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(54) **Title:** PIEZOELECTRIC DEVICE WITH A SENSOR AND METHOD FOR MEASURING THE BEHAVIOUR OF SAID PIEZOELECTRIC DEVICE

(57) **Abstract:** The first object of the invention is directed to a piezoelectric device (10) shaped as a tridimensional object with at least two surfaces, wherein said piezoelectric device (10) comprises a first set of two or more electrodes (8a, 8b). Said piezoelectric device (10) is remarkable in that at least one of the surfaces which is free of electrodes from said first set of two or more electrodes (8a, 8b) is covered with at least a second set of electrodes. The second object of the invention is directed to a method for measuring the behaviour of a piezoelectric device.

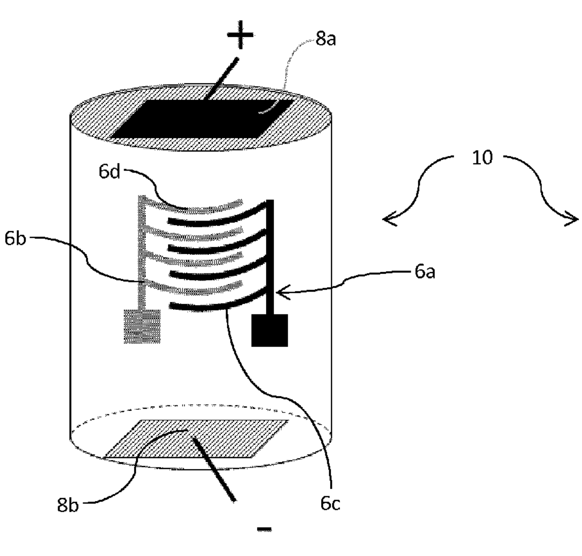

Fig. 1

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PIEZOELECTRIC DEVICE WITH A SENSOR AND METHOD FOR MEASURING THE BEHAVIOUR OF SAID PIEZOELECTRIC DEVICE

Description

Technical field

[0001] The invention is directed to the field of the piezoelectric material. More particularly, the invention is directed to the field of the measurement of the deformation of the piezoelectric actuator.

Background art

[0002] In the field of piezoelectric device, it is known to couple a sensor to an actuator by bonding or gluing, thus requiring different material to manufacture a sensor. This also increases the number of steps for the fabrication of such material, such as the step for activating the bonding. For instance, US patent application published US 2007/0165333 A1 describes a piezoelectric sensor bonded through a non-conductive adhesive to a piezoelectric actuator to determine the pressure and/or the temperature.

[0003] One example of piezoelectric device (used in the filtration of information) is surface acoustic wave (SAW) device. A SAW device is a piezoelectric device in which an input transducer and output transducer are on the same outer surface of the device. The input transducer (that can be considered as an actuator) and the output transducer (that can be considered as a sensor) are generally interdigitated electrodes and must be on the same surface in order to transform the electrical energy into a mechanical energy in the form of SAWs. Therefore, no galvanic isolation is achieved. Moreover, the interdigitated electrodes are deposited by precise deposition technique, such as lithography or photolithography, which forces the user to functionalize the piezoelectric device on a same and single surface.

[0004] US patent application published US 2009/0009193 A1 describes a moisture-sensitive element which consists in a sensing layer formed on a interdigital capacitor which is formed on a printed circuit board (PCB). This moisture-sensitive element works by applying an electric field between the two electrodes composing the interdigital capacitor. Thus, if moisture (water) enters the electric field, the total dielectric constant of the interdigital capacitor will increase and this variation can be detected by a LCR meter that is then placed between the electrodes of the interdigital capacitor.

[0005] The system known in the art are limited on the fact that either the actuator and the sensor must be on a similar surface (in the case of SAW device, as explained above) or that the sensor are embedded inside a device (in the case of the moisture-sensitive element). The adhesion of further material between the actuator and the sensor is also required.

Summary of invention

Technical Problem

[0006] The invention has for technical problem to alleviate at least one of the drawbacks present in the prior art. More particularly, the invention has for technical problem to provide a piezoelectric sensor in piezoelectric actuation device after it has been fabricated without changing the manufacturing process.

Technical solution

[0007] The first object of the invention is directed to a piezoelectric device shaped as a tridimensional object with at least two surfaces, wherein said piezoelectric device comprises a first set of two or more electrodes. Said piezoelectric device is remarkable in that at least one of the surfaces which is free of electrodes from said first set of two or more electrodes is covered with at least a second set of electrodes. Each electrode of the first set being respectively on one of the at least two surfaces.

[0008] According to a preferred embodiment, said second set of electrodes is made of at least two interdigitated electrodes.

[0009] According to a preferred embodiment, said second set of electrodes is made of at least two electrodes distributed along a single conductive line.

[0010] According to a preferred embodiment, said interdigitated electrodes are on two distinct surfaces of said piezoelectric device.

[0011] According to a preferred embodiment, said piezoelectric device is made of a ceramic material, preferentially of the perovskite structure and even more preferentially made of lead zirconate titanate or $LiNbO_3$.

[0012] According to a preferred embodiment, said second set of electrodes is made of at least one electrical conductor comprising electrically conductive nanoparticles, preferentially nanoparticles made of silver, gold, copper, aluminium or indium tin oxide, alias ITO.

[0013] According to a preferred embodiment, said interdigitated electrodes are spaced from each other with a gap comprised between 10 µm and 100 µm.

[0014] According to a preferred embodiment, the electric conductors constituting said interdigitated electrodes have a width comprised between 5 µm and 1 mm, preferentially between 20µm and 100µm.

[0015] According to a preferred embodiment, said piezoelectric device is a pyroelectric device.

[0016] According to a preferred embodiment, said piezoelectric device is a multi-layer piezoelectric device, comprising alternating dielectric layers and metallic layers, the number of metallic layers being equal to *n* and the number of piezoelectric layers being equal to *n*+1, *n* being an integer.

[0017] According to a preferred embodiment, said metallic layers are made of metallic electrodes, preferably of interdigitated metallic electrodes, more preferably of interdigitated nickel or platinum of palladium electrodes.

[0018] According to a preferred embodiment, said electrodes of said second set of electrodes are planar.

[0019] The second object of the invention is directed to a method for measuring the behaviour of a piezoelectric device, said method comprising the steps of

a. providing a piezoelectric device with a first set of two or more electrodes, said piezoelectric device being shaped as tridimensional object with at least two surfaces,
b. printing at least a second set of electrodes on at least one of the faces which is free of electrodes,
c. determining the variation of the electrical charges on said second set of electrodes.

[0020] According to a preferred embodiment, said second set of electrode is made of at least two interdigitated electrodes.

[0021] According to a preferred embodiment, said second set of electrode is made of at least two electrodes distributed along a single conductive line.

[0022] According to a preferred embodiment, said printing is performed on at least two distinct surfaces of said piezoelectric device.

[0023] According to a preferred embodiment, said step (b) is performed by inkjet printing.

[0024] According to a preferred embodiment, said step (b) is performed by aerosol printing.

[0025] According to a preferred embodiment, said step (b) is performed with an ink made of electrically conductive nanoparticles.

[0026] According to a preferred embodiment, said ink made of electrically conductive nanoparticles is an ink made of silver, gold, copper, aluminium or indium tin oxide, alias ITO.

[0027] The third object is directed to a multi-layer piezoelectric device comprising alternating dielectric layers and metallic layers, two opposites sides, a first set of two electrodes, said two electrodes being respectively on the opposite sides, wherein the device further comprises a second set of electrodes, said second set being on an external surface of said device between the two electrodes of the first set.

[0028] According to a preferred embodiment, the number of metallic layers being equal to n and the number of piezoelectric layers being equal to n+1, n being an integer.

Advantages of the invention

[0029] The invention is particularly interesting in that piezoelectric actuator can be functionalized with piezoelectric sensor by simple deposition of the sensor onto the piezoelectric actuator, namely by inkjet printing or aerosol printing. This enables the functionalization of every type of piezoelectric device, without addition of any material not being part of the device.

[0030] Isolation galvanic can be achieved because the second set of electrodes is not necessarily in contact with the first set of electrodes.

[0031] The space occupation of the printed sensor is negligible compared to the size of the piezoelectric actuator, due to the low thickness of the second set of electrodes.

[0032] Moreover, the outer surface of the piezoelectric layer, which before was of no or few utility, because requiring any kind of activation in order to bond or glue any further element is now of great use, since it is the same dielectric material which is printed by the interdigitated electrodes.

Brief description of the drawings

[0033] Figure 1 shows a representation of a mechanical deformation sensor with a cylindrical shape and with an interdigital capacitor as a *deposited sensor*, in accordance with the present invention.

[0034] Figure 1A shows a representation of a mechanical deformation sensor with a cuboid shape and with a piece of conductor as a *deposited sensor*, in accordance with the present invention.

[0035] Figure 2 shows a representation of a mechanical deformation sensor with a cuboid shape and with an interdigital capacitor as a *deposited sensor*, in accordance with the present invention.

[0036] Figure 2A shows a representation of a mechanical deformation sensor with a cylindrical shape and with a piece of conductor as a *deposited sensor*, in accordance with the present invention.

[0037] Figure 3 shows a representation of a multilayer capacitor device in accordance with the present invention.

Description of an embodiment

[0038] The principle of the invention is to deposit on a piezoelectric actuator a sensor, so-called *deposited sensor*, which will be used to measure the deformation of the piezoelectric actuator.

[0039] The piezoelectric actuator 10 is typically a device made of piezoelectric material, preferentially ceramic material. Those materials have also dielectric properties. The crystal structure of the ceramic material can be the perovskite structure. For example, such material can be lead zirconate titanate (PZT) or lithium niobate ($LiNbO_3$). Two electrodes (8a, 8b), that are used to actuate said piezoelectric actuator, are connected to one part of the piezoelectric actuator, either on the same face (not represented) or on two distinct faces or surfaces, respectively (as shown on figure 1 or 2).

[0040] As shown in figure 1 or 2, the two electrodes (8a, 8b) consist respectively in a positive electrode and in a negative electrode. The positive electrode 8a (as indicated on the figures) can be interchanged with the negative electrode 8b.

[0041] The piezoelectric actuator (when electric charges are displaced in a solid in response to an applied mechanical stress) can also be a pyroelectric sensor (when electric charges are displaced in a solid in response to a variation of temperature).

[0042] The *deposited sensor* can be an interdigital capacitor 6 (see figures 1 and 2), or a piece of conductor 60 (see figures 1A and 2A), preferentially planar, which is deposited on one unique face or surface of the piezoelectric device which is free of electrode, preferentially on the outer surface of the piezoelectric actuator, by a special deposition method, which is printing, preferentially inkjet printing or aerosol printing. This particular deposition method allows for the use of every kind of shape of the piezoelectric actuator, since printing, or inkjet printing, or aerosol printing, can be achieved on every kind of tri-dimensional shape. The deposited sensor 6 or the piece of conductor 60, i.e. the second set of electrodes is respectively on a face or a surface adjacent to at least one face or surface comprising one electrode (8a, 8b) of the first set.

[0043] When the piezoelectric actuator comprised a printed *deposited sensor*, a mechanical deformation sensor has been developed.

[0044] When the piezoelectric actuator comprised a printed *deposited sensor*, a temperature sensor has also been developed.

[0045] The *deposited sensor* can be realized on every free surface of the piezoelectric actuator as it functions completely independently from the electrodes of the piezoelectric actuator. Isolation galvanic is thus reached when the electrodes of the piezoelectric actuator are not connected to any of the electrodes of the *deposited sensor*.

[0046] In the case the *deposited sensor* is an interdigitated capacitor, it has two electrodes, a first electrode 6a and a second electrode 6b, each of them being interdigitated with the other (see figures 1 or 2). Each of said two electrodes is made for example of silver, which is a highly electrical conductive component (6.30×10^7 S/m at 20°C). Alternatively, gold (4.10×10^7 S/m at 20°C) or copper (5.96×10^7 S/m at 20°C) can be used. Alternatively, every electrically conductive component which has a conductivity superior to 10^6 S/m and is printable may be used.

[0047] Each of the two electrodes (6a, 6b) has a plurality of extending electrodes (6c and 6d). The first extending electrodes 6c of the first electrode 6a are provided interlaced with the plurality of second extending electrodes 6d of the second electrode 6b.

[0048] The two electrodes (6a, 6b) forming the interdigital capacitor 6 are spaced from each other by a gap which is comprised between 10 µm and 100 µm, *i.e.* the pitch between a first extending electrode 6c and a second extending electrode 6d is comprised between 10 µm and 100 µm.

[0049] The width/size of the two electrodes forming the interdigital capacitor, *i.e.* the interlaced overlapping length of the first extending electrode 6c and the second extending electrode 6d is comprised between 5 µm and 1 mm. Preferentially, the width is comprised between 20 µm and 100 µm.

[0050] The thickness of the interdigital capacitor is as low as 1 µm, thereby reducing considerably the space occupation of the sensing structure compared to the size of the piezoelectric device. This has the advantages of allowing for the wide use of such device, since they present a compact form.

[0051] In the case the *deposited sensor* is a conductor line 60, it can be made of a straight line of conducting material with two or four pads 65 for contacts (see figure 1A). The conductive line 60 and the contact pads 65 are made for example of silver, which is a highly electrical conductive component

(6.30×10^7 S/m at 20°C). Alternatively, gold (4.10×10^7 S/m at 20°C) or copper (5.96×10^7 S/m at 20°C) can be used. Alternatively, every electrically conductive component which has a conductivity superior to 10^6 S/m and is printable may be used. This conductive line 60 can also be a meander, as displayed in figure 2A.

[0052] The width of the conductive line 60 can be typically between 10 and 1 mm, preferably between 10 and 100 µm. The length of the line can be between 50 µm and 1 cm, preferably between 200 µm and 1 mm.

[0053] The thickness of the conductive line can as low as 1 µm, thereby reducing considerably the space occupation of the sensing structure compared to the size of the piezoelectric device. This has the advantages of allowing for the wide use of such device, since they present a compact form.

[0054] The piezoelectric device can also be a multilayer capacitor device 100 (MLC), where metallic electrodes 2 and piezoelectric layers 4 alternate (see figure 3). The condition for depositing the *sensor* of the present invention is that the outer layer of the piezoelectric actuator must be made of dielectric material, preferentially ceramic material such as lead zirconate titanate (PZT), so that the metallic layer or layers (*e.g.*, electrodes in silver) remains electrically isolated from the inner electrodes of the MLC. Inside the MLC, the metallic layers alternate with the dielectric layers and that the number of metallic layers is equal to *n* while the number of dielectric layer is equal to *n*+1 (n being an integer). The device 100 comprises two opposites sides, the first set of two electrodes being respectively on the opposite sides. The second set of electrodes is on an external surface of said device between the two electrodes of the first set. The second set is printed on said external surface.

[0055] In a practical case, let's consider the top layer (which is a free surface, namely free of any electrodes) of the piezoelectric actuator 100. The dimensions of the piezoelectric device 100 are for example 5 mm × 5 mm × 2.4 mm in the case where the piezoelectric device is with a shape of a polyhedron with six faces. The piezoelectric device comprises two electrodes (8a, 8b) on two distinct faces, preferably on two distinct opposed faces. The electrodes (8a, 8b) can also been present on two distinct faces, which are not necessarily two opposed faces (not shown on figure 3). The inkjet/aerosol printing of silver electrode(s) is performed on the free surface (see figure 3). The pattern of these electrodes (6, 60) can be either interdigitated, similar to figures 1 and 2, or a conductive line 60 similar to figures 1A or 2A. This deposition is usually followed by an annealing step that is used to dry and sinter the metallic nanoparticles of silver ink (this can also be achieved with gold or copper nanoparticles). This annealing step enables electric conductivity. The annealing step has been performed at 200°C during 30 minutes at atmospheric pressure.

[0056] The electric field applied between the two electrodes (8a, 8b) of the piezoelectric actuator 100 induces a mechanical deformation into the whole actuator. This deformation is detected by the *deposited sensor*. If the latter is made of interdigitated electrodes 6, the deformation is sensed via the piezoelectric effect that will induce charge movement that can be detected via an LCR-meter or an oscilloscope (not shown) connected between the electrodes (6a,6b) of the interdigitated capacitor. If the sensor is a conductive line 60, the deformation is sensed via the variation of resistance of the conductive line (piezoresistive effect). This resistance can be measured when a dc current is applied to the two external pads 65a in figures 1A or 2A, and then one measures the resulting voltage between the two inner contact pads 65b displayed in figures 1A or 2A. This gives information on the actuator device 100.

[0057] Such data on the actuator device are very interesting and can be adapted in implementation such as high resolution microscopy, any application requiring monitoring the displacement of an object preferably on the micrometer scale, a piezoelectric transformer. Fatigue monitoring system, strain sensor, temperature sensor and humidity sensor are achievable thanks to the functionalisation of a piezoelectric device, namely thanks to the mechanical deformation sensor of the present invention.

Claims

1. Piezoelectric device (10, 100) shaped as a tridimensional object with at least two surfaces,
wherein said piezoelectric device (10, 100) comprises a first set of two or more electrodes (8a, 8b), each electrode being respectively on one of the at least two surfaces,
characterized in that
at least one of the surfaces which is free of electrodes from said first set of two or more electrodes (8a, 8b) is covered with at least a second set of electrodes (6, 60), respectively, said surface covered with second set of electrodes being adjacent to at least one of the surfaces with the electrodes of the first set.

2. Piezoelectric device (10, 100) according to claim 1, characterized in that said second set of electrodes is made of at least two interdigitated electrodes (6a, 6b).

3. Piezoelectric device (10, 100) according to claim 1, characterized in that said second set of electrodes is made of at least two electrodes distributed along a single conductive line (60).

4. Piezoelectric device (10, 100) according to any one of claims 1-3, characterized in that said piezoelectric device (10, 100) is made of a ceramic material, preferentially of the perovskite structure and even more preferentially made of lead zirconate titanate or $LiNbO_3$.

5. Piezoelectric device (10, 100) according to any one of claims 1-4, characterized in that said second set of electrodes (6, 60) is made of at least one electrical conductor comprising electrically conductive nanoparticles, preferentially nanoparticles made of silver, gold, copper, aluminium or indium tin oxide, alias ITO.

6. Piezoelectric device (10, 100) according to any one of claims 2 or 4-5, characterized in that said interdigitated electrodes (6a, 6b) are spaced from each other with a gap comprised between 10 μm and 100 μm.

7. Piezoelectric device (10, 100) according to any one of claims 5-6, characterized in that the electric conductors constituting said interdigitated electrodes (6a, 6b) have a width comprised between 5 μm and 1 mm, preferentially between 20μm and 100μm.

8. Piezoelectric device (10, 100) according to any one of claims 1-7, characterized in that said piezoelectric device (10, 100) is a pyroelectric device.

9. Piezoelectric device (100) according to any one of claims 1-8, characterized in that said piezoelectric device (100) is a multi-layer piezoelectric device, comprising alternating dielectric layers and metallic layers, the number of metallic layers being equal to n and the number of piezoelectric layers being equal to n+1, n being an integer.

10. Piezoelectric device (100) according to claim 9, characterized in that said metallic layers are made of metallic electrodes, preferably of interdigitated metallic electrodes, more preferably of interdigitated nickel or platinum of palladium electrodes.

11. Piezoelectric device (10, 100) according to any one of claims 1-10, characterized in that said electrodes (6, 60) of said second set of electrodes are planar.

12. Multi-layer piezoelectric device comprising alternating dielectric layers and metallic layers, two opposites sides, a first set of two electrodes, said two electrodes being respectively on the opposite sides, wherein the device further comprises a second set of electrodes, said second set being on an external surface of said device between the two electrodes of the first set.

13. Method for measuring the behaviour of a piezoelectric device (10, 100), said method comprising the steps of
    a) providing a piezoelectric device with a first set of two or more electrodes, said piezoelectric device being shaped as tridimensional object with at least two surfaces with respectively one of the electrodes of the first set,
    b) printing at least a second set of electrodes on at least one of the surfaces which is free of electrodes, respectively, said surface with said second set being adjacent to at least one of the surfaces with the electrodes of the first set,
    c) determining the variation of the electrical charges on said second set of electrodes.

14. Method according to claim 13, characterized in that said second set of electrode is made of at least two interdigitated electrodes (6a, 6b).

15. Method according to claim 13, characterized in that said second set of electrode is made of at least two electrodes distributed along a single conductive line (60), wherein step c) of determining the variation of the electrical charges on said second set of electrodes is performed by determining the variation of resistance of the conductive line (60).

16. Method according to any one of claims 13-15, wherein said step (b) is performed by inkjet printing.

17. Method according to any one of claims 13-16, wherein said step (b) is performed by aerosol printing.

18. Method according to any one of claims 13-17, wherein said step (b) is performed with an ink made of electrically conductive nanoparticles.

19. Method according to claim 18, wherein said ink made of electrically conductive nanoparticles is an ink made of silver, gold, copper, aluminium or indium tin oxide, alias ITO.

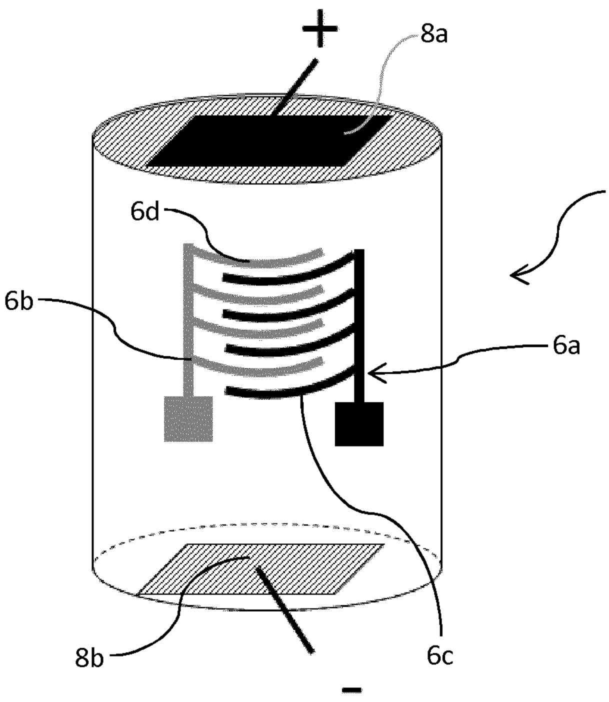

Fig. 1

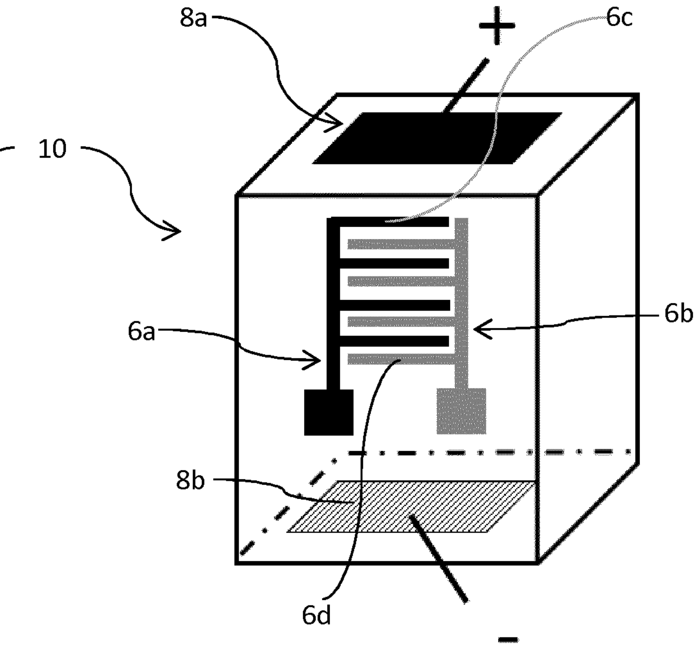

Fig. 2

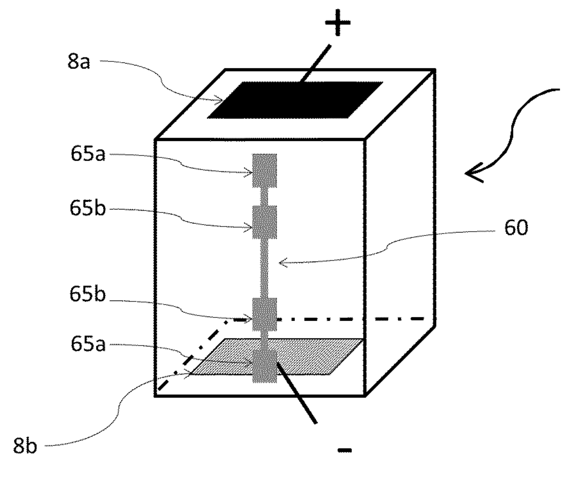

Fig. 1A

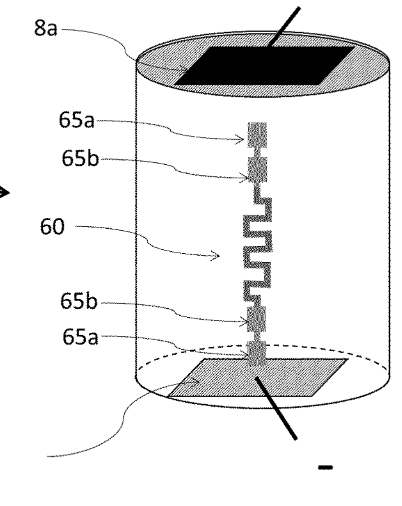

Fig. 2A

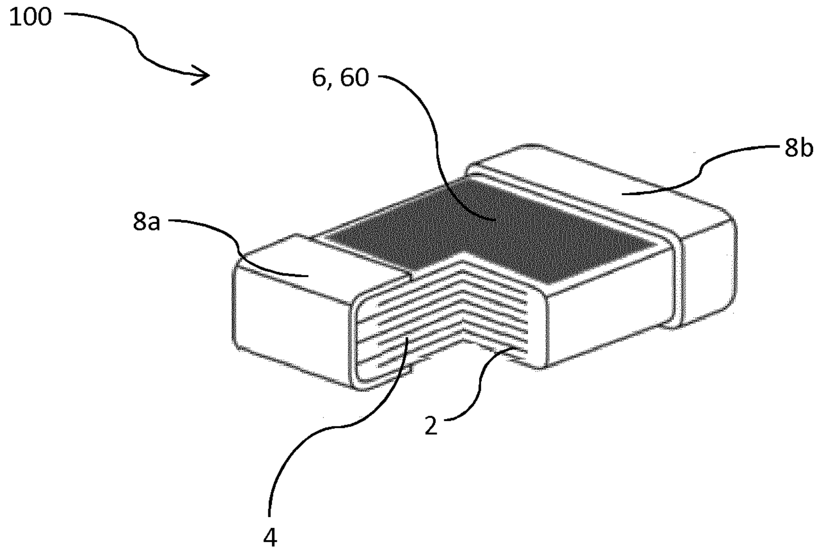

Fig.3

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2018/086743

A. CLASSIFICATION OF SUBJECT MATTER
INV. H01L41/047 H01L41/08 H01L41/083 H01L41/29
ADD.

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

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

C. 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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X	CN 102 820 422 A (UNIV BEIJING) 12 December 2012 (2012-12-12)	1,2,4, 6-8,13, 14,16,17
Y	paragraphs [0037] - [0043], [0058] -	5,18,19
A	[0071]; figures 1-4	3,15
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Y	paragraphs [0038] - [0043]; figures 1,2	5

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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Date of the actual completion of the international search	Date of mailing of the international search report
18 March 2019	01/04/2019

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Steiner, Markus

1

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Information on patent family members

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