnect placed on top, a later encapsulation step can eliminate this issue. Despite the above consideration, the
25 method according to the present disclosure is fully adaptable even to non-liquid electrical conductors, such as for instance stretchable metallizations made of metallic thin films or layers or conductive ink and paste.

[0028] To this aim, the present inventors implemented in the method described hereinafter a temporary substrate that creates a temporary surface of
30 controlled roughness, shape and planarity, composed of both a soft polymeric material and electronic components' surfaces. After the removal of the temporary substrate, a newly formed, exposed temporary surface of the resulting structure

is exactly as desired depending on the needs and circumstances, such as for instance fully planar or with a controlled surface roughness. The creation of this tailored surface, upon which an electronic circuit is created, results in a surface critical for a solder-free assembly and electrical connection of electronic components (particularly for circuits made from liquid metals such as eutectic gallium-indium alloys), in such a way that even a very thin layer (e.g. down to 10 nm in thickness) of a conductive material can be patterned on the exposed surface, thus favouring the manufacturing of fully compliant, solder-free and even very thin soft-stretchable electronic devices.

[0029] As a way of example, and without limitation, in Figure 1 there is depicted one embodiment of the present method, as it has been implemented in a real-world hybrid soft-rigid electromechanical device according to the present disclosure. Additionally, Figure 2 depicts a general process flow diagram of one aspect of the present method.

[0030] As depicted, during a first method step (Figure 1a), a so-called temporary substrate **100** is provided. The temporary substrate **100** is used for instance to align and hold-in-place rigid or semi-rigid electronic components **200** (at least one). The temporary substrate **100** itself acts as a physical support to electronic components **200** and can be made of several different materials. Some suitable exemplary substrate materials are for instance rigid ones such as plastics (e.g. polyethylene terephthalate (PET)), metals or glass, or flexible/bendable materials such as polyimide (PI). The temporary substrate **100** could also be a thermal or UV release tape.

[0031] According to an embodiment of the method, for purposes which will become more apparent with the following description, the temporary substrate **100** can be coated with a removable adhesive or release layer **101** (Figure 1b), allowing or at least facilitating late removal of the temporary substrate **100**. Said layer **101** can be substantially made of a solvent-soluble material such as polyvinyl alcohol (PVA) polyacrylic acid (PAA), poly(styrene sulfonate) (PSS), glucose or dextrose, just to cite some. For “solvent-soluble material” is herein meant a material that can be dissolved by a solvent such as an organic or an aqueous solvent (e.g. simply water, ethanol or isopropyl alcohol to cite a few). In

particular, the material of the removable adhesive layer **101** can be coated directly on the temporary substrate **100**, followed by the placement of the electronic components **200**, and dehydration and/or curing of the adhesive material. During a second step, as depicted in Figure 1c, the electronic components **200** are pick-and-placed on the temporary substrate **100**. For securing the electronic components **200** on the temporary substrate **100**, the adhesive properties of the removable adhesive layer **101** can be exploited; additionally or alternatively, and depending on the circumstances, the bottom surface of the electronic components **200** can be coated with a thin (e.g. between 1 and 100 μm) additional solvent-soluble layer (not shown) via a process such as dip-coating or pad printing.

[0032] During a third step, as depicted in Figure 1d, the electronic components **200** are encapsulated into a soft matrix **300** substantially composed of a soft polymeric material. To this aim, a soft curable material is provided in such a way to embed the electronic components **200** according to a method known in the art such as overmolding, spray coating, dispensing (pouring), forming, compression molding, dip coating and the like. In one particular aspect or embodiment, the temporary substrate **100** can be connected to a first mold **400** having a first receiving cavity 400c, and a soft curable material is injected, poured or otherwise placed within said first receiving cavity 400c and subsequently cured, thereby embedding said electronic components **200** into a cured soft material. The term “curing” is herein used to refer to the toughening or hardening of a polymer material by cross-linking of polymer chains, brought about by electron beams, heat, and/or chemical additives such as crosslinkers, as well known to a person skilled in the art. When the additives are activated by ultraviolet radiation, the process is also called UV cure. The situation at the end of this third step presents a structure comprising electronic components **200** embedded into a soft matrix **300** without any presence of electrical conductors or interconnects. The thickness of the soft matrix **300** may range from 1 μm to 10 cm according to the needs and/or circumstances. Additional layers for bonding or transfer the device on various substrates, such as hotmelt adhesive (e.g. thermoplastic polyurethane) for heat press transfer (e.g. on textile), can be also added.

[0033] Concerning the soft matrix **300**, in preferred aspects this is substantially made of a soft polymeric material, or combinations of many soft polymeric materials, possibly biocompatible ones, whenever needed, to fit with biomedical applications of the hybrid soft-rigid devices herein disclosed. The term
5 “soft” is herein meant to include any material that is compressible, reversibly compressible, elastic, flexible, stretchable or any combination thereof. Particularly, a soft material includes materials having a small Young’s modules (typically of <100 MPa, such as between 0.01 and 100 MPa), providing a large elongation upon a strain stress, typically of >5% of the elongation of a soft
10 structure at rest. In such a way, the obtained device is highly compliant even for thickness of several millimeters to centimeters upon experiencing a deformation.

[0034] In preferred aspects or embodiments of the present invention, soft materials are stretchable, i.e. elastically deformable upon elongation, preferably in more directions. Examples of suitable materials for the soft polymeric matrix
15 **300** are for instance thermosets or thermoplastics such as styrene butadiene styrene (SBS) or styrene ethylene butylene styrene (SEBS), soft foams such as polyurethanes including reticulated polyurethanes, polyvinyl chloride (PVC), neoprene, uncrosslinked neoprene, cross-linked polyethylene, polyether, ethylene-vinyl acetate (EVA), polyethylene-vinyl acetate (PEVA), polypropylene
20 glycol (PPG), latex, elastomeric materials such as silicone rubber (e.g. polydimethylsiloxane PDMS) or fluorosilicone rubber, thermoplastic elastomers such as styrenic block copolymer (SBC), ethylene propylene diene monomer (EDPM) rubber, butyl rubber, nitrile rubber, or combinations of any of the foregoing.

[0035] In some circumstances, particularly in the case where hybrid electromechanical devices are sought for biomedical application, the soft matrix
25 **300** may also comprise, or being substantially composed of, one or more compounds selected from a non-exhaustive list comprising natural polymeric material (i.e., non-synthetic polymers, polymers that can be found in nature) and/or polymers derived from the Extra Cellular Matrix (ECM) as gelatin, elastin,
30 collagen, agar/agarose, chitosan, fibrin, proteoglycans, a polyamino-acid or its derivatives, preferably polylysine or gelatin methyl cellulose, carbomethyl

cellulose, polysaccharides and their derivatives, preferably glycosaminoglycans such as hyaluronic acid, chondroitinsulfate, dermatansulfate, heparansulfate, heparine, keratansulfate or alginate, nucleotides, polylipides, fatty acids, as well as any derivative thereof, fragment thereof and any combination thereof.

5 [0036] As it will be appreciated by a person skilled in the art, the soft matrix **300** may also be produced so to obtain a gel or a hydrogel. As used herein, the term “gel” refers to a non-fluid colloidal network or polymer network that is expanded throughout its whole volume by a fluid. The term “hydrogel” refers to a gel in which the swelling agent is water. In the frame of manufacturing of e.g.
10 sensors for biomedical application or implantable neuroprosthetic interfaces, the choice of a soft material and in some instances gels/hydrogel is ideal, particularly for its concomitant ability to tolerate mechanical deformations caused by movements, muscle contractions, and other geometrical changes without experiencing major losses in its performances. Generally speaking, “deformation”
15 may refer to any compression, expansion, contraction, bending, torsion, linear or area strain experienced by at least a portion of the electromechanical devices according to the present disclosure.

[0037] Turning back to the method according to the embodiment of the present invention as depicted in the drawings, once the soft material **300** is
20 cured/set, during a fourth step as depicted in Figure 1e the temporary substrate **100** is removed. The exposed surface **301** of the so-obtained structure is possibly cleaned and, as a result there is obtained a continuous, levelled surface **301** comprising at least a portion 301m of the exposed surface of the material **300** and the exposed surface 301d of the at least one component **200**, the levelled
25 surface **301** incorporating therefore the structural injected material **300** and the exposed electronic components **200**, this representing a critical step enabling for the rest of the manufacturing of the hybrid soft-rigid electromechanical device. Surface morphology of the surface **301** of the material exposed after removal of the temporary substrate **100** is continuous and controlled; this is a requisite for
30 the patterning of the conductive paths **600**, as detailed hereinafter.

[0038] For the sake of clarity, the term “levelled” is herein meant to refer to a feature of the surface **301** by which electronic components **200** and the soft

material **300** creates a continuous and uninterrupted surface having substantially no gaps between them and no part higher than another at the direct interface between electronic components **200** and the adjacent soft material **300**. The temporary substrate **100** may have an engineered roughness that can be advantageously transferred to the surface **301** resulting from the first molding process. The role of this roughness is to enhance adhesion of conductive tracks on the soft substrate **300** and to promote adhesion of the last encapsulation layer, as will be detailed later on.

[0039] At this point, the entire structure can be possibly flipped (turned upside-down) in such a way to use the first mold **400** as a carrier substrate, and a mask **500** for patterning a metallization is placed/created by e.g. alignment of a stencil mask or patterning of a photoresist mask via photolithography.

[0040] During a fifth step, as depicted in Figure 1f, at least one conductive path **600** is formed on the previously obtained cured soft material **300**, particularly on the exposed surface **301**, and in direct contact with at least one of said electronic components **200**. This is in strong contrast to classical stretchable electronics manufacturing, which is based on a first placement of the “hard” electronic parts subsequently overmolded with an elastomeric material.

[0041] Compliant electrical conductors, arrays, paths and/or strips, also referred to herein sometimes as “conductive interconnects”, can be deposited on the surface **301** of the exposed molded part by means of a mask. In some aspects, said at least one conductive path **600** can have a thickness comprised between 10 nm and 5 mm, such as between 10 nm and 1 mm, between 10 nm and 500 μm , between 10 nm and 100 μm , between 10 nm and 1 μm , between 10 and 500 nm, or between 10 and 100 nm.

[0042] Conductive paths **600** can be provided in the form of a thin film or layer of a conductive material. Generally speaking, a “thin film” as used herein relates to a film or layer of a material having a thickness much smaller than the other dimensions, e.g. at least one fifth compared to the other dimensions. Typically, a thin film is a solid layer having an upper surface and a bottom surface, with any suitable shape, and a thickness generally in the order of nanometers or even micrometers, depending on the needs and circumstances, e.g. the manufacturing

steps used to produce it. However, the film can even be a so-called “single layered film” or “monolayer”, a substantially two-dimensional layer of covalently-bonded monomers. As used herein, a “two-dimensional” layer or film is a sheet-like macromolecule consisting of interconnected repeat units having a thickness in the order of a single molecule (monomolecular). In some aspects, the film according to the invention has a thickness comprised between about 1 and 1000 nanometers, such as for instance between about 10 and 800 nanometers, between about 50 and 500 nanometers, between about 100 and 600 nanometers, between about 200 and 500 nanometers, or between about 300 and 500 nanometers.

[0043] By way of example, conductive paths **600** may be provided on the cured soft material surface **301** by depositing a metal such as Au, Pd, Pt, Ir or alloys thereof via e.g. physical vapour deposition such as thermal evaporation or sputtering, chemical vapour deposition, spray coating, lamination, Cluster ion implantation or Supersonic Cluster Beam Implantation. Additionally or alternatively, said at least one conductive path **600** is substantially composed of composite materials such as a metallic and/or carbon-based inks and pastes deposited on the cured soft material surface **301** by e.g. spray coating, sputtering, screen printing or inkjet printing. Additionally or alternatively, said at least one conductive path **600** is substantially composed of liquid metals or alloys thereof, preferably one of gallium and a gallium-based alloy, deposited on the cured soft material surface **301** by e.g. physical vapour deposition, chemical vapour deposition, spray coating, thermal evaporation/condensation, direct writing screen printing, doctor blading or inkjet printing. Combinations of any of the above solutions are also envisageable.

[0044] In some aspects, a thin film or layer of a metal such as Au, Pd, Pt, Ir or alloys thereof is first deposited on the cured soft material surface **301** to perform as a wetting layer facilitating the deposition and the adhesion of a liquid metal that eventually alloys with the metal film. By way of example, a film may be provided on the surface **301** by depositing a metal such as Au, Pd, Pt, Ir or alloys thereof via physical vapour deposition, chemical vapour deposition, spray, condensation or sputtering, followed by a second layer of liquid gallium or an alloy

thereof (e.g. eGaln or galinstan). As a way of example, this wetting layer-thin film can have a thickness comprised between 1 nm and 1µm, such as about 50 nm.

[0045] In a final step, the resulting structure is encapsulated within a soft curable material **302** which is then cured, thereby embedding said at least one
5 conductive path **600** into a cured soft material.

[0046] In one particular aspect, as depicted in Figure 1g, this final step comprises:

[0047] - connecting the first mold **400** to a second mold **401** having a second receiving cavity 401c; and

10 [0048] - injecting a soft curable material into said second receiving cavity and curing said soft curable material **302**, thereby embedding said at least one conductive path **600** into a cured soft material. At the end of the entire process, the final hybrid soft-rigid structure is removed from any carrier support (Figure 1h).

15 [0049] According to the present disclosure and depending on the needs and/or circumstances, during a further optional step not depicted in the drawings one or more through vias can be formed in the soft cured polymeric matrix **300** so as to expose one or more portions of the conductive path(s) **600**, wherein said exposed portions can be used for instance as contacting pads for electrical
20 connection, for instance wiring connection or stacking and connecting multiple hybrid soft-rigid devices with methods known in the art.

[0050] Still according to the present disclosure and depending on the needs and/or circumstances, the surface **301** can have a controlled microtextured topology comprising a plurality of protrusions separated by grooves. Said
25 protrusions can be shaped as regular or irregular polyhedral pillars as well as long stripes arranged on the surface **301** in any suitable direction. According to a preferred aspect, the dimensions (height, length and/or thickness) of the pillars, as well as the depth of the grooves, can usually span from 0.5 to 100 µm. It has been successfully demonstrated in the past by the present inventors that adding
30 a controlled microtexture topology on a support substrate enables to produce smooth thin films of liquid metals such as gallium or alloys thereof by imbibition, thus obtaining improved electrical conductors and gallium super-lyophilic

substrates having smooth film of liquid metals on extended areas, with tailored thickness and electrical properties. In this context, the temporary support **100** and/or the removable adhesive layer **101** are designed to include such a microtexture so to transfer it to the soft material **300** (and the resulting surface **301**) upon the molding process. Notwithstanding, the temporary support **100** and/or the removable adhesive layer **101** are designed to include microtexture-free areas for placing electronic components **200** so to obtain a levelled surface **301** at the end of the first molding/encapsulating step.

[0051] As anticipated, the present invention further relates to a hybrid soft-rigid electromechanical device manufactured by performing a method according to the present disclosure. A hybrid soft-rigid electromechanical device in accordance to the present specification can be, or incorporated into, a sensor, particularly deformable sensors, such as strain sensors or touch sensors; a wearable ("on-body" and "on-organ") electronic device; an electrode array for cell culture and tissue slice culture; a sensing robotic skin; a stretchable/deformable antenna; or an implantable device suitable to be used as e.g. a neuroprosthetic interface with the central nervous system, i.e. the spinal cord, brain, or the peripheral nervous systems, i.e. the ganglia and nerves, or soft biological tissue, for instance for the purpose of stimulating and/or recording neurological or cardiac activity or even for stimulating electrical potential of excitable cells or the like.

[0052] A hybrid soft-rigid electromechanical device as described herein, depending on the needs and the applications, can have any suitable shape, with the most suitable for many of the above-cited applications being a flat, planar shape having a thickness comprised between 1 μm and 10 cm such as between 1 μm and 1 cm, between 1 μm and 1 mm, between 1 and 500 μm , between 1 and 300 μm or between 1 and 100 μm .

[0053] The device can comprise electrical conductors in contact with both the soft polymeric matrix and the rigid electronic components, said electrical conductors being operatively in contact with said rigid electronic components (e.g. PCBs, FCBs, LEDs and the like) in a solder-free fashion, and said electrical conductors having a thickness comprised between about 1 and 1000

nanometers, such as for instance between about 10 and 800 nanometers, between about 50 and 500 nanometers, between about 100 and 600 nanometers, between about 200 and 500 nanometers or between about 300 and 500 nanometers. Furthermore, said electrical conductors can be preferably made of
5 a thin film or layer of a metal such as Au, Pd, Pt, Ir or alloys thereof and/or liquid metals or alloys thereof, preferably but not limited to one of gallium and a gallium-based alloy.

[0054] It has therefore been demonstrated by means of the above detailed description of the embodiments of the present invention as depicted in the
10 drawings that the present invention allows to obtain the wished results and in particular to overcome the drawbacks affecting manufacturing methods according to the prior art.

[0055] Although the present invention has been clarified by means of the above detailed description of the embodiments as depicted in the drawings, the
15 present invention is not limited to the embodiments as described above and/or depicted in the drawings, the scope of the present invention being defined by the appended claims.

Claims

Claim 1. A method for manufacturing a hybrid soft-rigid electromechanical device comprising the steps of:

i) placing at least one electronic component **(200)** on a temporary substrate **(100)**;

ii) encapsulating said at least one electronic component **(200)** within a first soft curable material **(300)** and curing said first soft curable material **(300)**, thereby embedding said at least one electronic component **(200)** into a first cured soft material arising from curing said first soft curable material **(300)**;

iii) removing said temporary substrate **(100)**, thereby exposing a surface **(301)** of said cured soft material **(300)** and a surface (200d) of said at least one electronic component **(200)**;

iv) forming at least one conductive path **(600)** extending at least in part on said exposed surface **(301)**, and being in direct contact with said at least one electronic component **(200)**; and

v) encapsulating the resulting structure within a second soft curable material **(302)** and curing said second soft curable material **(302)**, thereby embedding said at least one conductive path **(600)** and said at least one electronic component **(200)** into a second cured soft material arising from curing said second curable soft material **(302)**.

Claim 2. The method of claim 1, wherein step ii) comprises:

ii') disposing a first mold **(400)** having a first receiving cavity on said temporary substrate **(100)**;

ii'') filling said first soft curable material **(300)** into said first receiving cavity and curing said first soft curable material **(300)**, thereby embedding said at least one electronic component **(200)** into said first cured soft material arising from curing said first soft curable material **(300)**.

Claim 3. The method of claims 1 or 2, wherein step v) comprises:

v') disposing on said first mold **(400)** a second mold **(401)** having a second receiving cavity; and

v”) filling said second soft curable material **(302)** into said second receiving cavity of said second mold (401) and curing said second soft curable material (302), thereby embedding said at least one conductive path **(600)** and said at least one electronic component (200) into said cured soft material arising from curing said second soft curable material **(302)**.

5 Claim 4. The method of any previous claims, wherein one or both of said first and second soft material **(300)** and **(302)** is a rubber material.

Claim 5. The method of any previous claims, comprising coating the temporary substrate **(100)** with a removable adhesive layer **(101)** before
10 placing said at least one electronic component **(200)** on said temporary substrate **(100)**.

Claim 6. The method of any previous claims, wherein said at least one conductive path **(600)** is substantially composed of composite materials such a metallic and/or carbon-based inks and pastes, a solid metal conductive
15 layer or film, liquid metals or alloy thereof as well as combinations thereof.

Claim 7. The method of claim 6, wherein said liquid metals or alloys thereof comprise one of gallium and a gallium-based alloy.

Claim 8. The method of any previous claims, wherein said at least one conductive path **(600)** has a thickness comprised between 10 nm and 5 mm.

20 Claim 9. The method of any previous claims, wherein said at least one electronic component **(200)** and said at least one conductive path **(600)** are operatively put in direct contact in a solder-free fashion.

Claim 10. The method of any previous claims, wherein forming said at least one conductive path **(600)** is performed by physical vapor deposition, chemical vapor deposition, spray, condensation, screen printing, inkjet
25 printing as well as combinations thereof.

Claim 11. A hybrid soft-rigid electromechanical device manufactured by performing a method according to claims 1 to 10.

Figure 1

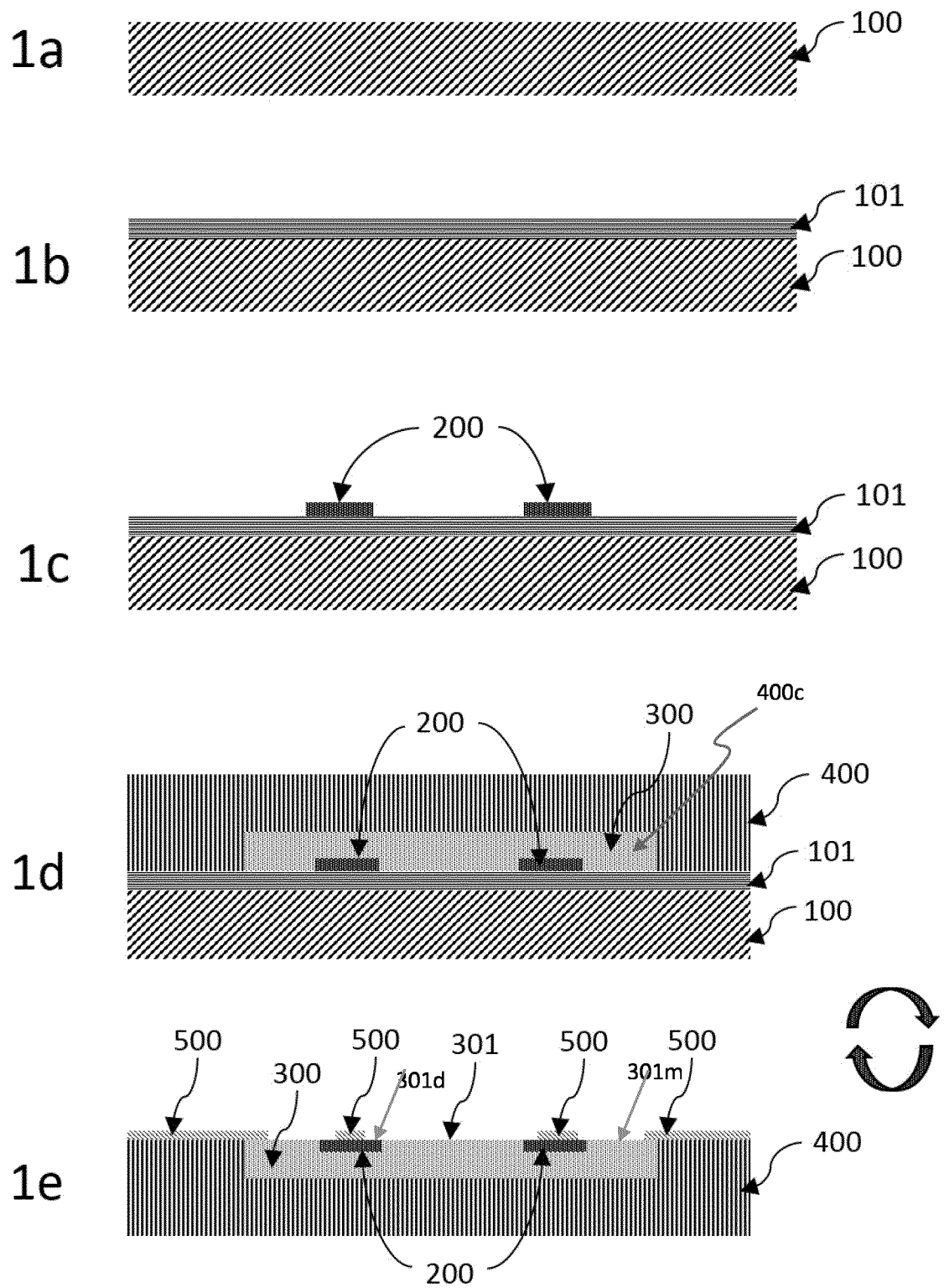


Figure 1 (continued)

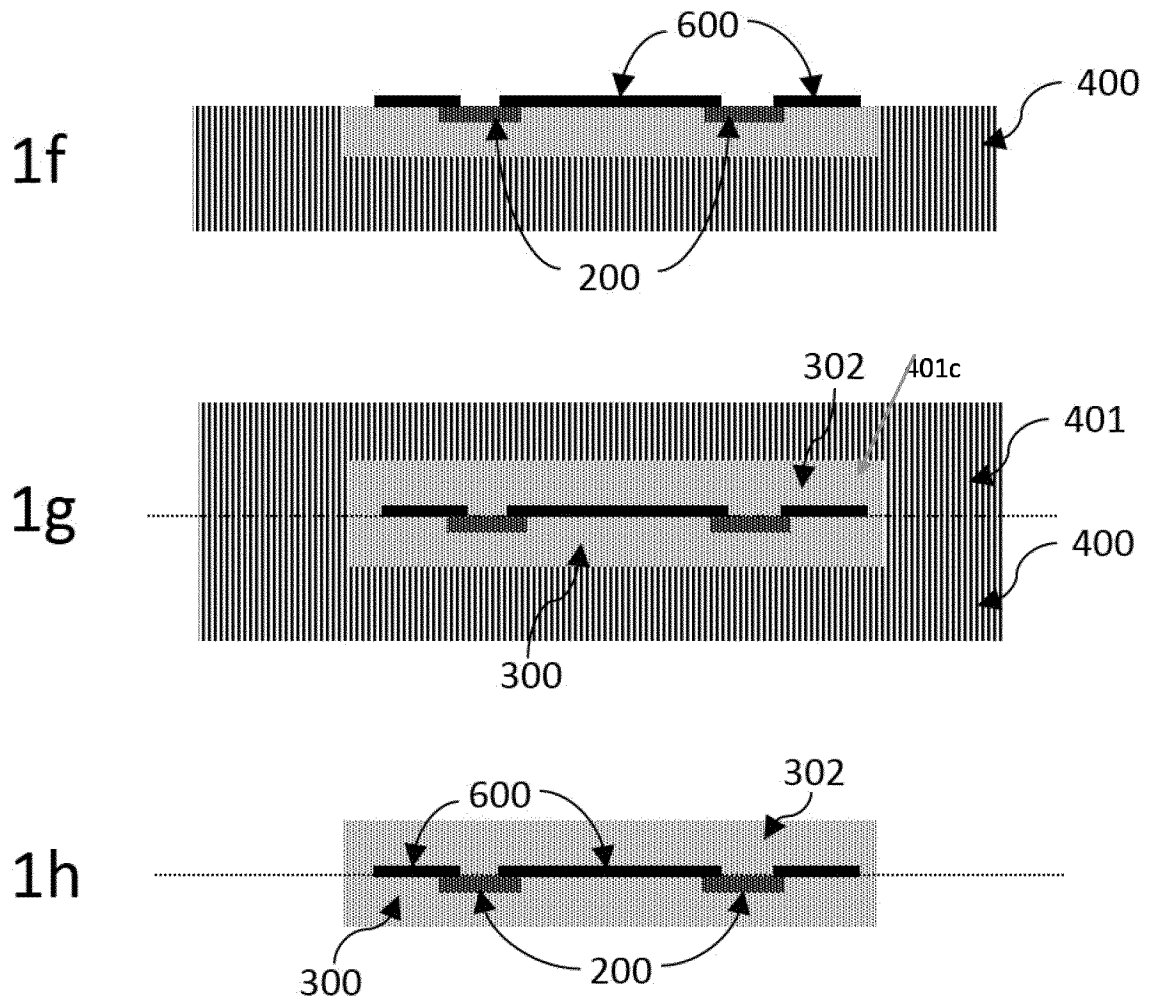
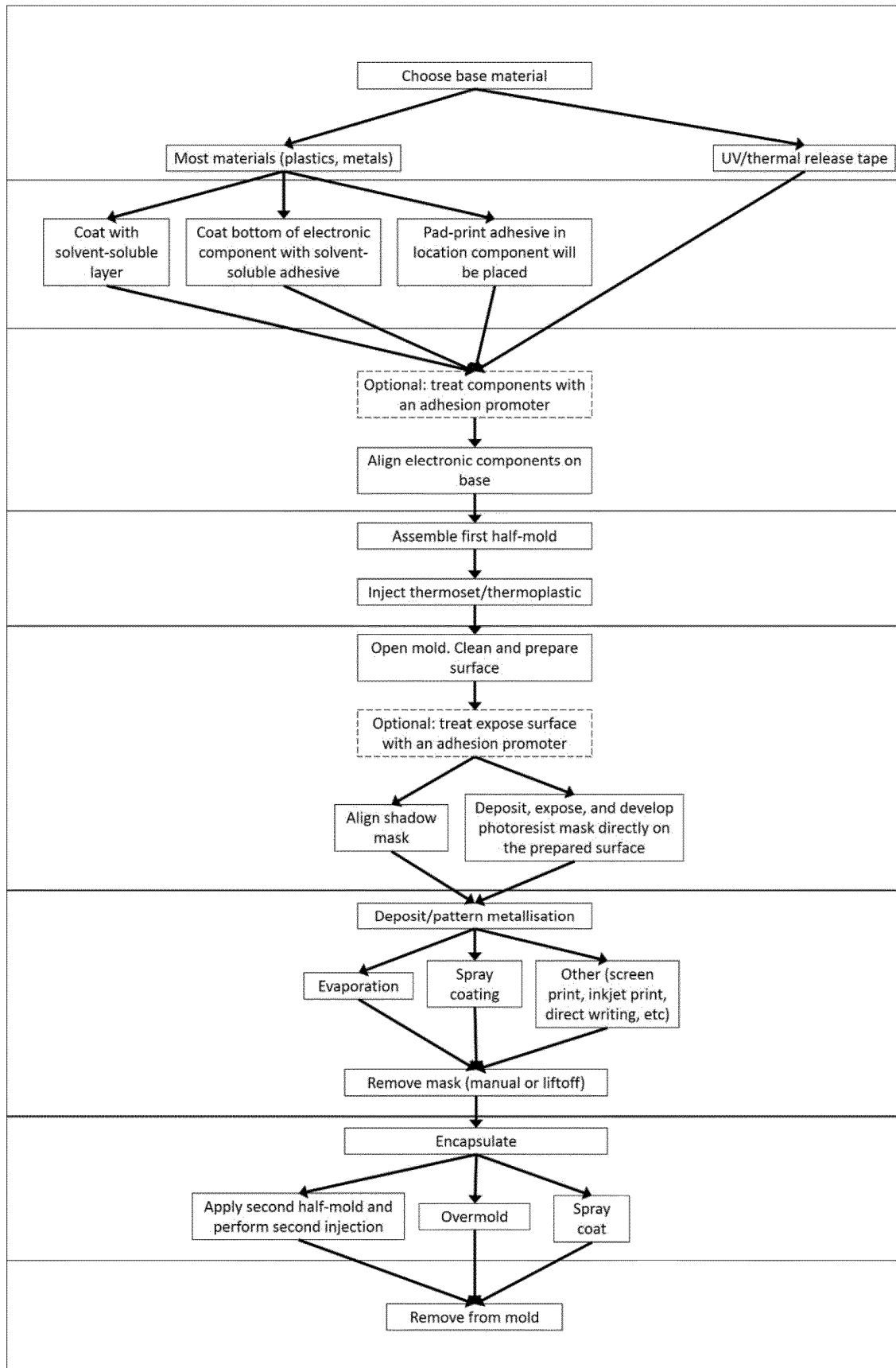


Figure 2



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/061887

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L21/56 H01L23/00 H05K1/02
ADD. H01L23/31

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H01L H05K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data

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X	US 2014/303452 A1 (GHAFFARI ROOZBEH [US]) 9 October 2014 (2014-10-09)	11
Y	paragraphs [0111], [0124], [0131]; figures 3A-E	1-10
Y	----- US 2013/334698 A1 (MOHAMMED ILYAS [US] ET AL) 19 December 2013 (2013-12-19) paragraphs [0038] - [0044]; figures 3-5	1-10
Y	----- WO 2017/001978 A1 (LETIZIA MARCO [CH]; MAODDI PIETRO [CH]) 5 January 2017 (2017-01-05) page 11, line 14 - page 12, line 26	6-8
X	----- US 2013/333094 A1 (ROGERS JOHN A [US] ET AL) 19 December 2013 (2013-12-19) paragraph [0144]; figure 11	11
	----- -/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/061887

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	BONGSOO KIM ET AL: "Interfacing Liquid Metals with Stretchable Metal Conductors", ACS APPLIED MATERIALS & INTERFACES, vol. 7, no. 15, 22 April 2015 (2015-04-22), pages 7920-7926, XP055267456, US ISSN: 1944-8244, DOI: 10.1021/am508899z the whole document -----	6-8

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International application No

PCT/EP2019/061887

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