(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 February 2014 (20.02.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/028822 A1

(51) **International Patent Classification**:
H02N 2/02 (2006.01) ***H01L 41/04*** (2006.01)

(21) **International Application Number**:
PCT/US2013/055304

(22) **International Filing Date**:
16 August 2013 (16.08.2013)

(25) **Filing Language**: English

(26) **Publication Language**: English

(30) **Priority Data**:

61/683,860	16 August 2012 (16.08.2012)	US
61/717,810	24 October 2012 (24.10.2012)	US
61/719,999	30 October 2012 (30.10.2012)	US
61/734,609	7 December 2012 (07.12.2012)	US
61/734,622	7 December 2012 (07.12.2012)	US
61/734,616	7 December 2012 (07.12.2012)	US

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(81) **Designated States** *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) **Designated States** *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

— *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

(54) **Title**: ELECTRICAL INTERCONNECT TERMINALS FOR ROLLED DIELECTRIC ELASTOMER TRANSDUCERS

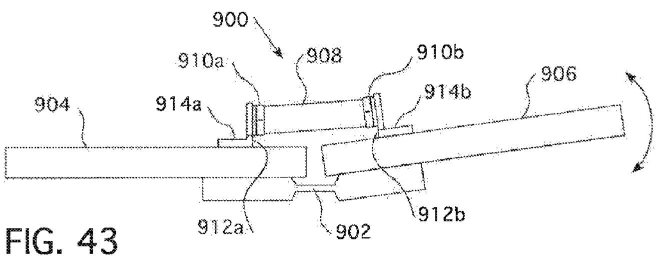

FIG. 43

(57) **Abstract**: A dielectric elastomer transducer comprising a first and second ends and first and second electrical terminals connected to the respective first and second ends of the dielectric elastomer transducer is provided. A system also includes a substrate, a conductive flexure with one end attached to the substrate and another end configured to receive a load. A first electrical connector pin is attached to the flexure to receive the first electrical terminal and a second electrical connector pin is attached to the substrate to receive the second electrical terminal. Another system also includes a living hinge flexibly coupling two separate substrates, where at least one of the substrates is movable in response to energizing the dielectric elastomer transducer.

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ELECTRICAL INTERCONNECT TERMINALS FOR ROLLED DIELECTRIC ELASTOMER TRANSDUCERS

RELATED APPLICATIONS

This application claims the benefit, under 35 USC § 119(e), of U.S. Provisional Application Nos.: 61/683,860 filed August 16, 2012 entitled "ROLL ACTUATORS IN AXIAL TENSION, MODEL AND DATA"; 61/717,810 filed October 24, 2012 entitled "DIELECTRIC ELASTOMER TRANSDUCER WITH QUICK-CONNECT TERMINALS"; 61/719,999 filed October 30, 2012 entitled "MACHNINE AND METHODS FOR MAKING ROLLED DIELECTRIC ELASTOMER TRANSDUCERS"; 61/734,609 filed December 7, 2012 entitled "RESONANT FREQUENCIES"; 61/734,616 filed December 7, 2012 entitled "ROLL ACTUATORS"; and 61/734,622 filed December 7, 2012 entitled "SKIN CONTACT WITH DIELECTRIC ELASTOMER ACTUATORS – SYSTEMS FOR SAFETY"; the entirety of each of which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention is directed in general to electroactive polymers and more specifically to electrical interconnect terminals for rolled dielectric elastomer transducer and manufacturing process for making same.

BACKGROUND OF THE INVENTION

A tremendous variety of devices used today rely on actuators of one sort or another to convert electrical energy to mechanical energy. Conversely, many power generation applications operate by converting mechanical action into electrical energy. Employed to harvest mechanical energy in this fashion, the same type of device may be referred to as a generator. Likewise, when the structure is employed to convert physical stimulus such as vibration or pressure into an electrical signal for measurement purposes, it may be characterized as a sensor. Yet, the term "transducer" may be used to generically refer to any of the devices.

A number of design considerations favor the selection and use of advanced dielectric elastomer materials, also referred to as "electroactive polymers", for the fabrication of transducers. These considerations include potential force, power density, power conversion/consumption, size, weight, cost, response time, duty cycle, service requirements, environmental impact, etc. As such, in many applications, electroactive polymer technology offers an ideal replacement for piezoelectric, shape-memory alloy and electromagnetic devices such as motors and solenoids.

An electroactive polymer transducer comprises two electrodes having deformable characteristics and separated by a thin elastomeric dielectric material. When a voltage difference is applied to the electrodes, the oppositely charged electrodes attract each other thereby compressing the polymer dielectric layer therebetween. As the electrodes are pulled closer together, the dielectric polymer film becomes thinner (the Z-axis component contracts) as it expands in the planar directions (along the X- and Y-axes), i.e., the displacement of the film is in-plane. The electroactive polymer film may also be configured to produce movement in a direction orthogonal to the film structure (along the Z-axis), i.e., the displacement of the film is out-of-plane. For example, U.S. Pat. No. 7,567,681 discloses electroactive polymer film constructs which provide such out-of-plane displacement – also referred to as surface deformation or as thickness mode deflection.

The material and physical properties of the electroactive polymer film may be varied and controlled to customize the deformation undergone by the transducer. More specifically, factors such as the relative elasticity between the polymer film and the electrode material, the relative thickness between the polymer film and electrode material and/or the varying thickness of the polymer film and/or electrode material, the physical pattern of the polymer film and/or electrode material (to provide localized active and inactive areas), the tension or pre-strain placed on the electroactive polymer film as a whole, and the amount of voltage applied to or capacitance induced upon the film may be controlled and varied to customize the features of the film when in an active mode.

Numerous applications exist that benefit from the advantages provided by such electroactive polymer films whether using the film alone or using it in an electroactive polymer actuator. One of the many applications involves the use of electroactive polymer transducers as actuators to produce haptic, tactile, vibrational feedback (the communication of information to a user through forces applied to the user's body), and the like, in user interface devices. There are many known user interface devices which employ such feedback, typically in response to a force initiated by the user. Examples of user interface devices that may employ such feedback include keyboards, keypads, game controller, remote control, touch screens, computer mice, trackballs, stylus sticks, joysticks, etc. The user interface surface can comprise any surface that a user manipulates, engages, and/or observes regarding feedback or information from the device. Examples of such interface surfaces include, but are not limited to, a key (e.g., keys on a keyboard), a game pad or buttons, a display screen, etc.

Use of electroactive polymer materials in consumer electronic media devices as well as the numerous other commercial and consumer applications highlights the need to increase production volume and reduce manufacturing cost. There is a need for methods to easily and quickly install electroactive polymer devices. In addition, like incandescent light bulbs, dielectric elastomer transducers occasionally burn out and need to be replaced. It is desirable to minimize the time, effort, and expense required to replace them. Also, it is sometimes desirable to situate actuators directly on a printed circuit board. This can eliminate costs of cables and connectors, and save space. The art discloses many approaches to making electrical and mechanical connections to dielectric elastomer transducers. U.S. Pat. No. 7,915,789 B2, for example, discloses the use of machine screws to make both the electrical and mechanical connections. In U.S. Pat. No. 7,940,476 B2, the electrical connections are made with a conventional flex cable and the mechanical connections are made with screw fasteners. These approaches in the art have some drawbacks. A screwdriver is required to tighten the machine screws in U.S. Pat. No. 7,915,789 B2 which can loosen with use to cause an unreliable electrical contact. The costs of the flex cable and connectors disclosed in U.S. Pat. No. 7,940,476 B2 can be significant.

The present disclosure provides electrical interconnects, such as quick-connect terminals, for dielectric elastomer transducers. The electrical interconnects enable the transducer to be electrically coupled to external systems. The terminals provide both electrical and mechanical connection. A non-limiting illustration of a quick-connect dielectric elastomer transducer is provided by terminals that interface the dielectric elastomer transducer with male connector pins.

SUMMARY OF THE INVENTION

In one embodiment, a dielectric elastomer transducer comprises a first end and a second end, a first electrical terminal connected to the first end of the dielectric elastomer transducer, and a second electrical terminal connected to the second end of the dielectric elastomer transducer.

In another embodiment, a system comprises a solid dielectric elastomer transducer roll comprising a first end and a second end, a first electrical terminal connected to the first end of the solid dielectric elastomer transducer roll, a second electrical terminal connected to the second end of the solid dielectric elastomer transducer roll, a substrate, a conductive flexure comprising one end attached to the substrate and another end configured to receive a load, a first electrical connector pin attached to the flexure to receive the first electrical terminal, and a second electrical connector pin attached to the substrate to receive the second electrical terminal.

In yet another embodiment, a system comprises a solid dielectric elastomer transducer roll comprising a first end and a second end, a first electrical terminal connected to the first end of the solid dielectric elastomer transducer roll, a second electrical terminal connected to the second end of the solid dielectric elastomer transducer roll, a first substrate comprising a first electrical connecter pin to receive the first electrical terminal, a second substrate comprising a second electrical connector pin to receive the second electrical terminal, and a living hinge flexibly coupling the first and second substrates. At least one of the first and second substrates is movable in response to energizing the solid dielectric elastomer transducer roll.

These and other features and advantages of the invention will become apparent to those persons skilled in the art upon reading the details of the invention as more fully described below. In addition, variations of the processes and devices described herein include combinations of the embodiments or of aspects of the embodiments where possible are within the scope of this disclosure even if those combinations are not explicitly shown or discussed.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention is best understood from the following detailed description when read in conjunction with the accompanying drawings. To facilitate understanding, the same reference numerals have been used (where practical) to designate similar elements are common to the drawings. Included in the drawings are the following:

Fig. 1 illustrates a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 2 illustrates tension σ_p that accumulates when removing film from a liner while winding a hollow rolled dielectric elastomer transducer;

Fig. 3 illustrates radial stress ΔP developed in the hollow dielectric elastomer transducer rolls shown in Fig. 2 caused by the tension σ_p;

Fig. 4 is a graphical illustration depicting the accumulation of radial stress ΔP in the hollow dielectric elastomer transducer rolls shown in Fig. 2 as additional wraps are added to the hollow rolled dielectric elastomer transducer;

Fig. 5 illustrates inner windings of a hollow dielectric elastomer transducer rolls that have collapsed under the accumulated radial stress P imposed by tension σ_p in the outer windings;

Fig. 6 illustrates a cylindrical solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Figs. 7A-7K illustrate a manufacturing process for turning an electroded dielectric film laminate into a solid dielectric elastomer transducer roll, as shown in Figs. 7I and 7K in accordance with one embodiment of the present invention, where:

Fig. 7A illustrates lamination of dielectric films in accordance with one embodiment of the present invention;

Fig. 7B illustrates cutting a frame away from the dielectric film laminate in accordance with one embodiment of the present invention;

Fig. 7C illustrates removal of the frame from the dielectric film laminate in accordance with one embodiment of the present invention;

Fig. 7D illustrates mounting a carrier plate with the dielectric film laminate on a rolling machine in accordance with one embodiment of the present invention;

Fig. 7E illustrates the process of rolling the dielectric film laminate by moving the carrier plate under a counter rotating scrub roller into a solid roll of dielectric elastomer film in accordance with one embodiment of the present invention;

Fig. 7F illustrates the process of rolling the dielectric film laminate shown in Fig. 7E towards the end of the process in accordance with one embodiment of the present invention;

Fig. 7G illustrates the carrier plate retracting after the rolling process is complete in accordance with one embodiment of the present invention;

Fig. 7H illustrates transfer of a solid dielectric elastomer transducer roll to a cutting fixture for segmenting the roll into individual solid dielectric elastomer transducer rolls shown in Fig. 7G in accordance with one embodiment of the present invention;

Fig. 7I illustrates the solid dielectric elastomer transducer roll segmented into individual solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention;

Fig. 7J illustrates application of conductive adhesive into a terminal cup for electrically attaching to ends of the solid dielectric elastomer transducer rolls shown in Figs. 7H and 7I in accordance with one embodiment of the present invention;

Fig. 7K illustrates attaching and curing the terminal cups onto the ends of the solid dielectric elastomer transducer roll shown in Fig. 1 in accordance with one embodiment of the present invention;

Fig. 8 is a detail view of the rolling machine used in steps illustrated in Figs. 7D-F in accordance with one embodiment of the present invention;

Fig. 9 is a detail view of the cutting fixture for segmenting the solid dielectric elastomer transducer roll into individual solid dielectric elastomer transducer rolls shown in Figs. 7H and 7J in accordance with one embodiment of the present invention;

Fig. 10 is an end view of an individual segmented solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention after segmentation and prior to exposing the end to a solvent;

Fig. 11 is an end view of an individual segmented solid dielectric elastomer transducer roll after the application of a solvent to cause local swelling and separation of the layers in accordance with one embodiment of the present invention;

Fig. 12 illustrates a motion control system for controlling the rolling process of rolling up a solid dielectric elastomer transducer roll with a carrier plate under a scrub roller as illustrated in Figs. 7D-F and Fig. 8 in accordance with one embodiment of the present invention;

Fig. 13 illustrates a simplified motion control system for the rolling process illustrated in Figs. 7D-F and Fig. 8 where slip can occur between the scrub roller and a growing solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 14 illustrates a textile covering positioned over an outside surface of the scrub roller illustrated in Fig. 13 in accordance with one embodiment of the present invention;

Fig. 15 is a detailed view of the textile covering illustrated in Fig. 14 in accordance with one embodiment of the present invention;

Fig. 16 illustrates circumferential lengthening of outer layers of solid dielectric elastomer transducer roll caused by rolling a pre-strained dielectric elastomer film with excessive pre-strain during the rolling process;

Fig. 17 illustrates a wrinkle mechanism in the loosely packed space between individual solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention;

Fig. 18 illustrates an electrode pattern with overlap regions to provide support in bands between solid dielectric elastomer transducer rolls to prevent wrinkles that would otherwise start in the overlapping regions;

Fig. 19 illustrates a non-limiting example fixture for positioning electrical terminal caps on ends of a solid dielectric elastomer transducer roll during curing;

Fig. 20 illustrates a derivation model of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 21 is a graphical illustration depicting force provided by each additional ring in a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 22 is a graphical illustration depicting capacitance change versus axial displacement of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 23 is a graphical illustration depicting blocked force versus applied voltage response of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 24 is a graphical illustration depicting blocked force versus axial displacement showing the difference between the solid dielectric elastomer transducer roll in compression versus tension in accordance with one embodiment of the present invention;

Fig. 25 is a graphical illustration of blocked force versus longitudinal displacement showing the difference between the solid dielectric elastomer transducer roll in compression versus tension in accordance with one embodiment of the present invention;

Fig. 26 is a graphical representation of stiffness of solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention;

Fig. 27 illustrates a solid dielectric elastomer transducer roll in flat roll mode where the roll is placed under compression in a radial direction rather than in an axial direction in accordance with one embodiment of the present invention;

Fig. 28 illustrates a geometric model of a solid dielectric elastomer transducer roll in flat roll mode where the roll is placed under compression in a radial direction in accordance with one embodiment of the present invention;

Fig. 29 is a graphical illustration depicting stretch ratio versus percent compression in a radial direction of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 30 illustrates a static equilibrium diagram of a solid dielectric elastomer transducer roll in flat roll mode under static load in accordance with one embodiment of the present invention;

Fig. 31 is a graphical illustration depicting capacitance versus compression in a radial direction of a solid dielectric elastomer transducer roll in flat roll mode in accordance with one embodiment of the present invention;

Figs. 32A, 32B, 32C and 32D illustrate a solid dielectric elastomer transducer roll under increasing compression force in a radial direction in accordance with one embodiment of the present invention;

Fig. 33 illustrates a finite element analysis model of a solid dielectric elastomer transducer roll undergoing radial compression in accordance with one embodiment of the present invention;

Fig. 34 illustrates the delamination of a solid dielectric elastomer transducer roll undergoing radial compression in accordance with one embodiment of the present invention;

Fig. 35 illustrates an exploded view of a quick-connect solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 36 is a detail view of an electrical quick-connect terminal shown in Fig. 35 in accordance with one embodiment of the present invention;

Fig. 37 illustrates a quick-connection system for quick-connecting solid dielectric elastomer transducer rolls to a substrate, such as a printed circuit board, and conductive flexure in accordance with one embodiment of the present invention;

Fig. 38 illustrates a solid dielectric elastomer transducer roll with female quick-connect terminals in the context of a printed circuit board substrate in accordance with one embodiment of the present invention;

Fig. 39 illustrates a ring connect solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 40 illustrates an alternative ring connect solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention.

Fig. 41 illustrates a metal component for manufacturing the ring connect terminals for a solid dielectric elastomer transducer roll shown in Fig. 40 in accordance with one embodiment of the present invention;

Figs. 42A-42G illustrate a process for manufacturing the ring connect terminal for a solid dielectric elastomer transducer roll shown in Fig. 40 in accordance with one embodiment of the present invention, where:

Fig. 42A illustrates a metal sheet defining apertures that will serve as the ring portion of the ring connect terminal for the solid dielectric elastomer transducer roll shown in Fig. 40 in accordance with one embodiment of the present invention;

Fig. 42B illustrates a metal part stamped out from the metal sheet shown in Fig. 42A in accordance with one embodiment of the present invention;

Fig. 42C illustrates a 90° fold up of the four tabs of the metal component shown in Fig. 42B in the direction of the arrows in accordance with one embodiment of the present invention;

Fig. 42D illustrates a 180° over fold of the four tabs of the metal component shown in Fig. 42C in the direction indicated by the arrows in accordance with one embodiment of the present invention;

Fig. 42E illustrates a 90° down fold of the four tabs of the metal component shown in Fig. 42D in the direction indicated by the arrows in accordance with one embodiment of the present invention;

Fig. 42F is a finished electrical terminal manufactured according with the steps depicted in Figs. 42A-E in accordance with one embodiment of the present invention;

Fig. 42G illustrates an assembled ring connect solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention;

Fig. 42H illustrates the assembled ring connect solid dielectric elastomer transducer roll shown in Fig. 42G with mounting fasteners provided through corresponding rings of the assembled electrical terminal in accordance with one embodiment of the present invention;

Fig. 43 illustrates a quick-connect dielectric elastomer transducer roll in combination with a living hinge coupling two substrates in accordance with one embodiment of the present invention;

Fig. 44 illustrates the quick-connect dielectric elastomer transducer roll in combination with the living hinge coupling two substrates shown in Fig. 43 configured as a positioner in accordance with one embodiment of the present invention;

Fig. 45 illustrates the quick-connect dielectric elastomer transducer roll in combination with the living hinge coupling two substrates shown in Fig. 43 configured as an aileron in accordance with one embodiment of the present invention;

Fig. 46 illustrates the quick-connect dielectric elastomer transducer roll in combination with the living hinge coupling two substrates shown in Fig. 43 configured as a flow restrictor valve in accordance with one embodiment of the present invention;

Fig. 47 illustrates the quick-connect dielectric elastomer transducer roll in combination with the living hinge coupling two substrates shown in Fig. 43 configured as a pump in accordance with one embodiment of the present invention;

Fig. 48 is an exploded view of a compression dielectric elastomer transducer roll comprising a dielectric elastomer transducer roll and electrical terminals coupled to each end of the transducer roll in accordance with one embodiment of the present invention; and

Fig. 49 is a perspective view of the assembled compression dielectric elastomer transducer roll comprising the electrical terminals attached to each end of the each end of the dielectric elastomer transducer roll by a conductive adhesive in accordance with one embodiment of the present invention.

Variation of the invention from that shown in the figures is contemplated.

DETAILED DESCRIPTION OF THE INVENTION

Examples of electroactive polymer devices and their applications are described, for example, in U.S. Pat. Nos. 6,343,129; 6,376,971; 6,543,110; 6,545,384; 6,583,533; 6,586,859; 6,628,040; 6,664,718; 6,707,236; 6,768,246; 6,781,284; 6,806,621; 6,809,462; 6,812,624; 6,876,135; 6,882,086; 6,891,317; 6,911,764; 6,940,221; 7,034,432; 7,049,732; 7,052,594; 7,062,055; 7,064,472; 7,166,953; 7,199,501; 7,199,501; 7,211,937; 7,224,106; 7,233,097; 7,259,503; 7,320,457; 7,362,032; 7,368,862; 7,378,783; 7,394,282; 7,436,099; 7,492,076; 7,521,840; 7,521,847; 7,567,681; 7,595,580; 7,608,989; 7,626,319; 7,750,532; 7,761,981; 7,911,761; 7,915,789; 7,952,261; 8,183,739; 8,222,799; 8,248,750; and in U.S. Patent Application Publication Nos.; 2007/0200457; 2007/0230222; 2011/0128239; and 2012/0126959, the entireties of which are incorporated herein by reference.

In various embodiments, the present invention provides various improvements over conventional hollow rolled dielectric elastomer transducers and manufacturing processes for making same. Embodiments of the present invention overcome these drawbacks by winding dielectric elastomer films into a solid roll that does not waste space, and that does not collapse as turns are added. A rolling machine also is disclosed, along with a manufacturing process, materials, and fixtures for manufacturing dielectric elastomer actuator rolls with the machine, as described herein in the detailed description of the invention section of the present disclosure.

In other embodiments, the present invention provides a dielectric elastomer transducer comprising quick-connect terminals for electrically coupling the dielectric elastomer transducer to external systems. The electrical terminals provide both electrical and mechanical connection. A non-limiting example of a quick-connect dielectric elastomer transducer is provided by electrical terminals that interface the dielectric elastomer transducer with male connector pins, such as FASTON quick-connects and terminals by AMP, Inc., for example. The electrical terminal provided in this example comprises two cantilever springs integrated with a cap, all made of an electrically conductive material. The caps are joined to the ends the solid dielectric elastomer transducer roll with conductive adhesive. The spring terminals reversibly engage a male connector pin.

In various embodiments, the present invention provides a dielectric elastomer transducer with quick-connect mounting. An electrically conductive adhesive provides the electrical and mechanical connections of the dielectric elastomer transducer to the terminals that cap it. The terminals comprise cap-like or cup-like regions into which the electrically conductive adhesive can be dispensed. The caps are then attached to the ends of the transducer and the adhesive is cured. A solvent may be added to the electrically conductive adhesive in order to produce a local swelling at the end of the dielectric elastomer transducer where it couples to the adhesive. This swelling separates the layers of the transducer so that the adhesive can penetrate into the interstitial space between layers. Once cured, the inter-digitated layers of adhesive and dielectric provide a connection that is mechanically and electrically robust. The terminals may be configured to adapt the dielectric elastomer transducer to the FASTON connector standard. The quick-connect dielectric elastomer transducer can be mounted on a printed circuit board (PCB)-mountable conductive flexure with one or more male pins sized for female FASTON terminals, for example. The flexure is soldered in an offset and/or angled orientation in order to leave a gap between the male pins that is slightly longer than the rest-length of the dielectric elastomer transducer. Mounting the dielectric elastomer transducer in the gap produces the desired pre-strain. The dielectric elastomer transducer also can be combined with a living hinge where an actuator enables direct movement of a substrate to which the transducer is coupled. The substrate itself thus becomes a component in various systems, such as positioners, ailerons, flow restrictor valves, pumps, among others.

Various embodiments of such electrical interconnect terminals for rolled dielectric elastomer transducer rolls are described hereinbelow in connection with Figs. 35-49. However, prior to describing Figs. 35-49, the present disclosure initially turns to a description of Figs. 1-34 to provide a context for the description that follows.

The various embodiments discussed hereinbelow in connection with Figs. 1-19 provide a dielectric elastomer transducer rolls formed by rolling laminated films into a compact spiral, which will be referred to herein as "solid." Multiple individual solid dielectric elastomer transducer rolls may be produced by segmented cutting of the transducer rolls, where the cutting affords electrical connections to the ends of the rolls. A conductive adhesive formulated with solvent may be used to swell the ends of the roll to improve mechanical and electrical connection of the rolls to the terminals. Also provided is a rolling machine for dielectric elastomer actuators comprised of a scrub roller that counter-rotates with respect to an advancing plate. Another rolling machine is provided in which motion control is simplified by spinning the scrub roller faster than the carrier plate advances. A non-stick textile cover for the scrub roller is provided to minimize adhesion by minimizing contact area through the use of knit threads that can locally deflect to minimize contact stress. An electrode pattern is also provided for transducer rolls in which electrodes overlap to support areas of the roll that could otherwise buckle and initiate wrinkles. Also provided are novel fixtures for cutting the roll and adhering terminals, to be used in conjunction with the rolling machine.

The solid transducer rolls overcome buckling problems that normally would limit the number of turns that can be added to a hollow type transducer roll. Solid transducer rolls also save space that is wasted by the hollow type rolls known in the art. A rolling machine forms solid rolls with geometric tolerances finer than hand-rolling, at greater speed and lower cost. A compliant, textile, non-stick cover for the scrub roller in the machine simplifies motion control and reduces machine cost. An overlapping electrode pattern prevents wrinkles.

Fig. 1 illustrates a solid dielectric elastomer transducer roll **100** in accordance with one embodiment of the present invention. The solid dielectric elastomer transducer roll **100** comprised of two layers of dielectric film **102**, **104**, one of which has been patterned with one or more layers of electrodes **106**, **108** on both sides. The layers of dielectric film **102**, **104** are wound together into a tight solid spiral cylinder. The area **110** in which the electrodes **106**, **108** overlap acts as a dielectric elastomer transducer. Electrical connection to the two plates of the capacitor can be made where the electrodes **106**, **108** meet the ends of the cylinder. The electrodes **106**, **108** are offset relative to each other to provide electrical connection at the ends **112**, **114** of the solid dielectric elastomer transducer roll **100** such that the first electrode **106** is accessible at the top **112** and the second electrode **108** is accessible at the bottom **114** of the transducer **100**. Although in the illustrated embodiment, the solid dielectric elastomer transducer roll **100** has a right circular cylindrical form, other forms are contemplated such as triangular, square, rectangular, among other polyhedral forms.

Fig. 2 illustrates tension σ_p that accumulates when removing film **120** from a liner **122** while winding a hollow **124** rolled dielectric elastomer transducer **126**. Some peeling stress σ_p is unavoidable when removing the film **120** having a thickness "t" from the liner **122**.

Fig. 3 illustrates radial stress ΔP developed in the hollow rolled dielectric elastomer transducer **126** shown in Fig. 2 caused by the tension σ_p created when the film **120** is peeled from the liner **122** (not shown). Radial stress ΔP (pressure) in the compressed layers below must support the tension of each new wrap.

Fig. 4 is a graphical illustration depicting the accumulation of radial stress ΔP in the hollow rolled dielectric elastomer transducer **126** shown in Fig. 2 as additional wraps are added to the hollow rolled dielectric elastomer transducer

126. As more wraps are added the radial stress ΔP (pressure) in the center increases. If the force becomes large enough, the inner layers may delaminate and buckle, like an arch collapsing. As indicated by the radial stress ΔP [Pa] versus radial distance [m] curve **130** in graph **128**, the radial stress ΔP on the innermost layer **132** is much higher than the radial stress ΔP on the outermost layer **134**.

In the context of Figs. 2-4, the peel stress σ_p and strain in a single layer of dielectric film **120** are given below for values typical of a dielectric elastomer coating:

$$\sigma_p = \frac{\sigma_{PEEL}}{t} = \frac{[3.8\ \mathrm{N/m}]}{[80\mathrm{E}-6\ \mathrm{m}]} = 0.048\ \mathrm{MPa} \qquad \text{Eq. 1}$$

$$s = \frac{\sigma_p}{Y} = \frac{[0.048\ \mathrm{MPa}]}{[0.6\ \mathrm{MPa}]} = 0.08 = 8\%\ \text{strain} \qquad \text{Eq. 2}$$

The force balance for a half-wrap of film, as shown in Fig. 3, can be solved for the radial stress ΔP.

$$\sum F_z = -2\sigma_p t\ell + 2r\ell\Delta P = 0 \qquad \text{Eq. 3}$$

$$\Delta P = \frac{\sigma_p t}{r} = \frac{\sigma_{PEEL}}{r} \qquad \text{Eq. 4}$$

The radial stress ΔP in layer "*i*" is due to the accumulated stress of the layers above it as given in the equation below. For typical values of peel stress σ_p on a hollow rolled dielectric elastomer transducer **126** with 1 mm internal radius, the calculated pressures have been plotted in Fig. 4.

$$P_i = \Delta P_i + \sum_{0}^{i-1} \Delta P \qquad \text{Eq. 5}$$

Fig. 5 illustrates inner windings **132** of the hollow rolled dielectric elastomer transducer **126** that have collapsed under the accumulated radial stress P imposed by tension σ_p in the outer windings **134**. This "collapsing of the inner layers" problem with the conventional hollow rolled dielectric elastomer transducer **126** provides the motivation for the present inventors' development of the solid dielectric elastomer transducer roll **100** shown in Fig. 6.

Fig. 6 illustrates a cylindrical solid dielectric elastomer transducer roll **100** in accordance with one embodiment of the present invention. The cylindrical solid dielectric elastomer transducer roll **100** does not exhibit a collapse of the inner layers **136** under the accumulated radial stress *P* imposed by tension σ_p in the outer windings **138**.

Figs. 7A-7K illustrate a manufacturing process for turning an electroded dielectric film laminate **101** into a solid dielectric elastomer transducer roll **178**, as shown in Figs. 7I and 7K in accordance with one embodiment of the present invention. The process rolls the dielectric film laminate **101** into a tight spiral without an opening extending axially in the center of the solid dielectric elastomer transducer roll **178**.

Fig. 7A illustrates a step of the process where two dielectric films **102**, **104** are laminated **150** in accordance with one embodiment of the present invention. The first dielectric film **102** comprises a first electrode layer **106** on a top portion and a second electrode layer **108** on a bottom portion. The first dielectric film **102** with the electrodes **106**, **108** patterned on both sides thereof are held in tension (pre-stressed) in a rigid frame **152**. The first film **102** with the frame **152** is then laminated to the second dielectric film **104** while it is still attached to the liner **154** used to coat it. The electroded dielectric film laminate **101** (not shown in Fig. 7A) comprising the laminated films **102**, **104** is positioned on a carrier plate **156**, which will be used to hold the dielectric film laminate **101** during the rolling process.

Fig. 7B illustrates another step of the process where the frame **152** is cut **158** away from the dielectric film laminate **101** (not shown in Fig. 7B) in accordance with one embodiment of the present invention. The cut path **160** is inside the inner perimeter of the frame **152**.

Fig. 7C illustrates another step of the process where the frame **152** is removed **162** from the dielectric film laminate **101** in accordance with one embodiment of the present invention.

Fig. 7D illustrates another step of the process where the carrier plate **156** with the dielectric film laminate **101** is mounted **164** on a rolling machine **166** in accordance with one embodiment of the present invention. The rolling machine **166** comprises a scrub roller **168**, which rolls up the dielectric film laminate **101**.

Fig. 7E illustrates another step in the process where the dielectric film laminate **101** on the carrier plate **156** is rolled into a solid roll of dielectric elastomer film under a counter rotating **172** scrub roller **168** as the carrier plate **156** is moved **170** in direction **174** by a conveyor or other suitable drive mechanism in accordance with one embodiment of the present invention. As the dielectric film laminate **101** is rolled, it is released from the liner **154**. The process continues until the entire dielectric film laminate **101** is rolled. Fig. 7F illustrates the process of rolling the dielectric film laminate **101** shown in Fig. 7E towards the end of the process in accordance with one embodiment of the present invention.

Fig. 7G illustrates another step of the process where the carrier plate **156** is retracted **176** in direction **177** after the rolling process is complete in accordance with one embodiment of the present invention. As shown, a solid dielectric elastomer transducer roll **178** is provided at the end of this step.

Fig. 7H illustrates another step in the process where the solid dielectric elastomer transducer roll **178** is transferred **180** to a cutting fixture **182** for segmenting the roll **178** with a cutter **184**, such as a blade or slitter, into individual solid dielectric elastomer transducer rolls shown in Fig. 7G in accordance with one embodiment of the present invention.

Fig. 7I illustrates another step in the process where the solid dielectric elastomer transducer roll **178** is segmented **186** into individual solid dielectric elastomer transducer rolls **178a**, **178b**, and **178c** in accordance with one embodiment of the present invention.

Fig. 7J illustrates another step in the process where a conductive adhesive **192** is applied **190** into an electrical terminal **194** having a cup shape for electrically attaching to ends of the solid dielectric elastomer transducer rolls

178a, **178b**, and **178c** shown in FIG. 7H and 7I in accordance with one embodiment of the present invention.

Fig. 7K illustrates another step in the process where terminals **194a₁**, **194a₂** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178a**, terminals **194b₁**, **194b₂** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178b**, and terminals **194c₁**, **194c₂** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178c** in accordance with one embodiment of the present invention.

Fig. 8 is a detail view of the rolling machine **166** used in the steps illustrated in Figs. 7D-G in accordance with one embodiment of the present invention.

Fig. 9 is a detail view of the cutting fixture **182** for segmenting the solid dielectric elastomer transducer roll **178** into individual solid dielectric elastomer transducers rolls **178a**, **178b**, and **178c** shown in Figs. 7h and 7J in accordance with one embodiment of the present invention. The cutting fixture **182** comprises a movable jaw **196** and a fixed jaw **198**. The movable jaw comprises alignment slots **202** and the fixed jaw comprises alignment slots **204**, which are aligned with the alignment slots **202** of the movable jaw **202**. The cutting fixture comprises an aperture for receiving the solid dielectric elastomer transducer roll **178** therein. The movable jaw **196** moves relative to the fixed jaw **198** to define a longitudinal aperture **200** for receiving and holding the solid dielectric elastomer transducer roll **178** in place during the segmenting process. The cutter **184** is advanced through the alignment slots **202** in the movable jaw **196**, through the solid dielectric elastomer transducer roll **178**, and the alignment slots **204** in the fixed jaw **198**. The clamping action of the jaws **196**, **198** also straightens the solid dielectric elastomer transducer roll **178** within the aperture **200** in preparation for segmentation.

Fig. 10 is an end view of an individual segmented solid dielectric elastomer transducer roll **100** in accordance with one embodiment of the present invention after segmentation and prior to exposing the end to a solvent.

Fig. 11 is an end view of an individual segmented solid dielectric elastomer transducer roll **100'** after the application of a solvent to the end to cause local swelling and separation of the layers **206**, **208**, and **210** in accordance with one embodiment of the present invention. This improves penetration of the conductive adhesive **192**, shown in Fig. 7J. During the curing process **196** shown in Fig. 7K, the solvent evaporates, leaving inter-digitated glue that makes a robust electrical and mechanical connection between the capping end-terminal **194** shown in Figs. 7J and 7K and the electrodes **106**, **108** of the solid dielectric elastomer transducer roll **100**. In one embodiment, the electrically conductive adhesive **192** may be formulated with a solvent that swells the ends of the roll **100** to improve mechanical and electrical connection of the rolls **100** to the terminals **194**.

Fig. 12 illustrates a motion control system **212** for controlling the process of rolling the dielectric film laminate **101** into a solid dielectric elastomer transducer roll **178** with the rolling machine **166**. The scrub roller **168** portion of the rolling machine **166** has a radius r_{scrub}. The motion control system **212** may be any electronic processor or digital logic based programmable motion controller configured to control the velocity and direction of rotation of the scrub roller **168** and the velocity and direction of translation of the carrier plate **156** in accordance with the present invention. As previously discussed in connection with Figs. 7D-G, the carrier plate **156** is advanced in direction **174** at velocity V_{plate} while the scrub roller **168** is rotated in a counter direction **172** at velocity V_{scrub}. As the outer surface of the scrub roller **168** contacts the dielectric film laminate **101**, the dielectric film laminate **101** begins to roll up to form the solid dielectric elastomer transducer roll **178**. The solid dielectric elastomer transducer roll **178** grows in diameter until the carrier plate **156** reaches the end of stroke. As matching the speeds of the carrier plate **156** and the scrub roller **168** can improve the rolling process and excess speed on the carrier plate **156** can jam the solid dielectric elastomer transducer roll **178** under the scrub roller **168**. On the other hand, if the solid dielectric elastomer transducer roll **178** is sticky and adheres to the scrub roller **168**, excess velocity on the scrub roller **168** can lift the solid dielectric elastomer transducer roll **178** off the liner **154** and wrap it around the scrub roller **168**. Each of these situations can result in damaging the solid dielectric elastomer transducer roll **178**. Accordingly, the motion control system **212** may be programmed in accordance with the following considerations to provide various levels of control ranging from the simple to the complex.

By way of example, the motion control system **212** may be configured in various forms from a relatively simple control system to a more complex control system. In one embodiment, the control system **212** may be configured to match the velocity of the carrier plate **156** V_{plate} in direction **174** and the velocity of the scrub roller **168** V_{scrub} in direction **172** such that $|V_{plate}| = |V_{scrub}|$. In another embodiment, the motion control system **212** may be configured to account for the velocity of the transducer roll V_{roll} in direction **214** as a new variable to compensate for the movement of the center of the solid dielectric elastomer transducer roll **178** as the diameter grows such that $|V_{plate}| - |V_{roll,\,x}| = |V_{scrub}|$. In yet another embodiment, the motion control system **212** may be configured to account for a stretch coefficient "k" to compensate for stretching of the dielectric film laminate **101** as it is peeled from the liner **154** such that $|V_{plate}| - |V_{roll,\,x}| = k|V_{scrub}|$. Finally, in another embodiment, the motion control system **212** may be configured to employ at least one sensor to sense force and provide a closed loop feedback mechanism to the motion control system **212**.

The complexity of the various configurations of the motion control system **212** outlined above can be avoided if the solid dielectric elastomer transducer roll **178** does not stick to the scrub roller **168**. In that case, the scrub roller **168** can be rotated quickly relative to the carrier plate **156** so that it always brushes the solid dielectric elastomer transducer roll **178** back, as illustrated below in Fig. 13.

Fig. 13 illustrates a simplified implementation of the motion control system **212** that is configured to account for slip **218** that can occur between the scrub roller **168** and the growing diameter of the solid dielectric elastomer transducer roll **178**. Accordingly, the motion control system **212** may be configured to control the velocity of the carrier plate **156** V_{plate} in direction **174** relative to the velocity of the scrub roller **168** V_{scrub} in direction **172** such that $|V_{plate}| << |V_{scrub}|$.

Fig. 14 illustrates a textile covering **222** positioned over an outside surface of the scrub roller **168** illustrated in Fig. 13. The textile covering **222** is made of a non-stick material to provide non-stick contact between the scrub roller **168** and the solid dielectric elastomer transducer roll **178** in accordance with one embodiment of the present invention. Fig. 15 is a detailed view of the textile covering **222** provided over the outside surface of the scrub roller **168** as illustrated in Fig. 14 in accordance with one embodiment of the present invention. With reference to Figs. 14 and 15, a suitable non-stick contact between the scrub roller **168** and the solid dielectric elastomer transducer roll **178** may be achieved by covering the scrub roller with a knit fabric **222**. The knit fabric **222** minimizes the dielectric-to-roller contact area and thus minimizes the adhesion force. The knit fabric **222** insures that the contact area is primarily empty air. Because the knit fibers can deflect, stress concentrations on the solid dielectric elastomer transducer roll **178** film are smaller than those provided by, for example, a roller made of a hard grooved plastic. This protects the solid dielectric elastomer transducer roll **178** from mechanical damage during the rolling process.

Fig. 16 illustrates circumferential lengthening of outer layers of the dielectric elastomer transducer roll **224** caused by rolling a pre-strained dielectric elastomer film with excessive pre-strain during the rolling process. An advantage of the rolling process according to one embodiment of present invention is the ability to apply a minimum of pre-strain to the dielectric elastomer transducer roll during the rolling process. In one aspect, the minimum pre-strain is only the pre-strain required for peeling the dielectric film laminate from the liner during the rolling process. This is useful because excessive pre-strain can cause relaxation of longitudinal pre-strain that can lead circumferential lengthening of the outer layers **226** of the transducer roll **224**. As shown in Fig. 16, the outer layers **224** of the transducer roll **224** have delaminated in some places and not others, causing buckling. So, even if the inner layers of the transducer roll **224** do not buckle, the outer layers **224** may slip. This problem with pre-strain may be minimized by rolling up the unstrained dielectric film laminate directly from the liner on which it was coated in accordance with one embodiment of the present invention.

Fig. 17 illustrates a wrinkling mechanism in the loosely packed space between individual electroded solid dielectric elastomer transducer rolls **178a**, **178b** in accordance with one embodiment of the present invention. The bands **226** of un-electroded film in between electroded solid dielectric elastomer transducer rolls **178a, 178b** can cause rolling problems. The dielectric layers in these bands **226** are supported only loosely by underlying layers, and can therefore buckle **228** in response to non-uniform rotation along the length of the roll **168**. This is illustrated in Fig. 17, where the electroded solid dielectric elastomer transducer rolls **178a, 178b** have undergone slightly different rotation relative to the rotation rates of the band **226** therebetween. The electroded solid dielectric elastomer transducer rolls **178a, 178b** portions of the transducer roll **178** are supported by the electrodes whereas the band **226** therebetween is unsupported and can buckle. The force of peeling the laminate film from the liner can also produce V-shaped wrinkles in these bands **226**. The wrinkles propagate along the length of the roll as turns are added, which is undesirable. To minimize this problem, the regions of adjacent electroded solid dielectric elastomer transducer rolls **178a, 178b** can be overlapped as described hereinbelow in Fig. 18.

Fig. 18 illustrates an electrode pattern **230** with overlapping regions **232** to provide support in bands between adjacent (juxtaposed) layers of electrode materials to be segmented into individual solid dielectric elastomer transducer rolls **178a, 178b**. The electrode pattern **230** prevents wrinkles that would otherwise start in the overlapping regions **232** and also enables segmenting the roll into individual solid dielectric elastomer transducer rolls **178a, 178b**. The first dielectric film **102** is shown delaminated from the second dielectric film **104** for illustration purposes. As shown, the first and second electrodes **106, 108** are applied on opposite sides of the dielectric film **102** in a staggered (offset) manner to create overlapping regions **232**. A first side of the dielectric film **102** includes multiple layers of electrode **106_1**, **106_2**, and **106_3** material juxtaposed relative to each other and spaced apart by a gap **235** therebetween. A second side of the dielectric film **102** includes multiple layers of electrode **108$_1$**, **108$_2$**, and **108$_3$** material juxtaposed relative to each other and spaced apart by a gap **237** therebetween. The layers of electrodes **106$_1$**, **106$_2$**, and **106$_3$** on the first side of the dielectric film **102** are offset or staggered from the layers of electrodes **108$_1$**, **108$_2$**, **108$_3$** on the second side of the dielectric film **102** to create the overlapping regions **232$_1$**, **232$_2$** and so on. The second dielectric film **104** is still releasably attached to the liner **154** which is attached to the carrier plate **156**. As previously discussed, the first dielectric film **102** with the electrodes **106$_1$**, **106$_2$**, **106$_3$**, **108$_1$**, **108$_2$**, and **108$_3$** formed on each side thereof is laminated to the second dielectric film **104** on the liner **154**.

Fig. 19 illustrates a non-limiting example of fixture **234** for positioning the electrical terminal caps **194a$_1$**, **194a$_2$** on ends of a solid dielectric elastomer transducer roll **178a** during curing. The fixture **234** comprises a slot **236** to receive the solid dielectric elastomer transducer roll **178a** and blade terminals **238** for receiving the electrical terminal caps **194a$_1$**, **194a$_2$**. As previously discussed in Figs.7I and 7J, the electrical terminal caps **194a$_1$**, **194a$_2$** are filled with an electrically conductive adhesive **192**. The ends of the solid dielectric elastomer transducer roll **178a** are then inserted into each one of the conductive adhesive **192** filled electrical terminal caps **194a$_1$**, **194a$_2$** and then a cam **240** is used to apply a clamping force to the assembled solid dielectric elastomer transducer roll **178a** and conductive adhesive **192** filled electrical terminal caps **194a$_1$**, **194a$_2$** during the curing process.

Having described embodiments of solid dielectric elastomer transducer rolls, methods for manufacturing the solid dielectric elastomer transducer rolls, and machines for manufacturing the solid dielectric elastomer transducer rolls, the specification now turns to a description of capacitance models for a solid dielectric elastomer transducer roll in axial tension and compression modes as well as radial (flat mode) compression modes.

Fig. 20 illustrates a derivation model **300** of a solid dielectric elastomer transducer roll **302**, similar to the solid dielectric elastomer transducer roll **100**, **178** described above, in accordance with one embodiment of the present invention. The diagram depicted in Fig. 20 shows the solid dielectric elastomer transducer roll **302** in a relaxed state and also shows a comparison of an outer ring **304** of the solid dielectric elastomer transducer roll **302** in a relaxed state and the outer ring **304'** when it is in tension. The solid dielectric elastomer transducer roll **302** has a length x_o when the solid dielectric elastomer transducer roll **302** is not in tension and a length $(x_o + x)$ or λx_o when tensioned. The model assumes the spiral equivalent of N rings and the volume inside each ring is conserved due to the incompressibility of the rings within and the volume of the ring itself is conserved. Each ring is an annular capacitor and the total capacitance is the sum of the all N rings.

The main equations developed in accordance with the model are:

Effective Number of Rings in Roll	$N = \left(\frac{y_0}{t_0 \pi}\right)^{1/2}$	Eq. 6
Blocked Force	$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1}$	Eq. 7
Spring Rate	$k = Y(y_0 + y_p)t_0 / (x_0 + x_p)$	Eq. 8
Free Stroke	$\Delta x \cong \frac{F_{total}}{k}$	Eq. 9
Roll Diameter	$D_{composite} = 2N(t_{film} + t_{elec})$	Eq. 10

A Spiral Is Equivalent To N Rings

The outer ring **304** of the un-tensioned solid dielectric elastomer transducer roll **302** has an outer radius b_o that is equal to the N rings of thickness t_o:

$$b_0 = Nt_0 \qquad \text{Eq. 11}$$

The area of the film is same whether it is laid out flat ($y_{0}l$) or rolled up into a circle (πb^2_o):

$$A_{film} = y_0 l = \pi b_0^2 \qquad \text{Eq. 12}$$

$$y_o t_0 = \pi \left(N t_0\right)^2 \qquad \text{Eq. 13}$$

$$N t_0 = \left(\frac{y_0 t_0}{\pi}\right)^{1/2} \qquad \text{Eq. 14}$$

$$N = \left(\frac{y_0}{t_0 \pi}\right)^{1/2} \qquad \text{Eq. 15}$$

<u>Volume Inside Each Ring Is Conserved</u>

$$Volume_0 = Volume(\lambda) \qquad \text{Eq. 16}$$

$$Volume_0 = \pi a_0^2 x_0 \qquad \text{Eq. 17}$$

$$Volume(\lambda) = \pi a^2 \qquad \text{Eq. 18}$$

$$\pi a_0^2 x_0 = \pi a^2 \lambda x_0 \qquad \text{Eq. 19}$$

$$a_0^2 = a^2 \lambda \qquad \text{Eq. 20}$$

$$a^2 = \lambda^{-1} a_0^2 \qquad \text{Eq. 21}$$

$$a = \lambda^{-1/2} a_0 \qquad \text{Eq. 22}$$

<u>Volume Of Each Ring Itself Is Conserved</u>

$$Volume_0 = Volume(\lambda) \qquad \text{Eq. 23}$$

$$Volume_0 = \pi\left(b_0^2 - a_0^2\right)x_0 \qquad \text{Eq. 24}$$

$$Volume(\lambda) = \pi\left(b^2 - a^2\right)\lambda x_0 \qquad \text{Eq. 25}$$

$$\pi\left(b_0^2 - a_0^2\right)x_0 = \pi\left(b^2 - a^2\right)\lambda x \qquad \text{Eq. 26}$$

$$\left(b_0^2 - a_0^2\right) = \left(b^2 - a^2\right)\lambda \qquad \text{Eq. 27}$$

$$b^2 = \lambda^{-1}\left(b_0^2 - a_0^2\right) + a^2 \qquad \text{Eq. 28}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + a^2\right)^{1/2} \qquad \text{Eq. 29}$$

Using the results from Eq. 22, this can be simplified further:

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + a^2\right)^{1/2} \qquad \text{Eq. 30}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + \left(\lambda^{-1/2} a_0\right)^2\right) \qquad \text{Eq. 31}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2\right) + \lambda^{-1} a_0^2\right)^{1/2} \qquad \text{Eq. 32}$$

$$b = \left(\lambda^{-1}\left(b_0^2 - a_0^2 + a_0^2\right)\right)^{1/2} \qquad \text{Eq. 33}$$

$$b = \left(\lambda^{-1} b_0^2\right)^{1/2} \qquad \text{Eq. 34}$$

$$b = \lambda^{-1/2} b_0 \qquad \text{Eq. 35}$$

__**Capacitance Of The Annular Capacitor**__

Initially the capacitance is:

$$C_0 = \frac{2\pi\varepsilon\varepsilon_0 x_0}{\ln\left(\frac{b_0}{a_0}\right)} \qquad \text{Eq. 36}$$

After it has been stretched it becomes longer, so that the length becomes (λx_0) and the radii (a and b) are no longer the initial radii (a_0 and b_0):

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0 \lambda}{\ln\left(\frac{b}{a}\right)} \qquad \text{Eq. 37}$$

Substituting results from Equations 22 and 35 allows the stretched capacitance to be expressed in terms of initial geometry.

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0 \lambda}{\ln\left(\frac{b}{a}\right)} \qquad \text{Eq. 38}$$

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0 \lambda}{\ln\left(\frac{\lambda^{-1/2} b_0}{\lambda^{-1/2} a_0}\right)} \qquad \text{Eq. 39}$$

$$C(\lambda) = \frac{2\pi\varepsilon\varepsilon_0 x_0}{\ln\left(\frac{b_0}{a_0}\right)} \lambda \qquad \text{Eq. 40}$$

Capacitance is expected to vary linearly with the stretch ratio. To get the force each ring provides note that electrostatic force depends on the change in capacitance with excursion from rest.

$$F_{elec} = V^2 \frac{\partial C}{\partial x} \quad \text{Eq. 41}$$

Note that the stretch ratio can be expressed in terms of that excursion from rest.

$$\lambda = 1 + \frac{x}{x_0} \quad \text{Eq. 42}$$

$$C(x) = \frac{2\pi\varepsilon\varepsilon_0 x_0}{\ln\left(\frac{b_0}{a_0}\right)}\left(1 + \frac{x}{x_0}\right) \quad \text{Eq. 43}$$

The derivative cancels out the initial length of the actuator (x_0). This means that the electric force will not be predicted to change as the length of the actuator changes.

$$\frac{\partial C}{\partial x} = \frac{2\pi\varepsilon\varepsilon_0 x_0}{x_0 \ln\left(\frac{b_0}{a_0}\right)} \quad \text{Eq. 44}$$

$$\frac{\partial C}{\partial x} = \frac{2\pi\varepsilon\varepsilon_0}{\ln\left(\frac{b_0}{a_0}\right)} \quad \text{Eq. 45}$$

$$F_{elec} = (1/2)V^2 \frac{\partial C}{\partial x} = \frac{V^2 \pi\varepsilon\varepsilon_0}{\ln\left(\frac{b_0}{a_0}\right)} \quad \text{Eq. 46}$$

Note that the outer radius b_0 is just the inner radius (a_0) plus the thickness of the film (t_0).

$$F_{elec} = (1/2)V^2 \frac{\partial C}{\partial x} = \frac{V^2 \pi\varepsilon\varepsilon_0}{\ln\left(\frac{a_0 + t}{a_0}\right)} \quad \text{Eq. 47}$$

To get the total force we must sum up the contributions of all N of the rings. Note that each ring has an outer radius that is one thickness greater than the inner radius.

$$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} \left(\ln\left(\frac{(n+1)t_0}{n t_0} \right) \right)^{-1}$$ Eq. 48

Canceling like terms

$$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} \left(\ln\left(\frac{(n+1)}{n} \right) \right)^{-1}$$ Eq. 49

$$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1}$$ Eq. 50

The thickness of a layer has not, in fact, disappeared. It appears in the upper limit of the series (N). The total number of layers (N) can be expressed simply in terms of the initial geometry.

$$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1} \text{, where } N = \left(\frac{y_0}{t_0 \pi} \right)^{1/2}$$ Eq. 51

The expected capacitance change is the force expression (Eq. 51) without the Voltage term $\frac{1}{2}V^2$:

$$\frac{\partial C}{\partial x} = 2\pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1} \text{, where } N = \left(\frac{y_0}{t_0 \pi} \right)^{1/2}$$ Eq. 52

Both of the above are measurable. A candidate example geometry includes 48.8603 rings or approximately 49 rings. Accordingly, for approximately 49 rings, a predicted force and capacitance change rate is:

$$F_{elec} = \pi \varepsilon \varepsilon_0 V^2 \sum_{n=1}^{N} (\ln(n+1) - \ln(n))^{-1}$$ Eq. 53

$$F_{elec} = \pi [2.85][8.854\text{E-}12 \text{ F/m}][1200\text{V}]^2 \sum_{n=1}^{49} (\ln(n+1) - \ln(n))^{-1}$$ Eq. 54

$$\frac{\partial C}{\partial x} = \pi[2.85][8.854\text{E-}12\ \text{F/m}]\sum_{n=1}^{49}\left(\ln(n+1)-\ln(n)\right)^{-1} \qquad \text{Eq. 55}$$

Fig. 21 is a graphical illustration **306** depicting force **308** provided by each additional ring in a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. Force [N] is shown along the vertical axis and ring number is shown along the horizontal axis. Accordingly, the additional force **308** provided by each ring grows linearly with the ring number. This is in conformity with expectations, as the area of each ring scales linearly with circumference. The total force of 0.1426 N approximately matches the total force for a model based on simpler assumptions: i.e., dielectric stacked, not rolled, (Eq. 56).

The calculation for parallel layers, not rolled up provides:

$$F_{elec} = (1/2)V^2\frac{\partial C}{\partial x} = (1/2)\frac{V^2\varepsilon\varepsilon_0 y_i}{z_i} \qquad \text{Eq. 56}$$

Accordingly, the model provides a measurable prediction for capacitance change:

dC/dx=Ftot/(0.5*(1200^2)) = 1.9806e-007 [F/m]

Fig. 22 is a graphical illustration **310** depicting capacitance change versus axial displacement of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. Capacitance C[F] is shown along the vertical axis and axial displacement x[mm] is shown along the horizontal axis. The data substantially agrees with the model. In the graphical illustration **310** capacitance change in two solid dielectric elastomer transducer rolls with 10 mm active length are depicted by curves **312** and 14 mm total length are depicted by curves **314**. A peak *dC/dx* of 8.91E-8 F/m was observed when the transducer rolls were in tension. Although this is just (8.9E-8/1.9806E-7) = 44% of the expected *dC/dx*, the active area did not really experience all of the displacement. Some of the displacement was taken up by deformation in the passive 4 mm of the solid dielectric elastomer transducer roll. To estimate the effect that this compliance will have on measured *dC/dx*, two cases may be considered (1) negligible electrode stiffness and (2) a relatively large electrode stiffness, for example equal to the film stiffness.

<u>**Case 1 – Electrode Negligible**</u>

Assuming that the active and passive areas have equal stiffness (that is, electrode is negligible), then the observed dC/dx is scaled by (total:active = 14 mm:10 mm). The observed dC/dx is then (14/10)*([8.9E-8 F/m]/[1.9806E-7 F/m]) = 63% of expected.

<u>**Case 2 – Electrode Stiff**</u>

If the stiffness of the electrode is not negligible, then it must be taken into account. In planar devices, it may be observed that a standard electrode coating on two sides of a film increases pseudo-DC stiffness of a film by an amount equivalent to multiplying Young's modulus of the film by two. The roll is comprised of two compliances in series. The active Area is 10 mm long and has two layers of electrode, and the passive 4mm long and has one layer.

$$s1=0.010\text{m}/(2^*\text{Y\_film}^*\text{Area})$$

$$s2=0.004\text{m}/(1.5^*\text{Y\_film}^*\text{Area})$$

And the proportion of deformation occurring in the active area is

$$\Delta x_1/\Delta x_{tot}=(5/(5+2.6667)=0.6522.$$

Scaling by this factor, dC/dx is found to be ((1/0.6522)*[8.9E-8 F/m])/[1.98E-7 F/m]=69% of expected. In the absence of control data measuring electrode stiffness directly, this provides the best estimate of how the observed capacitance change relates to the nested ring model.

Fig. 23 is a graphical illustration **316** depicting blocked force versus applied voltage response **318** of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. The response **318** was obtained by measuring a sample on an INSTRON instrument for measuring tension / compression, made by INSTRON of Norwood, MA, at 1200V and a blocked force at 1200V of 0.102N was observed, as shown in Fig. 23. The blocked force measurement is ([0.102 N]/[0.1363 N])=74% of the model prediction.

Fig. 24 is a graphical illustration **320** depicting blocked force versus axial displacement demonstrating the difference between the solid dielectric elastomer transducer roll in compression versus tension in accordance with one embodiment of the present invention. Measuring blocked force on the INSTRON instrument, shows a clear difference between using the solid dielectric elastomer transducer roll in compression **322** versus tension **324**, consistent with the slope differences observed in *dC/dx*. In compression, layers of the solid dielectric elastomer transducer roll undergo localized buckling rather than uniform compression. This occurs at forces (0.1 N) lower than the Euler buckling limit for the entire column (1.5N calculated, 1.4 N observed).

Fig. 25 is a graphical illustration **326** of blocked force versus longitudinal displacement showing the difference between the solid dielectric elastomer transducer roll in compression **328** versus tension **330** in accordance with one embodiment of the present invention.

Fig. 26 is a graphical representation **332** of stiffness of solid dielectric elastomer transducer rolls in accordance with one embodiment of the present invention. The simplest prediction of stiffness for the solid rolls is to neglect electrode stiffness and the rigid boundary conditions:

$$k_{simple}=YA/l = [0.6E6\ \text{Pa}]*([2*160E\text{-}3\ \text{m}]*[40E\text{-}6\ \text{m}])/[14E\text{-}3\ \text{m}]=548.6\ \text{N/m}.$$

This estimate of the stiffness is relatively good. Observed stiffness is higher than theoretical by only 6-13% in these two samples.

$$[582\ \text{N/m}\ ,\ 621\ \text{N/m}]./[548.6\ \text{N/m}] = [1.06\ 1.13]$$

This suggests that the effect of the electrode on the stiffness of the solid dielectric elastomer transducer rolls is relatively small and not the 2x factor in the active area that was considered in the dC/dx calculation above. It appears a better assumption may be to treat the electrode stiffness as negligible and to estimate that the observed dC/dx is about 63% of that expected by the model.

Fig. 27 illustrates a solid dielectric elastomer transducer roll **400** in flat roll mode where the roll **400** is placed under compression **402** in a radial direction rather than in an axial direction in accordance with one embodiment of the present invention. As shown, a portion of the solid dielectric elastomer transducer roll **400** is clamped between jaws **404a, 404b** such that is compresses the transducer roll **400** radially rather axially. Experimental results indicate that the peak capacitance change dC/dx in radial ("flat roll") mode is approximately 5-times the capacitance change dC/dx in axial mode.

Fig. 28 illustrates a geometric model **410** of a solid dielectric elastomer transducer roll **412** in radial ("flat roll") mode where the roll **412** is placed under compression in a radial direction in accordance with one embodiment of the present invention. The cross-sectional area of the uncompressed roll **412** is depicted as a circle in phantom, whereas the cross-sectional area $A(x)$ of the roll **412'** under radial compression is depicted in solid line as a flattened elongated structure with flat regions in the center over a length l and rounded ends. The model assumes the following:

Long out of plane → Plane strain;

Incompressible → $A(x) = A_0$; and

Flat regions slip → Equal strain around perimeter.

The geometric model for the solid dielectric elastomer transducer roll **412** in radial mode ("flat roll') is described by the following equations:

$$P_0 = \pi x_0 \quad \text{Eq. 57}$$

$$P(x) = 2\ell + \pi(x_0 - x) \quad \text{Eq. 58}$$

$$A_0 = \frac{\pi}{4} x_0^2 \quad \text{Eq. 59}$$

$$A(x) = \ell(x_0 - x) + \frac{\pi}{4}(x_0 - x)^2 \quad \text{Eq. 60}$$

$$A_0 = A(x) \quad \text{Eq. 61}$$

$$\frac{\pi}{4} x_0^2 = \ell(x_0 - x) + \frac{\pi}{4}(x_0 - x)^2 \quad \text{Eq. 62}$$

$$\ell = \frac{\pi\left(x_0^2 - (x_0 - x)^2\right)}{4(x_0 - x)} \quad \text{Eq. 63}$$

$$P(x) = 2\ell + \pi(x_0 - x) \qquad \text{Eq. 64}$$

$$\lambda_p(x) = \frac{P(x)}{P_0} = \frac{P(x)}{\pi x_0} \qquad \text{Eq. 65}$$

$$C = C_0 \lambda_p^2 \qquad \text{Eq. 66}$$

Fig. 29 is a graphical illustration **414** depicting stretch ratio versus percent compression in a radial direction of a solid dielectric elastomer transducer roll in accordance with one embodiment of the present invention. Stretch ration [L/L_0] is shown along the vertical axis and percent compression [x/x_0] is shown along the horizontal axis. The curve **416** shows non-linear behavior of stretch ration versus percent compression.

Fig. 30 illustrates a static equilibrium diagram **418** of a solid dielectric elastomer transducer roll **420** in radial compression ("flat roll") mode under static load in accordance with one embodiment of the present invention. Static equilibrium is defined as follows:

$$F_{elec} + F_S + F_L = 0 \qquad \text{Eq. 67}$$

where F_{elec} is electric force, F_S is spring force and F_L is an external load. The electric force is proportional to the capacitance change dC/dx which is in turn proportional to the stretch ratio of the dielectric layers $\lambda = P/P_0$. Because this stretch is approximately quadratic with respect to compression of the roll, (Figs. 29 and 31), the electric force, which is the slope of the capacitance curve, can be approximated with a single constant such that $dC/dx = k_1 x$. The spring force is also approximated well with a single term such that $F_s = k_3 x^2$

$$\tfrac{1}{2} V^2 (k_1 x) + k_3 x^2 + F_L = 0 \qquad \text{Eq. 68}$$

$$k_1 V^2/2\, x + k_3 x^2 + F_L = 0 \qquad \text{Eq. 69}$$

$$k_3 x^2 + (\tfrac{1}{2} k_1 V^2) x + F_L = 0 \qquad \text{Eq. 70}$$

The equilibrium displacement of the roll subjected to the static load is found from the roots of the quadratic equation, where $a = k_3$, $b = \tfrac{1}{2} k_1 V^2$ and $c = F_L$.

$$x = [-b \pm \sqrt{(b^2 - 4ac)}] / 2a \qquad \text{Eq. 71}$$

The Pseudo-DC Roll Model

$$F_{elec} = ½\ V^2\ dC/dx \qquad \text{Eq. 72}$$

$$F_{elec} = ½\ V^2\ (k_1 x) \qquad \text{Eq. 73}$$

$$F_S = k_3 x^2 \qquad \text{Eq. 74}$$

F_L = -4, [N], for example.

Fig. 31 is a graphical illustration **422** depicting capacitance versus compression in a radial direction of a solid dielectric elastomer transducer roll in flat roll mode in accordance with one embodiment of the present invention. Capacitance C[F] is shown along the vertical axis and compression x[m] is shown along the horizontal axis. The flat roll model curve **424** provides a reasonable first approximation of the capacitance change versus compression as compared to the measurements results **426**. Potential contributors to the difference between actual measurements **426** and the model **424** may be that just 7.5 mm of 10 mm active length was compressed in an INSTRON test instrument and the rigid boundary may limit extension of the outer layers.

Figs. 32A, 32B, 32C and 32D illustrate a solid dielectric elastomer transducer roll **430** under increasing compression force in a radial direction in accordance with one embodiment of the present invention. From left to right, the solid dielectric elastomer transducer roll **430** undergoes increasing compression force such that the roll **430** in under no compression force, roll **430'** is under greater compression force than the roll **430**, roll **430''** is under greater compression force than the roll **430'**, and the roll **430'''** is under greater compression force than the roll **430''**. As shown in Figs. 32B, 32C and 32D, the roll begins to delaminate as it is subjected to increasing greater compression forces. This delamination causes deviation from the model, and presents a practical limit on compression of the roll.

Fig. 33 illustrates a finite element analysis model **432** of a solid dielectric elastomer transducer roll **434** undergoing radial compression in accordance with one embodiment of the present invention and indicates where stretch orientation is and is not well-aligned with the orientation of the layers.

Fig. 34 illustrates the delamination of inner layers **434** of a solid dielectric elastomer transducer roll **436** undergoing radial compression in accordance with one embodiment of the present invention. As the finite element analysis predicts, delamination occurs in regions where the principal stretch is oriented through the thickness of dielectric films.

Fig. 35 illustrates an exploded view of a quick-connect solid dielectric elastomer transducer roll **500** in accordance with one embodiment of the present invention. The quick-connect solid dielectric elastomer transducer roll **500** comprises a solid dielectric elastomer transducer roll **502** and first and second electrical quick-connect terminals **504a**, **504b**. The first quick-connect terminal **504a** is attached to one end of the solid dielectric elastomer transducer roll **502** by electrically conductive adhesive **506a**. The second quick-connect terminal **504b** is attached to another end of the solid dielectric elastomer transducer roll **502** by electrically conductive adhesive **506b**. The electrically conductive adhesive **506a** is received in a cavity **508a** defined in a cap **510a** portion of the quick-connect terminal **504a**. The end of the solid dielectric elastomer transducer roll **502** is then inserted into the cavity **508a** filled with the conductive adhesive **506a**. Although not shown in this view, the second quick-connect terminal **504b** also comprises a cap portion **510b** defining cavity for receiving the conductive adhesive **506b** and the other end of the solid dielectric elastomer transducer roll **502**. Although the first and second electrical quick-connect terminals **504a**, **504b** are shown to be female quick-connect terminals, in other embodiments, they may be male or combinations thereof.

Fig. 36 is a detail view of an electrical quick-connect terminal **504** shown in Fig. 35 in accordance with one embodiment of the present invention. The quick-connect terminal **504** comprises first and second cantilever springs **512a**, **512b** defining a space **514** for slidably receiving a conductive male pin (tab, blade) connector, as described in more detail in Fig. 37. A cap **510** portion of the quick-connect terminal **504** receives a conductive adhesive and one end of the solid dielectric elastomer transducer roll **502**, as shown and described in Fig. 35.

Fig. 37 illustrates quick-connection system **520** for quick-connecting first and second solid dielectric elastomer transducer rolls **502a**, **502b** to a substrate (not shown), such as a printed circuit board, and conductive flexure **522** in accordance with one embodiment of the present invention. The first solid dielectric elastomer transducer roll **502a** comprises first and second quick-connect terminals **504aa**, **504ab** configured to slidably receive on one end an integral male pin **524a** coupled to the flexure **522** and to slidably receive on the other end a 90° male pin **526a** configured to be mounted to the substrate via a base portion **528a**. The second solid dielectric elastomer transducer roll **502b** comprises first and second quick-connect terminals **504ab**, **504bb** configured to slidably receive on one end an integral male pin **524b** coupled to the flexure **522** and to slidably receive on the other end a 90° male pin **526b** configured to be mounted to the substrate via a base portion **528b**. The flexure **522** also comprises a base portion **530** to couple the flexure **522** to the substrate and a feature **532** for mounting a load. The substrate mountable base portions **528a**, **528b**, **530** are compatible with soldering or may be attached to the substrate by other connection mechanisms such screws, rivets, and the like. In one embodiment, the tabs **524a**, **524b**, **526a**, **526b** may be FASTON male pin and connectors provided by AMP, Inc., for example.

Fig. 38 illustrates a solid dielectric elastomer transducer roll **502** with female quick-connect terminals **504ab, 504bb** in the context of a printed circuit board substrate **534** in accordance with one embodiment of the present invention. The female quick-connect terminals **504ab**, **504bb** slidably receive respective 90° tabs **524b** and **526b**. The base portions **528a**, **528b** of the respective 90° tabs **526a**, **526b** are soldered to the substrate **534**. The flexure **522** also is soldered to the substrate **534** by base portion **530**. In one embodiment, the flexure **522** is electrically coupled to drive electronics through the connection of the base portion **530** to the substrate **534**. A mechanical load can be applied in the region **536** shown in broken line. One end of the solid dielectric elastomer transducer roll **502** is attached to the substrate **534** through a standard male connector **526b**. The other end is attached to the custom flexure **522** that includes an integral male pin

524b cut to the same standard as the substrate mounted standard male connector **526b**. The flexure **522** is able to move in direction **538** to place the solid dielectric elastomer transducer roll **502** under tension and compression as it moves back and forth. Although the substrate **534** is configured to hold two solid dielectric elastomer transducer rolls **502**, one was omitted for clarity.

Fig. 39 illustrates a ring connect solid dielectric elastomer transducer roll **600** in accordance with one embodiment of the present invention. The ring connect solid dielectric elastomer transducer roll **600** comprises a solid dielectric elastomer transducer roll **602** and first and second ring connect terminals **604a**, **604b**. The ring connect terminals **604a**, **604b** comprise cylindrical axial portions **606a**, **606b** and metal rings **608a**, **608b**. The cylindrical axial portions **606a**, **606b** define cavities **612** (only one shown) to receive the ends of the solid dielectric elastomer transducer roll **602** and to simplify the application of a conductive adhesive to the ends of the solid dielectric elastomer transducer roll **602**. Because this version uses screw fasteners **610a**, **610b**, it requires a screw driver to replace modules. As previously described in connection with Figs. 10 and 11 exposing the end of the solid dielectric elastomer transducer roll **602** to a solvent produces a local swelling and separation of the layers that allows penetration of the conductive adhesive. After curing, the inter-digitated glue provides a robust electrical and mechanical connection between the terminals **604a**, **604b** and the solid dielectric elastomer transducer roll **602**. It will be appreciated by those skilled in the art, that the cavities of axial portions **606a**, **606b** need not be cylindrical but may have other shapes to conform to the ends of the dielectric elastomer transducer including, but not limited to, oval for flattened roll transducers or rectangular for multilayer stack transducers.

Fig. 40 illustrates an alternative ring connect solid dielectric elastomer transducer roll **700** in accordance with one embodiment of the present invention. The ring connect solid dielectric elastomer transducer roll **700** comprises a solid dielectric elastomer transducer roll **702** and first and second ring connect terminals **704a**, **704b**. The ring connect terminals **704a**, **704b** comprise caps **706a**, **706b** and metal rings **708a**, 708b. The caps **706a**, **706b** define cavities **712** (only one shown) to receive the ends of the solid dielectric elastomer transducer roll **702** and to simplify application of a conductive adhesive to the ends of the solid dielectric elastomer transducer roll **702**. Because this version uses screw fasteners **710a**, **710b**, it requires a screw driver to replace modules. As previously described in connection with Figs. 10 and 11 exposing the end of the solid dielectric elastomer transducer roll **702** to a solvent produces a local swelling and separation of the layers that allows penetration of the conductive adhesive. After curing, the inter-digitated glue provides a robust electrical and mechanical connection between the terminals **704a**, **704b** and the solid dielectric elastomer transducer roll **702**.

Fig. 41 illustrates a metal component 800 for manufacturing the ring connect terminal **704a** for a solid dielectric elastomer transducer roll shown in Fig. 40 in accordance with one embodiment of the present invention. The component **800** is made of metal and can be stamped, laser cut, die cut, or any other suitable technique. The component **800** comprises a ring **802** and four tabs **804**, **806**, **808**, and **810** that are folded or bent in a predetermined manner to manufacture the ring connect terminal **704a**.

Figs. 42A-42G illustrate a process for manufacturing the ring connect terminal **704a** (Fig. 40) for a solid dielectric elastomer transducer roll shown in Fig. 40 in accordance with one embodiment of the present invention.

Fig. 42A illustrates a metal sheet **820** defining apertures **822** that will serve as the ring portion of the ring connect terminal **704a** (Fig. 40) for the solid dielectric elastomer transducer roll shown in Fig. 40 in accordance with one embodiment of the present invention. Several components **800** such as that shown in Fig. 41 will be made from the metal sheet **820**.

Fig. 42B illustrates a metal component **824** stamped out from the metal sheet 820 shown in Fig. 42A in accordance with one embodiment of the present invention. The metal component defines an aperture **822** that will form the ring portion of the ring connect terminal 704a (Fig. 40). The cap **706a** (Fig. 40) is formed by folding or bending the four tabs **826**, **828**, **830**, and **832**.

Fig. 42C illustrates a 90° up fold of the four tabs **826**, **828**, **830**, and **832** of the metal component **824** shown in Fig. 42B in the direction indicated by the arrows in accordance with one embodiment of the present invention.

Fig. 42D illustrates a 180° over fold of the four tabs **826**, **828**, **830**, and **832** of the metal component **824** shown in Fig. 42C in the direction indicated by the arrows in accordance with one embodiment of the present invention;

Fig. 42E illustrates a 90° down fold of the four tabs **826**, **828**, **830**, and **832** of the metal component **824** shown in Fig. 42D in the direction indicated by the arrows in accordance with one embodiment of the present invention;

Fig. 42F is a finished electrical ring connect terminal 704b manufactured according with the steps depicted in Figs. 42A-E in accordance with one embodiment of the present invention;

Fig. 42G illustrates an assembled ring connect solid dielectric elastomer transducer roll **700**. The ring connect solid dielectric elastomer transducer roll **700** comprises the finished ring connect terminals **704a**, **704b** attached to both ends of a solid dielectric elastomer transducer roll **702** with conductive adhesive to form a ring connect solid dielectric elastomer transducer roll **700** in accordance with one embodiment of the present invention. The metal rings **708a**, **708b** are used to receive mounting fasteners to connect the ring connect solid dielectric elastomer transducer roll **700** to a substrate.

Fig. 42H illustrates the ring connect solid dielectric elastomer transducer roll **700** shown in Fig. 42G with mounting fasteners **708a**, **708b** in accordance with one embodiment of the present invention. The ring connect solid dielectric elastomer transducer roll **700** shown in Fig. 42H comprises mounting screw fasteners **710a**, **710b** provided through the corresponding rings **708a**, **708b** in the finished electrical terminals **704a**, **704b**.

Fig. 43 illustrates a quick-connect dielectric elastomer transducer roll **900** in combination with a living hinge **902** coupling two substrates **904**, **906** in accordance with one embodiment of the present invention. With the quick-connect dielectric elastomer transducer roll **900** combined with the living hinge **902**, the substrate, a printed circuit board, for example, serves to carry the drive electronics and also can act as an actuated lever to save space, cost, and weight. As shown in Fig. 43, the quick-connect dielectric elastomer transducer roll **900** comprises a solid dielectric elastomer transducer roll **908** with female terminals **910a**, **910b** connected to each end thereof with conductive adhesive. The first terminal **910a** on one end of the quick-connect dielectric elastomer transducer roll **900** is connected to a 90° male pin **912a** mounted to the first substrate **904** via a base portion **914a**. The second terminal **910a** on the other end of the quick-connect dielectric elastomer transducer roll **900** is connected to a 90° male pin **912b** mounted to the second substrate **906** via a base portion **914b**. The living hinge **902** flexibly couples the two substrates **904**, **906**. At least one of the substrates **904**, **906** is movable in response to energizing the solid dielectric elastomer transducer roll **908**. In Fig. 43, when the solid dielectric elastomer transducer roll **908** is energized, the rightmost substrate 906 is movable and can act as an actuated lever.

Fig. 44 illustrates the quick-connect dielectric elastomer transducer roll **900** in combination with the living hinge **902** shown in Fig. 43 coupling two substrates **904**, **906** configured as a positioner in accordance with one embodiment of the present invention.

Fig. 45 illustrates the quick-connect dielectric elastomer transducer roll 900 in combination with the living hinge **902** shown in Fig. 43 coupling two substrates **904**, **906** configured as an aileron in accordance with one embodiment of the present invention.

Fig. 46 illustrates the quick-connect dielectric elastomer transducer roll **900** in combination with the living hinge **902** coupling two substrates **904**, **906** shown in Fig. 43 configured as a flow restrictor valve **920** in accordance with one embodiment of the present invention. A flexible diaphragm **922** is positioned next to the movable substrate **906**. An intake port **924** fluidically coupled to the flexible diaphragm **922** draws in the medium and an outlet port **926** fluidically coupled to the flexible diaphragm **922** delivers the medium from the flexible diaphragm **922**. The flow through the outlet port **926** is regulated by a flow valve **928** coupled to the substrate **906**. As the substrate **906** is positioned towards an opening of the outlet port **926** in direction **921**, the flow of the medium is restricted. As the substrate **906** is positioned away from an opening of the outlet port **926** in direction **923**, the flow is un-restricted.

Fig. 47 illustrates the quick-connect dielectric elastomer transducer roll **900** in combination with the living hinge **902** coupling two substrates **904**, **906** shown in Fig. 43 configured as a pump **930** in accordance with one embodiment of the present invention. A flexible diaphragm **932** is positioned next to the movable substrate **906**. A flap **938** is coupled to the outlet port **936** such that it closes during an up-stroke **933** of the substrate **906** and opens during a down-stroke **931** of the substrate **906**. An intake port **934** fluidically coupled to the flexible diaphragm **932** draws in the medium for the pump during the up-stroke **933** and an outlet port **936** fluidically coupled to the flexible diaphragm **932** delivers the medium from the flexible diaphragm **932** during the down-stroke **931**.

Fig. 48 is an exploded view of a compression dielectric elastomer transducer roll **1000** comprising a dielectric elastomer transducer roll **1002** and electrical terminals **1004a**, **1004b** coupled to each end of the transducer roll **1002** in accordance with one embodiment of the present invention. Each of the terminals **1004a**, **1004b** comprises a cup **1010b** and a protrusion **1006b** (only shown for one terminal **1004b**), which is configured to be compressed onto each end **1008a**, **1008b** of the transducer roll **1002**. Conductive adhesive also may be used to make the bond between the terminals **1004a**, **1004b** and each end **1008a**, **1008b** or the transducer roll **1002** more permanent.

Fig. 49 is a perspective view of the assembled compression dielectric elastomer transducer roll **1000** comprising the electrical terminals **1004a**, **1004b** attached to each end of the each end of the dielectric elastomer transducer roll **1002** by a conductive adhesive in accordance with one embodiment of the present invention.

As for other details of the present invention, materials and alternate related configurations may be employed as within the level of those with skill in the relevant art. The same may hold true with respect to process-based aspects of the invention in terms of additional acts as commonly or logically employed. In addition, though the invention has been described in reference to several examples, optionally incorporating various features, the invention is not to be limited to that which is described or indicated as contemplated with respect to each variation of the invention. Various changes may be made to the invention described and equivalents (whether recited herein or not included for the sake of some brevity) may be substituted without departing from the true spirit and scope of the invention. Any number of the individual parts or subassemblies shown may be integrated in their design. Such changes or others may be undertaken or guided by the principles of design for assembly.

Although generally described herein in terms of a solid dielectric elastomer transducer roll, those skilled in the art will recognize that the present invention is equally applicable to all types of transducer architecture including dielectric elastomer rolls, solid dielectric elastomer rolls, and dielectric elastomer multi-layer stacks.

Various aspects of the subject matter described herein are set out in the following numbered clauses in any combination thereof:

1. A dielectric elastomer transducer comprising a first end and a second end, wherein a first electrical terminal is connected to the first end of the dielectric elastomer transducer; and a second electrical terminal is connected to the second end of the dielectric elastomer transducer.

2. The dielectric elastomer transducer according to Claim 1, further comprising a conductive adhesive connecting the first and second electrical terminals to the respective first and second ends of the dielectric elastomer transducer.

3. The dielectric elastomer transducer according to Claim 1, wherein the first and second electrical terminals each comprise a cap defining a cavity to receive therein one end of the dielectric elastomer transducer.

4. The dielectric elastomer transducer according to Claim 1, wherein the first and second electrical terminals each comprise a quick-connect terminal.

5. The dielectric elastomer transducer according to Claim 4, wherein the quick-connect terminal comprises a first and a second cantilever spring defining a space capable of slidably receiving a conductive male pin.

6. The dielectric elastomer transducer according to Claim 1, wherein the first and second electrical terminals each comprise a ring connect terminal comprising an axial portion and a metal ring or wherein the first and second electrical terminals comprise a cup with a protrusion configured to compress onto the respective first and second ends of the dielectric elastomer transducer.

7. A system, comprising a dielectric elastomer transducer comprising a first end and a second end; a first electrical terminal connected to the first end of the dielectric elastomer transducer; a second electrical terminal connected to the second end of the dielectric elastomer transducer; a substrate; a conductive flexure comprising one end attached to the substrate and another end configured to receive a load; a first electrical connector pin attached to the flexure to receive the first electrical terminal; and a second electrical connector pin attached to the substrate to receive the second electrical terminal.

8. The system according to Claim 7, wherein the first and second electrical terminals are quick-connect female connectors and the first and second connector are male pins.

9. The system according to Claim 7, wherein the first pin is electrically coupled to the flexure.

10. The system according to Claim 7, wherein the second pin is a 90° male pin comprising a base portion configured to be mounted to the substrate.

11. The system according to Claim 7, wherein the flexure comprises a base portion to couple the one end of the flexure to the substrate.

12. The system according to Claim 11, wherein the substrate comprises, a first substrate comprising a first electrical connecter pin to receive the first electrical terminal; a second substrate comprising a second electrical connector pin to receive the second electrical terminal; wherein the system further includes a living hinge flexibly coupling the first and second substrates; and wherein at least

one of the first and second substrates is movable in response to energizing the dielectric elastomer transducer.

13. The system according to Claim 12, further comprising a flexible diaphragm positioned next to the movable substrate; an intake port fluidically coupled to the flexible diaphragm to draw in a medium into the flexible diaphragm; and an outlet port fluidically coupled to the flexible diaphragm to deliver the medium from the flexible diaphragm.

14. The dielectric elastomer transducer of any one of Claims 1 to 14, wherein the transducer has an architecture selected from the group consisting of dielectric elastomer rolls, solid dielectric elastomer rolls, and dielectric elastomer multi-layer stacks.

Also, it is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein. Reference to a singular item, includes the possibility that there are plural of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "an," "said," and "the" include plural referents unless the specifically stated otherwise. In other words, use of the articles allow for "at least one" of the subject item in the description above as well as the claims below. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation. Without the use of such exclusive terminology, the term "comprising" in the claims shall allow for the inclusion of any additional element – irrespective of whether a given number of elements are enumerated in the claim, or the addition of a feature could be regarded as transforming the nature of an element set forth in the claims. Stated otherwise, unless specifically defined herein, all technical and scientific terms used herein are to be given as broad a commonly understood meaning as possible while maintaining claim validity.

WHAT IS CLAIMED IS:

1. A dielectric elastomer transducer comprising a first end and a second end, wherein a first electrical terminal is connected to the first end of the dielectric elastomer transducer; and a second electrical terminal is connected to the second end of the dielectric elastomer transducer.

2. The dielectric elastomer transducer according to Claim 1, further comprising a conductive adhesive connecting the first and second electrical terminals to the respective first and second ends of the dielectric elastomer transducer.

3. The dielectric elastomer transducer according to Claim 1, wherein the first and second electrical terminals each comprise a cap defining a cavity to receive therein one end of the dielectric elastomer transducer.

4. The dielectric elastomer transducer according to Claim 1, wherein the first and second electrical terminals each comprise a quick-connect terminal.

5. The dielectric elastomer transducer according to Claim 4, wherein the quick-connect terminal comprises a first and a second cantilever spring defining a space capable of slidably receiving a conductive male pin.

6. The dielectric elastomer transducer according to Claim 1, wherein the first and second electrical terminals each comprise a ring connect terminal comprising an axial portion and a metal ring or wherein the first and second electrical terminals comprise a cup with a protrusion configured to compress onto the respective first and second ends of the dielectric elastomer transducer.

7. A system, comprising:

a dielectric elastomer transducer comprising a first end and a second end;

a first electrical terminal connected to the first end of the dielectric elastomer transducer;

a second electrical terminal connected to the second end of the dielectric elastomer transducer;

a substrate;

a conductive flexure comprising one end attached to the substrate and another end configured to receive a load;

a first electrical connector pin attached to the flexure to receive the first electrical terminal; and

a second electrical connector pin attached to the substrate to receive the second electrical terminal.

8. The system according to Claim 7, wherein the first and second electrical terminals are quick-connect female connectors and the first and second connector are male pins.

9. The system according to Claim 7, wherein the first pin is electrically coupled to the flexure.

10. The system according to Claim 7, wherein the second pin is a 90° male pin comprising a base portion configured to be mounted to the substrate.

11. The system according to Claim 7, wherein the flexure comprises a base portion to couple the one end of the flexure to the substrate.

12. The system according to Claim 11, wherein the substrate comprises, a first substrate comprising a first electrical connecter pin to receive the first electrical terminal;

a second substrate comprising a second electrical connector pin to receive the second electrical terminal; and wherein the system further includes a living hinge flexibly coupling the first second substrates; and wherein at least one of the first and second substrates is movable in response to energizing the dielectric elastomer transducer.

13. The system according to Claim 12, further comprising:

a flexible diaphragm positioned next to the movable substrate;

an intake port fluidically coupled to the flexible diaphragm to draw in a medium into the flexible diaphragm; and

an outlet port fluidically coupled to the flexible diaphragm to deliver the medium from the flexible diaphragm.

14. The dielectric elastomer transducer of any one of Claims 1 to 14, wherein the transducer has an architecture selected from the group consisting of dielectric elastomer rolls, solid dielectric elastomer rolls, and dielectric elastomer multi-layer stacks.

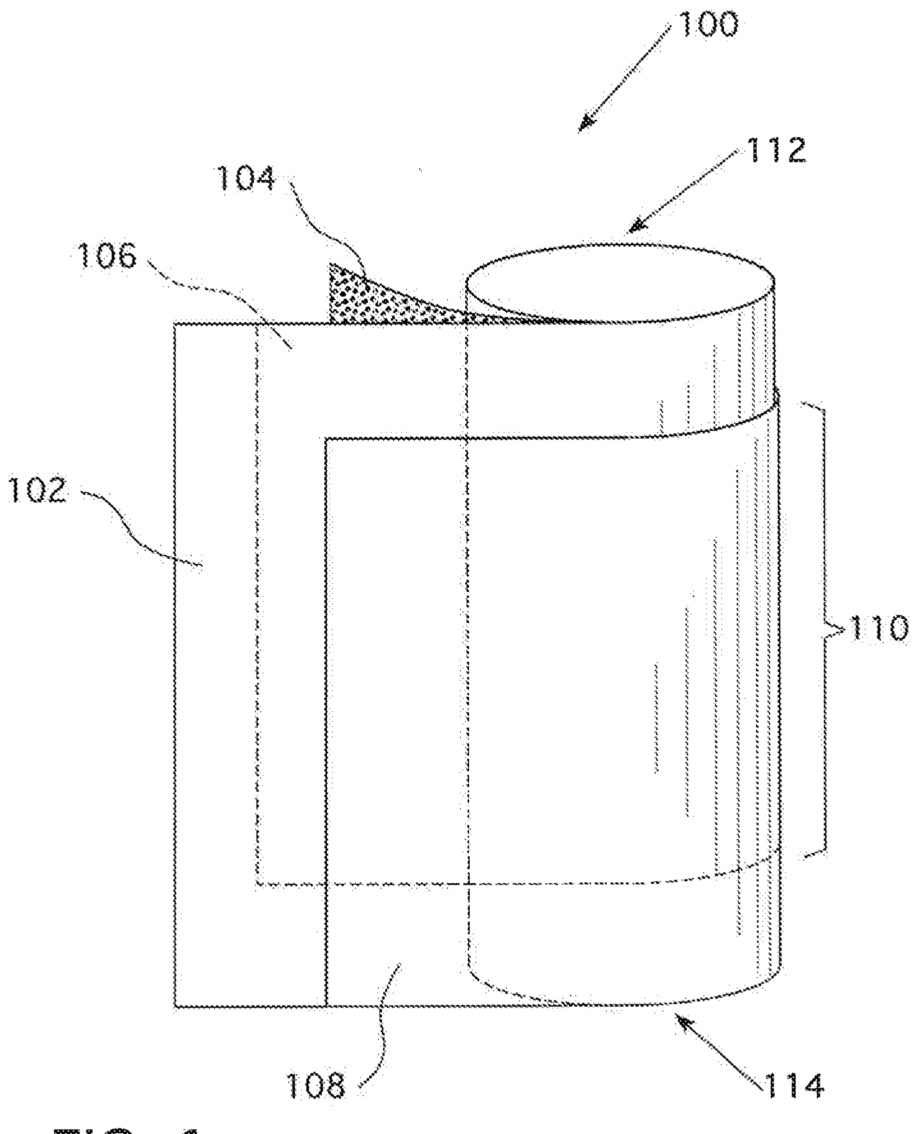


FIG. 1

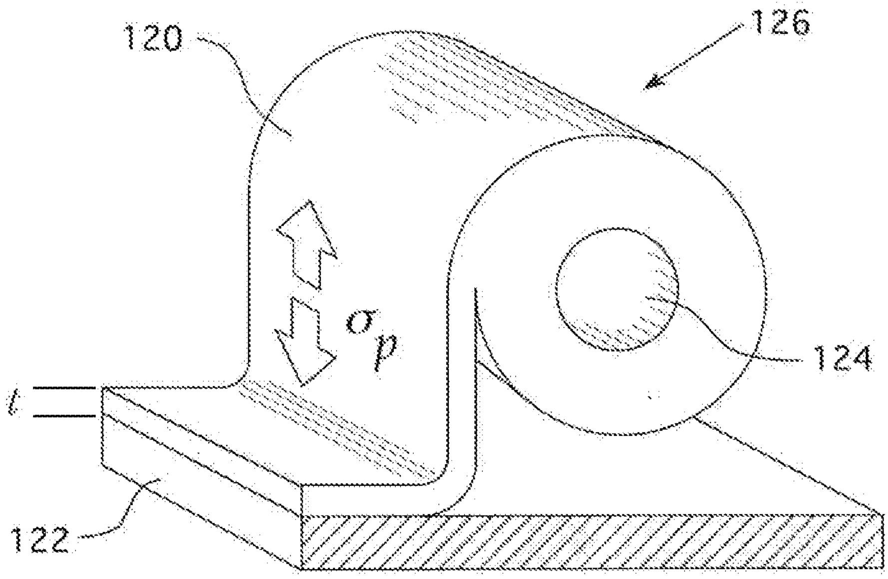


FIG. 2

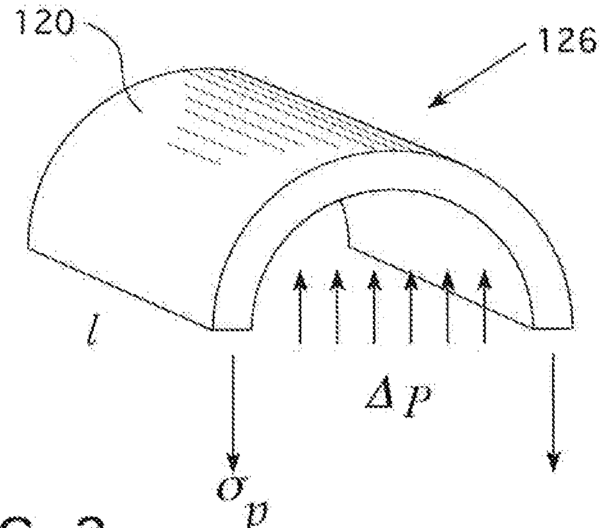


FIG. 3

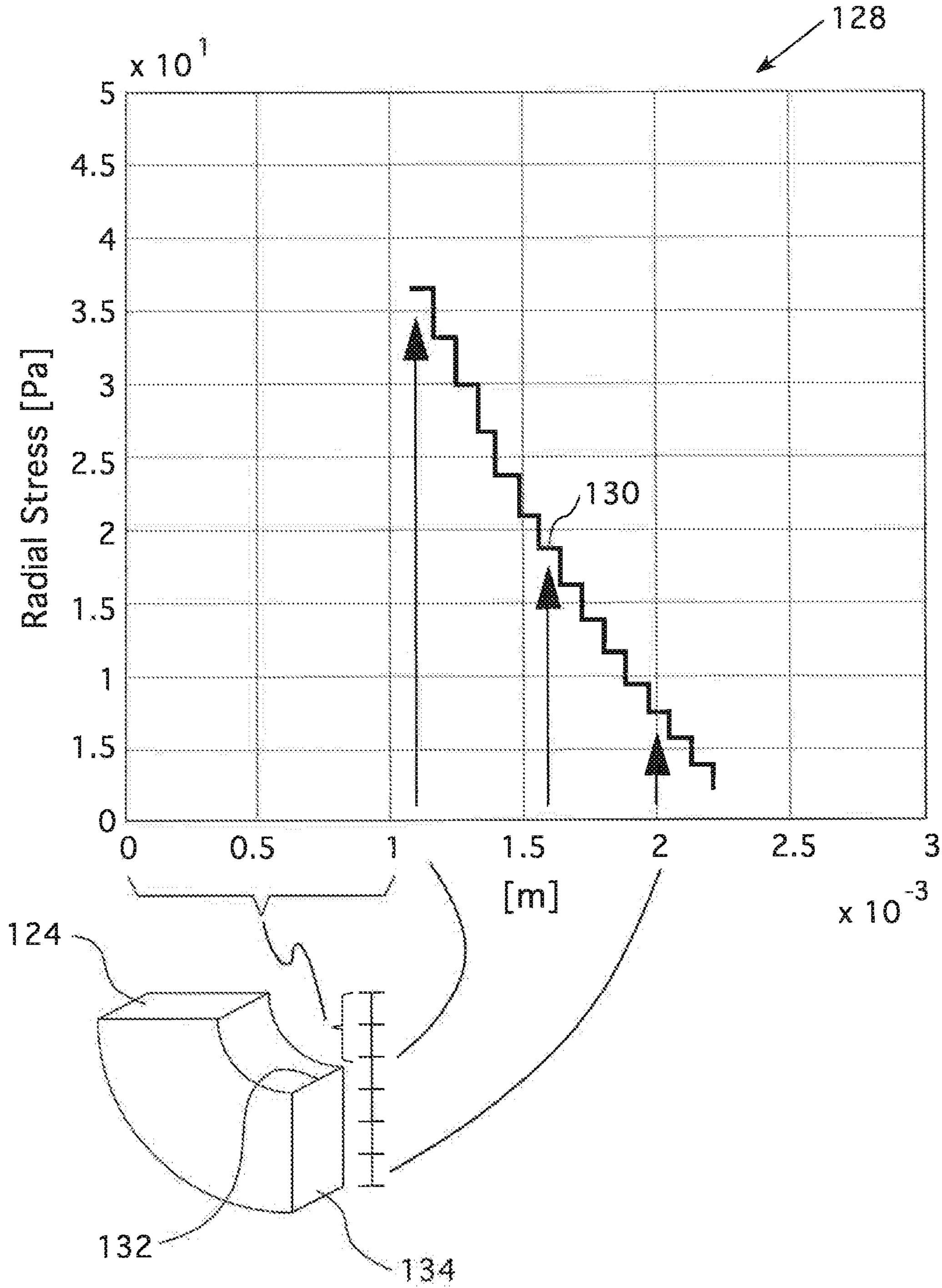

128
x 10^1
5
4.5
4
3.5
3
2.5
2
1.5
1
1.5
0
Radial Stress [Pa]
130
0
0.5
1
1.5
2
2.5
3
[m]
x 10^-3
124
132
134

FIG. 4

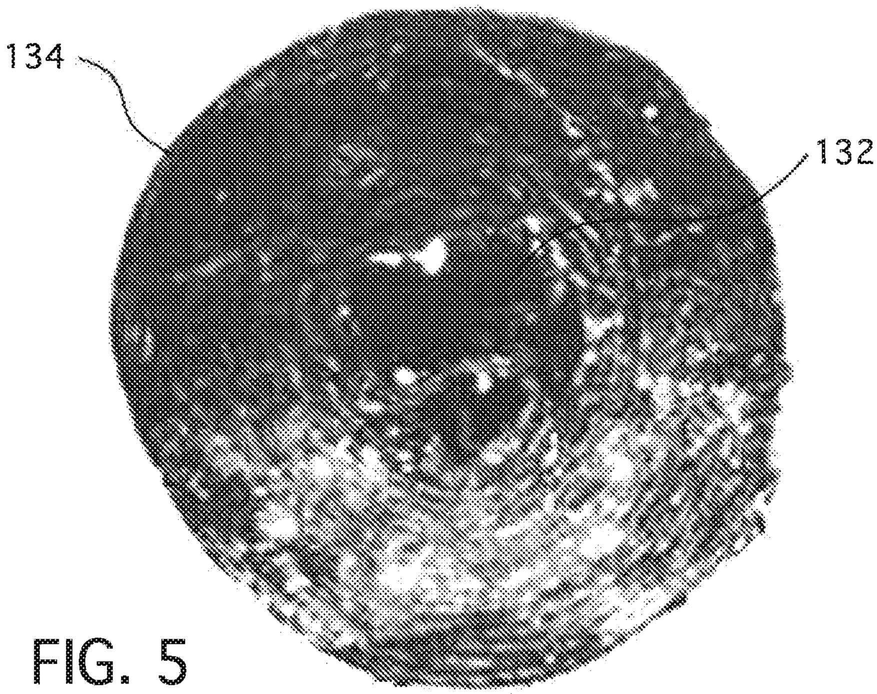


FIG. 5

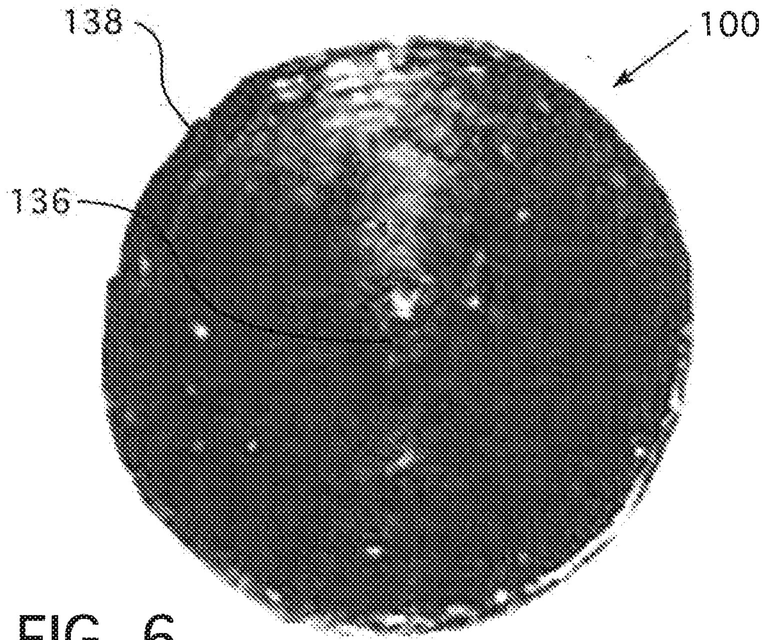


FIG. 6

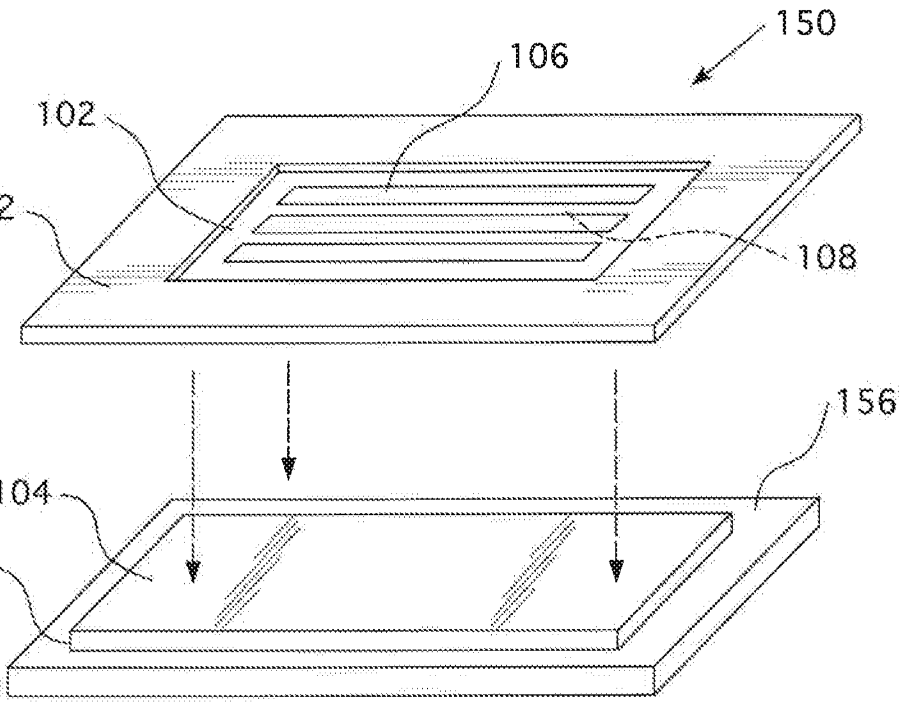


FIG. 7A

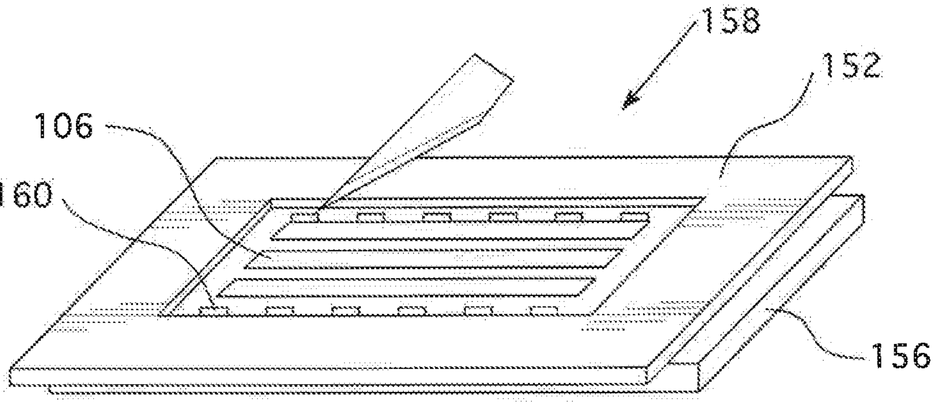


FIG. 7B

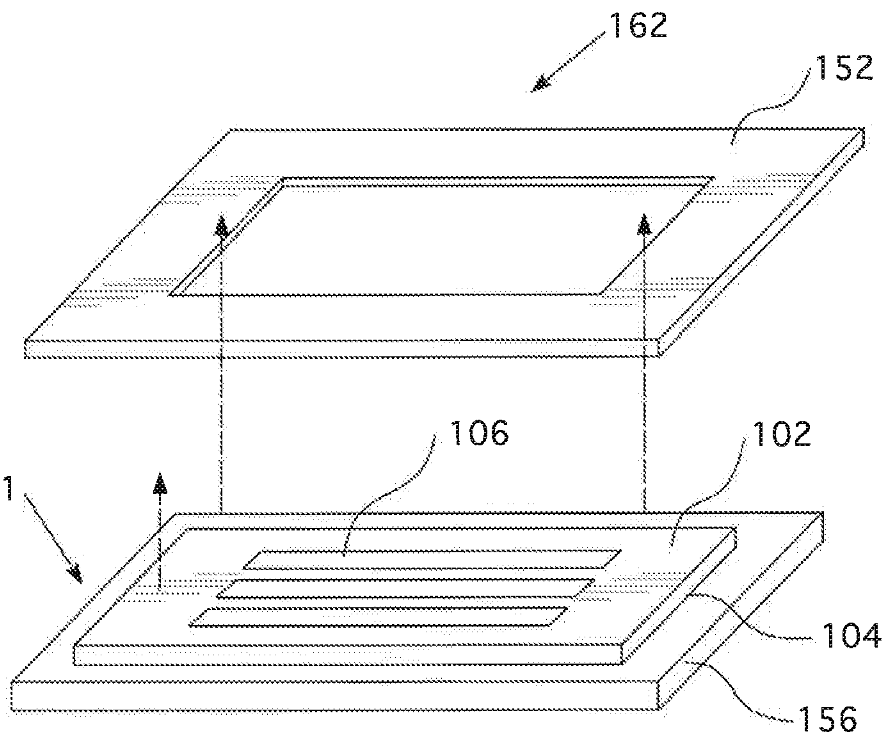


FIG. 7C

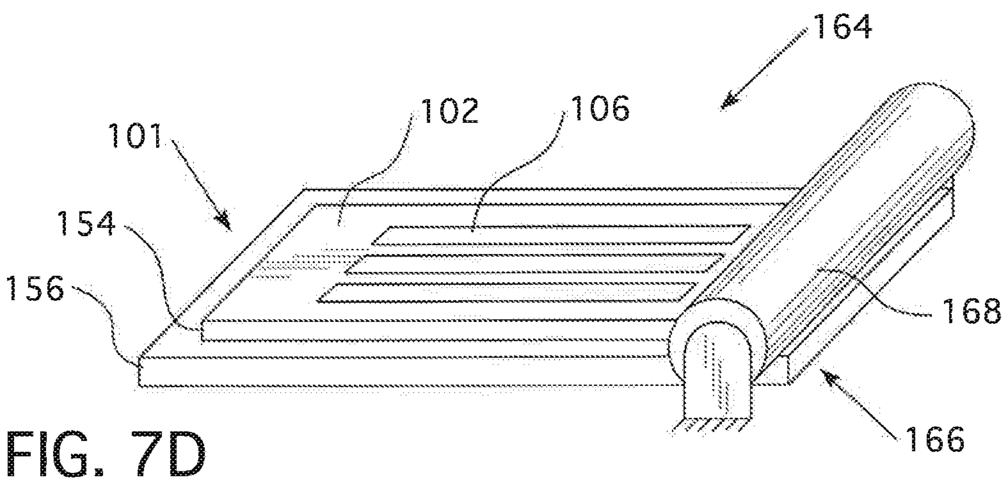


FIG. 7D

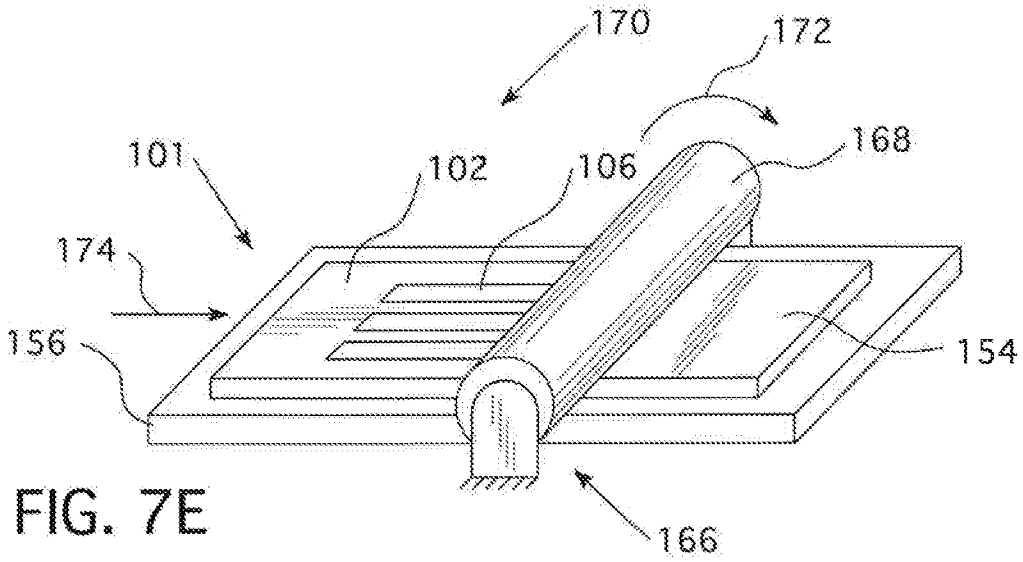

170
172
168
101
102
106
174
154
156
166

FIG. 7E

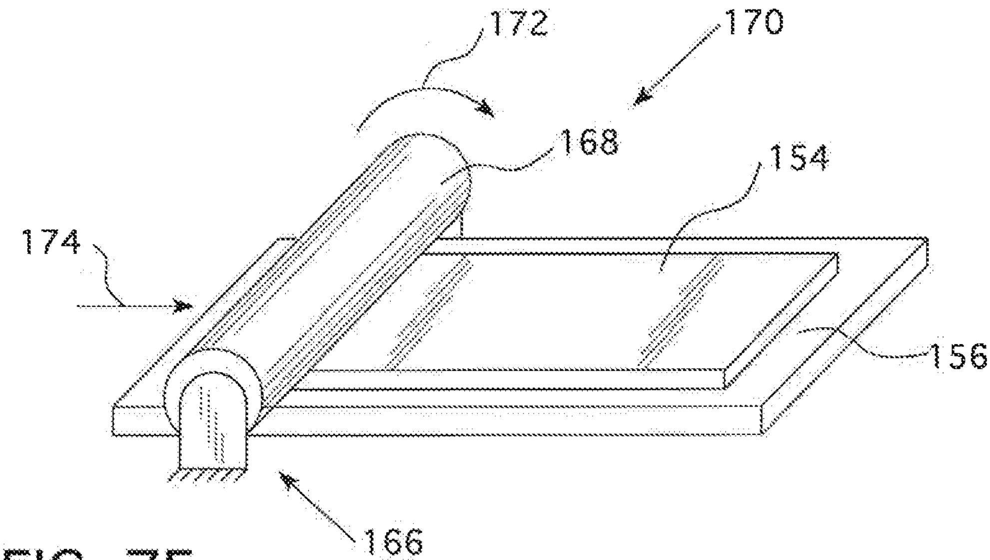

172
170
168
154
174
156
166

FIG. 7F

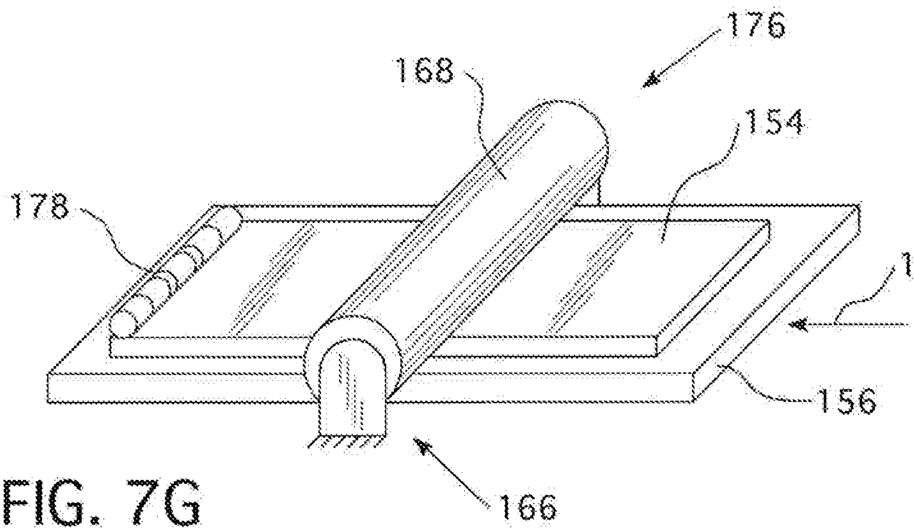


FIG. 7G

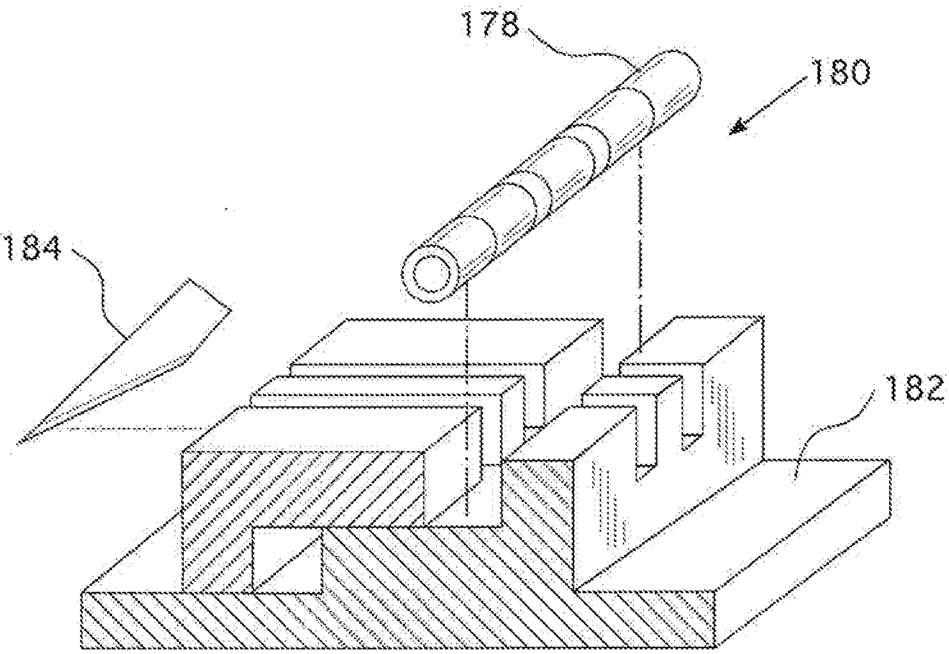


FIG. 7H

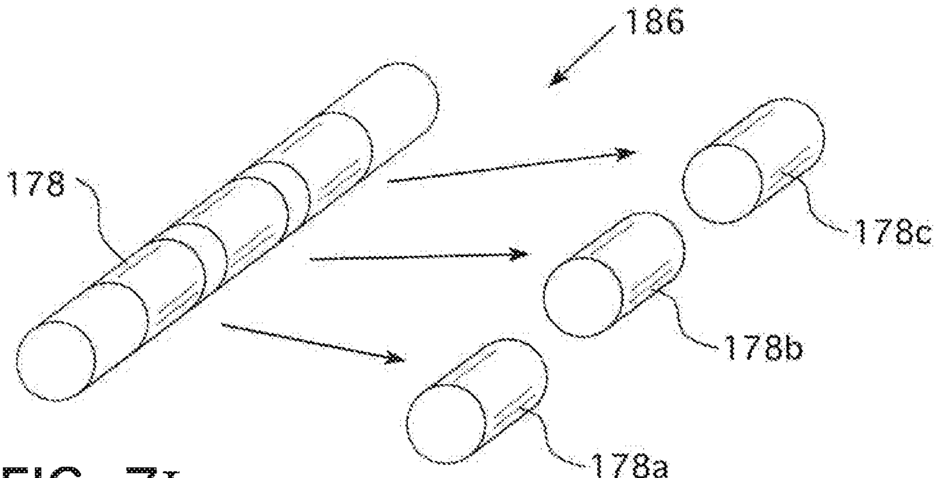


FIG. 7I

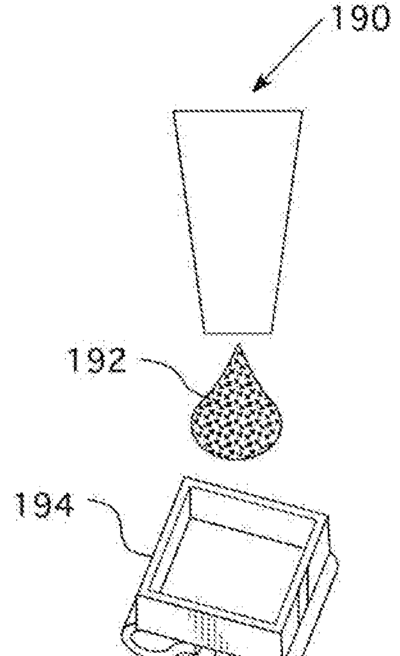


FIG. 7J

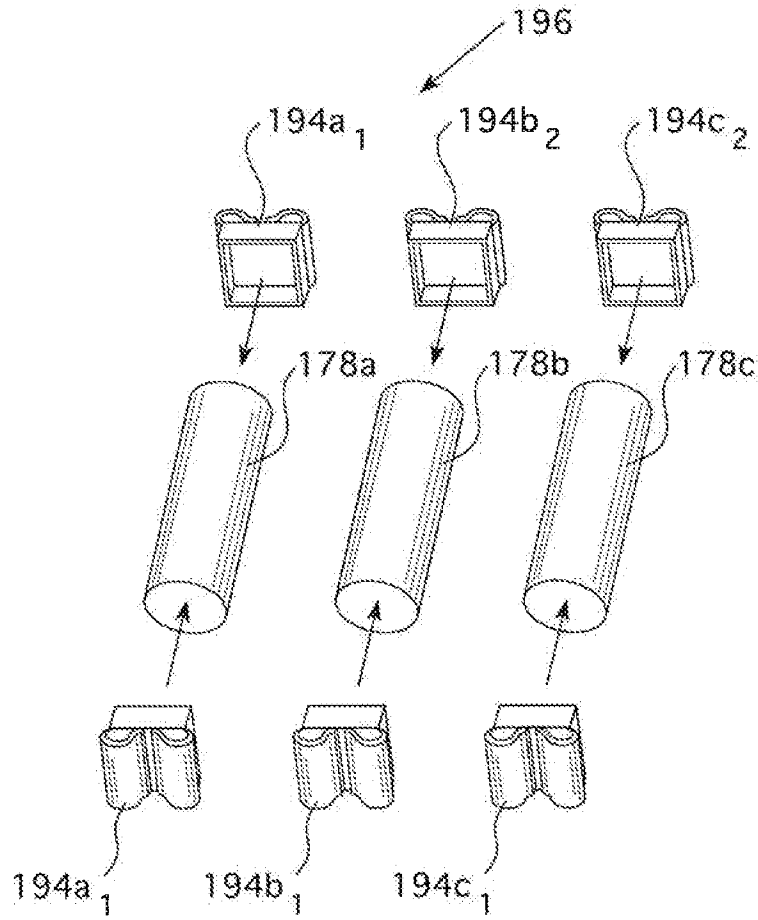


FIG. 7K

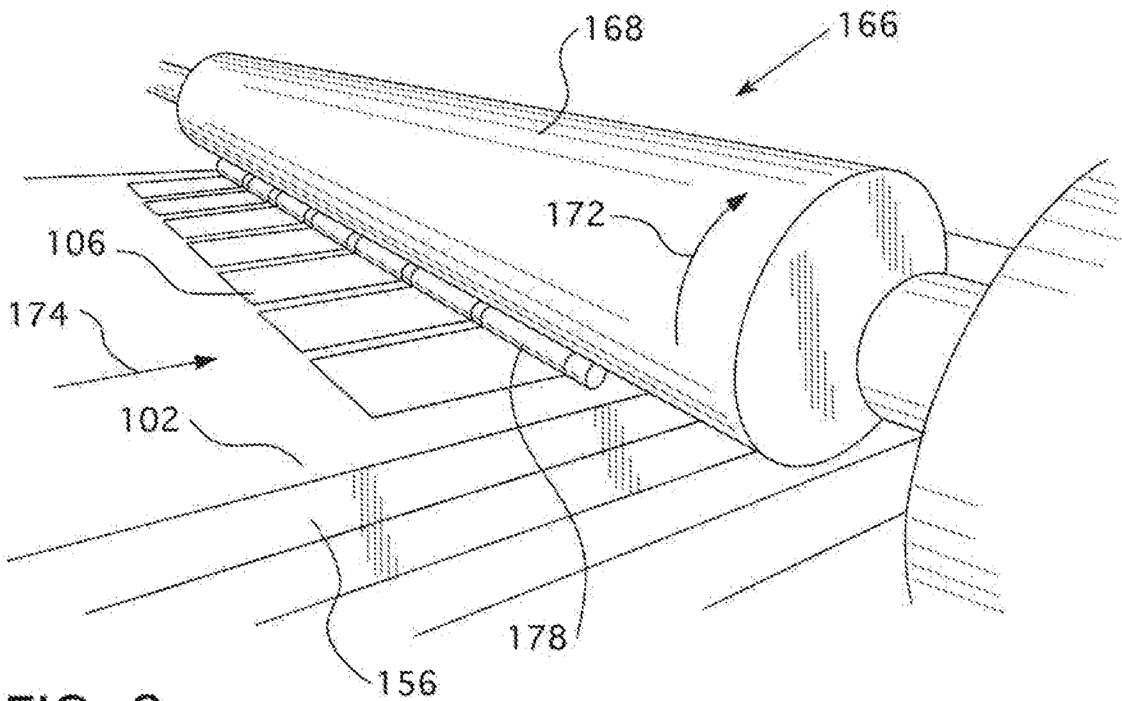

168
166
172
106
174
102
178
156

FIG. 8

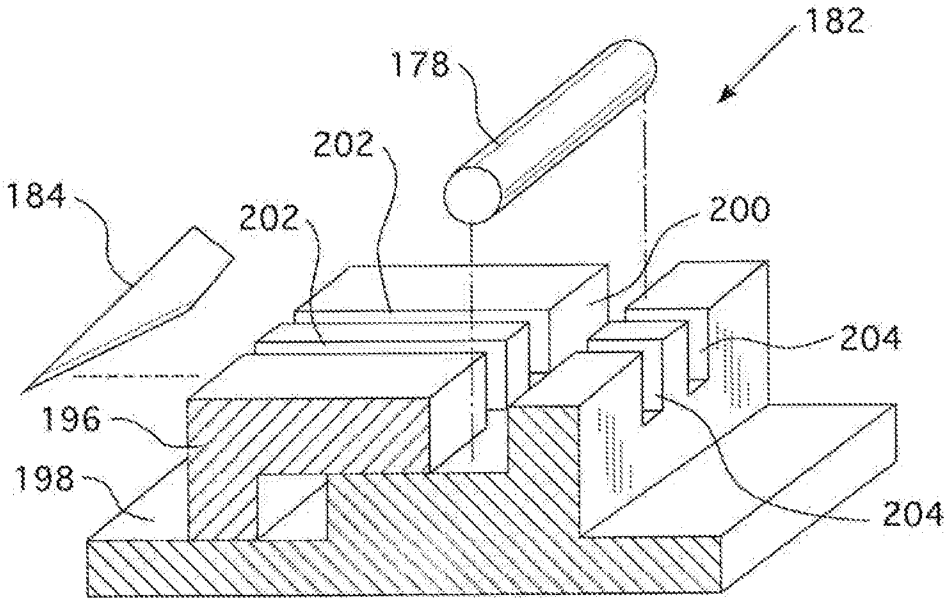

182
178
202
184
202
200
204
196
198
204

FIG. 9

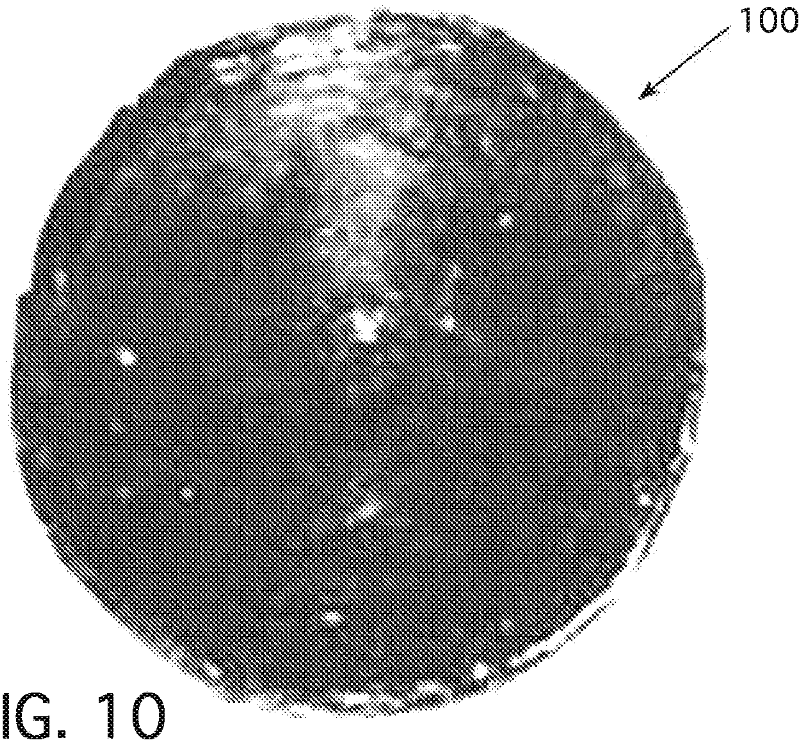


FIG. 10

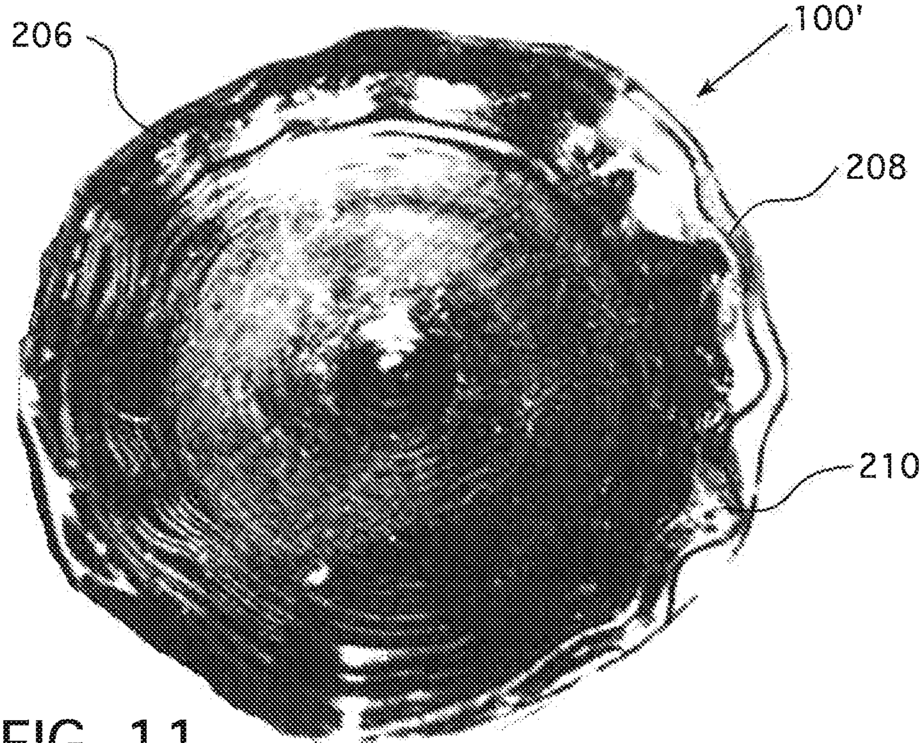


FIG. 11

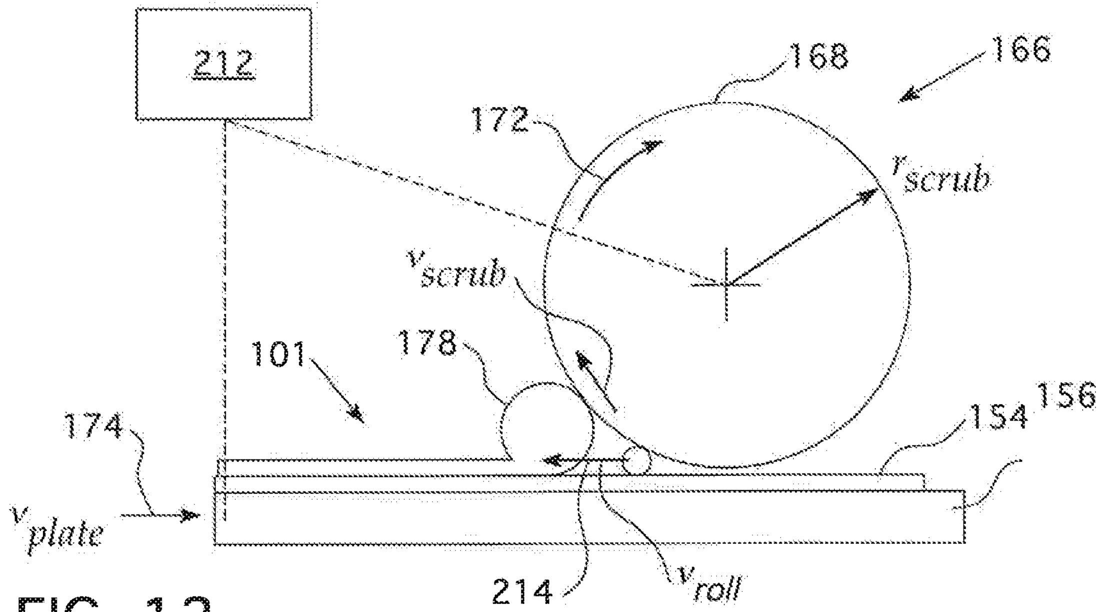

212
168
166
172
r_{scrub}
v_{scrub}
101
178
174
154
156
v_{plate}
214
v_{roll}

FIG. 12

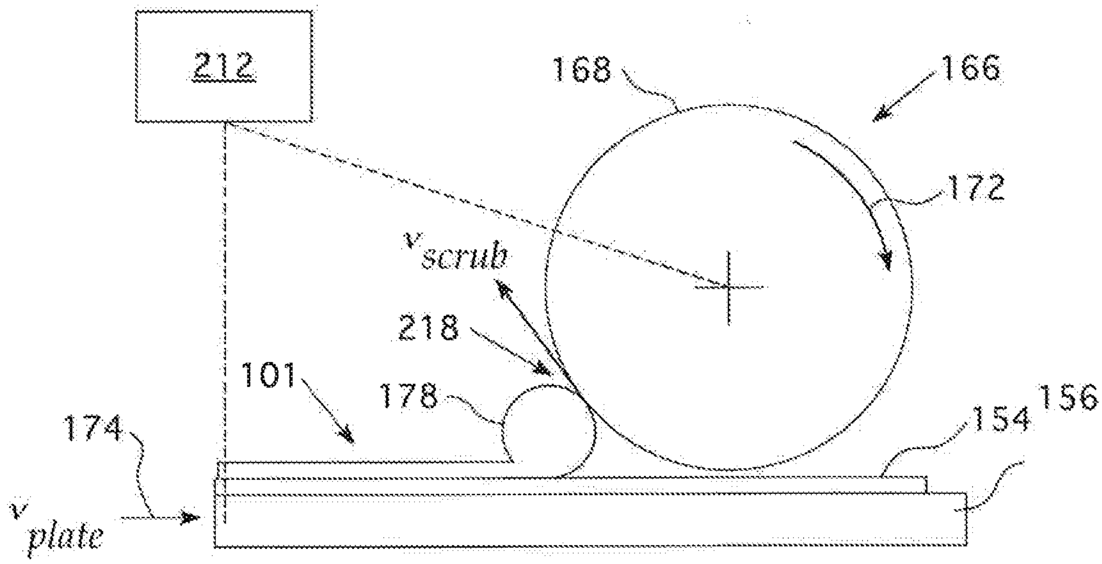

212
168
166
172
v_{scrub}
218
101
178
174
154
156
v_{plate}

FIG. 13

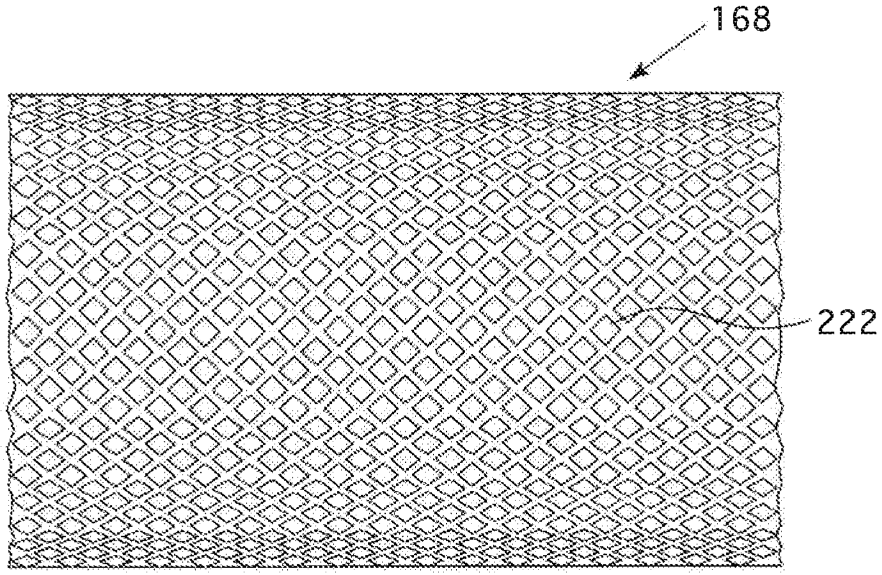


FIG. 14

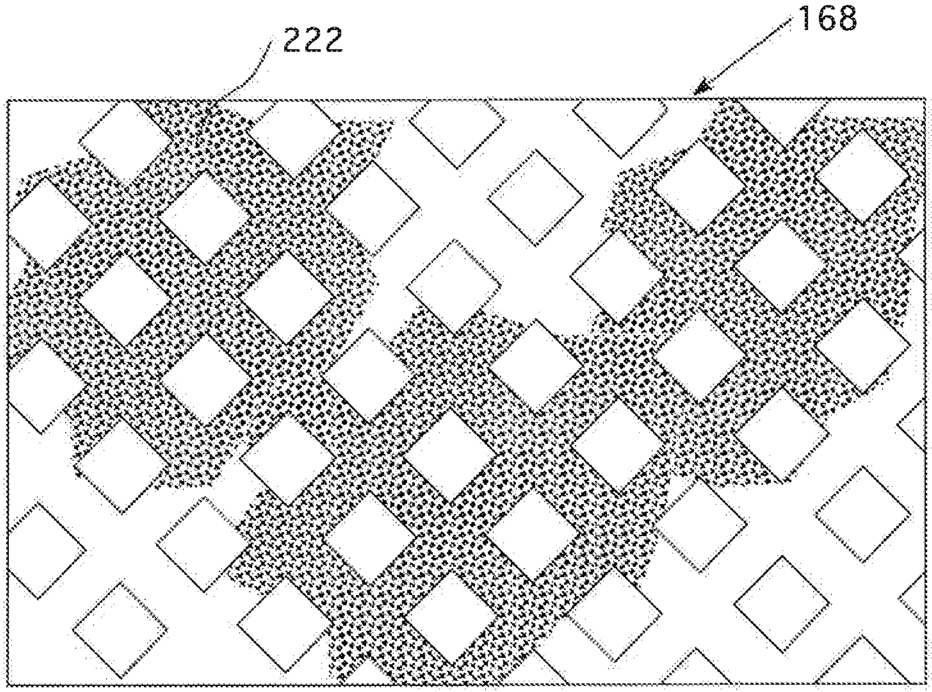


FIG. 15

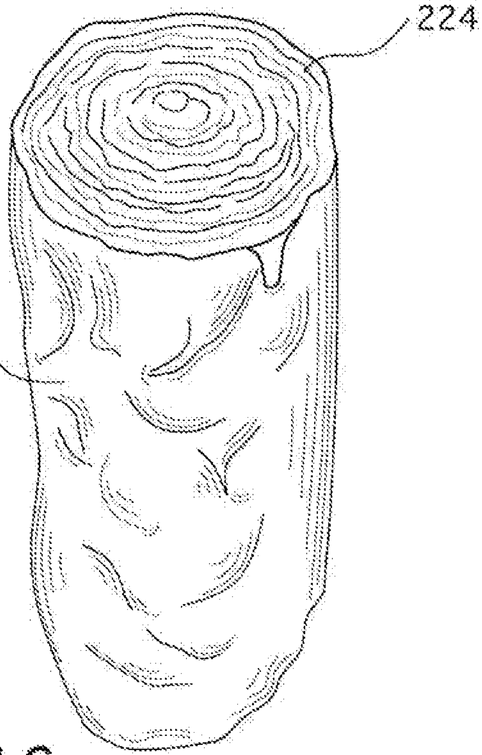

224
226

FIG. 16

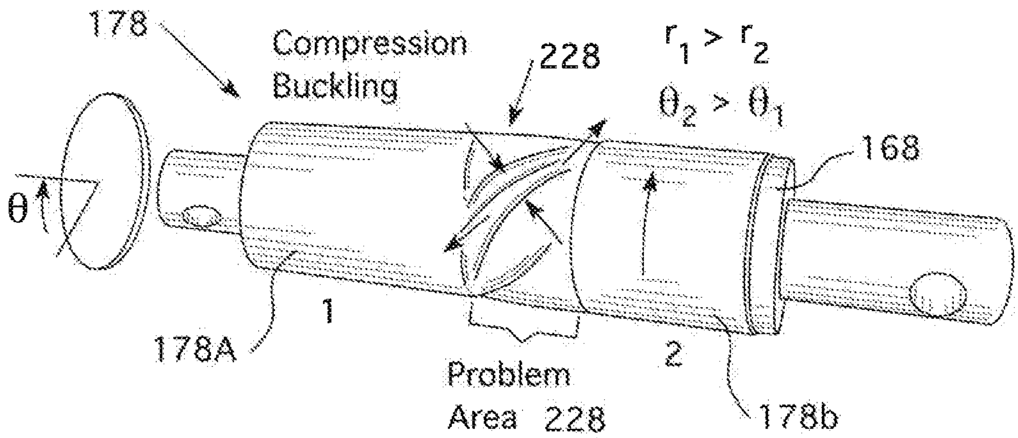

178
Compression
Buckling
228
$r_1 > r_2$
$\theta_2 > \theta_1$
168
θ
178A
1
Problem
Area 228
2
178b

FIG. 17

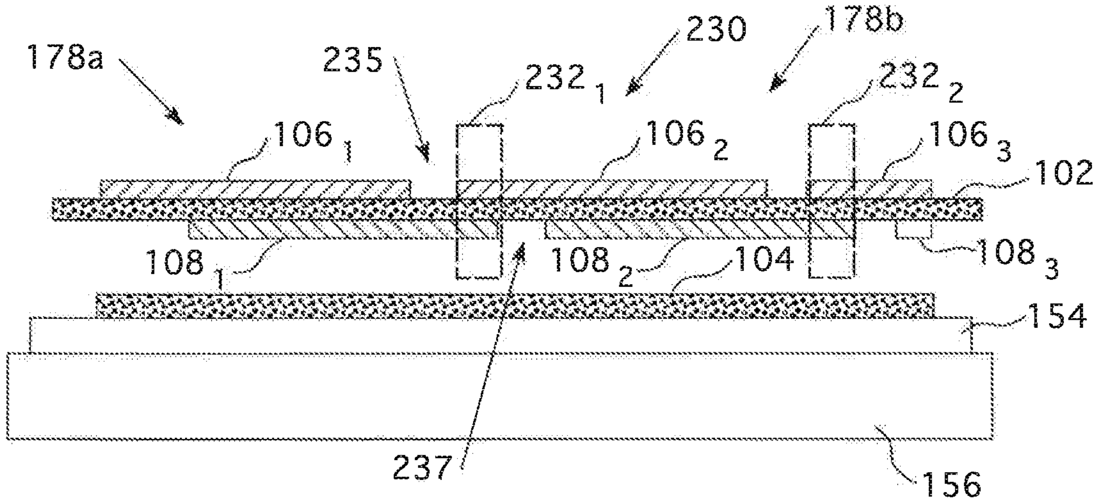

178a
235
232 1
230
178b
232 2
106 1
106 2
106 3
102
108 1
108 2
104
108 3
154
237
156

FIG. 18

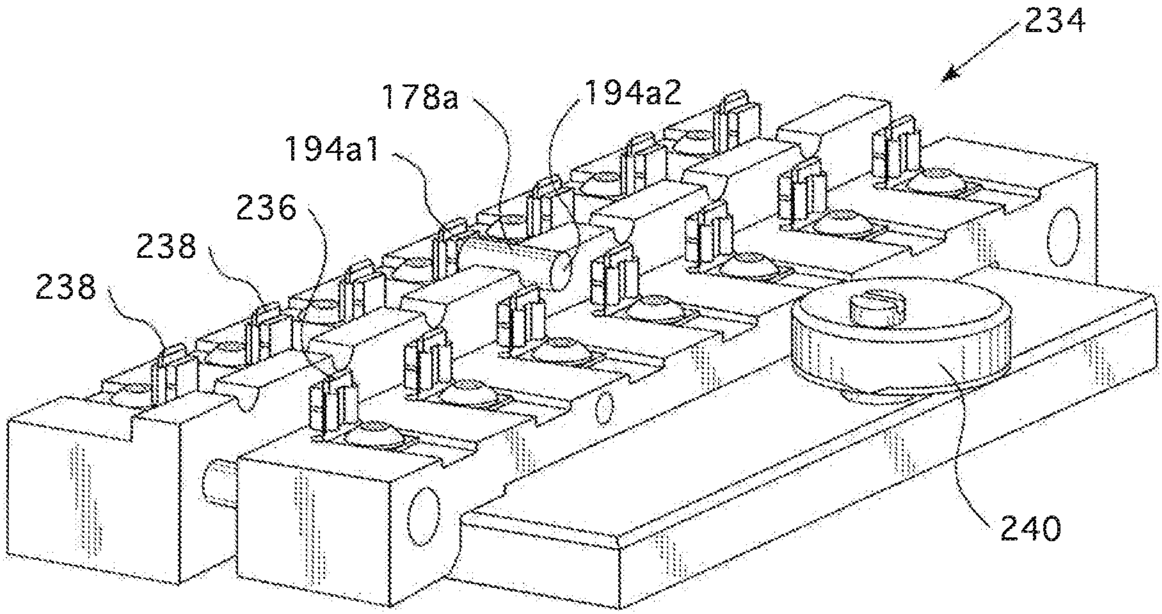

234
178a
194a2
194a1
236
238
238
240

FIG. 19

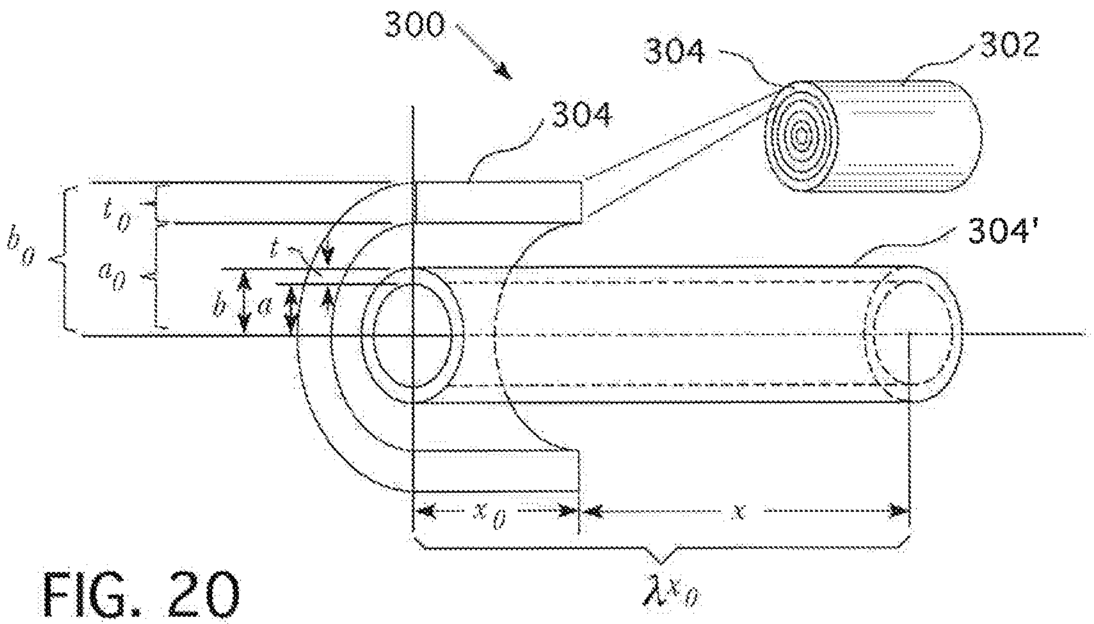

300
304
302
304
304'
t_0
b_0
a_0
t
b
a
x_0
x
λx_0

FIG. 20

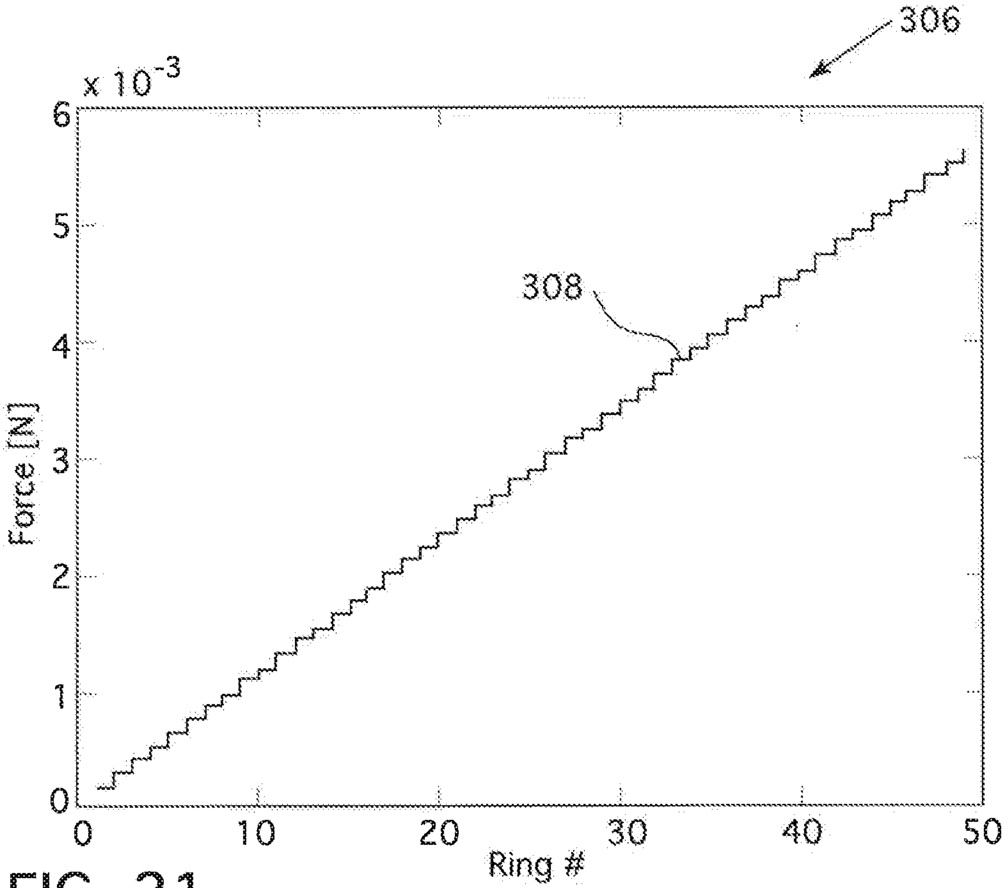

306
x 10^-3
308
Force [N]
Ring #
0
1
2
3
4
5
6
10
20
30
40
50

FIG. 21

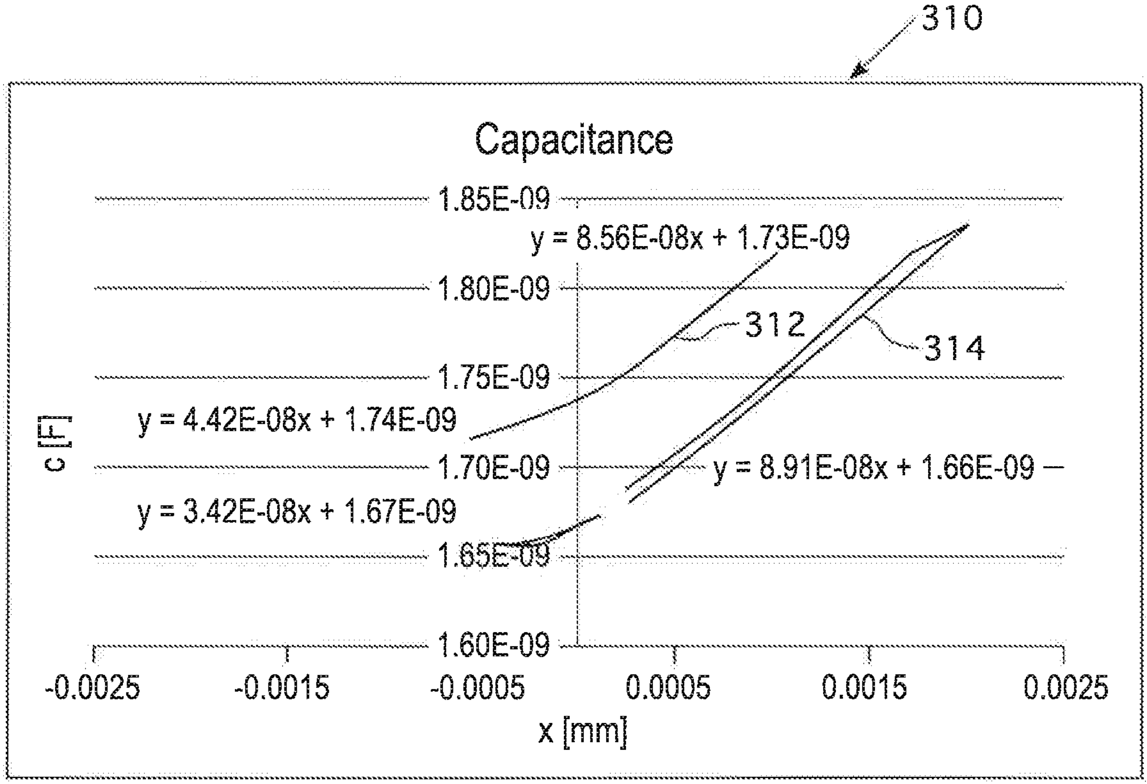

310
Capacitance
1.85E-09
y = 8.56E-08x + 1.73E-09
1.80E-09
312
314
1.75E-09
y = 4.42E-08x + 1.74E-09
c [F]
1.70E-09
y = 8.91E-08x + 1.66E-09
y = 3.42E-08x + 1.67E-09
1.65E-09
1.60E-09
-0.0025
-0.0015
-0.0005
0.0005
0.0015
0.0025
x [mm]

FIG. 22

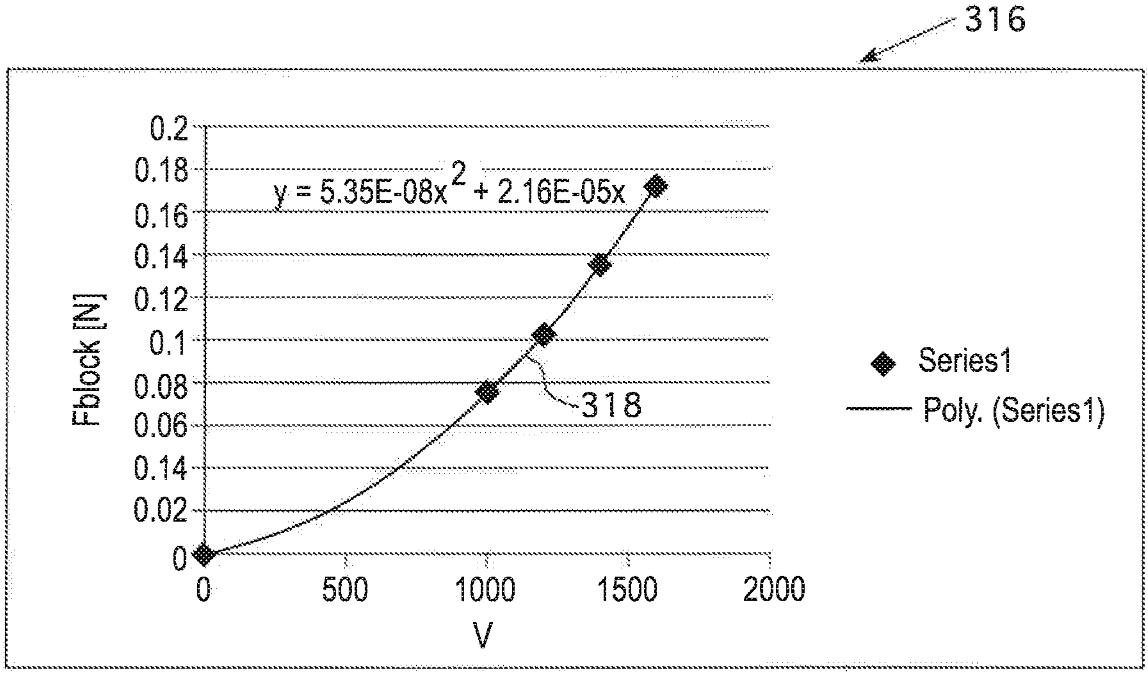

316
0.2
0.18
y = 5.35E-08x^2 + 2.16E-05x
0.16
0.14
0.12
0.1
0.08
0.06
0.14
0.02
0
Fblock [N]
318
Series1
Poly. (Series1)
0
500
1000
1500
2000
V

FIG. 23

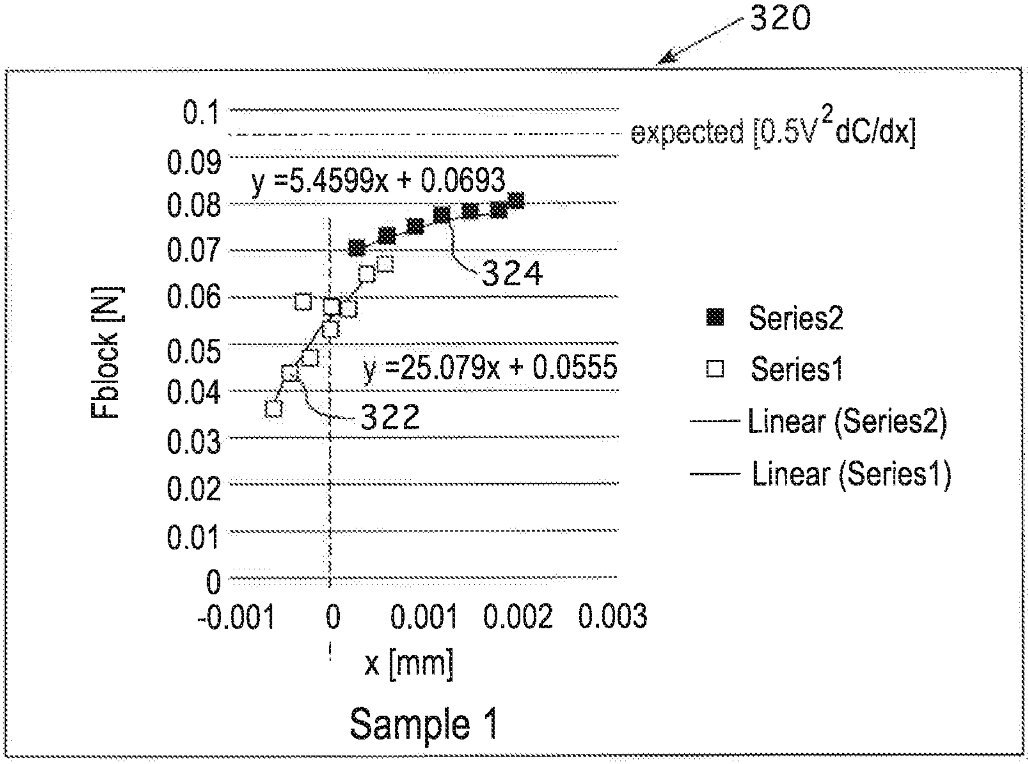

320
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
expected [0.5V2dC/dx]
y =5.4599x + 0.0693
324
y =25.079x + 0.0555
322
Fblock [N]
-0.001
0
0.001
0.002
0.003
x [mm]
Series2
Series1
Linear (Series2)
Linear (Series1)
Sample 1

FIG. 24

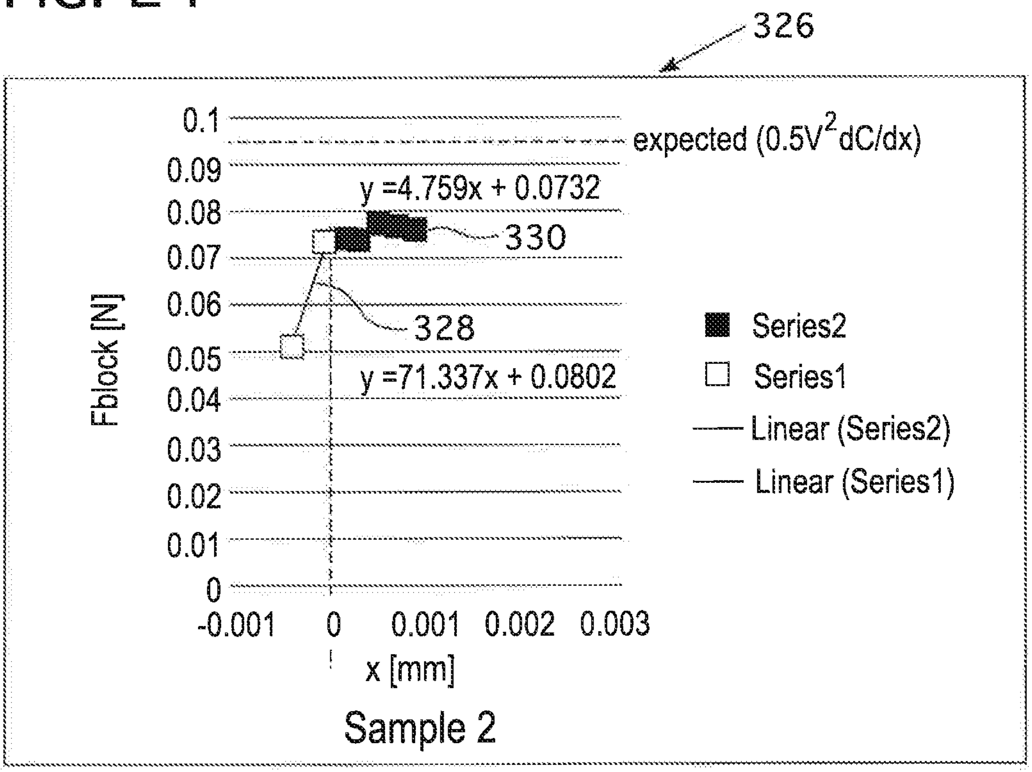

326
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
expected (0.5V2dC/dx)
y =4.759x + 0.0732
330
328
y =71.337x + 0.0802
Fblock [N]
-0.001
0
0.001
0.002
0.003
x [mm]
Series2
Series1
Linear (Series2)
Linear (Series1)
Sample 2

FIG. 25

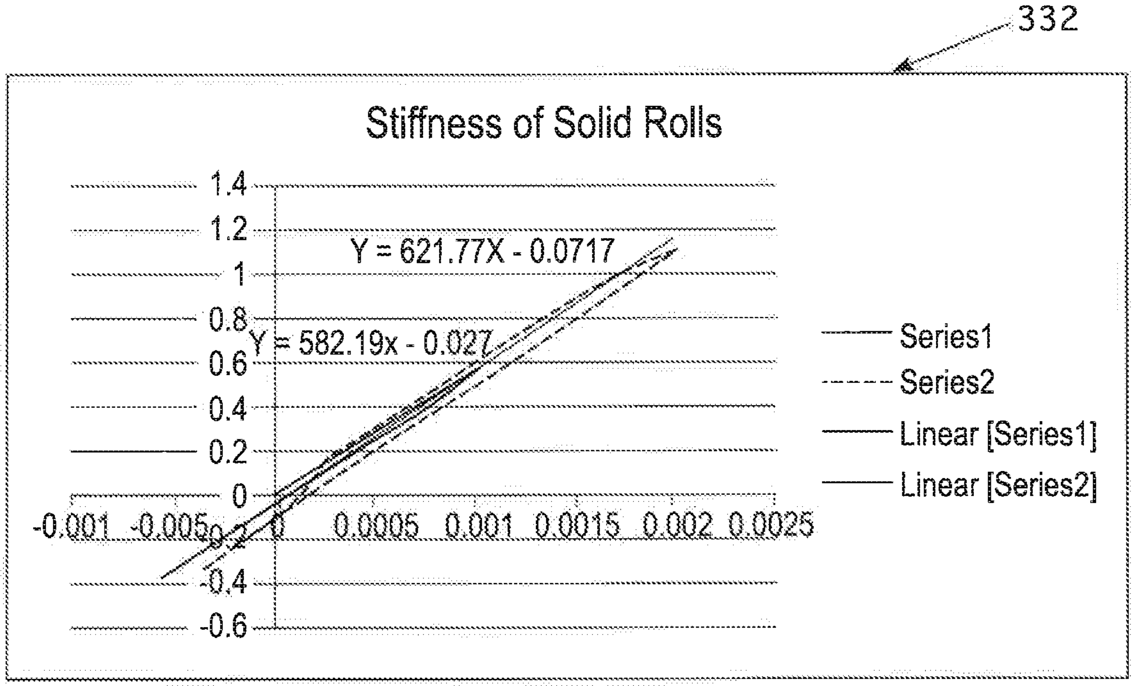

332
Stiffness of Solid Rolls
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.4
-0.6
-0.001
-0.005
0
0.0005
0.001
0.0015
0.002
0.0025
Y = 621.77X - 0.0717
Y = 582.19x - 0.027
Series1
Series2
Linear [Series1]
Linear [Series2]

FIG. 26

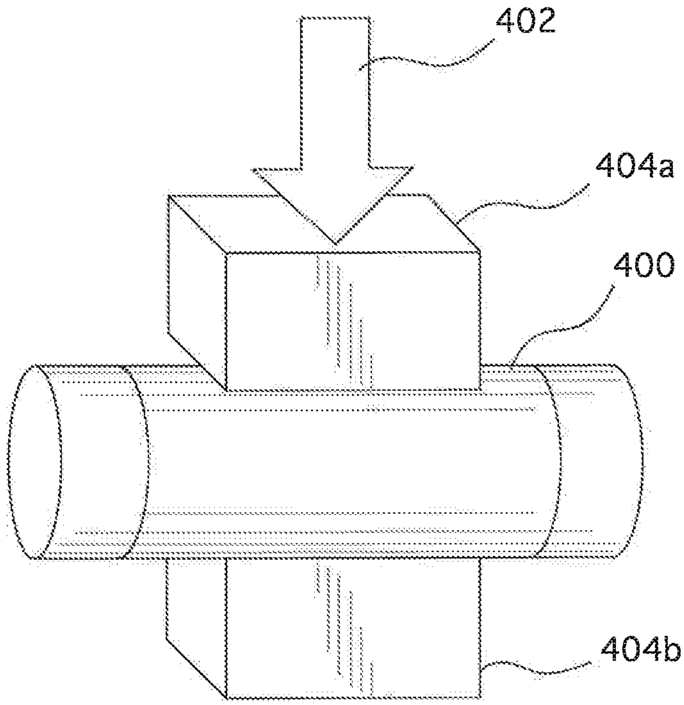

402
404a
400
404b

FIG. 27

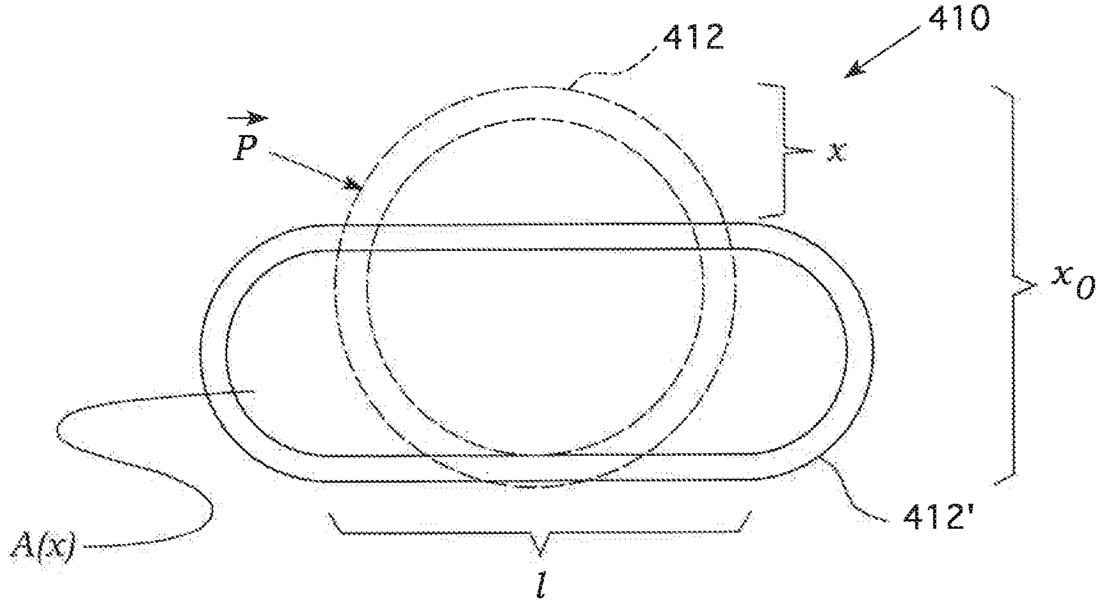

412
410
P
x
x0
A(x)
412'
l

FIG. 28

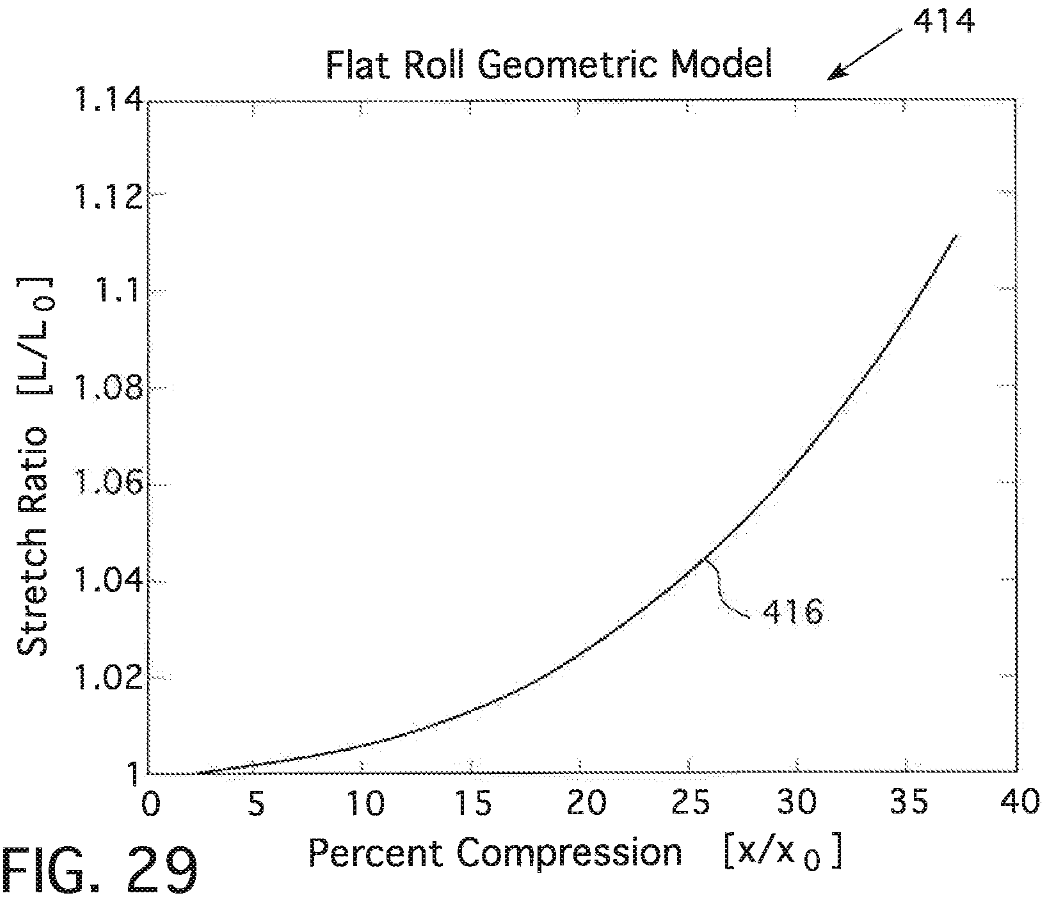

414
Flat Roll Geometric Model
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
Stretch Ratio [L/L0]
416
0
5
10
15
20
25
30
35
40
Percent Compression [x/x0]

FIG. 29

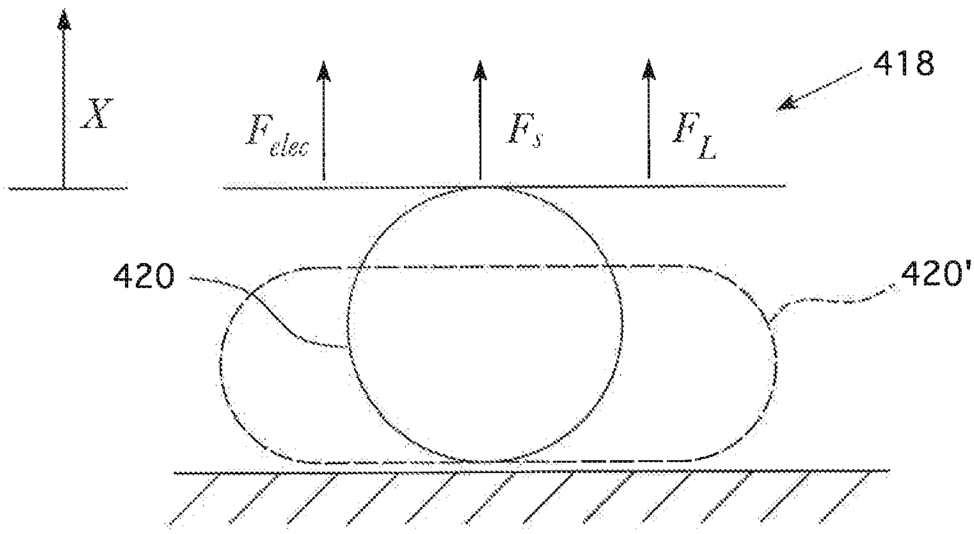

418
X
F_{elec}
F_s
F_L
420
420'

FIG. 30

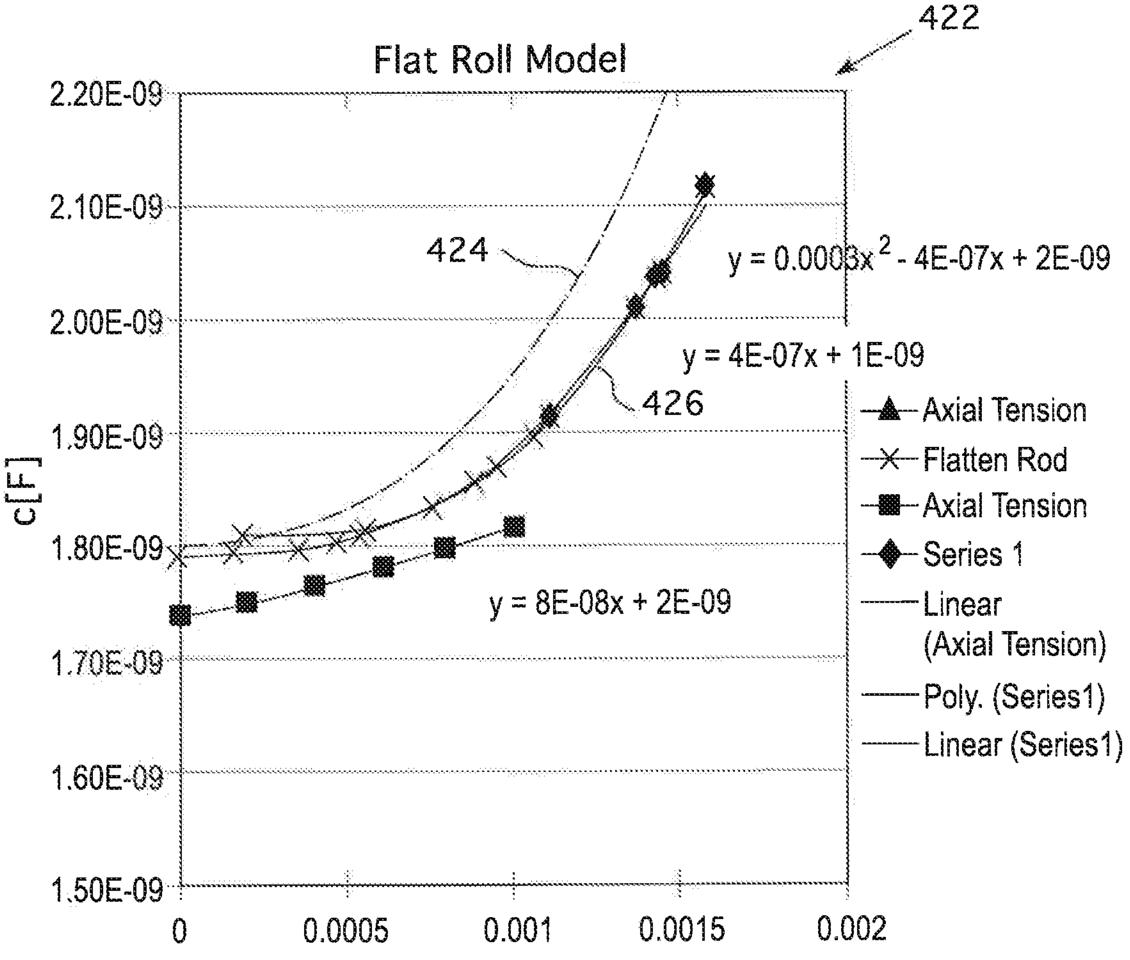

422
Flat Roll Model
2.20E-09
2.10E-09
2.00E-09
1.90E-09
1.80E-09
1.70E-09
1.60E-09
1.50E-09
c[F]
0
0.0005
0.001
0.0015
0.002
x [m]
424
426
y = 0.0003x² - 4E-07x + 2E-09
y = 4E-07x + 1E-09
y = 8E-08x + 2E-09
Axial Tension
Flatten Rod
Axial Tension
Series 1
Linear (Axial Tension)
Poly. (Series1)
Linear (Series1)

FIG. 31

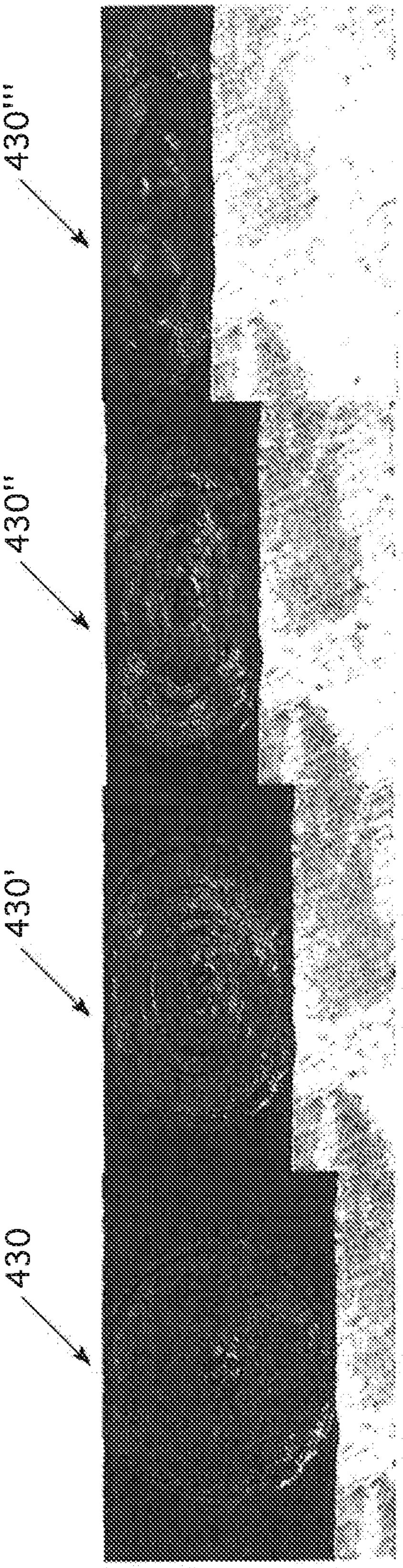


FIG. 32A FIG. 32B FIG. 32C FIG. 32D

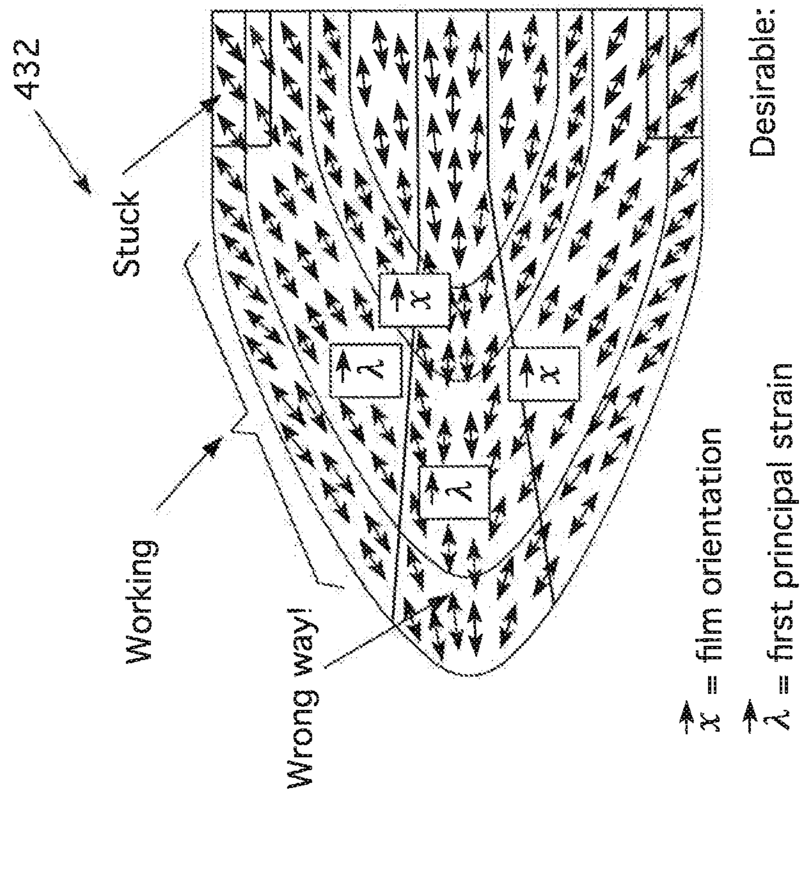
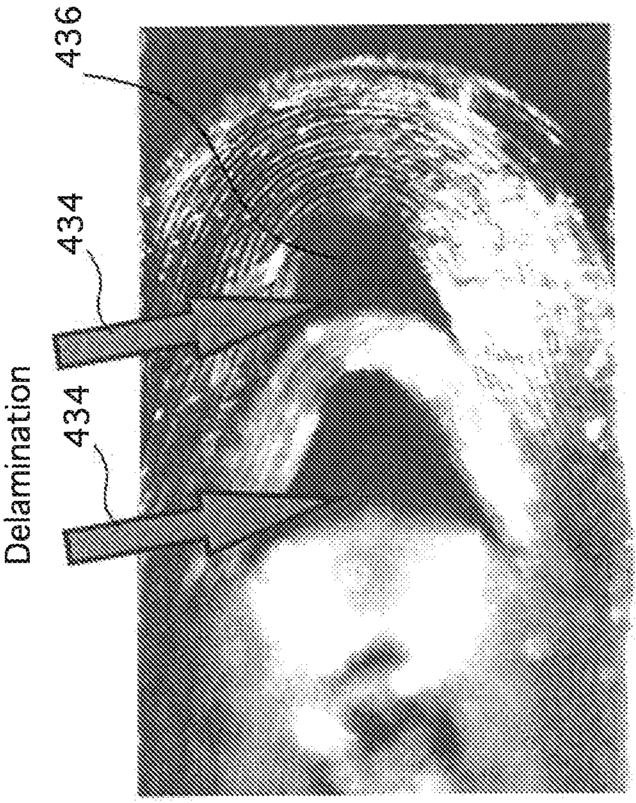


FIG. 33



Desirable: $\text{abs}\left(\left(\frac{\vec{\lambda}}{\|\vec{\lambda}\|}\right) \bullet \vec{x}\right) = 1$, everywhere

FIG. 34

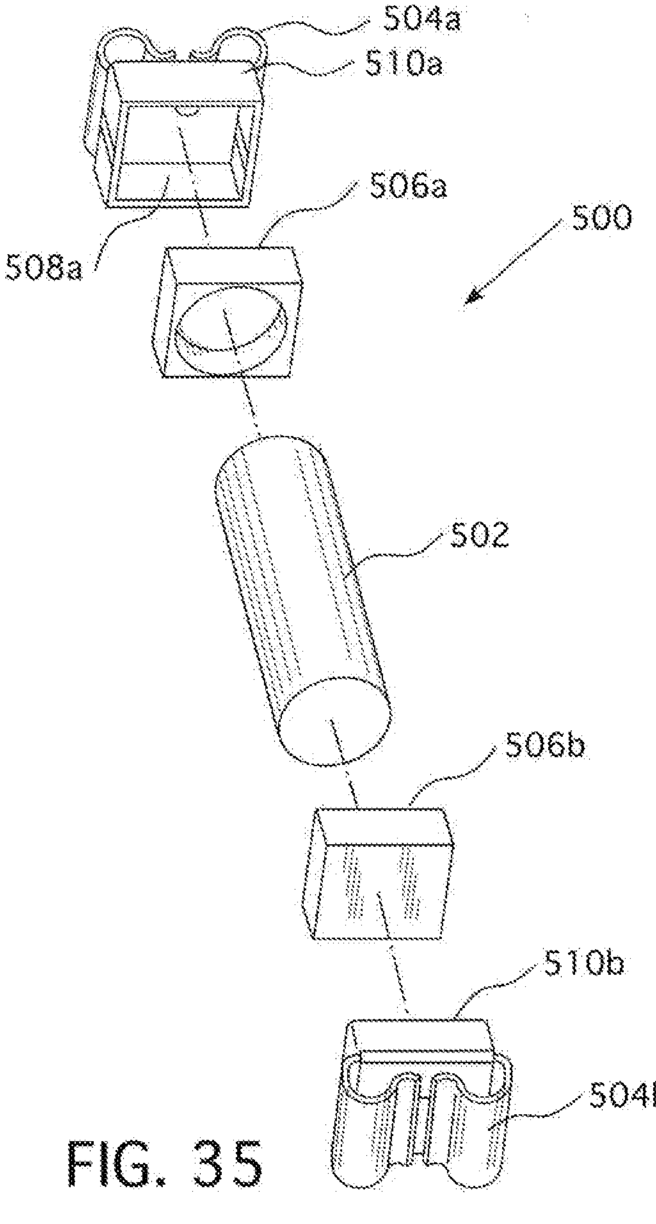

504a
510a
506a
500
508a
502
506b
510b
504b

FIG. 35

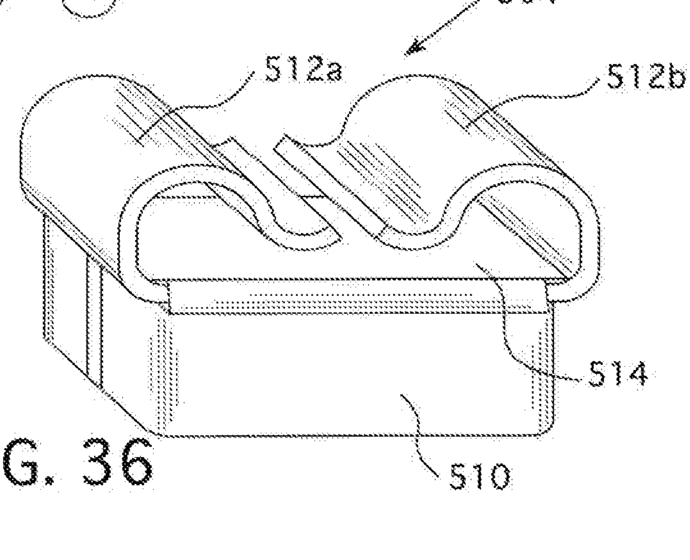

504
512a
512b
514
510

FIG. 36

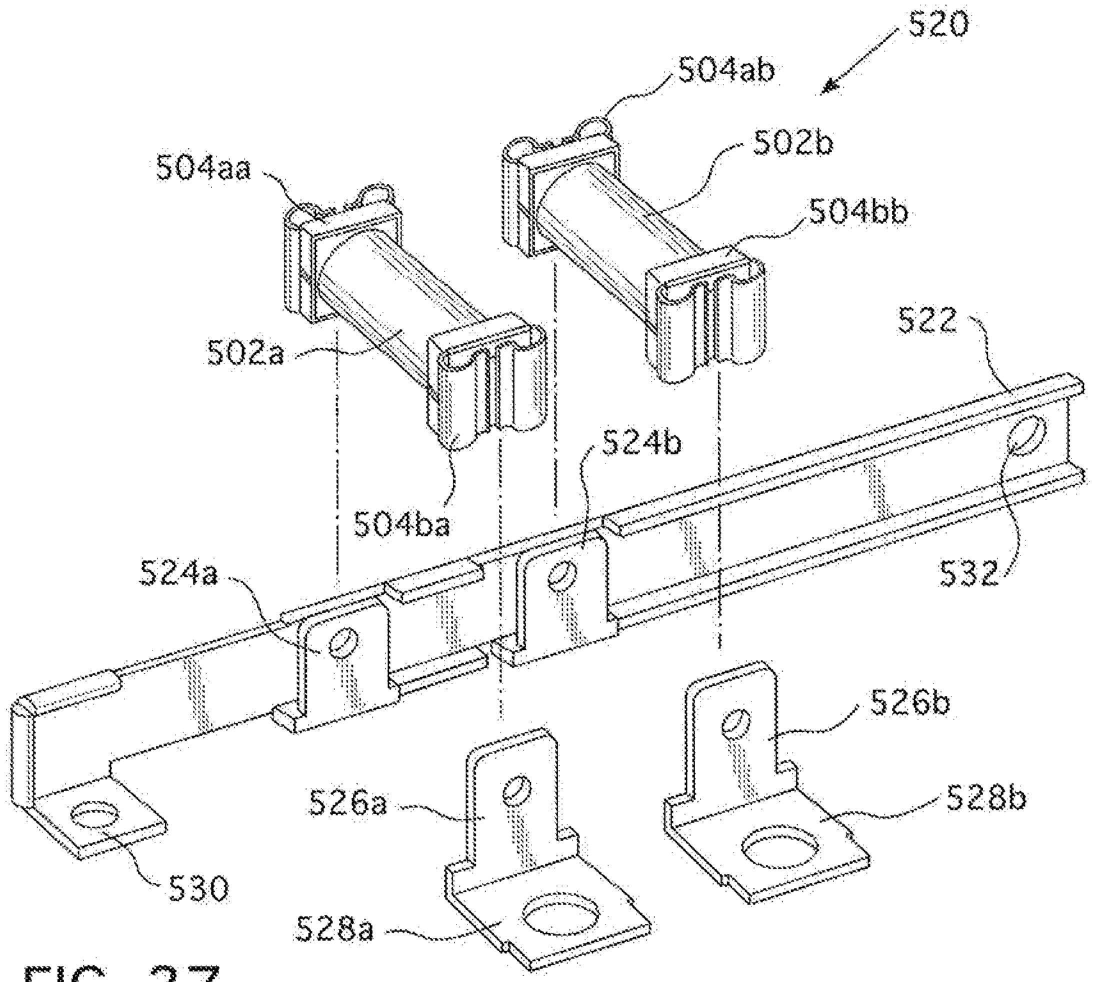

520
504ab
504aa
502b
504bb
522
502a
524b
504ba
524a
532
526b
526a
528b
530
528a

FIG. 37

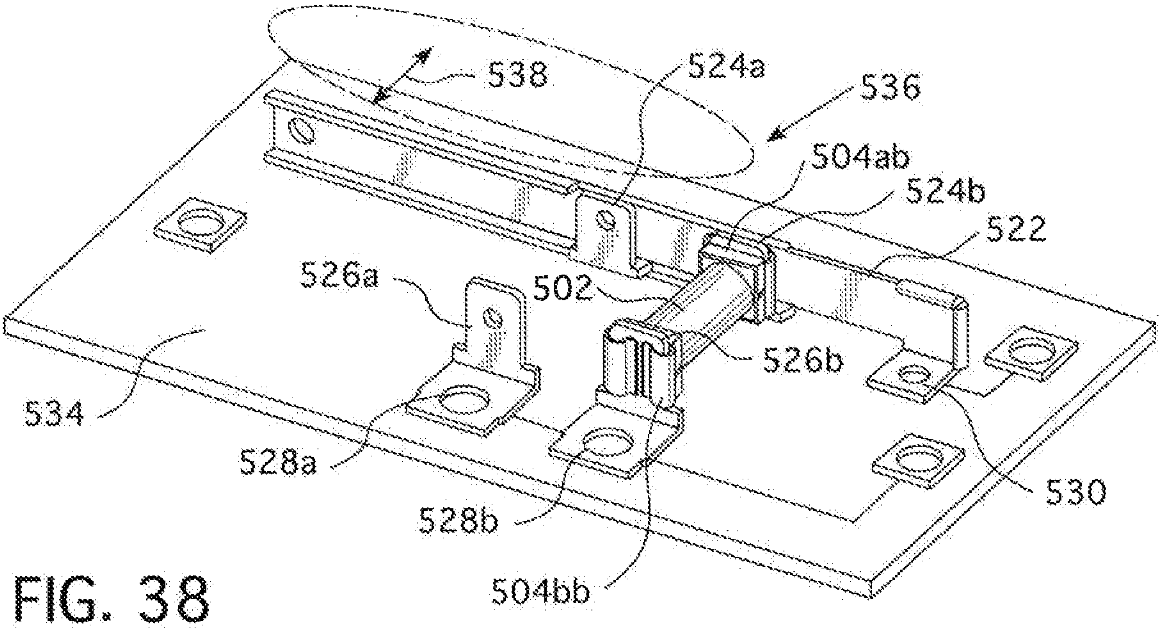

538
524a
536
504ab
524b
522
526a
502
526b
534
528a
530
528b
504bb

FIG. 38

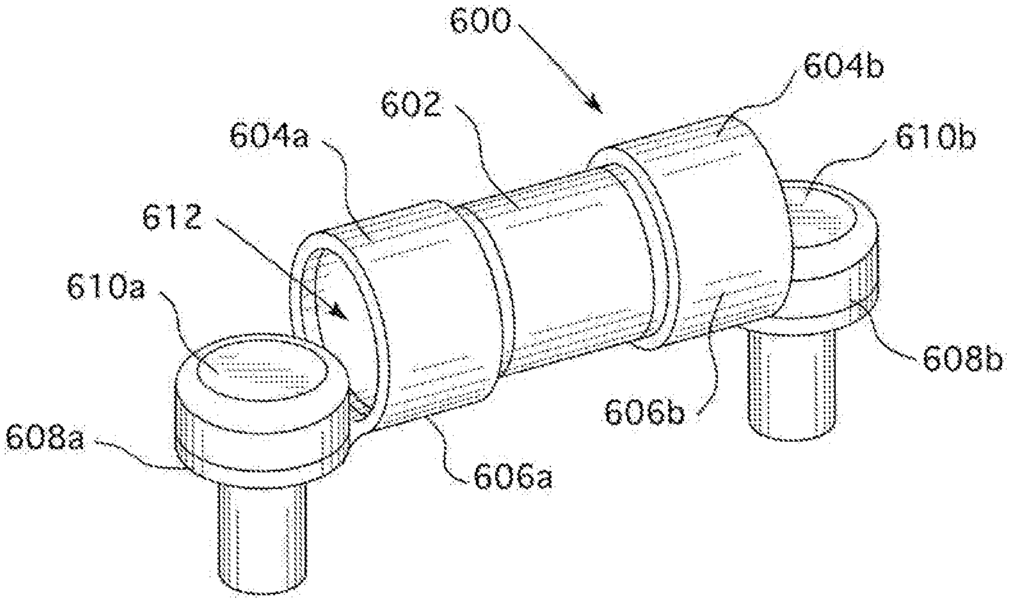

600
604b
602
604a
610b
612
610a
608b
606b
608a
606a

FIG. 39

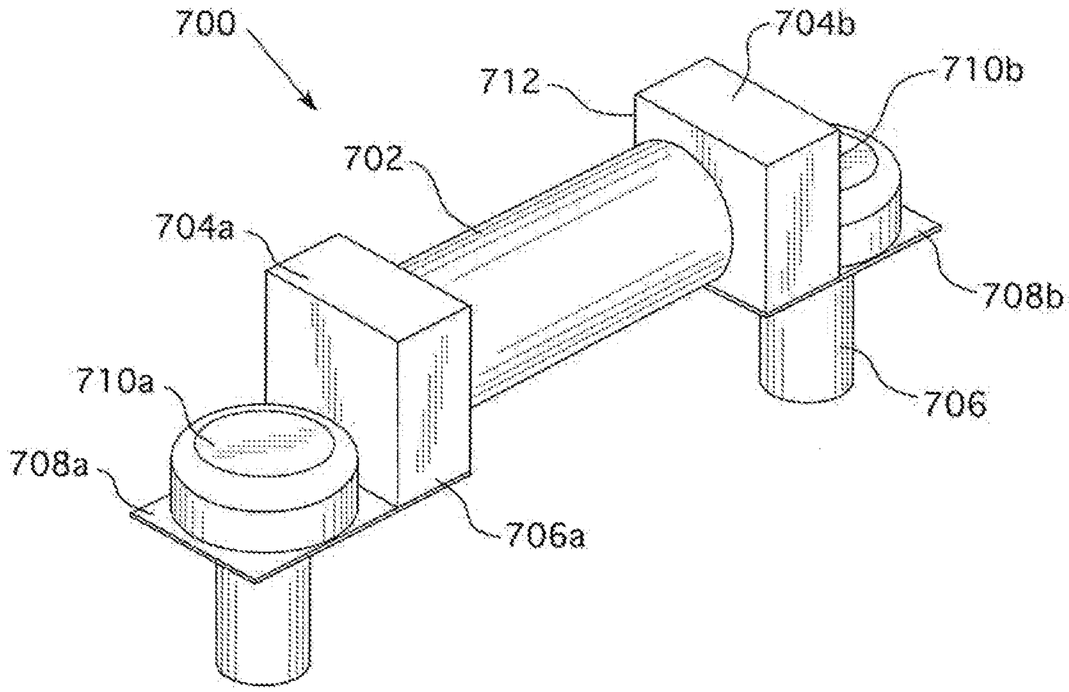

700
704b
712
710b
702
704a
708b
710a
706
708a
706a

FIG. 40

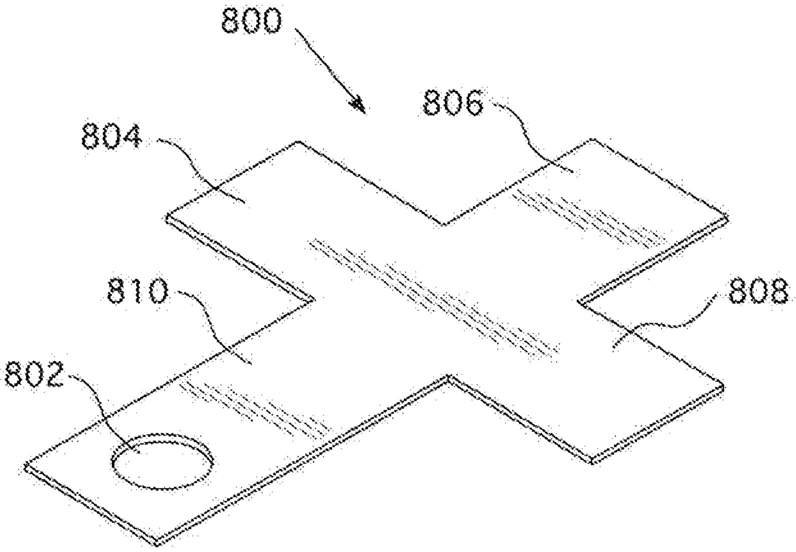

800
806
804
810
808
802

FIG. 41

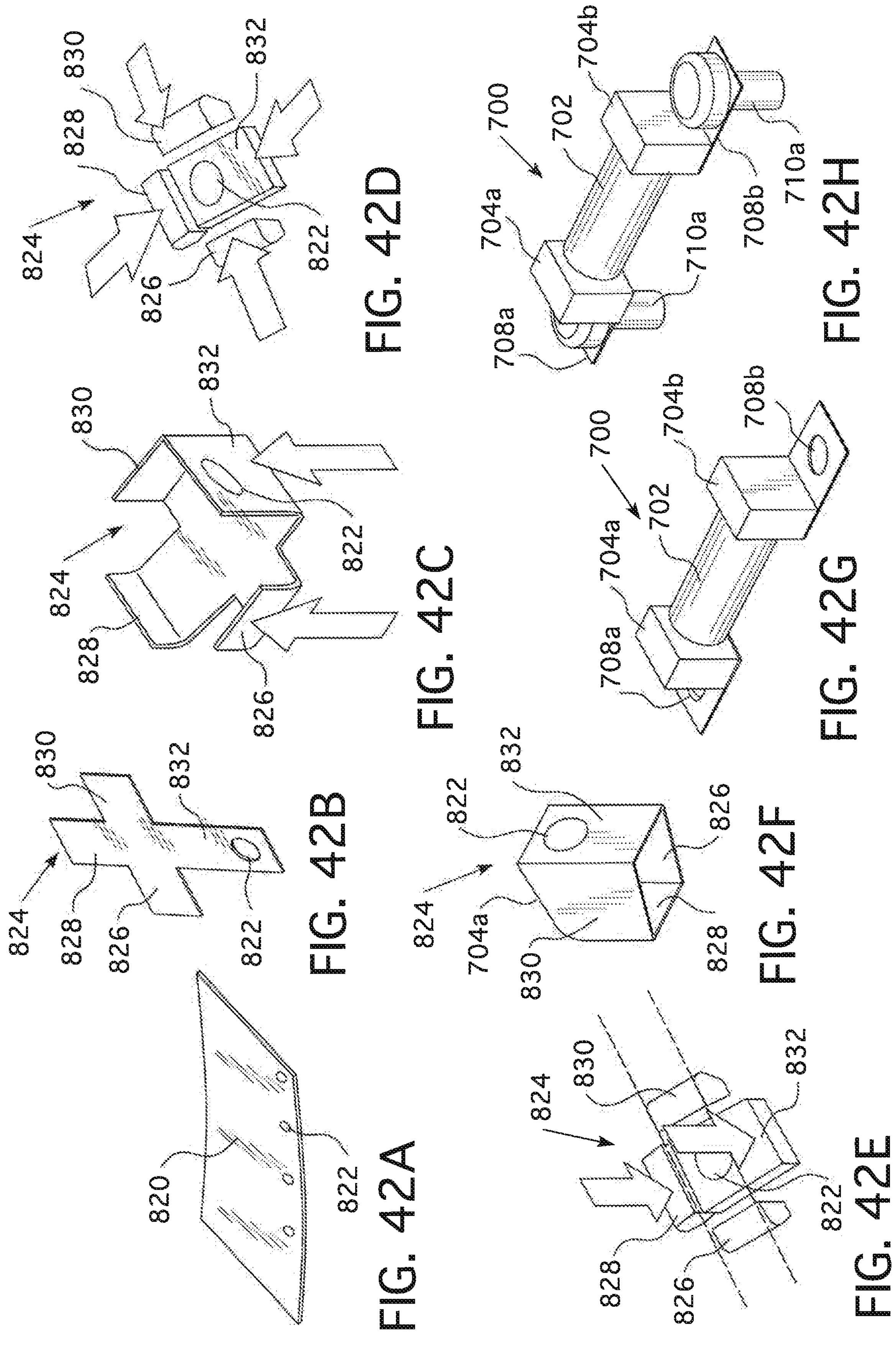


FIG. 42A
FIG. 42B
FIG. 42C
FIG. 42D
FIG. 42E
FIG. 42F
FIG. 42G
FIG. 42H

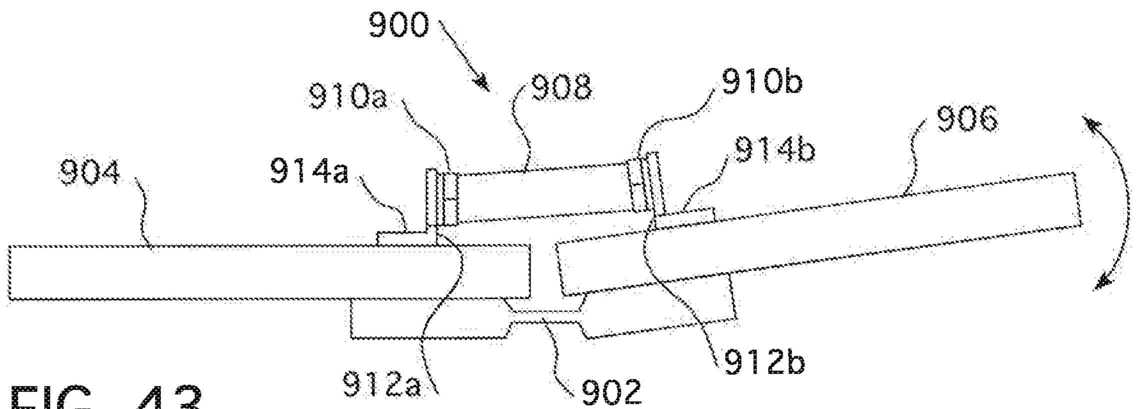


FIG. 43

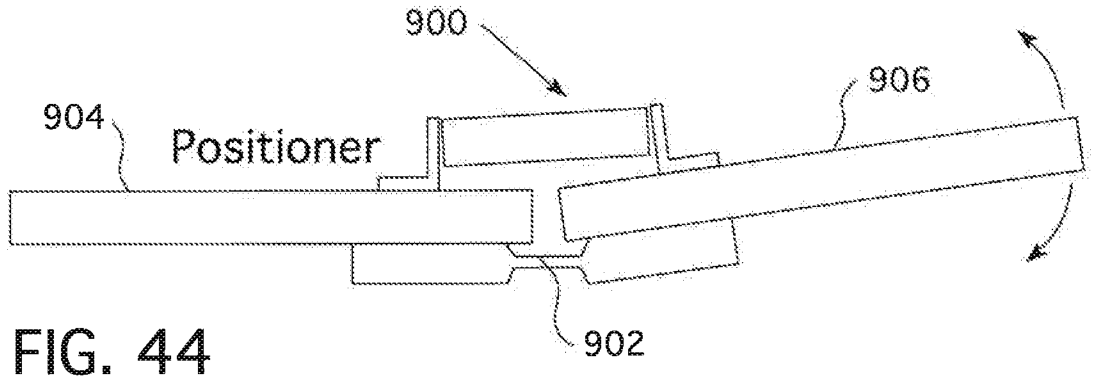


FIG. 44

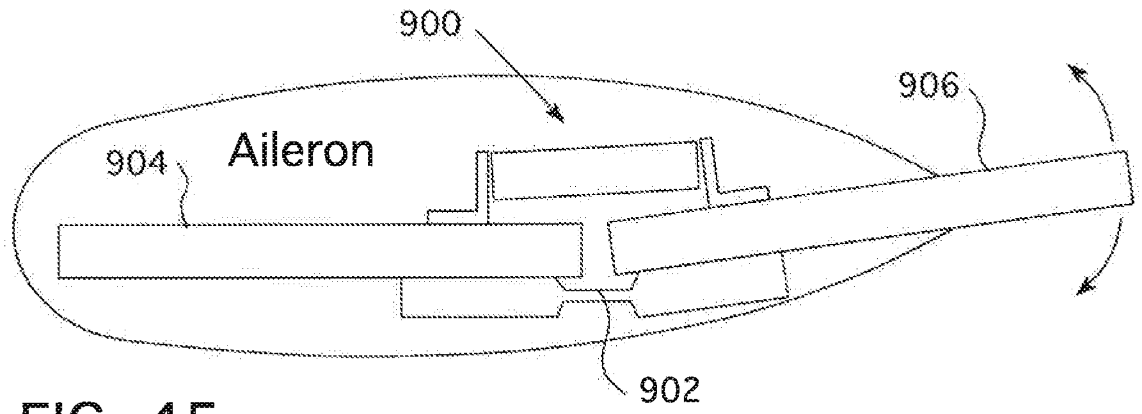


FIG. 45

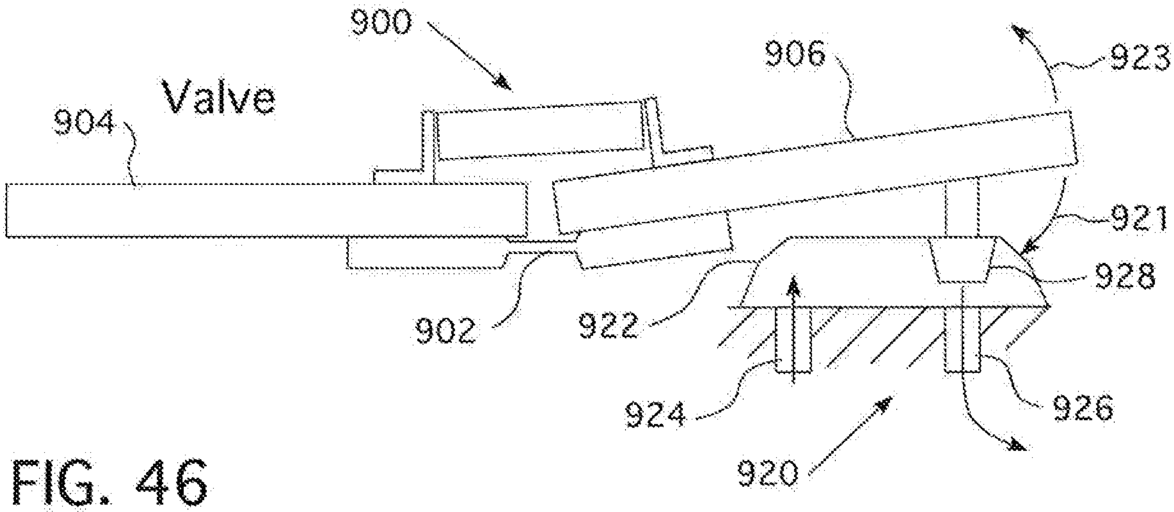

900
Valve
906
923
904
921
928
902
922
924
926
920

FIG. 46

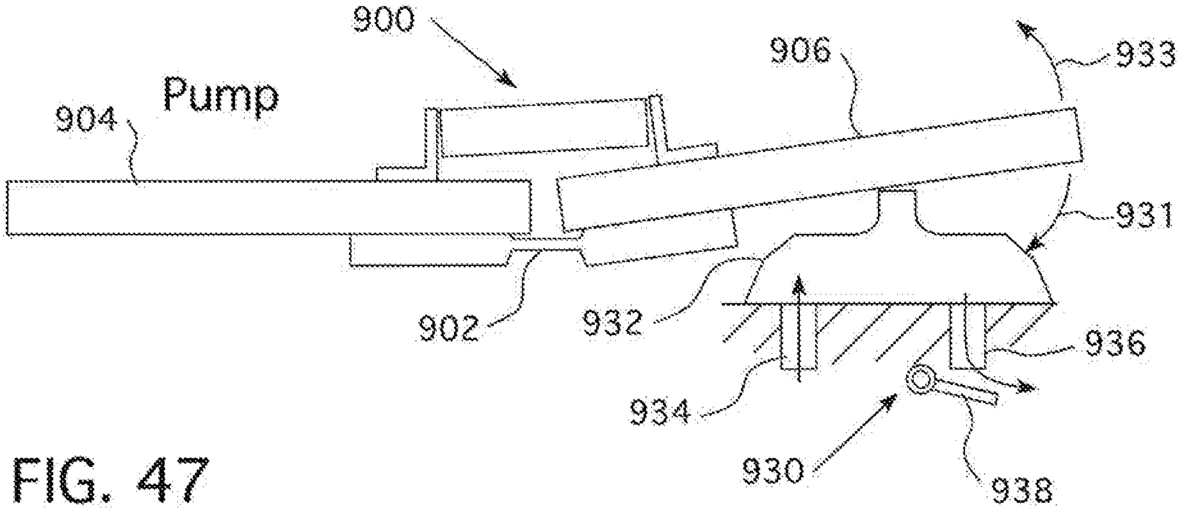

900
Pump
906
933
904
931
902
932
936
934
930
938

FIG. 47

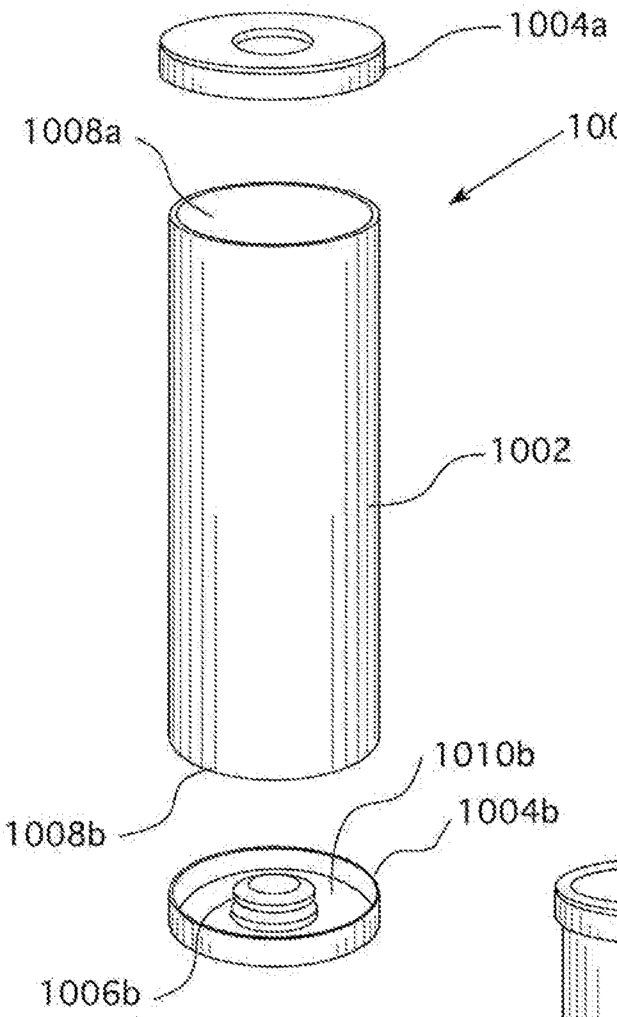

1004a
1000
1008a
1002
1010b
1004b
1008b
1006b

FIG. 48

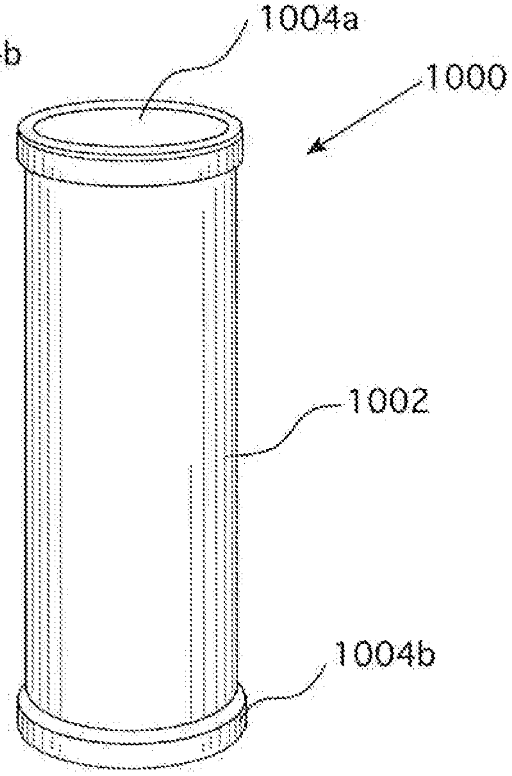

1004a
1000
1002
1004b

FIG. 49

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A. CLASSIFICATION OF SUBJECT MATTER

H02N 2/02(2006.01)i, H01L 41/04(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)
H02N 2/02; H01L 41/04; C08K 3/00; H01L 41/26; H01L 41/053; C08L 21/00; H02N 1/00; H01L 41/00; H04R 31/00

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: dielectric elastomer transducer, terminal, flexure, connector, roll

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011-0025170 A1 (MARCUS A. ROSENTHAL et al.) 03 February 2011 See abstract, paragraphs [0011],[0014],[0126],[0131]-[0138],[0147], claims 1,9-10, and figures 2A-3Z,8A-8E.	1-6,14
A		7-13
A	WO 2011-118315 A1 (TOKAI RUBBER INDUSTRIES, LTD. et al.) 29 September 2011 See abstract, paragraphs [0071],[0091]-[0093], claims 9-11, and figures 1-6.	1-14
A	US 2010-0109486 A1 (ILYA POLYAKOV et al.) 06 May 2010 See paragraphs [0041],[0043],[0045],[0047], claims 1-2,18,27, and figures 1A-4D.	1-14
A	US 2007-0114885 A1 (MOPHAMED YAHIA BENSLIMANE et al.) 24 May 2007 See abstract, paragraphs [0060]-[0071],[0120],[0133], claims 1,44, and figures 2a-3b.	1-14
A	US 2012-0068572 A1 (WERNER JENNINGER et al.) 22 March 2012 See paragraphs [0132]-[0136], claims 1-2, and figures 1a-3b.	1-14

☐ Further documents are listed in the continuation of Box C.   ☒ See patent family annex.

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"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
16 December 2013 (16.12.2013)	**17 December 2013 (17.12.2013)**

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