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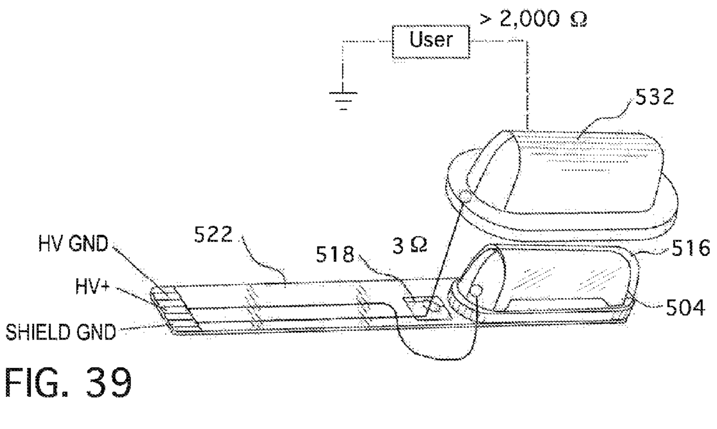

FIG. 39

(57) Abstract: An apparatus includes a substrate, a dielectric elastomer transducer electrically coupled to the substrate, and a compliant electrically conductive housing coupled to the dielectric elastomer transducer. A portion of the compliant electrically conductive housing projects through an opening defined in a housing. A method is disclosed for making the apparatus.

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ROLLED AND COMPLIANT DIELECTRIC ELASTOMER ACTUATORS

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 compliant actuators comprising rolled dielectric elastomer transducers.

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 while maintaining precision and consistency of the films. There is also a need to ensure the safety of the consumer during use of electroactive polymer devices which may be operated at high operating voltages.

Conventional rolled dielectric elastomer transducer based cylindrical actuators are desirable because a cylindrical shape is functional and familiar. It matches many mechanical components, such as, for example, solenoids, air cylinders, shock absorbers, etc. so mounting hardware is readily available, for example, the clevis, the ball joint, and the threaded rod. Engineers' familiarity with cylindrical actuators simplifies their efforts to integrate them in new designs. Nevertheless, hollow, rolled dielectric elastomer tubes and tubes with an internal spring, called "spring rolls" have some drawbacks. Empty space inside the tube is wasted, making the transducer larger than strictly necessary. Also, accumulated tension from winding the outer layers of the tube tends to buckle and collapse the tube. In a tubular roll made with a highly prestrained acrylic dielectric, this imposed a practical limit of only a few turns per transducer.

Multilayer stacked actuators similarly eliminate wasted empty volume to maximize the density of active material. They may be particularly desired in applications where they are mounted onto a flat surface.

The present disclosure provides dielectric elastomer compliant actuators comprising dielectric elastomer transducers provided in various packages and configurations for interfacing with devices and users. Such compliant actuators may be integrated into various products and may be configured as active buttons and display surfaces for custom button clicks, navigation cues, and the like. Soft, shielded actuators may be projected through hard cases and housing of products such as smartphones, game consoles, pad computers, and the like.

SUMMARY OF THE INVENTION

In one embodiment, an apparatus comprises a substrate, a dielectric elastomer transducer electrically coupled to the substrate, and a compliant electrically conductive housing coupled to the dielectric elastomer transducer.

In another embodiment, an apparatus comprises a housing defining an opening, a substrate, a dielectric elastomer transducer electrically coupled to the substrate, and a compliant electrically conductive housing coupled to the dielectric elastomer transducer, wherein a portion of the compliant electrically conductive housing projects through the opening defined in the housing.

In yet another embodiment, a method comprises providing a substrate, attaching electrical terminals to the substrate, attaching a dielectric elastomer transducer to the electrical terminals, and applying an electrically insulative coating on the dielectric elastomer transducer.

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 compliant actuator module configuration for a touch interface in accordance with one embodiment of the present invention;

Fig. 36 illustrates an exploded view of the solid dielectric elastomer transducer roll module and various connection options in accordance with one embodiment of the present invention;

FIG. 37 is an exploded view of the compliant actuator module shown in Fig. 35 configured to electrically mount to a flex circuit in accordance with one embodiment of the present invention;

Fig. 38 illustrates a bottom perspective view of the electrical shield in accordance with one embodiment of the present invention;

Fig. 39 illustrates a schematic diagram of the compliant actuator module electrical isolation feature making it electrically safe for a user to touch the actuator module with the fingertip in accordance with one embodiment of the present invention;

Fig. 40 illustrates a series of molding steps in the manufacturing process of a compliant actuator module in accordance with one embodiment of the present invention;

Figs. 41-43 illustrate one method of assembling the shield laminate to the compliant actuator module in accordance with one embodiment of the present invention, where:

Fig. 41 illustrates a solid dielectric elastomer transducer roll module attached to a flex circuit in accordance with one embodiment of the present invention;

Fig. 42 illustrates a partial cut-away view of the shield and the solid dielectric elastomer transducer roll module attached to the flex circuit in accordance with one embodiment of the present invention;

Fig. 43 illustrates a compound mold for molding the shield onto the solid dielectric elastomer transducer roll module to form the compliant actuator module in accordance with one embodiment of the present invention;

Figs. 44-47 illustrate techniques for pre-straining circular solid dielectric elastomer transducer rolls into a stack orientation in accordance with one embodiment of the present invention, where:

Figs. 44 and 45 illustrate a pulling technique in accordance with one embodiment of the present invention;

Figs. 46 and 47 illustrate another pulling technique in accordance with one embodiment of the present invention;

Figs. 48-50 illustrate a cantilever beam inertial module for handheld devices in accordance with one embodiment of the present invention, where:

Fig. 49 illustrates a top view of the cantilever beam inertial module in accordance with one embodiment of the present invention;

Fig. 50 illustrates a partial perspective view of the cantilever beam inertial module showing the mass attached to one end of the conductive strip in accordance with one embodiment of the present invention;

Fig. 51 illustrates a handheld device comprising a soft active button based on dielectric elastomer actuators described herein in accordance with one embodiment of the present invention;

Fig. 52 illustrates a device comprising one or more soft active buttons based on dielectric elastomer actuators described herein in accordance with one embodiment of the present invention;

Fig. 53 illustrates a game console device comprising one or more soft active buttons based on dielectric elastomer actuators described herein in accordance with one embodiment of the present invention;

Fig. 54 illustrates a screen comprising one or more compliant actuator modules as described hereinbefore in accordance with one embodiment the present invention;

Fig. 55 illustrates another screen comprising one or more compliant actuator modules as described hereinbefore in accordance with one embodiment the present invention; and

Fig. 56 illustrates a handheld device comprising one or more compliant actuator modules as described hereinbefore in accordance with one embodiment 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.

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 can 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.

The present disclosure also provides dielectric elastomer based compliant actuators that use electrical energy to generate a force which conveys information to a user in contact with the compliant which can be integrated into a variety of product packages. The compliant actuators comprise at least one solid rolled dielectric elastomer transducers provided in various package configurations for interfacing with devices and users. Such actuators may be integrated into various products and may be configured as active buttons and display surfaces for custom button clicks, navigation cues, and the like. Soft, shielded actuators may be project through hard cases and housing of products such as smartphones, game consoles, pad computers, and the like. With suitable packaging techniques, the dielectric elastomer actuators can be safely touched by a user.

Such compliant actuators and related packaging therefore are described in connection with Figs. 35-56. However, prior to describing Figs. 35-56, the present disclosure initially turns to a description of Figs. 1-34 to provide a context for the description that follows.

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:

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

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

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

$$\sum F_i = -2\sigma_p tl + 2rl\Delta P = 0 \quad \text{Eq. 3}$$

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

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.

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

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 **$194a_1$**, **$194a_2$** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178a**, terminals **$194b_1$**, **$194b_2$** are attached and cured **196** onto the ends of the solid dielectric elastomer transducer roll **178b**, and terminals **$194c_1$**, **$194c_2$** 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 $\mathbf{106_1}$, $\mathbf{106_2}$, and $\mathbf{106_3}$ 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 $\mathbf{108_1}$, $\mathbf{108_2}$, and $\mathbf{108_3}$ material juxtaposed relative to each other and spaced apart by a gap **237** therebetween. The layers of electrodes $\mathbf{106_1}$, $\mathbf{106_2}$, and $\mathbf{106_3}$ on the first side of the dielectric film **102** are offset or staggered from the layers of electrodes $\mathbf{108_1}$, $\mathbf{108_2}$, $\mathbf{108_3}$ on the second side of the dielectric film **102** to create the overlapping regions $\mathbf{232_1}$, $\mathbf{232_2}$ 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 $\mathbf{106_1}$, $\mathbf{106_2}$, $\mathbf{106_3}$, $\mathbf{108_1}$, $\mathbf{108_2}$, and $\mathbf{108_3}$ 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 $\mathbf{194a_1}$, $\mathbf{194a_2}$ 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 $\mathbf{194a_1}$, $\mathbf{194a_2}$. As previously discussed in Figs.7I and 7J, the electrical terminal caps $\mathbf{194a_1}$, $\mathbf{194a_2}$ 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	$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} \left(\ln(n+1) - \ln(n)\right)^{-1}$	Eq. 7
Spring Rate	$k = Y(y_0 + y_p)t_0 / (x_0 + x_p)$	Eq. 8

Free Stroke	$\Delta x \cong \frac{F_{load}}{k}$	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 ($y_{o}t$) or rolled up into a circle ($\pi b^2{}_o$):

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

$$y_o t_0 = \pi (Nt_0)^2 \qquad \text{Eq. 13}$$

$$Nt_0 = \left(\frac{y_0 t_0}{\pi}\right)^{1/2} \qquad \text{Eq. 14}$$

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

Volume Inside Each Ring Is Conserved

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

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

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

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

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

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

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

Volume Of Each Ring Itself Is Conserved

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Capacitance Of The Annular Capacitor

Initially the capacitance is:

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

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):

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

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

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

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

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

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.

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

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

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

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

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

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.

$$F_{total} = V^2 \pi \varepsilon \varepsilon_0 \sum_{n=1}^{N} \left(\ln\left(\frac{(n+1)t_0}{nt_0} \right) \right)^{-1} \qquad \text{Eq. 48}$$

Canceling like terms

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

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

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.

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

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

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

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:

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

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

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

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:

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

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.

Case 1 – Electrode Negligible

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.

Case 2 – Electrode Stiff

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:

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

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:

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

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

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

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

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

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

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

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

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

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

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 $dC/dx=k_1x$. The spring force is also approximated well with a single term such that $F_s=k_3x^2$

$$\tfrac{1}{2} V^2 (k_1x) + k_3x^2 + F_L = 0 \qquad \text{Eq. 68}$$

$$k_1V^2/2\, x + k_3x^2 + F_L = 0 \qquad \text{Eq. 69}$$

$$k_3x^2 + (\tfrac{1}{2} k_1V^2)x + F_L = 0 \qquad \text{Eq. 70}$$

The equilibrium displacement of the roll subjected to the static load is found from the roots of the quadratic equation, where $a = k_3$, $b = \tfrac{1}{2} k_1V^2$ and $c = F_L$.

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

The Pseudo-DC Roll Model

$$F_{elec} = \tfrac{1}{2} V^2\, dC/dx \qquad \text{Eq. 72}$$

$$F_{elec} = \tfrac{1}{2} V^2 (k_1x) \qquad \text{Eq. 73}$$

$$F_S = k_3x^2 \qquad \text{Eq. 74}$$

$F_L = -4$, [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 compliant actuator module **500** configuration for a touch interface in accordance with one embodiment of the present invention. The compliant actuator module **500** is packaged in a manner that is safe to touch. In the embodiment shown in Fig. 35, the compliant actuator module **500** is integrated with a case or housing **512** defining an aperture **514** to provide touch access to a portion of the compliant actuator module **500**. In one embodiment, the compliant actuator module **500** comprises a compliant electrically conductive housing **502** and a solid dielectric elastomer transducer roll module **504** attached to a module support **508**, which is specific to the case or housing in which the compliant actuator module **500** is integrated with. The module support **508** is configured to fixedly attach the substrate **506** to the housing **512**. Optionally, the compliant actuator module **500** may comprise mounting fasteners **510**. A portion of the compliant conductive housing **502** protrudes through an opening **514** defined in the housing **512** or housing of a device. The compliant conductive housing **502** is made of an electrically conductive material and is electrically connected to case ground (shield ground) at terminal **518** by an electrically conductive adhesive **520**. In one embodiment, a flex connector **522** electrically couples the solid dielectric elastomer transducer roll module **504** to an electronic system through electrical contacts and / or traces **524**. The configured to generate drive signals for the solid dielectric elastomer transducer roll **504**.

Fig. 36 illustrates an exploded view of the solid dielectric elastomer transducer roll module **504** and various connection options in accordance with one embodiment of the present invention. The solid dielectric elastomer transducer roll module **504** comprises a substrate **506** which includes holes **526a**, **526b** for injection molding and for wire termination. The substrate also includes electrically conductive terminals **528** that are suitable for soldering wires or for soldering surface mount technology (SMT) components thereto. The conductive terminals **528a**, **528b** are accessible above and below the substrate as discussed hereinbelow. SMT terminal points **530** are soldered to the conductive terminals **528a**, **528b**. A solid dielectric elastomer transducer roll **531** is then attached to the substrate **506** and conductive silicone **534** is applied at the ends of the solid dielectric elastomer transducer roll **531**, by insert molding or other techniques, to electrically couple the transducer roll **534** to the terminal points **530** and the conductive terminals **528a**, **528b**. An electrically insulative silicone coating **516** is applied to the exterior surface of the transducer roll **534**, by insert molding, or other techniques. The electrically insulative silicone coating **516** is interposed between the transducer roll **534** and the compliant electrically conductive housing **502**.

There are various options for providing electrical connections to the solid dielectric elastomer transducer roll module **504**. One option includes attaching the flex circuit **522** to the transducer module **504** via SMT conductive terminals **536a**, **536b** provided underneath the substrate **506**. The conductive terminals of the flex circuit **522** are coupled to a high voltage driver circuit. The SMT conductive terminals **536a**, **536b** on the bottom layer of the substrate **506** are electrically coupled to the SMT conductive terminals **528a**, **528b** on the top layer of the substrate **506**. The bottom SMT conductive terminals **536a**, **536b** may be used to attach the transducer roll module **504** to other substrates and / or external devices.

Alternatively, the transducer roll module **504** may be electrically coupled by electrical wires **538a**, **538b** attached through conductive via through-holes **526a**, **526b** through the substrate **506**. The high voltage positive (HV+) lead wire **538a** is connected to the positive terminal of a high voltage drive circuit and the high voltage ground (HV GND) lead wire **538b** is connected to the ground terminal of the high voltage drive circuit. Housing ground (SHIELD GND) is connected to terminal **518**. Alternatively, the transducer roll module **504a** may be electrically connected to other systems and / or substrates by way of quick-connect interconnects such as those described in commonly owned PCT International Patent Application [Atty. Docket No. BMS123012PCT], which is hereby incorporated by reference in its entirety.

FIG. 37 is an exploded view of the compliant actuator module **500** shown in Fig. 35 configured to electrically mount to a flex circuit **522** in accordance with one embodiment of the present invention. The compliant actuator module **500** comprises a solid dielectric elastomer transducer roll module **504**, an electrical shield **532**, and a flex circuit **522**. The electrical shield **532** provides electrical isolation and makes it electrically safe for a user to touch the actuator module **500** with the fingertip. Fig. 38 illustrates a bottom perspective view of the electrical shield **532** in accordance with one embodiment of the present invention. With reference to Figs, 37 and 39, the illustrated embodiment of the electrical shield **532** is fabricated by laminating abrasion-resistant thermoplastic polyurethane (TPU) to an electrically conductive material such as metal plated fabric and vacuum forming it to make a stretchable or compliant conductive shield. The electrical shield **532** is soft to the touch with a low durometer (for example, Shore A 50-80) and can be configured as an active button for handsets, game controllers, and the like. In one embodiment, a 10/1000" (10 mil) thick TPU allows the actuator sufficient freedom to move. In other embodiments, the electrically conductive fabric can be sandwiched between two thinner layers of TPU, for example, 5/1000" (5 mil). Other structures can be used. The fabric can be embedded in a castable or moldable electrically insulative polymer or elastomeric matrix such as a rubber, polyurethane, silicone, olefin, fluoropolymer, styrenic copolymer, olefinic copolymer, or the like. Other flexible/stretchable conductive materials such as conductive polymers, conductive polymer composites or corrugated metal foil, can be used with or in lieu of the conductive fabric. The fabric can be produced by any method for producing textiles such as weaving, knitting, or felting.

Fig. 39 illustrates a schematic diagram of the compliant actuator module **500** electrical isolation feature making it electrically safe for a user to touch the actuator module **500** with the fingertip in accordance with one embodiment of the present invention. As shown the HV+ terminal on the flex circuit **522** is electrically coupled to the positive terminal (**528a** as shown in Fig. 36) of the solid dielectric elastomer transducer roll module **504**. The SHIELD GND terminal of the flex circuit **522** is electrically coupled to the electrical shield **532** through the terminal **518**. To connect the shield **532** to the terminal **518**, a small portion of the conductive textile is exposed and soldered to the terminal **518**. In the event a fault occurs, such as short circuit between the solid dielectric elastomer transducer roll module **504** and the shield **532** through the electrically insulative silicone coating **516**, the shield provides a shunt path (~3Ω) to the SHIELD GND relative to a high impedance user resistance path (~2000Ω) to ground. Accordingly, any stray current is shunted to ground and the shunt current is isolated from the user with a layer of compliant insulation, such as for example, electrically insulative silicone coating **516**. When the shunt is detected, a signal is provided to a ground fault circuit interrupter (GFCI) circuit breaker that shuts down the high voltage power supply to prevent the user from being shocked. A robust chain of electrical and mechanical connections are employed to couple the compliant actuator module **500** to rigid electronics.

Fig. 40 illustrates a series of molding steps in the manufacturing process of a compliant actuator module **500** in accordance with one embodiment of the present invention. First, SMT anchors are soldered on a substrate **506** printed circuit board (PCB). A substrate 506 is provided in Mold 1, where the terminals are molded. The solid dielectric elastomer transducer roll module **504** is attached to the substrate **506**. In Mold 2, a potting compound is over-molded over the solid dielectric elastomer transducer roll module **504** attached to the substrate **506**. Shields **532** are vacuum formed in Mold 3.

Figs. 41-43 illustrate one method of assembling the shield **532** laminate to the compliant actuator module **500** in accordance with one embodiment of the present invention. Fig. 41 illustrates a solid dielectric elastomer transducer roll module **504** attached to a flex circuit **522** in accordance with one embodiment of the present invention. A flex seal **540** is attached with conductive adhesive at a seam **542** formed between the flex circuit **522** and the substrate **506**. Fig. 42 illustrates a partial cut-away view of the shield **532** and the solid dielectric elastomer transducer roll module **504** attached to the flex circuit **522** in accordance with one embodiment of the present invention. Fig. 43 illustrates a compound mold **558** for molding the shield **532** onto the solid dielectric elastomer transducer roll module **504** to form the compliant actuator module **500** in accordance with one embodiment of the present invention.

With reference now to Figs. 41-43, the shield **532** comprises a conductive knit fabric **544** laminated between first and second electrically insulative sheets **546a**, **546b** of polyurethane and / or TPU. A potting compound **548** is applied to the inside portion of the shield **532** to provide better adhesion to an outer surface **550** of the solid dielectric elastomer transducer roll module **504**. A portion of the second urethane sheet **546b** is removed to expose a portion **552** of the conductive knit fabric **544**. A conductive weave **554** (e.g., copper) is attached to the solder pad **518** and a conductive adhesive **556** is applied over the conductive weave **554**, which coincides with the exposed portion **552** of the conductive knit fabric **544**. The shield **532** is then assembled with the solid dielectric elastomer transducer roll module **504** and the conductive adhesive **556** and the assembly is placed in a compound mold **558**.

Figs. 44-47 illustrate techniques for pre-straining circular solid dielectric elastomer transducer rolls **560** into a stack orientation in accordance with one embodiment of the present invention. Figs. 44 and 45 illustrate a pulling technique in accordance with one embodiment of the present invention. A circular solid dielectric elastomer transducer roll **560** is placed in a pulling fixture

562 and a pulling force **563** is applied to the pulling fixture **562** in a direction towards a hard flat surface **564** over a vertical displacement of *d*. This creates a solid dielectric elastomer transducer roll **568** with a flat surface **566** on one side of the roll. The flat surface **566** enables two flatted circular solid dielectric elastomer transducer rolls **568** to be stacked together with the flat surfaces facing each other.

Figs. 46 and 47 illustrate another pulling technique in accordance with one embodiment of the present invention. The circular solid dielectric elastomer transducer roll **560** is placed the pulling fixture **562** comprising an inclusion **570** that has a flat surface **572** on the side facing the circular solid dielectric elastomer transducer roll **560**. The pulling force **563** is applied to the pulling fixture **562** in a direction towards the hard flat surface **564** over a vertical displacement of *d'*, where *d'* > *d*. This creates a solid dielectric elastomer transducer roll **576** with flat surfaces **574a**, **574b** on both sides of the roll. The flat surfaces **574a**, **574b** enable two or more flatted circular solid dielectric elastomer transducer rolls **576** to be stacked together with the flat surfaces facing each other

Figs. 48-50 illustrate a cantilever beam inertial module **600** for handheld devices in accordance with one embodiment of the present invention. Fig. 49 illustrates a top view of the cantilever beam inertial module **600** in accordance with one embodiment of the present invention. The cantilever beam inertial module **600** comprises a housing **602**, a cantilever mounted solid dielectric elastomer transducer roll **604**, and a mass **606**. One end of the solid dielectric elastomer transducer roll **604** is attached to the housing **602** and the other end is attached to the cantilevered mass **606**. The other end of the mass **606** is free floating.

Fig. 49 illustrates a perspective bottom view of the cantilever beam inertial module **600**. First and second conductive terminals **608a**, **608b** are provided on the housing **602** for making electrical contact with the solid dielectric elastomer transducer roll **604a**. In one embodiment, the conductive terminals **608a**, **608b** are SMT compatible terminals. In other embodiments, the conductive terminals **608a**, **608b** may be configured as solder pads with holes or with connectors. The first conductive terminal **608a** is electrically coupled to the near end of the solid dielectric elastomer transducer roll **604** and the second conductive terminal **608b** is electrically coupled to a conductive strip **610**, which provides an electrical connection to the far end of the solid dielectric elastomer transducer roll **604**.

Fig. 50 illustrates a partial perspective view of the cantilever beam inertial module **600** showing the mass **606** attached to one end of the conductive strip **610** in accordance with one embodiment of the present invention. This can also be seen in Fig. 49. Conductive adhesive is provided to electrically couple the ends of the solid dielectric elastomer transducer roll **604** to terminals **612a, 612b**.

Fig. 51 illustrates a handheld device **700** comprising a soft active button **702** based on dielectric elastomer actuators described herein in accordance with one embodiment of the present invention. The soft active button **702** is similar to the compliant actuator module **500** described hereinbefore. A portion of the soft active button **702** projects through the housing **704** of the handheld device **700**. When the soft active button **702** is actuated, it can provide tactile feedback to the user **706** including custom button clicks and navigation cues. As previously discussed, an electrically conductive shield provides a touch interface that is electrically safe for the user **706** to touch with a fingertip **708**.

Fig. 52 illustrates a device **800** comprising one or more soft active buttons **802** based on dielectric elastomer actuators described herein in accordance with one embodiment of the present invention. The soft active buttons **802** are similar to the compliant actuator modules **500** described hereinbefore. A portion of the soft active button **802** projects through the housing **804** of the handheld device **800**. When the soft active button **802** is actuated, it can provide tactile feedback to the user including custom button clicks and navigation cues. As previously discussed, an electrically conductive shield provides a touch interface that is electrically safe for the user to touch with a fingertip.

Fig. 53 illustrates a game console device **900** comprising one or more soft active buttons **902** based on dielectric elastomer actuators described herein in accordance with one embodiment of the present invention. The soft active buttons **902** are similar to the compliant actuator modules **500** described hereinbefore. A portion of the soft active button **902** projects through the housing **904** of the handheld device **900**. When the soft active button **902** is actuated, it can provide tactile feedback to the user including custom button clicks and gaming cues. As previously discussed, an electrically conductive shield provides a touch interface that is electrically safe for the user to touch with a fingertip.

Fig. 54 illustrates a screen **1000** comprising one or more compliant actuator modules **1002** as described hereinbefore in accordance with one embodiment the present invention. The one or more compliant actuator modules **1002** are similar to the compliant actuator modules **500** described hereinbefore. The compliant actuator module **1002** is attached to a housing **1004** portion of the screen **1000** and provides tactile feedback. Blank-rolls or counter spring **1006** and shims **1008** may be included in the housing **1004** to enhance performance.

Fig. 55 illustrates another screen **1100** comprising one or more compliant actuator modules **1102** as described hereinbefore in accordance with one embodiment the present invention. The one or more compliant actuator modules **1002** are similar to the compliant actuator modules **500** described hereinbefore. The compliant actuator module **1002** is attached to a housing **1104** portion of the screen **1100** and provides tactile feedback.

Fig. 56 illustrates a handheld device **1200** comprising one or more compliant actuator modules **1202** as described hereinbefore in accordance with one embodiment the present invention. The one or more compliant actuator modules **1202** are similar to the compliant actuator modules **500** described hereinbefore. The handheld device **1200** comprises a compliant (e.g., rubber) dome keypad **1204** with an integrated compliant actuator modules **1202**. Soft compliant active buttons **1206** projects through holes **1208** defined in a hard housing **1210** of the handheld device **1200**. The active buttons **1206** may be employed in other products such as handset housings, game controllers, headphone cushions, among other products.

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. An apparatus, comprising a substrate; a dielectric elastomer transducer electrically coupled to the substrate; and a compliant electrically conductive housing coupled to the dielectric elastomer transducer.

2. The apparatus according to Claim 1, further comprising an electrically insulative coating interposed between the dielectric elastomer transducer and the compliant electrically conductive housing.

3. The apparatus according to one of Claims 1 and 2, further comprising first electrically conductive terminals located on a top surface of the substrate to electrically couple the dielectric elastomer transducer to the substrate.

4. The apparatus according to Claim 3, further comprising second electrically conductive terminals located on a bottom surface of the substrate to electrically couple the dielectric elastomer transducer to an external device, wherein the first and second electrically conductive terminals are electrically coupled.

5. The apparatus according to Claim 4, further comprising one or more conductive via through-holes electrically coupling the first and second electrically conductive terminals through the substrate.

6. The apparatus according to any one of Claims 1 to 5, wherein the compliant electrically conductive housing comprises a conductive material embedded in an electrically insulative material or laminated between a first and a second sheet of electrically insulative material.

7. The apparatus according to Claim 6, wherein the electrically insulative material comprises at least one member selected from the group consisting of a polyurethane, a silicone, an acrylate, a styrenic copolymer, an olefinic copolymer, an olefinic polymer, a fluoroelastomer, a rubber, and a thermoplastic polyurethane.

8. The apparatus according to any one of Claims 1 to 7, wherein the compliant electrically conductive housing is electrically coupled to a low impedance shield.

9. An apparatus, comprising a first housing defining an opening; a substrate; a dielectric elastomer transducer electrically coupled to the substrate; and a compliant electrically conductive second housing coupled to the dielectric elastomer transducer, wherein a portion of the compliant electrically conductive housing projects through the opening defined in the first housing.

10. The apparatus according to Claim 10, further comprising a support to fixedly attach the substrate to the first housing.

11. The apparatus according to one of Claims 9 and 10, further comprising a flex circuit electrically coupled to the substrate.

12. The apparatus according to any one of Claims 9 to 11, comprising electrical terminals provided on the first housing to electrically couple the dielectric elastomer transducer to an energy source; and a mass located within the first housing and fixedly coupled to the one end of the dielectric elastomer transducer; wherein the other end of the dielectric elastomer transducer is fixedly coupled to the first housing; and wherein the other end of the mass is free floating.

13. A method, comprising attaching electrical terminals to a substrate; attaching a dielectric elastomer transducer to the electrical terminals; and applying an electrically insulative coating on the dielectric elastomer transducer.

14. The method according to Claim 13, further comprising applying a compliant electrically conductive housing over the dielectric elastomer transducer.

15. The method according to Claim 14, further comprising applying a conductive material composite formed by laminating a conductive material between a first and a second electrically insulative sheet or embedding a conductive material within an electrically insulating material.

16. The method according to Claim 15, further comprising applying a potting compound to a portion of the conductive material composite and applying the potted portion to the dielectric elastomer transducer.

17. The method according to Claim 16, further comprising attaching the conductive material composite to the dielectric elastomer transducer.

18. The apparatus according to any of Claims 1 to 12 wherein the transducer architecture is one selected from the group consisting of dielectric elastomer rolls, solid dielectric elastomer rolls, and dielectric elastomer multi-layer stacks.

19. The apparatus according to any of Claim 6 to 8 wherein the conductive material is at least one selected from the group consisting of conductive fabric, conductive polymer, conductive composite, or corrugated metal foil.

20. The apparatus according to any of Claim 15 to 18, wherein the conductive material is at least one selected from the group consisting of conductive fabric, conductive polymer, conductive composite, or corrugated metal foil.

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. An apparatus, comprising:
a substrate;
a dielectric elastomer transducer electrically coupled to the substrate; and
a compliant electrically conductive housing coupled to the dielectric elastomer transducer.

2. The apparatus according to Claim 1, further comprising an electrically insulative coating interposed between the dielectric elastomer transducer and the compliant electrically conductive housing.

3. The apparatus according to one of Claims 1 and 2, further comprising first electrically conductive terminals located on a top surface of the substrate to electrically couple the dielectric elastomer transducer to the substrate.

4. The apparatus according to Claim 3, further comprising second electrically conductive terminals located on a bottom surface of the substrate to electrically couple the dielectric elastomer transducer to an external device, wherein the first and second electrically conductive terminals are electrically coupled.

5. The apparatus according to Claim 4, further comprising one or more conductive via through-holes electrically coupling the first and second electrically conductive terminals through the substrate.

6. The apparatus according to any one of Claims 1 to 5, wherein the compliant electrically conductive housing comprises a conductive material embedded in an electrically insulative material or laminated between a first and a second sheet of electrically insulative material.

7. The apparatus according to Claim 6, wherein the electrically insulative material comprises at least one member selected from the group consisting of a polyurethane, a silicone, an acrylate, a styrenic copolymer, an olefinic copolymer, an olefinic polymer, a fluoroelastomer, a rubber, and a thermoplastic polyurethane.

8. The apparatus according to any one of Claims 1 to 7, wherein the compliant electrically conductive housing is electrically coupled to a low impedance shield.

9. An apparatus, comprising:

a first housing defining an opening;

a substrate;

a dielectric elastomer transducer electrically coupled to the substrate; and

a compliant electrically conductive second housing coupled to the dielectric elastomer transducer, wherein a portion of the compliant electrically conductive housing projects through the opening defined in the first housing.

10. The apparatus according to Claim 10, further comprising a support to fixedly attach the substrate to the first housing.

11. The apparatus according to one of Claims 9 and 10, further comprising a flex circuit electrically coupled to the substrate.

12. The apparatus according to any one of Claims 9 to 11, comprising:

electrical terminals provided on the first housing to electrically couple the dielectric elastomer transducer to an energy source; and

a mass located within the first housing and fixedly coupled to the one end of the dielectric elastomer transducer;

wherein the other end of the dielectric elastomer transducer is fixedly coupled to the first housing; and

wherein the other end of the mass is free floating.

13. A method, comprising:

attaching electrical terminals to a substrate;

attaching a dielectric elastomer transducer to the electrical terminals; and

applying an electrically insulative coating on the dielectric elastomer transducer.

14. The method according to Claim 13, further comprising applying a compliant electrically conductive housing over the dielectric elastomer transducer.

15. The method according to Claim 14, further comprising applying a conductive material composite formed by laminating a conductive material between a first and a second electrically insulative sheet or embedding a conductive material within an electrically insulating material.

16. The method according to Claim 15, further comprising applying a potting compound to a portion of the conductive material composite and applying the potted portion to the dielectric elastomer transducer.

17. The method according to Claim 16, further comprising attaching the conductive material composite to the dielectric elastomer transducer.

18. The apparatus according to any of Claims 1 to 12 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.

19. The apparatus according to any of Claim 6 to 8 wherein the conductive material is at least one selected from the group consisting of conductive fabric, conductive polymer, conductive composite, or corrugated metal foil.

20. The apparatus according to any of Claim 15 to 18, wherein the conductive material is at least one selected from the group consisting of conductive fabric, conductive polymer, conductive composite, or corrugated metal foil.

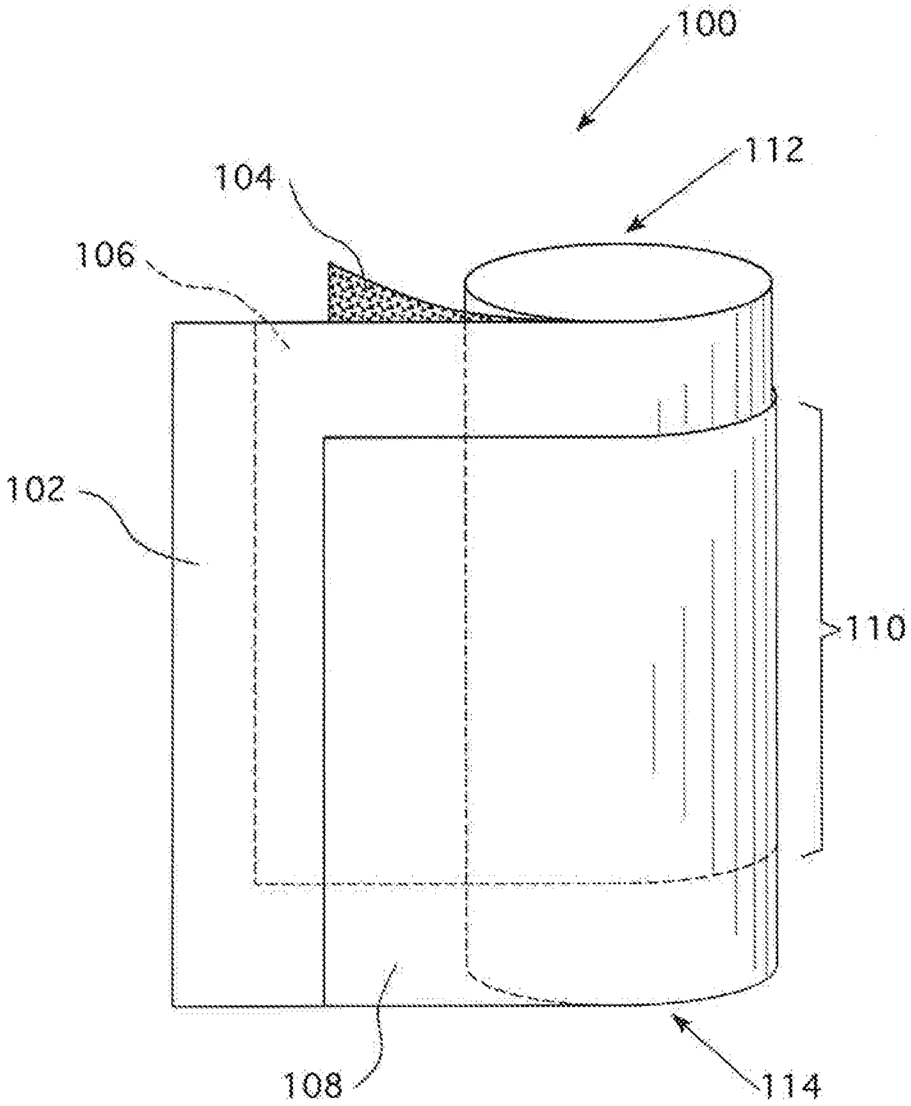


FIG. 1

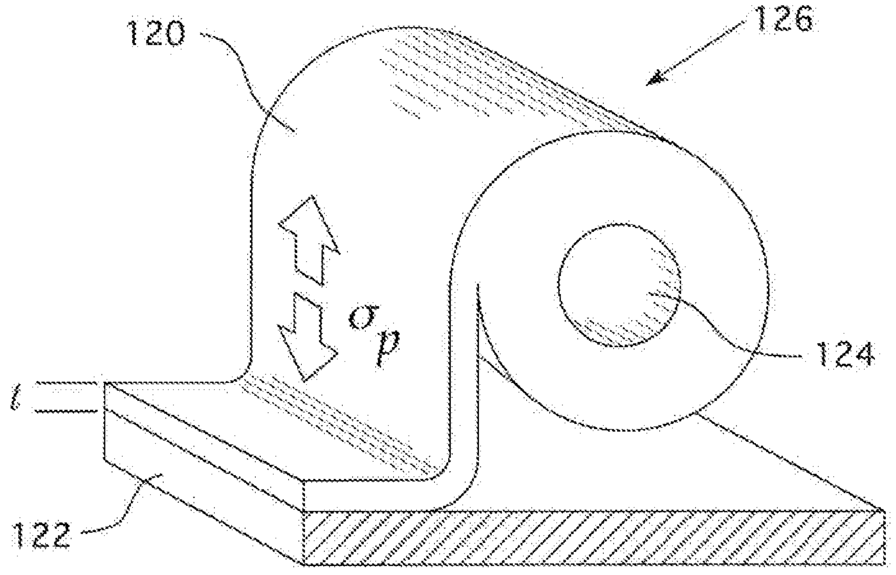


FIG. 2

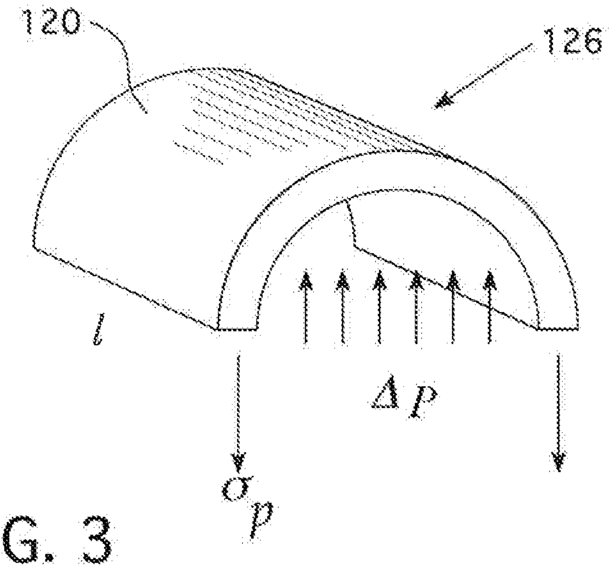


FIG. 3

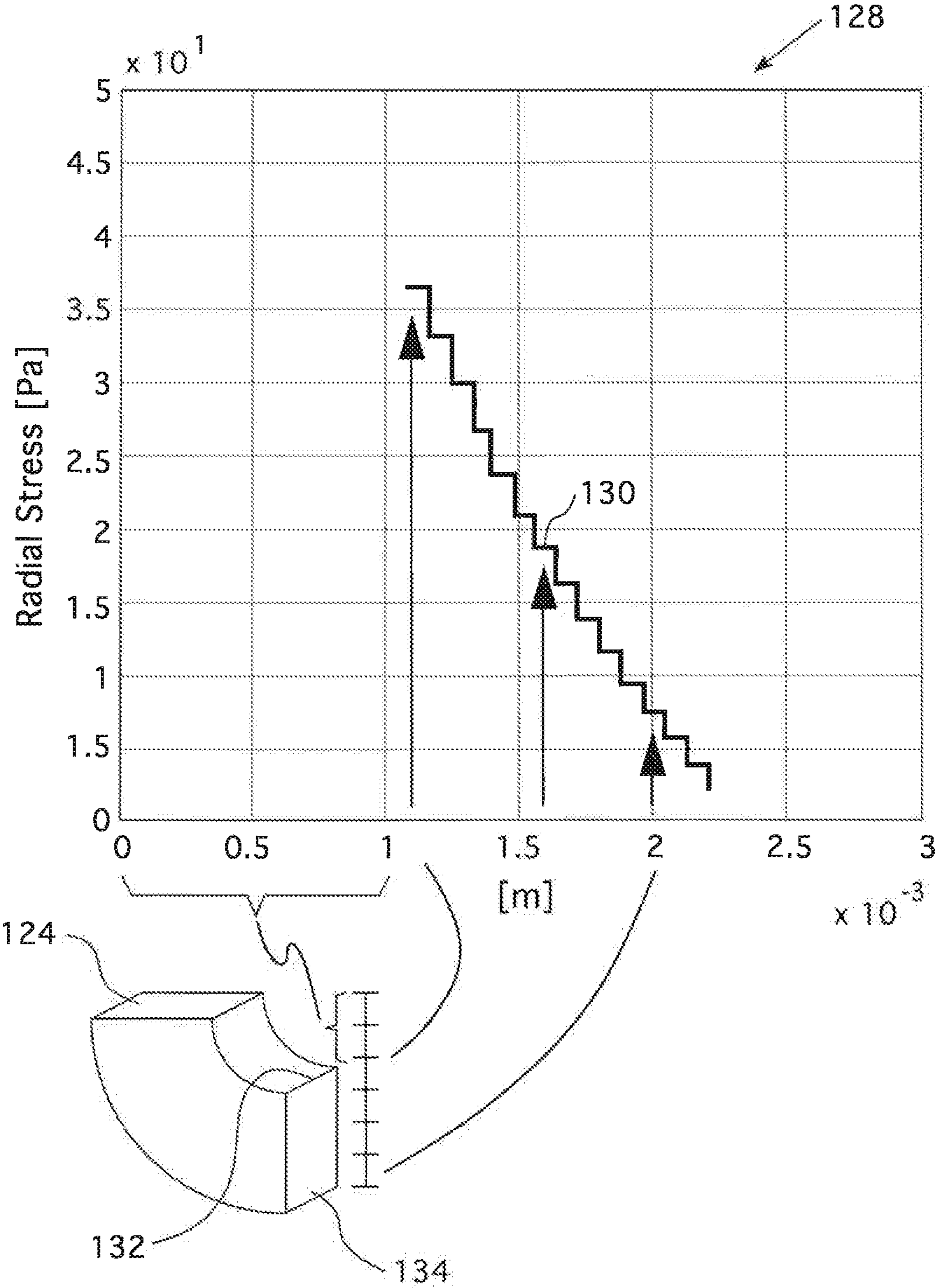

128
x 10^1
5
4.5
4
3.5
3
2.5
2
1.5
1
1.5
0
Radial Stress [Pa]
130
0
0.5
1
1.5
2
2.5
3
[m]
x 10^-3
124
132
134

FIG. 4

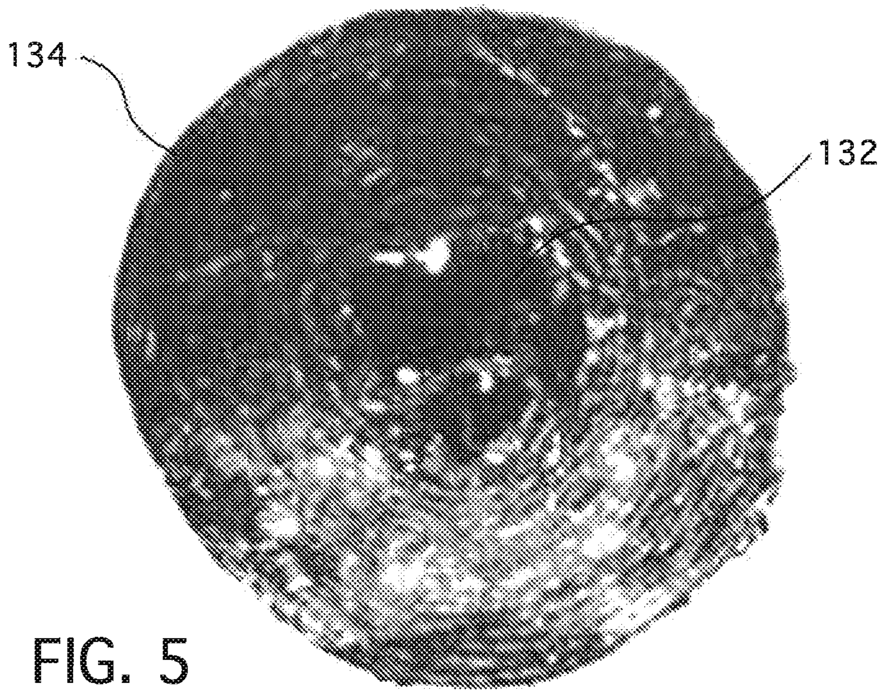


FIG. 5

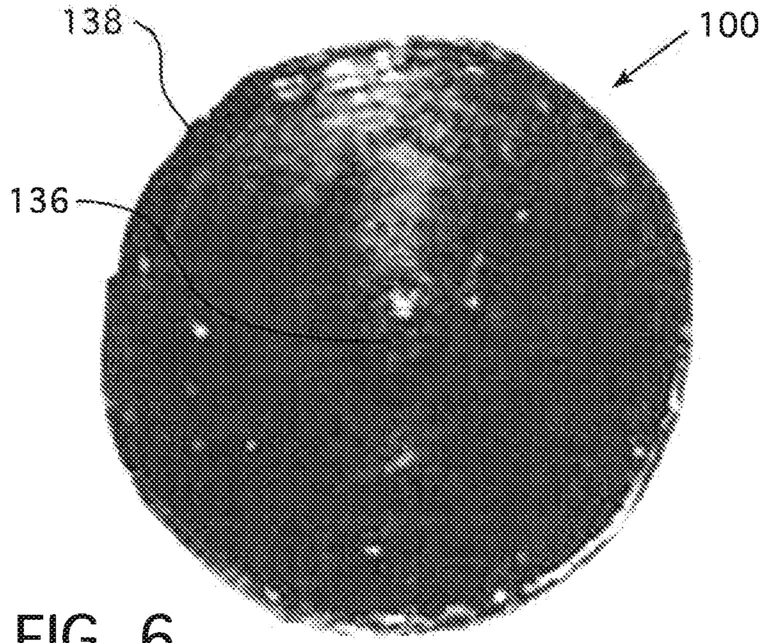


FIG. 6

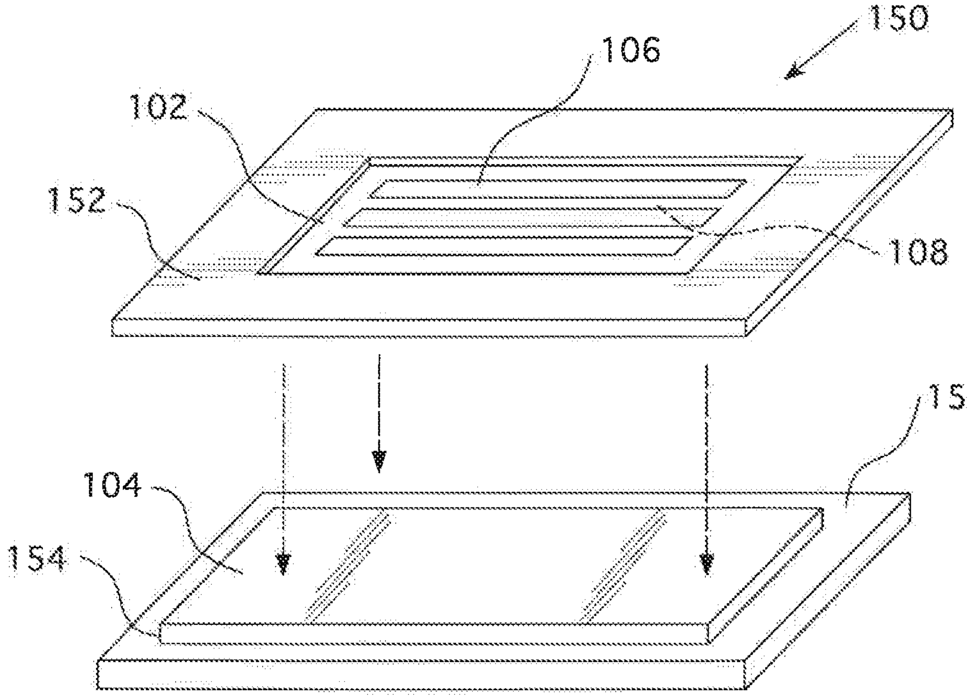


FIG. 7A

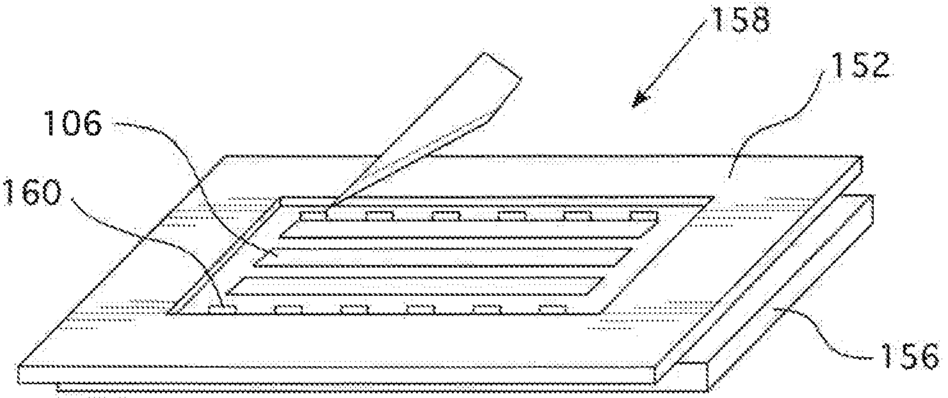


FIG. 7B

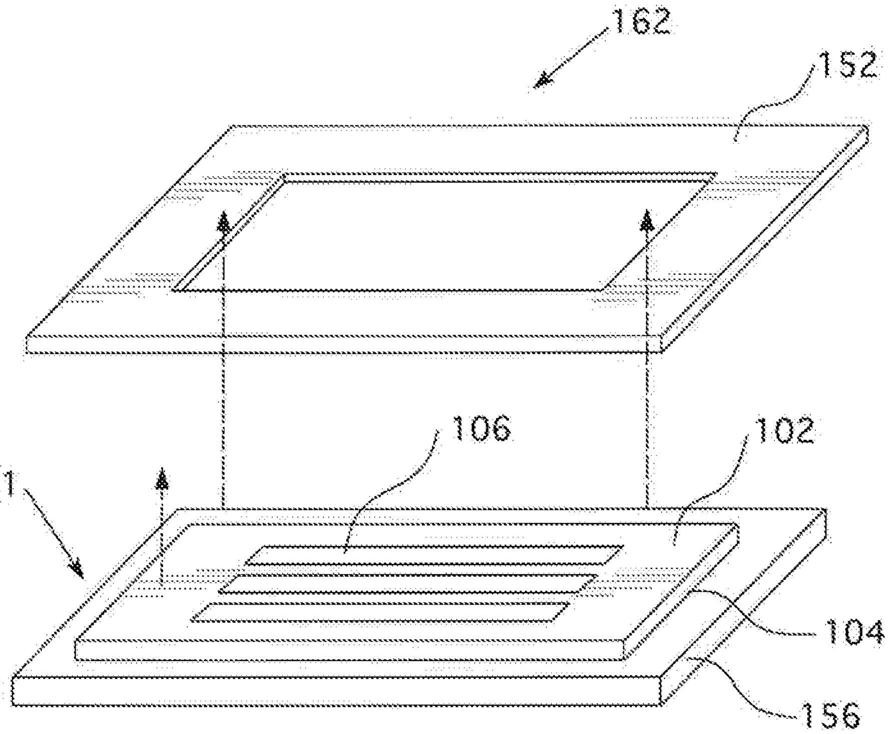


FIG. 7C

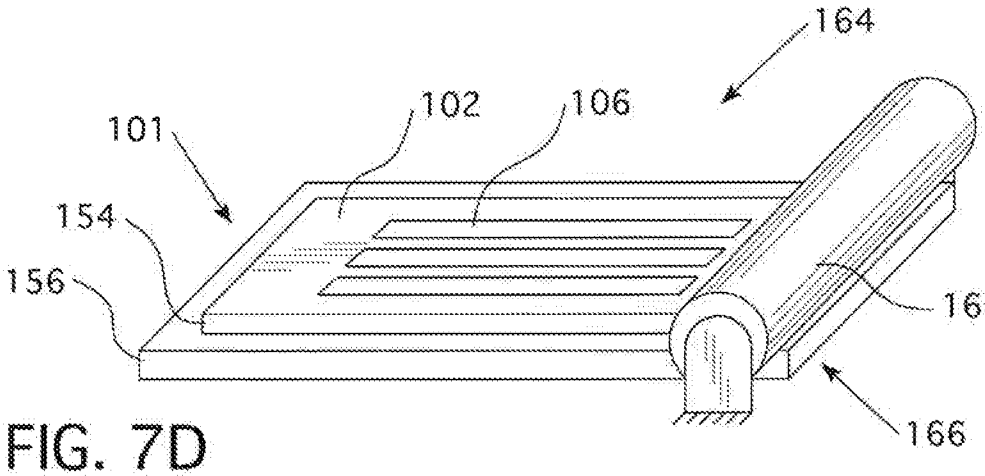


FIG. 7D

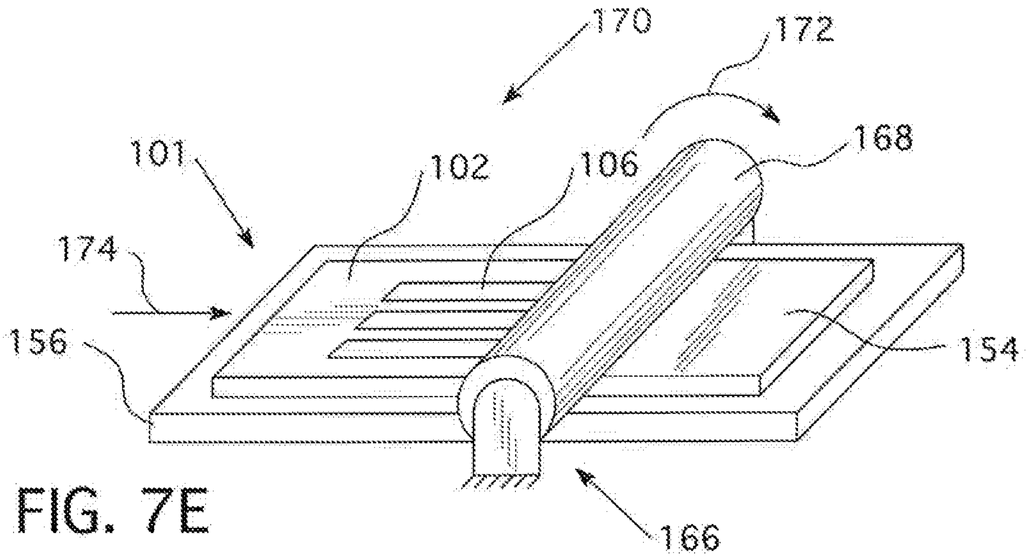

170
172
168
101
102
106
174
156
154
166

FIG. 7E

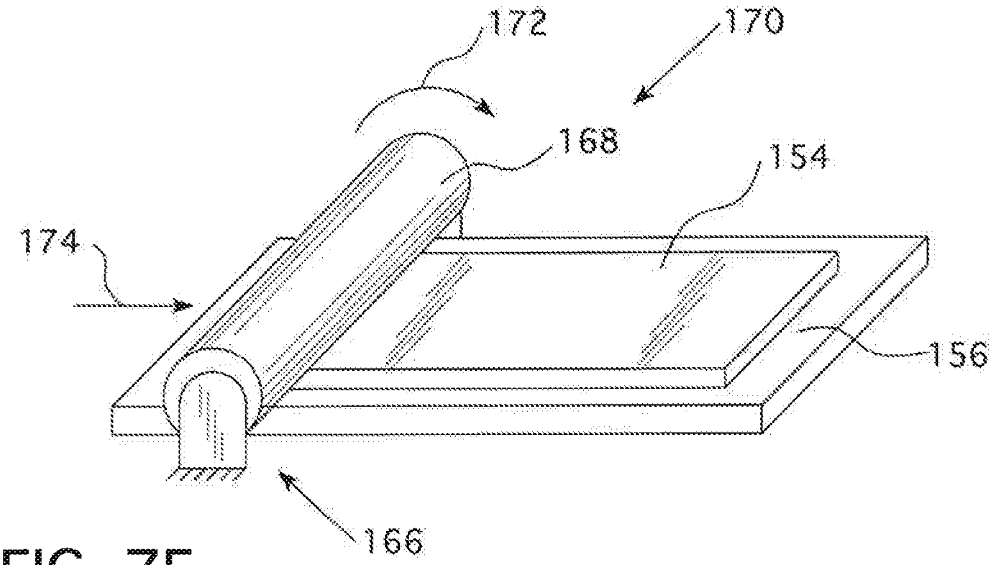

172
170
168
154
174
156
166

FIG. 7F

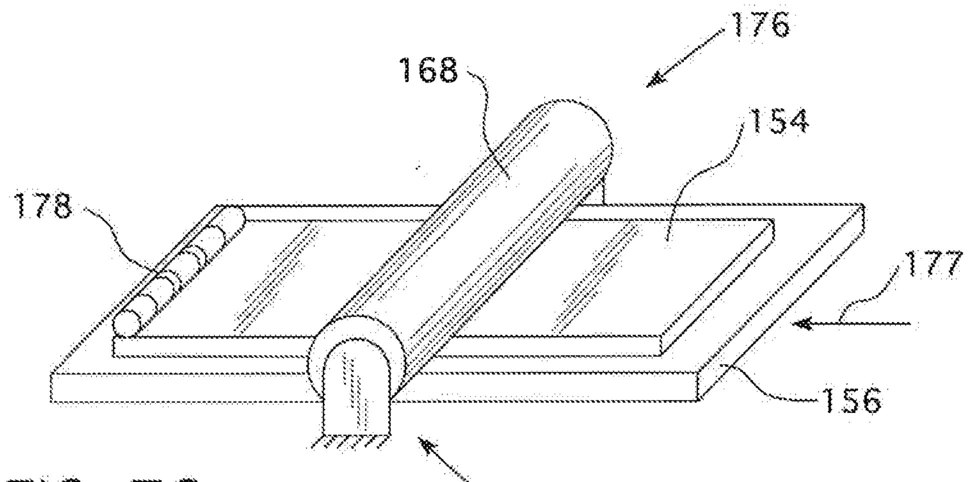


FIG. 7G

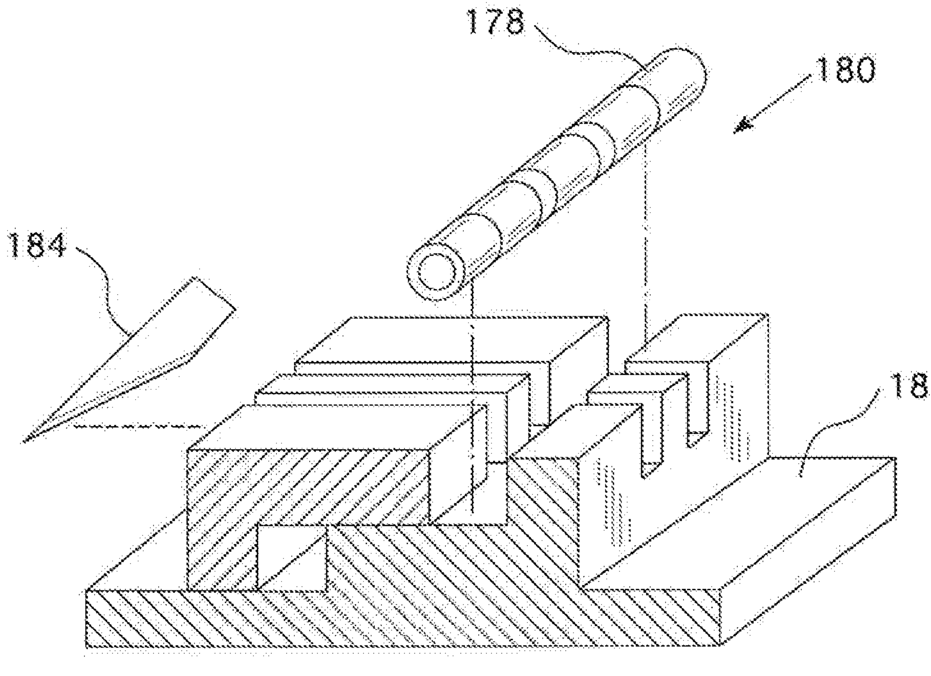


FIG. 7H

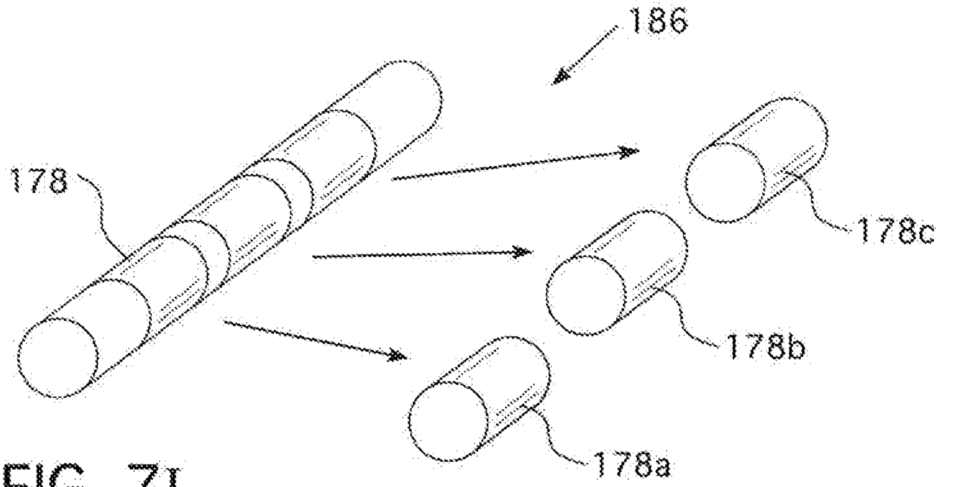


FIG. 7I

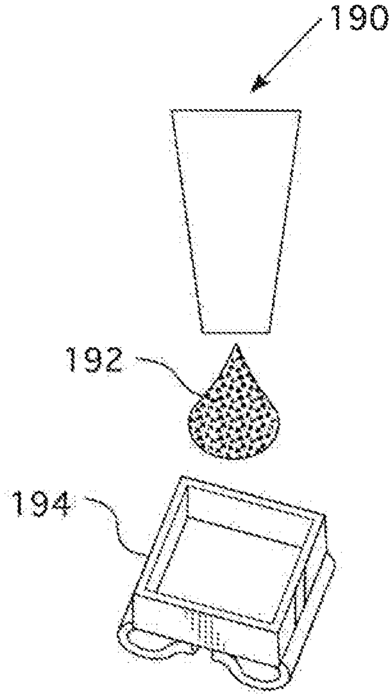


FIG. 7J

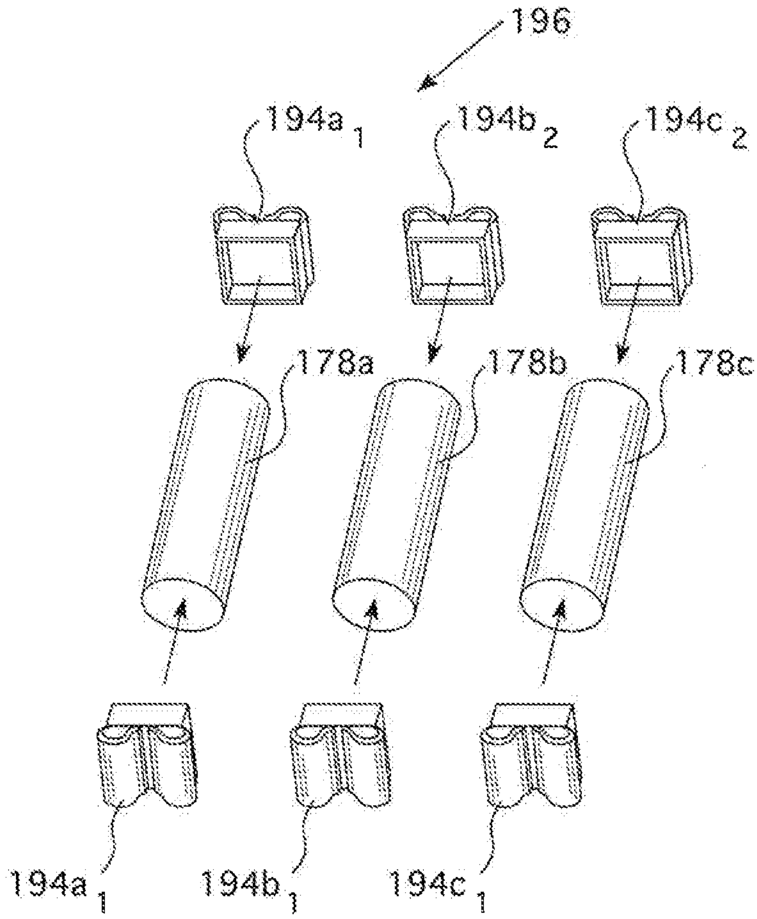


FIG. 7K

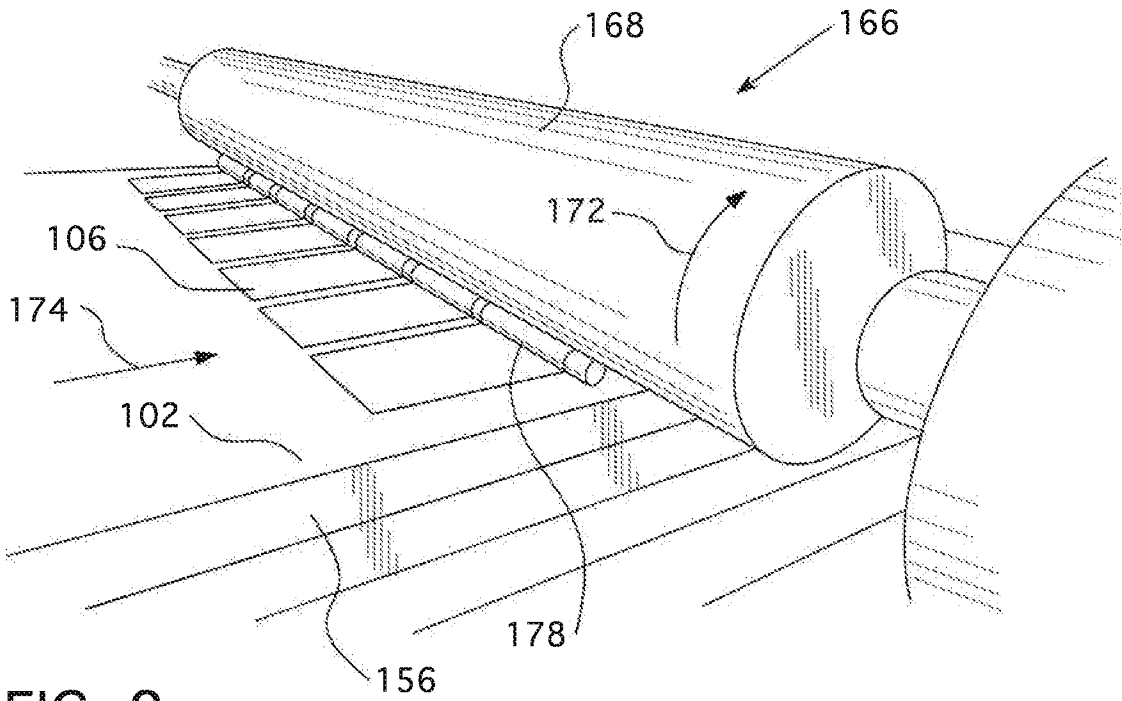

168
166
172
106
174
102
178
156

FIG. 8

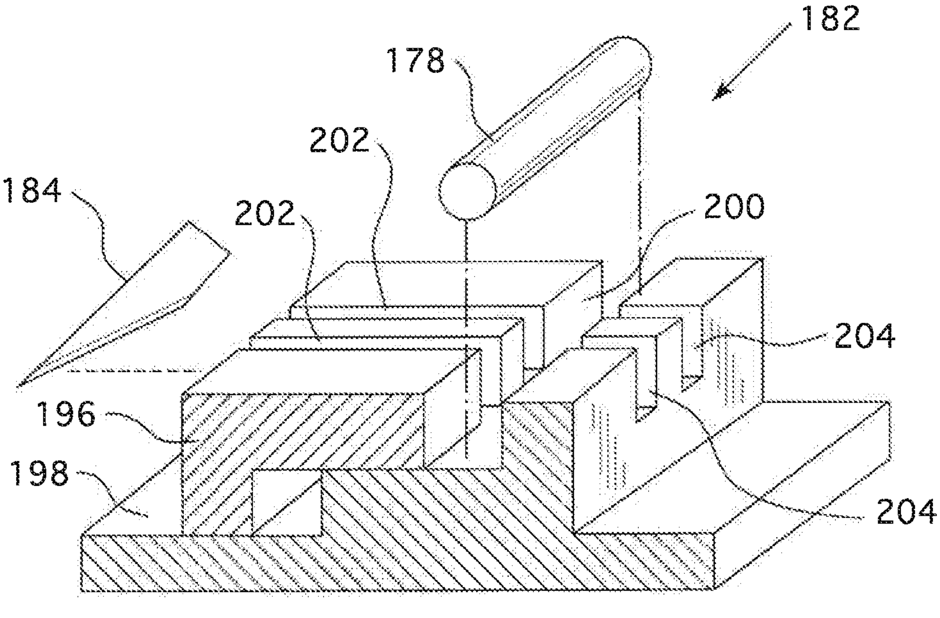

182
178
202
184
202
200
204
196
198
204

FIG. 9

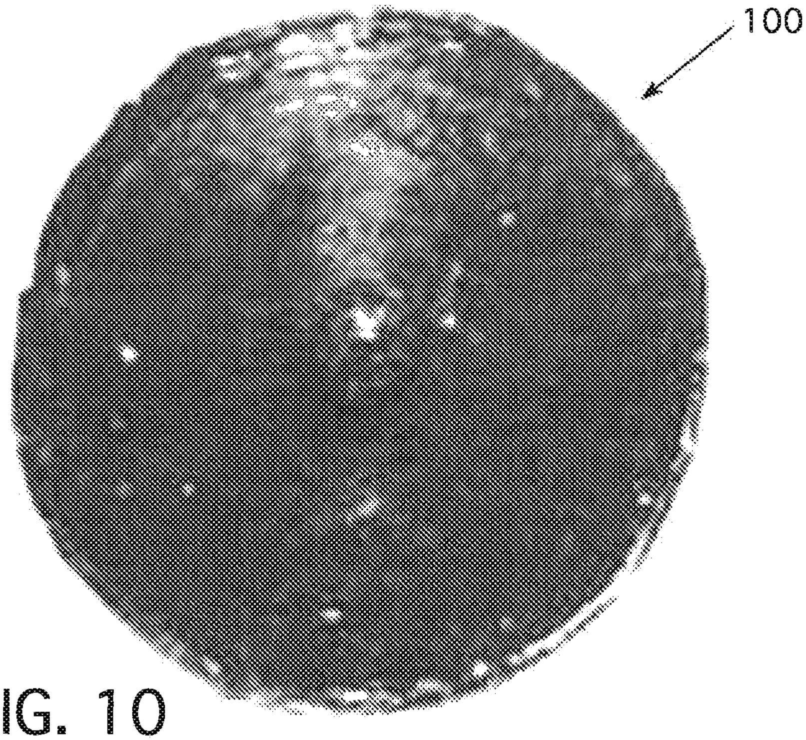


FIG. 10

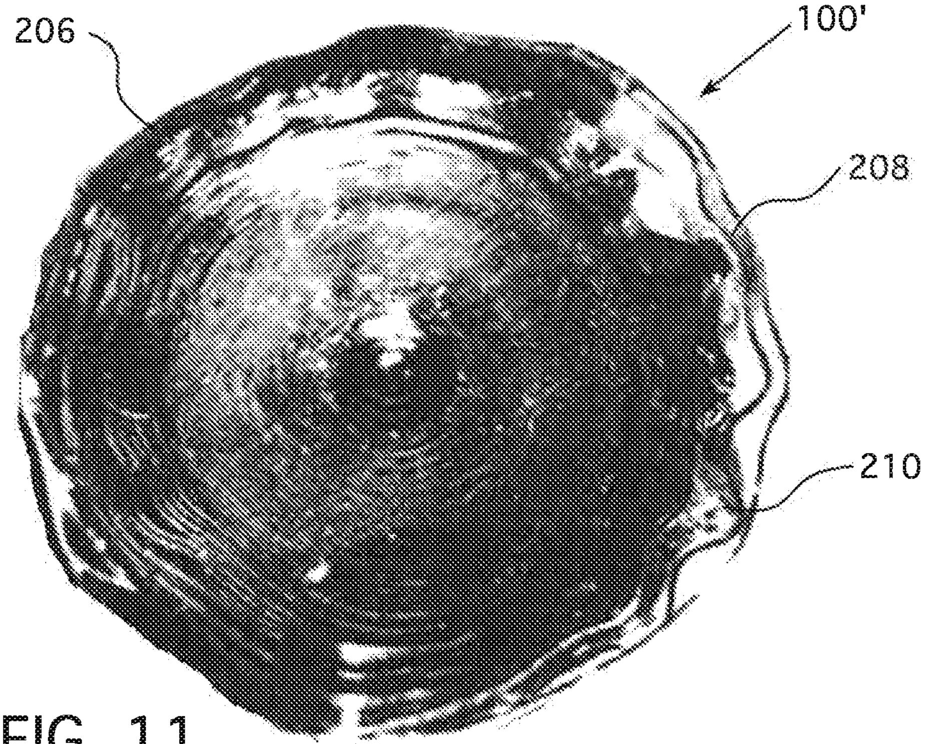


FIG. 11

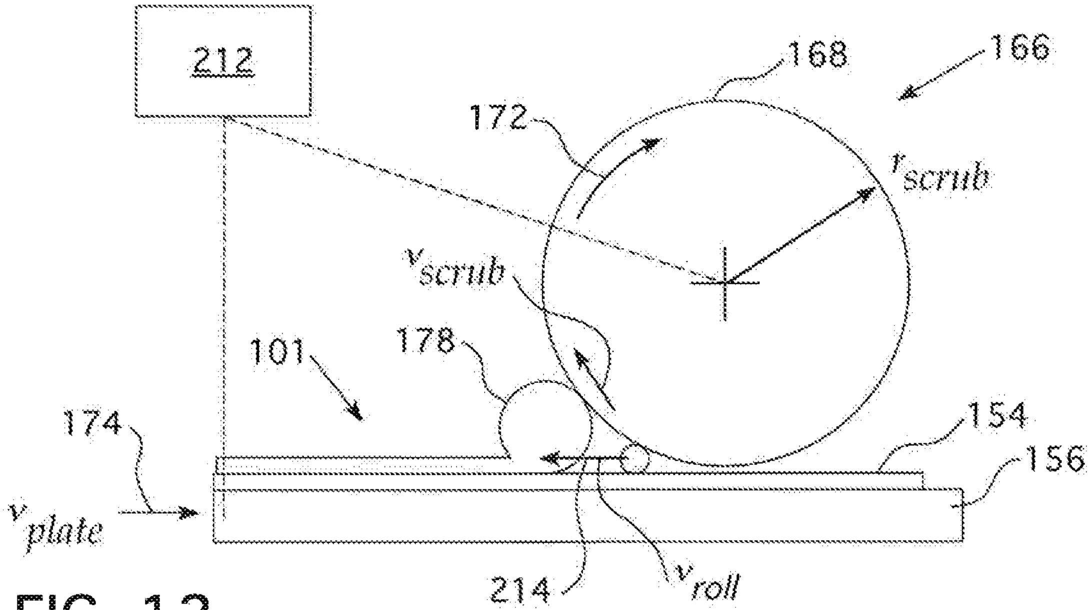

212
168
166
172
r_{scrub}
v_{scrub}
101
178
174
154
156
v_{plate}
214
v_{roll}

FIG. 12

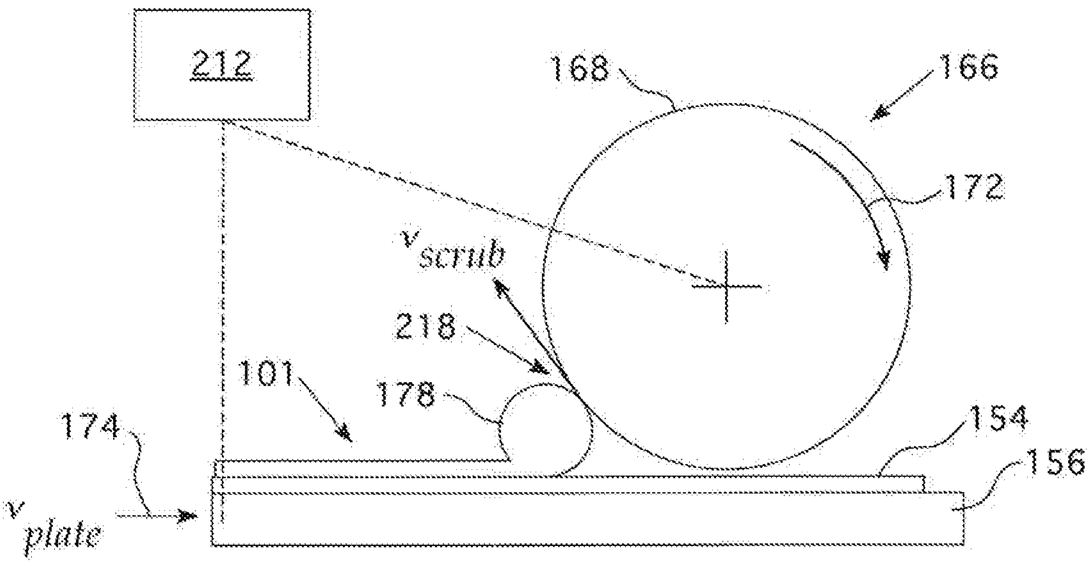

212
168
166
172
v_{scrub}
218
101
178
174
154
156
v_{plate}

FIG. 13

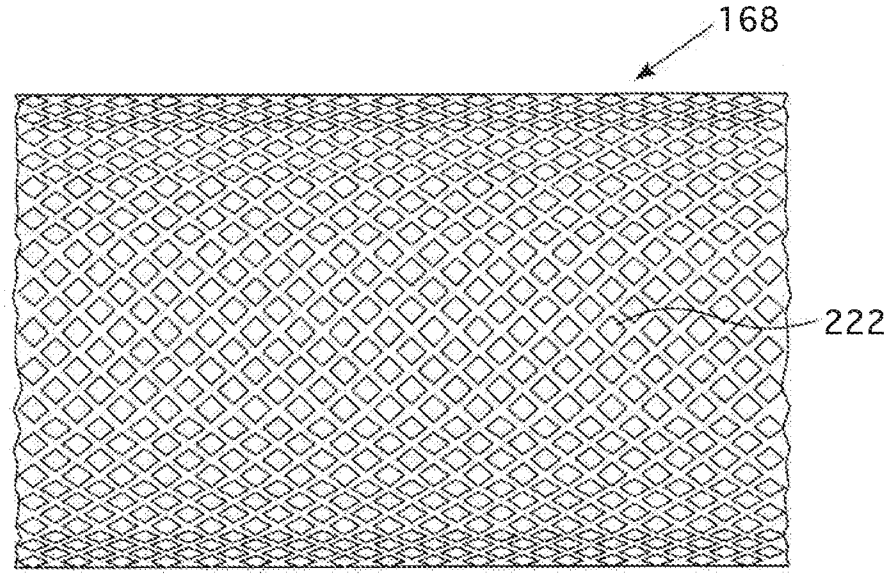


FIG. 14

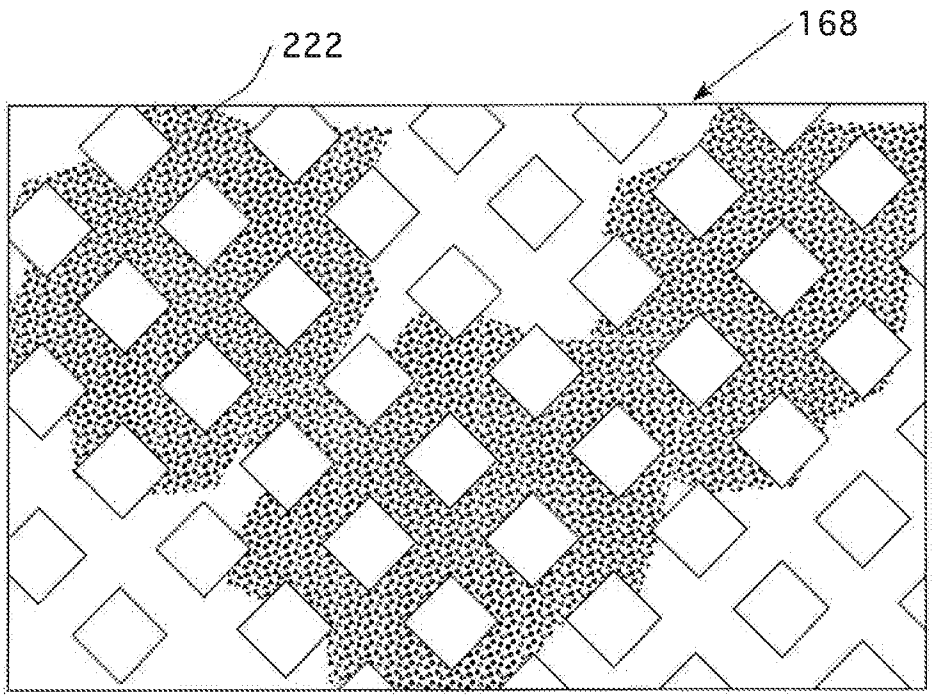


FIG. 15

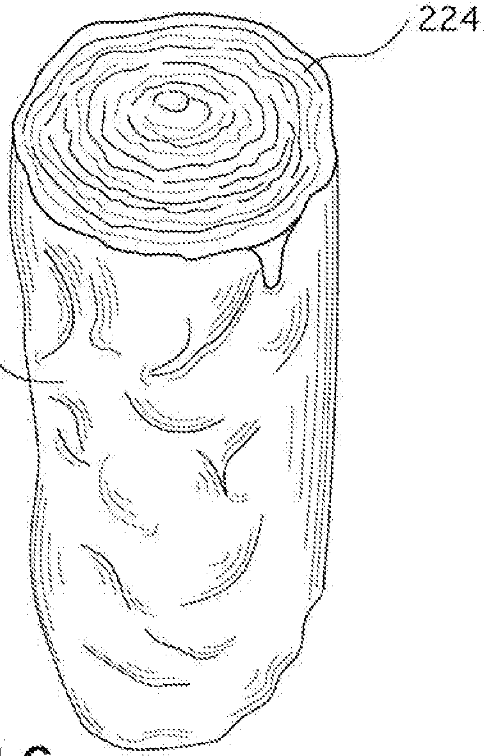

224
226

FIG. 16

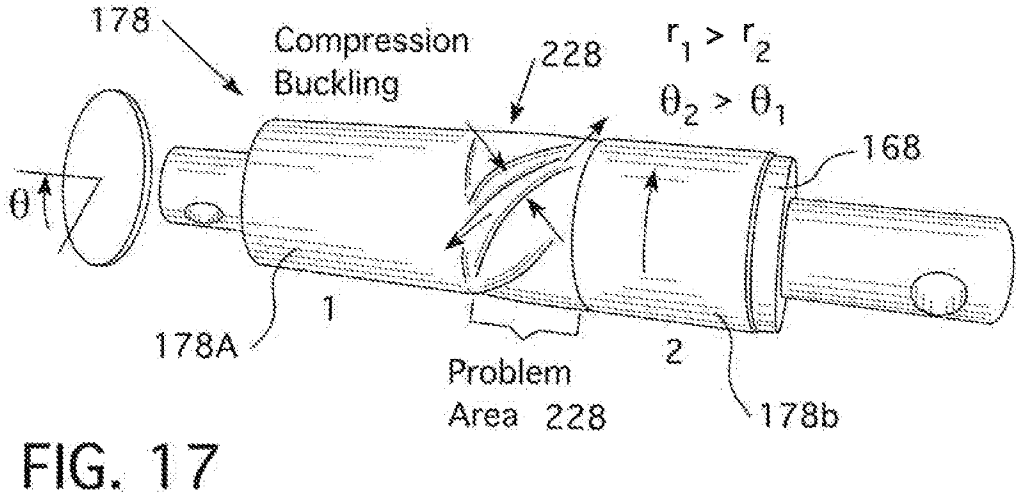

178
Compression
Buckling
228
$r_1 > r_2$
$\theta_2 > \theta_1$
168
θ
1
178A
Problem
Area 228
2
178b

FIG. 17

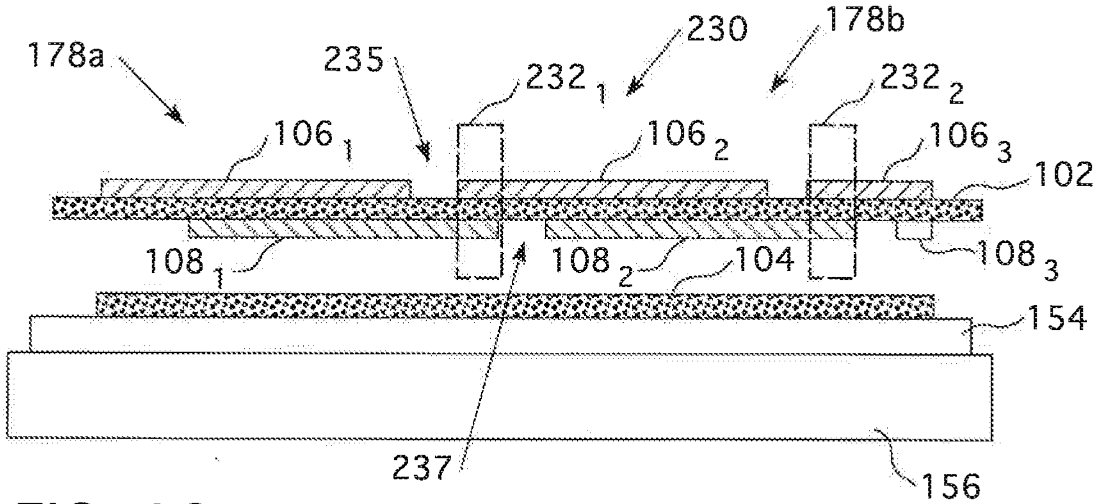

178a
235
232 1
230
178b
232 2
106 1
106 2
106 3
102
108 1
108 2
104
108 3
154
237
156

FIG. 18

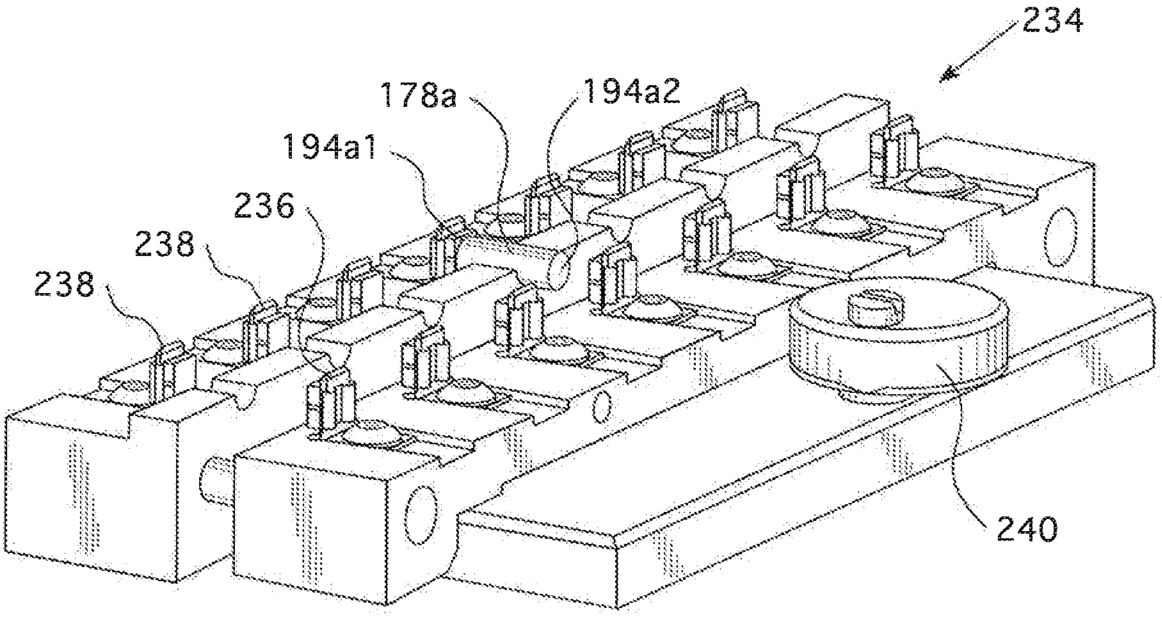

234
178a
194a2
194a1
236
238
238
240

FIG. 19

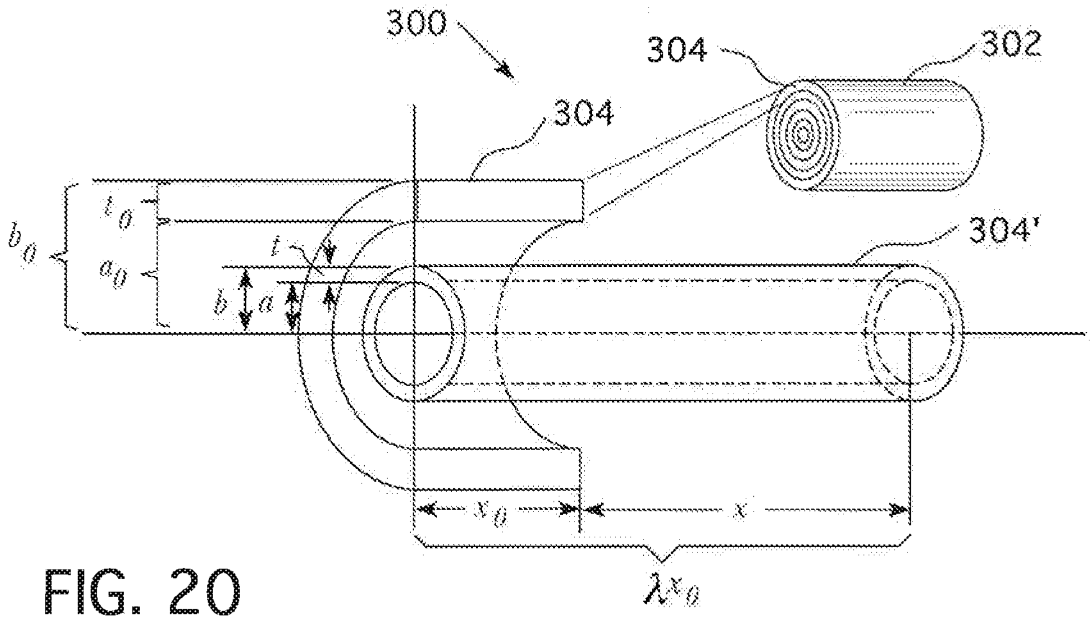

300
304
302
304
304'
t_0
b_0
a_0
t
b
a
x_0
x
λx_0

FIG. 20

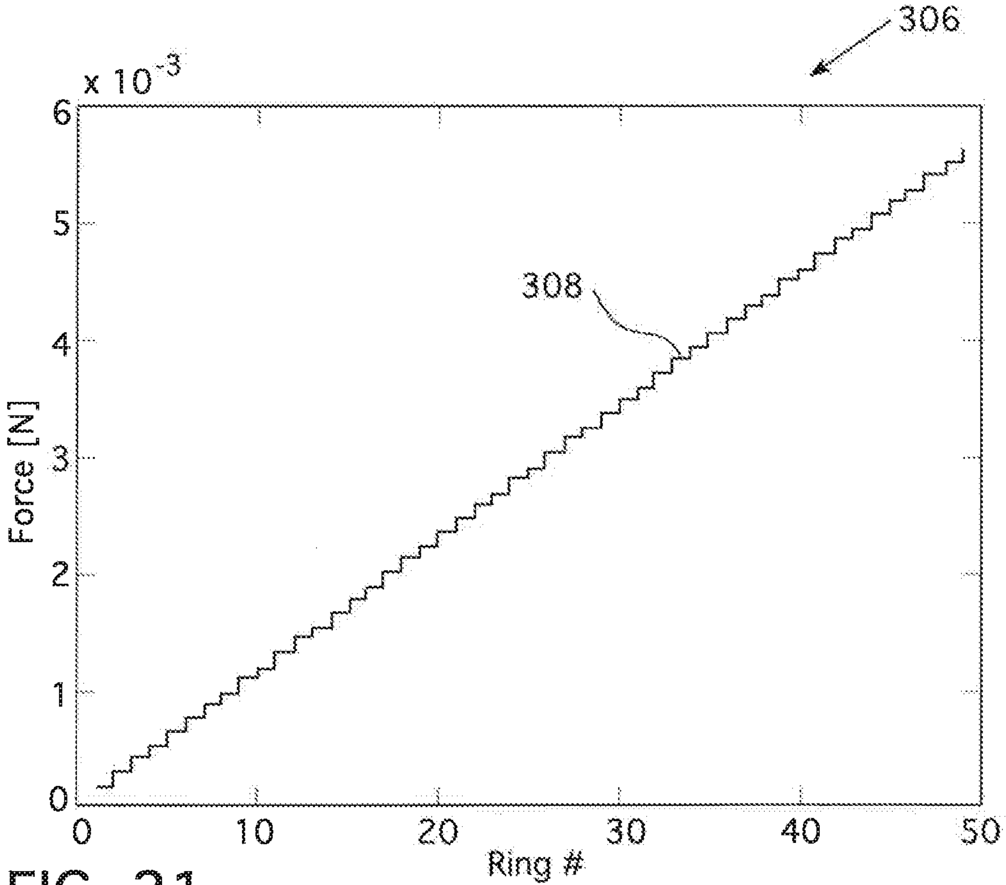

306
x 10^-3
308
Force [N]
Ring #
0
1
2
3
4
5
6
0
10
20
30
40
50

FIG. 21

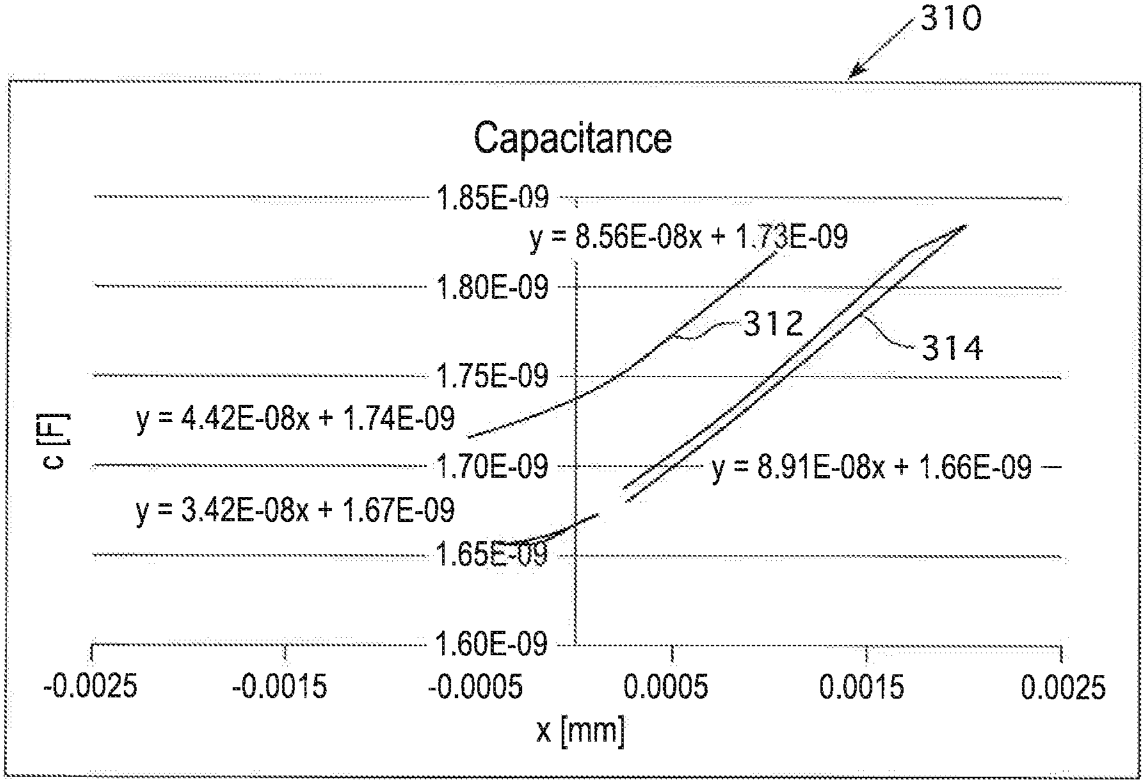

310
Capacitance
1.85E-09
1.80E-09
1.75E-09
1.70E-09
1.65E-09
1.60E-09
y = 8.56E-08x + 1.73E-09
y = 4.42E-08x + 1.74E-09
y = 3.42E-08x + 1.67E-09
y = 8.91E-08x + 1.66E-09
312
314
c [F]
-0.0025
-0.0015
-0.0005
0.0005
0.0015
0.0025
x [mm]

FIG. 22

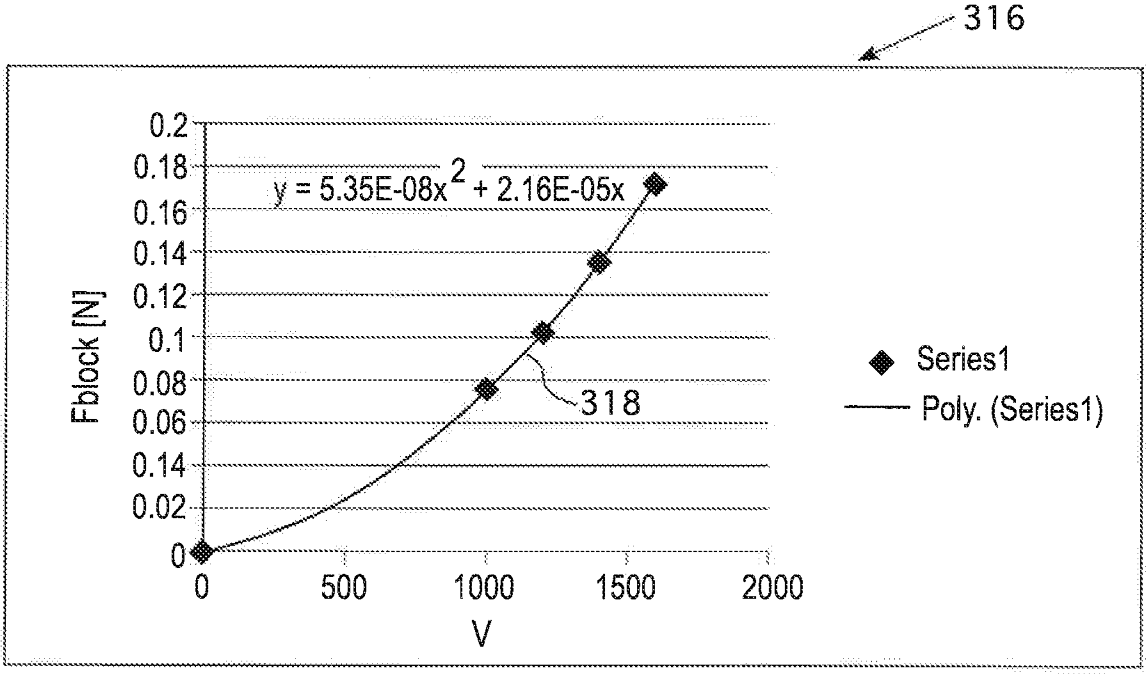

316
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.14
0.02
0
y = 5.35E-08x2 + 2.16E-05x
Fblock [N]
318
Series1
Poly. (Series1)
0
500
1000
1500
2000
V

FIG. 23

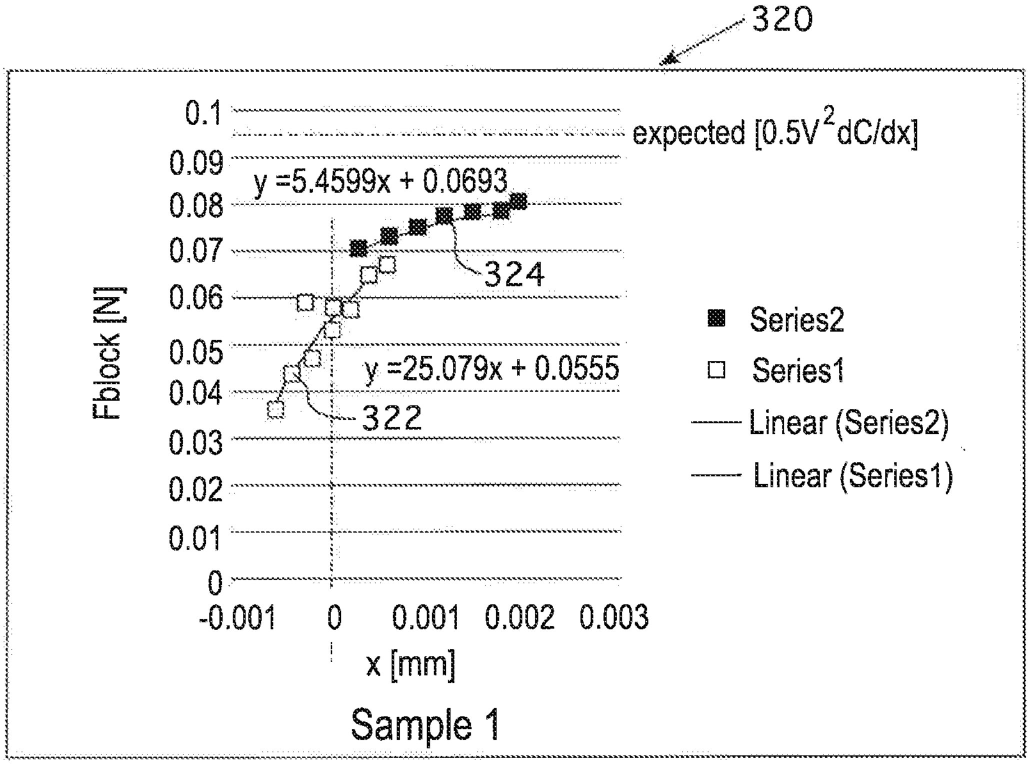

320
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
expected [0.5V2dC/dx]
y =5.4599x + 0.0693
324
y =25.079x + 0.0555
322
Fblock [N]
-0.001
0
0.001
0.002
0.003
x [mm]
Series2
Series1
Linear (Series2)
Linear (Series1)
Sample 1

FIG. 24

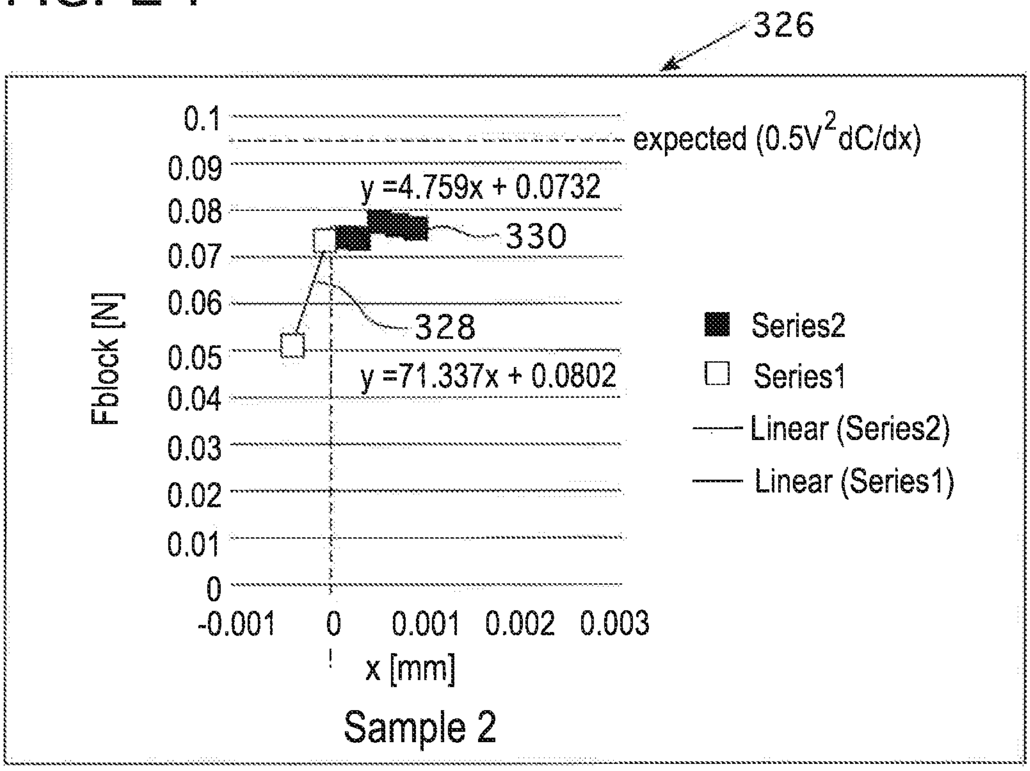

326
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
expected (0.5V2dC/dx)
y =4.759x + 0.0732
330
328
y =71.337x + 0.0802
Fblock [N]
-0.001
0
0.001
0.002
0.003
x [mm]
Series2
Series1
Linear (Series2)
Linear (Series1)
Sample 2

FIG. 25

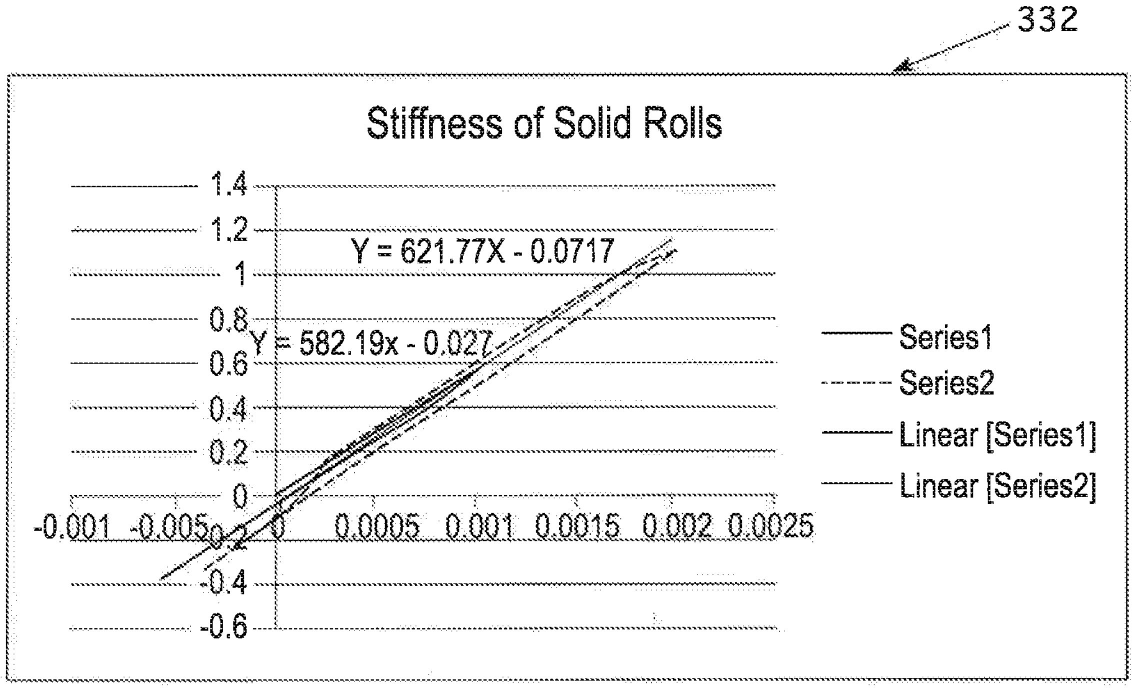

332
Stiffness of Solid Rolls
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.001
-0.005
0
0.0005
0.001
0.0015
0.002
0.0025
Y = 621.77X - 0.0717
Y = 582.19x - 0.027
Series1
Series2
Linear [Series1]
Linear [Series2]

FIG. 26

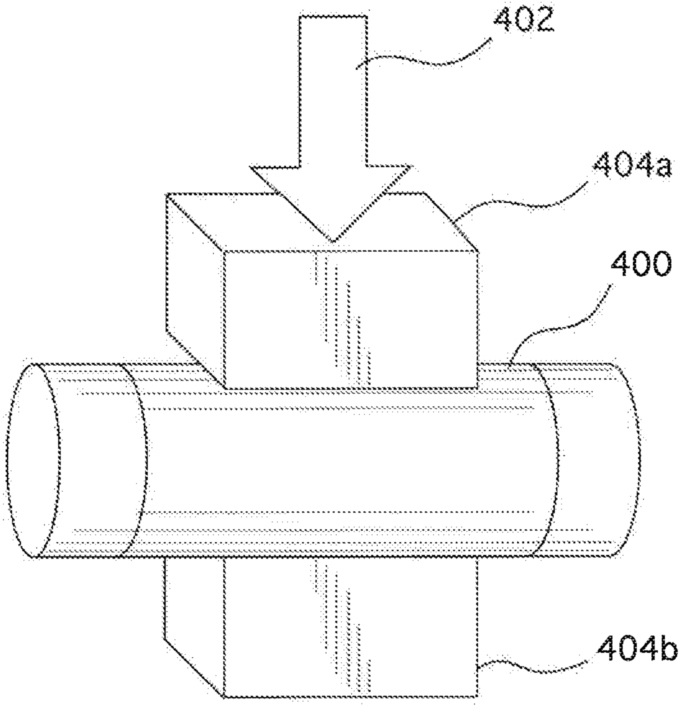

402
404a
400
404b

FIG. 27

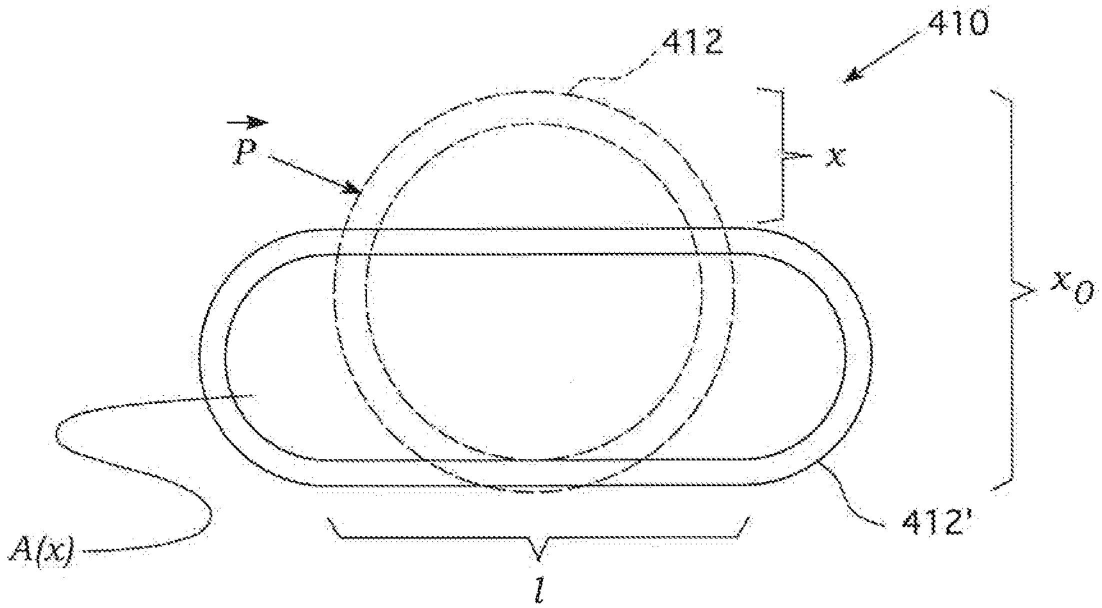

412
410
P
x
x0
A(x)
412'
l

FIG. 28

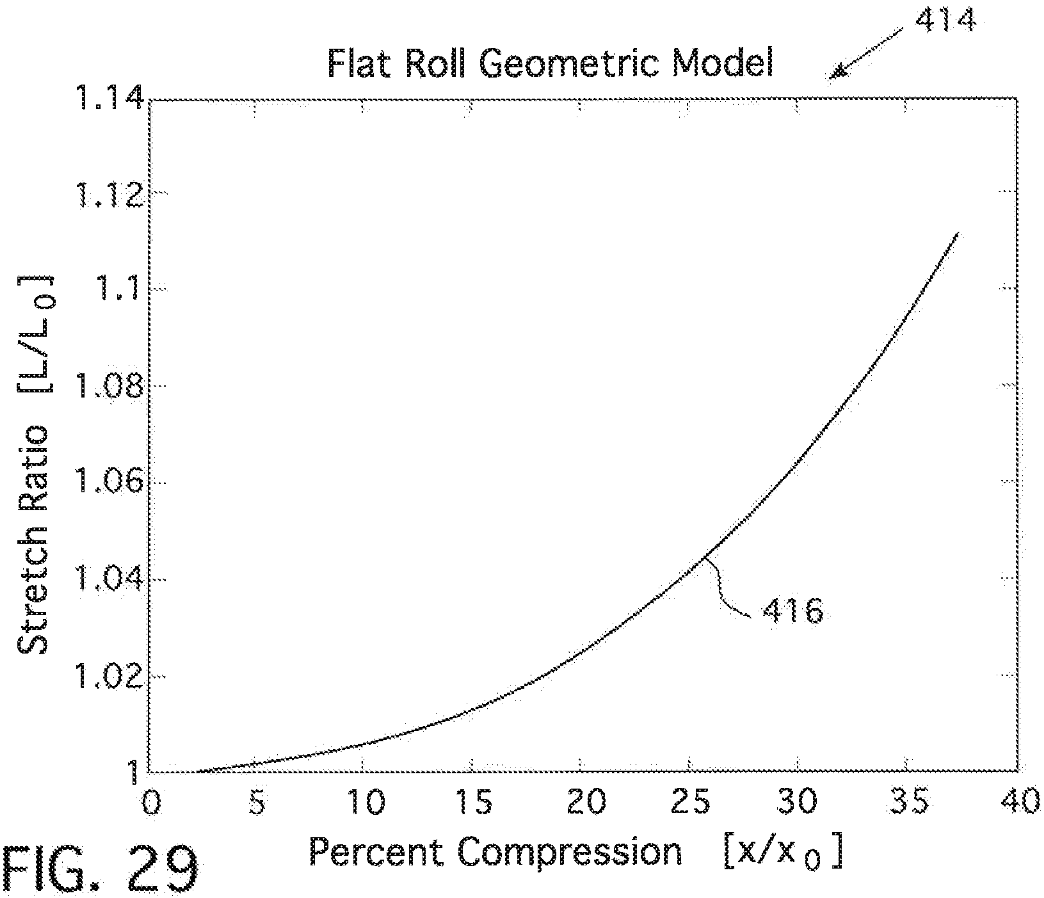

414
Flat Roll Geometric Model
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
Stretch Ratio [L/L0]
416
0
5
10
15
20
25
30
35
40
Percent Compression [x/x0]

FIG. 29

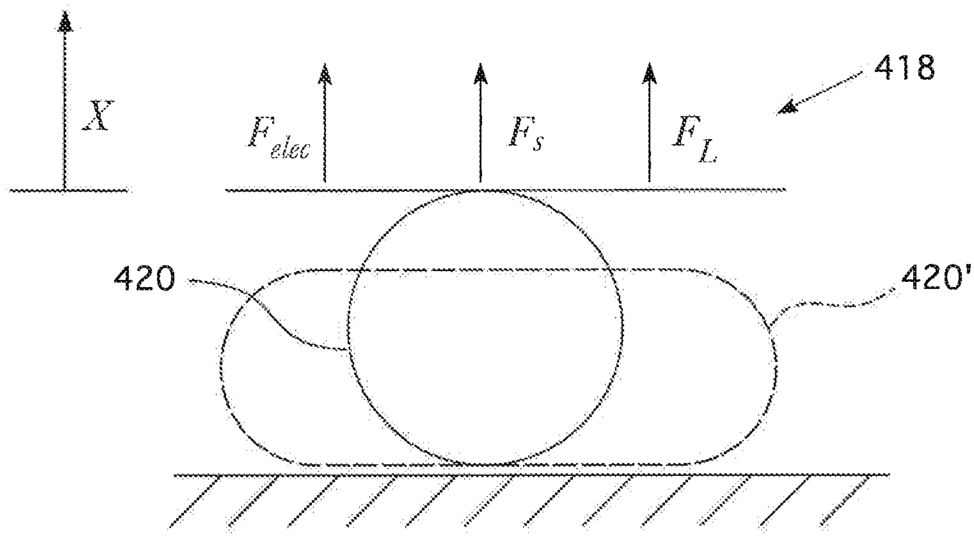

418
X
F_{elec}
F_s
F_L
420
420'

FIG. 30

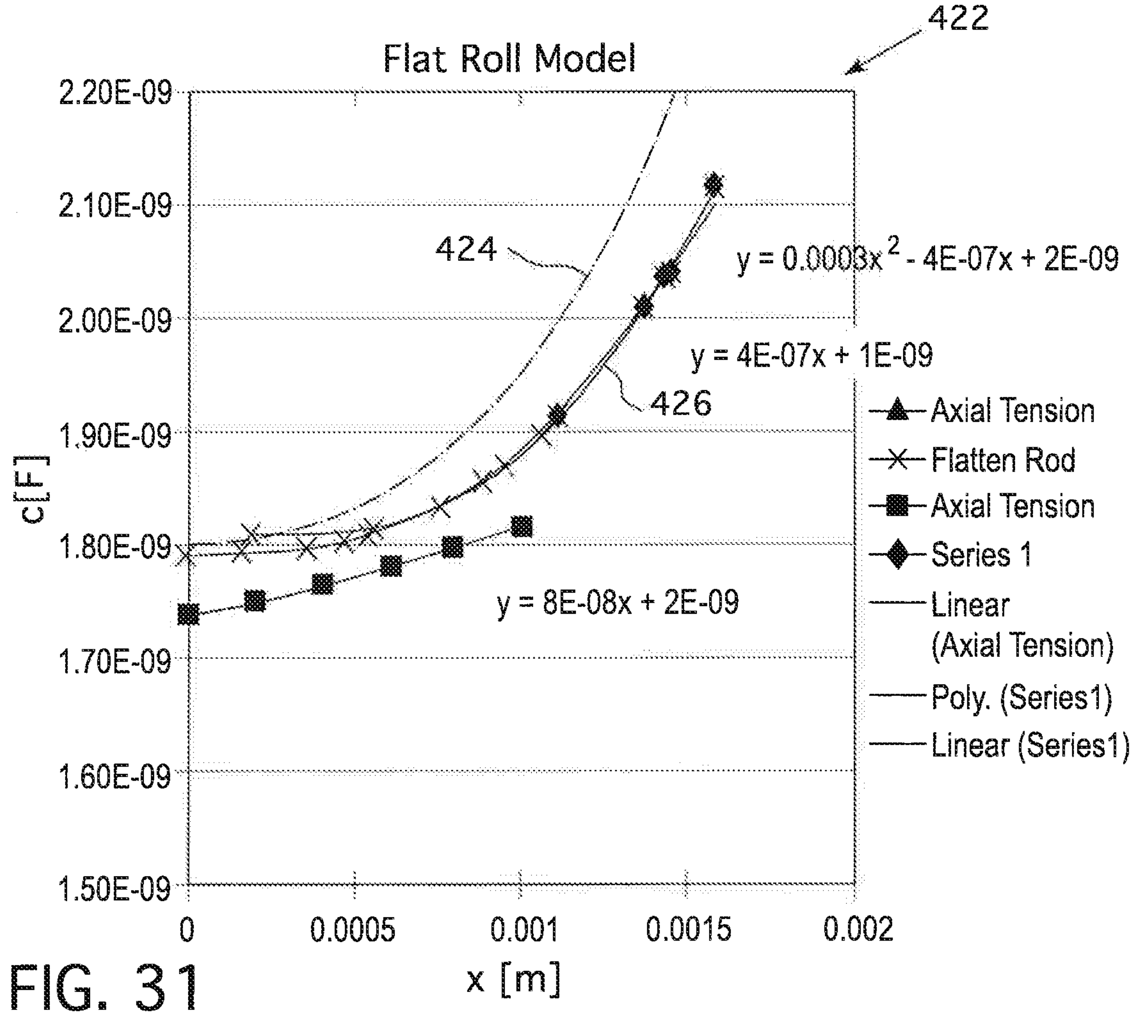

422
Flat Roll Model
2.20E-09
2.10E-09
2.00E-09
1.90E-09
1.80E-09
1.70E-09
1.60E-09
1.50E-09
c[F]
424
426
y = 0.0003x² - 4E-07x + 2E-09
y = 4E-07x + 1E-09
y = 8E-08x + 2E-09
Axial Tension
Flatten Rod
Axial Tension
Series 1
Linear (Axial Tension)
Poly. (Series1)
Linear (Series1)
0
0.0005
0.001
0.0015
0.002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

FIG. 31

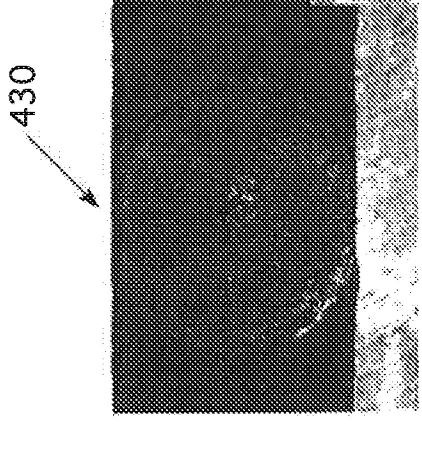


FIG. 32A

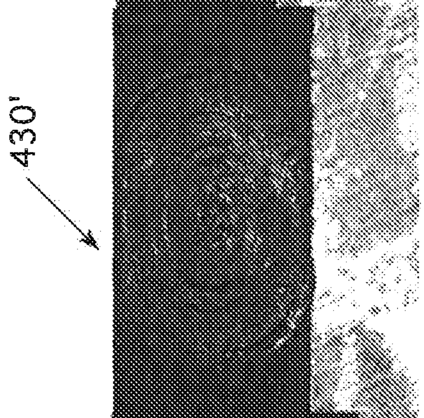


FIG. 32B

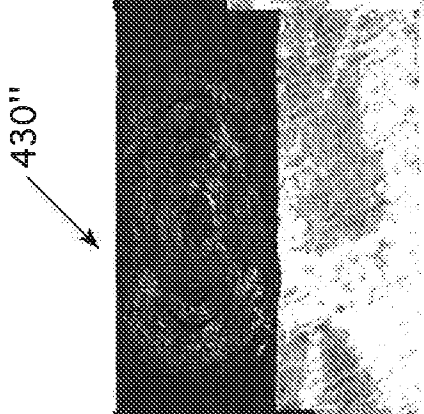


FIG. 32C

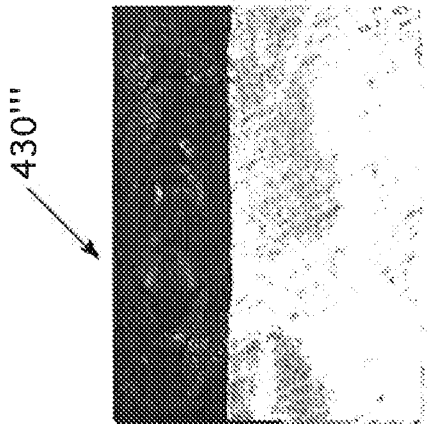
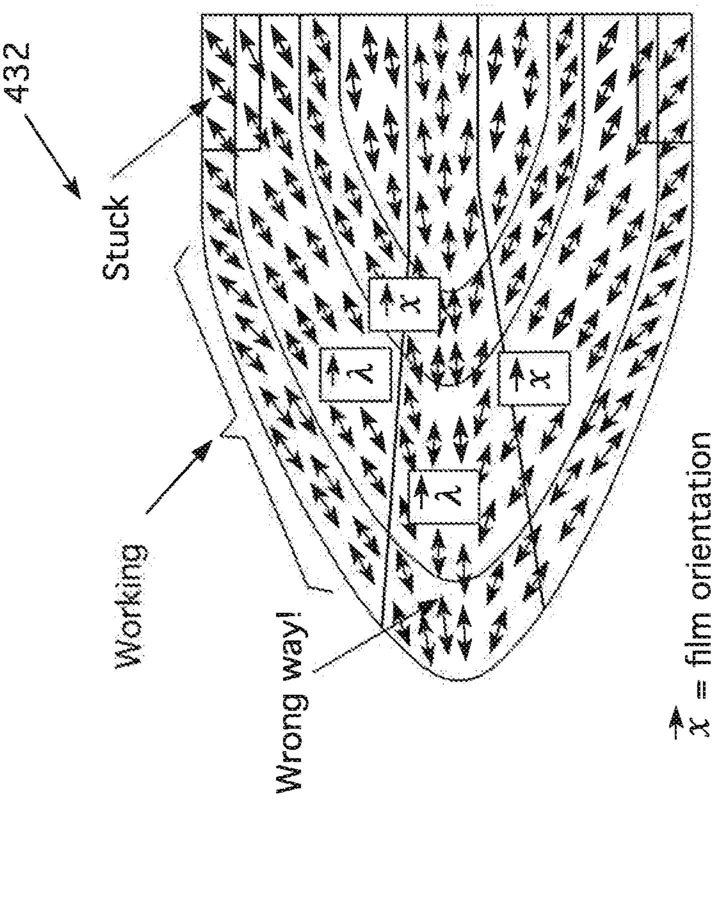


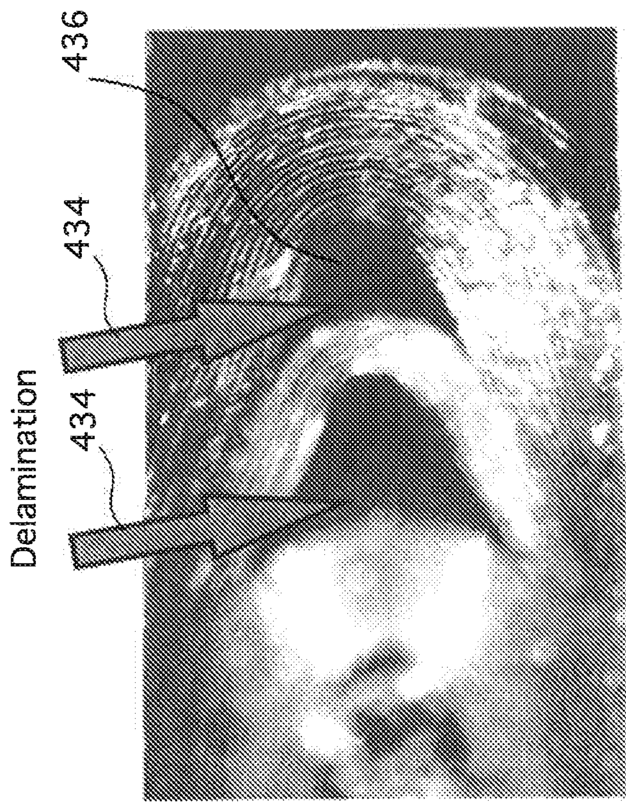
FIG. 32D



$\vec{x}$ = film orientation

$\vec{\lambda}$ = first principal strain

FIG. 33



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

FIG. 34

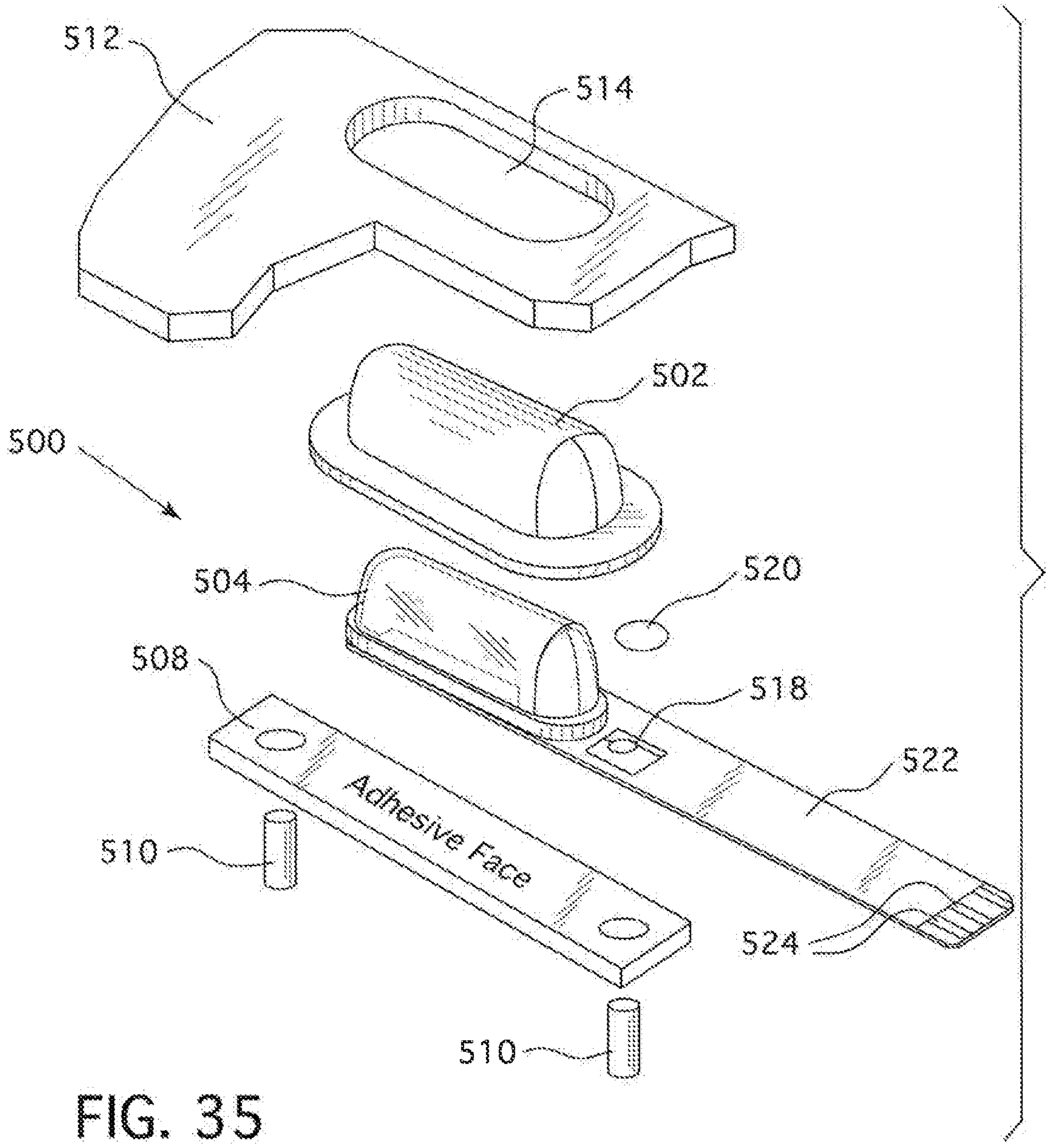


FIG. 35

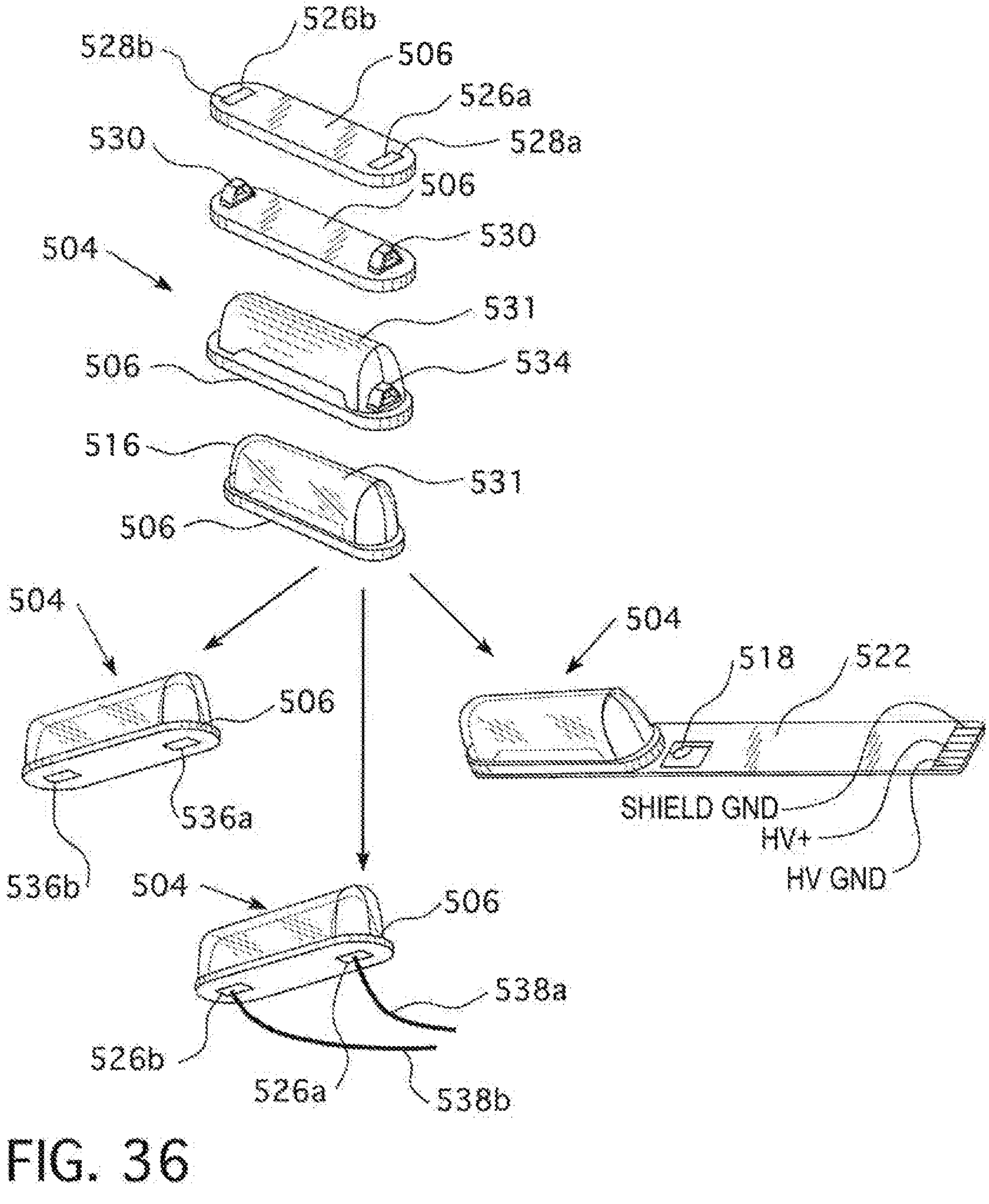

526b
528b
506
526a
528a
530
506
530
504
531
506
534
516
531
506
504
504
506
518
522
SHIELD GND
HV+
HV GND
536a
536b
504
506
538a
526b
526a
538b

FIG. 36

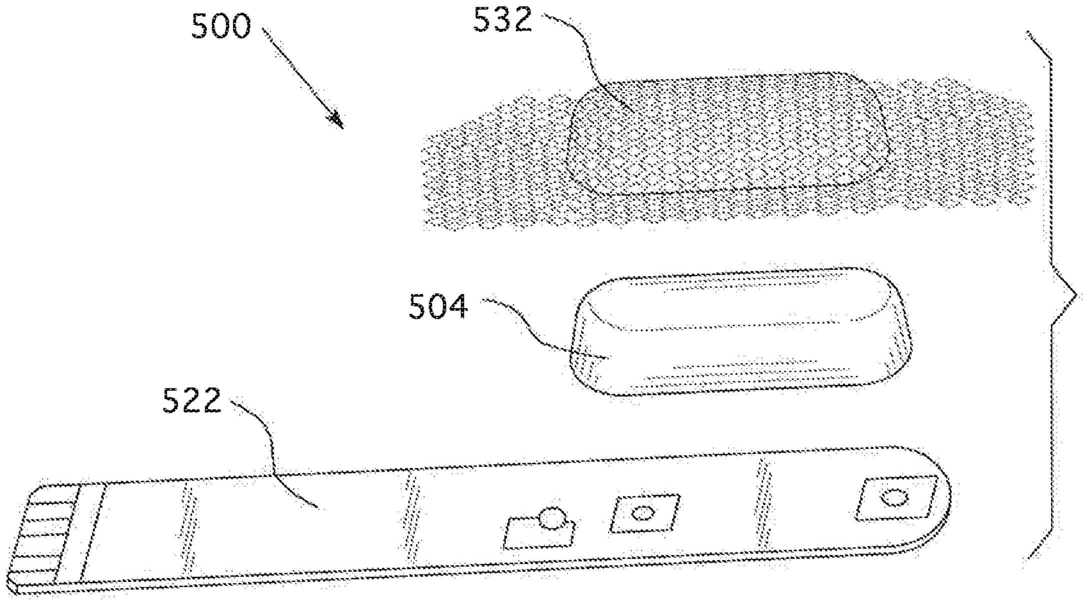


FIG. 37

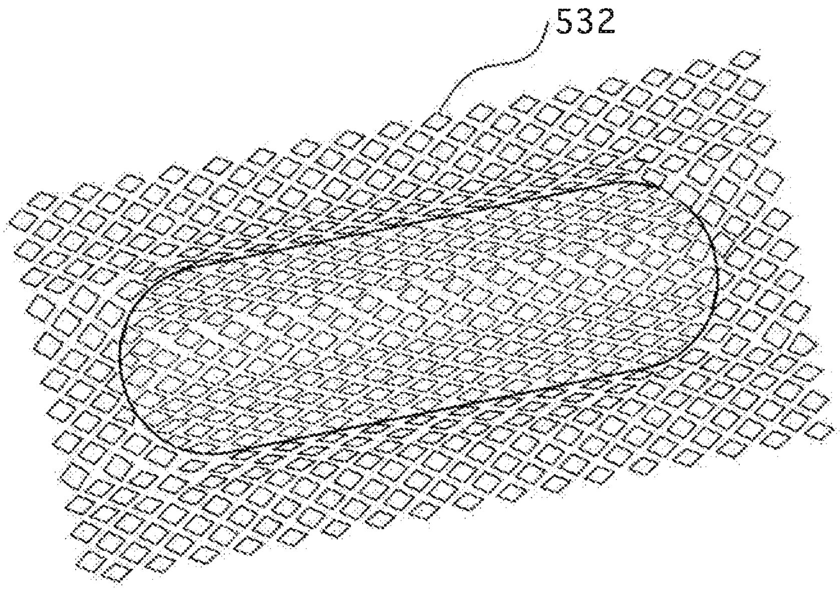


FIG. 38

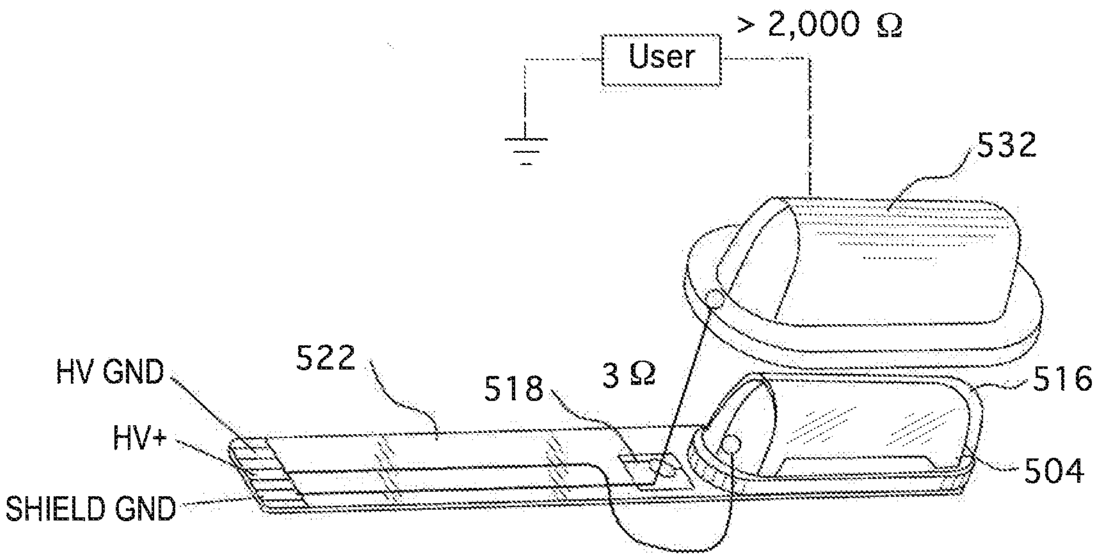

> 2,000 Ω
User
532
522
518
3 Ω
516
504
HV GND
HV+
SHIELD GND

FIG. 39

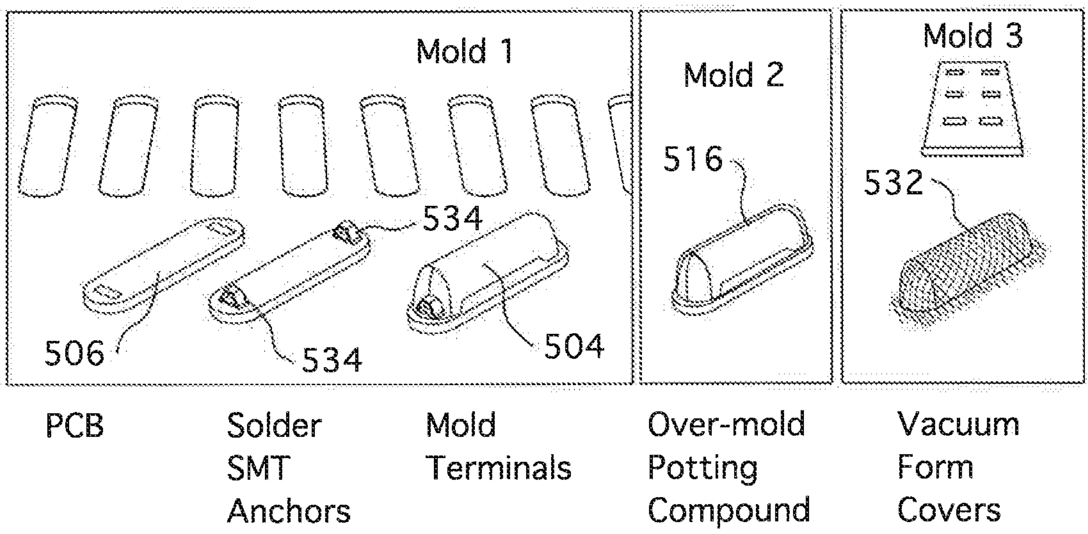

Mold 1
Mold 2
Mold 3
534
516
532
506
534
504
PCB
Solder SMT Anchors
Mold Terminals
Over-mold Potting Compound
Vacuum Form Covers

FIG. 40

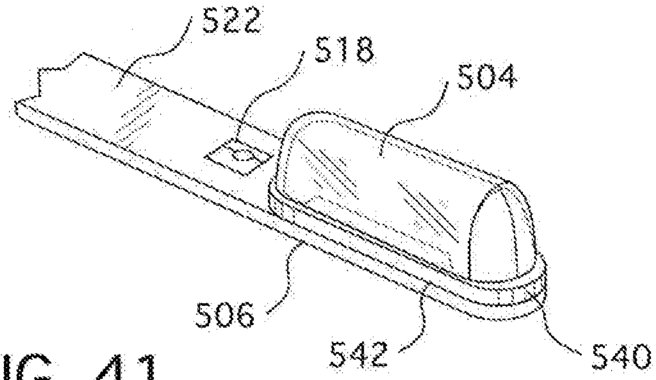


FIG. 41

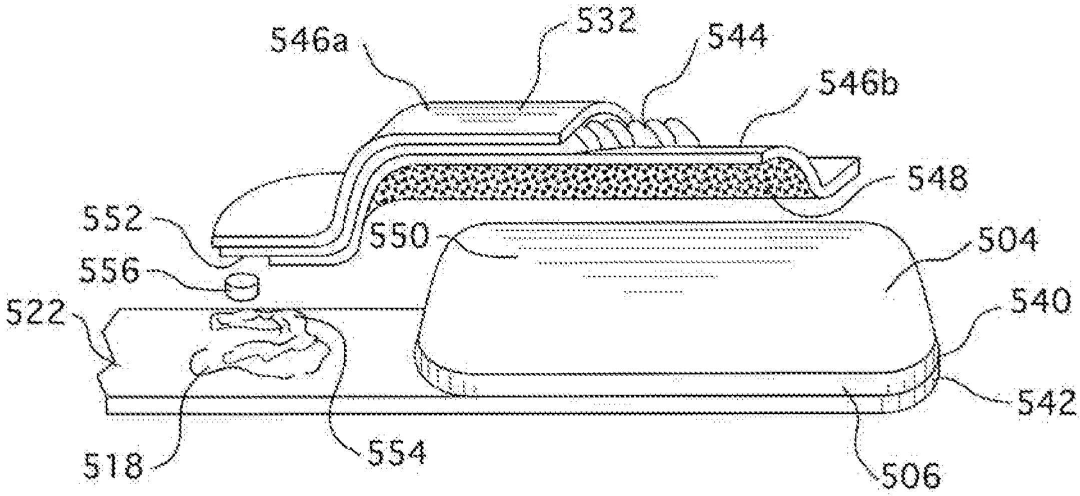


FIG. 42

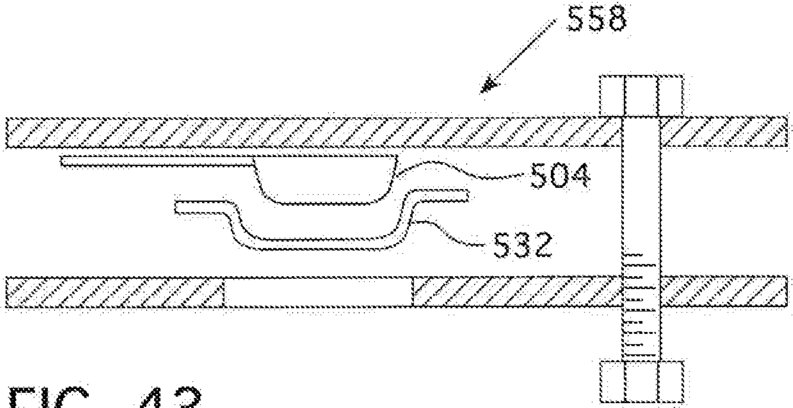


FIG. 43

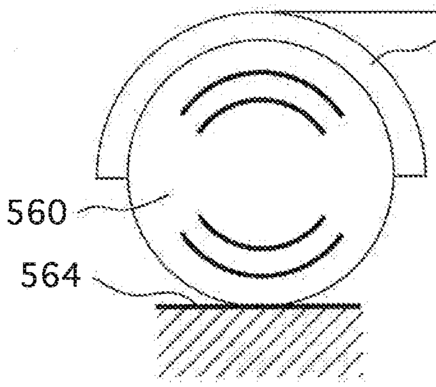


FIG. 44

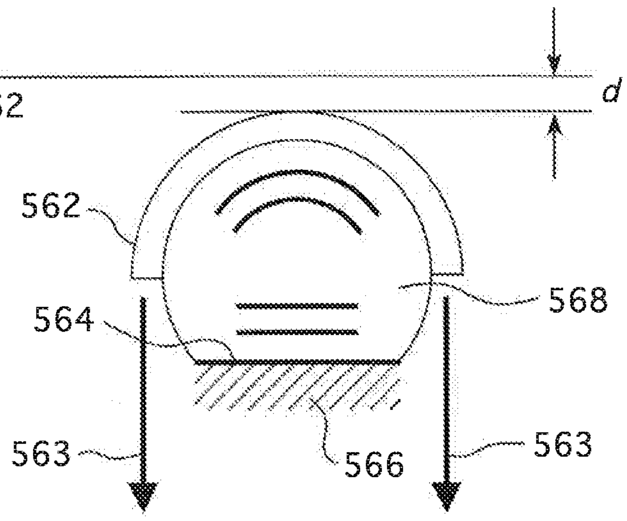


FIG. 45

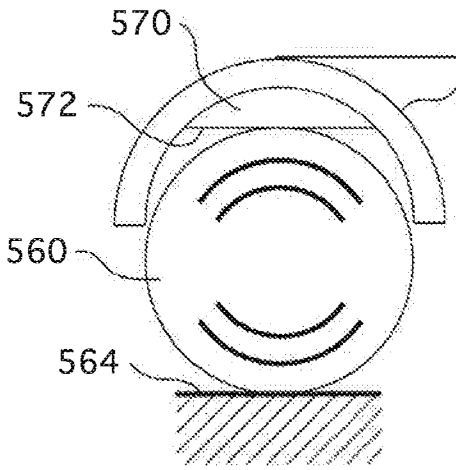


FIG. 46

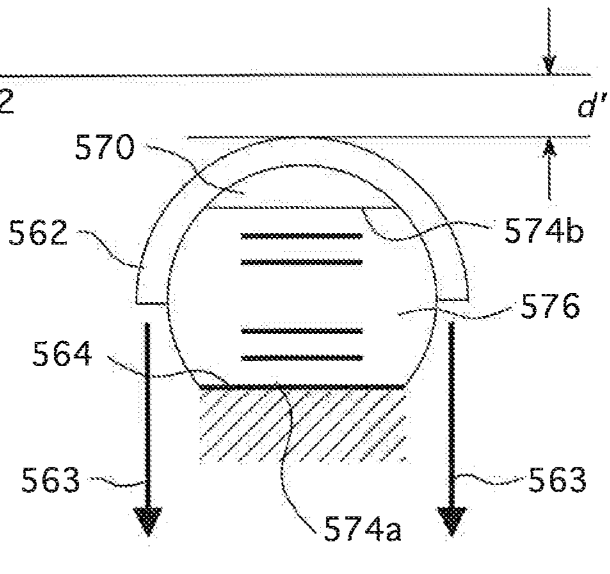


FIG. 47

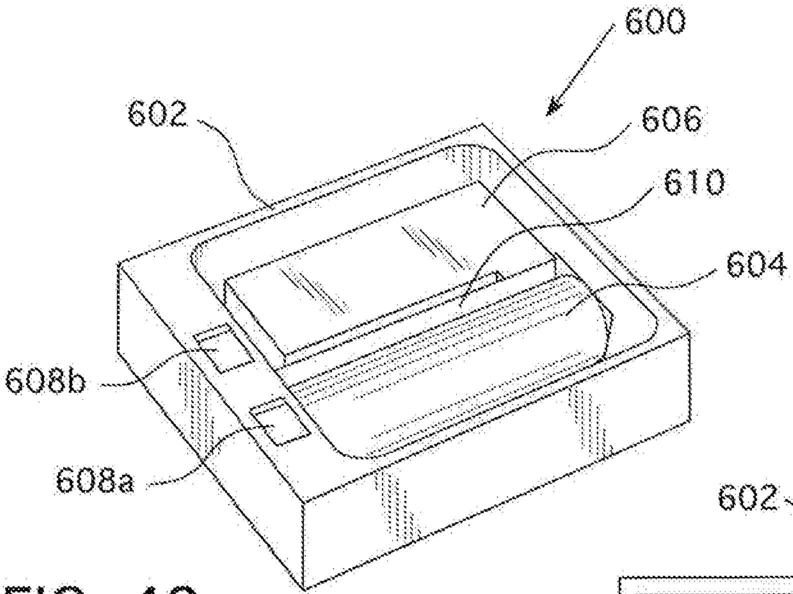


FIG. 48

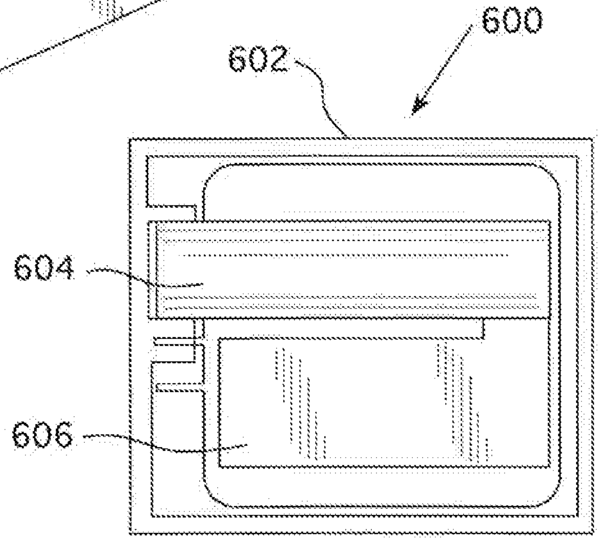


FIG. 49

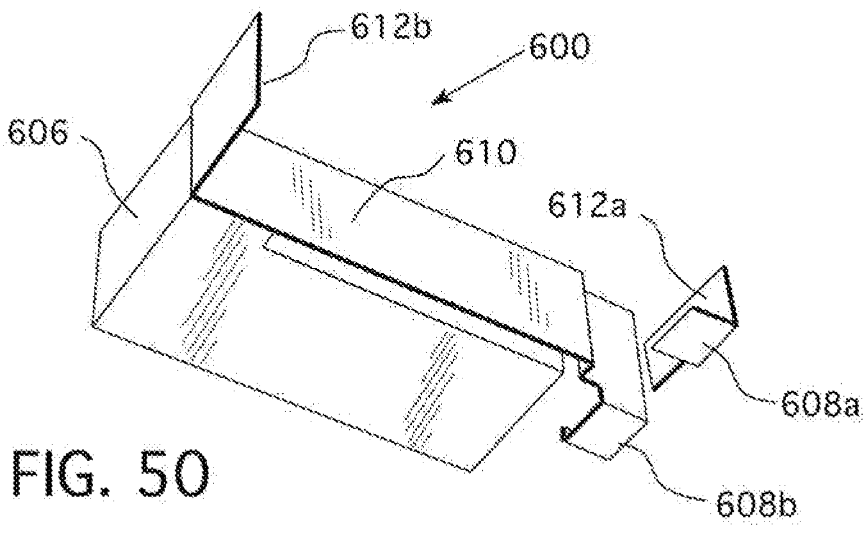


FIG. 50

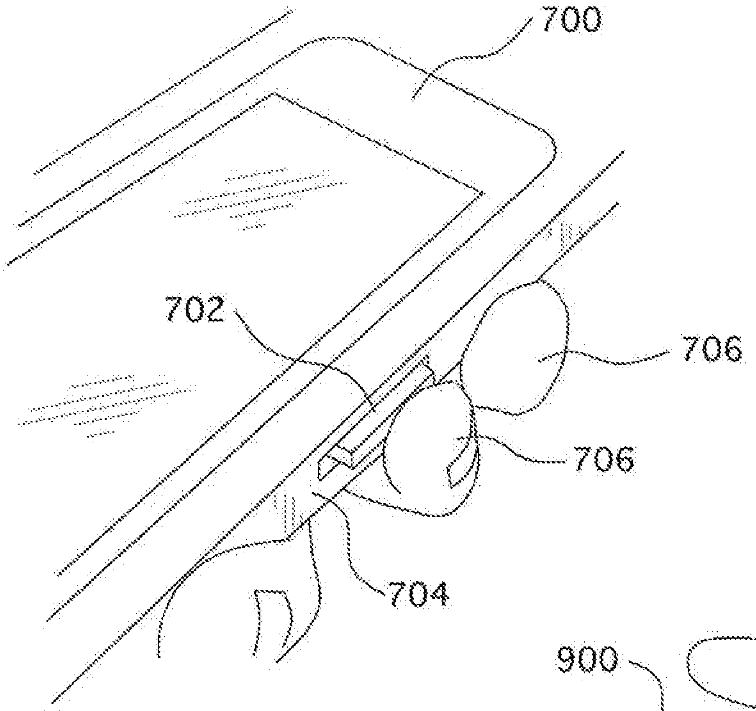


FIG. 51

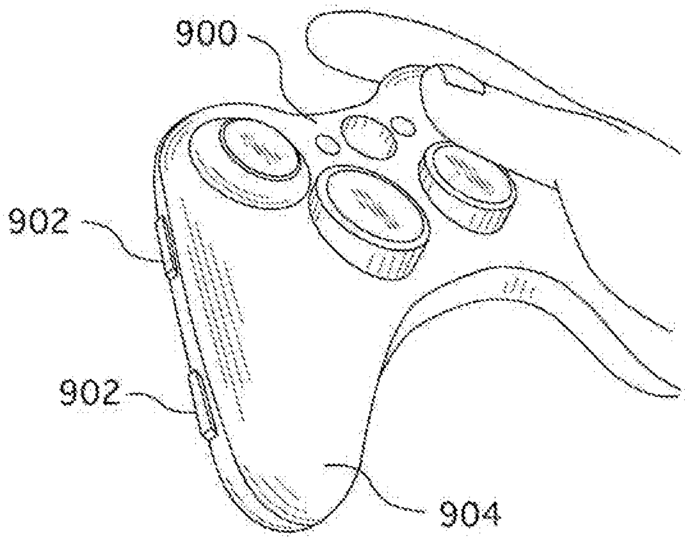


FIG. 53

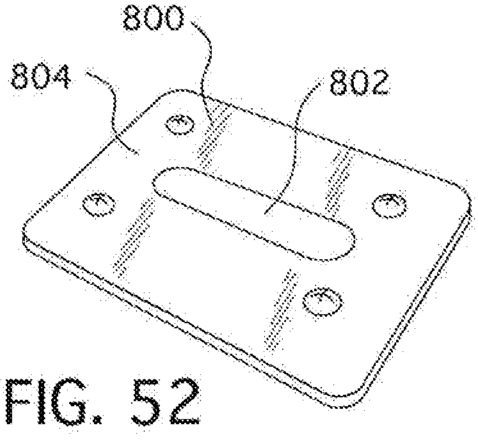


FIG. 52

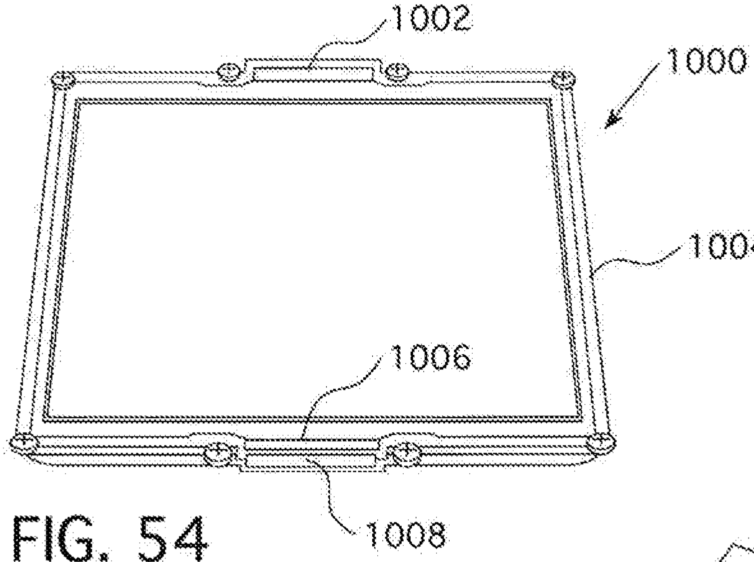


FIG. 54

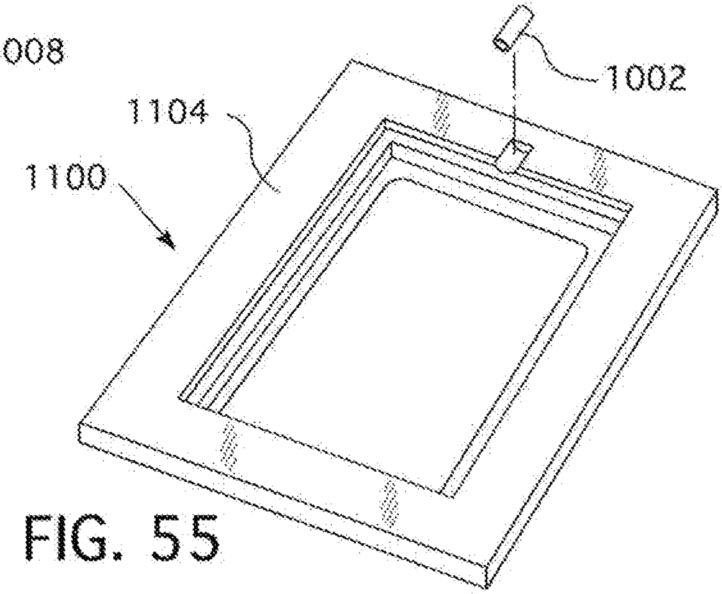


FIG. 55

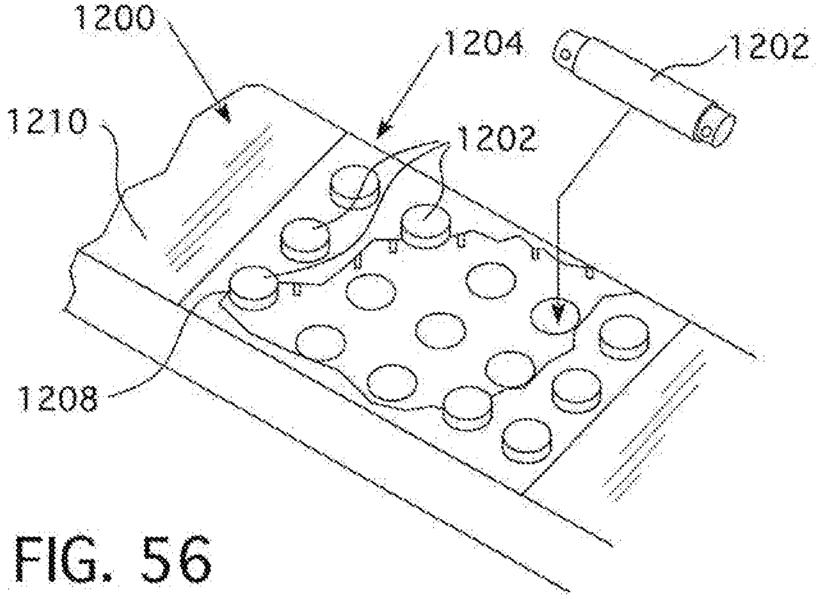


FIG. 56

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/055307

A. CLASSIFICATION OF SUBJECT MATTER

H02N 2/04(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 2/04; H01L 41/04; H01L 41/26; G10H 3/14; H01L 41/08; G06F 1/00; H01L 41/053; G01N 29/00; H02N 11/00

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: roll, dielectric elastomer transducer, actuator, housing, insulate, coat, terminal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 6336367 B1 (HEIKKI RAISANEN) 08 January 2002 See column 2, line 2 - column 4, line 29, claims 1,4,7, and figures 1-6A.	1,3-5 2,9-11,13-17
A	WO 2011-097020 A2 (BAYER MATERIALSCIENCE AG et al.) 11 August 2011 See abstract, page 15, line 14 - page 17, line 2, claims 1-2, and figures 2A-2F.	1-5,9-11,13-17
A	US 2010-0109486 A1 (ILYA POLYAKOV et al.) 06 May 2010 See paragraphs [0041]-[0047], claims 1-2,18,27, and figures 1A-4D.	1-5,9-11,13-17
A	US 2004-0159224 A1 (HEIKKI EERO RAISANEN) 19 August 2004 See paragraphs [0030]-[0034], claims 1-3, and figures 1a-1d.	1-5,9-11,13-17
A	US 2009-0174293 A1 (JON HEIM) 09 July 2009 See paragraphs [0066]-[0069], claims 1-5,7,10, and figures 4A-6B.	1-5,9-11,13-17
A	US 2005-0040733 A1 (ANDREW, A. GOLDENBERG et al.) 24 February 2005 See abstract, paragraphs [0032]-[0035], and figures 1a-2d.	1-5,9-11,13-17

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 December 2013 (16.12.2013)	**17 December 2013 (17.12.2013)**

Name and mailing address of the ISA/KR
Korean Intellectual Property Office
189 Cheongsa-ro, Seo-gu, Daejeon Metropolitan City, 302-701, Republic of Korea
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Authorized officer
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Telephone No. +82-42-481-3463

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2013/055307

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 7
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claim 7 is too broad to make a meaningful search because this is a dependent claim of multiple dependent claim which also refers to other multiple dependent claim.

3. ☒ Claims Nos.: 6,8,12,18-20
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2013/055307

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Information on patent family members

International application No.

PCT/US2013/055307

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