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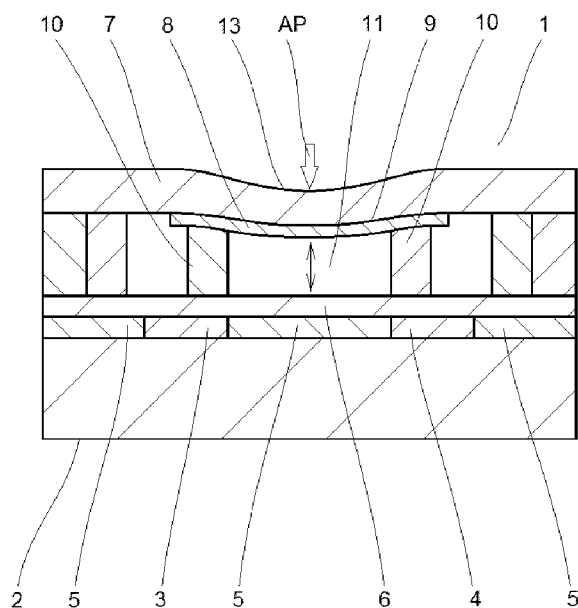


FIG. 1

(57) Abstract: According to an example aspect of the present invention, there is provided an artificial skin cell structure (1) comprising a bottom polymer layer (2); a pair of electrodes (3, 4) and an organic semiconductor layer (5) disposed on the polymer bottom layer (2), the pair of electrodes (3, 4) being disposed within the organic semiconductor layer (5); a dielectric layer disposed on the organic semiconductor layer (6); a flexible top polymer layer (7) disposed above the dielectric layer (6); a flexible top electrode (8) disposed on the bottom surface (9) of the top polymer layer (7), the location of the top electrode (8) substantially matching the location of the pair of electrodes (3, 4), wherein the top polymer layer (7) is spaced from the dielectric layer (6) and supported by a plurality of supporting members (10), thereby forming an air gap (11) between the top polymer layer (7) and the dielectric layer (6).

ARTIFICIAL SKIN CELL STRUCTURE AND PRODUCTION METHOD THEREOF

FIELD

5 **[0001]** The present invention relates to an artificial skin cell structure. Further, the present invention relates to a method of producing an artificial skin cell structure. Furthermore, the present invention relates to an artificial skin having a sensor network.

BACKGROUND

10 **[0002]** Artificial electronic skin emulates the properties of natural skin via containing large arrays of pressure- and touch-sensitive pixels on a flexible and/or stretchable substrate. The smart skin sensor system offers a unique solution to the measurement of real-time pressure and touches profiles on flat, curved, rigid or soft surfaces and can be used in many applications. For example robotic devices capable of
15 adjusting the amount of force needed to hold and use different objects and the skin enables robotic systems with human-like sensing capabilities. New concepts of user interfaces based on pressure sensitivity were created. Usage of artificial skin allows digitizing information in medicine. There are multiple applications of artificial skin e.g. in sport.

[0003] Different concepts of artificial skin have been demonstrated previously:
20 resistive, capacitive, piezoelectric based on polyvinylidene fluoride (PVDF) films, and optical. However many of them have low sensitivity and/or they are not suitable for integration into flexible substrates.

[0004] Artificial electronic skin based on pressure-sensitive rubber and organic transistors embedded on a plastic film is proposed in T. Someya, T. Sekitani, S. Iba, Y.
25 Kato, H. Kawaguchi, T. Sakurai, A large-area, flexible pressure sensor matrix with organic field-effect transistors for artificial skin applications, Proceedings of the National Academy of Sciences of the United States of America. 101 (2004) 9966–9970. The skin, consisting of an organic transistor matrix, is used to readout pressure data from sensors based on pressure-sensitive rubber. Although the mobility of organic semiconductors is known to be

about two or three orders of magnitude less than that of poly- and single-crystalline silicon, the slower speed is tolerable for most applications of artificial electronic skin.

[0005] Artificial electronic skin based on a matrix of organic transistors and using a capacitive sensing principle is proposed in S.C. Mannsfeld, B.C. Tee, R.M. Stoltenberg, C.V.H. Chen, S. Barman, B.V. Muir, et al., Highly sensitive flexible pressure sensors with microstructured rubber dielectric layers, Nature Materials. 9 (2010) 859–864. The skin consists of a transistor matrix with a flexible polydimethylsiloxane (PDMS) polymer film on top. An array of tiny square pyramids is moulded into the film. The flexible film acts as the dielectric material at the gate electrodes of a transistor made from a single crystal of the organic semiconductor rubrene. When the pyramids are squeezed, the transistor gate is brought closer to the channel, thus changing capacitance and transistor current.

[0006] Artificial electronic skin based on a matrix of transistors has high sensitivity. It is suitable for integration on flexible substrates. However, only laboratory prototypes of such skin, predominantly made by subtractive photolithographic processes, have been demonstrated so far. The next important step is to find a way to fabricate artificial electronic skin at a low cost.

SUMMARY OF THE INVENTION

[0007] The invention is defined by the features of the independent claims. Some specific embodiments are defined in the dependent claims.

[0008] According to a first aspect of the present invention, there is provided an artificial skin cell structure comprising a bottom polymer layer, a pair of electrodes and an organic semiconductor layer disposed on the polymer bottom layer, the pair of electrodes being disposed within the organic semiconductor layer, optionally a dielectric layer disposed on the organic semiconductor layer, a flexible top polymer layer disposed above the organic semiconductor layer, or optionally above the dielectric layer, a flexible top electrode disposed on the bottom surface of the top polymer layer, the location of the top electrode substantially matching the location of the pair of electrodes, wherein the top polymer layer is spaced from the organic semiconductor layer, or optionally from the dielectric layer, and supported by a plurality of supporting members, thereby forming an

air gap between the top polymer layer and the organic semiconductor layer, or optionally between the top polymer layer and the dielectric layer.

[0009] Various embodiments of the first aspect may comprise at least one feature from the following bulleted list:

- 5 • a portion of the supporting members form a frame around the electrodes
- the pair of electrodes is made of silver
- the top electrode is made of a silver nanoparticle ink
- the supporting members are made of a photopolymer
- a pitch between supporting members is in a range between 400 [μm] and 800 [μm]
- 10 • a width of a supporting member is in the range between 110 [μm] and 170 [μm]
- a height of a supporting member is in the range between 3 [μm] and 7 [μm]

[0010] According to an embodiment, a fabrication method utilizing printable electronics is used to bring artificial electronic skin into production. Different printing technologies are utilized for realization of various mechanical and electrical structures.

- 15 **[0011]** Gravure printing was used to make spacer structures in C.-Y. Lo, J. Hiitola-Keinänen, O.-H. Huttunen, J. Petäjä, J. Hast, A. Maaninen, et al., Novel roll-to-roll lift-off patterned active-matrix display on flexible polymer substrate, *Microelectronic Engineering*, 86 (2009) 979–983.

- 20 **[0012]** Inkjet printing was used for cell gap spacers in liquid crystal displays by N. Maruyama, Y. Kumashiro, K. Yamamoto, Development of cell gap spacer in LCD for ink-jet printing, in: *Electronics System-Integration Technology Conference, 2008. ESTC 2008*. 2nd, 2008: pp. 985–988, optical microlenses by C.-H. Tien, C.-H. Hung, T.-H. Yu, Microlens arrays by direct-writing inkjet print for LCD backlighting applications, *Display Technology, Journal of*, 5 (2009) 147–151, and high pillars by B.-J. de Gans, P.C. Duineveld, U.S. Schubert, Inkjet printing of polymers: state of the art and future developments, *Advanced Materials*, 16 (2004) 203–213. Lamination of separately processed foils has been used for TFT fabrication in T. Hassinen, T. Ruotsalainen, P. Laakso, R. Penttilä, H.G. Sandberg, Roll-to-roll compatible organic thin film transistor

manufacturing technique by printing, lamination, and laser ablation, Thin Solid Films. 571 (2014) 212–217.

[0013] Printable electronics manufacturing methods offer a low cost alternative to current electronics manufacturing processes. Additionally, printed electronics processing
5 can yield very large volumes in a short time, still offering the customization possibility for dedicated applications.

[0014] In view of the foregoing, an embodiment provides a fully printed pressure sensor matrix with organic field-effect transistors for artificial electronic skin applications.

[0015] According to a second aspect of the present invention, there is provided a
10 method comprising providing a top polymer layer, printing a top electrode and a plurality of supporting members on the top polymer layer, providing a bottom polymer layer, forming a pair of electrodes of the bottom polymer layer, printing an organic semiconductor layer on the bottom polymer layer, optionally printing a dielectric layer on the organic semiconductor layer, positioning the top polymer layer such that the surface
15 having the top electrode and the supporting members thereon faces the organic semiconductor layer and/or the dielectric layer, and the top electrode and the pair of electrodes are aligned, and bonding the layers together. Hence, in a first variation of the method, a dielectric layer is omitted, and in a second variation, a dielectric layer is used.

[0016] Various embodiments of the second aspect may comprise at least one feature
20 from the following bulleted list:

- the step of forming the pair of electrodes comprises depositing a layer of conducting material on the bottom polymer layer, and forming the pair of electrodes by removing excessive conducting material
- depositing the layer of conducting material on the bottom polymer layer takes place
25 by means of evaporating a silver layer
- removing excessive conducting material takes place by means of etching
- etchant is rotary screen printed
- at least one of the semiconductor layer and the dielectric layer is gravure printed from organic solvents

- silver deposition, screen printing, and gravure printing are done with roll-to-roll-machines
- the top electrode of the bottom polymer layer is made of a silver nanoparticle ink.
- the top polymer layer is treated with O₂ plasma prior to printing the silver nanoparticle ink
- the silver nanoparticle ink is sintered
- the supporting members are formed by printing a photopolymer
- the surface having the top electrode is dip-coated prior to printing the supporting members
- the surface having the top electrode is pre-treated prior to printing the supporting members in order to control the aspect ratio of the supporting members
- the method further comprising forming a frame by printing a portion of the supporting members around the electrodes
- the method further comprising forming a frame or pattern by printing an additional adhesive around the electrodes in order to promote adhesion in lamination.

[0017] According to a third aspect of the present invention, there is provided an artificial skin having a sensor network comprising a plurality of artificial skin cell structures according to the embodiments arranged in rows and columns, a plurality of row conductors and column conductors, wherein the top electrodes of the cell structures located on a common row are connected to a corresponding row conductor, and one of the pair of electrodes of the cell structures located on a common column are connected to a corresponding column conductor.

[0018] According to a variation of the third aspect of the present invention, there is provided an artificial skin having a sensor network comprising a plurality of artificial skin cell structures according to the embodiments arranged in rows and columns, a plurality of row conductors and column conductors, wherein the top electrodes of the cell structures are connected to a corresponding column conductor, and the pair of bottom electrodes of the cell structures are connected to the corresponding row conductor and common ground connector, such as in Fig. 12, for instance.

[0019] According to a fourth aspect of the present invention, there is provided a method of producing an artificial skin having a sensor network with a plurality of artificial skin cell structures, the method comprising:

- printing a plurality of top electrodes on a surface of the top polymer layer;
- printing a plurality of supporting members on the surface of the top polymer layer;
- providing a bottom polymer layer;
- forming a plurality of pairs of electrodes on a surface of the bottom polymer layer;
- 5 – forming row conductors, column conductors and ground conductors on the surfaces of the top polymer layer and/or the bottom polymer layer;
- printing an organic semiconductor layer on the surface of the bottom polymer layer;
- optionally printing a dielectric layer on the organic semiconductor layer;
- positioning the top polymer layer and the bottom polymer layer such that the
- 10 surface having the top electrode and the supporting members thereon faces the dielectric layer, and that the top electrodes and the pairs of electrodes are aligned with each other; and
- bonding the top polymer layer and the bottom polymer layer together so that the supporting members are directly attached to at least one of the dielectric layer, the
- 15 bottom polymer layer, the organic semiconductor layer and the electrodes.

[0020] There are also embodiments of the fourth aspect that use printed adhesive patterns outside of the active sensor area, between the sensors, in order to make the lamination structure more rigid (see Figs 5 and 6). Then, the air gaps remain at the sensor areas but otherwise the structure can include hardened adhesive between the layers. It is

20 also possible to use conductive adhesive for making vias from the bottom layer electrode wiring to the top layer electrode wiring. Conductive adhesive can also be used for forming the interconnections and bridging of needed row, column and ground connectors.

[0021] Considerable advantages are obtained by means of certain embodiments of the present invention. An artificial skin cell structure is provided. A pressure sensor matrix

25 with organic field-effect transistors for artificial skin applications has been designed, fabricated and tested. The fabrication process includes standard, low cost mass production steps of printed electronics. The laminated air-gap transistor structure is simple, and can be scaled in all dimensions. Inkjet printing being a digital processing method can be used for tuning individual pixels with spacer height and spacing, or making arbitrary patterns for

30 the pixels. By choosing thin substrates the flexibility and sensitivity can be enhanced, but at the same time the challenges increase in processing of the thin substrates. By choosing transparent conductors, the structure can be made almost transparent. In addition to the

simple touch sensor application, the proposed air-gap structure opens up new possibilities for other more dedicated (e.g. gas) sensing purposes.

BRIEF DESCRIPTION OF THE DRAWINGS

- 5 **[0022]** FIGURE 1 illustrates a schematic cross sectional view of an artificial skin cell structure in accordance with at least some embodiments of the present invention,
- [0023]** FIGURE 2 illustrates a schematic view of the manufacturing process of an artificial skin cell structure in accordance with at least some embodiments of the present invention,
- 10 **[0024]** FIGURE 3 illustrates a schematic view of a microscope image of the spacers and frame dots of an artificial skin cell structure in accordance with at least some embodiments of the present invention, showing the different wetting on different surface,
- [0025]** FIGURE 4 illustrates a distance-height-diagram of a spacer on top of a PEN substrate of an artificial skin cell structure in accordance with at least some embodiments
- 15 of the present invention,
- [0026]** FIGURE 5 illustrates a photo of a fabricated top foil of an artificial skin cell structure in accordance with at least some embodiments of the present invention, wherein gates are black and frames are grey,
- [0027]** FIGURE 6 illustrates a schematic view of a final demonstration matrix with
- 20 laminated top and bottom foils of an artificial skin cell structure in accordance with at least some embodiments of the present invention,
- [0028]** FIGURE 7 illustrates a microscope image showing the electrodes and spacers through the transparent top foil of an artificial skin cell structure in accordance with at least some embodiments of the present invention,
- 25 **[0029]** FIGURE 8 illustrates a drain current vs. gate-source voltage measurement diagram during pressure application on a sample matrix of an artificial skin cell structure in accordance with at least some embodiments of the present invention,

[0030] FIGURE 9 illustrates a drain current vs. drain-source voltage measurement diagram for different gate-source voltages during pressure application on a sample matrix of an artificial skin cell structure in accordance with at least some embodiments of the present invention,

5 [0031] FIGURE 10 illustrates a drain current vs. time measurement diagram during increasing and decreasing pressure application on a sample matrix of an artificial skin cell structure in accordance with at least some embodiments of the present invention,

[0032] FIGURE 11 illustrates a drain current vs. time measurement diagram during repetitive pressure application on a sample matrix of an artificial skin cell structure in
10 accordance with at least some embodiments of the present invention, and

[0033] FIGURE 12 illustrates a schematic view of an artificial skin architecture based on artificial skin cell structures in accordance with at least some embodiments of the present invention.

15

EMBODIMENTS

[0034] In FIGURE 1 a schematic cross sectional view of an artificial skin cell structure 1 in accordance with at least some embodiments of the present invention is illustrated. The artificial skin cell structure comprises a bottom polymer layer 2. A pair of electrodes 3, 4 and an organic semiconductor layer 5 are disposed on the polymer bottom
20 layer 2. The pair of electrodes 3, 4 is disposed within the organic semiconductor layer 5. Further, a dielectric layer 6 is disposed on the organic semiconductor layer 5. A flexible top polymer layer 7 is disposed above the dielectric layer 6. Additionally, a flexible top electrode 8 is disposed on the bottom surface 9 of the top polymer layer 7. The location of the top electrode 8 is substantially matching the location of the pair of electrodes 3, 4. The
25 top polymer layer 7 is spaced from the dielectric layer 6 and supported by a plurality of supporting members 10, thereby forming an air gap 11 between the top polymer layer 7 and the dielectric layer 6.

[0035] The skin cell 1 consists of two plastic foils, i.e. the bottom polymer layer 2 and a top polymer layer 7, with patterned structures on both sides, forming a transistor
30 structure. The air-gap 11 is formed between the foils due to a printed spacer structure, i.e.

the supporting member 10. The proposed skin cell 1 can be considered as an air-gap *field effect transistor* (FET).

[0036] An applied pressure AP changes the gate distance from the channel. The displacement can be seen in the source-drain current of the air-gap transistor. Drain current
5 via the cell is

$$I_D = \frac{C_{press} \mu W}{L} \left\{ (V_{GS} - V_T) - \frac{1}{2} V_{DS} \right\} V_{DS} \quad (1)$$

where μ is the electron mobility in the channel of FET, W and L are width and length of the channel, V_{GS} is gate voltage, V_{DS} is source - drain voltage, V_T is threshold voltage. The value of the C_{press} is dielectric layer capacitor C_{ox} and air layer capacitor C_{air} in series and it
10 can be expressed by

$$C_{press} = A \epsilon_0 \frac{\epsilon_{rox}}{d_{air} \epsilon_{rox} + d_{ox}} \quad (2)$$

where ϵ_0 is the absolute dielectric constant and ϵ_{rox} the relative dielectric constant of the dielectric layer. The relative dielectric constant of air is considered to be 1. d_{ox} and d_{air} represent the thickness of the insulator and the air-gap 11, respectively, and A is the
15 surface area of the gate.

[0037] Pressure AP applied to the top surface 13 of the top foil 7 causes the foil bending. As a result the distance d_{air} between gate electrode and transistor channel is changed. Thus C_{press} is a function of applied pressure in accordance with Eq. (2)
20 consequently. Then the drain current is pressure dependent at constant gate potential in accordance with Eq. (1).

[0038] In FIGURE 2 schematic view of the manufacturing process of an artificial skin cell structure 1 in accordance with at least some embodiments of the present invention is illustrated. The manufacturing method comprises providing a top polymer layer 7 and
25 printing a top electrode 8 and a plurality of supporting members 10 on the top polymer layer 7. Additionally, the manufacturing method comprises providing a bottom polymer layer 2, forming a pair of electrodes 3, 4 of the bottom polymer layer 2, printing an organic

semiconductor layer 5 on the bottom polymer layer 2, and printing a dielectric layer 6 on the organic semiconductor layer 5. Further, the manufacturing method comprises positioning the top polymer layer 7 such that the surface 9 having the top electrode 8 and the supporting members 10 thereon faces the dielectric layer 6 and the top electrode 8 and the pair of electrodes 3, 4 are aligned, and bonding the layers together. Bonding takes place between the supporting members (10) and the dielectric layer (6) or the bottom polymer layer (2). It is also possible that bonding takes place between the supporting members (10) and the organic semiconductor layer 5 and/or the electrodes 3, 4.

[0039] According to an embodiment, the method also comprises printing conducting lines on the top polymer layer 7 and the bottom polymer layer 2 for creating external electrical connections for the cell structure.

[0040] As the bottom foil, a roll-to-roll fabricated transistor foil may be e.g. used (transistors without the top gate). In this foil, the electrodes 3, 4 may be e.g. formed by first roll-to-roll evaporating a thin 40 nm silver layer, and then etching the electrode patterns using rotary screen printed etchant. After the washing and drying steps the semiconductor (e.g. GRAPE114 from BASF) and dielectric (e.g. poly(methyl methacrylate) PMMA from Aldrich) may be gravure printed from organic solvents. Silver deposition, screen and gravure printing may be all done with roll-to-roll machines on a 300 mm wide poly(ethyleneterephthalate) PET substrate. The layers are printed in steps, so that the roll is rewound before printing the following layer.

[0041] In the fabrication process of the skin cell structure 1 shown in Fig. 2 a top foil, i.e. the flexible top polymer layer 7, which has an inkjet printed electrode 8 and spacers, i.e. supporting members 10, is illustrated on the left side (a). The bottom foil, i.e. the bottom polymer layer 2, has roll-to-roll processed silver source 3 and drain 4 electrodes, and gravure printed semiconductor and dielectric layers 5, 6. On the right side (b) the lamination process is shown. Top and bottom foils are aligned and then laminated under heat H and pressure P.

[0042] A 50 μm thick polyethylene 2,6-naphthalate (PEN) plastic foil may be e.g. used as the top foil (e.g. Teonex Q65FA, DuPont Teijin Films). The gate electrodes and spacers may be inkjet printed e.g. using a PiXDRO LP50 advanced research printer capable of driving industrial multinozzle piezoelectric printheads. For the gate electrodes, a silver nanoparticle ink (e.g. DGP 40LT-15C, Advanced Nano Products) may be printed

using e.g. an SX3 printhead with 10 pL nominal drop volume by Fujifilm Dimatix. Prior to printing, the PEN foil may be treated with O₂ plasma (2 min at maximum power 200W) in order to ensure optimal wetting and film formation of the silver nanoparticle ink. Printing process parameters, such as nozzle driving voltage waveform, substrate temperature (60 °C), print resolution (650 dpi) and multinozzle printing strategy may be optimized in order to obtain printed gate electrode patterns with high definition. Sintering of the printed nanoparticle ink may be e.g. done in oven at 150°C for 60 minutes.

[0043] An inkjet printable low-viscosity UV-curable photopolymer with a peak absorption wavelength of 365 nm (e.g. Norland Optical Adhesive NOA 89, Norland Products Incorporated) may be used as the spacer material. Printing process parameters may be optimized in order to obtain repeatable drop formation to ensure a uniform spacer matrix. Prior to printing, the surface of the PEN foil with printed gate electrodes may be e.g. treated by dip-coating with a 20 wt-% dilution of Novec EGC-1720 (3M), a solution of a fluorosilane polymer carried in a hydrofluoroether solvent (HFE-7100, 3M). The purpose of the surface pre-treatment is to modify the wetting behavior of the photopolymer in order to control the aspect ratio of the printed spacers on both bare PEN and gate electrode surfaces. Printing may be e.g. carried out using a KM512LHX printhead with 42 pL nominal drop volume by Konica Minolta. The spacer pattern may be a matrix of single printed droplets at a varying pitch of e.g. 400, 500 and 800 µm over the whole printed gate electrode foil.

[0044] In FIGURE 3 a schematic view of a microscope image of the spacers, i.e. the supporting members 10, and frame dots, i.e. the frame 12, of an artificial skin cell structure 1 in accordance with at least some embodiments of the present invention is illustrated, showing the different wetting on different surface. In Fig. 3 the spacing is 400 µm.

[0045] The inkjet deposited droplets form very well defined dots having a width and height of 110-170 µm and 3-7 µm, respectively, depending on the surface material (PEN/silver gate electrode). The spacers have a height of 6,5 µm. The inkjet process offers the flexibility of controlling the aspect ratio of the spacers via controlling the droplet volume, surface wetting behavior and post deposition curing parameters.

[0046] In the above embodiment, the pitch between supporting members 10 is in the range between 400 and 800 µm, the width of supporting members 10 is in the range 110-170 µm and the height of supporting members 10 is in the range 3-7 µm. However, there

are also embodiments in which the pitch is less than 400. There are also embodiment having the pitch over 800 μm . Also the width of supporting members 10 can be less than 110. In some embodiments, the width is more than 170 μm . In some embodiments, the height of supporting members 10 is less than 3 μm . There are also embodiments having the height more than 7 μm . In general, the parameters can be selected according to the desired properties of the artificial skin, such as the sensitivity of the skin.

[0047] In addition to the spacers, a “gluing” frame printed with the same spacer material around the structures in order to enhance adhesion in the lamination process is shown. The frame may be printed with different parameters than the spacers in order to get a proper dense supportive frame structure. Printing resolution may be set such (360 dpi) that the printed droplets are as close to each other as possible but not quite touching, in order to maintain the droplet aspect ratio and resulting frame thickness. UV curing may be carried out using the same parameters as for the spacer matrix. In this case the bonding can take place between the supporting members (10) and bottom polymer foil (2).

[0048] Curing of the printed spacers may be e.g. performed in a UV-curing oven for 2 minutes using a 120 W/cm lamp with a D-bulb having a peak radiation intensity at 350-400 nm (F300S, Fusion UV Systems, Inc.).

[0049] In FIGURE 4 a distance-height-diagram of a spacer. i.e. supporting member 10, on top of a PEN substrate of an artificial skin cell structure in accordance with at least some embodiments of the present invention is illustrated. In other words, a profile of a spacer on top of a PEN substrate is shown.

[0050] In FIGURE 5 a photo of a fabricated top foil of an artificial skin cell structure 1 in accordance with at least some embodiments of the present invention is illustrated, wherein gates are black and frames are grey.

[0051] In FIGURE 6 a schematic view of a final demonstration matrix with laminated top and bottom foils of an artificial skin cell structure in accordance with at least some embodiments of the present invention is illustrated. The top foil shown in FIGURE 5 is placed on top of the bottom foil face-to-face. Gates electrodes are aligned over the transistor channels. Heat and pressure may be e.g. applied for 5 minutes on top of the hot plate. Temperature may be e.g. varied between 100°C and 110°C in different lamination tests. A 500 g weight may be e.g. used in order to apply pressure on the array area.

[0052] The flexibility of the laminated demonstration matrix sheet is limited by the substrate thicknesses, but even more dominantly by the adhesion between the laminated substrates. In order to get a good “gluing” effect in lamination, it is good to use a large contact area. This is why the frame structures are added for extra adhesion (cf. FIGURE 5 and FIGURE 6). It is also beneficial that the spacer or frame material has a good bonding force with the substrate or the active layers. The adhesion can be enhanced by increasing the spacer density or even using a different gluing material in the areas between the pixels.

[0053] In FIGURE 7 a microscope image showing the electrodes and spacers through the transparent top foil of an artificial skin cell structure in accordance with at least some embodiments of the present invention is illustrated.

[0054] FIGURE 8, FIGURE 9, FIGURE 10, and FIGURE 11 show experimental measurement results. In FIGURE 8 a gate voltage-drain current-measurement diagram during pressure application on a sample matrix of an artificial skin cell structure in accordance with at least some embodiments of the present invention is illustrated. The pressure sensitive transistor transfer curve (I_{Drain} vs. $V_{\text{Gate-Source}}$) is shown for 2 applied forces (no force, strong force). In FIGURE 9 a drain current vs. drain-source voltage measurement diagram during pressure application on a sample matrix of an artificial skin cell structure in accordance with at least some embodiments of the present invention is illustrated. In FIGURE 10 a drain current vs. time measurement diagram during increasing and decreasing pressure application on a sample matrix of an artificial skin cell structure in accordance with at least some embodiments of the present invention is illustrated. The point pressure was applied in increasing and decreasing steps, and the resulting change in transistor current is shown. In FIGURE 11 a drain current vs. time measurement diagram during repetitive pressure application on a sample matrix of an artificial skin cell structure in accordance with at least some embodiments of the present invention is illustrated. The repetitive pressure application and releasing show good repeatability.

[0055] The pressure sensitive cells were characterized individually. A sample matrix was placed under a probe manipulator. A probe with a dull head (with 200 μm radius) was used for applying the pressure. As the top foil was 50 μm thick, the area of the pressure application on the top could be considered point-like. From that point the pressure spread in the bending top foil over a larger area. The probe was pressed and released using manipulator screws.

[0056] Transistors were biased on and the current from source 3 to drain 4 was measured continuously during the pressure application. Different forces were applied and the effect could be seen in the transistor measurement results (cf. FIGURE 8 and FIGURE 9). Larger pressing force increases the current as the gate air gap decreases. The transistor behavior changed according to the field effect change explained in section 1. There was no change in dielectric leakage through to the gate even when a strong force was applied. In FIGURE 10 the cell current is plotted over time, with different pressing force applied. The cell demonstrates reversibility (it returns to the initial value) and good sensitivity. The small delay before reaching a stable current level can be explained by the physical recovery of the substrate after displacement. Sharp peaks in the plot are due to uneven pressure application (manual probe adjustment). The response time was faster than the chosen measuring time (300 ms sampling period). Also the probe manipulator system did not allow a fast pressure application. The response time is most probably limited to the mechanical delay in substrate recovery after displacement, and not limited by the transistor switching speed (which is in range of milliseconds). FIGURE 10 and FIGURE 11 show similar response to applied pressures for two capacitive cells of the same matrix. FIGURE 11 shows multiple press and release actions on the cell, and a good recovery to the initial value. The spacer spacing in the samples used in these results is 800 μm .

[0057] In FIGURE 12 a schematic view of an artificial skin architecture 14 based on artificial skin cell structures in accordance with at least some embodiments of the present invention is illustrated. The sensor network consists of a matrix of printed transistors with built in capacitive sensor elements. For reading sensor signals a word line 16 is connected to the gate electrodes of the transistors, and a bit line 15 is connected to the drain electrodes. All elements are fabricated on a flexible substrate by methods of printed electronics.

[0058] It is to be understood that the embodiments of the invention disclosed are not limited to the particular structures, process steps, or materials disclosed herein, but are extended to equivalents thereof as would be recognized by those ordinarily skilled in the relevant arts. It should also be understood that terminology employed herein is used for the purpose of describing particular embodiments only and is not intended to be limiting.

[0059] Reference throughout this specification to one embodiment or an embodiment means that a particular feature, structure, or characteristic described in

connection with the embodiment is included in at least one embodiment of the present invention. Thus, appearances of the phrases “in one embodiment” or “in an embodiment” in various places throughout this specification are not necessarily all referring to the same embodiment. Where reference is made to a numerical value using a term such as, for
5 example, about or substantially, the exact numerical value is also disclosed.

[0060] As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be
10 construed as a de facto equivalent of any other member of the same list solely based on their presentation in a common group without indications to the contrary. In addition, various embodiments and examples of the present invention may be referred to herein along with alternatives for the various components thereof. It is understood that such embodiments, examples, and alternatives are not to be construed as de facto equivalents of
15 one another, but are to be considered as separate and autonomous representations of the present invention.

[0061] Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in one or more embodiments. In the following description, numerous specific details are provided, such as examples of lengths, widths,
20 shapes, etc., to provide a thorough understanding of embodiments of the invention. One skilled in the relevant art will recognize, however, that the invention can be practiced without one or more of the specific details, or with other methods, components, materials, etc. In other instances, well-known structures, materials, or operations are not shown or described in detail to avoid obscuring aspects of the invention.

[0062] While the forgoing examples are illustrative of the principles of the present invention in one or more particular applications, it will be apparent to those of ordinary skill in the art that numerous modifications in form, usage and details of implementation can be made without the exercise of inventive faculty, and without departing from the principles and concepts of the invention. Accordingly, it is not intended that the invention
25 be limited, except as by the claims set forth below.

[0063] The verbs “to comprise” and “to include” are used in this document as open limitations that neither exclude nor require the existence of also un-recited features. The

features recited in depending claims are mutually freely combinable unless otherwise explicitly stated. Furthermore, it is to be understood that the use of "a" or "an", that is, a singular form, throughout this document does not exclude a plurality.

INDUSTRIAL APPLICABILITY

- 5 [0064] At least some embodiments of the present invention find industrial application in production and utilization of artificial electronic skin.

REFERENCE SIGNS LIST

	1	skin cell structure
	2	bottom layer
5	3	first electrode
	4	second electrode
	5	semiconductor layer
	6	dielectric layer
	7	top layer
10	8	flexible top electrode
	9	bottom surface
	10	supporting member
	11	air gap
	12	frame
15	13	top surface
	14	artificial skin architecture
	15	bit line
	16	word line
	17	sensor
20	AP	applied pressure
	P	pressure
	H	heat

CITATION LIST

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CLAIMS:

1. An artificial skin cell structure (1) comprising:
 - 5 – a bottom polymer layer (2);
 - a pair of electrodes (3, 4) and an organic semiconductor layer (5) disposed on the polymer bottom layer (2), the pair of electrodes (3, 4) being disposed within the organic semiconductor layer (5);
 - a flexible top polymer layer (7) disposed above the organic semiconductor layer
 - 10 (5);
 - a flexible top electrode (8) disposed on the bottom surface (9) of the top polymer layer (7), the location of the top electrode (8) substantially matching the location of the pair of electrodes (3, 4), wherein
 - the top polymer layer (7) is spaced from the organic semiconductor layer (5) and
 - 15 supported by a plurality of supporting members (10), thereby forming an air gap (11) between the top polymer layer (7) and the organic semiconductor layer (5).
2. An artificial skin cell structure (1) comprising:
 - a bottom polymer layer (2);
 - 20 – a pair of electrodes (3, 4) and an organic semiconductor layer (5) disposed on the polymer bottom layer (2), the pair of electrodes (3, 4) being disposed within the organic semiconductor layer (5);
 - a dielectric layer (6) disposed on the organic semiconductor layer (5);
 - a flexible top polymer layer (7) disposed above the dielectric layer (6);
 - 25 – a flexible top electrode (8) disposed on the bottom surface (9) of the top polymer layer (7), the location of the top electrode (8) substantially matching the location of the pair of electrodes (3, 4), wherein
 - the top polymer layer (7) is spaced from the dielectric layer (6) and supported by a plurality of supporting members (10), thereby forming an air gap (11) between the
 - 30 top polymer layer (7) and the dielectric layer (6).
3. An artificial skin cell structure (1) of claim 1 or 2, wherein a portion of the supporting members (10) form a frame (12) around the electrodes.

4. An artificial skin cell structure (1) according to any one of claims 1 to 3, wherein the pair of electrodes (3, 4) is made of silver.
- 5 5. An artificial skin cell structure (1) according to any one of claims 1 to 4, wherein the top electrode (8) is made of a silver nanoparticle ink.
6. An artificial skin cell structure (1) according to any one of claims 1 to 5, wherein the supporting members (10) are made of a photopolymer.
- 10 7. An artificial skin cell structure (1) according to any one of claims 1 to 6, wherein a pitch between supporting members (10) is in a range between 400 [μm] and 800 [μm].
8. An artificial skin cell structure (1) according to any one of claims 1 to 7, wherein a
15 width of a supporting member (10) is in the range between 110 [μm] and 170 [μm].
9. An artificial skin cell structure (1) according to any one of claims 1 to 8, wherein a height of a supporting member (10) is in the range between 3 [μm] and 7 [μm].
- 20 10. A method of producing an artificial skin cell structure (1), the method comprising:
- providing a top polymer layer (7);
 - printing a top electrode (8) and a plurality of supporting members (10) on the top polymer layer (7);
 - providing a bottom polymer layer (2);
 - 25 – forming a pair of electrodes (3, 4) of the bottom polymer layer (2);
 - printing an organic semiconductor layer (5) on the bottom polymer layer (2);
 - optionally printing a dielectric layer (6) on the organic semiconductor layer (5);
 - positioning the top polymer layer (7) such that the surface (9) having the top electrode (8) and the supporting members (10) thereon faces the dielectric layer (6)
 - 30 and the top electrode (8) and the pair of electrodes (3, 4) are aligned; and
 - bonding the layers together.

11. A method according to claim 10, wherein the step of forming the pair of electrodes (3, 4) comprises:

- depositing a layer of conducting material on the bottom polymer layer (2); and
- forming the pair of electrodes (3, 4) by removing excessive conducting material.

5

12. The method of producing an artificial skin cell structure (1) according to claim 11, wherein depositing the layer of conducting material on the bottom polymer layer (2) takes place by means of evaporating a silver layer.

10 13. The method of producing an artificial skin cell structure (1) according to claim 11 or 12, wherein removing excessive conducting material takes place by means of etching.

14. The method of producing an artificial skin cell structure (1) according to claim 13, wherein etchant is rotary screen printed.

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15. The method according to any one of claims 11-14, wherein at least one of the semiconductor layer (5) and the dielectric layer (6) is gravure printed from organic solvents.

20 16. The method according to any one of claims 11-15, wherein silver deposition, screen printing, and gravure printing are done with roll-to-roll-machines.

17. The method according to any one of claims 11-15, wherein the top electrode (8) of the bottom polymer layer (2) is made of a silver nanoparticle ink.

25

18. The method of producing an artificial skin cell structure (1) according to claim 17, wherein the top polymer layer (7) is treated with O₂ plasma prior to printing the silver nanoparticle ink.

30 19. The method of producing an artificial skin cell structure (1) according to claim 17 or 18, wherein the silver nanoparticle ink is sintered.

20. The method according to any one of claims 10-19, wherein the supporting members (10) are formed by printing a photopolymer.

21. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 20, wherein the surface (9) having the top electrode (8) is dip-coated prior to printing the supporting members (10).

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22. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 21, wherein the surface (9) having the top electrode (8) is pre-treated prior to printing the supporting members (10) in order to control the aspect ratio of the supporting members (10).

10

23. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 22, the method further comprising:

- forming (12) a frame by printing a portion of the supporting members (10) around the electrodes.

15

24. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 23, the method comprising printing conducting lines on the top polymer layer (7).

20 25. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 24, the method comprising printing conducting lines on the bottom polymer layer (7).

25 26. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 25, wherein the step of bonding comprises bonding the top polymer layer (7) and bottom polymer layer (2) together so that the supporting members (10) are attached to the dielectric layer (6).

30 27. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 25, wherein the step of bonding comprises bonding the top polymer layer (7) and bottom polymer layer (2) together so that the supporting members (10) are attached directly to the bottom polymer layer (2).

28. The method of producing an artificial skin cell structure (1) according to any one of claims 10 to 25, wherein the step of bonding comprises bonding the top polymer layer (7) and bottom polymer layer (2) together so that the supporting members (10) are attached directly to the organic semiconductor layer (5) and/or the electrodes (3, 4).

5

29. An artificial skin having a sensor network comprising:

- a plurality of artificial skin cell structures (1) according to any one of claims 1 to 9 arranged in rows and columns;
- a plurality of row conductors and column conductors, wherein
- 10 – the top electrodes (8) of the cell structures (1) located on a common row are connected to a corresponding row conductor, and one of the pair of electrodes (3, 4) of the cell structures (1) located on a common column are connected to a corresponding column conductor.

15 30. An artificial skin having a sensor network comprising:

- a plurality of artificial skin cell structures (1) according to any one of claims 1 to 9 arranged in rows and columns;
- a plurality of row conductors and column conductors, wherein
- the top electrodes (8) of the cell structures (1) located on a common column are
- 20 connected to a corresponding column conductor, and the pair of bottom electrodes (3, 4) of the cell structures (1) located on a common row and ground are connected to corresponding column and ground conductors.

25 31. A method of producing an artificial skin having a sensor network with a plurality of artificial skin cell structures (1), the method comprising:

- providing a top polymer layer (7);
- printing a plurality of top electrodes (8) on a surface of the top polymer layer (7);
- printing a plurality of supporting members (10) on the surface of the top polymer layer (7);
- 30 – providing a bottom polymer layer (2);
- forming a plurality of pairs of electrodes (3, 4) on a surface of the bottom polymer layer (2);

- forming row conductors, column conductors and ground conductors on the surfaces of the top polymer layer (7) and/or the bottom polymer layer (2);
 - printing an organic semiconductor layer (5) on the surface of the bottom polymer layer (2);
 - 5 – optionally printing a dielectric layer (6) on the organic semiconductor layer (5);
 - positioning the top polymer layer (7) and the bottom polymer layer (2) such that the surface (9) having the top electrode (8) and the supporting members (10) thereon faces the dielectric layer (6), and that the top electrodes (8) and the pairs of electrodes (3, 4) are aligned with each other; and
 - 10 – bonding the top polymer layer (7) and the bottom polymer layer (2) together so that the supporting members (10) are directly attached to at least one of the dielectric layer (6), the bottom polymer layer (2), the organic semiconductor layer (5) and the electrodes.
- 15 32. The method of claim 31, comprising:
- using printed adhesive patterns outside of the active sensor area, between the sensors, in order to make the lamination structure more rigid.
33. The method of claim 31 or 32, comprising:
- 20 – using conductive adhesive for making vias from the bottom layer electrode wiring to the top layer electrode wiring,
34. The method according to any one of claims 31 to 33, comprising:
- 25 – using conductive adhesive for forming the interconnections and bridging of needed row, column and ground connectors.

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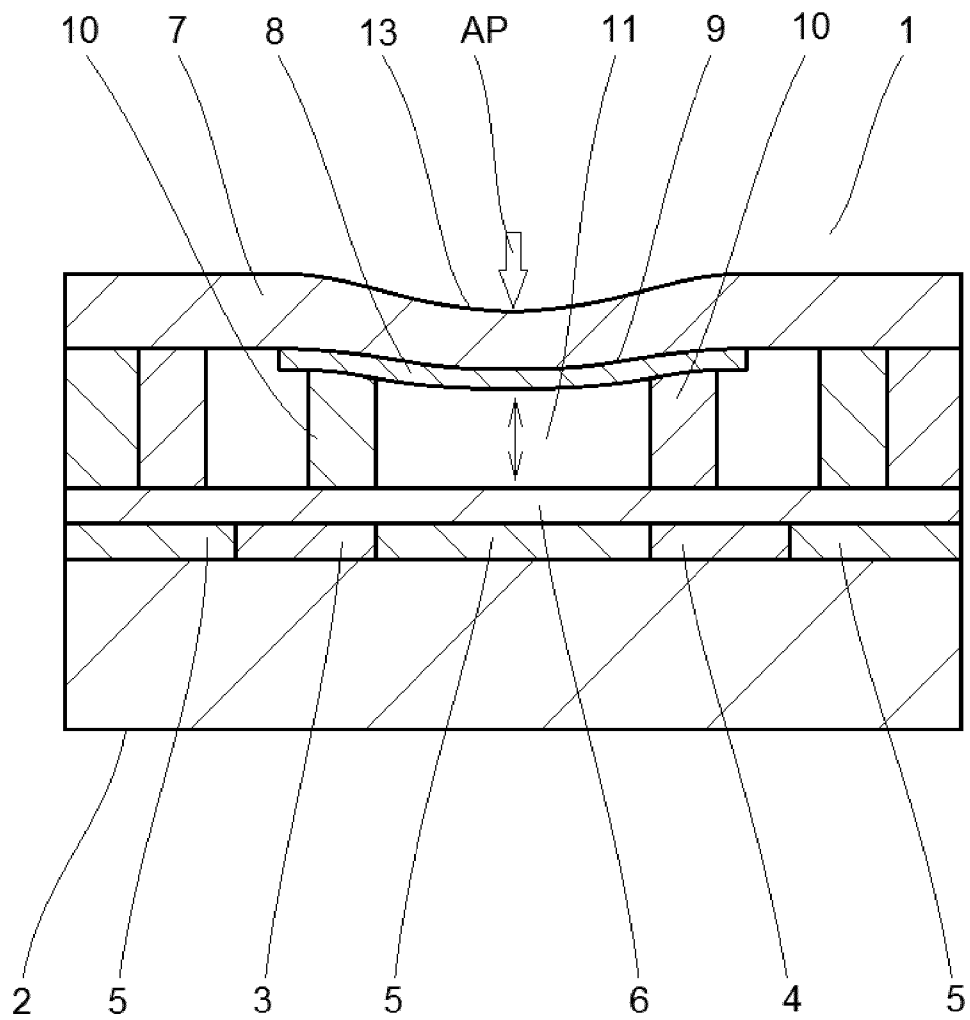


FIG. 1

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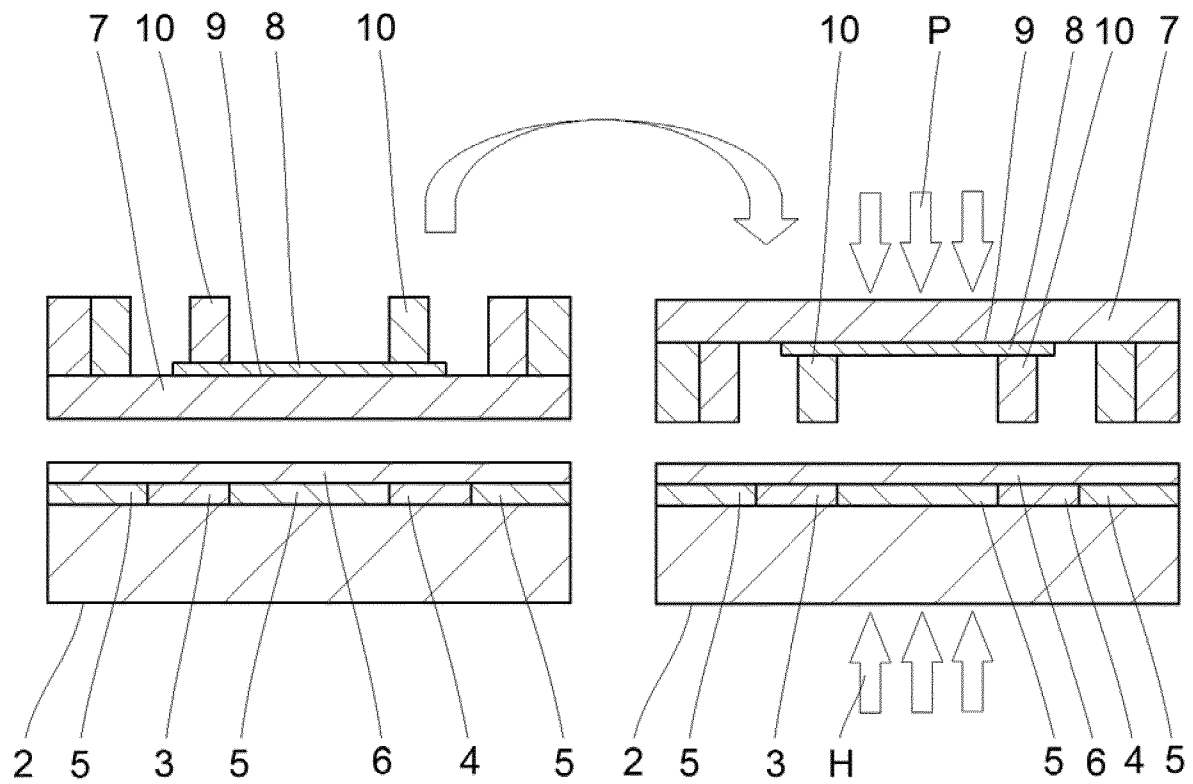


FIG. 2

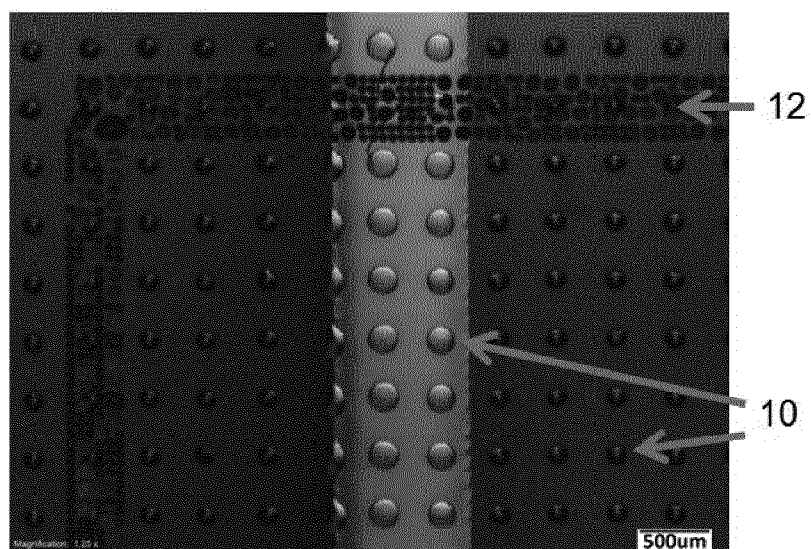


FIG. 3

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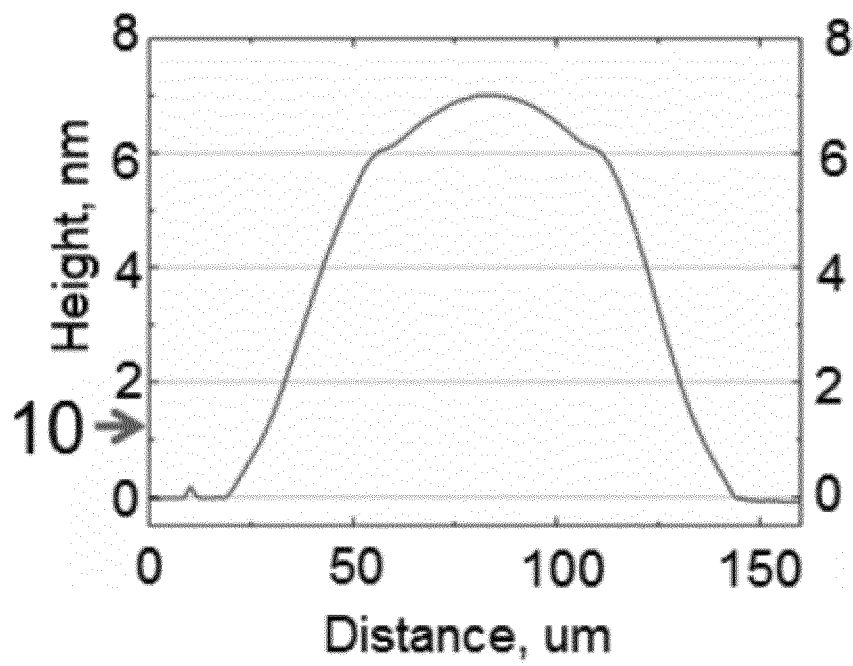


FIG. 4

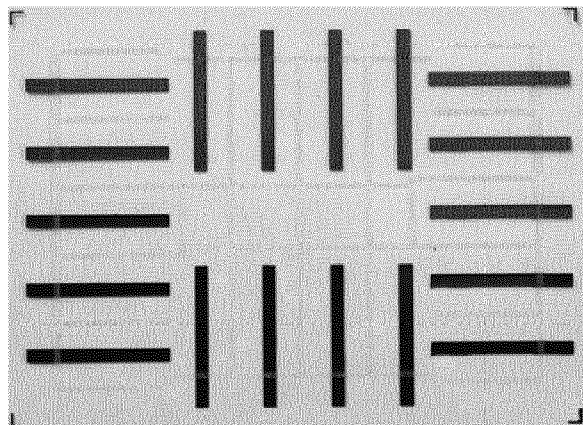


FIG. 5

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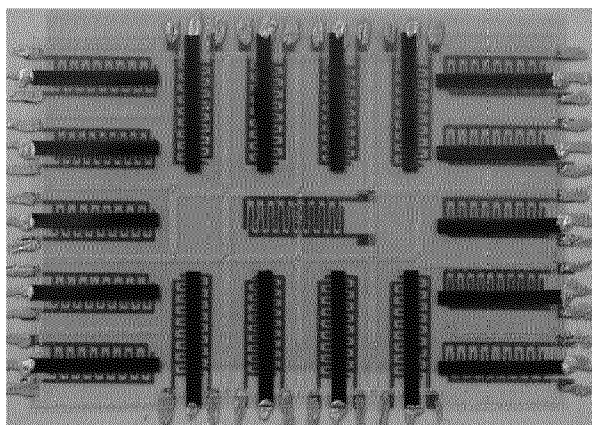


FIG. 6

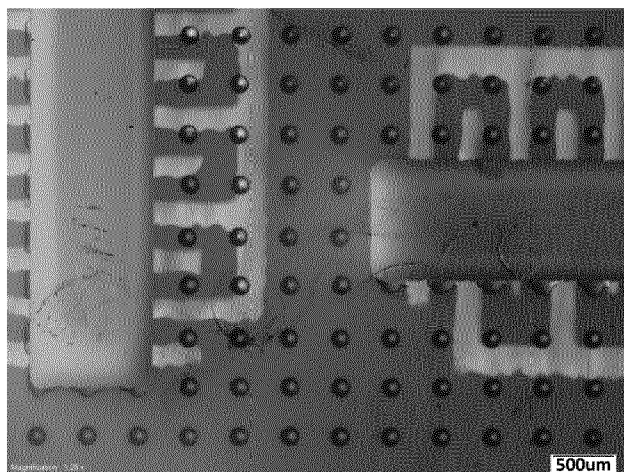


FIG. 7

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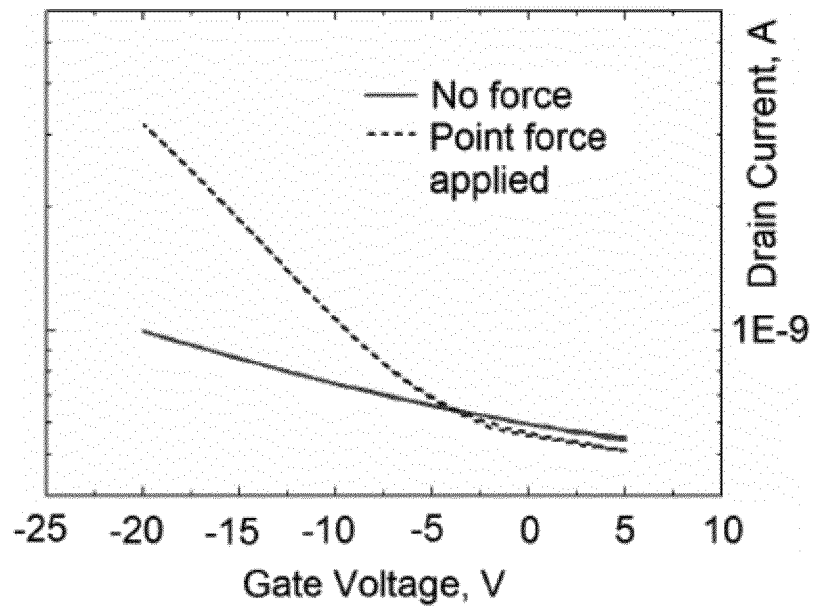


FIG. 8

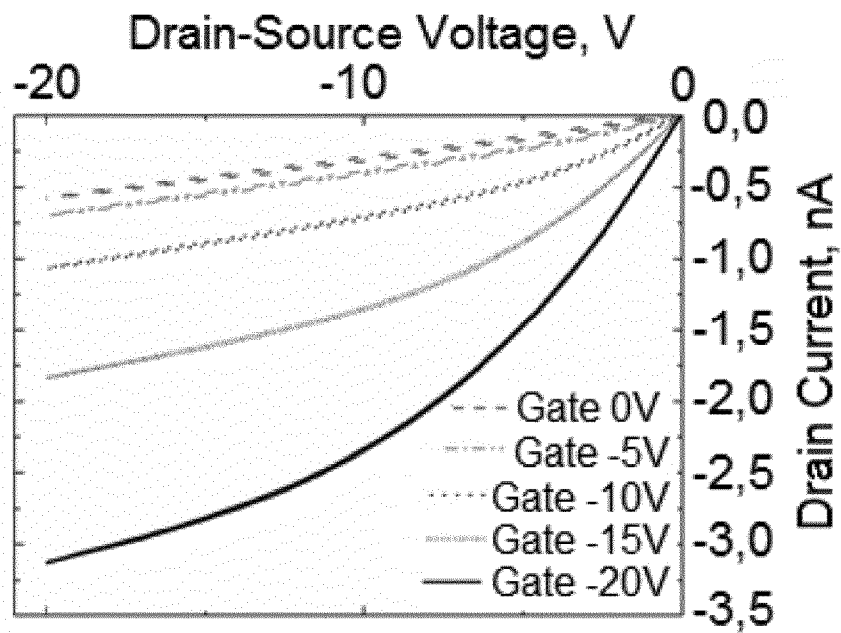


FIG. 9

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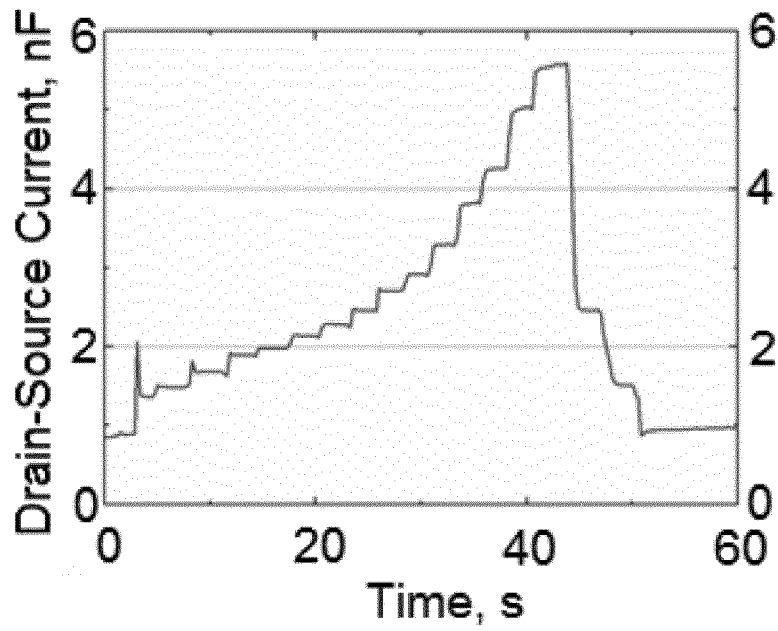


FIG. 10

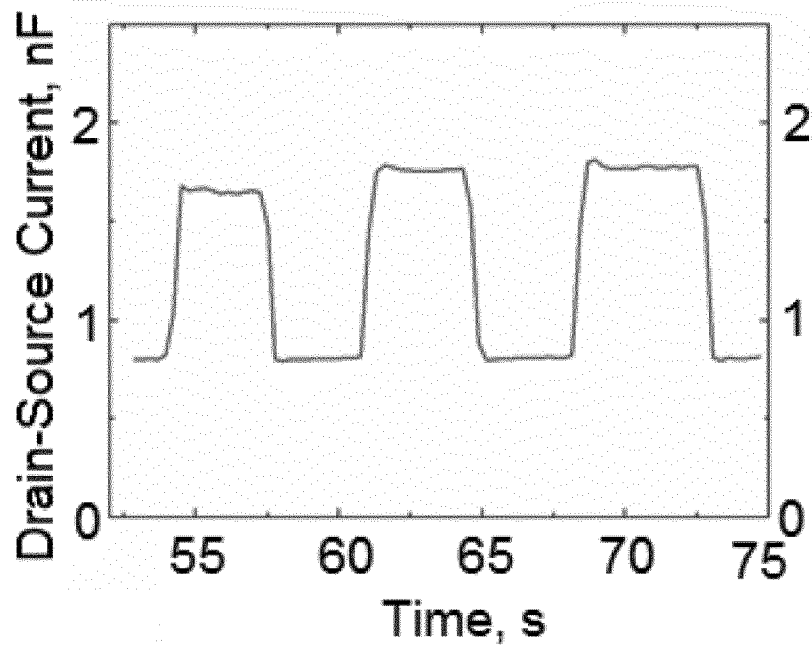


FIG. 11

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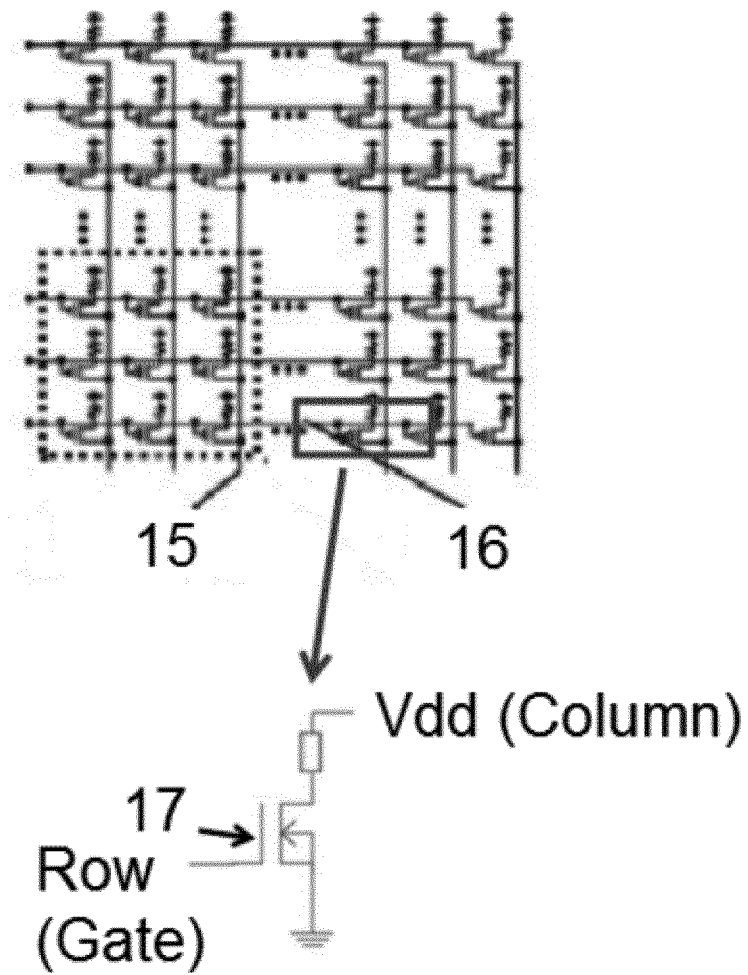


FIG. 12

INTERNATIONAL SEARCH REPORT

International application No
PCT/FI2016/050297

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01L9/00 G01L1/14 H01L29/84
ADD. H01L51/05

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)
G01L H01L

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)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	YAPING ZANG ET AL: "Flexible suspended gate organic thin-film transistors for ultra-sensitive pressure detection", NATURE COMMUNICATIONS, vol. 6, 3 March 2015 (2015-03-03), page 6269, XP055287155, DOI: 10.1038/ncomms7269	1-9,29,30
Y	Introduction Methods; page 8 figures 1,4 ----- -/--	10-28,31-34

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

Date of the actual completion of the international search

11 July 2016

Date of mailing of the international search report

19/07/2016

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Authorized officer

Dardel, Blaise

INTERNATIONAL SEARCH REPORT

International application No
PCT/FI2016/050297

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	C.-Y. LO; J. HIITOLA-KEINANEN; O.-H. HUTTUNEN; J. PETAJA; J. HAST; A. MAANINEN ET AL.: "Novel roll-to-roll lift-off patterned active-matrix display on flexible polymer substrate", MICROELECTRONIC ENGINEERING, vol. 86, 2009, pages 979-983, XP002759687, cited in the application Process; page 980 figures 1,2	10-28, 31-34
A	----- VILKMAN MARJA ET AL: "Fully roll-to-roll processed organic top gate transistors using a printable etchant for bottom electrode patterning", ORGANIC ELECTRONICS, vol. 20, 7 February 2015 (2015-02-07), pages 8-14, XP029212566, ISSN: 1566-1199, DOI: 10.1016/J.ORGEL.2015.01.031 Process; page 9 figures 1,2,3	10-28, 31-34
A	----- T. HASSINEN; T. RUOTSALAINEN; P. LAAKSO; R. PENTTILA; H.G. SANDBERG: "Roll-to-roll compatible organic thin film transistor manufacturing technique by printing, lamination, and laser ablation", THIN SOLID FILMS, vol. 571, 2014, pages 212-217, XP002759688, cited in the application Lamination; page 213 figures 1,2	10-28, 31-34
A	----- US 2012/062245 A1 (BAO ZHENAN [US] ET AL) 15 March 2012 (2012-03-15) paragraphs [0027], [0030], [0031], [0033], [0062], [0063] figures 1,6 -----	1-34

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/FI2016/050297

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