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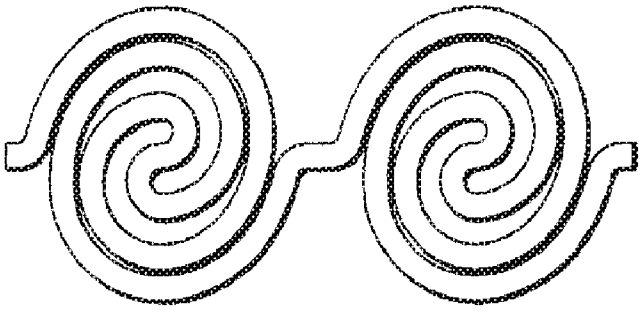


FIG. 1(C)
(PRIOR ART)

(57) Abstract: The invention provides an electronic device that includes a first functional body, a second functional body, and at least one connection member connecting the first functional body to the second functional body. The at least one connection member has a spiral pattern, and is suspended in air to allow tor stretching, flexing or compressing.

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ARCHIMEDEAN SPIRAL DESIGN FOR DEFORMABLE ELECTRONICS

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/099,324, filed January 2, 2015, the entire disclosure of which is hereby incorporated by reference.

FIELD OF THE INVENTION

[0002] This application relates to deformable electronic devices, particularly, to spiral-shaped electrical interconnects to be used in island-interconnect deformable electronic devices.

BACKGROUND

[0003] Recent years have witnessed the rapid development of deformable electronic devices, which are emerging as an attractive and promising new technology. Such electronics can be incorporated into wearable devices, such as flexible displays, stretchable circuits, hemispherical electronic eyes, and epidermal devices, to name a few. With deformable electronics, devices can be made to fit into a variety of physical spaces without the standard geometric constraints of non-deformable electronic devices. Indeed, such devices may be developed on the nano-, micro-, centi-, or meter level scale for various applications.

[0004] Many methods have been utilized to form deformable electronic devices and there are generally two conventional approaches. The first approach is to use organic materials that are intrinsically stretchable to form the electronic devices; however, such organic materials are undesirable for use in high-performance electronics because they have low electrical mobility

(i.e., ability for charged particles to move through a medium in response to an electric field). The second approach utilizes an "island-interconnect" structure where multiple inorganic electronic devices are each placed on a rigid island (e.g., substrate) and electrically connected by interconnects that are stretchable, thus making the entire island-interconnect system stretchable. The island-interconnect structures are typically supported by elastomeric substrates, and recent developments in foldable electronics utilize the concept of paper folding (i.e., origami) to increase the flexibility and deformability of the resulting structures. Indeed, one major objective is to improve the flexibility and deformability of stretchable electronic devices to allow them to be used in an even wider variety of applications than was previously possible. With the island-interconnect method, known interconnects are patterned to form a serpentine shape or a semi-similar serpentine shape to improve deformability. The serpentine-based design utilizes the concept of kirigami (i.e., paper-cutting) to make non-straight lines from a two-dimensional plane, such that in-plane stretching is compensated by out-of-plane deformation. However, even the serpentine-based design is limited in its stretchability capacity.

[0005] Accordingly, additional methods of forming interconnects that improve stretchability are desired, such that electronic devices with wide functionality and improved portability may be developed.

SUMMARY

[0006] To improve deformability of island-interconnect structures, the invention is directed to spiral-based interconnects, which are more stretchable than conventional serpentine-based interconnects.

[0007] Accordingly, one aspect of the invention is directed to an electronic device which includes a first functional body, a second functional body, and at least one connection member connecting the first functional body to the second functional body, wherein the at least one connection member has a spiral pattern and is suspended in air to allow for stretching, flexing or compressing.

DESCRIPTION OF THE DRAWINGS

[0008] These and other features of the preferred embodiments of the invention will become more apparent in the detailed description in which reference is made to the appended drawings wherein:

[0009] FIGS. 1(A)-1(C) are top view drawings of three interconnect structure geometries according to an embodiment of the invention;

[0010] FIGS. 2(A)-(C) are top view drawings of the three interconnect structure geometries illustrated in FIGS. 1(A)-(C) showing exemplary dimensions for each according to an embodiment of the invention;

[0011] FIGS. 3(A)-(C) are top view drawings of deformed and undeformed states of the three interconnect structures illustrated in FIGS. 1(A)-1(C);

[0012] FIGS. 4(A)-(C) are graphs depicting the strain behavior of each of the three interconnect structures illustrated in FIGS. 2(A)-(C);

[0013] FIG. 5 is a top view drawing of a spiral interconnect structure according to an embodiment of the invention;

[0014] FIG. 6(A) is a top view drawing of a modified spiral interconnect structure according to an embodiment of the invention;

[0015] FIG. 6(B) is a graph depicting the strain behavior of the modified spiral interconnect structure of FIG. 6(A); and

[0016] FIGS. 7(A)-(B) are top view drawings of an island-interconnect structure formed of the spiral interconnect of FIG. 1(C), according to an embodiment of the invention.

DETAILED DESCRIPTION

[0017] The invention is directed generally to spiral-based interconnect geometries for use in island-interconnect deformable electronic devices. Deformable electronic devices typically include a plurality of individual electronic devices which are electrically connected by connection member(s), also known as interconnects. The connection members are electrically conductive so as to allow electrical signals to be conducted between the individual devices. The electronic devices are not particularly limited and may be, for example, energy storage and energy source devices (e.g., batteries, solar cells, and supercapacitors), consumer products (e.g., foldable displays, illumination devices, antenna, and foldable toys), and wearable electronics (e.g., health monitoring systems and communication systems). The interconnect geometries of the invention allow these products to be made more compact, portable and durable without sacrificing performance.

[0018] As set forth herein, and without being bound by any particular theory, it is believed that a spiral-shaped interconnect allows for increased stretchability of the island-interconnect device. It is believed that a uniform and small curvature in a spiral pattern used for the interconnect contributes to a greater stretchability. Instead of applying a periodic pattern to the design of the interconnect, a non-periodic pattern provides a higher degree of freedom during the design process, especially under certain extreme conditions.

[0019] As set forth herein, the spiral interconnect geometries have a higher stretchability as compared to known serpentine-based interconnect geometries. The spiral interconnects are stretchable up to 250% under elastic deformation and up to 325% without failure.

[0020] Exemplary in-plane shapes of three interconnect patterns (also referred to as "connection members") are shown in FIGS. 1(A)-(C) as follows: regular serpentine (FIG. 1(A)) self-similar serpentine (FIG. 1(B)) and Archimedean spiral structure 100 (FIG. 1(C)). The regular serpentine (FIG. 1(A)) has been extensively used in forming interconnects and is known in the art, and the self-similar serpentine pattern (FIG. 1(B)) has been recently studied. The Archimedean spiral structure 100 illustrated in FIG. 1(C) is the primary object of this invention.

[0021] The interconnects of FIGS. 1(A)-(C) may be formed from a material configured to withstand the imposed bending stress formed when adjacent and adjoined functional bodies are moved relative to one another to form a resulting electronic device. In one embodiment, the interconnect may include at least one flexible layer (not shown). For example, the interconnect can be formed of a relatively soft material, such as a polymer, gel, and the like. The polymer, for example, can be poly-para-xylylene or an electrically conductive polymer (Parylene-C, polyimide, polydimethylsiloxane (PDMS)). Alternatively, the interconnect can be formed of any conductive material known in the art suitable for use as a conductor, such as metals (e.g., copper, chromium, aluminum, gold, silver, iron, cobalt, titanium, etc.), nano fibers, conductive oxides (e.g., ZnO, indium tin oxide (ITO), fluorine doped tin oxide (FTO), ReO_3, IrO_2, CrO_2, etc.), and positive temperature coefficient thermistors (PTC) and negative temperature coefficient thermistors (NTC).

[0022] In another example, the interconnect can be formed from a plurality of layers, such as a first layer forming a top or bottom of the interconnect, or double layers on both the top and

bottom of the interconnect, and/or multiple layers as necessary depending on the requirements of a particular application.

[0023] Each of the geometries illustrated in FIGS. 1(A)-(C) may have any dimensions suitable for a particular use and known to one skilled in the art. In one exemplary embodiment illustrated in FIGS. 2(A)-(C), each of the patterns are formed of an interconnect body 102 having a thickness (not shown) of about 1 micron and an interconnect body width (w) of about 40 microns. The radius (r) of the regular serpentine of FIG. 2(A) and the semi-similar serpentine of FIG. 2(B) is about 20 μm and 10 μm, respectively. The length (l) of each serpentine fold for the regular serpentine is about 310 microns, and lengths (l_1, l_2) of each serpentine fold for the self-similar serpentine are 235 microns and 580 microns, respectively. These dimensions are provided only by way of example and any dimensions suitable for a particular use or application may be used.

[0024] In one exemplary embodiment, the Archimedean spiral structure 100 may be prescribed by an analytical function in the polar coordinate as $r = A \cdot \theta^q$, wherein r is the radius of the spiral pattern, $\theta = [0, 3\pi]$, A is a geometrical pre-factor, and q is the power which determines the shape of the function. There is no limit on the value of variables A or q, which are related and which dictate the shape of the spiral pattern. In another exemplary embodiment, the Archimedean spiral structure 100 is prescribed by an analytical function in the polar coordinate as $r = \pm 60\theta^{1/2}$, $\theta = [0, 3\pi]$, wherein r is the radius of the spiral pattern. In one embodiment, the body width (w) of the spiral structure 100 is about 40 microns. In this way, all three patterns (FIGS. 2(A)-(C)) have approximately the same span of about 1,000 μm in the x-direction, the same height of about 400 μm in the y-direction, and the same contour length of about 5,650 μm. In one embodiment where copper is used to form the interconnects, the Young's modulus E is

119 GPa, and the Poisson's ratio ν is 0.34. Plasticity is considered and described by $\sigma = E\varepsilon_y + E_p\varepsilon_p^n$ with $\varepsilon_Y = 0.3\%$ as the yield strain, $E_p = 530$ MPa, and $n = 0.44$.

[0025] To compare the interconnect geometries of FIGS. 2(A)-(C), a uniform criterion was developed. For a typical island-interconnect structure, at the unstrained state, the islands, also referred to as functional bodies, should occupy the majority of the in-plane area to increase the areal coverage. By way of example, a 2 mm × 2 mm island and a 1 mm gap between islands may be utilized, where a 2 mm × 2 mm island size is consistent with the size of some small conventional electronic chips and the areal coverage can achieve over 45%. As such, the area to be filled in by the interconnects, i.e., connection members, is 2 mm × 1 mm. In this area, one interconnect or a plurality of interconnects may be used. Taking into consideration electrical conductivity of the resulting structure, the use of a plurality of interconnects is preferred since the breaking of one interconnect does not cause the electrical failure of the entire structure. Accordingly, in one embodiment, four identical interconnects are placed in the gap between each island and each interconnect occupies no more than 0.5 mm (height) × 1 mm (width) of space. Another criterion to uniformly compare the stretchability among the different interconnects illustrated in FIGS. 1(A)-(C) is that the same cross-sectional area and in-plane contour length for each island should be used, thus the electrical resistance among the different interconnects is kept consistent.

[0026] To analyze the stretchability of each interconnect geometry illustrated in FIGS. 2(A)-2(C), a finite element analysis was performed using commercially available finite element analysis software, ABAQUS, manufactured by Dassault Systemes of Velizy-Villacoublay, France. A buckling analysis is carried out in order to obtain the first ten buckling modes, which are then imported with random weight factors as imperfections. During the analysis, 20-node

quadratic elements with reduced integration (C3D20R) are used and the mesh convergence is ensured. Next, a prescribed displacement force is applied to the rightmost end of each interconnect to stretch the interconnect while the leftmost end remains fixed. At a certain loading step, the prescribed displacement force is removed to ascertain whether the deformation is recoverable.

[0027] The results of the stretchability tests are illustrated in FIGS. 3(A)-(C). These figures show the elastic stretchability of each of the three patterns of FIGS. 2(A)-(c) under the constraints of the same in-plane span and contour length. Here, elastic stretchability is defined as the critical strain at which the interconnect enters the plastic deformation zone, i.e., where the maximum equivalent strain exceeds the yield strain. The capability of restoration after the stretching force is removed was also analyzed. Thus, both the deformed state at the critical strain and the released state when the stretching force is removed are shown for each the three interconnect geometries, with the legend showing the equivalent plastic strain. To compare, the two states (deformed and released) of the interconnect at the halfway point of the critical strain are also provided, which is still within the elastic range and thus the deformation is fully recoverable.

[0028] As shown in FIGS. 3(A)-3(C), the results clearly show that the Archimedean spiral structure 100 has the largest elastic stretchability, up to 200%, while the regular serpentine and the self-similar serpentine have 112% and 98% elastic stretchability, respectively. The illustrations of the deformed states show that in-plane stretching is accompanied by out-of-plane deformation (mainly twisting and bending) for each interconnect. In other words, the out-of-plane deformation compensates the in-plane deformation. Particularly for the Archimedean spiral structure 100, the unfolding-like deformation occurs in order to compensate the in-plane

stretching. From an application perspective, a low level out-of-plane deformation is desired in order to allow for denser stacking of the devices in the thickness direction. When the critical strain is released, the interconnect recovers almost to its undeformed shape, even when plastic deformation has already occurred. This is because, at the critical point or a little over the critical point, the regions that enter the plastic zone are very limited and the majority of the interconnect is still within the elastic domain. The plastic deformation is localized at the regions with large curvature.

[0029] The strain behavior of each of the interconnect patterns tested above is provided in the graphs of FIGS. 4(A)-(C). Here, the stretchability of each interconnect is defined as the critical strain at which the maximum value of the maximum principal strain exceeds the fracture strain, 1%. FIGS. 4(A)-(C) also illustrate the out-of-plane deformation among these three interconnect patterns. The legend indicates the percentage of the materials with plastic deformation. Here, it is shown that the Archimedean spiral structure 100 still has the largest stretchability of up to 270%, while the other two serpentine structures have less stretchability at about 220%. The Archimedean spiral structure 100 had the highest level of out-of-plane deformation as the outer ring of the spiral rotated to compensate for the in-plane stretching, but the maximum out-of-plane deformation, 300 μm, is within the range of the thickness of an island or device, which will not affect the stacking density in the vertical direction. As the legend shows, the percentage of plastic deformation is rather small, on the order of 1%, which indicates that the spiral structure 100 has a good capability of restoring to its undeformed state even after entering the plastic deformation zone.

[0030] The comparisons set forth in FIGS. 3(A)-(C) and FIGS. 4(A)-(C) suggest that a uniform and small curvature to the interconnect pattern may contribute to a greater stretchability

under the constraints of the same in-plane span and contour length. The regular and semi-similar serpentines (FIGS. 1(A) and 1(B), respectively) have zero curvature over their straight line segments, but large curvatures at the junctions between their straight lines. Because of design limitations for the serpentine-based structures, large curvatures are needed to have a large areal filling ratio. Thus, the curvature for the serpentine based structure transforms from zero curvature to large curvature along its length, which results in lower stretchability.

[0031] According to another embodiment, as illustrated in FIG. 5, a modified spiral structure 102 is used to form an interconnect, where the curvature evolves smoothly along the contour length such that it is elongated. In one embodiment, the modified spiral structure has a polar angle varying from 0 to 3π.

[0032] In another embodiment, two Archimedean spiral structures 100 are used to form an interconnect. To make the spiral-based structure more versatile so that it can better fit into a non-square area, a modified Archimedean spiral structure 100' may be used, as illustrated in FIG. 6(A). Here, the ratio between the horizontal and vertical dimensions is adjusted to fit into a non-square area. The approach is to modify the original Archimedean spiral structure 100 by multiplying with a smooth approximation to a step function of θ in polar coordinate system and then inserting straight lines to fit the in-plane area. As set forth in FIG. 6(A), the interconnect body width (w) is 40 microns, and the length (l) of each fold is 300 microns, but any particular dimensions suitable for use in a particular application may be used.

[0033] The stretchability of the modified Archimedean spiral structure 100' was analyzed by applying a prescribed displacement force at one end while the other end is fixed, as set forth herein. The results of this stretchability test are provided in FIG. 6(B). The same legend as that used in FIGS. 4(A)-(C) was used and the results for the original spiral structure 100 are marked

on FIG. 6(B). Clearly, the graph shows that the modified Archimedean spiral structure 100' is even more stretchable than the original spiral structure 100, with over 250% elastic stretchability and 325% stretchability before fracture. The maximum out-of-plane displacement is about 450 μm, which is an acceptable level. Without being bound by any particular theory, it is believed that the modified Archimedean spiral structure 100' is more stretchable because the newly added straight portions 104 allow the structure to more easily generate out-of-plane deformation without introducing large curvatures.

[0034] In one aspect, the spiral structure 100 is coupled to and positioned between opposing functional bodies 700 to form an island-interconnect structure 702, as illustrated in FIGS. 7(A). In another embodiment illustrated in FIG. 7(B), two spiral structures 100 are used to form island-interconnect structure 702'. In an alternative embodiment, the island-interconnect structure 702 may be formed of a plurality of spiral structures 100, each coupled to opposing functional bodies 700. Each interconnect can thus be selectively movable between a fixed position, in which no relative movement between connected functional bodies 700 can be allowed, and a pliable position, in which relative movement between connected functional bodies 700 can be allowed.

[0035] Although several embodiments of the invention have been disclosed in the foregoing specification, it is understood by those skilled in the art that many modifications and other embodiments of the invention will come to mind to which the invention pertains, having the benefit of the teaching presented in the foregoing description and associated drawings. It is thus understood that the invention is not limited to the specific embodiments disclosed hereinabove, and that many modifications and other embodiments are intended to be included within the scope of the appended claims. Moreover, although specific terms are employed herein, as well as in

the claims which follow, they are used only in a generic and descriptive sense, and not for the purposes of limiting the described invention, nor the claims which follow.

What is claimed is:

1. An electronic device comprising:

a first functional body;

a second functional body; and

at least one connection member connecting the first functional body to the second functional body, wherein the at least one connection member has a spiral pattern and is suspended in air to allow for stretching, flexing or compressing.

2. The electronic device of claim 1, wherein the spiral pattern is an Archimedean spiral.

3. The electronic device of claim 2, wherein the Archimedean spiral is prescribed by a function $r = A \cdot \theta^q$, wherein r is the radius of the spiral pattern, $\theta = [0, 3\pi]$, A is a geometrical pre-factor, and q is a power that determines a shape of function.

4. The electronic device of claim 2, wherein the Archimedean spiral is prescribed by a function $r = \pm 60\theta^{1/1.7}$, wherein r is the radius of the spiral pattern and $\theta = [0, 3\pi]$.

5. The electronic device of claim 2, wherein the Archimedean spiral is elongated.

6. The electronic device of claim 1, wherein the at least one connection member is selectively movable between a fixed position and a pliable position, such that the first functional body is movable relative to the second functional body and vice versa.

7. The electronic device of claim 1, wherein the at least one connection member is a conductor.

8. The electronic device of claim 7, wherein the at least one connection member is formed of copper, chromium, aluminum, gold, silver, iron, cobalt, titanium, conductive nano fibers, ZnO, indium tin oxide (ITO), fluorine doped tin oxide (FTO), ReO_3, IrO_2, CrO_2, poly-para-xylylene, Parylene-C, polyimide, or polydimethylsiloxane.

9. The electronic device of claim 1, wherein the at least one connection member has a thickness of about one micron.

10. The electronic device of claim 1, wherein the electronic device is a battery.

11. The electronic device of claim 1, wherein the at least one connection member has an elastic stretchability of up to 200%.

12. The electronic device of claim 1, wherein the at least one connection member comprises at least two electrically connected connection members, each connection member having a spiral pattern.

13. The electronic device of claim 12, wherein the at least two electrically connected connection members have an elastic stretchability of up to 250%.

14. The electronic device of claim 1, wherein the electronic device comprises a plurality of

functional bodies, each functional body being connected by at least one connection member having a spiral pattern.

15. The electronic device of claim 1, wherein the at least one connection member is formed from a plurality of layers.

16. The electronic device of claim 15, wherein at least one of the plurality of layers is a flexible layer.

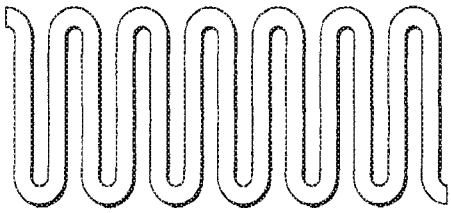


FIG. 1(A)
(PRIOR ART)

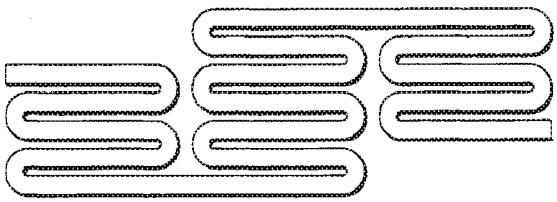


FIG. 1(B)
(PRIOR ART)

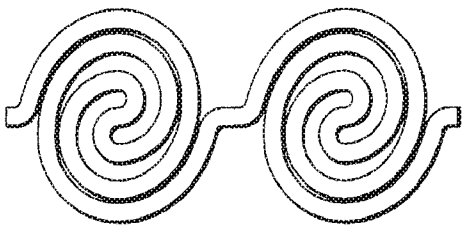


FIG. 1(C)
(PRIOR ART)

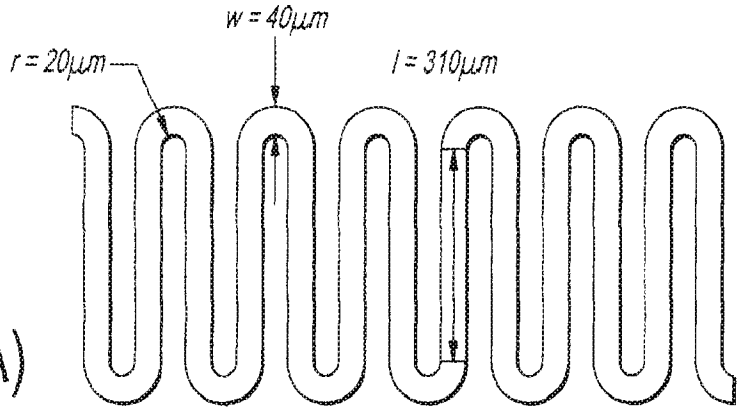


FIG. 2(A)

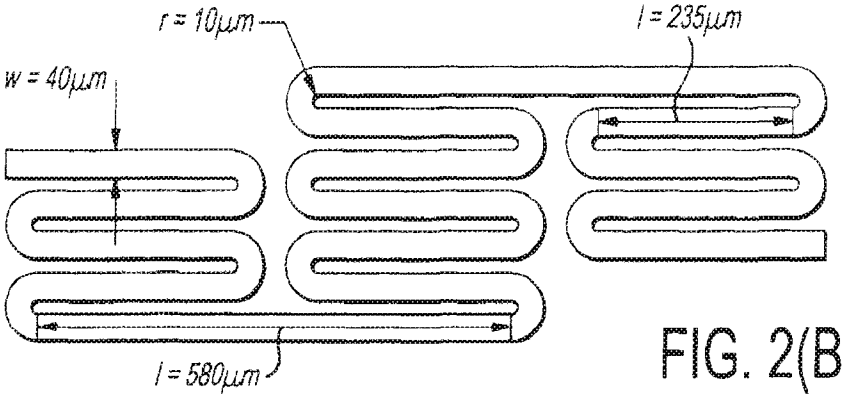


FIG. 2(B)

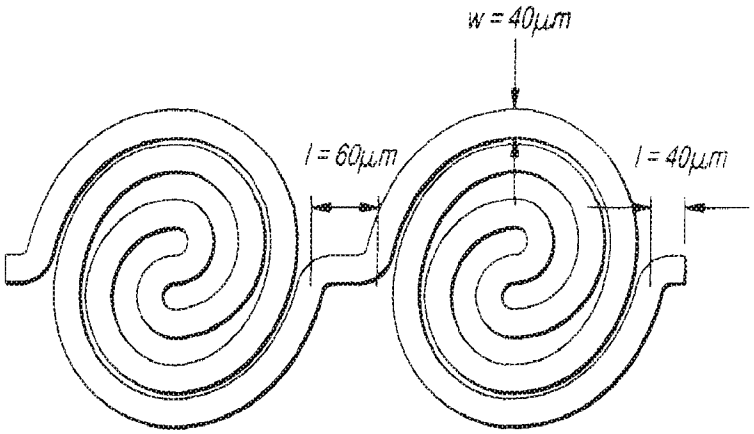


FIG. 2(C)

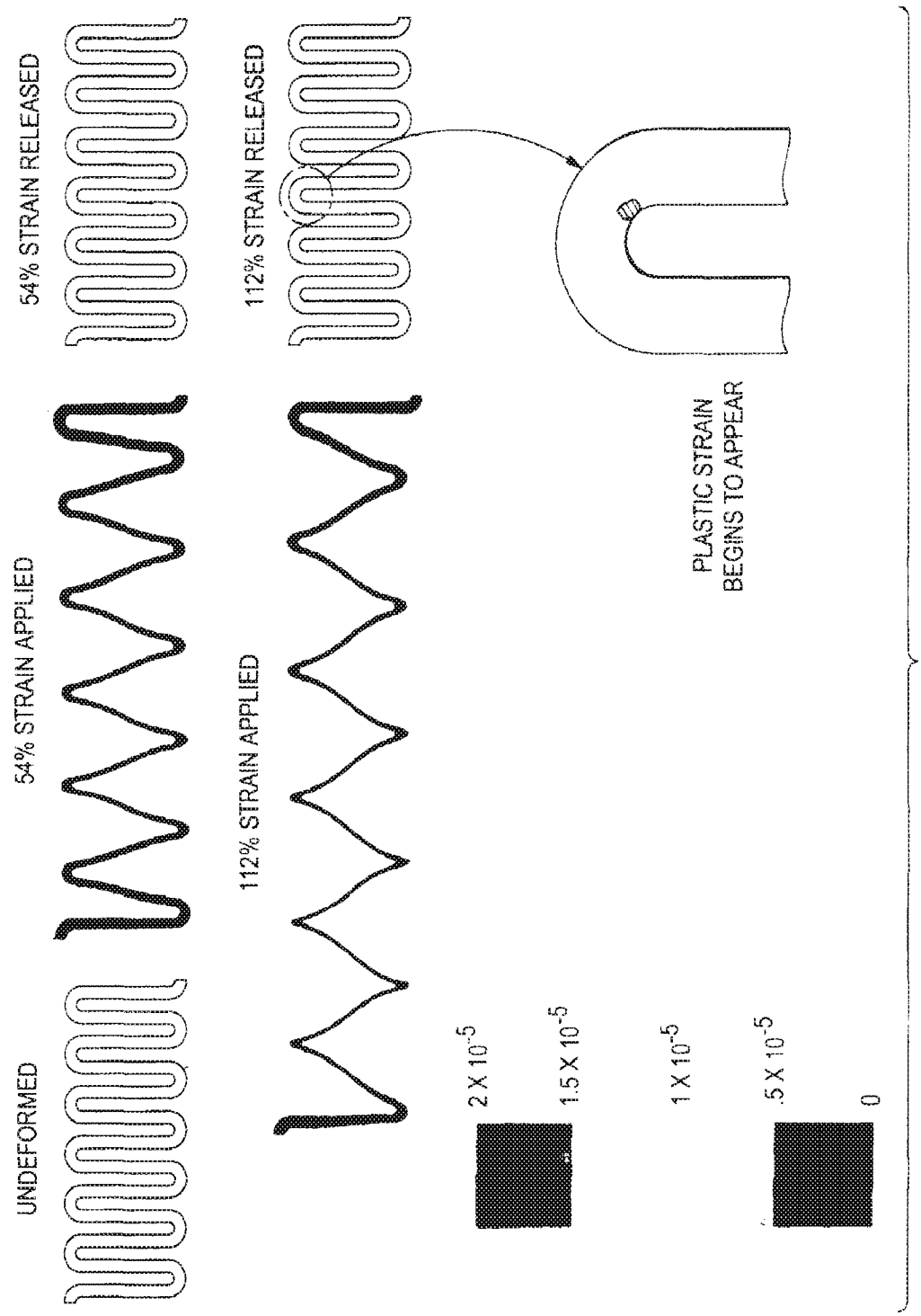

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112% STRAIN RELEASED
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FIG. 3(A)

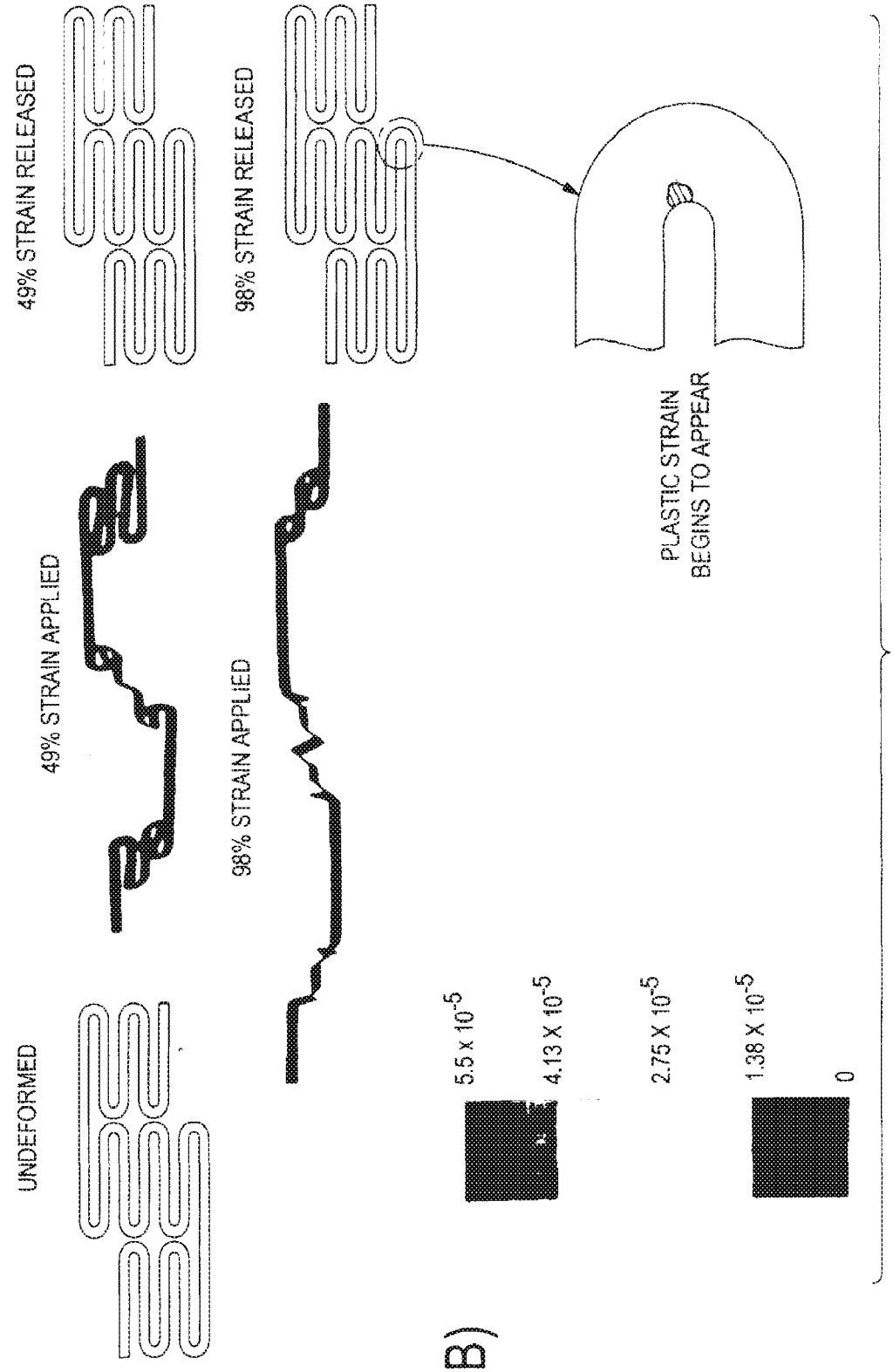

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FIG. 3(B)

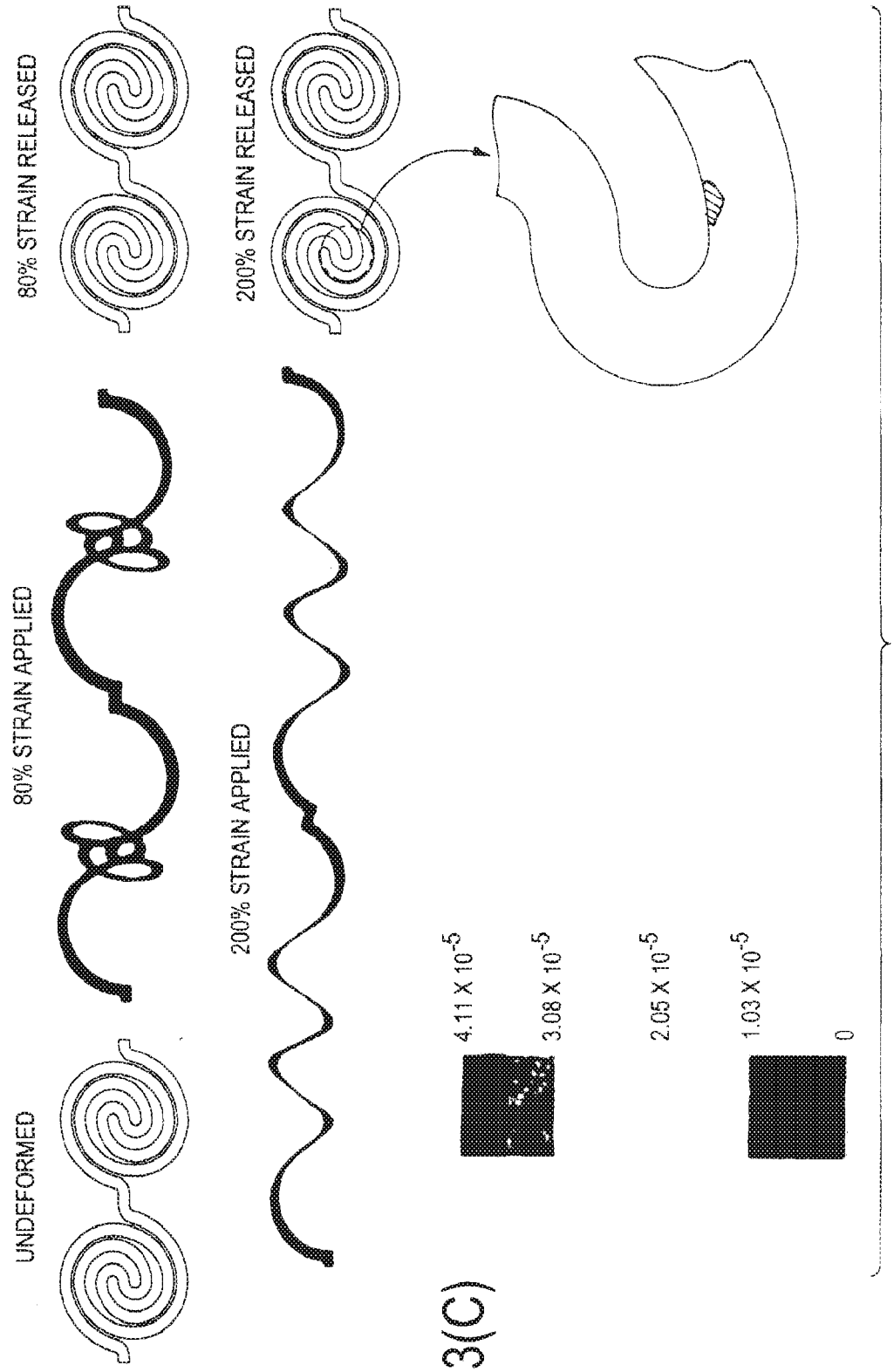

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FIG. 3(C)

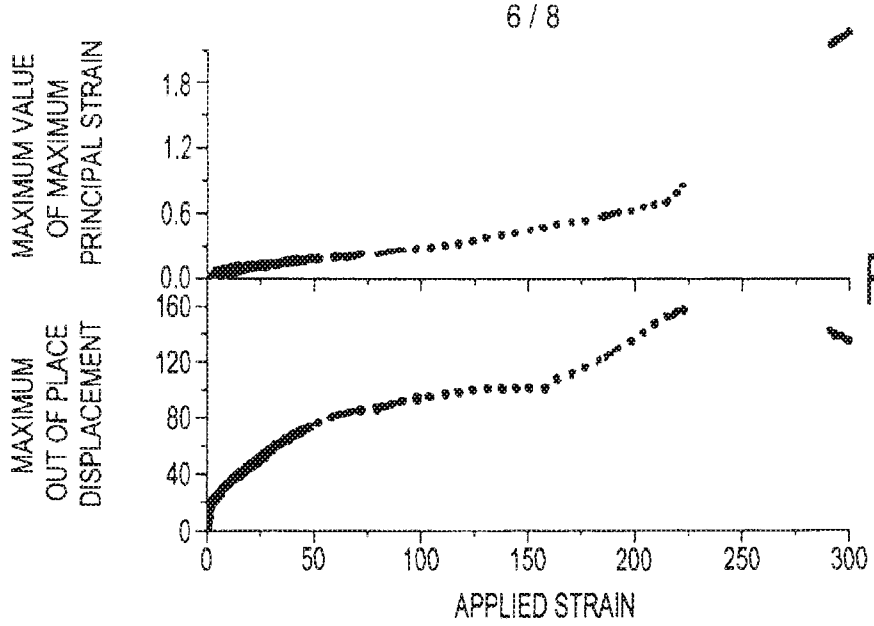


FIG. 4(A)

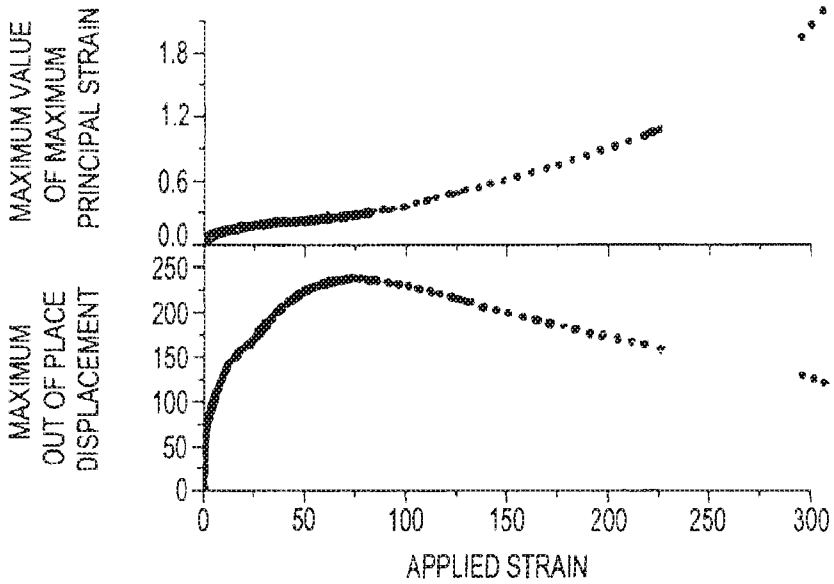


FIG. 4(B)

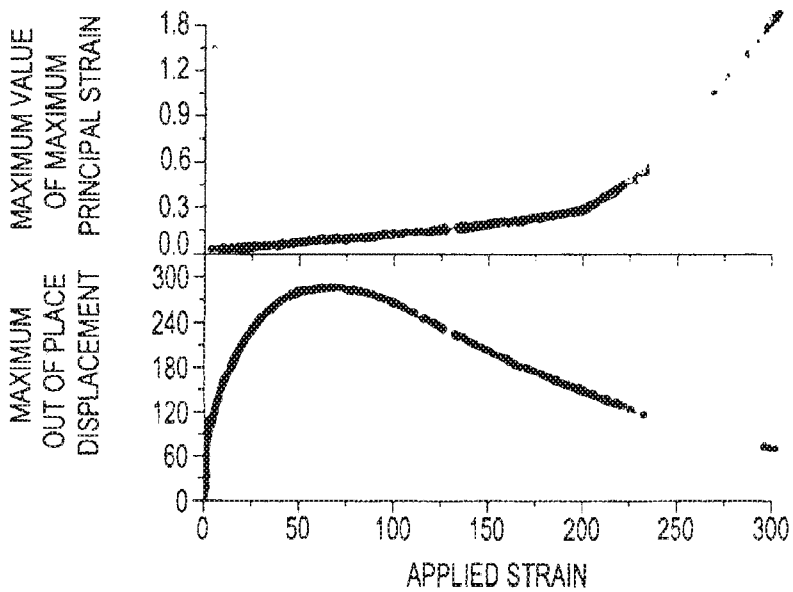


FIG. 4(C)

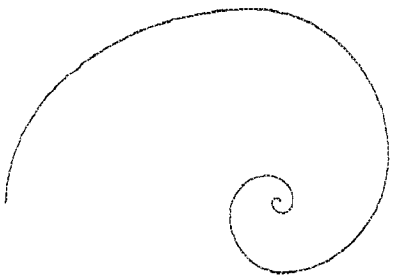
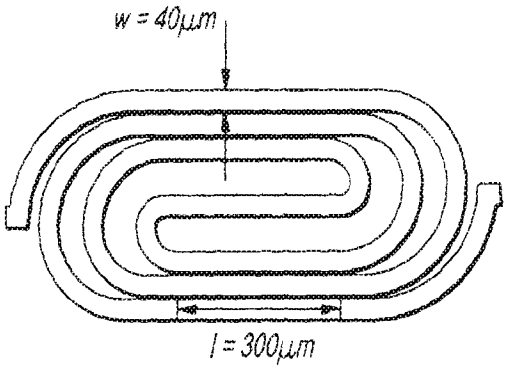


FIG. 5

FIG. 6(A)



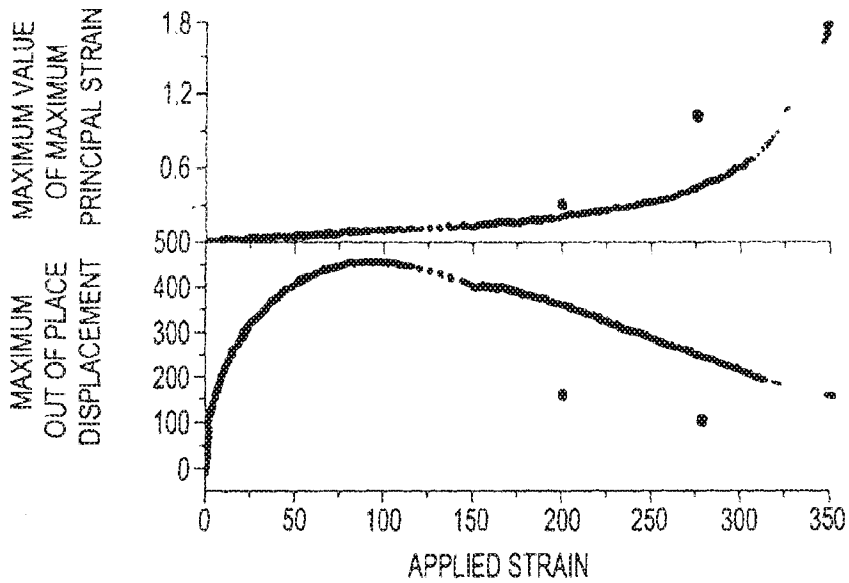


FIG. 6(B)

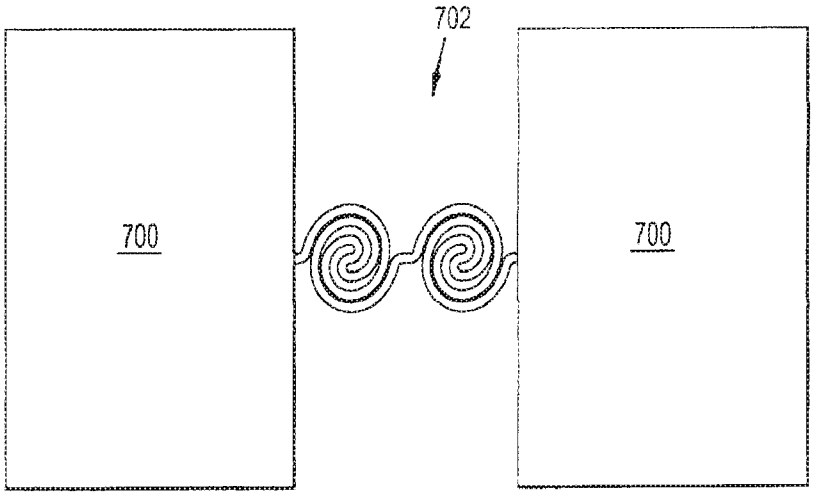


FIG. 7(A)

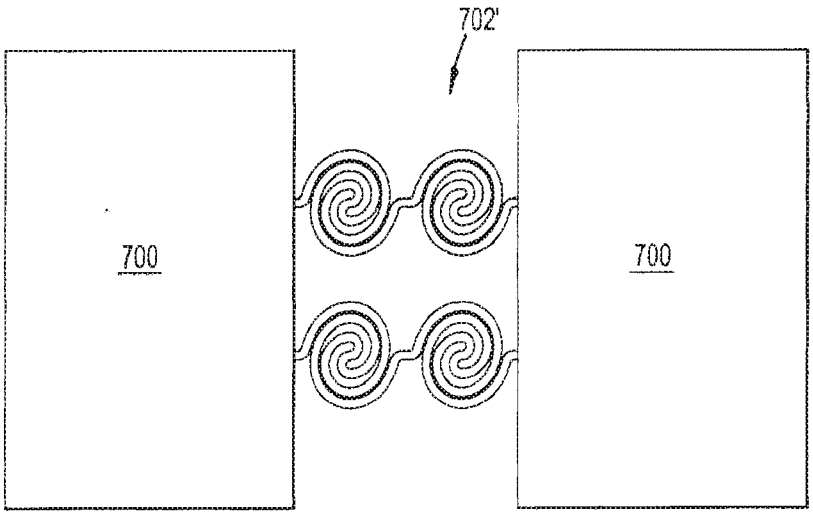


FIG. 7(B)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2015/068038

A. CLASSIFICATION OF SUBJECT MATTER

H01B 5/08(2006.01)i, H01B 7/06(2006.01)i, H01B 1/08(2006.01)i

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)
H01B 5/08; H01L 21/60; H01L 21/4763; H01L 23/34; H01L 23/48; H01R 41/00; H01L 25/065; H01L 23/538; H01B 7/06; H01B 1/08

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: spiral, pattern, design, deformable, stretch, connect

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2002-0094701 A1 (DAVID KALMAN BIEGELSEN et al.) 18 July 2002 See abstract, paragraphs [0009],[0038],[0043] and claim 1.	1-16
Y	US 2009-0283891 A1 (RONALD DEKKER et al.) 19 November 2009 See abstract, claims 1,14,15 and figure 2.	1-16
A	WO 03-021679 A2 (NATIONAL MICROELECTRONIC RESEARCH CENTRE UNIVERSITY COLLEGE CORK - NATIONAL UNIVERSITY OF IRELAND CORK et al.) 13 March 2003 See abstract, claims 1-19 and figure 6.	1-16
A	US 6455931 B1 (WILLIAM J. HAMILTON, JR. et al.) 24 September 2002 See abstract, claims 1-11 and figure 21.	1-16
A	US 2005-0280157 A1 (JERRY A. ROUSH et al.) 22 December 2005 See abstract, paragraphs [0034]-[0041] and figures 1-5c.	1-16

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

☒ See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"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	Date of mailing of the international search report
29 April 2016 (29.04.2016)	**04 May 2016 (04.05.2016)**

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.
PCT/US2015/068038

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