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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
29 July 2010 (29.07.2010)

PCT

(10) International Publication Number
WO 2010/085575 A1

(51) International Patent Classification:
G06F 3/041 (2006.01)

(21) International Application Number:
PCT/US2010/021676

(22) International Filing Date:
21 January 2010 (21.01.2010)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/146,279 21 January 2009 (21.01.2009) US

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

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

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

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

(54) **Title**: ELECTROACTIVE POLYMER TRANSDUCERS FOR TACTILE FEEDBACK DEVICES

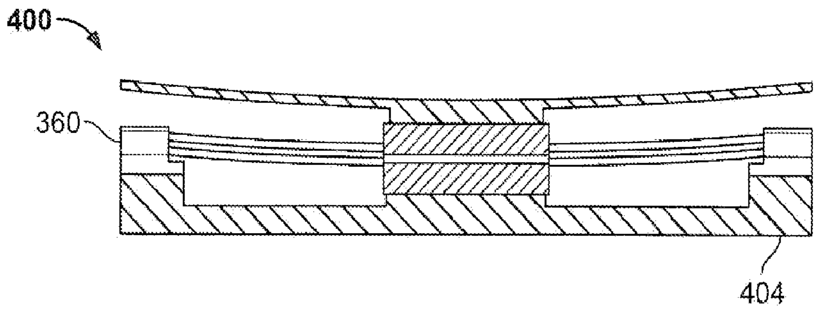

FIG. 30B

(57) **Abstract**: Electroactive transducers as well as methods of producing a haptic effect in a user interface device simultaneously with a sound generated by a separately generated audio signal and electroactive polymer transducers for sensory feedback applications in user interface devices are disclosed.

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ELECTROACTIVE POLYMER TRANSDUCERS FOR TACTILE FEEDBACK DEVICES

RELATED APPLICATION

[0001] The present application is a non-provisional of U.S. Provisional Application No. 61/146,279 filed January 21, 2009 entitled "METHODS AND DEVICES FOR DRIVING ELECTROACTIVE POLYMERS" the entirety of which is incorporated by reference.

FIELD OF THE INVENTION

[0002] The present invention is directed to the use of electroactive polymer transducers to provide sensory feedback.

BACKGROUND

[0003] 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 actuator 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.

[0004] A number of design considerations favor the selection and use of advanced dielectric elastomer materials, also referred to as "electroactive polymers" (EAPs), 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, EAP technology offers an ideal replacement for piezoelectric, shape-memory alloy (SMA) and electromagnetic devices such as motors and solenoids.

[0005] Examples of EAP devices and their applications are described in U.S. Patent Nos. 7,394,282; 7,378,783; 7,368,862; 7,362,032; 7,320,457; 7,259,503; 7,233,097; 7,224,106; 7,211,937; 7,199,501; 7,166,953; 7,064,472; 7,062,055; 7,052,594; 7,049,732; 7,034,432; 6,940,221; 6,911,764; 6,891,317; 6,882,086; 6,876,135; 6,812,624; 6,809,462; 6,806,621; 6,781,284; 6,768,246; 6,707,236; 6,664,718; 6,628,040; 6,586,859; 6,583,533; 6,545,384; 6,543,110; 6,376,971 and 6,343,129; and in U.S. Patent Application Publication Nos. 2009/0001855; 2009/0154053; 2008/0180875; 2008/0157631; 2008/0116764; 2008/0022517; 2007/0230222; 2007/0200468; 2007/0200467; 2007/0200466; 2007/0200457; 2007/0200454; 2007/0200453; 2007/0170822; 2006/0238079;

2006/0208610; 2006/0208609; and 2005/0157893, and U.S. patent application no. 12/358,142 filed on January 22, 2009; PCT application No. PCT/US09/63307; and PCT Publication No. W0 2009/067708 the entireties of which are incorporated herein by reference.

[0006] An EAP 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 EAP 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. U.S. Patent Application Serial No. 2005/0157893 discloses EAP film constructs which provide such out-of-plane displacement – also referred to as surface deformation or thickness mode deflection.

[0007] The material and physical properties of the EAP film may be varied and controlled to customize the surface 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 EAP 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 surface features of the film when in an active mode.

[0008] Numerous transducer-based applications exist which would benefit from the advantages provided by such EAP films. One such application includes the use of EAP films to produce haptic feedback (the communication of information to a user through forces applied to the user's body) in user interface devices. There are many known user interface devices which employ haptic feedback, typically in response to a force initiated by the user. Examples of user interface devices that may employ haptic 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.

[0009] The haptic feedback provided by these types of interface devices is in the form of physical sensations, such as vibrations, pulses, spring forces, etc., which a user senses either directly (e.g., via touching of the screen), indirectly (e.g., via a vibrational effect such a when a cell phone vibrates in a purse or bag) or otherwise sensed (e.g., via an action of a moving body that creates a pressure disturbance but does not generate an audio signal in the traditional sense).

[0010] Often, a user interface device with haptic feedback can be an input device that "receives" an action initiated by the user as well as an output device that provides haptic feedback indicating that the action was initiated. In practice, the position of some contacted or touched portion or surface, e.g., a button, of a user interface device is changed along at least one degree of freedom by the force applied by the user, where the force applied must reach some minimum threshold value in order for the contacted portion to change positions and to effect the haptic feedback. Achievement or registration of the change in position of the contacted portion results in a responsive force (e.g., spring-back, vibration, pulsing) which is also imposed on the contacted portion of the device acted upon by the user, which force is communicated to the user through his or her sense of touch.

[0011] One common example of a user interface device that employs a spring-back, "bi-stable" or "bi-phase" type of haptic feedback is a button on a mouse, keyboard, touchscreen, or other interface device. The user interface surface does not move until the applied force reaches a certain threshold, at which point the button moves downward with relative ease and then stops – the collective sensation of which is defined as "clicking" the button. Alternatively, the surface moves with an increasing resistance force until some threshold is reached at which point the force profile changes (e.g., reduces). The user-applied force is substantially along an axis perpendicular to the button surface, as is the responsive (but opposite) force felt by the user. However, variations include application of the user applied force laterally or in-plane to the button surface.

[0012] In another example, when a user enters input on a touch screen the, screen confirms the input typically by a graphical change on the screen along with, without an auditory cue. A touch screen provides graphical feedback by way of visual cues on the screen such as color or shape changes. A touch pad provides visual feedback by means of a cursor on the screen. While above cues do provide feedback, the most intuitive and effective feedback from a finger actuated input device is a tactile one such as the detent of a keyboard key or the detent of a mouse wheel. Accordingly, incorporating haptic feedback on touch screens is desirable.

[0013] Haptic feedback capabilities are known to improve user productivity and efficiency, particularly in the context of data entry. It is believed by the inventors hereof that further improvements to the character and quality of the haptic sensation communicated to a user may further increase such productivity and efficiency. It would be additionally beneficial if such improvements were provided by a sensory feedback mechanism which is easy and cost-effective to manufacture, and does not add to, and preferably reduces, the space, size and/or mass requirements of known haptic feedback devices.

[0014] While the incorporation of EAP based transducers can improve the haptic interaction on such user interface devices, there remains a need to employ such EAP transducers without increasing the profile of the user interface device.

SUMMARY OF THE INVENTION

[0015] The present invention includes devices, systems and methods involving electroactive transducers for sensory applications. In one variation, a user interface device having sensory feedback is provided. One benefit of the present invention is to provide the user of a user interface device with haptic feedback whenever an input is triggered by software or another signal generated by the device or associated components.

[0016] The methods and devices described herein seek to improve upon the structure and function of EAP-based transducers systems. The present disclosure discusses customized transducer constructs for use in various applications. The present disclosure also provides numerous devices and methods for driving EAP transducers as well as EAP transducer-based devices and systems for mechanical actuation, power generation and/or sensing.

[0017] These and other features, objects 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.

[0018] The EPAM cartridges that can be used with these designs include, but are not limited to Planar, Diaphragm, Thickness Mode, and Passive Coupled devices (Hybrids)

[0019] In one variation of a user interface device including an electroactive polymer transducer, the device includes a chassis, a user interface surface, a first power supply, at least one electroactive polymer transducer adjacent to the user interface surface, the electroactive polymer transducer further comprising an electrically conductive surface, where a portion of the user interface surface and the electrically conductive surface form a circuit with the first power supply, such that in a normal state the electrically conductive surface is electrically isolated from the portion of the user interface surface to open the circuit causing the electroactive polymer transducer to remain in an unpowered state, and where the user interface surface is flexibly coupled to the chassis such that deflection of the user interface surface into the electro active polymer transducer closes the circuit to energize the electroactive polymer transducer such that a signal provided to the electro active polymer transducer produces a haptic sensation at the user interface surface.

[0020] Additional variations of the user interface as described above can include a plurality of electroactive polymer transducers, each adjacent to a user interface surface and each having respective electrically conductive surfaces such that deflection of one user interface surface into the conductive surface causes the respective electroactive polymer transducer and electrically conductive surface to form the closed circuit and where the remaining electro active polymer transducers to remain in the unpowered state.

[0021] In another variation, the user interface device includes a low voltage power supply and a high voltage power supply coupled to a switch, such that deflection of the electroactive polymer transducer and the electrically conductive surface closes the switch allowing the high voltage power supply to energize the electroactive polymer actuator.

[0022] Another variation of a user interface device comprises a device similar to that described above, where at least one electroactive polymer transducer is coupled to the user interface surface, the electroactive polymer transducer further comprising an electrically conductive surface, the electrically conductive surface forming a circuit with the first power supply, such that in a normal state the electrically conductive surface is electrically isolated from the circuit to open the circuit such that the electroactive polymer transducer remains in an unpowered state; and where the electroactive polymer transducer is flexibly coupled to the chassis such that deflection of the user interface surface deflects the electroactive polymer transducer into contact with the circuit of the first power supply to close the circuit and energize the electroactive polymer actuator such that a signal provided to the electro active polymer transducer produces a haptic sensation at the user interface surface.

[0023] In another variation, the user interface device includes a plurality of electroactive polymer transducers, each adjacent to a user interface surface and each having respective electrically conductive surfaces such that deflection of one user interface surface into the conductive surface causes the respective electroactive polymer transducer and electrically conductive surface to form the closed circuit and where the remaining electro active polymer transducers remain in the unpowered state.

[0024] The following disclosure also includes a method of producing a haptic effect in a user interface device where the haptic effect mimics a bi-stable switch effect. In one example, this method includes providing a user interface surface having an electroactive polymer transducer coupled thereto, where the electroactive polymer transducer comprises at least one electroactive polymer film, displacing the user interface surface by a displacement amount to also displace the electroactive polymer film and increase a resistance force applied by the electroactive polymer film against the user interface surface, delaying activation of the electroactive polymer transducer during displacement of the electroactive polymer film, and activating the electroactive polymer transducer to vary the resistance force without decreasing the displacement amount to create the haptic effect that mimics the bi-stable switch effect. Delayed activation of the electroactive polymer can occur after a pre-determined time. Alternatively, delaying the activation of the electroactive polymer occurs after a pre-determined displacement of the electroactive polymer film.

[0025] Another variation of a method under the following disclosure includes producing a pre-determined haptic effect in a user interface device. The method can include providing a waveform circuit configured to produce at least one pre-determined haptic waveform signal, routing a signal to the waveform circuit such that when the signal equals a triggering value, the waveform circuit generates the haptic waveform signal, and providing the haptic waveform signal to a power supply coupled to an electroactive polymer transducer such that the power supply drives the electroactive polymer transducer to produce a complex haptic effect controlled by the haptic waveform signal.

[0026] The disclosure also includes a method of producing a haptic feedback sensation in a user interface device having a user interface surface, by transmitting an input signal from a drive circuit to an electroactive polymer transducer where the input signal actuates the electroactive polymer transducer and provide the haptic feedback sensation at the user interface surface, and transmitting a dampening signal to reduce mechanical displacement of the user interface surface after the desired haptic feedback sensation. Such a method can be used to produce a haptic effect sensation that comprises a bi-stable key-click effect.

[0027] Yet another method as disclosed herein includes a method of producing a haptic feedback in a user interface device by providing an electro active polymer transducer with the user interface device, the electro active polymer transducer having a first phase and having a second phase, where the electro active polymer transducer comprises a first lead common to the first phase, a second lead common to the second phase, and a third lead common to the first and second phases, maintaining a first lead at a high voltage while maintaining the second lead to a ground, and driving the third lead to vary from the ground to the high voltage to enable activation of the first or second phase upon the deactivation of the respective other phase.

[0028] The present invention may be employed in any type of user interface device including, but not limited to, touch pads, touch screens or key pads or the like for computer, phone, PDA, video game console, GPS system, kiosk applications, etc.

[0029] 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 method-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.

[0030] These and other features, objects 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.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] 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 that are common to the drawings. Included in the drawings are the following:

[0032] Figs. 1A and 1B illustrate some examples of a user interface that can employ haptic feedback when an EAP transducer is coupled to a display screen or sensor and a body of the device.

[0033] Figs. 2A and 2B, show a sectional view of a user interface device including a display screen having a surface that reacts with haptic feedback to a user's input.

[0034] Figs. 3A and 3B illustrate a sectional view of another variation of a user interface device having a display screen covered by a flexible membrane with active EAP formed into active gaskets.

[0035] Fig. 4 illustrates a sectional view of an additional variation of a user interface device having a spring biased EAP membrane located about an edge of the display screen.

[0036] Fig. 5 shows a sectional view of a user interface device where the display screen is coupled to a frame using a number of compliant gaskets and the driving force for the display is a number of EAP actuators diaphragms.

[0037] Figs. 6A and 6B show sectional views of a user interface 230 having a corrugated EAP membrane or film coupled to a display.

[0038] Figs. 7A and 7B illustrate a top perspective view of a transducer before and after application of a voltage in accordance with one embodiment of the present invention.

[0039] Figs. 8A and 8B show exploded top and bottom perspective views, respectively, of a sensory feedback device for use in a user interface device.

[0040] Fig. 9A is a top planar view of an assembled electroactive polymer actuator of the present invention; Figs. 9B and 9C are top and bottom planar views, respectively, of the film portion of the actuator of Fig. 8A and, in particular, illustrate the two-phase configuration of the actuator.

[0041] Figs. 9D and 9E illustrate an example of arrays of electro active polymer transducer for placing across a surface of a display screen that is spaced from a frame of the device.

[0042] Figs. 9F and 9G are an exploded view and assembled view, respectively, of an array of actuators for use in a user interface device as disclosed herein.

[0043] Fig. 10 illustrates a side view of the user interface devices with a human finger in operative contact with the contact surface of the device.

[0044] Figs. 11A and 11B graphically illustrate the force-stroke relationship and voltage response curves, respectively, of the actuator of Figs. 9A-9C when operated in a single-phase mode.

[0045] Figs. 11C and 11D graphically illustrate the force-stroke relationship and voltage response curves, respectively, of the actuator of Figs. 9A-9C when operated in a two-phase mode.

[0046] Figs. 12A to 12C illustrate another variation of a two phase transducer.

[0047] Fig. 12D illustrates a graph of displacement versus time for the two phase transducer of Figs. 12A to 12C.

[0048] Fig. 13 is a block diagram of electronic circuitry, including a power supply and control electronics, for operating the sensory feedback device.

[0049] Figs. 14A and 14B shows a partial cross sectional view of an example of a planar array of EAP actuators coupled to a user input device.

[0050] Figs. 15A and 15B schematically illustrate a surface deformation EAP transducer employed as an actuator which utilizes polymer surface features to provide work output when the transducer is activated;

[0051] Figs. 16A and 16B are cross-sectional views of exemplary constructs of an actuator of the present invention;

[0052] Figs. 17A-17D illustrate various steps of a process for making electrical connections within the subject transducers for coupling to a printed circuit board (PCB) or flex connector;

[0053] Figs. 18A-18D illustrate various steps of a process for making electrical connections within the subject transducers for coupling to an electrical wire;

[0054] Fig. 19 is a cross-sectional view of a subject transducer having a piercing type of electrical contact;

[0055] Figs. 20A and 20B are top views of a thickness mode transducer and electrode pattern, respectively, for application in a button-type actuator;

[0056] Fig. 21 illustrates a top cutaway view of a keypad employing an array of button-type actuators of Figs. 6A and 6B;

[0057] Fig. 22 illustrates a top view of a thickness mode transducer for use in a novelty actuator in the form of a human hand;

[0058] Fig. 23 illustrates a top view of thickness mode transducer in a continuous strip configuration;

[0059] Fig. 24 illustrates a top view of a thickness mode transducer for application in a gasket-type actuator;

[0060] Figs. 25A-25D are cross-sectional views of touch screens employing various type gasket-type actuators;

[0061] Figs. 26A and 26B are cross-sectional views of another embodiment of a thickness mode transducer of the present invention in which the relative positions of the active and passive areas of the transducer are inversed from the above embodiments.

[0062] Figs. 27A-27D illustrate an example of an electroactive inertial transducer.

[0063] Fig. 28A illustrates one example of a circuit to tune an audio signal to work within optimal haptic frequencies for electroactive polymer actuators.

[0064] Fig. 28B illustrates an example of a modified haptic signal filtered by the circuit of Fig. 28A.

[0065] Figs. 28C and 28F illustrate additional circuits for producing signals for single and double phase electroactive transducers.

[0066] Figs. 28E and 28F show an example of a device having one or more electroactive polymer actuators within the device body and coupled to an inertial mass.

[0067] Figs. 29A to 29C show an example of electroactive polymer transducers when used in a user interface device where a portion of the transducer and/or user interface surface completes a switch to provide power to the transducer.

[0068] Figs. 30A to 30B illustrate another example of an electroactive polymer transducers configured to form two switches for powering of the transducer.

[0069] Figs. 31A to 31B illustrate various graph of delaying activation of an electroactive polymer transducer to produce a haptic effect that mimics a mechanical switch effect.

[0070] Fig. 32 illustrates an example of a circuit to drive an electroactive polymer transducer using a triggering signal (such as an audio signal) to deliver a stored waveform for producing a desired haptic effect.

[0071] Figs. 33A and 33B illustrate another variation for driving an electroactive polymer transducer by providing two-phase activation with a single drive circuit.

[0072] Figs. 34A shows an example of a displacement curve showing residual motion after a haptic effect a triggered by the signal of Fig. 34B.

[0073] Figs. 34C shows an example of a displacement curve employing electronic dampening to reduce the showing residual motion effect where the haptic effect and dampening signal are illustrated in Fig. 34D.

[0074] Fig. 35 illustrates an example of an energy harvesting circuit for powering an electroactive polymer transducer.

[0075] Variation of the invention from that shown in the figures is contemplated.

DETAILED DESCRIPTION OF THE INVENTION

[0076] The devices, systems and methods of the present invention are now described in detail with reference to the accompanying figures.

[0077] As noted above, devices requiring a user interface can be improved by the use of haptic feedback on the user screen of the device. Figs 1A and 1B illustrate simple examples of such devices **190**. Each device includes a display screen **232** for which the user enters or views data. The display screen is coupled to a body or frame **234** of the device. Clearly, any number of devices are included within the scope of this disclosure regardless of whether portable (e.g., cell phones, computers, manufacturing equipment, etc.) or affixed to other non-portable structures (e.g., the screen of an information display panel, automatic teller screens, etc.) For purposes of this disclosure, a display screen can also include a touchpad type device where user input or interaction takes place on a monitor or location away from the actual touchpad (e.g., a lap-top computer touchpad).

[0078] A number of design considerations favor the selection and use of advanced dielectric elastomer materials, also referred to as "electroactive polymers" (EAPs), for the fabrication of transducers especially when haptic feedback of the display screen **232** is sought. 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, EAP technology offers an ideal replacement for piezoelectric, shape-memory alloy (SMA) and electromagnetic devices such as motors and solenoids.

[0079] An EAP transducer comprises two thin film electrodes having elastic characteristics and separated by a thin elastomeric dielectric material. In some variations, the EAP transducer can comprise a non-elastic dielectric material. In any case, 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 (the x- and y-axes components expand).

[0080] Figs. 2A-2B, shows a portion of a user interface device **230** with a display screen **232** having a surface that is physically touched by the user in response to information, controls, or stimuli on the display screen. The display screen **234** can be any type of a touch pad or screen panel such as a liquid crystal display (LCD), organic light emitting diode (OLED) or the like. In addition, variations of interface devices **230** can include display screens **232** such as a "dummy" screen, where an image transposed on the screen (e.g., projector or graphical covering). The screen can include conventional monitors or even a screen with fixed information such as common signs or displays.

[0081] In any case, the display screen **232** includes a frame **234** (or housing or any other structure that mechanically connects the screen to the device via a direct connection or one or more ground elements), and an electroactive polymer (EAP) transducer **236** that couples the screen **232** to the frame or housing **234**. As noted herein, the EAP transducers can be along an edge of the screen **232** or an array of EAP transducers can be placed in contact with portion of the screen **232** that are spaced away from the frame or housing **234**.

[0082] Figs. 2A and 2B illustrate a basic user interface device where an encapsulated EAP transducer **236** forms an active gasket. Any number of active gasket EAPs **236** can be coupled between the touch screen **232** and frame **234**. Typically, enough active gasket EAPs **236** are provided to produce the desired haptic sensation. However, the number will often vary depending on the particular application. In a variation of the device, the touch screen **232** may either comprise a display screen or a sensor plate (where the display screen would be behind the sensor plate).

[0083] The figures show the user interface device **230** cycling the touch screen **232** between an inactive and active state. Fig. 2A shows the user interface device **230** where the touch screen **232** is in an inactive state. In such a condition, no field is applied to the EAP transducers **236** allowing the transducers to be at a resting state. Fig. 2B shows the user interface device **230** after some user input triggers the EAP transducer **236** into an active state where the transducers **236** cause the display screen **232** to move in the direction shown by arrows **238**. Alternatively, the displacement of one or more EAP transducers **236** can vary to produce a directional movement of the display screen **232** (e.g., rather than the entire display screen **232** moving uniformly one area of the screen **232** can displace to a larger degree than another area). Clearly, a control system coupled to the user interface device **230** can be configured to cycle the EAPS **236** with a desired frequency and/or to vary the amount of deflection of the EAP **236**.

[0084] Figs. 3A and 3B illustrate another variation of a user interface device **230** having a display screen **232** covered by a flexible membrane **240** that functions to protect the display screen **232**. Again, the device can include a number of active gasket EAPs **236** coupling the display screen **232** to a base or frame **234**. In response to a user input, the screen **232** along with the membrane **240** displaces when an electric field is applied to the EAPs **236** causing displacement so that the device **230** enters an active state.

[0085] Fig. 4 illustrates an additional variation of a user interface device **230** having a spring biased EAP membrane **244** located about an edge of the display screen **232**. The EAP membrane **244** can be placed about a perimeter of the screen or only in those locations that permit the screen to produce haptic feedback to the user. In this variation, a passive compliant gasket or spring **244** provides a force against the screen **232** thereby placing the EAP membranes **242** in a state of tension. Upon providing an electric field **242** to the membrane (again, upon a signal generated by a user input), the EAP membranes **242** relax to cause displacement of the screen **232**. As noted by arrows **246**, the user input device **230** can be configured to produce movement of the screen **232** in any direction relative to the bias provided by the gasket **244**. In addition, actuation of less than all the EAP membranes **242** produces non-uniform movement of the screen **232**.

[0086] Fig. 5 illustrates yet another variation of a user interface device **230**. In this example, the display screen **232** is coupled to a frame **234** using a number of compliant gaskets **244** and the driving force for the display **232** is a number of EAP actuators diaphragms **248**. The EAP actuator diaphragms **248** are spring biased and upon application of an electric field can drive the display screen. As shown, the EAP actuator diaphragms **248** have opposing EAP membranes on either side of a spring. In such a configuration, activating opposite sides of the EAP actuator diaphragms **248** makes the assembly rigid at a neutral point. The EAP actuator diaphragms **248** act like the opposing bicep and triceps muscles that control movements of the human arm. Though not shown, as discussed in U.S. Patent Application Serial Nos. 11/085,798 and 11/085,804 the actuator diaphragms **248** can be stacked to provide two-phase output action and/or to amplify the output for use in more robust applications.

[0087] Figs. 6A and 6B show another variation of a user interface **230** having an EAP membrane or film **242** coupled between a display **232** and a frame **234** at a number of points or ground elements **252** to accommodate corrugations or folds in the EAP film **242**. As shown in Fig. 6B, the application of an electric field to the EAP film **242** causes displacement in the direction of the corrugations and deflects the display screen **232** relative to the frame **234**. The user interface **232** can optionally include bias springs **250** also coupled between the display **232** and the frame **234**and/or a flexible protective membrane **240** covering a portion (or all) of the display screen **232**.

[0088] It is noted that the figures discussed above schematically illustrate exemplary configurations of such tactile feedback devices that employ EAP films or transducers. Many variations are within the scope of this disclosure, for example, in variations of the device, the EAP transducers can be implemented to move only a sensor plate or element (e.g., one that is triggered upon user input and provides a signal to the EAP transducer) rather then the entire screen or pad assembly.

[0089] In any application, the feedback displacement of a display screen or sensor plate by the EAP member can be exclusively in-plane which is sensed as lateral movement, or can be out-of-plane (which is sensed as vertical displacement). Alternatively, the EAP transducer material may be segmented to provide independently addressable/movable sections so as to provide angular displacement of the plate element or combinations of other types of displacement. In addition, any number of EAP transducers or films (as disclosed in the applications and patent listed above) can be incorporated in the user interface devices described herein.

[0090] The variations of the devices described herein allows the entire sensor plate (or display screen) of the device to act as a tactile feedback element. This allows for extensive versatility. For example, the screen can bounce once in response to a virtual key stroke or, it can output consecutive bounces in response to a scrolling element such as a slide bar on the screen, effectively simulating the mechanical detents of a scroll wheel. With the use of a control system, a three-dimensional outline can be synthesized by reading the exact position of the user's finger on the screen and moving the screen panel accordingly to simulate the 3D structure. Given enough screen displacement, and significant mass of the screen, the repeated oscillation of the screen may even replace the vibration function of a mobile phone. Such functionality may be applied to browsing of text where a scrolling (vertically) of one line of text is represented by a tactile "bump", thereby simulating detents. In the context of video gaming, the present invention provides increased interactivity and finer motion control over oscillating vibratory motors employed in prior art video game systems. In the case of a touchpad, user interactivity and accessibility may be improved, especially for the visually impaired, by providing physical cues.

[0091] The EAP transducer may be configured to displace to an applied voltage, which facilitates programming of a control system used with the subject tactile feedback devices. For example, a software algorithm may convert pixel grayscale to EAP transducer displacement, whereby the pixel grayscale value under the tip of the screen cursor is continuously measured and translated into a proportional displacement by the EAP transducer. By moving a finger across the touchpad, one could feel or sense a rough 3D texture. A similar algorithm may be applied on a web page, where the border of an icon is fed back to the user as a bump in the page texture or a buzzing button upon moving a finger over the icon. To a normal user, this would provide an entirely new sensory experience while surfing the web, to the visually impaired this would add indispensable feedback.

[0092] EAP transducers are ideal for such applications for a number of reasons. For example, because of their light weight and minimal components, EAP transducers offer a very low profile and, as such, are ideal for use in sensory/haptic feedback applications. .

[0093] Figs. 7A and 7B illustrate an example of an EAP film or membrane **10** structure. A thin elastomeric dielectric film or layer 12 is sandwiched between compliant or stretchable electrode plates or layers 14 and 16, thereby forming a capacitive structure or film. The length "l" and width "w" of the dielectric layer, as well as that of the composite structure, are much greater than its thickness "t". Typically, the dielectric layer has a thickness in range from about 10 μm to about 100 μm, with the total thickness of the structure in the range from about 15 μm to about 10 cm. Additionally, it is desirable to select the elastic modulus, thickness, and/or the microgeometry of electrodes 14, 16 such that the additional stiffness they contribute to the actuator is generally less than the stiffness of the dielectric layer 12, which has a relatively low modulus of elasticity, i.e., less than about 100 MPa and more typically less than about 10 MPa, but is likely thicker than each of the electrodes. Electrodes suitable for use with these compliant capacitive structures are those capable of withstanding cyclic strains greater than about 1% without failure due to mechanical fatigue.

[0094] As seen in Fig. 7B, when a voltage is applied across the electrodes, the unlike charges in the two electrodes 14, 16 are attracted to each other and these electrostatic attractive forces compress the dielectric film 12 (along the Z-axis). The dielectric film 12 is thereby caused to deflect with a change in electric field. As electrodes 14, 16 are compliant, they change shape with dielectric layer 12. Generally speaking, deflection refers to any displacement, expansion, contraction, torsion, linear or area strain, or any other deformation of a portion of dielectric film 12. Depending on the architecture, e.g., a frame, in which capacitive structure 10 is employed (collectively referred to as a "transducer"), this deflection may be used to produce mechanical work. Various different transducer architectures are disclosed and described in the above-identified patent references.

[0095] With a voltage applied, the transducer film 10 continues to deflect until mechanical forces balance the electrostatic forces driving the deflection. The mechanical forces include elastic restoring forces of the dielectric layer 12, the compliance or stretching of the electrodes 14, 16 and any external resistance provided by a device and/or load coupled to transducer 10. The resultant deflection of the transducer 10 as a result of the applied voltage may also depend on a number of other factors such as the dielectric constant of the elastomeric material and its size and stiffness. Removal of the voltage difference and the induced charge causes the reverse effects.

[0096] In some cases, the electrodes 14 and 16 may cover a limited portion of dielectric film 12 relative to the total area of the film. This may be done to prevent electrical breakdown around the edge of the dielectric or achieve customized deflections in certain portions thereof. Dielectric material outside an active area (the latter being a portion of the dielectric material having sufficient electrostatic force to enable deflection of that portion) may be caused to act as an external spring force on the active area during deflection. More specifically, material outside the active area may resist or enhance active area deflection by its contraction or expansion.

[0097] The dielectric film 12 may be pre-strained. The pre-strain improves conversion between electrical and mechanical energy, i.e., the pre-strain allows the dielectric film 12 to deflect more and provide greater mechanical work. Pre-strain of a film may be described as the change in dimension in a direction after pre-straining relative to the dimension in that direction before pre-straining. The pre-strain may comprise elastic deformation of the dielectric film and be formed, for example, by stretching the film in tension and fixing one or more of the edges while stretched. The pre-strain may be imposed at the boundaries of the film or for only a portion of the film and may be implemented by using a rigid frame or by stiffening a portion of the film.

[0098] The transducer structure of Figs. 7A and 7B and other similar compliant structures and the details of their constructs are more fully described in many of the referenced patents and publications disclosed herein.

[0099] In addition to the EAP films described above, sensory or haptic feedback user interface devices can include EAP transducers designed to produce lateral movement. For example, various components including, from top to bottom as illustrated in Figs. 8A and 8B, actuator **30** having an electroactive polymer (EAP) transducer **10** in the form of an elastic film which converts electrical energy to mechanical energy (as noted above). The resulting mechanical energy is in the form of physical "displacement" of an output member, here in the form of a disc **28**.

[0100] With reference to Figs. 9A-9C, EAP transducer film **10** comprises two working pairs of thin elastic electrodes **32a**, **32b** and **34a**, **34b** where each working pair is separated by a thin layer of elastomeric dielectric polymer **26** (e.g., made of acrylate, silicone, urethane, thermoplastic elastomer, hydrocarbon rubber, fluororelastomer, or the like). When a voltage difference is applied across the oppositely-charged electrodes of each working pair (i.e., across electrodes **32a** and **32b**, and across electrodes **34a** and **34b**), the opposed electrodes attract each other thereby compressing the dielectric polymer layer **26** therebetween. As the electrodes are pulled closer together, the dielectric polymer **26** becomes thinner (i.e., the z-axis component contracts) as it expands in the planar directions (i.e., the x- and y-axes components expand) (see Figs. 9B and 9C for axis references). Furthermore, like charges distributed across each electrode cause the conductive particles embedded within that electrode to repel one another, thereby contributing to the expansion of the elastic electrodes and dielectric films. The dielectric layer **26** is thereby caused to deflect with a change in electric field. As the electrode material is also compliant, the electrode layers change shape along with dielectric layer **26**. Generally speaking, deflection refers to any displacement, expansion, contraction, torsion, linear or area strain, or any other deformation of a portion of dielectric layer **26**. This deflection may be used to produce mechanical work.

[0101] In fabricating transducer **20**, elastic film is stretched and held in a pre-strained condition by two or more opposing rigid frame sides **8a**, **8b**. In those variations employing a 4-sided frame, the film is stretched bi-axially. It has been observed that the pre-strain improves the dielectric strength of the polymer layer **26**, thereby improving conversion between electrical and mechanical energy, i.e., the pre-strain allows the film to deflect more and provide greater mechanical work. Typically, the electrode material is applied after pre-straining the polymer layer, but may be applied beforehand. The two electrodes provided on the same side of layer **26**, referred to herein as same-side electrode pairs, i.e., electrodes **32a** and **34a** on top side **26a** of dielectric layer **26** (see Fig. 9B) and electrodes **32b** and **34b** on bottom side **26b** of dielectric layer **26** (see Fig. 9C), are electrically isolated from each other by inactive areas or gaps **25**. The opposed electrodes on the opposite sides of the polymer layer from two sets of working electrode pairs, i.e., electrodes **32a** and **32b** for one working electrode pair and electrodes **34a** and **34b** for another working electrode pair. Each same-side electrode pair preferably has the same polarity, while the polarity of the electrodes of each working electrode pair are opposite each other, i.e., electrodes **32a** and **32b** are oppositely charged and electrodes **34a** and **34b** are oppositely charged. Each electrode has an electrical contact portion **35** configured for electrical connection to a voltage source (not shown).

[0102] In the illustrated embodiment, each of the electrodes has a semi-circular configuration where the same-side electrode pairs define a substantially circular pattern for accommodating a centrally disposed, rigid output disc **20a**, **20b** on each side of dielectric layer **26**. Discs **20a**, **20b**, the functions of which are discussed below, are secured to the centrally exposed outer surfaces **26a**, **26b** of polymer layer **26**, thereby sandwiching layer **26** therebetween. The coupling between the discs and film may be mechanical or be provided by an adhesive bond. Generally, the discs **20a**, **20b** will be sized relative to the transducer frame **22a**, **22b**. More specifically, the ratio of the disc diameter to the inner annular diameter of the frame will be such so as to adequately distribute stress applied to transducer film **10**. The greater the ratio of the disc diameter to the frame diameter, the greater the force of the feedback signal or movement but with a lower linear displacement of the disc. Alternately, the lower the ratio, the lower the output force and the greater the linear displacement.

[0103] Depending upon the electrode configurations, transducer **10** can be capable of functioning in either a single or a two-phase mode. In the manner configured, the mechanical displacement of the output component, i.e., the two coupled discs **20a** and **20b**, of the subject sensory feedback device described above is lateral rather than vertical. In other words, instead of the sensory feedback signal being a force in a direction perpendicular to the display surface **232** of the user interface and parallel to the input force (designated by arrow **60a** in Fig. 10) applied by the user's finger **38** (but in the opposing or upward direction), the sensed feedback or output force (designated by double-head arrow **60b** in Fig. 10) of the sensory/haptic feedback devices of the present invention is in a direction parallel to the display surface **232** and perpendicular to input force **60a**. Depending on the rotational alignment of the electrode pairs about an axis perpendicular to the plane of transducer **10** and relative to the position of the display surface **232** mode in which the transducer is operated (i.e., single phase or two phase), this lateral movement may be in any direction or directions within 360°. For example, the lateral feedback motion may be from side to side or up and down (both are two-phase actuations) relative to the forward direction of the user's finger (or palm or grip, etc.). While those skilled in the art will recognize certain other actuator configurations which provide a feedback displacement which is transverse or perpendicular to the contact surface of the haptic feedback device, the overall profile of a device so configured may be greater than the aforementioned design.

[0104] Figs. 9D-9G illustrate an example of an array of electro-active polymers that can be placed across the display screen of the device. In this example, voltage and ground sides **200a** and **200b**, respectively, of an EAP film array **200** (see Fig. 9F) for use in an array of EAP actuators for use in the tactile feedback devices of the present invention. Film array **200** includes an electrode array provided in a matrix configuration to increase space and power efficiency and simplify control circuitry. The high voltage side **200a** of the EAP film array provides electrode patterns **202** running in vertically (according to the view point illustrated in Fig. 9D) on dielectric film **208** materials. Each pattern **202** includes a pair of high voltage lines **202a**, **202b**. The opposite or ground side **200b** of the EAP film array provides electrode patterns **206** running transversally relative to the high voltage electrodes, i.e., horizontally.

[0105] Each pattern **206** includes a pair of ground lines **206a**, **206b**. Each pair of opposing high voltage and ground lines (**202a**, **206a** and **202b**, **206b**) provides a separately activatable electrode pair such that activation of the opposing electrode pairs provides a two-phase output motion in the directions illustrated by arrows **212**. The assembled EAP film array **200** (illustrating the intersecting pattern of electrodes on top and bottom sides of dielectric film **208**) is provided in Fig. 9F within an exploded view of an array **204** of EAP transducers **222**, the latter of which is illustrated in its assembled form in Fig. 9G. EAP film array **200** is sandwiched between opposing frame arrays **214a**, **214b**, with each individual frame segment **216** within each of the two arrays defined by a centrally positioned output disc **218** within an open area. Each combination of frame/disc segments **216** and electrode configurations form an EAP transducer **222**. Depending on the application and type of actuator desired, additional layers of components may be added to transducer array **204**. The transducer array **220** may be incorporated in whole to a user interface array, such as a display screen, sensor surface, or touch pad, for example.

[0106] When operating sensory/haptic feedback device **2** in single-phase mode, only one working pair of electrodes of actuator **30** would be activated at any one time. The single-phase operation of actuator **30** may be controlled using a single high voltage power supply.

As the voltage applied to the single-selected working electrode pair is increased, the activated portion (one half) of the transducer film will expand, thereby moving the output disc **20** in-plane in the direction of the inactive portion of the transducer film. Fig. 11A illustrates the force-stroke relationship of the sensory feedback signal (i.e., output disc displacement) of actuator **30** relative to neutral position when alternatingly activating the two working electrode pairs in single-phase mode. As illustrated, the respective forces and displacements of the output disc are equal to each other but in opposite directions. Fig. 11B illustrates the resulting non-linear relationship of the applied voltage to the output displacement of the actuator when operated in this single-phase mode. The "mechanical" coupling of the two electrode pairs by way of the shared dielectric film may be such as to move the output disc in opposite directions. Thus, when both electrode pairs are operated, albeit independently of each other, application of a voltage to the first working electrode pair (phase 1) will move the output disc **20** in one direction, and application of a voltage to the second working electrode pair (phase 2) will move the output disc **20** in the opposite direction. As the various plots of Fig. 11B reflect, as the voltage is varied linearly, the displacement of the actuator is non-linear. The acceleration of the output disk during displacement can also be controlled through the synchronized operation of the two phases to enhance the haptic feedback effect. The actuator can also be partitioned into more than two phases that can be independently activated to enable more complex motion of the output disk.

[0107] To effect a greater displacement of the output member or component, and thus provide a greater sensory feedback signal to the user, actuator **30** is operated in a two-phase mode, i.e., activating both portions of the actuator simultaneously. Fig. 11C illustrates the force-stroke relationship of the sensory feedback signal of the output disc when the actuator is operated in two-phase mode. As illustrated, both the force and stroke of the two portions **32**, **34** of the actuator in this mode are in the same direction and have double the magnitude than the force and stroke of the actuator when operated in single-phase mode. Fig. 11D illustrates the resulting linear relationship of the applied voltage to the output displacement of the actuator when operated in this two-phase mode. By connecting the mechanically coupled portions **32**, **34** of the actuator electrically in series and controlling their common node **55**, such as in the manner illustrated in the block diagraph **40** of Fig. 13, the relationship between the voltage of the common node **55** and the displacement (or blocked force) of the output member (in whatever configuration) approach a linear correlation. In this mode of operation, the non-linear voltage responses of the two portions **32**, **34** of actuator **30** effectively cancel each other out to produce a linear voltage response. With the use of control circuitry **44** and switching assemblies **46a**, **46b**, one for each portion of the actuator, this linear relationship allows the performance of the actuator to be fine-tuned and modulated by the use of varying types of waveforms supplied to the switch assemblies by the control circuitry. Another advantage of using circuit **40** is the ability to reduce the number of switching circuits and power supplies needed to operate the sensory feedback device. Without the use of circuit **40**, two independent power supplies and four switching assemblies would be required. Thus, the complexity and cost of the circuitry are reduced while the relationship between the control voltage and the actuator displacement are improved, i.e., made more linear. Another advantage is that during 2-phase operation, the actuator obtains synchronicity, which eliminates delays that could reduce performance.

[0108] Figs. 12A to 12C illustrate another variation of a 2-phase electroactive polymer transducer. In this variation, the transducer **10** comprises a first pair of electrodes **90** about the dielectric film **96** and a second pair of electrodes **92** about the dielectric film **96** where the two pairs of electrodes **90** and **92** are on opposite sides of a bar or mechanical member **94** that facilitates coupling to another structure to transfer movement. As shown in Fig. 12A, both electrodes **90** and **92** are at the same voltage (e.g., both being at a zero voltage). In the first phase, as illustrated in Fig. 12B, one pair of electrodes **92** is energized to expand the film and move the bar **94** by a distance D. The second pair of electrodes **90** is compressed by nature of being connected to the film but is at a zero voltage. Fig. 12C shows a second phase in which the voltage of the first pair of electrodes **92** is reduced or turned off while voltage is applied to the second pair of electrodes **90** is energized. This second phase is synchronized with the first phase so that the displacement is 2 times D. Fig. 12D illustrates the displacement of the transducer **10** of Figs. 12A to 12C over time. As shown, Phase 1 occurs as the bar **94** is displaced by amount D when the first electrode **92** is energized for Phase 1. At time T1 the beginning of Phase 2 occurs and the opposite electrode **90** is energized in synchronization with the reduction of the voltage of the first electrode **92**. The net displacement of the bar **94** over the two phases is 2 x D.

[0109] Various types of mechanisms may be employed to communicate the input force **60a** from the user to effect the desired sensory feedback **60b** (see Fig. 10). For example, a capacitive or resistive sensor **50** (see Fig. 13) may be housed within the user interface pad **4** to sense the mechanical force exerted on the user contact surface input by the user. The electrical output **52** from sensor **50** is supplied to the control circuitry **44** that in turn triggers the switch assemblies **46a**, **46b** to apply the voltage from power supply **42** to the respective transducer portions **32**, **34** of the sensory feedback device in accordance with the mode and waveform provided by the control circuitry.

[0110] Another variation of the present invention involves the hermetic sealing of the EAP actuators to minimize any effects of humidity or moisture condensation that may occur on the EAP film. For the various embodiments described below, the EAP actuator is sealed in a barrier film substantially separately from the other components of the tactile feedback device. The barrier film or casing may be made of, such as foil, which is preferably heat sealed or the like to minimize the leakage of moisture to within the sealed film. Portions of the barrier film or casing can be made of a compliant material to allow improved mechanical coupling of the actuator inside the casing to a point external to the casing. Each of these device embodiments enables coupling of the feedback motion of the actuator's output member to the contact surface of the user input surface, e.g., keypad, while minimizing any compromise in the hermetically sealed actuator package. Various exemplary means for coupling the motion of the actuator to the user interface contact surface are also provided. Regarding methodology, the subject methods may include each of the mechanical and/or activities associated with use of the devices described. As such, methodology implicit to the use of the devices described forms part of the invention. Other methods may focus on fabrication of such devices.

[0111] Fig. 14A shows an example of a planar array of EAP actuators **204** coupled to a user input device **190**. As shown, the array of EAP actuators **204** covers a portion of the screen **232** and is coupled to a frame **234** of the device **190** via a stand off **256**. In this variation, the stand off **256** permits clearance for movement of the actuators **204** and screen **232**. In one variation of the device **190** the array of actuators **204** can be multiple discrete actuators or an array of actuators behind the user interface surface or screen **232** depending upon the desired application. Fig. 14B shows a bottom view of the device **190** of Fig. 14A. As shown by arrow **254** the EAP actuators **204** can allow for movement of the screen **232** along an axis either as an alternative to, or in combination with movement in a direction normal to the screen **232**.

[0112] The transducer/actuator embodiments described thus far have the passive layer(s) coupled to both the active (i.e., areas including overlapping electrodes) and inactive regions of the EAP transducer film. Where the transducer/actuator has also employed a rigid output structure, that structure has been positioned over areas of the passive layers that reside above the active regions. Further, the active/activatable regions of these embodiments have been positioned centrally relative to the inactive regions. The present invention also includes other transducer/actuator configurations. For example, the passive layer(s) may cover only the active regions or only the inactive regions. Additionally, the inactive regions of the EAP film may be positioned centrally to the active regions.

[0113] Referring to Figs. 15A and 15B, a schematic representation is provided of a surface deformation EAP actuator **10** for converting electrical energy to mechanical energy in accordance with one embodiment of the invention. Actuator 10 includes EAP transducer **12** having a thin elastomeric dielectric polymer layer 14 and top and bottom electrodes **16a**, **16b** attached to the dielectric **14** on portions of its top and bottom surfaces, respectively. The portion of transducer **12** comprising the dielectric and at least two electrodes is referred to herein as an active area. Any of the transducers of the present invention may have one or more active areas.

[0114] When a voltage difference is applied across the overlapping and oppositely-charged electrodes **16a**, **16b** (the active area), the opposed electrodes attract each other thereby compressing the portion of the dielectric polymer layer **14** therebetween. As the electrodes **16a, 16b** are pulled closer together (along the z-axis), the portion of the dielectric layer **14** between them becomes thinner as it expands in the planar directions (along the x- and y-axes). For incompressible polymers, i.e., those having a substantially constant volume under stress, or for otherwise compressible polymers in a frame or the like, this action causes the compliant dielectric material outside the active area (i.e., the area covered by the electrodes), particularly perimetrically about, i.e., immediately around, the edges of the active area, to be displaced or bulge out-of-plane in the thickness direction (orthogonal to the plane defined by the transducer film). This bulging produces dielectric surface features **24a-d**. While out-of-plane surface features **24** are shown relatively local to the active area, the out-of-plane is not always localized as shown. In some cases, if the polymer is pre-strained, then the surface features **24a-b** are distributed over a surface area of the inactive portion of the dielectric material.

[0115] In order to amplify the vertical profile and/or visibility of surface features of the subject transducers, an optional passive layer may be added to one or both sides of the transducer film structure where the passive layer covers all or a portion of the EAP film surface area. In the actuator embodiment of Figs. 15A and 15B, top and bottom passive layers **18a**, **18b** are attached to the top and bottom sides, respectively, of the EAP film **12**. Activation of the actuator and the resulting surface features **17a-d** of dielectric layer **12** are amplified by the added thickness of passive layers **18a**, **18b**, as denoted by reference numbers **26a**-d in Fig. 15B.

[0116] In addition to the elevated polymer/passive layer surface features **26a-d**, the EAP film 12 may be configured such that the one or both electrodes **16a**, **16b** are depressed below the thickness of the dielectric layer. As such, the depressed electrode or portion thereof provides an electrode surface feature upon actuation of the EAP film **12** and the resulting deflection of dielectric material **14**. Electrodes **16a**, **16c** may be patterned or designed to produce customized transducer film surface features which may comprise polymer surface features, electrode surface features and/or passive layer surface features.

[0117] In the actuator embodiment **10** of Figs. 15A and 15B, one or more structures **20a**, **20b** are provided to facilitate coupling the work between the compliant passive slab and a rigid mechanical structure and directing the work output of the actuator. Here, top structure **20a** (which may be in the form of a platform, bar, lever, rod, etc.) acts as an output member while bottom structure 20b serves to couple actuator **10** to a fixed or rigid structure **22**, such as ground. These output structures need not be discrete components but, rather, may be integrated or monolithic with the structure which the actuator is intended to drive. Structures **20a**, **20b** also serve to define the perimeter or shape of the surface features 26a-d formed by the passive layers **18a**, **18b**. In the illustrated embodiment, while the collective actuator stack produces an increase in thickness of the actuator's inactive portions, as shown in Fig. 15B, the net change in height Δh undergone by the actuator upon actuation is negative.

[0118] The EAP transducers of the present invention may have any suitable construct to provide the desired thickness mode actuation. For example, more than one EAP film layer may be used to fabricate the transducers for use in more complex applications, such as keyboard keys with integrated sensing capabilities where an additional EAP film layer may be employed as a capacitive sensor.

[0119] Fig. 16A illustrates such an actuator **30** employing a stacked transducer **32** having a double EAP film layer **34** in accordance with the present invention. The double layer includes two dielectric elastomer films with the top film **34a** sandwiched between top and bottom electrodes **34b**, **34c**, respectively, and the bottom film **36a** sandwiched between top and bottom electrodes **36b**, **36c**, respectively. Pairs of conductive traces or layers (commonly referred to as "bus bars") are provided to couple the electrodes to the high voltage and ground sides of a source of power (the latter not shown). The bus bars are positioned on the "inactive" portions of the respective EAP films (i.e., the portions in which the top and bottom electrodes do not overlap). Top and bottom bus bars **42a**, **42b** are positioned on the top and bottom sides, respectively, of dielectric layer **34a**, and top and bottom bus bars **44a**, **44b** positioned on the top and bottom sides, respectively, of dielectric layer **36a**. The top electrode **34b** of dielectric **34a** and the bottom electrode **36c** of dielectric **36a**, i.e., the two outwardly facing electrodes, are commonly polarized by way of the mutual coupling of bus bars **42a** and **44a** through conductive elastomer via 68a (shown in Fig. 16B), the formation of which is described in greater detail below with respect to Figs. 17A-17D. The bottom electrode 34c of dielectric 34a and the top electrode **36b** of dielectric **36a**, i.e., the two inwardly facing electrodes, are also commonly polarized by way of the mutual coupling of bus bars **42b** and **44b** through conductive elastomer via **68b** (shown in Fig. 16B). Potting material **66a**, **66b** is used to seal via **68a**, **68b**. When operating the actuator, the opposing electrodes of each electrode pair are drawn together when a voltage is applied. For safety purposes, the ground electrodes may be placed on the outside of the stack so as to ground any piercing object before it reaches the high voltage electrodes, thus eliminating a shock hazard. The two EAP film layers may be adhered together by film-to-film adhesive **40b**. The adhesive layer may optionally include a passive or slab layer to enhance performance. A top passive layer or slab **50a** and a bottom passive layer **52b** are adhered to the transducer structure by adhesive layer **40a** and by adhesive layer **40c**. Output bars **46a**, **46b** may be coupled to top and bottom passive layers, respectively, by adhesive layers **48a**, **48b**, respectively.

[0120] The actuators of the present invention may employ any suitable number of transducer layers, where the number of layers may be even or odd. In the latter construct, one or more common ground electrode and bus bar may be used. Additionally, where safety is less of an issue, the high voltage electrodes may be positioned on the outside of the transducer stack to better accommodate a particular application.

[0121] To be operational, actuator **30** must be electrically coupled to a source of power and control electronics (neither are shown). This may be accomplished by way of electrical tracing or wires on the actuator or on a PCB or a flex connector **62** which couples the high voltage and ground vias **68a**, **68b** to a power supply or an intermediate connection. Actuator 30 may be packaged in a protective barrier material to seal it from humidity and environmental contaminants. Here, the protective barrier includes top and bottom covers 60, 64 which are preferably sealed about PCB/flex connector **62** to protect the actuator from external forces and strains and/or environmental exposure. In some embodiments, the protective barrier maybe impermeable to provide a hermetic seal. The covers may have a somewhat rigid form to shield actuator **30** against physical damage or may be compliant to allow room for actuation displacement of the actuator **30**. In one specific embodiment, the top cover 60 is made of formed foil and the bottom cover **64** is made of a compliant foil, or vice versa, with the two covers then heat-sealed to board/connector **62**. Many other packaging materials such as metalized polymer films, PVDC, Aclar, styrenic or olefinic copolymers, polyesters and polyolefins can also be used. Compliant material is used to cover the output structure or structures, here bar **46b**, which translate actuator output.

[0122] The conductive components/layers of the stacked actuator/transducer structures of the present invention, such as actuator 30 just described, are commonly coupled by way of electrical vias (**68a** and **68b** in Fig. 16B) formed through the stacked structure. Figs. 17a-19 illustrate various methods of the present invention for forming the vias.

[0123] Formation of the conductive vias of the type employed in actuator **30** of Fig. 16B is described with reference to Figs. 17A-17D. Either before or after lamination of actuator **70** (here, constructed from a single-film transducer with diametrically positioned bus bars **76a**, **76b** placed on opposite sides of the inactive portions of dielectric layer **74**, collectively sandwiched between passive layers **78a**, **78b**) to a PCB/flex connector **72,** the stacked transducer/actuator structure **70** is laser drilled 80 through its entire thickness to PCB **72** to form the via holes **82a**, **82b**, as illustrated in Fig. 17B. Other methods for creating the via holes can also be used such as mechanically drilling, punching, molding, piercing, and coring. The via holes are then filled by any suitable dispensing method, such as by injection, with a conductive material, e.g., carbon particles in silicone, as shown in Fig. 17C. Then, as shown in Fig. 17D, the conductively filled vias **84a**, **84b** are optionally potted **86a**, **86b** with any compatible non-conductive material, e.g., silicone, to electrically isolate the exposed end of the vias. Alternatively, a non-conductive tape may be placed over the exposed vias.

[0124] Standard electrical wiring may be used in lieu of a PCB or flex connector to couple the actuator to the power supply and electronics. Various steps of forming the electrical vias and electrical connections to the power supply with such embodiments are illustrated in Figs. 18A-18D with like components and steps to those in Figs. 17A-17D having the same reference numbers. Here, as shown in Fig. 18A, via holes **82a**, **82b** need only be drilled to a depth within the actuator thickness to the extent that the bus bars **84a**, **84b** are reached. The via holes are then filled with conductive material, as shown in Fig. 18B, after which wire leads **88a**, **88b** are inserted into the deposited conductive material, as shown in Fig. 18C. The conductively filled vias and wire leads may then be potted over, as shown in Fig. 18D.

[0125] Fig. 19 illustrates another manner of providing conductive vias within the transducers of the present invention. Transducer **100** has a dielectric film comprising a dielectric layer **104** having portions sandwiched between electrodes **106a**, **106b**, which in turn are sandwiched between passive polymer layers **110a**, **110b**. A conductive bus bar 108 is provided on an inactive area of the EAP film. A conductive contact **114** having a piercing configuration is driven, either manually or otherwise, through one side of the transducer to a depth that penetrates the bus bar material **108**. A conductive trace **116** extends along PCB/flex connector **112** from the exposed end of piercing contact **114**. This method of forming vias is particularly efficient as it eliminates the steps of drilling the via holes, filling the via holes, placing a conductive wire in the via holes and potting the via holes.

[0126] The EAP transducers of the present invention are usable in a variety of actuator applications with any suitable construct and surface feature presentation. Figs. 20A-24 illustrate exemplary thickness mode transducer/actuator applications.

[0127] Fig. 20A illustrates a thickness mode transducer 120 having a round construct which is ideal for button actuators for use in tactile or haptic feedback applications in which a user physically contacts a device, e.g., keyboards, touch screens, phones, etc. Transducer 120 is formed from a thin elastomeric dielectric polymer layer 122 and top and bottom electrode patterns 124a, 124b (the bottom electrode pattern is shown in phantom), best shown in the isolated view in Fig. 20B. Each of the electrode patterns 124 provides a stem portion 125 with a plurality of oppositely extending finger portions 127 forming a concentric pattern. The stems of the two electrodes are positioned diametrically to each other on opposite sides of the round dielectric layer 122 where their respective finger portions are in appositional alignment with each other to produce the pattern shown in Fig. 20A. While the opposing electrode patterns in this embodiment are identical and symmetrical to each other, other embodiments are contemplated where the opposing electrode patterns are asymmetric, in shape and/or the amount of surface area which they occupy. The portions of the transducer material in which the two electrode materials do not overlap define the inactive portions 128a, 128b of the transducer. An electrical contact 126a, 126b is provided at the base of each of the two electrode stem portions for electrically coupling the transducer to a source of power and control electronics (neither are shown). When the transducer is activated, the opposing electrode fingers are drawn together, thereby compressing dielectric material 122 therebetween with the inactive portions 128a, 128b of the transducer bulging to form surface features about the perimeter of the button and/or internally to the button as desired.

[0128] The button actuator may be in the form of a single input or contact surface or may be provided in an array format having a plurality of contact surfaces. When constructed in the form of arrays, the button transducers of Fig. 20A are ideal for use in keypad actuators **130**, as illustrated in Fig. 21, for a variety of user interface devices, e.g., computer keyboards, phones, calculators, etc. Transducer array **132** includes a top array **136a** of interconnected electrode patterns and bottom array **136b** (shown in phantom) of electrode patterns with the two arrays opposed with each other to produce the concentric transducer pattern of Fig. 20A with active and inactive portions as described. The keyboard structure may be in the form of a passive layer **134** atop transducer array **132**. Passive layer **134** may have its own surface features, such as key border **138**, which may be raised in the passive state to enable the user to tactilely align his/her fingers with the individual key pads, and/or further amplify the bulging of the perimeter of the respective buttons upon activation. When a key is pressed, the individual transducer upon which it lays is activated, causing the thickness mode bulging as described above, to provide the tactile sensation back to the user. Any number of transducers may be provided in this manner and spaced apart to accommodate the type and size of keypad **134** being used. Examples of fabrication techniques for such transducer arrays are disclosed in U.S. Patent Application No. 12/163,554 filed on June 27, 2008 entitled ELECTROACTIVE POLYMER TRANSDUCERS FOR SENSORY FEEDBACK APPLICATIONS, which is incorporated by reference in its entirety.

[0129] Those skilled in the art will appreciate that the thickness mode transducers of the present invention need not be symmetrical and may take on any construct and shape. The subject transducers may be used in any imaginable novelty application, such as the novelty hand device **140** illustrated in Fig. 22. Dielectric material **142** in the form of a human hand is provided having top and bottom electrode patterns **144a**, **144b** (the underside pattern being shown in phantom) in a similar hand shape. Each of the electrode patterns is electrically coupled to a bus bar **146a**, **146b**, respectively, which in turn is electrically coupled to a source of power and control electronics (neither are shown). Here, the opposing electrode patterns are aligned with or atop each other rather than interposed, thereby creating alternating active and inactive areas. As such, instead of creating raised surface features on only the internal and external edges of the pattern as a whole, raised surface features are provided throughout the hand profile, i.e., on the inactive areas. It is noted that the surface features in this exemplary application may offer a visual feedback rather than a tactile feedback. It is contemplated that the visual feedback may be enhanced by coloring, reflective material, etc.

[0130] The transducer film of the present invention may be efficiently mass produced, particularly where the transducer electrode pattern is uniform or repeating, by commonly used web-based manufacturing techniques. As shown in Fig. 23, the transducer film **150** may be provided in a continuous strip format having continuous top and bottom electrical buses **156a**, **156b** deposited or formed on a strip of dielectric material **152**. Most typically, the thickness mode features are defined by discrete (i.e., not continuous) but repeating active regions **158** formed by top and bottom electrode patterns **154a**, **154b** electrically coupled to the respective bus bars **156a**, **156b**; the size, length, shape and pattern of which may be customized for the particular application. However, it is contemplated that the active region(s) may be provided in a continuous pattern. The electrode and bus patterns may be formed by known web-based manufacturing techniques, with the individual transducers then singulated, also by known techniques such as by cutting strip **150** along selected singulation lines **155**. It is noted that where the active regions are provided continuously along the strip, the strip is required to be cut with a high degree of precision to avoid shorting the electrodes. The cut ends of these electrodes may require potting or otherwise may be etched back to avoid tracking problems. The cut terminals of buses **156a**, **156b** are then coupled to sources of power/control to enable actuation of the resulting actuators.

[0131] Either prior to or after singulation, the strip or singulated strip portions, may be stacked with any number of other transducer film strips/strip portions to provide a multi-layer structure. The stacked structure may then be laminated and mechanically coupled, if so desired, to rigid mechanical components of the actuator, such an output bar or the like.

[0132] Fig. 24 illustrates another variation of the subject transducers in which a transducer 160 formed by a strip of dielectric material **162** with top and bottom electrodes 164a, 164b on opposing sides of the strip arranged in a rectangular pattern thereby framing an open area **165**. Each of the electrodes terminates in an electrical bus **166a**, **166b**, respectively, having an electrical contact point **168a**, **168b** for coupling to a source of power and control electronics (neither being shown). A passive layer (not shown) that extends across the enclosed area **165** may be employed on either side of the transducer film, thereby forming a gasket configuration, for both environmental protection and mechanical coupling of the output bars (also not shown). As configured, activation of the transducer produces surface features along the inside and outside perimeters **169** of the transducer strip and a reduction in thickness of the active areas **164a 164b**. It should be noted that the gasket actuator need not be a continuous, single actuator. One or more discrete actuators can also be used to line the perimeter of an area which may be optionally sealed with non-active compliant gasket material

[0133] Other gasket-type actuators are disclosed in U.S. Patent Application No. 12/163,554, referenced above. These types of actuators are suitable for sensory (e.g., haptic or vibratory) feedback applications such as with touch sensor plates, touch pads and touch screens for application in handheld multimedia devices, medical instrumentation, kiosks or automotive instrument panels, toys and other novelty products, etc.

[0134] Figs. 25A-25D are cross-sectional views of touch screens employing variations of a thickness mode actuator of the present invention with like reference numbers referencing similar components amongst the four figures. Referring to Fig. 25A, the touch screen device **170** may include a touch sensor plate **174**, typically made of a glass or plastic material, and, optionally, a liquid crystal display (LCD) **172**. The two are stacked together and spaced apart by EAP thickness mode actuator **180** defining an open space **176** therebetween. The collective stacked structure is held together by frame **178**. Actuator **180** includes the transducer film formed by dielectric film layer **182** sandwiched centrally by electrode pair **184a**, **184b**. The transducer film is in turn sandwiched between top and bottom passive layers **186a**, **186b** and further held between a pair of output structures **188a**, **188b** which are mechanically coupled to touch plate **174** and LCD **172**, respectively. The right side of Fig. 25A shows the relative position of the LCD and touch plate when the actuator is inactive, while the left side of Fig. 25A shows the relative positions of the components when the actuator is active, i.e., upon a user depressing touch plate **174** in the direction of arrow **175**. As is evident from the left side of the drawing, when actuator **180** is activated, the electrodes **184a**, **184b** are drawn together thereby compressing the portion of dielectric film **182** therebetween while creating surface features in the dielectric material and passive layers **186a**, **186b** outside the active area, which surface features are further enhanced by the compressive force caused by output blocks **188a**, **188b**. As such, the surface features provide a slight force on touch plate **174** in the direction opposite arrow **175** which gives the user a tactile sensation in response to depressing the touch plate.

[0135] Touch screen device **190** of Fig. 25B has a similar construct to that of Fig. 25A with the difference being that LCD **172** wholly resides within the internal area framed by the rectangular (or square, etc.) shaped thickness mode actuator **180**. As such, the spacing **176** between LCD **172** and touch plate **174** when the device is in an inactive state (as demonstrated on the right side of the figure) is significantly less than in the embodiment of Fig. 25A, thereby providing a lower profile design. Further, the bottom output structure **188b** of the actuator rests directly on the back wall **178'** of frame **178**. Irrespective of the structural differences between the two embodiments, device **190** functions similarly to device **170** in that the actuator surface features provide a slight tactile force in the direction opposite arrow **185** in response to depressing the touch plate.

[0136] The two touch screen devices just described are single phase devices as they function in a single direction. Two (or more) of the subject gasket-type actuators may be used in tandem to produce a two phase (bi-directional) touch screen device **200** as in Fig. 25C. The construct of device **200** is similar to that of the device of Fig. 25B but with the addition of a second thickness mode actuator **180'** which sits atop touch plate **174**. The two actuators and touch plate **174** are held in stacked relation by way of frame **178** which has an added inwardly extending top shoulder **178''**. As such, touch plate **174** is sandwiched directly between the innermost output blocks **188a**, **188b'** of actuators **180**, **180'**, respectively, while the outermost output blocks **188b**, **188a'** of actuators **180'**, respectively, buttress the frame members **178'** and **178''**, respectively. This enclosed gasket arrangement keeps dust and debris out of the optical path within space **176**. Here, the left side of the figure illustrates bottom actuator **180** in an active state and top actuator **180'** in a passive state in which sensor plate **174** is caused to move towards LCD **172** in the direction of arrow **195**. Conversely, the right side of the figure illustrates bottom actuator **180** in a passive state and top actuator **180'** in an active state in which sensor plate **174** is caused to move away from LCD **172** in the direction of arrow **195'**.

[0137] Fig. 25D illustrates another two phase touch sensor device **210** but with a pair of thickness mode strip actuators **180** oriented with the electrodes orthogonal to the touch sensor plate. Here, the two phase or bi-directional movement of touch plate **174** is in-plane as indicated by arrow **205**. To enable such in-plane motion, the actuator **180** is positioned such that the plane of its EAP film is orthogonal to those of LCD **172** and touch plate **174**. To maintain such a position, actuator 180 is held between the sidewall **202** of frame **178** and an inner frame member **206** upon which rests touch plate **174**. While inner frame member **206** is affixed to the output block **188a** of actuator **180**, it and touch plate **174** are "floating" relative to outer frame **178** to allow for the in-plane or lateral motion. This construct provides a relatively compact, low-profile design as it eliminates the added clearance that would otherwise be necessary for two-phase out-of-plane motion by touch plate **174**. The two actuators work in opposition for two-phase motion. The combined assembly of plate **174** and brackets **206** keep the actuator strips **180** in slight compression against the sidewall **202** of frame **178**. When one actuator is active, it compresses or thins further while the other actuator expands due to the stored compressive force. This moves the plate assembly toward the active actuator. The plate moves in the opposite direction by deactivating the first actuator and activating the second actuator.

[0138] Figs. 26A and 26B illustrate variation in which an inactive area of a transducer is positioned internally or centrally to the active region(s), i.e., the central portion of the EAP film is devoid of overlapping electrodes. Thickness mode actuator **360** includes EAP transducer film comprising dielectric layer **362** sandwiched between electrode layers **364a**, **354b** in which a central portion **365** of the film is passive and devoid of electrode material. The EAP film is held in a taut or stretched condition by at least one of top and bottom frame members **366a**, **366b**, collectively providing a cartridge configuration. Covering at least one of the top and bottom sides of the passive portion **365** of the film are passive layers **368a**, **368b** with optional rigid constraints or output members **370a**, **370b** mounted thereon, respectively. With the EAP film constrained at its perimeter by cartridge frame **366**, when activated (see Fig. 26B), the compression of the EAP film causes the film material to retract inward, as shown by arrows **367a**, **367b**, rather than outward as with the above-described actuator embodiments. The compressed EAP film impinges on the passive material **368a**, **368b** causing its diameter to decrease and its height to increase. This change in configuration applies outward forces on output members **370a**, **370b**, respectively. As with the previously described actuator embodiments, the passively coupled film actuators may be provided in multiples in stacked or planar relationships to provide multi-phase actuation and/or to increase the output force and/or stroke of the actuator.

[0139] Performance may be enhanced by prestraining the dielectric film and/or the passive material. The actuator may be used as a key or button device and may be stacked or integrated with sensor devices such as membrane switches. The bottom output member or bottom electrode can be used to provide sufficient pressure to a membrane switch to complete the circuit or can complete the circuit directly if the bottom output member has a conductive layer. Multiple actuators can be used in arrays for applications such as keypads or keyboards.

[0140] The various dielectric elastomer and electrode materials disclosed in U.S. Patent Application Publication No. 2005/0157893 are suitable for use with the thickness mode transducers of the present invention. Generally, the dielectric elastomers include any substantially insulating, compliant polymer, such as silicone rubber and acrylic, that deforms in response to an electrostatic force or whose deformation results in a change in electric field. In designing or choosing an appropriate polymer, one may consider the optimal material, physical, and chemical properties. Such properties can be tailored by judicious selection of monomer (including any side chains), additives, degree of cross-linking, crystallinity, molecular weight, etc.

[0141] Electrodes described therein and suitable for use include structured electrodes comprising metal traces and charge distribution layers, textured electrodes, conductive greases such as carbon greases or silver greases, colloidal suspensions, high aspect ratio conductive materials such as conductive carbon black, carbon fibrils, carbon nanotubes, graphene and metal nanowires, and mixtures of ionically conductive materials. The electrodes may be made of a compliant material such as elastomer matrix containing carbon or other conductive particles. The present invention may also employ metal and semi-inflexible electrodes.

[0142] Exemplary passive layer materials for use in the subject transducers include but are not limited to silicone, styrenic or olefinic copolymer, polyurethane, acrylate, rubber, a soft polymer, a soft elastomer (gel), soft polymer foam, or a polymer/gel hybrid, for example. The relative elasticity and thickness of the passive layer(s) and dielectric layer are selected to achieve a desired output (e.g., the net thickness or thinness of the intended surface features), where that output response may be designed to be linear (e.g., the passive layer thickness is amplified proportionally to the that of the dielectric layer when activated) or non-linear (e.g., the passive and dielectric layers get thinner or thicker at varying rates).

[0143] Regarding methodology, the subject methods may include each of the mechanical and/or activities associated with use of the devices described. As such, methodology implicit to the use of the devices described forms part of the invention. Other methods may focus on fabrication of such devices.

[0144] 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 method-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.

[0145] In another variation, the cartridge assembly or actuator **360** can be suited for use in providing a haptic response in a vibrating button, key, touchpad, mouse, or other interface.

In such an example, coupling of the actuator **360** employs a non-compressible output geometry. This variation provides an alternative from a bonded center constraint of an electroactive polymer diaphragm cartridge by using a non-compressible material molded into the output geometry.

[0146] In an electroactive polymer actuator with no center disc, actuation changes the condition of the Passive Film in the center of the electrode geometry, decreasing both the stress and the strain (force and displacement). This decrease occurs in all directions in the plane of the film, not just a single direction. Upon the discharge of the electroactive polymer, the Passive film then returns to an original stress and strain energy state. An electroactive polymer actuator can be constructed with a non-compressible material (one that has a substantially constant volume under stress). The actuator **360** is assembled with a non-compressible output pad **368a 368b** bonded to the passive film area at the center of the actuator **360** in the inactive region **365**, replacing the center disk. This configuration can be used to transfer energy by compressing the output pad at its interface with the passive portion **365**. This swells the output pad **368a** and **368b** to create actuation in the direction orthogonal to the flat film. The non compressible geometry can be further enhanced by adding constraints to various surfaces to control the orientation of its change during actuation. For the above example, adding a non-compliant stiffener to constrain the top surface of the output pad prevents that surface from changing its dimension, focusing the geometry change to desired dimensions of the output pad.

[0147] The variation described above can also allow coupling of biaxial stress and strain state changes of electroactive polymer Dielectric Elastomer upon actuation; transfers actuation orthogonal to direction of actuation; design of non-compressible geometry to optimize performance. The variations described above can include various transducer platforms, including: diaphragm, planar, inertial drive, thickness mode, hybrid (combination of planar & thickness mode described in the attached disclosure), and even roll – for any haptic feedback (mice, controllers, screens, pads, buttons, keyboards, etc.) These variations might move a specific portion of the user contact surface, e.g. a touch screen, keypad, button or key cap, or move the entire device.

[0148] Different device implementations may require different EAP platforms. For example, in one example, strips of thickness mode actuators might provide out-of-plane motion for touch screens, hybrid or planar actuators to provide key click sensations for buttons on keyboards, or inertial drive designs to provide rumbler feedback in mice and controllers.

[0149] Fig. 27A illustrates another variation of a transducer for providing haptic feedback with various user interface devices. In this variation, a mass or weight **262** is coupled to an electroactive polymer actuator **30**. Although the illustrated polymer actuator comprises a film cartridge actuator, alternative variations of the device can employ a spring biased actuator as described in the EAP patents and applications disclosed above.

[0150] Fig. 27B illustrates an exploded view of the transducer assembly of Fig. 27A. As illustrated the inertial transducer assembly **260** includes a mass **262** sandwiched between two actuators **30**. However, variations of the device include one or more actuators depending upon the intended application on either side of the mass. As illustrated, the actuator(s) is/are coupled to the inertial mass **262** and secured via a base-plate or flange. Actuation of the actuators **30** causes movement of the mass in an x-y orientation relative to the actuator. In additional variations, the actuators can be configured to provide a normal or z axis movement of the mass **262**.

[0151] Fig. 27C illustrates a side view of the inertial transducer assembly **260** of Fig. 27A. In this illustration, the assembly is shown with a center housing **266** and a top housing **268** that enclose the actuators **30** and inertial mass **262**. Also, the assembly **260** is shown with fixation means or fasteners **270** extending through openings or vias **24** within the housing and actuators. The vias **24** can serve multiple functions. For example, the vias can be for mounting purposes only. Alternatively, or in combination, the vias can electrically couple the actuator to a circuit board, flex circuit or mechanical ground. Fig. 27D illustrates a perspective view of the inertial transducer assembly **260** of Fig. 27C where the inertial mass (not shown) is located within a housing assembly **264**, **266**, and **268**). The parts of the housing assembly can serve multiple functions. For example, in addition to providing mechanical support and mounting and attachment features, they can incorporate features that serve as mechanical hard stops to prevent excessive motion of the inertial mass in x, y, and/or z directions which could damage the actuator cartridges. For example, the housing can include raised surfaces to limit excessive movement of the inertial mass. In the illustrated example, the raised surfaces can comprise the portion of the housing that contains the vias **24**. Alternatively, the vias **24** can be placed selectively so that any fastener **270** located therethrough functions as an effective stop to limit movement of the inertial mass.

[0152] Housing assemblies can **264** and **266** can also be designed with integrated lips or extensions that cover the edges of the actuators to prevent electrical shock on handling. Any and all of these parts can also be integrated as part of the housing of a larger assembly such as the housing of a consumer electronic device. For example, although the illustrated housing is shown as a separate component that is to be secured within a user interface device, alternate variations of the transducer include housing assemblies that are integral or part of the housing of the actual user interface device. For instance, a body of a computer mouse can be configured to serve as the housing for the inertial transducer assembly.

[0153] The inertial mass **262** can also serve multiple functions. While it is shown as circular in Figs. 27A and 27B to, variations of the inertial mass can be fabricated to have a more complex shape such that it has integrated features that serve as mechanical hard stops that limit its motion in x, y, and/or z directions. For example, Fig. 27E illustrates a variation of an inertial transducer assembly with an inertial mass **262** having a shaped surface **263** that engage a stop or other feature of the housing **264**. In the illustrated variation, the surface **263** of the inertial mass **262** engages fasteners **270**. Accordingly, the displacement of the inertial mass **262** is limited to the gap between the shaped surface **263** and the stop or fastener **270**. The mass of the weight can be chosen to tailor the resonant frequency of the total assembly, and the material of construction can be any dense material but is preferably chosen to minimize the required volume and cost. Suitable materials include metals and metal alloys such as copper, steel, tungsten, aluminum, nickel, chrome and brass, and polymer/metal composites materials, resins, fluids, gels, or other materials can be used.

[0154] FILTER SOUND DRIVE WAVEFORM FOR electroactive polymer HAPTICS

[0155] Another variation of the inventive methods and devices described herein involves driving the actuators in a manner to improve feedback. In one such example the haptic actuator is driven by a sound signal. Such a configuration eliminates the need for a separate processor to generate waveforms to produce different types of haptic sensations. Instead, haptic devices can employ one or more circuits to modify an existing audio signal into a modified haptic signal, e.g. filtering or amplifying different portions of the frequency spectrum. Therefore, the modified haptic signal then drives the actuator. In one example, the modified haptic signal drives the power supply to trigger the actuator to achieve different sensory effects. This approach has the advantages of being automatically correlated with and synchronized to any audio signal which can reinforce the feedback from the music or sound effects in a haptic device such as a gaming controller or handheld gaming console.

[0156] Fig. 28A illustrates one example of a circuit to tune an audio signal to work within optimal haptic frequencies for electroactive polymer actuators. The illustrated circuit modifies the audio signal by amplitude cutoff, DC offset adjustment, and AC waveform peak-to-peak magnitude adjustment to produce a signal similar to that shown in Fig. 28B. In certain variations, the electroactive polymer actuator comprises a two phase electroactive polymer actuator and where altering the audio signal comprises filtering a positive portion of an audio waveform of the audio signal to drive a first phase of the electroactive polymer transducer, and inverting a negative portion of the audio waveform of the audio signal to drive a second phase of the electroactive polymer transducer to improve performance of the electroactive polymer transducer. For example, a source audio signal in the form of a sine wave can be converted to a square wave (e.g., via clipping), so that the haptic signal is a square wave that produces maximum actuator force output.

[0157] In another example, the circuit can include one or more rectifiers to filter the frequency of an audio signal to use all or a portion of an audio waveform of the audio signal to drive the haptic effect. Fig. 28C illustrates one variation of a circuit designed to filter a positive portion of an audio waveform of an audio signal. This circuit can be combined, in another variation, with the circuit shown in Fig. 28D for actuators having two phases. As shown, the circuit of Fig. 28C can filter positive portions of an audio waveform to drive one phase of the actuator while the circuit shown in Fig. 28D can invert a negative portion of an audio waveform to drive the other phase of the 2-phase haptic actuator. The result is that the two phase actuator will have a greater actuator performance.

[0158] In another implementation, a threshold in the audio signal can be used to trigger the operation of a secondary circuit which drives the actuator. The threshold can be defined by the amplitude, the frequency, or a particular pattern in the audio signal. The secondary circuit can have a fixed response such as an oscillator circuit set to output a particular frequency or can have multiple responses based on multiple defined triggers. In some variations, the responses can be pre-determined based upon a particular trigger. In such a case, stored response signals can be provided in upon a particular trigger. In this manner, instead of modifying the source signal, the circuit triggers a pre-determined response depending upon one or more characteristics of the source signal. The secondary circuit can also include a timer to output a response of limited duration.

[0159] Many systems could benefit from the implementation of haptics with capabilities for sound, (e.g. computers, Smartphones, PDA's, electronic games). In this variation, filtered sound serves as the driving waveform for electroactive polymer haptics. The sound files normally used in these systems can be filtered to include only the optimal frequency ranges for the haptic feedback actuator designs. Figs. 28E and 28F illustrate one such example of a device **400**, in this case a computer mouse, having one or more electroactive polymer actuators **402** within the mouse body 400 and coupled to an inertial mass **404**.

[0160] Current systems operate at optimal frequencies of <200Hz. A sound waveform, such as the sound of a shotgun blast, or the sound of a door closing, can be low pass filtered to allow only the frequencies from these sounds that are <200 Hz to be used. This filtered waveform is then supplied as the input waveform to the EPAM power supply that drives the haptic feedback actuator. If these examples were used in a gaming controller, the sound of the shotgun blast and the closing door would be simultaneous to the haptic feedback actuator, supplying an enriched experience to the game player.

[0161] In one variation use of an existing sound signal can allow for a method of producing a haptic effect in a user interface device simultaneously with the sound generated by the separately generated audio signal. For example, the method can include routing the audio signal to a filtering circuit; altering the audio signal to produce a haptic drive signal by filtering a range of frequencies below a predetermined frequency; and providing the haptic drive signal to a power supply coupled to an electroactive polymer transducer such that the power supply actuates the electroactive polymer transducer to drive the haptic effect simultaneously to the sound generated by the audio signal.

[0162] The method can further include driving the electroactive polymer transducer to simultaneously generate both a sound effect and a haptic response.

[0163] Figs. 29A to 30B illustrate another variation of driving one or more transducers by using a structure of the transducer to power the transducer so that in a normal (preactivated) state, the transducers remain unpowered. The description below can be incorporated into any design described herein. The devices and methods for driving the transducers are especially useful when attempting to reduce a profile of the body or chassis of a user interface device.

[0164] In a first example, a user interface device **400** includes one or more electroactive polymer transducers or actuators **360** that can be driven to produce a haptic effect at a user interface surface **402** without requiring complex switching mechanisms. Instead, the multiple transducers **360** are powered by one or more power supplies **380**. In the illustrated example, the transducers **360** are thickness mode transducers as described above as well as in the applications previously incorporated by reference. However, the concepts presented for this variation can be applied to a number of different transducer designs.

[0165] As shown, the actuators **360** can be stacked in a layer including an open circuit comprising high voltage power supply **380** with one or more ground bus lines **382** serving as a connection to each transducer **360**. However, the device **400** is configured so that in a standby state, each actuator **360** remains unpowered because the circuit forming the power supply **380** remain as open.

[0166] Fig. 29B shows a single user interface surface **420** with a transducer **360** as shown in Fig. 29A. In order to complete the complete the connection between the bus lines **382** and power supply **380**, the user interface surface **402** includes one or more conductive surfaces **404**. In this variation, the conductive surface **404** comprises a bottom surface of the user interface **402**. The transducer **360** will also include an electrically conductive surface on an output member **370** or other portion of the transducer **360**.

[0167] In order to actuate the transducer **360**, as shown in Fig. 29C, when the user interface surface **402** is deflected into the transducer **360** the two conductive portions are electrically coupled to close the circuit. This action completes the circuit of the power supply **380**. In addition, depressing the user interface surface **402** not only closes the gap with the transducer **360**, it also can be used to close a switch with device **400** so that the device **400** recognizes that the surface **402** is actuated.

[0168] One benefit to this configuration is that not all of the transducers **360** are powered. Instead, only those transducers in which the respective user interface surface completed the circuit are powered. This configuration minimizes power consumption and can eliminate cross-talk between the actuators **360** in an array. This construction allows for extremely thin keypads and keyboards as it eliminates the need for a metallic or elastic dome type switch that is commonly used for such devices.

[0169] Figs. 30A and 30B illustrate another variation of a user interface device **400** having an electroactive polymer transducer **360** configured as an embedded switch. In the variation shown in Fig. 30A, there is first gap **406** between transducer **360** and the user interface surface **402** and a second gap **408** between the transducer **360** and the chassis **404**. In this variation, depressing the user interface surface **402**, as shown in Fig. 30B, closes a first switch or establishes a closed circuit between the user interface surface **402** and the transducer **360**. Closing of this circuit allows routing of power to the electroactive polymer transducer **360** from a high voltage power supply (not shown in Fig. 30A). Continued depression of the user interface surface **402** drives the transducer **360** into contact with an additional switch located on a chassis **404** of the device **400**. The latter connection enables input to the device **400** enabling a high voltage power supply to actuate the transducer **360** to produce a haptic sensation or tactile feedback at the user interface surface **402**. Upon release the connection between the transducer **350** and chassis **404** opens (establishing gap **408**). This action cuts off the signal to the device **400** effectively turning off the high voltage power supply and prevents the actuator from producing any haptic effect. Continued release of the user interface surface **402** separates the user interface surface **402** from the transducer **360** to establish gap **406**. The opening of this latter switch effectively disconnects the transducer **360** from the power supply.

[0170] In the variations described above, the user interface surface can comprise one or more keys of a keyboard (e.g., a QWERTY keyboard, or other type of input keyboard or pad). Actuation of the EPAM provides button click tactile feedback, which replaces the key depression of current dome keys. However, the configuration can be employed in any user interface device, including but not limited to: a keyboard, a touch screen, a computer mouse, a trackball, a stylus, a control panel, or any other device that would benefit from a haptic feedback sensation.

[0171] In another variation of the configuration described above, the closing of one or more gaps could close an open low-voltage circuit. The low-voltage circuit would then trigger a switch to provide power to the high voltage circuit. In this way, high voltage power is provided across the high voltage circuit and to the transducer only when the transducer is used to complete the circuit. So long as the low voltage circuit remains open, the high voltage power supply remains uncoupled and the transducers remain unpowered.

[0172] The use of the cartridges can allow for imbedding electrical switches into the overall design of the user interface surface and can eliminate the need to use traditional dome switches to activate the input signal for the interface device (i.e., so the device recognizes the input of the key), as well as activate the haptic signals for the keys (i.e., to generate a haptic sensation associated with selection of the key). Any number of switches can be closed with each key depression where such a configuration is customizable within the constraints of the design.

[0173] The imbedded actuator switches can route each haptic event by configuring the key so that each depression completes a circuit with a power supply that powers the actuator. This configuration simplifies the electronics requirements for the keyboard. The high voltage power required to drive the haptics for each key can be supplied by a single high voltage power supply for the entire keyboard. However, any number of power supplies can be incorporated into the design.

[0174] The EPAM cartridges that can be used with these designs includes Planar, Diaphragm, Thickness Mode, and Passive Coupled devices (Hybrids)

[0175] In another variation, the embedded switch design also allows for mimicking of a bi-stable switch such as a traditional dome type switch (e.g., a rubber dome or metal flexure switch). In one variation, the user interface surface deflects the electroactive polymer transducer as described above. However, the activation of the electroactive polymer transducer is delayed. Therefore, continued deflection of the electroactive polymer transducer increases a resistance force that is felt by the user at the user interface surface. The resistance is caused by deformation of the electroactive polymer film within the transducer. Then, either after a pre-determined deflection or duration of time after the transducer is deflected, the electroactive polymer transducer is activated such that the resistance felt by the user at the user interface surface is varied (typically reduced). However, the displacement of the user interface surface can continue. Such a delay in activation of the electroactive polymer transducer mimics the bistable performance traditional dome or flexure switches.

[0176] Fig. 31A illustrates a graph of delaying activation of an electroactive polymer transducer to produce the bi-stable effect. As illustrated, line **101** shows the passive stiffness curve of the electroactive polymer transducer as it is deflected but where activation of the transducer is delayed. Line **102** shows the active stiffness curve of the electroactive polymer transducer once activated. Line **103** shows the force profile of the electroactive polymer transducer as it moves along the passive stiffness curve, then when actuated, the stiffness drops to the active stiffness curve **102**. In one example, the electroactive polymer transducer is activated somewhere at the middle of the stroke.

[0177] The profile of line **103** is very close to a similar profile tracking stiffness of a rubber dome or metal flexure bi-stable mechanism. As shown, EAP actuators are suitable to simulate the force profile of the rubber dome. The difference between passive and active curve will be the main contributor to the feeling, meaning the higher the gap, the higher the chance and the more powerful sensation would be.

[0178] The shape of the curve and mechanism to achieve a desired curve or response can be independent of the actuator type. Additionally, the activation response of any type of actuator (e.g., diaphragm actuator, thickness mode, hybrid, etc.) can be delayed to provide the desired haptic effect. In such a case, the electroactive polymer transducer functions as a variable spring that changes the output reactive force by applying voltage. Fig. 31B illustrates additional graphs based on variations of the above described actuator using delays in activating the electroactive polymer transducer.

[0179] Another variation for driving an electroactive polymer transducer includes the use of stored wave form given a threshold input signal. The input signal can include an audio or other triggering signal. For example, the circuit shown in Fig. 32 illustrates an audio signal serving as a trigger for a stored waveform. Again, the system can use a triggering or other signal in place of the audio signal. This method drives the electroactive polymer transducer with one or more pre-determined waveforms rather than using simply driving the actuator directly from the audio signal. One benefit of this mode of driving the actuator is that the use of stored waveforms enables the generation of complex waveforms and actuator performance with minimal memory and complexity. Actuator performance can be enhanced by using a drive pulse optimized for the actuator (e.g. running at a preferred voltage or pulse width or at resonance) rather than using the analog audio signal. The actuator response can be synchronous with the input signal or can be delayed. In one example, a .25v trigger threshold can be used as the trigger. This low-level signal can then generate one or more pulse waveforms. In another variation, this driving technique can potentially allow the use of the same input or triggering signal to have different output signals based on any number of conditions (e.g., such as the position of the user interface device, the state of the user interface device, a program being run on the device, etc.).

[0180] Figs. 33A and 33B illustrate yet another variation for driving an electroactive polymer transducer by providing two-phase activation with a single drive circuit. As shown, of the three power leads in a two-phase transducer, one lead on one of the phases is held constant at high voltage, one lead on the other phase is grounded, and the third lead common to both phases is driven to vary in voltage from ground to high voltage. This enables the activation of one phase to occur simultaneously with the deactivation of the 2nd phase to enhance the snap-through performance of a two-phase actuator.

[0181] In another variation, a haptic effect on a user interface surface as described herein, can be improved by adjusting for the mechanical behavior of the user interface surface. For example, in those variations where an electroactive polymer transducer drives a touchscreen the haptic signal can eliminate undesired movement of the user interface surface after the haptic effect. When the device comprises a touch screen, typically movement of the screen (i.e., the user interface surface) occurs in a plane of the touchscreen or out-of-plan (e.g., a z-direction). In either case, the electroactive polymer transducer is driven by an impulse **502** to produce the haptic response as schematically illustrated in Fig. 34B. However, the resulting movement can be followed by a lagging mechanical ringing or oscillation **500** as shown in the graph of Fig. 34A illustrating a displacement of the user interface surface (e.g., the touchscreen). To improve the haptic effect, a method of driving the haptic effect can include the use of a complex waveform to provide electronic dampening to produce a realistic haptic effect. Such a waveform includes the haptic driving portion **502** as well as a dampening portion **504**. In the case where the haptic effect comprises a "key-click" as described above, the electronic dampening waveform can eliminate or reduce the lagging effect to produce a more realistic sensation. For example, the displacement curves of Figs. 34A and 34C illustrate displacement curves when trying to emulate a key click. However, any number of haptic sensations can be improved using electronic dampening of the sensation.

[0182] Fig. 35 illustrates an example of an energy generation circuit for powering an electroactive polymer transducer. Many electroactive polymer transducers require high voltage electronics to produce electricity. Simple, high-voltage electronics are needed that provide functionality and protection. A basic transducer circuit consists of a low voltage priming supply, a connection diode, an electroactive polymer transducer, a second connection diode and a high voltage collector supply. However, such a circuit may not be effective at capturing as much energy per cycle as desired and requires a relatively higher voltage priming supply.

[0183] Fig. 35 illustrates a simple power generation circuit design. One advantage of this circuit is in the simplicity of design. Only a small starting voltage (of approximately 9 volts) is necessary to get the generator going (assuming mechanical force is being applied). No control level electronics are necessary to control the transfer of high voltage into and out of the electroactive polymer transducer. A passive voltage regulation is achieved by zener diodes on the output of the circuit. This circuit is capable of producing high voltage DC power and can operate the electroactive polymer transducer at an energy density level around 0.04-0.06 joules per gram. This circuit is suitable for generating modest powers and demonstrating feasibility of electroactive polymer transducers. The illustrated circuit uses a charge transfer technique to maximize the energy transfer per mechanical cycle of an electroactive polymer transducer while still maintaining simplicity. Additional benefits include: allowing self priming with extremely low voltages (e.g., 9 volts); both variable frequency and variable stroke operation; maximizes energy transfer per cycle with simplified electronics (i.e. electronics that do not require control sequences); operates both in variable frequency and variable stroke applications; and provides over voltage protection to transducer.

[0184] 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 method-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.

[0185] 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 n the claims. Stated otherwise, unless specifically defined herein, all technical and scientific terms used herein are to be given as broad a commonly understood meaning as possible while maintaining claim validity.

What is claimed is:

1. A user interface device comprising:

a chassis;

a user interface surface;

a first power supply;

at least one electroactive polymer transducer adjacent to the user interface surface, the electroactive polymer transducer further comprising an electrically conductive surface;

where a portion of the user interface surface and the electrically conductive surface form a circuit with the first power supply, such that in a normal state the electrically conductive surface is electrically isolated from the portion of the user interface surface to open the circuit causing the electroactive polymer transducer to remain in an unpowered state; and

where the user interface surface is flexibly coupled to the chassis such that deflection of the user interface surface into the electroactive polymer transducer closes the circuit to energize the electroactive polymer transducer such that a signal provided to the electroactive polymer transducer produces a haptic sensation at the user interface surface.

2. The user interface device of claim 1, where the first power supply comprises a high voltage supply.

3. The user interface device of claim 1, where the at least one electroactive polymer transducer comprises a plurality of electroactive polymer transducers, each adjacent to a user interface surface and each having respective electrically conductive surfaces such that deflection of one user interface surface into the conductive surface causes the respective electroactive polymer transducer and electrically conductive surface to form the closed circuit and where the remaining electroactive polymer transducers remain in the unpowered state.

4. The user interface device of claim 1, where the user interface device comprises a device selected from a group consisting of a keyboard, keypads, game controller, remote control, a touch screen, a computer mouse, a trackball, a stylus, a control panel, and a joystick.

5. The user interface device of claim 1, where the user interface surface comprises a button, a key, a game pad, and a display screen.

6. The user interface device of claim 1, where the first power supply comprises a low voltage power supply and where the user interface device further comprises a high voltage power

supply coupled to a switch, such that deflection of the electroactive polymer transducer and the electrically conductive surface closes the switch allowing the high voltage power supply to energize the electroactive polymer actuator.

7. The user interface device of claim 1, where the deflection of the user interface surface occurs in a normal direction to the user interface surface.

8. The user interface device of claim 1, where the deflection of the user interface surface occurs in a planar direction with the user interface surface.

9. A user interface device comprising:

a chassis;

a first power supply;

a user interface surface;

at least one electroactive polymer transducer coupled to the user interface surface, the electroactive polymer transducer further comprising an electrically conductive surface, the electrically conductive surface forming a circuit with the first power supply, such that in a normal state the electrically conductive surface is electrically isolated from the circuit to open the circuit such that the electroactive polymer transducer remains in an unpowered state; and

where the electroactive polymer transducer is flexibly coupled to the chassis such that deflection of the user interface surface deflects the electroactive polymer transducer into contact with the circuit of the first power supply to close the circuit and energize the electroactive polymer actuator such that a signal provided to the electroactive polymer transducer produces a haptic sensation at the user interface surface.

10. The user interface device of claim 9, where the first power supply comprises a high voltage supply.

11. The user interface device of claim 9, where the at least one electroactive polymer transducer comprises a plurality of electroactive polymer transducers, each adjacent to a user interface surface and each having respective electrically conductive surfaces such that deflection of one user interface surface into the conductive surface causes the respective electroactive polymer transducer and electrically conductive surface to form the closed circuit and where the remaining electroactive polymer transducers to remain in the unpowered state.

12. The user interface device of claim 9, where the user interface device comprises a device selected from a group consisting of a keyboard, a touch screen, a computer mouse, a trackball, a stylus, a control panel, and a joystick.

13. The user interface device of claim 9, where the deflection of the user interface surface occurs in a normal direction to the user interface surface.

14. The user interface device of claim 9, where the deflection of the user interface surface occurs in a planar direction with the user interface surface.

15. A method of producing a haptic effect in a user interface device where the haptic effect mimics a bi-stable switch effect, the method comprising:

providing a user interface surface having an electroactive polymer transducer coupled thereto, where the electroactive polymer transducer comprises at least one electroactive polymer film;

displacing the user interface surface by a displacement amount to also displace the electroactive polymer film and increase a resistance force applied by the electroactive polymer film against the user interface surface;

delaying activation of the electroactive polymer transducer during displacement of the electroactive polymer film;

activating the electroactive polymer transducer to vary the resistance force without decreasing the displacement amount to create the haptic effect that mimics the bi-stable switch effect.

16. The method of claim 15, where delaying the activation of the electroactive polymer occurs after a pre-determined time.

17. The method of claim 15, where delaying the activation of the electroactive polymer occurs after a pre-determined displacement of the electroactive polymer film.

18. The method of claim 15, where the user interface device does not include a dome actuating mechanism.

19. A method of producing a pre-determined haptic effect in a user interface device , the method comprising:

providing a waveform circuit configured to produce at least one pre-determined haptic waveform signal;

routing a signal to the waveform circuit such that when the signal equals a triggering value, the waveform circuit generates the haptic waveform signal; and providing the haptic waveform signal to a power supply coupled to an electroactive polymer transducer such that the power supply drives the electroactive polymer transducer to produce a complex haptic effect controlled by the haptic waveform signal.

20. A method of producing a haptic feedback sensation in a user interface device having a user interface surface, the method comprising:

transmitting an input signal from a drive circuit to an electroactive polymer transducer where the input signal actuates the electroactive polymer transducer and provide the haptic feedback sensation at the user interface surface; and

transmitting a dampening signal to reduce mechanical displacement of the user interface surface after the desired haptic feedback sensation.

21. The method of claim 20, where the haptic effect sensation mimics a bi-stable key-click effect.

22. The method of claim 20, where the user interface device comprises a device selected from a group consisting of a keyboard, keypads, game controller, remote control, a touch screen, a computer mouse, a trackball, a stylus, a control panel, and a joystick..

23. The method of claim 20, where the user interface surface comprises a button, a key, a game pad, and a display screen

24. A method of producing a haptic feedback in a user interface device, the method comprising:

providing an electroactive polymer transducer with the user interface device, the electroactive polymer transducer having a first phase and having a second phase, where the electroactive polymer transducer comprises a first lead common to the first phase, a second lead common to the second phase, and a third lead common to the first and second phases;

maintaining a first lead at a high voltage while maintaining the second lead to a ground; and

driving the third lead to vary from the ground to the high voltage to enable activation of the first or second phase upon the deactivation of the respective other phase.

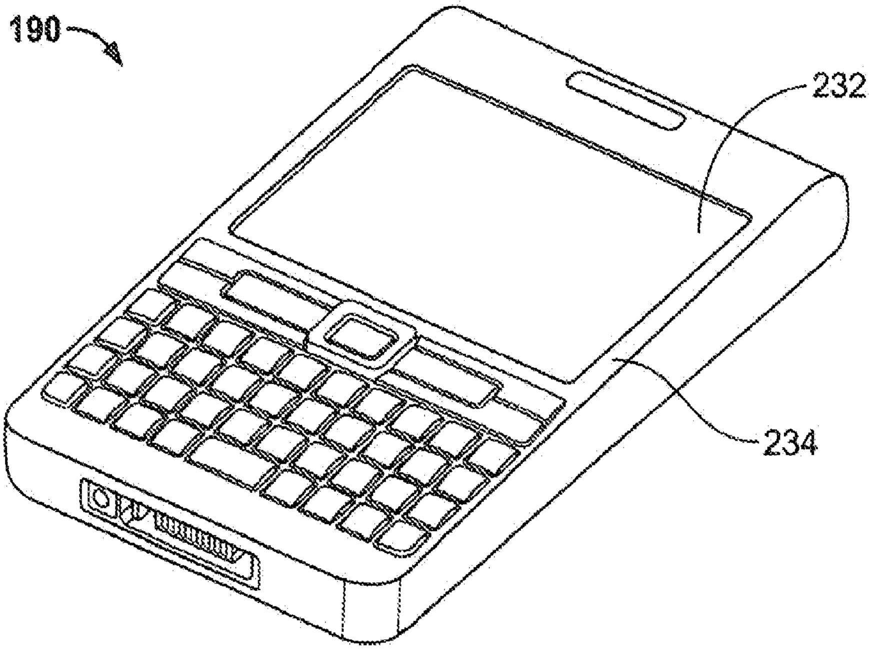

FIG. 1A

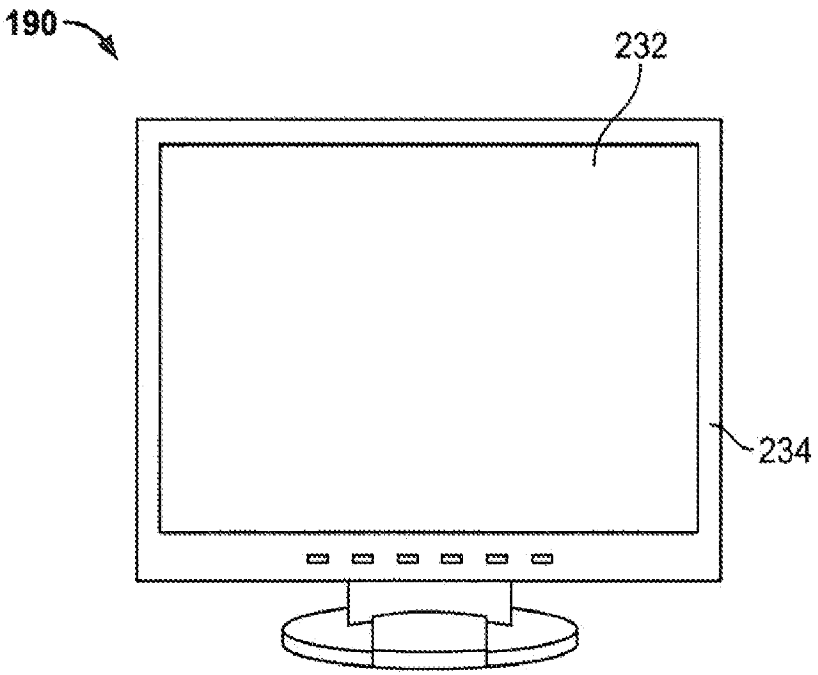

FIG. 1B

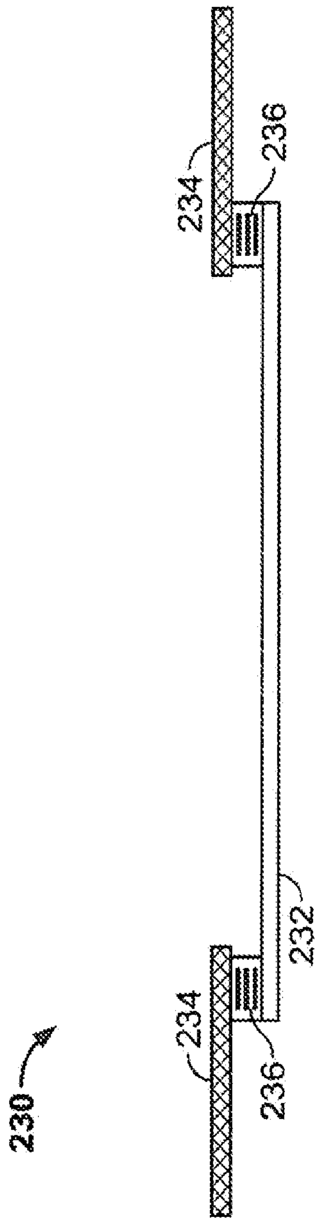

FIG. 2A

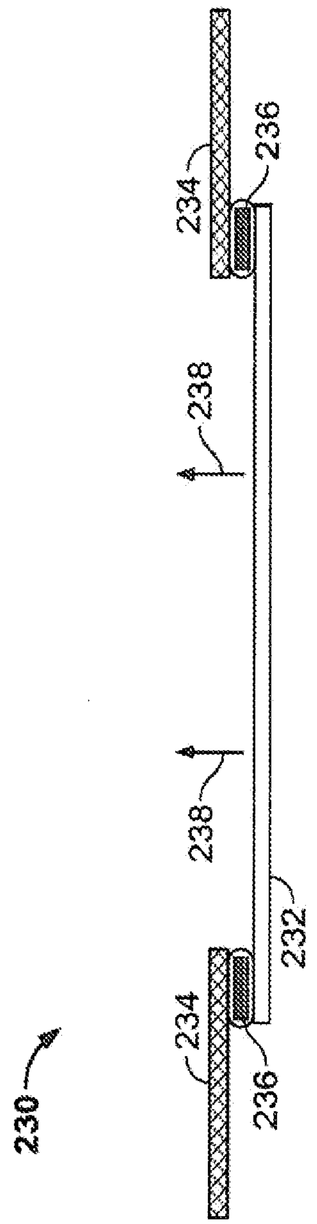

FIG. 2B

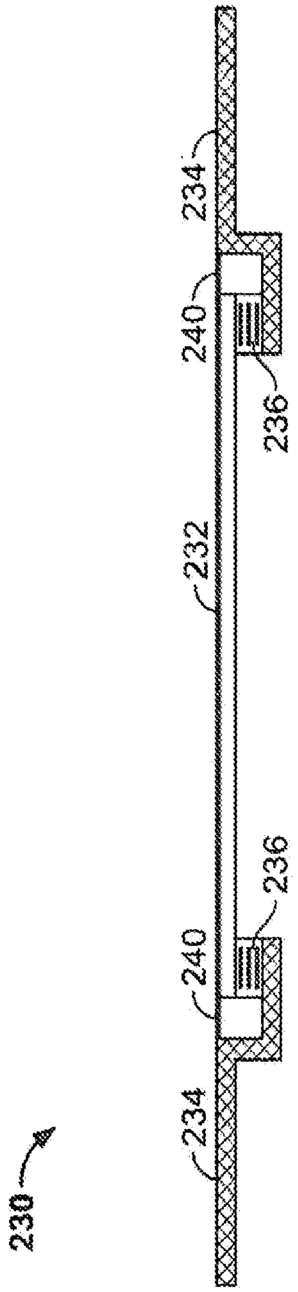

FIG. 3A

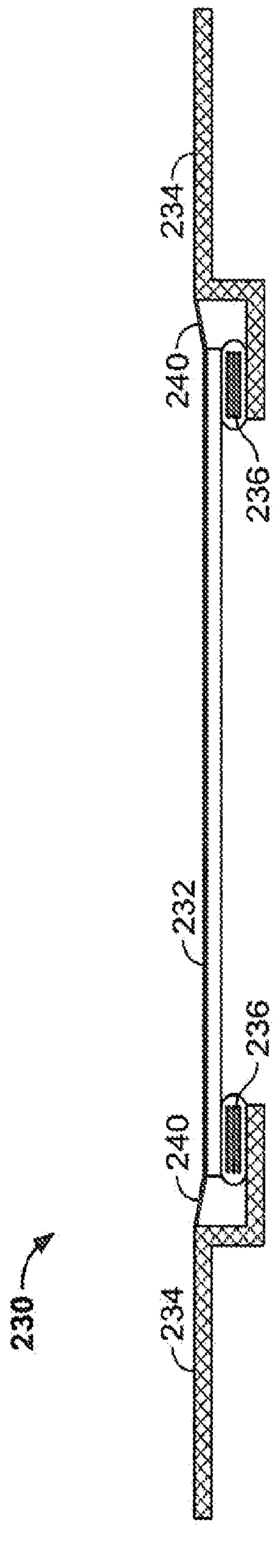

FIG. 3B

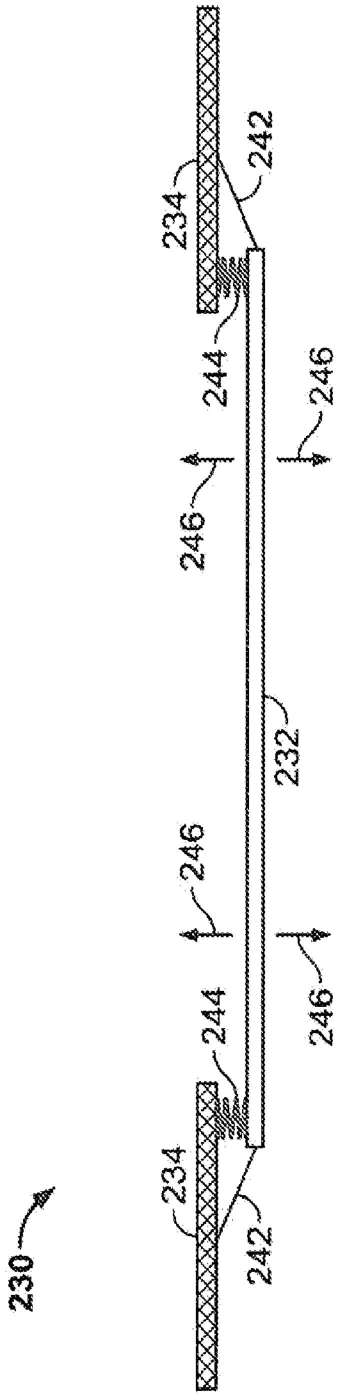
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FIG. 4

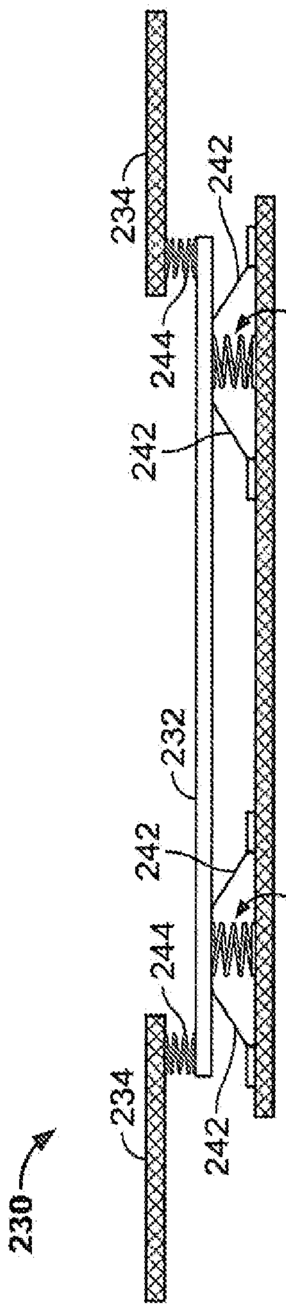
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FIG. 5

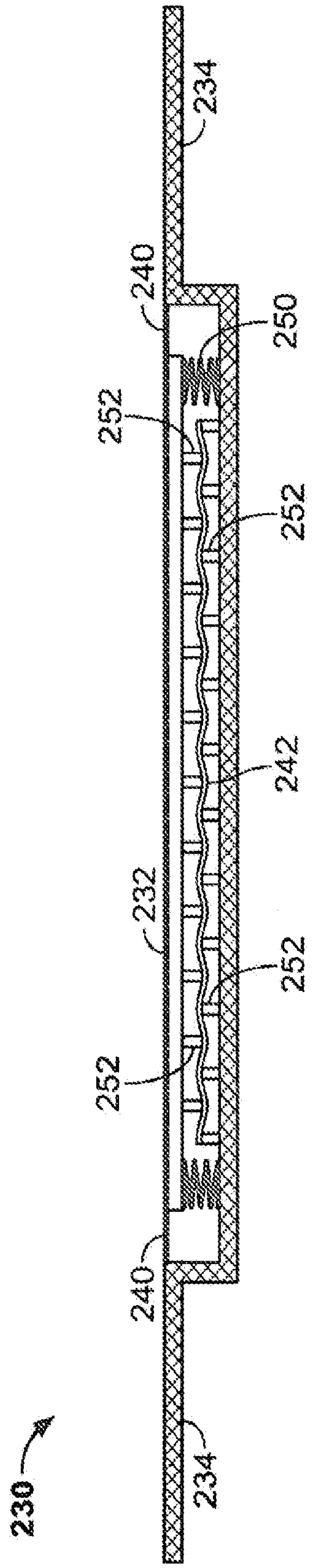
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FIG. 6A

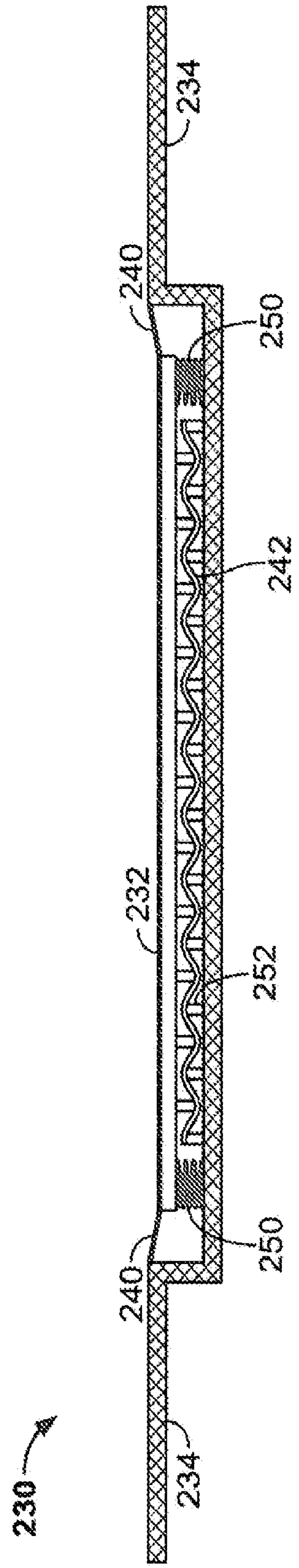
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FIG. 6B

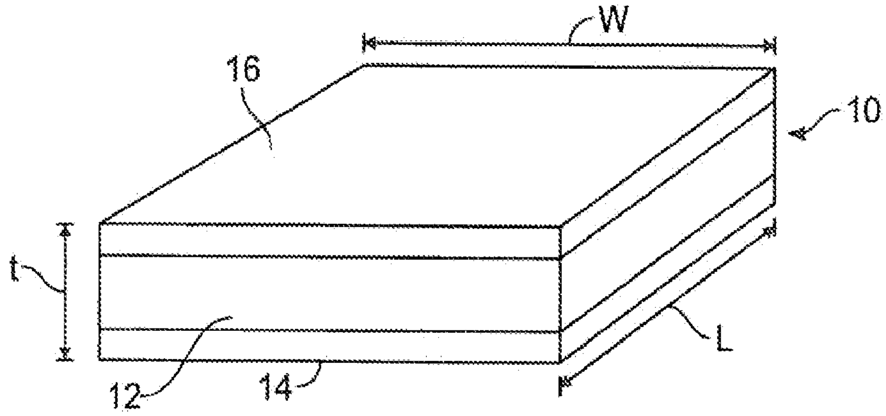


FIG. 7A

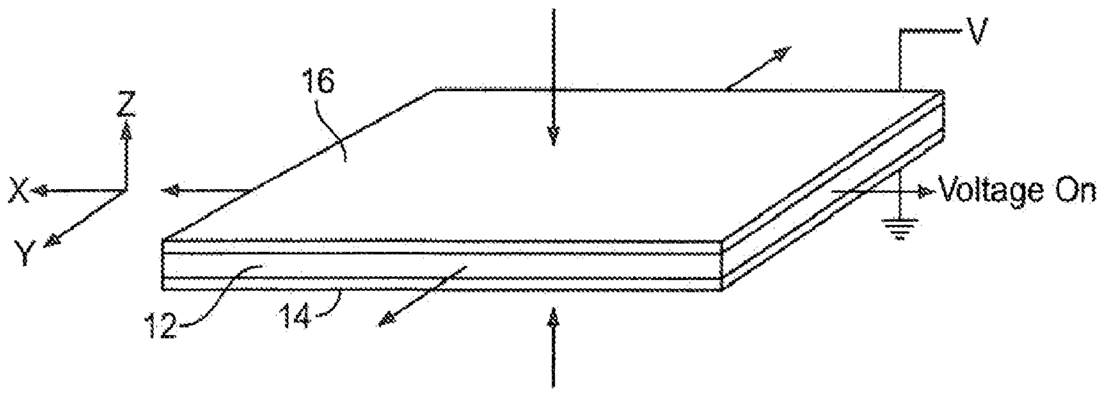
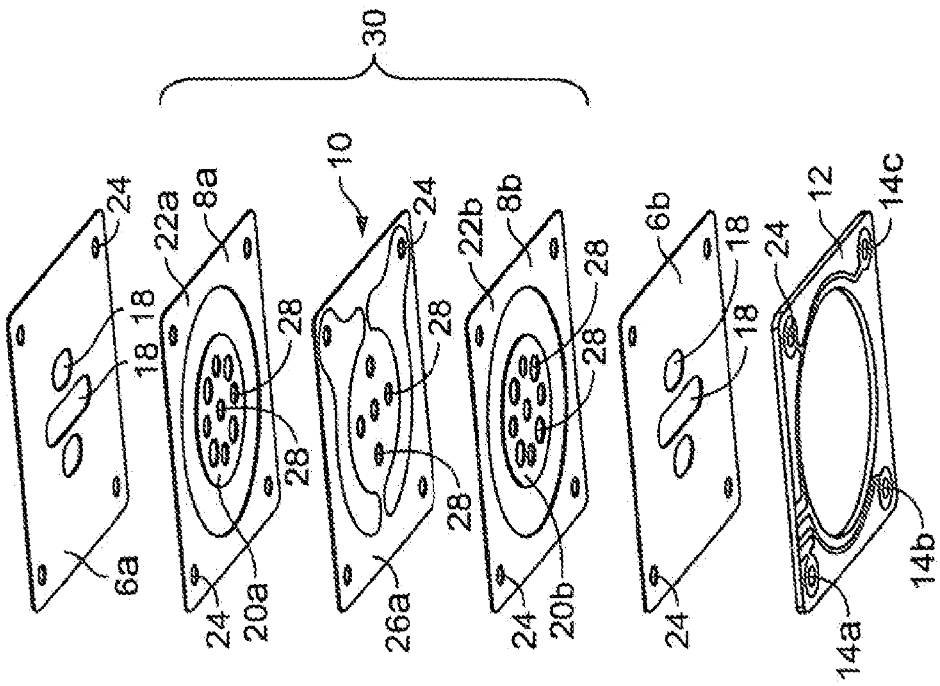


FIG. 7B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20a
28
26a
22b
8b
20b
6b
12
14a
14b
14c

FIG. 8B

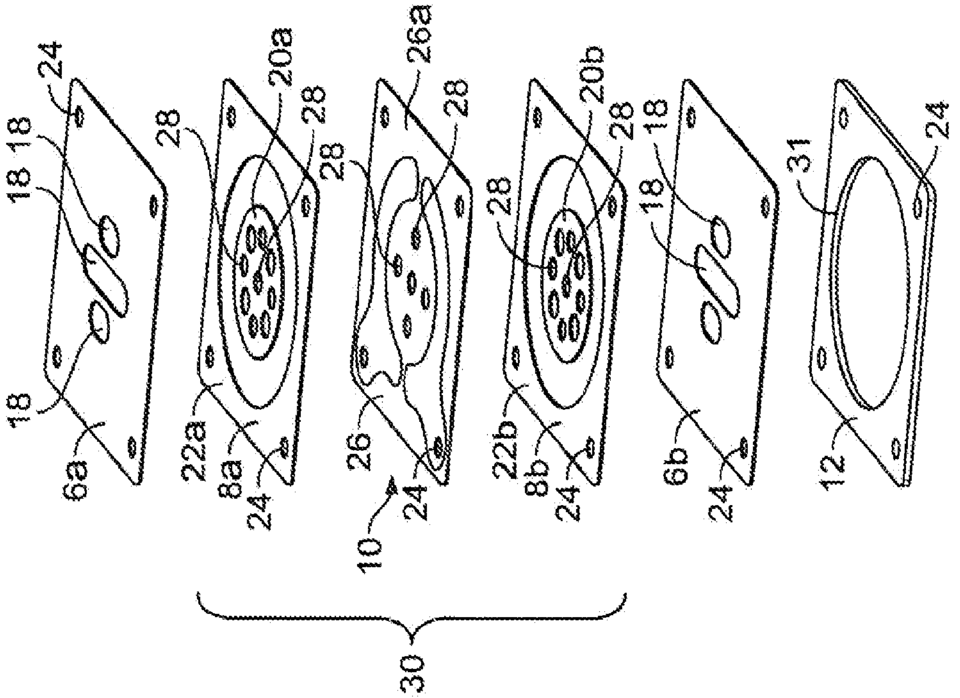
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FIG. 8A

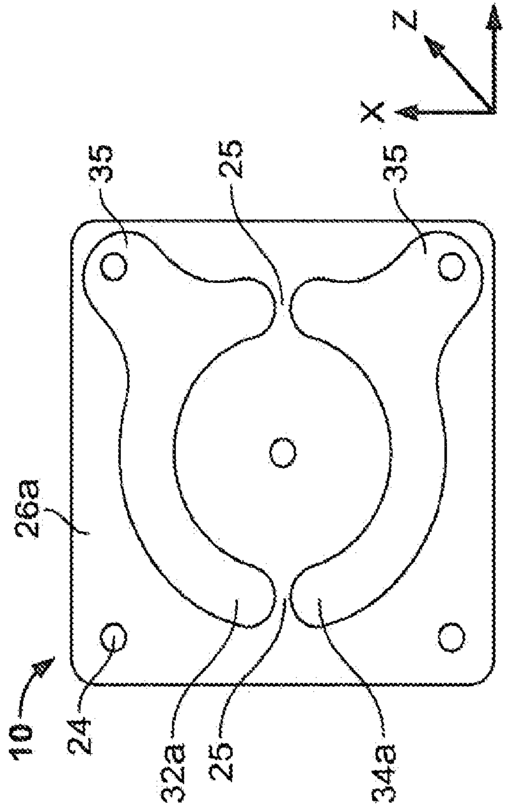


FIG. 9B

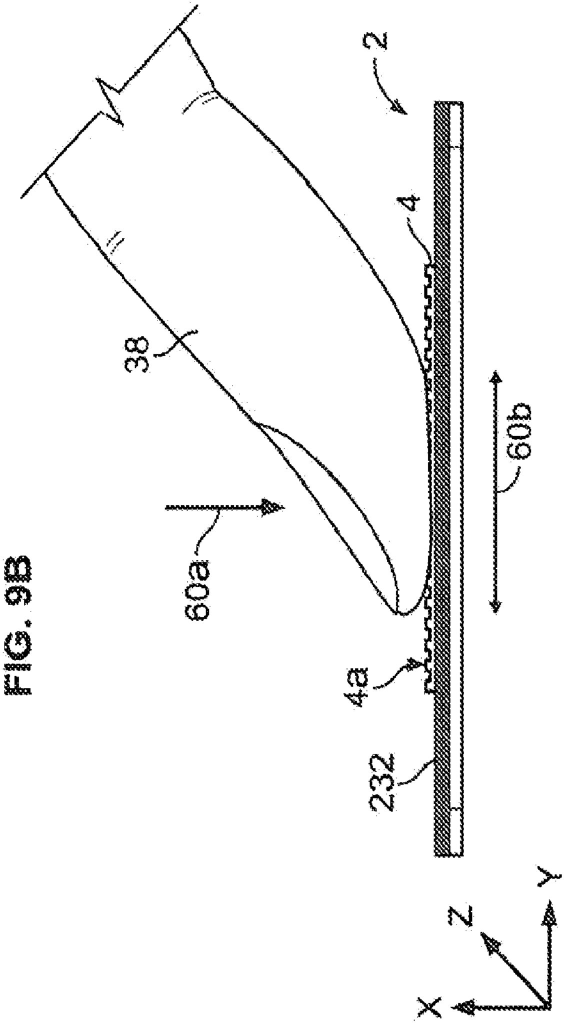


FIG. 10

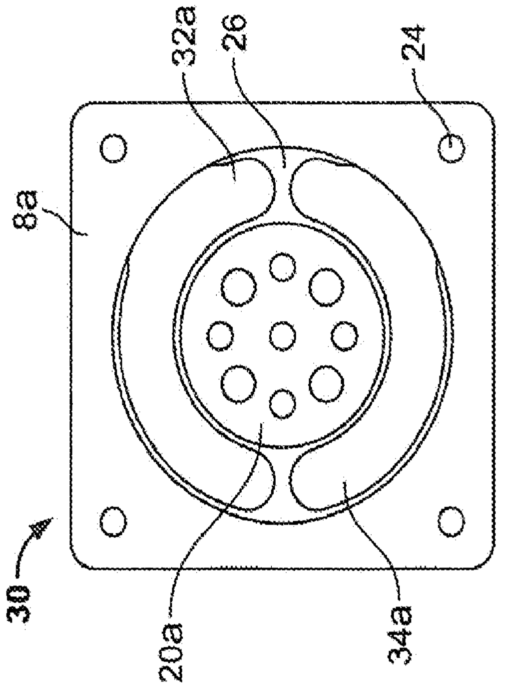


FIG. 9A

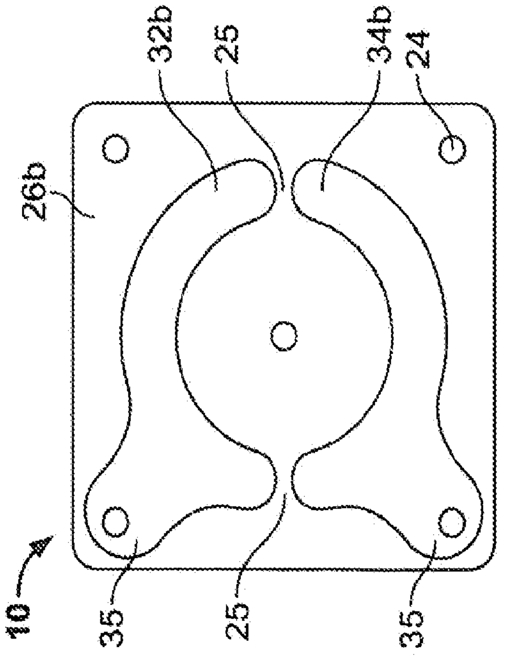


FIG. 9C

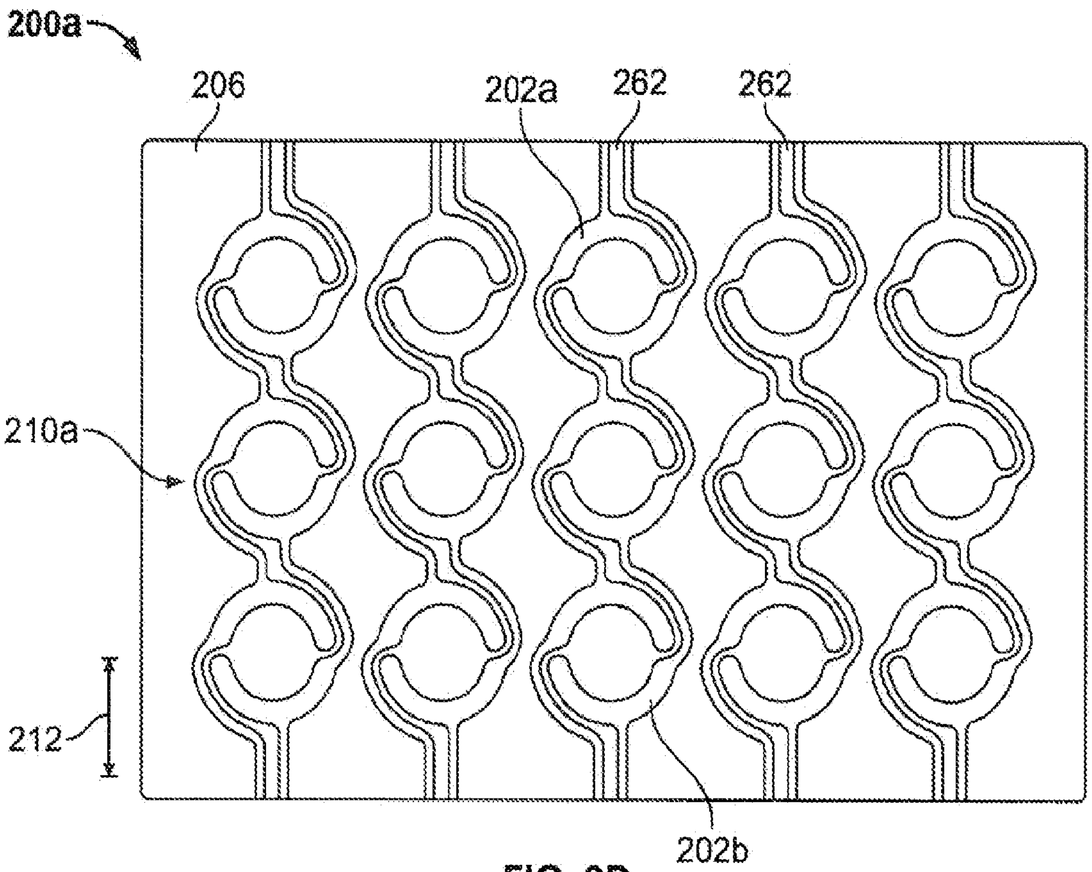

200a
206
202a
262
262
210a
212
202b

FIG. 9D

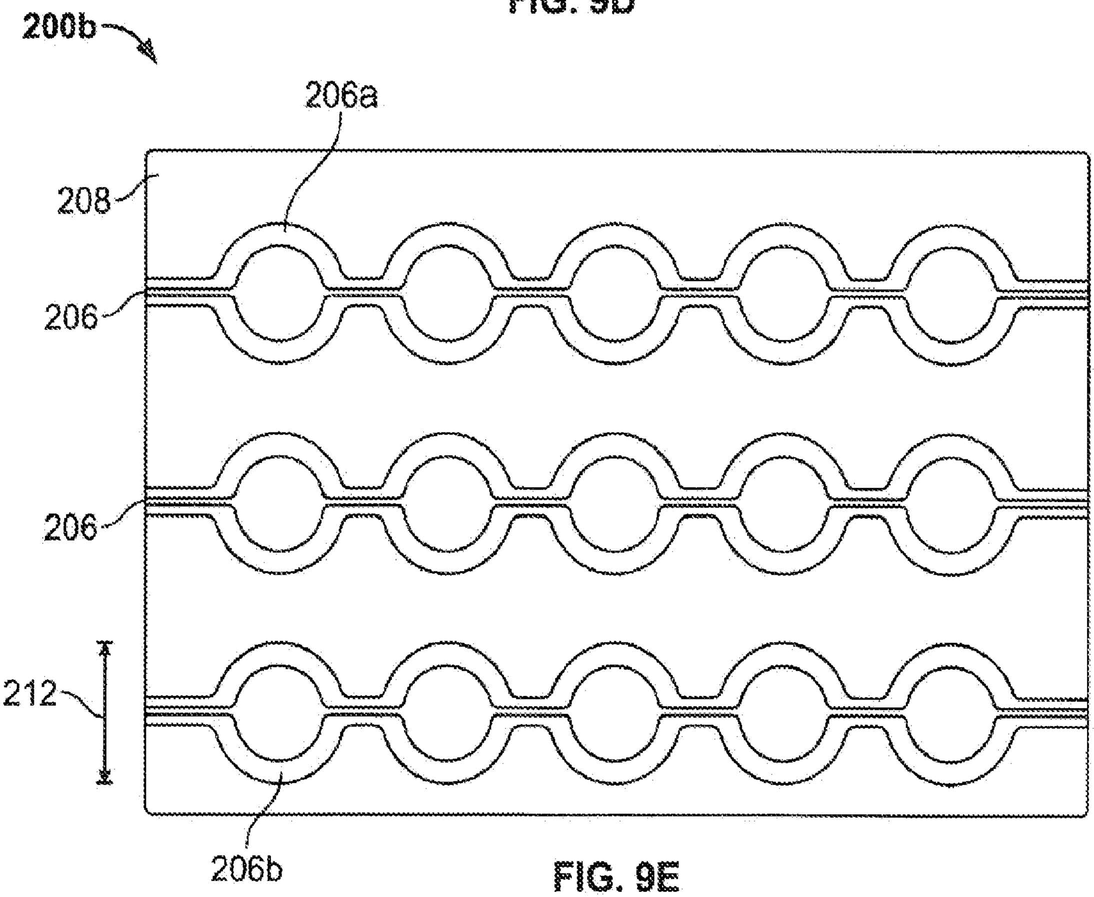

200b
206a
208
206
206
212
206b

FIG. 9E

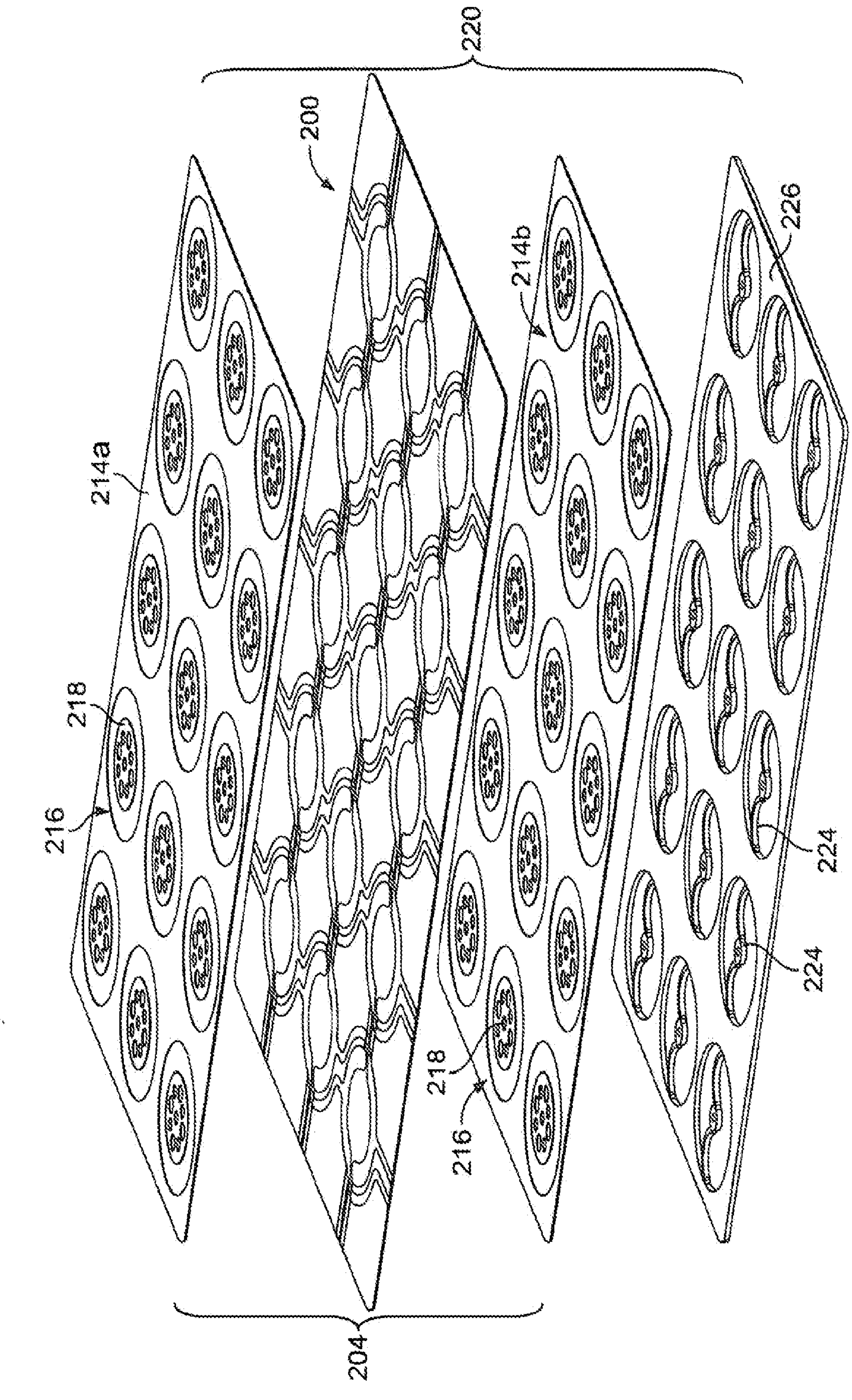


FIG. 9F

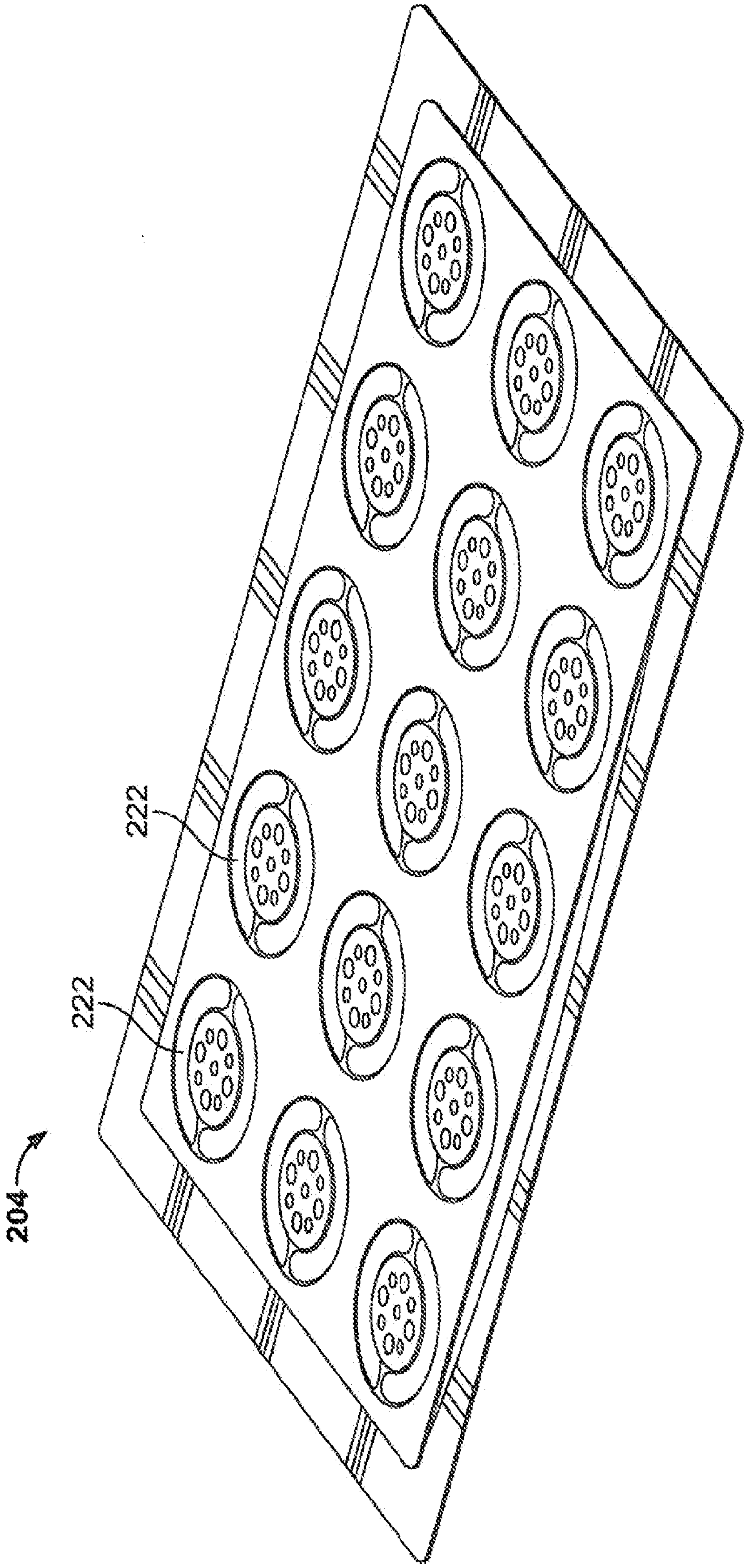


FIG. 9G

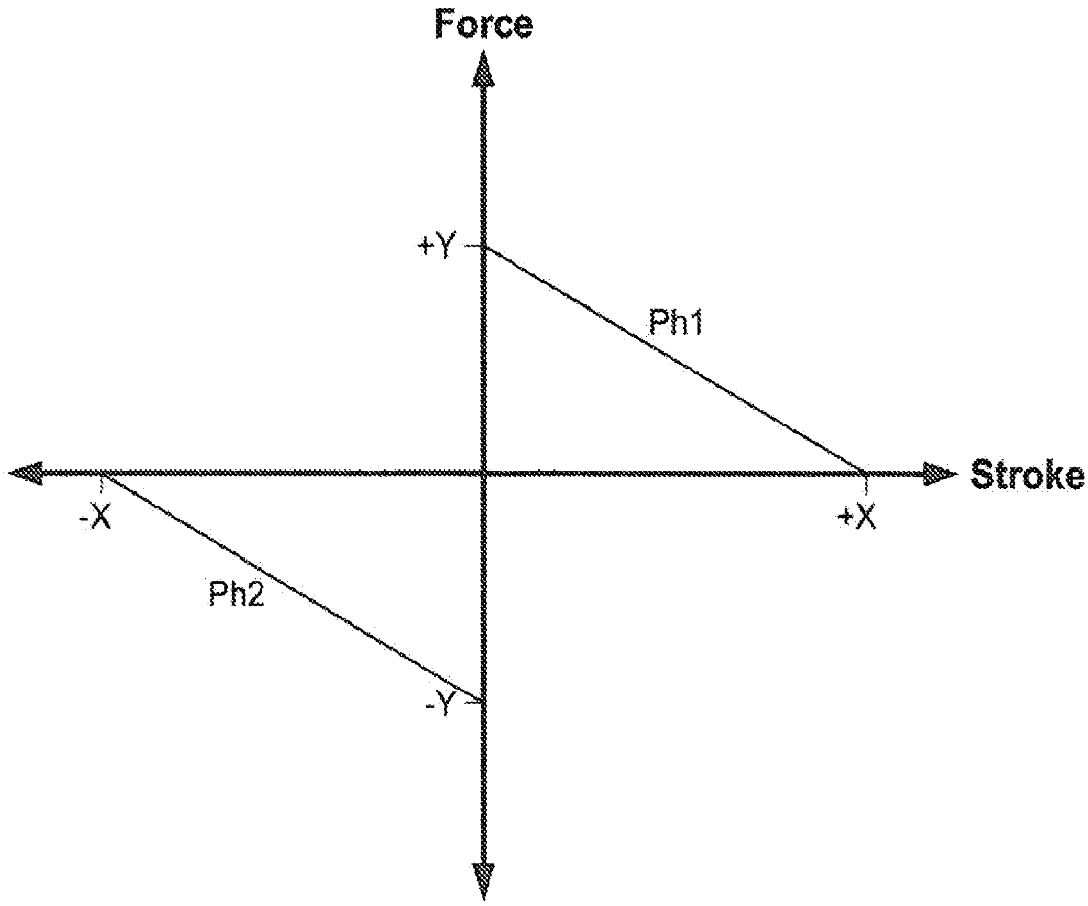


FIG. 11A

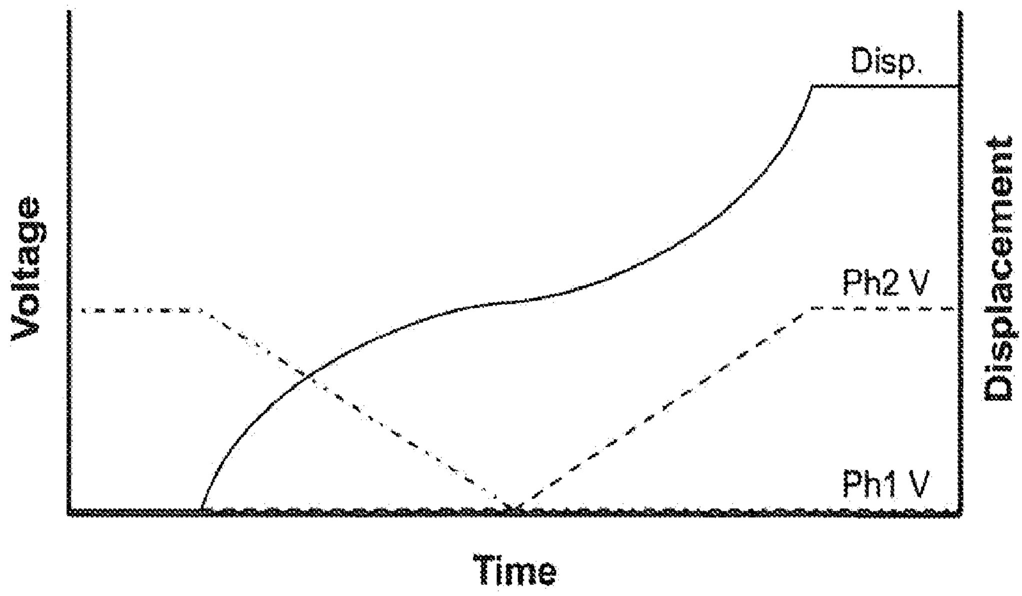


FIG. 11B

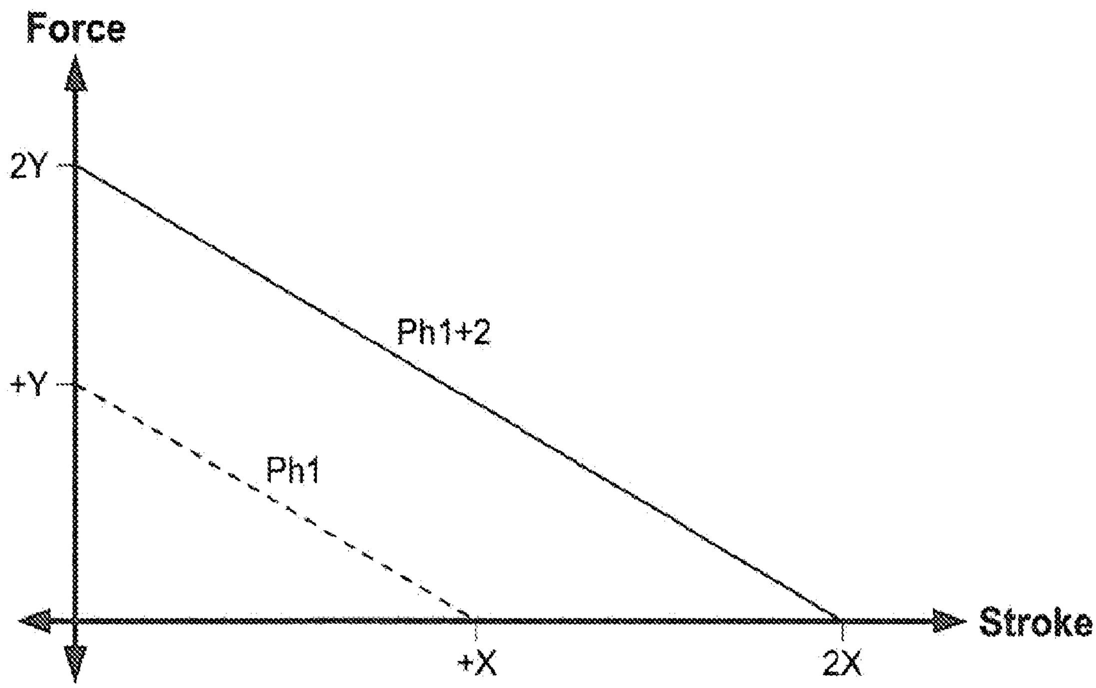


FIG. 11C

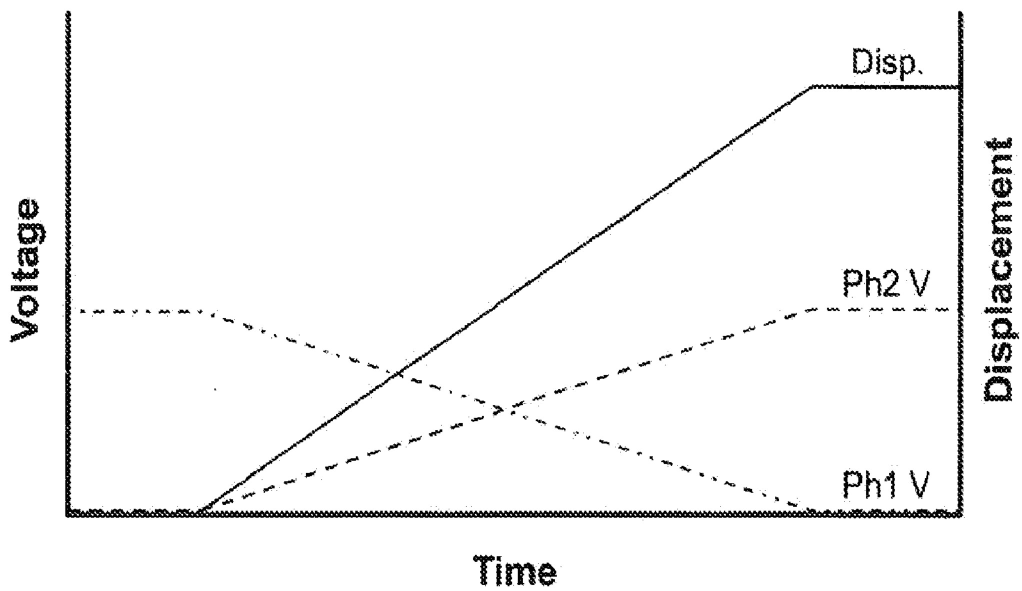


FIG. 11D

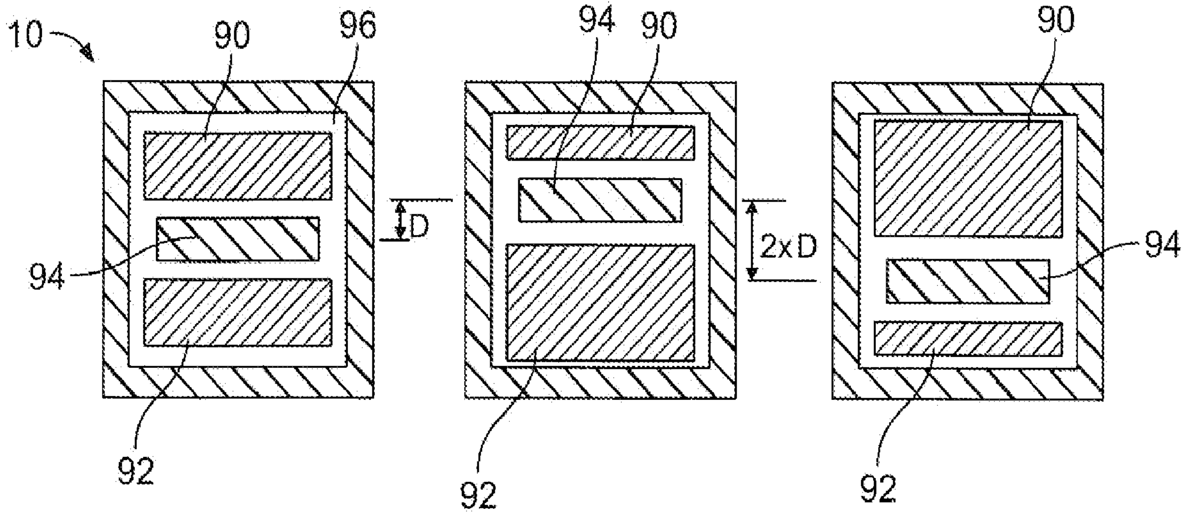


FIG. 12A FIG. 12B FIG. 12C

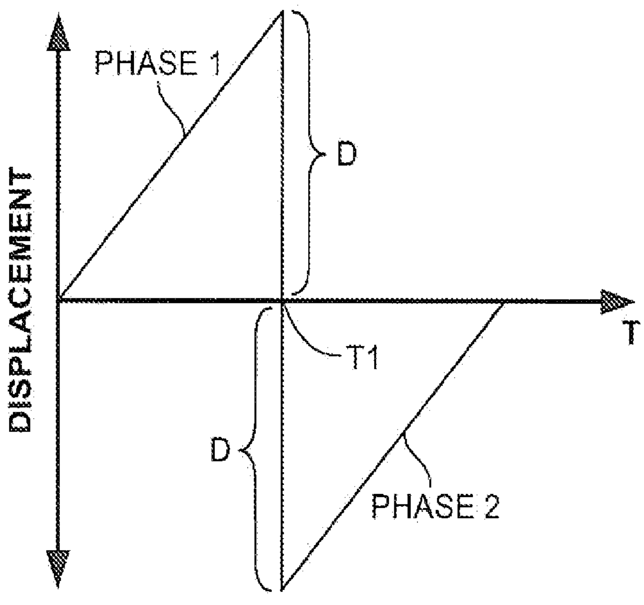


FIG. 12D

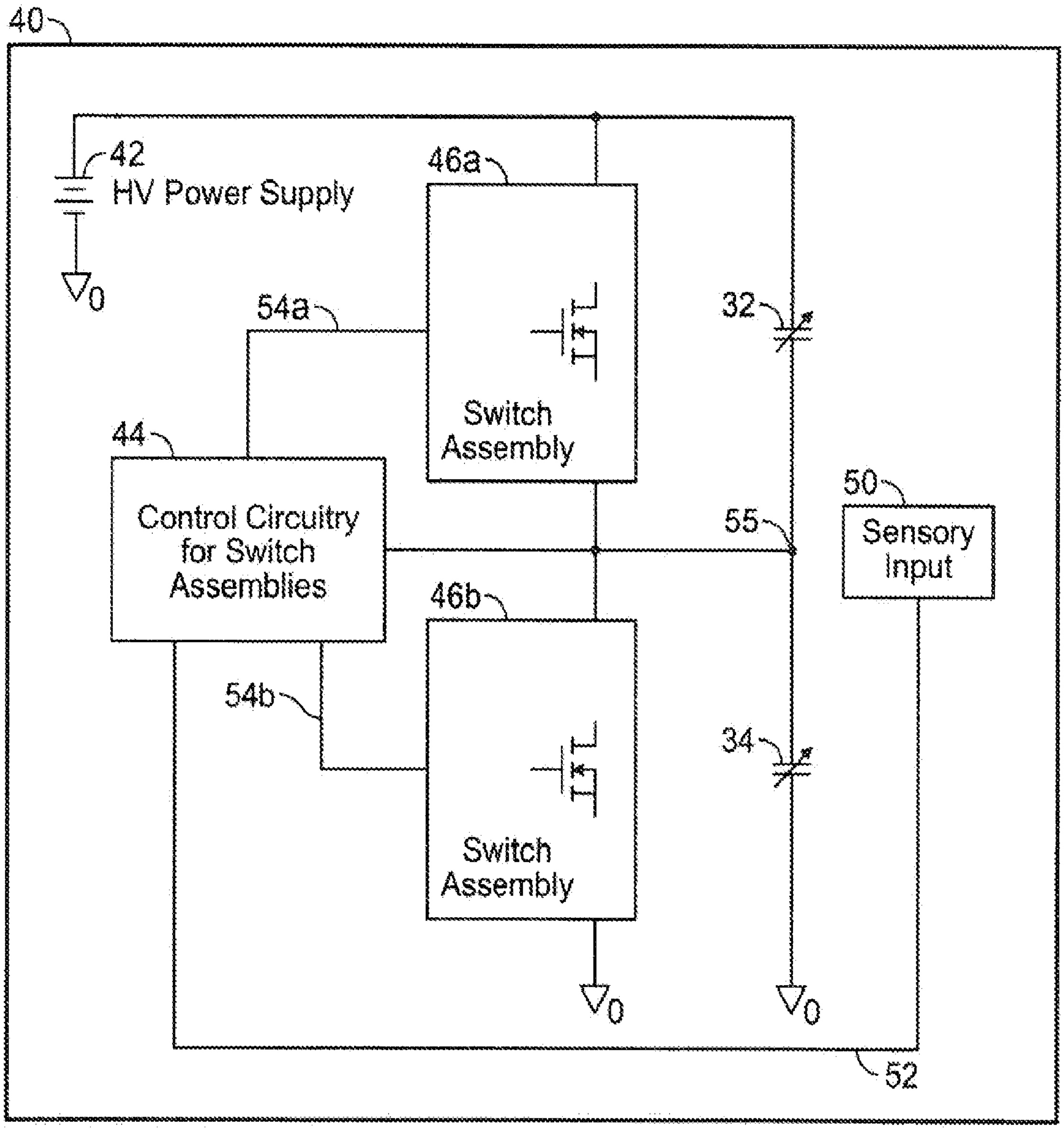

40
42
HV Power Supply
0
46a
54a
Switch
Assembly
32
44
Control Circuitry
for Switch
Assemblies
50
Sensory
Input
55
46b
54b
34
Switch
Assembly
0
0
52

FIG. 13

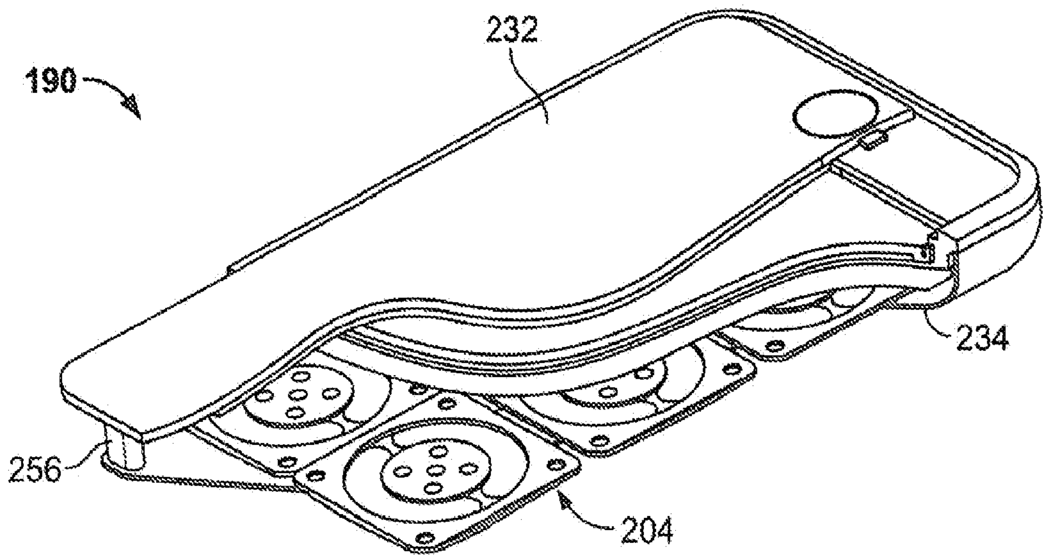


FIG. 14A

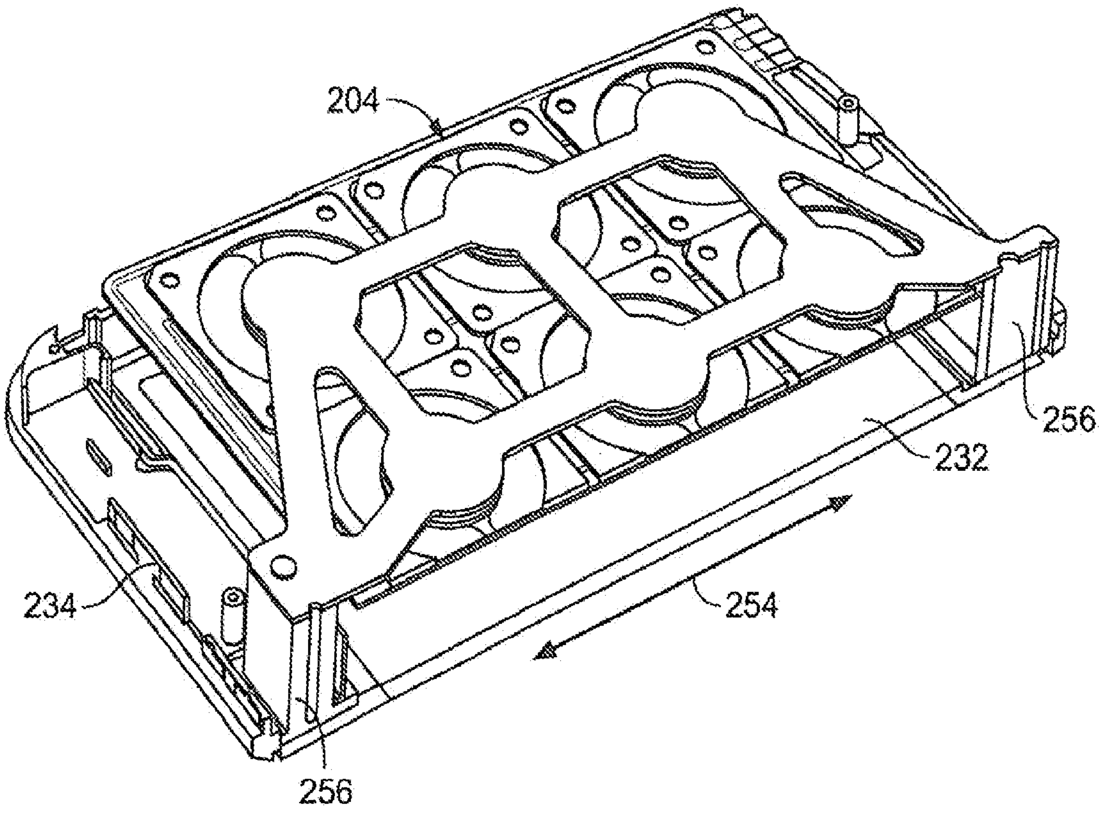


FIG. 14B

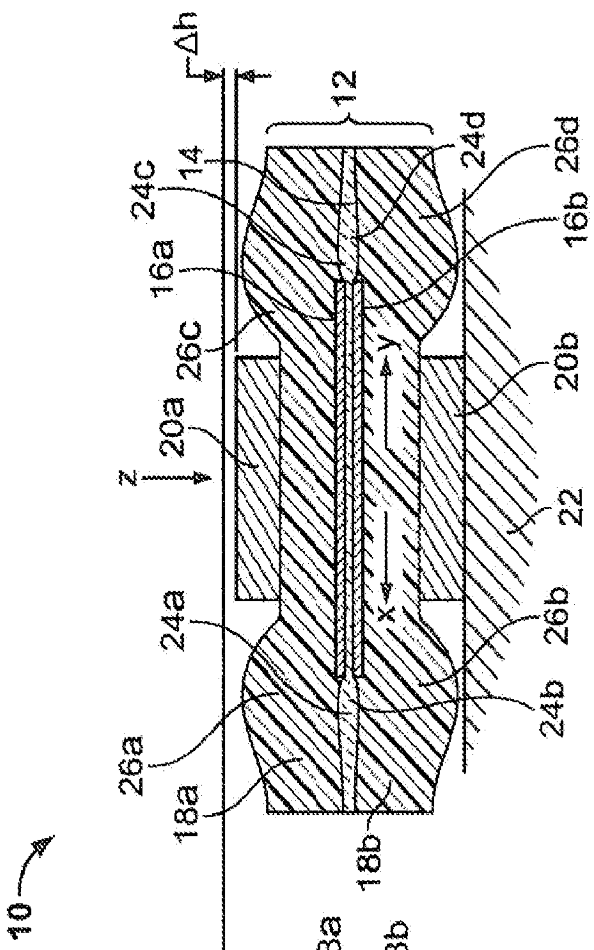


FIG. 15B

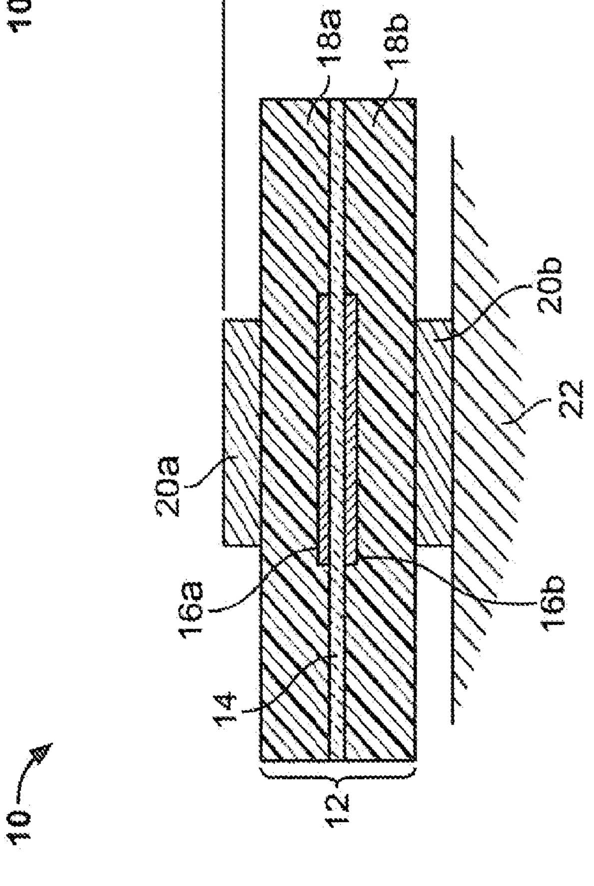


FIG. 15A

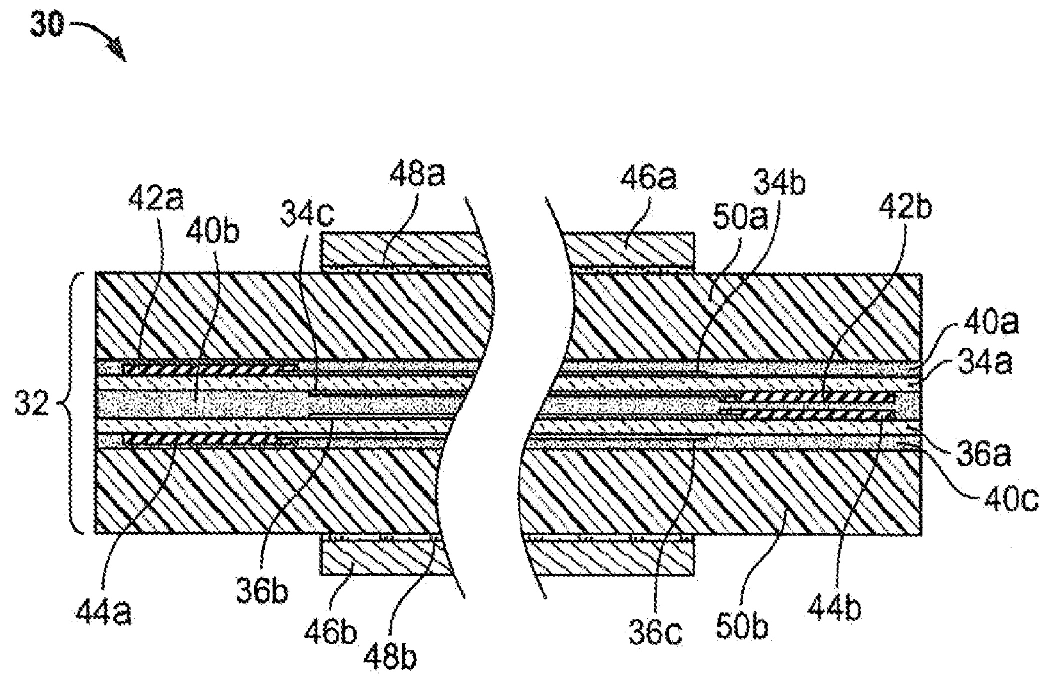


FIG. 16A

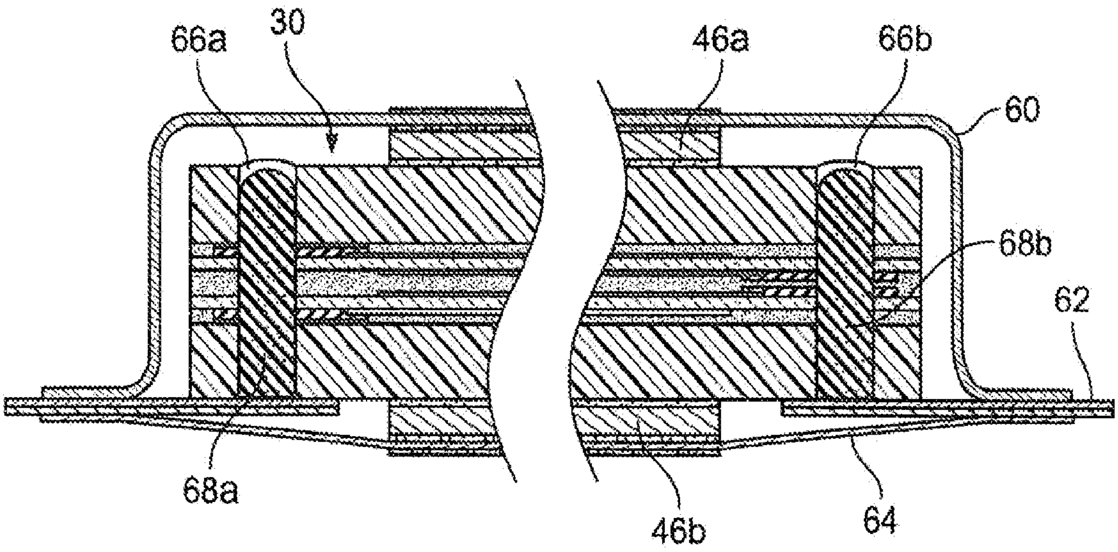


FIG. 16B

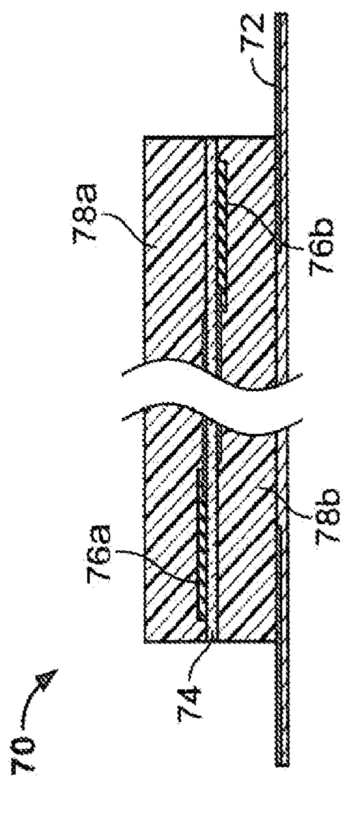


FIG. 17A

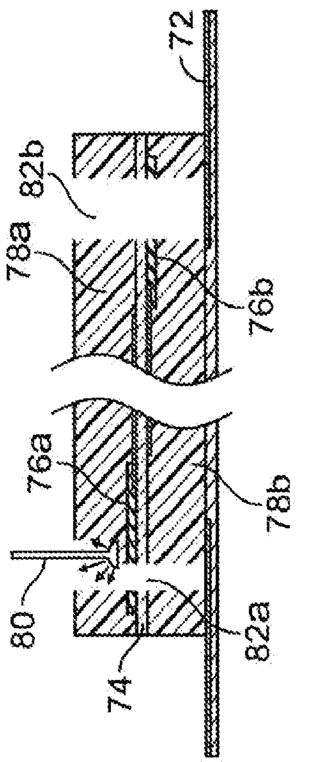


FIG. 17B

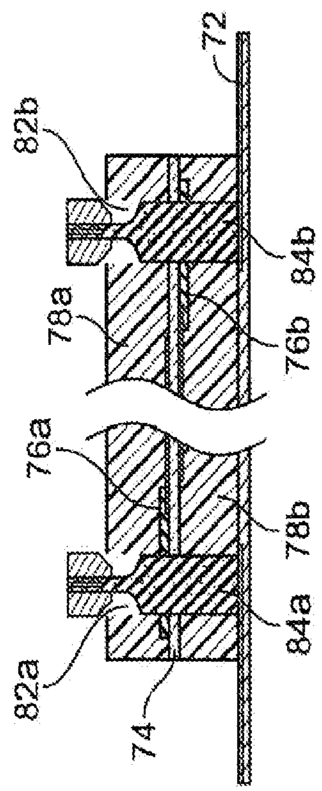


FIG. 17C

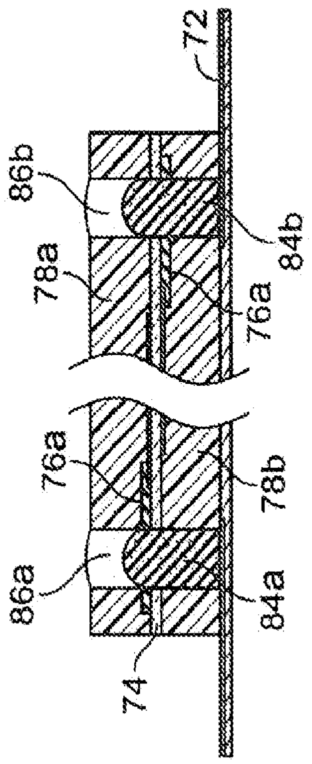


FIG. 17D

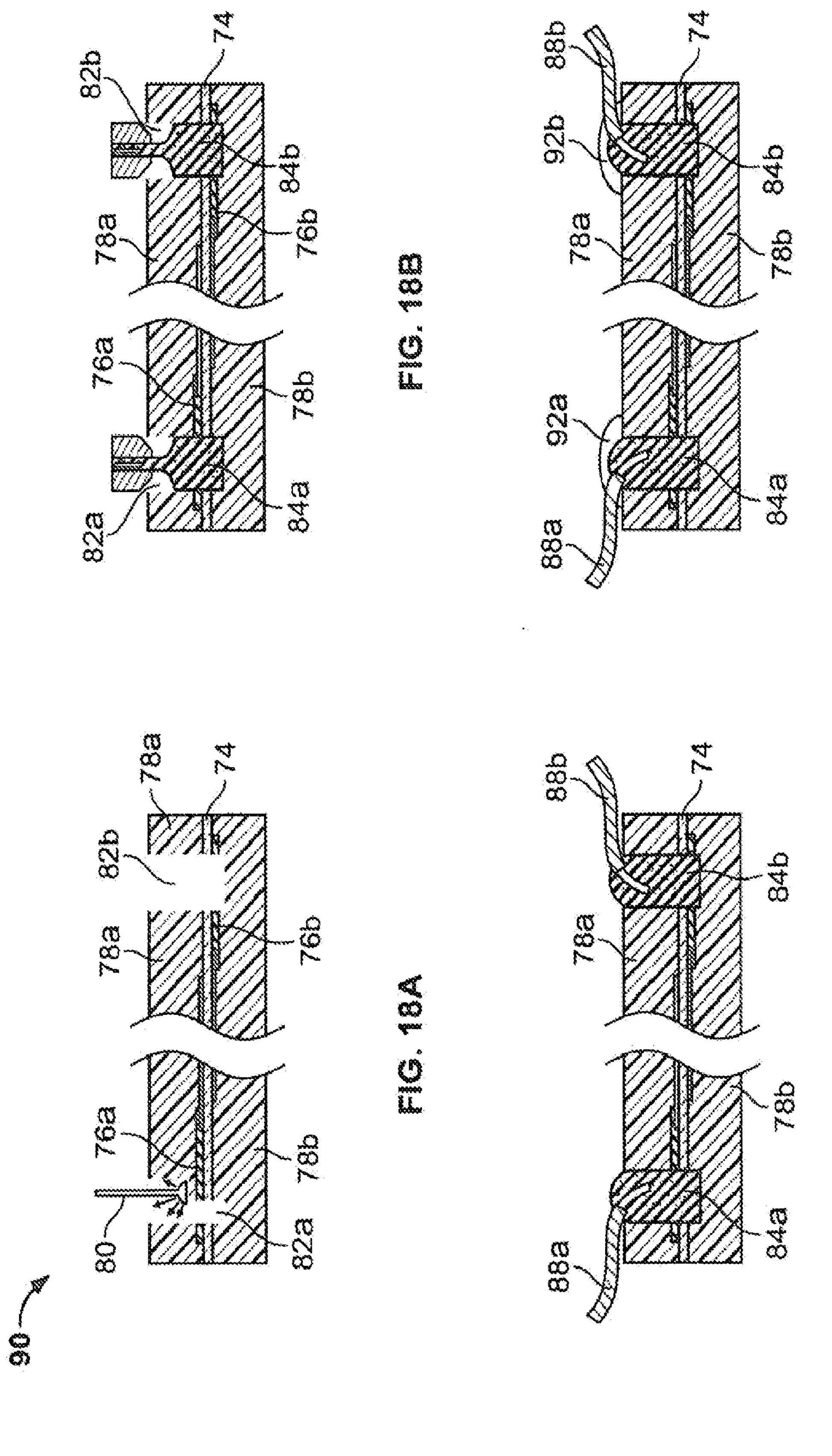


FIG. 18A

FIG. 18B

FIG. 18C

FIG. 18D

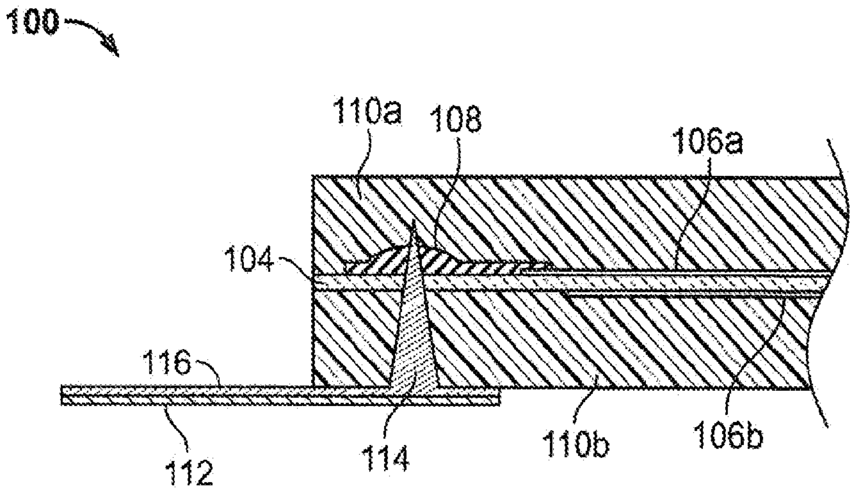


FIG. 19

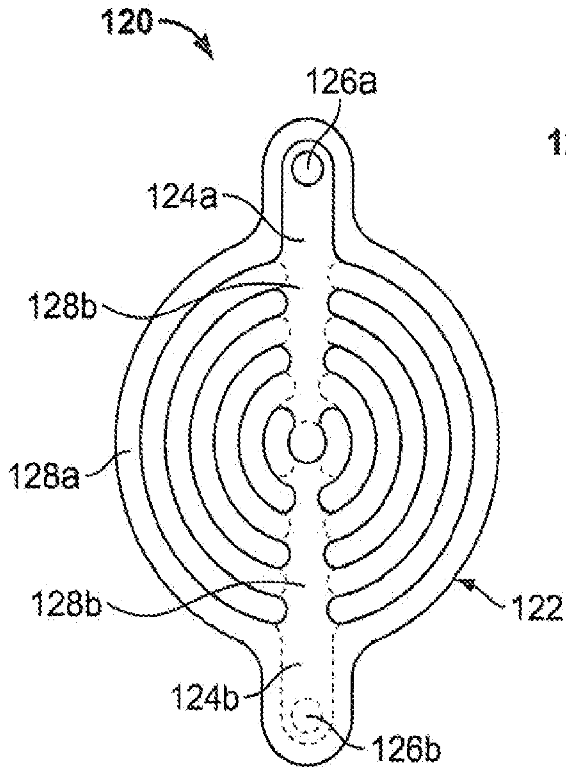


FIG. 20A

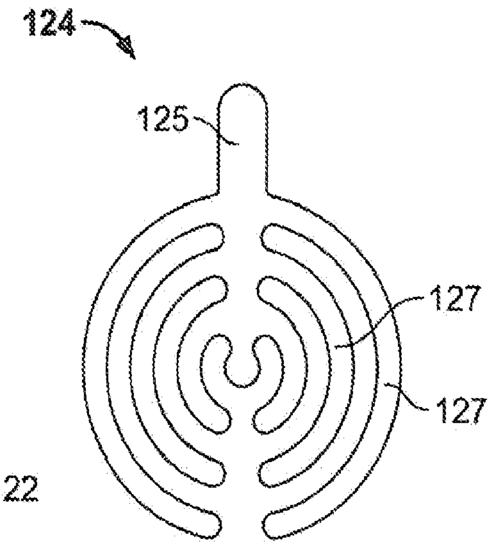


FIG. 20B

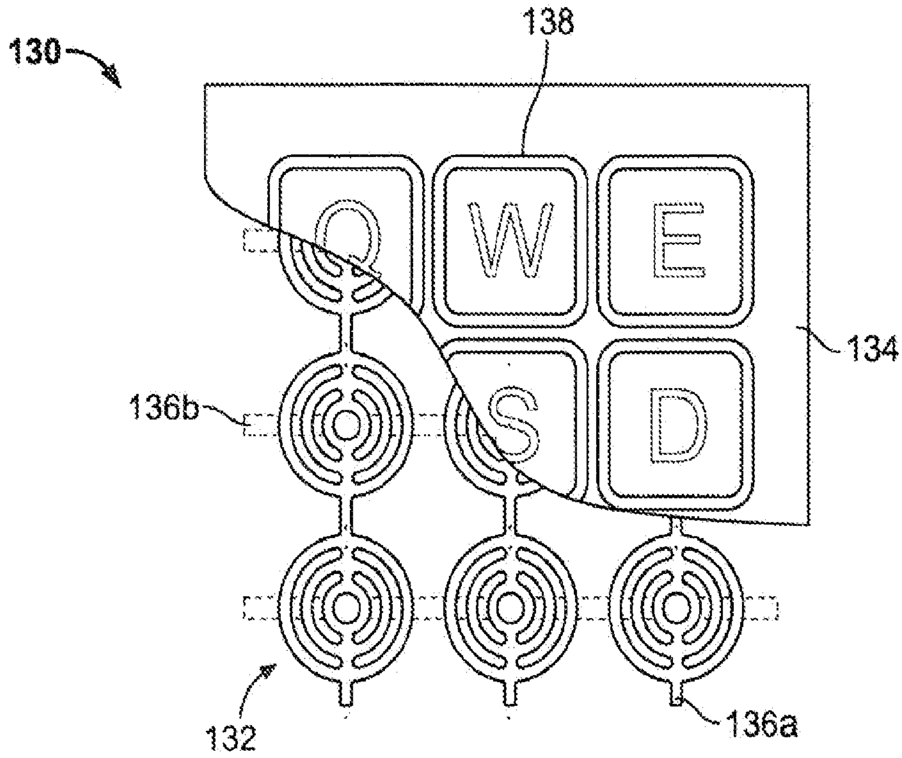

130
138
Q
W
E
134
136b
S
D
132
136a

FIG. 21

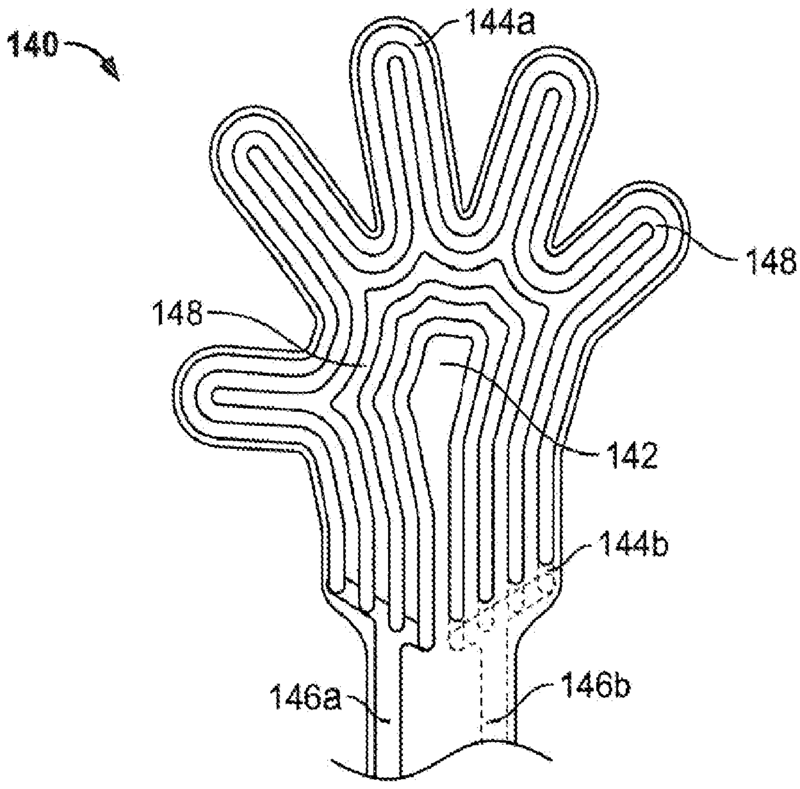

140
144a
148
148
142
144b
146a
146b

FIG. 22

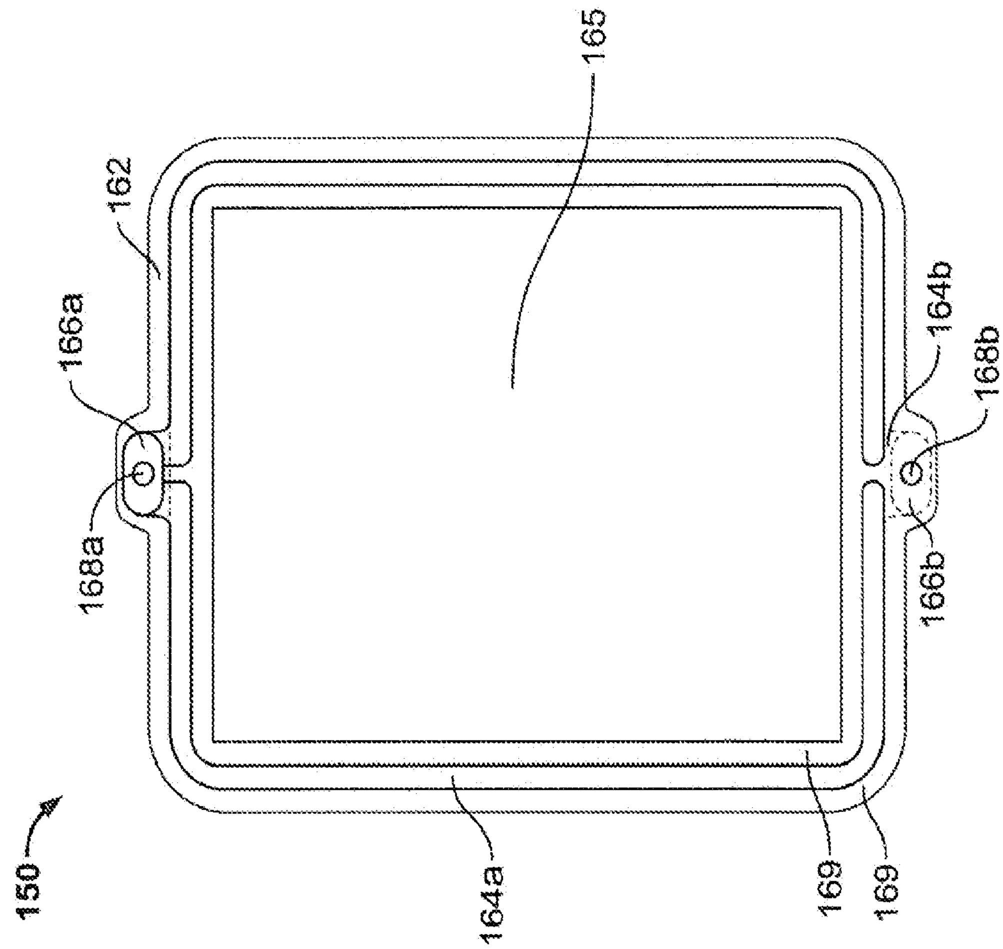

150
165
162
166a
168a
164b
168b
166b
164a
169
169

FIG. 24

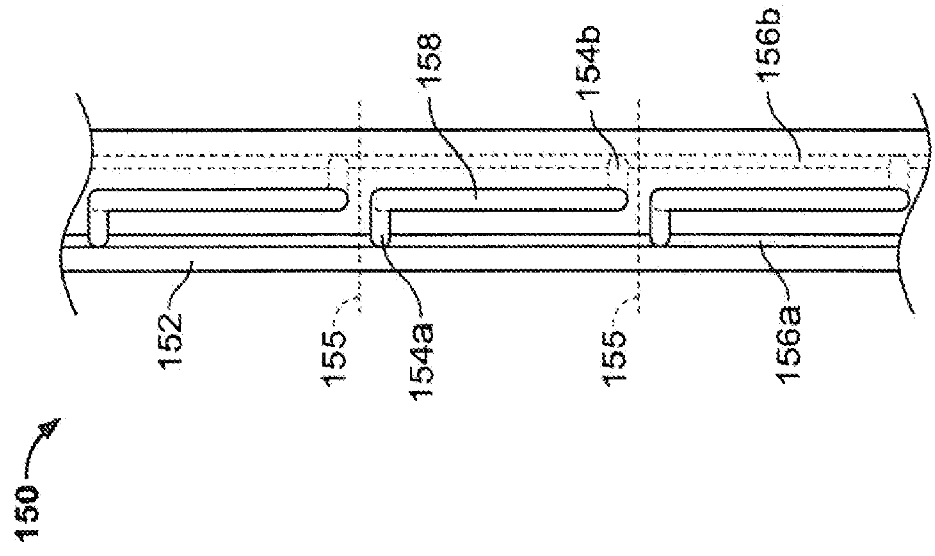

150
158
154b
156b
152
155
154a
155
156a

FIG. 23

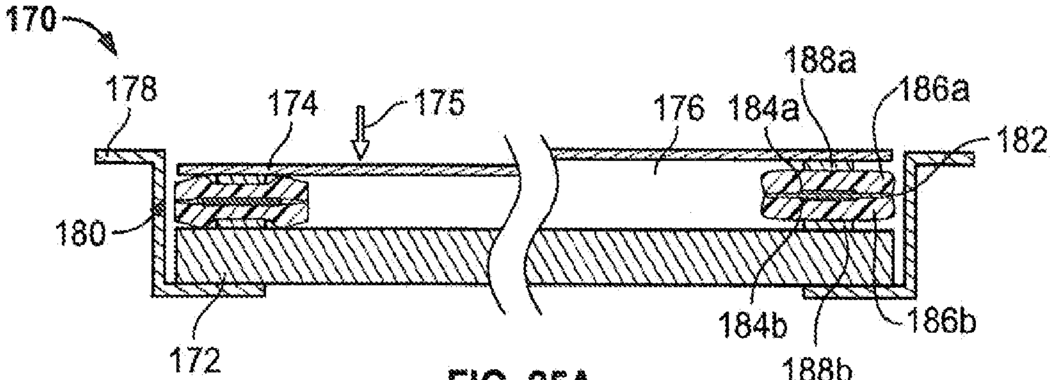


FIG. 25A

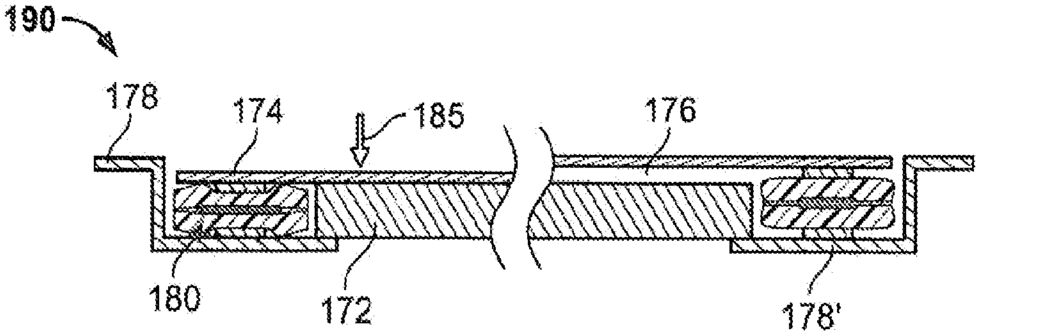


FIG. 25B

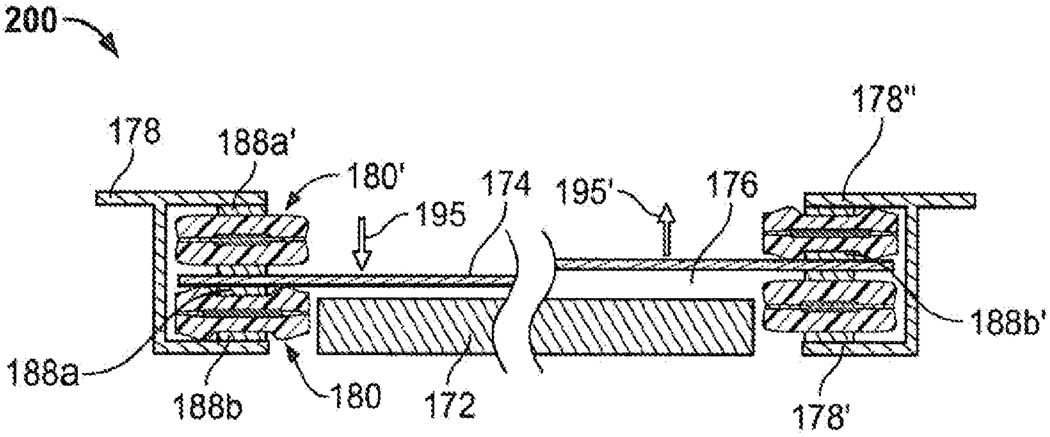


FIG. 25C

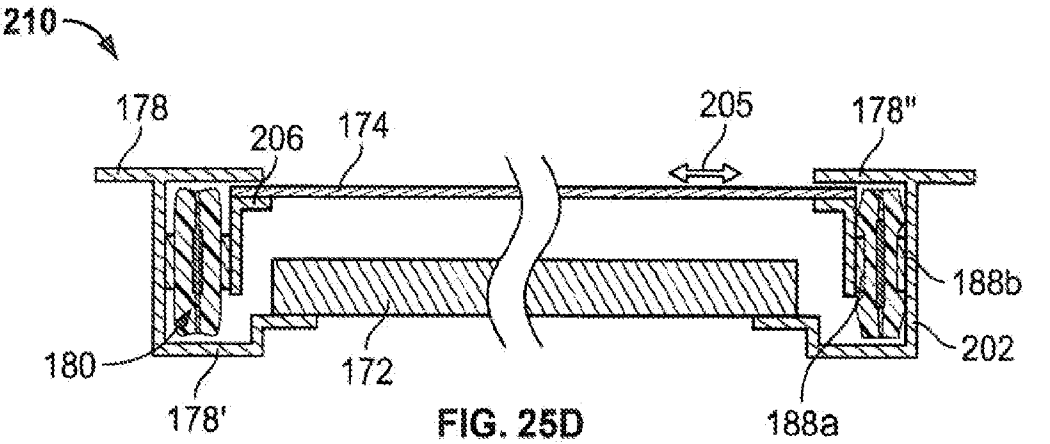


FIG. 25D

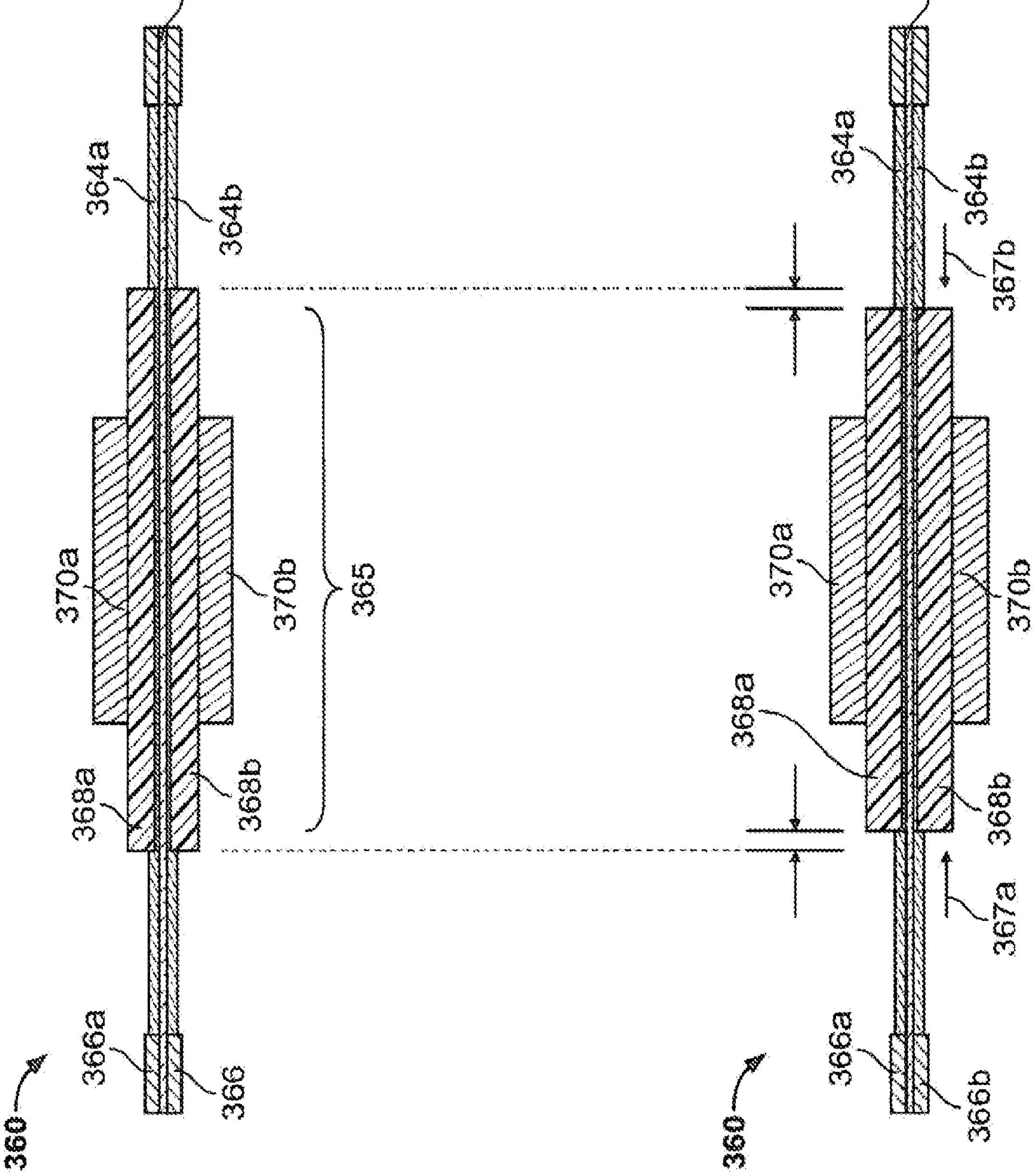


FIG. 26A

FIG. 26B

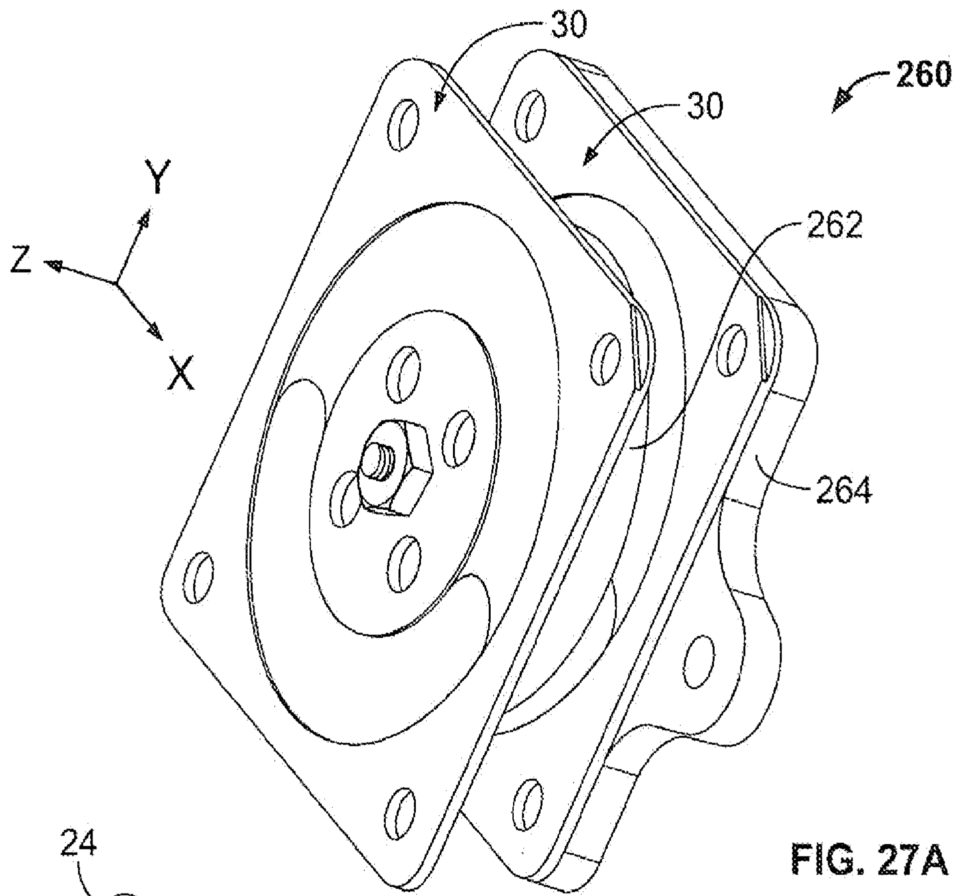


FIG. 27A

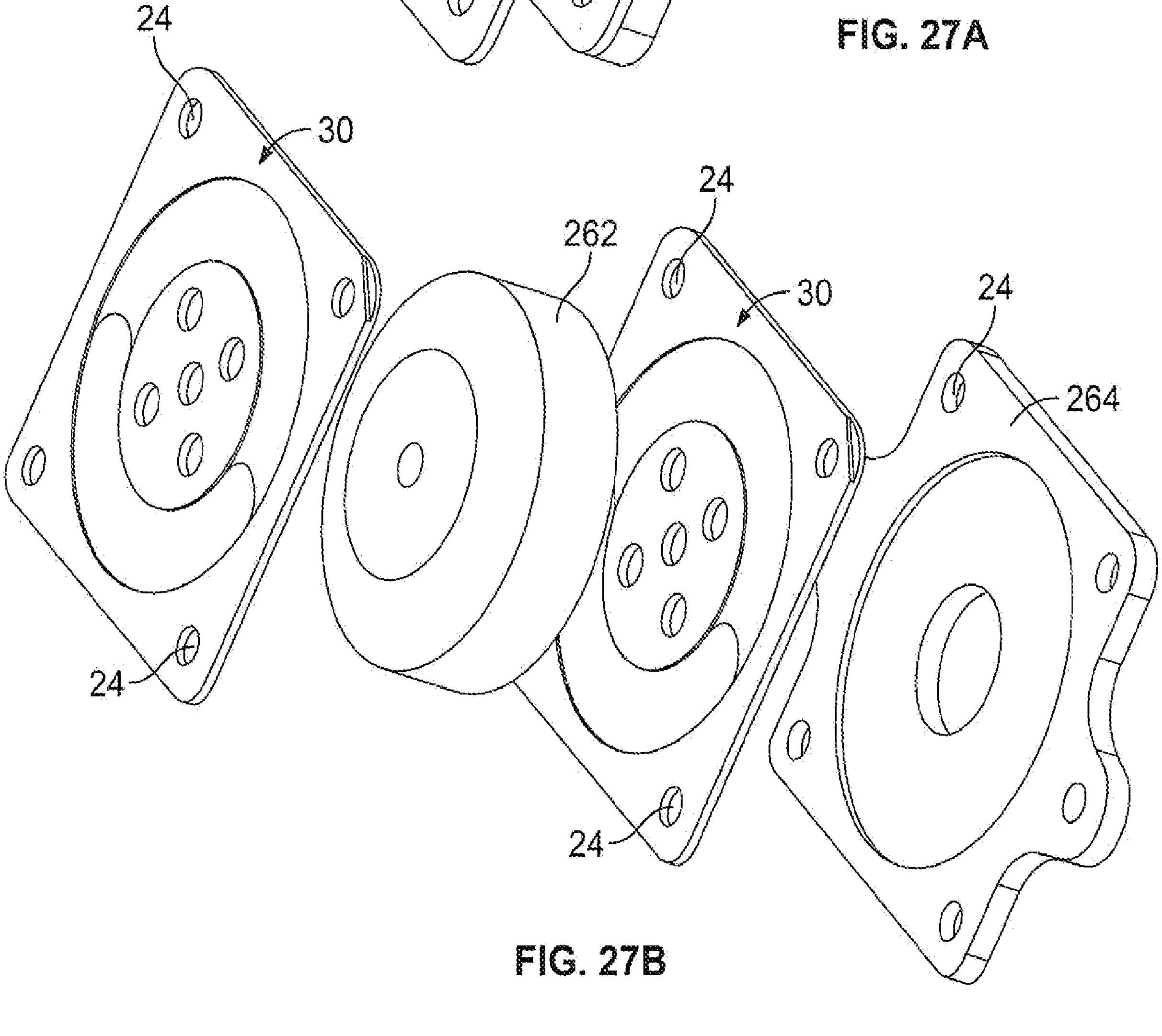


FIG. 27B

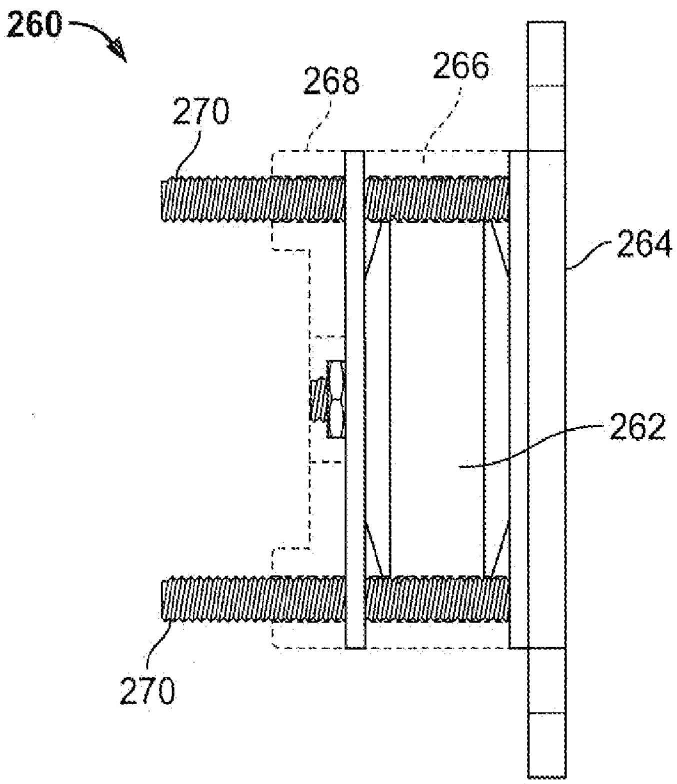


FIG. 27C

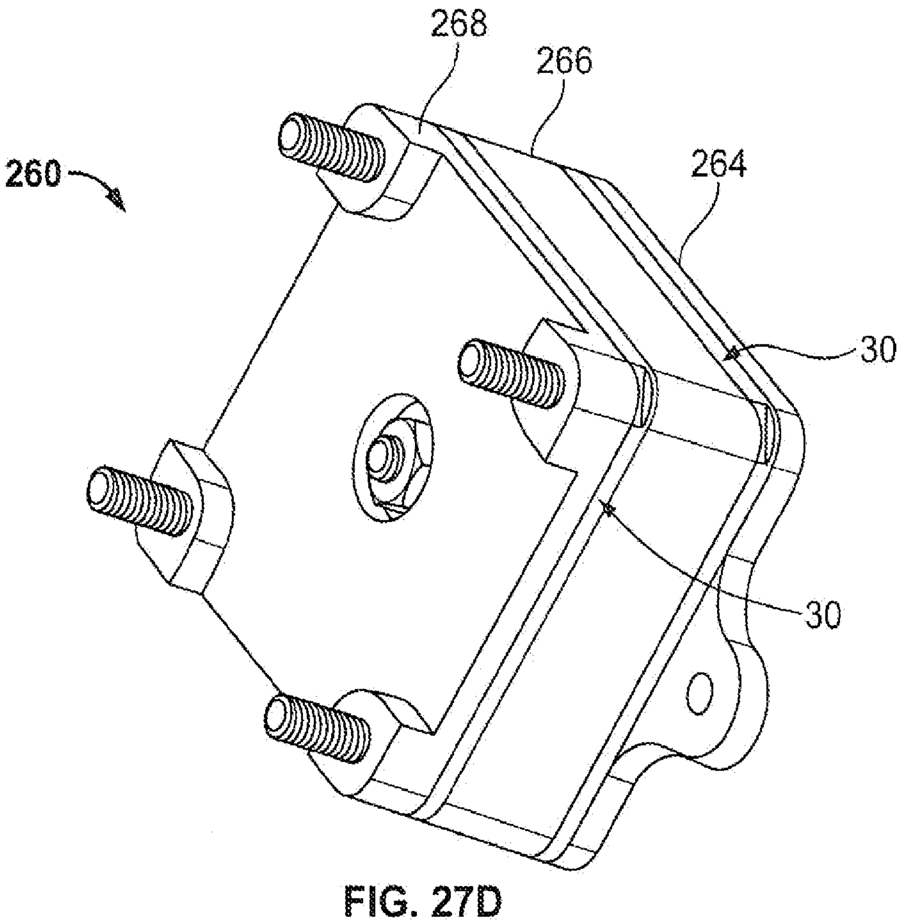


FIG. 27D

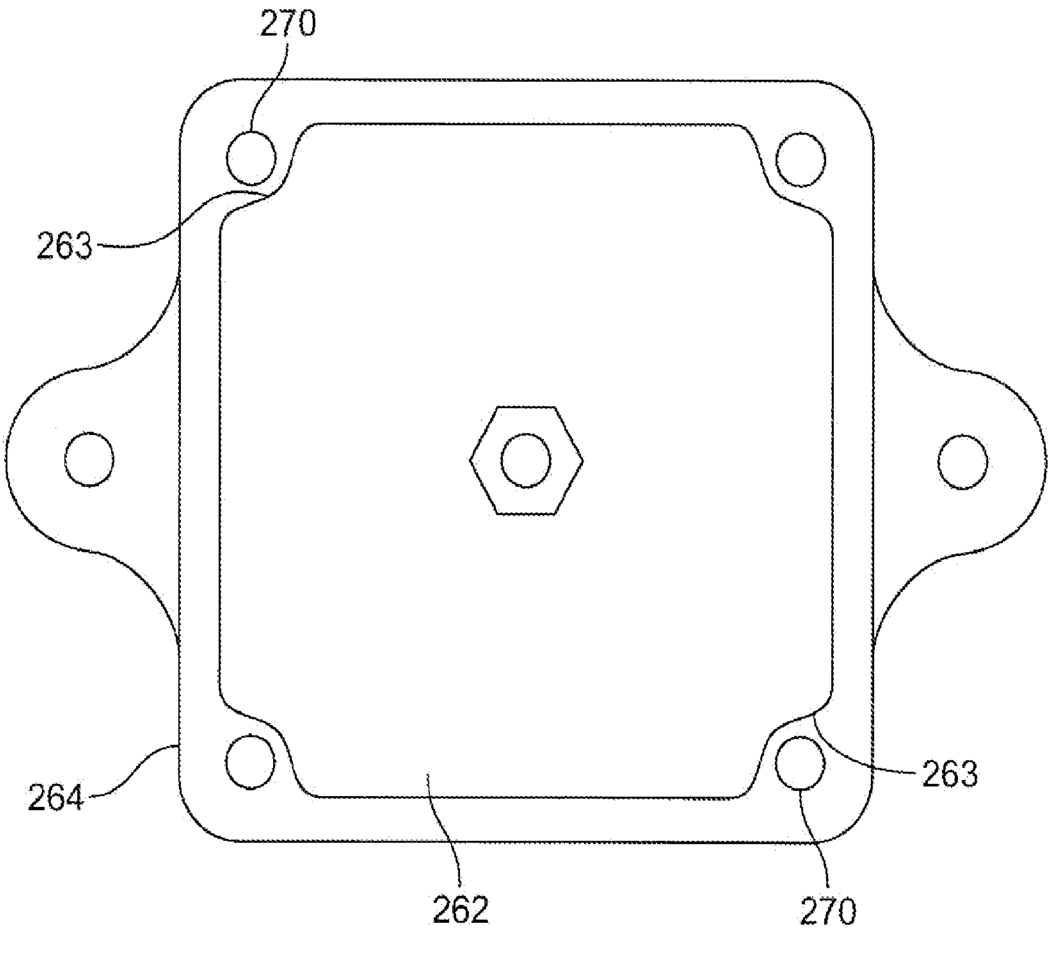


FIG. 27E

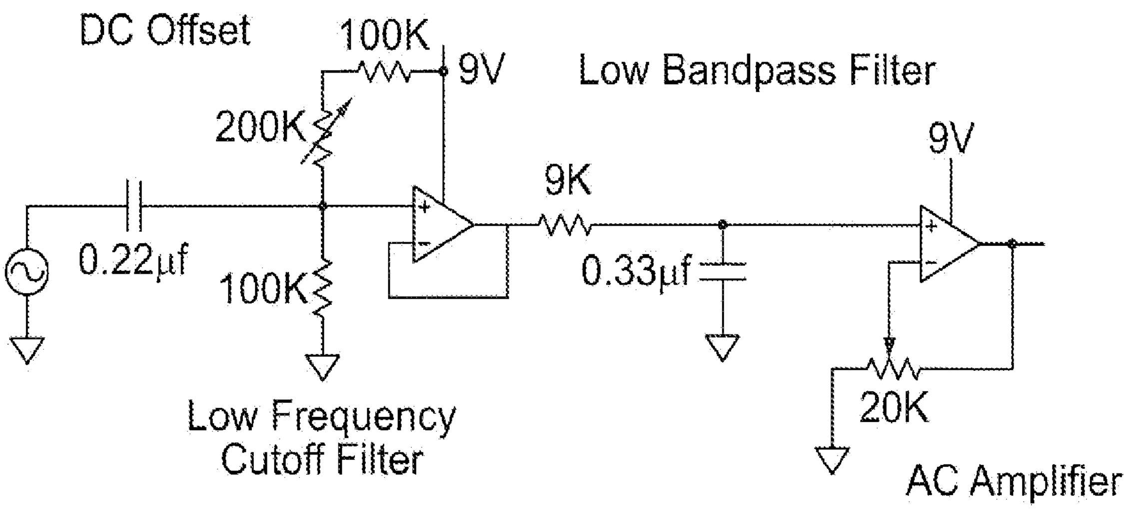


FIG. 28A

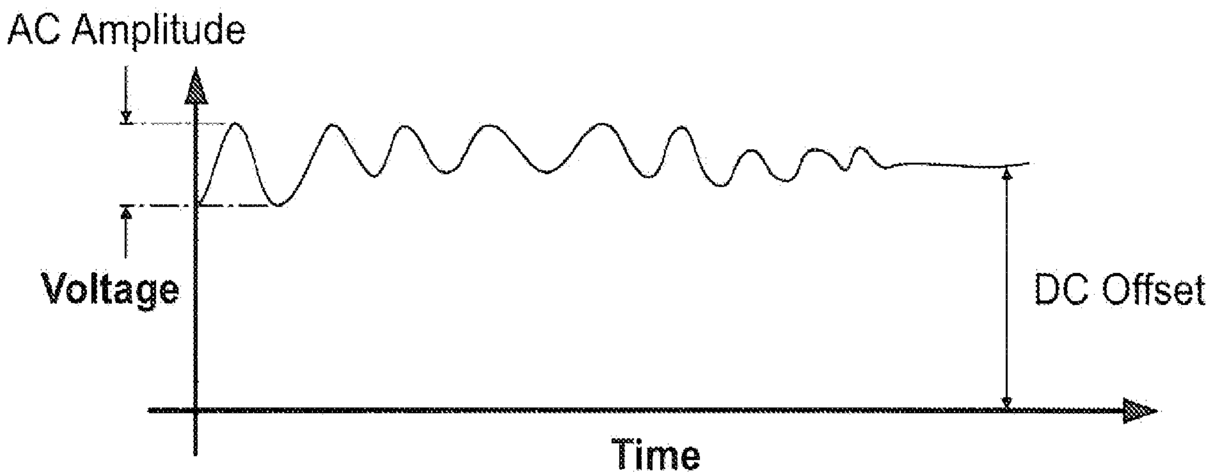
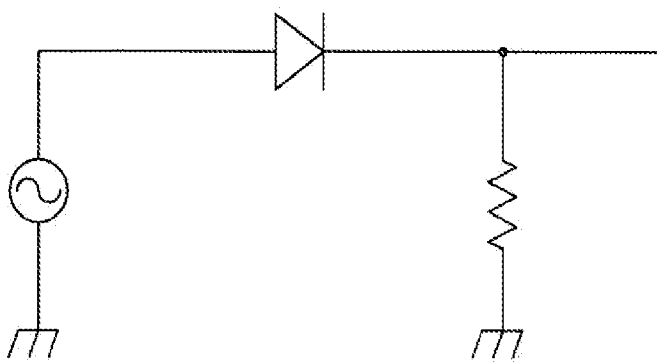
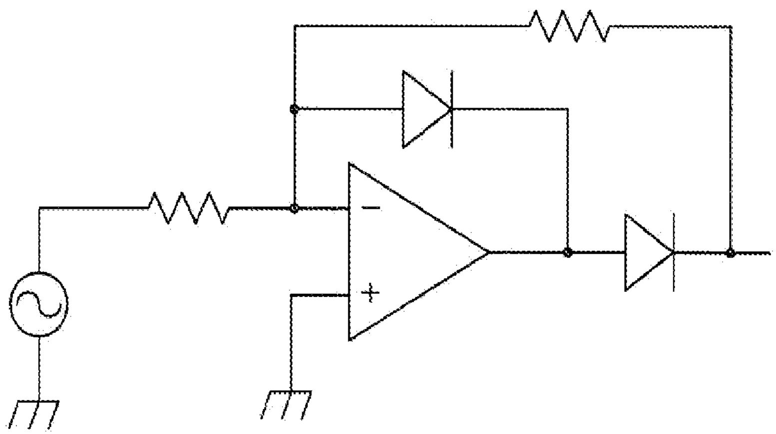


FIG. 28B



Positive Rectifier

FIG. 28C



Negative Rectifier & Inverter
for Other Phase

FIG. 28D

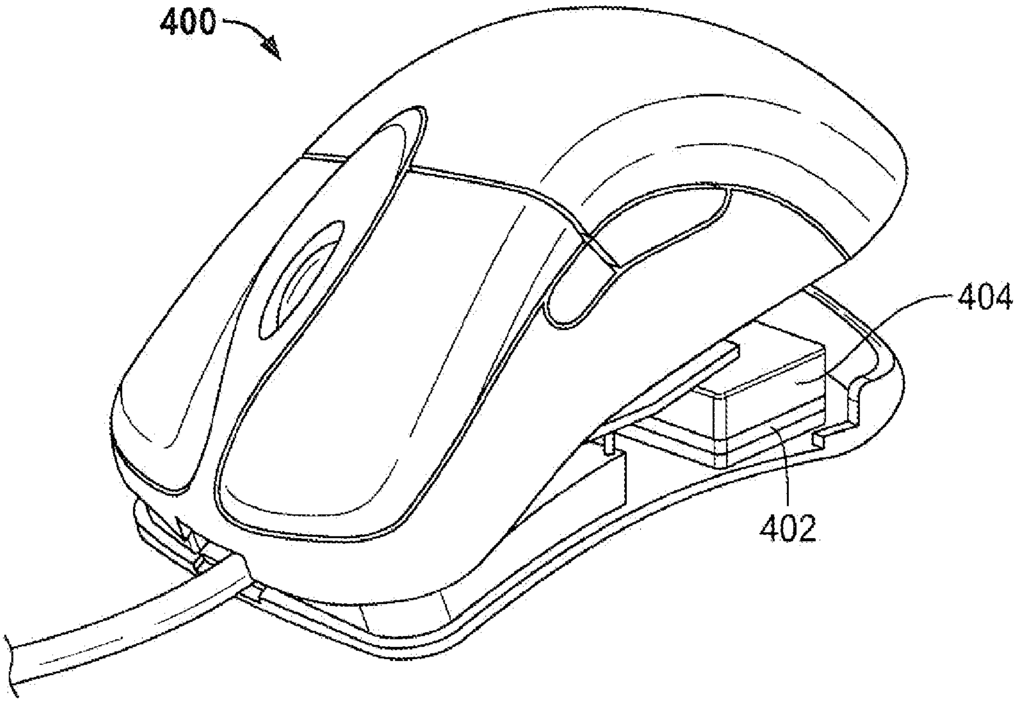


FIG. 28E

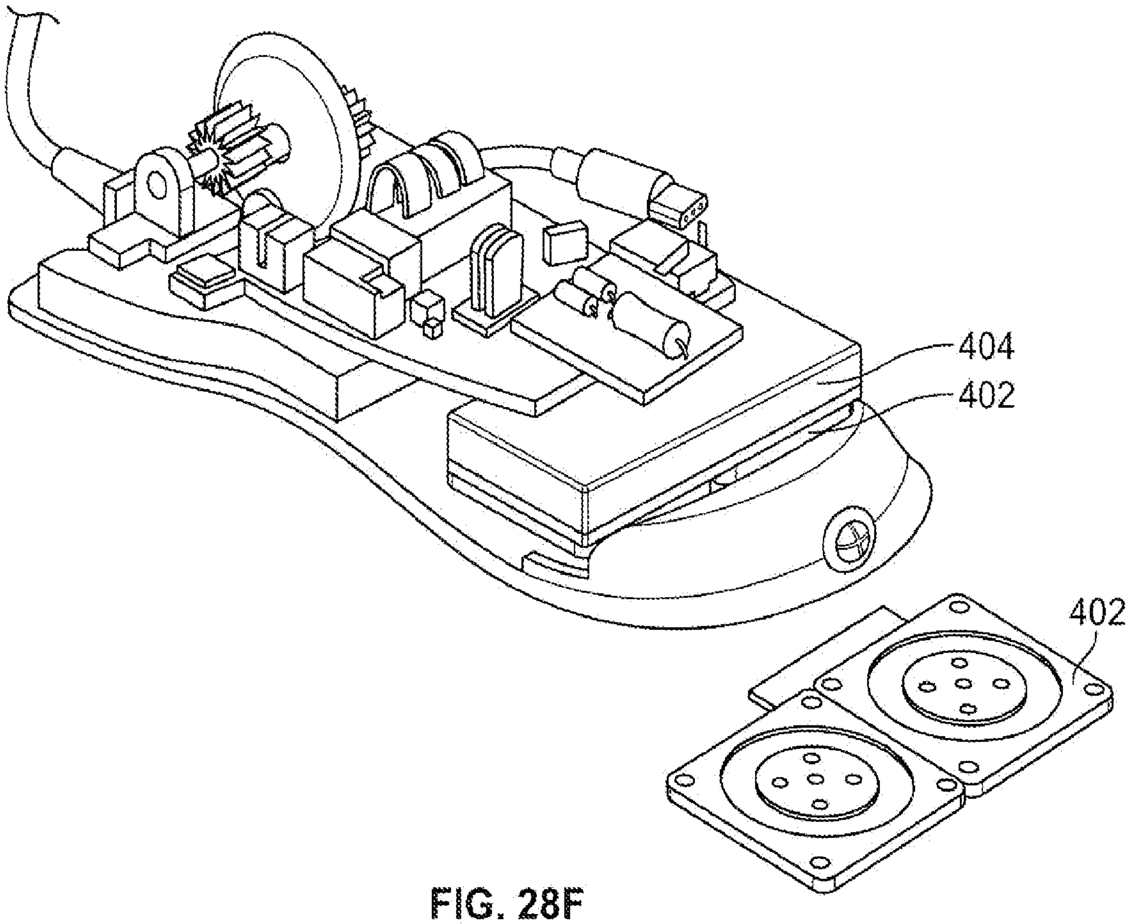


FIG. 28F

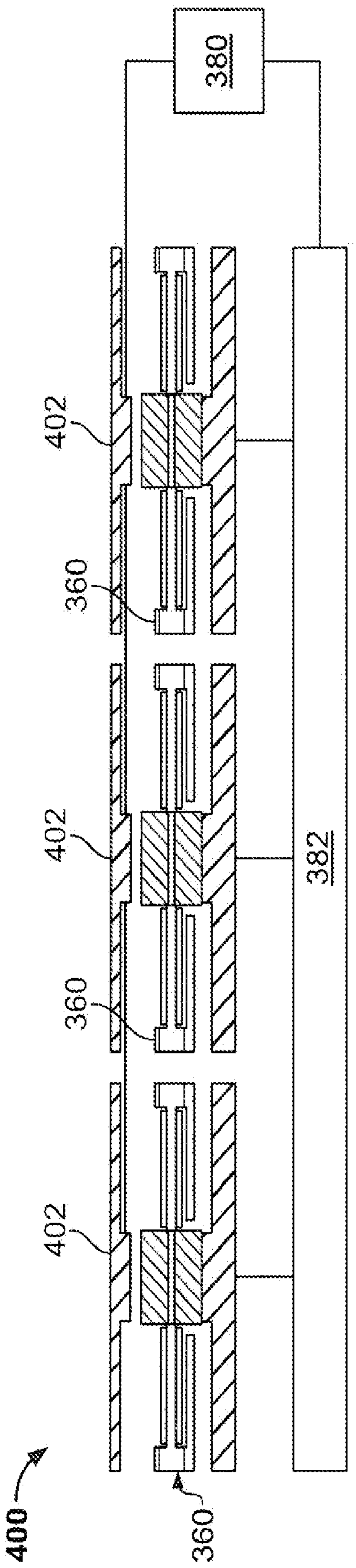


FIG. 29A

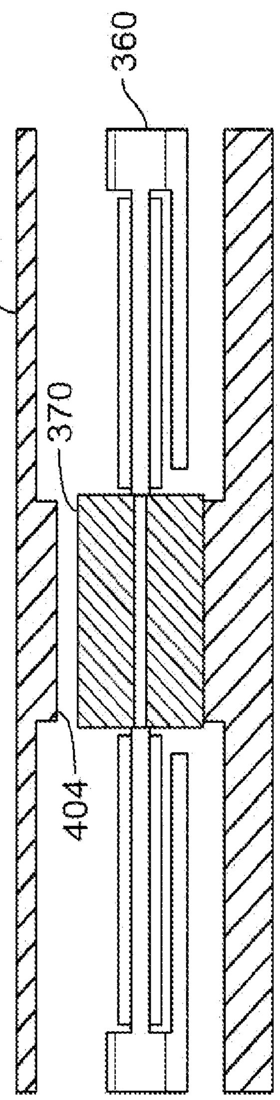


FIG. 29B

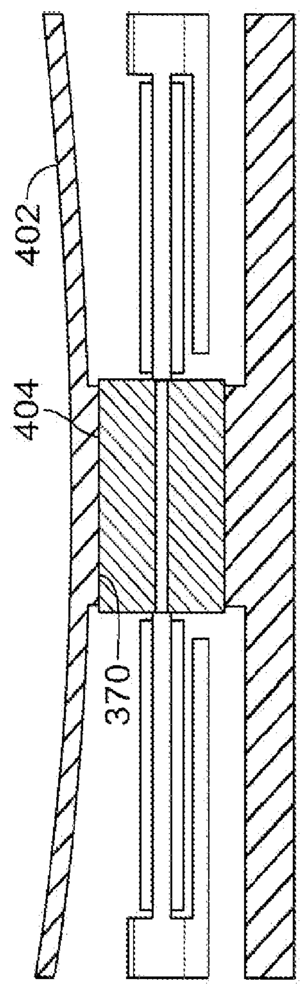


FIG. 29C

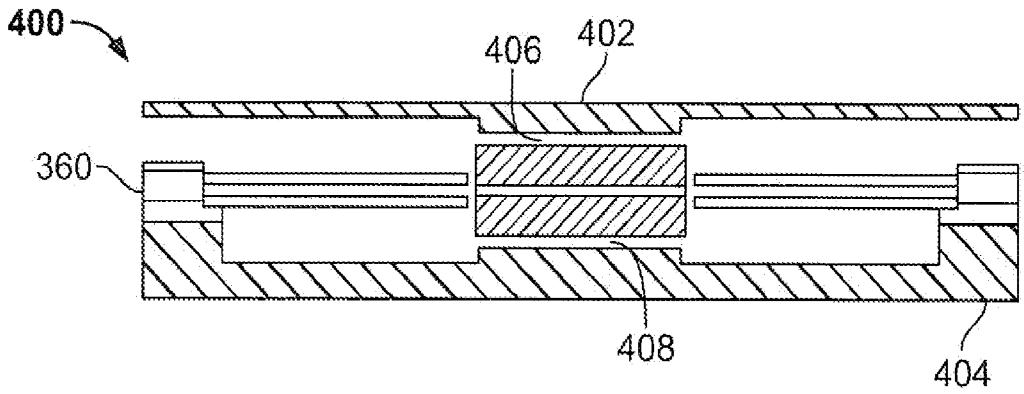


FIG. 30A

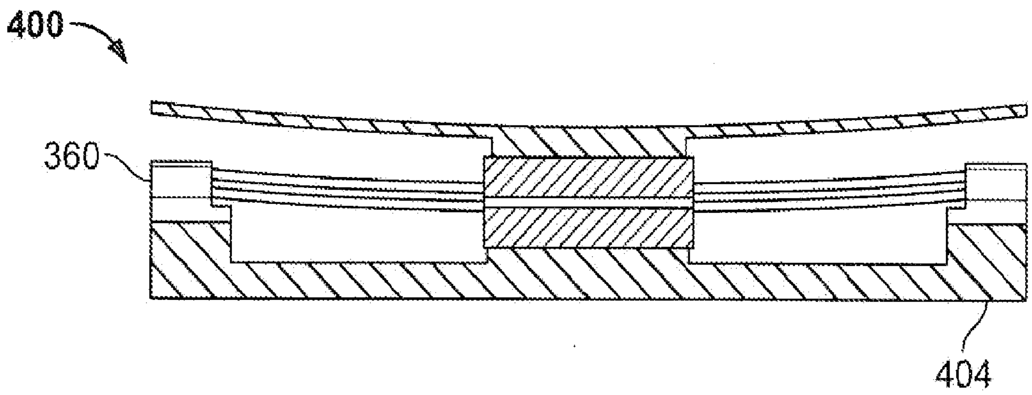


FIG. 30B

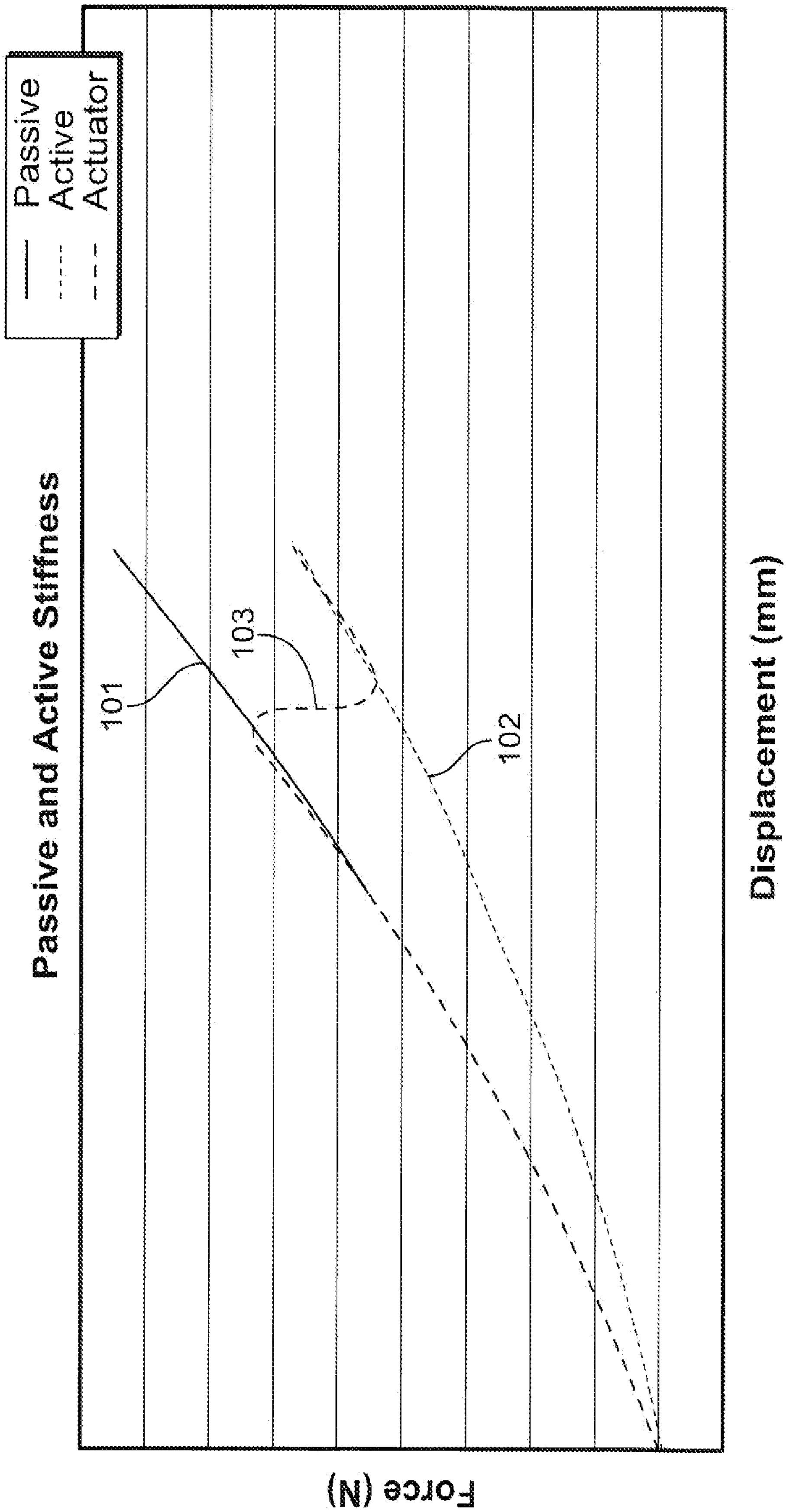

Passive and Active Stiffness
Passive
Active
Actuator
101
102
103
Displacement (mm)
Force (N)

FIG. 31A

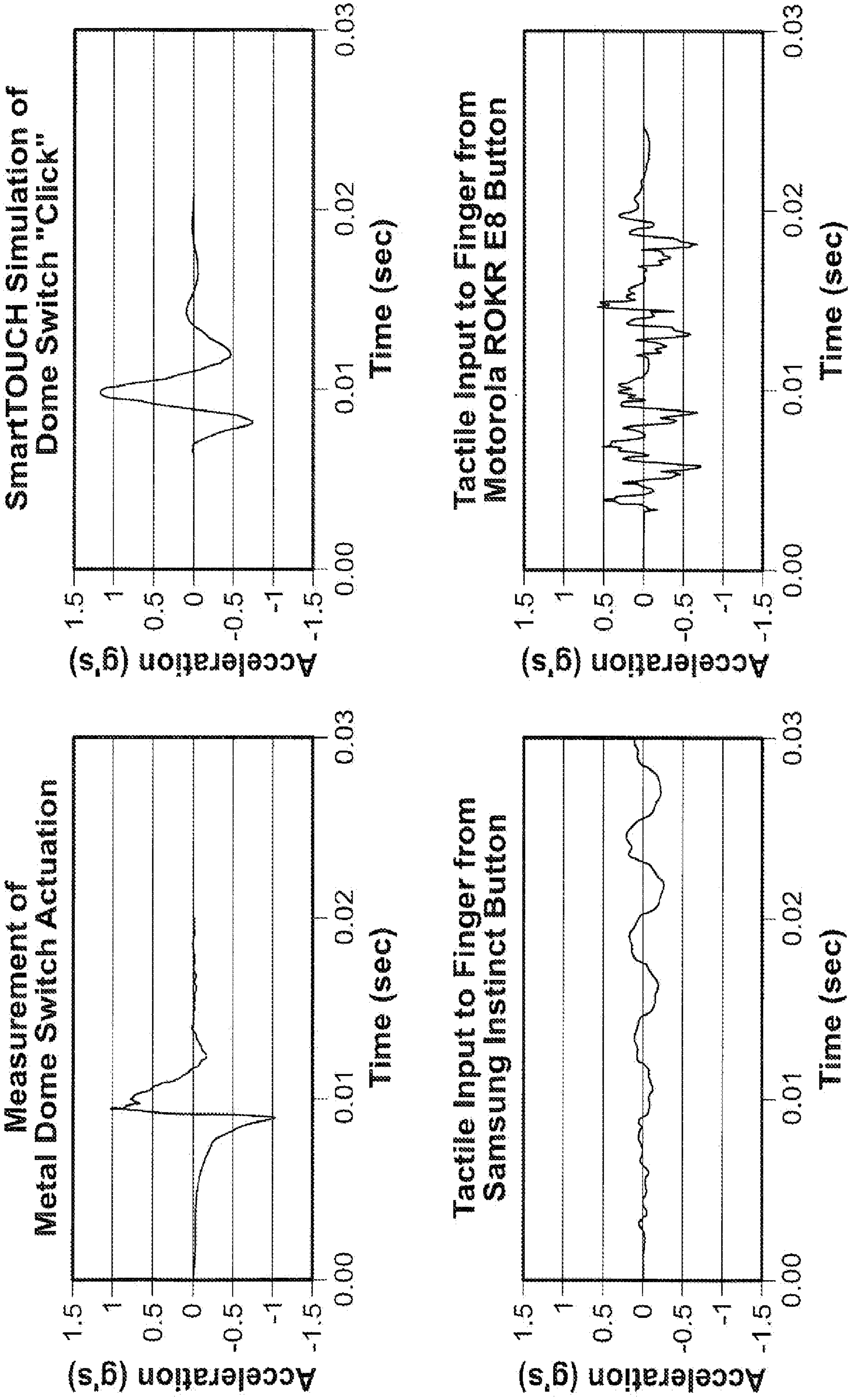

Measurement of
Metal Dome Switch Actuation
SmartTOUCH Simulation of
Dome Switch "Click"
Tactile Input to Finger from
Samsung Instinct Button
Tactile Input to Finger from
Motorola ROKR E8 Button
Acceleration (g's)
1.5
1
0.5
0
-0.5
-1
-1.5
Time (sec)
0.00
0.01
0.02
0.03

FIG. 31B

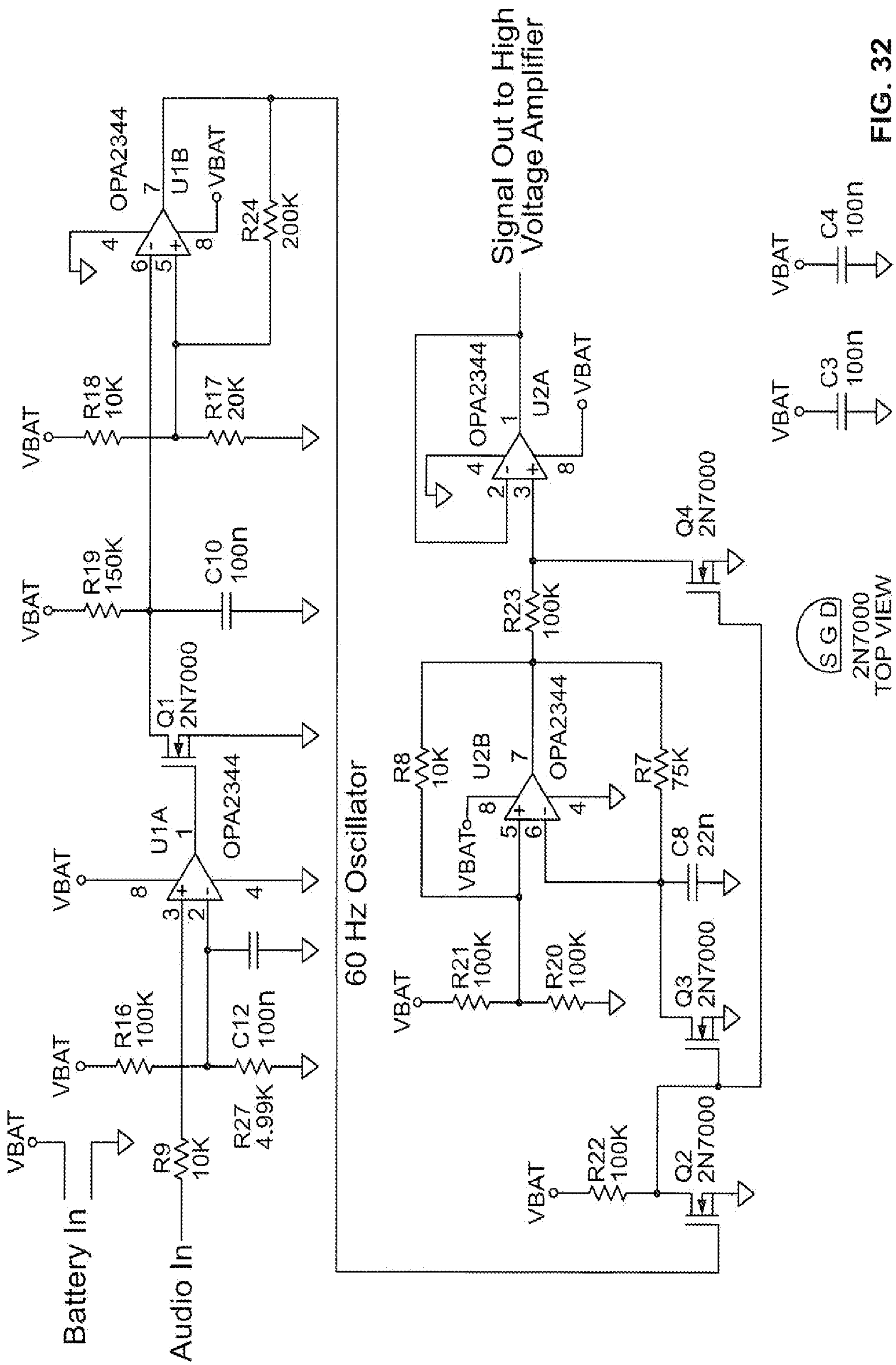

Battery In
Audio In
VBAT
R9 10K
R16 100K
R27 4.99K
C12 100n
U1A
OPA2344
60 Hz Oscillator
Q1 2N7000
R19 150K
C10 100n
R18 10K
R17 20K
OPA2344
U1B
R24 200K
Signal Out to High Voltage Amplifier
R22 100K
Q2 2N7000
Q3 2N7000
R21 100K
R20 100K
C8 22n
R8 10K
U2B
OPA2344
R7 75K
R23 100K
Q4 2N7000
OPA2344
U2A
C3 100n
C4 100n
S G D
2N7000 TOP VIEW

FIG. 32

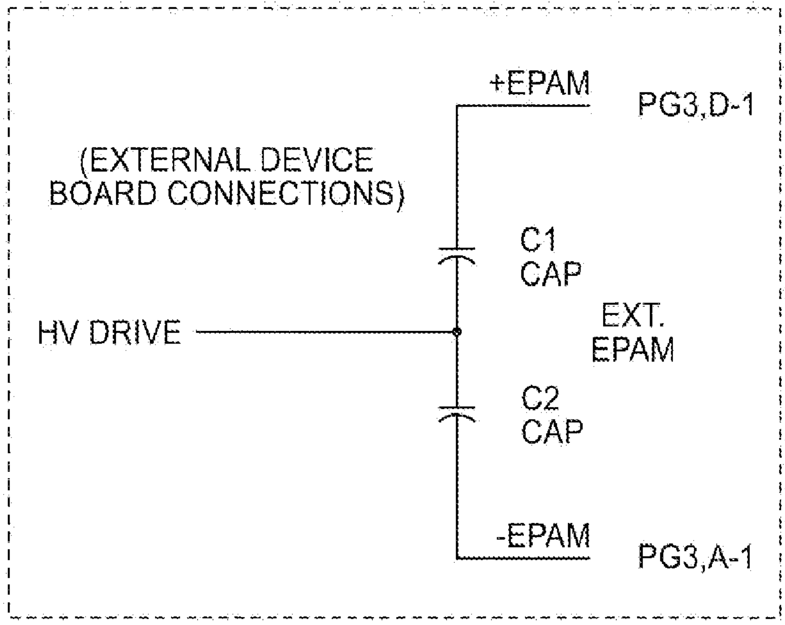


FIG. 33A

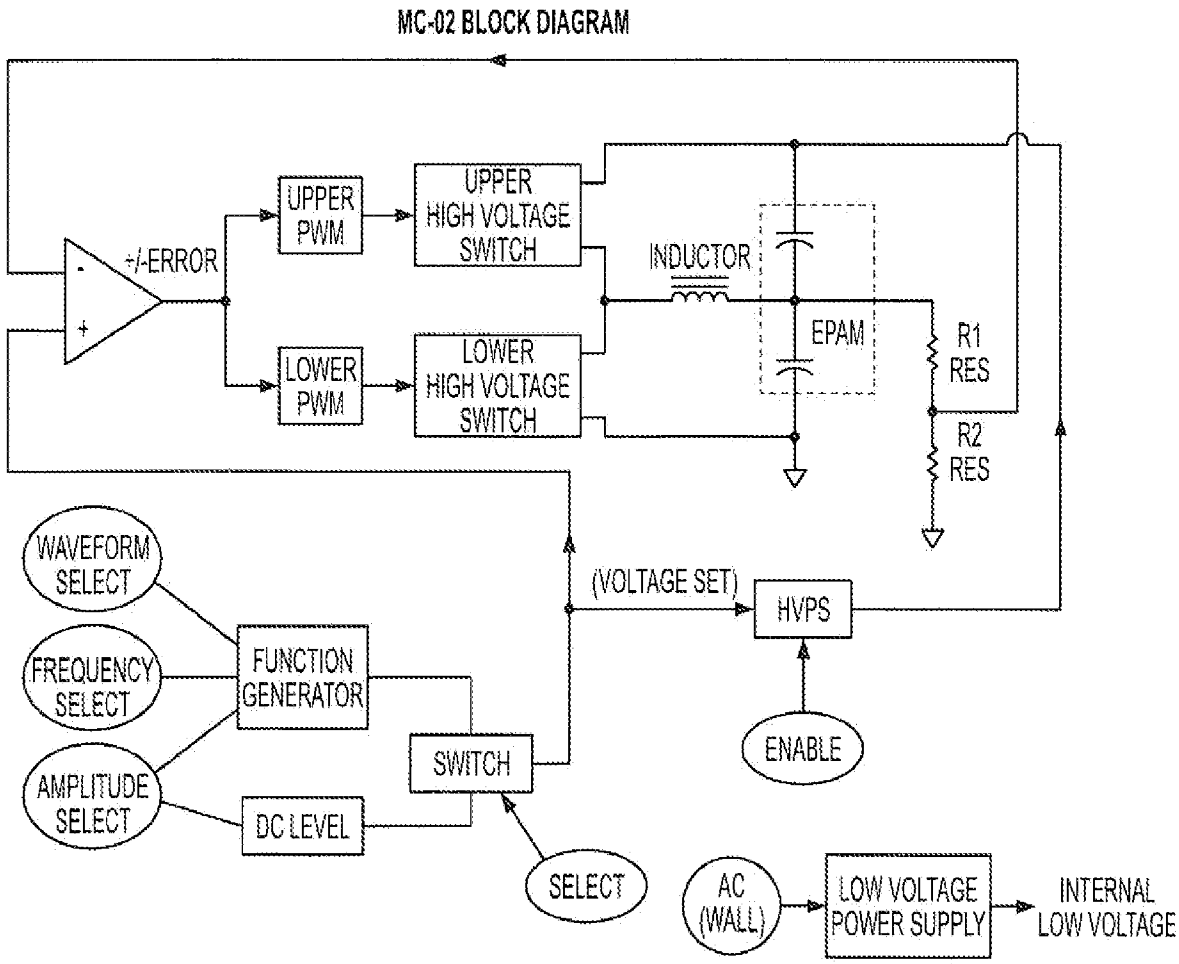


FIG. 33B

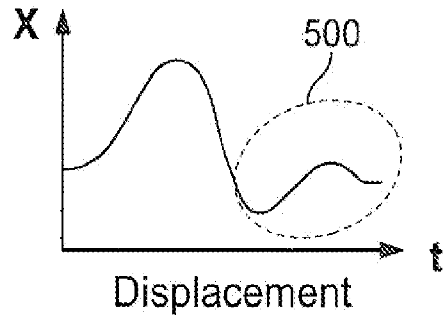


FIG. 34A

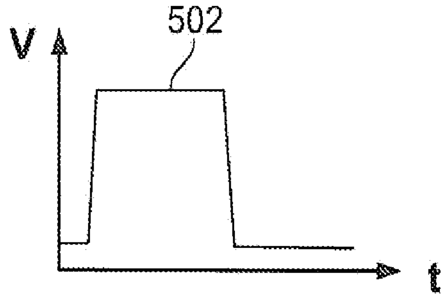


FIG. 34B

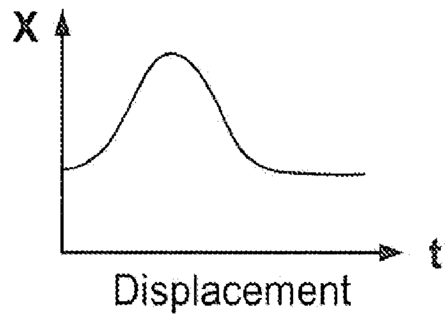


FIG. 34C

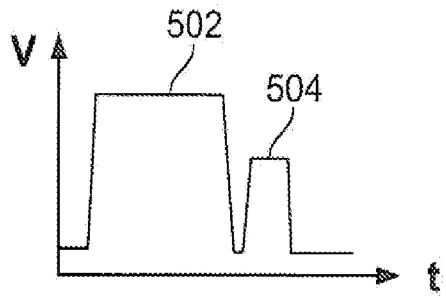


FIG. 34D

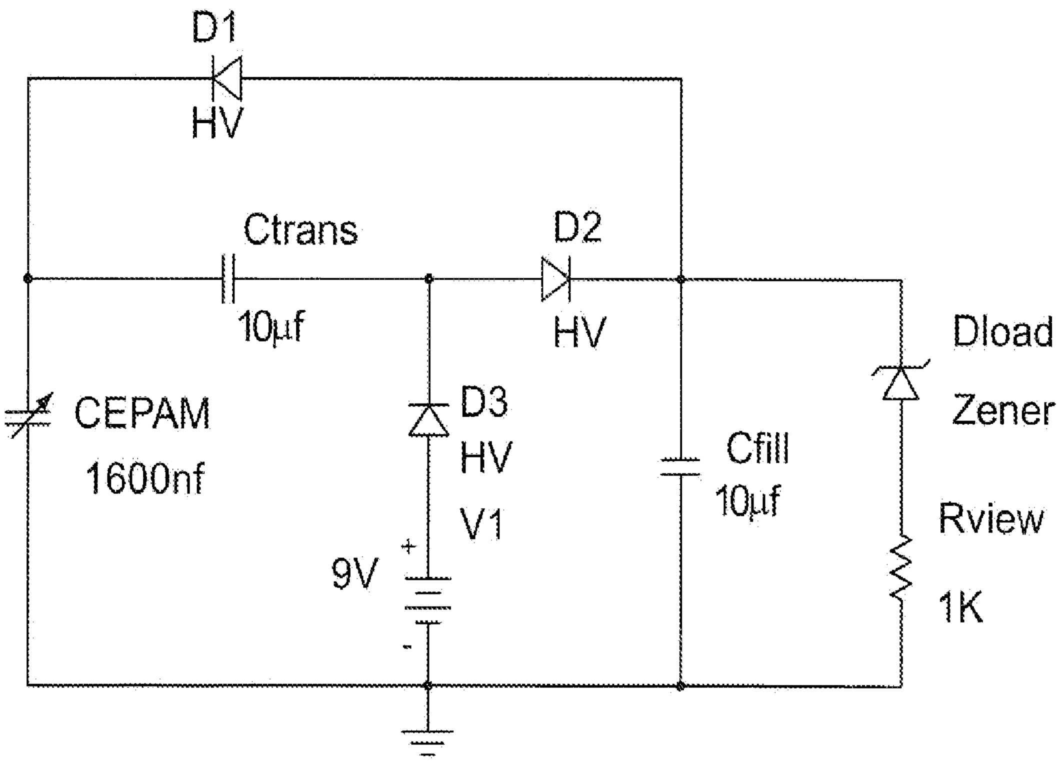


FIG. 35

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 10/21676

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - G06F 3/041 (2010.01)
USPC - 310/331; 345/173
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)
USPC: 310/331; 345/173

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
USPC: 310/329-331; 345/650, 156, 168, 173 (keyword limited - see search terms below)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST (PGPB, USPT, USOC, EPAB, JPAB); GOOGLE; Google Scholar
Terms: haptic, tactile, feedback, effect, electroactive, transducer, user, interface, eap, power, supply, high, voltage, actuator, bi-stable, delay, phase, waveform, planar, perpendicular.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2007/0146317 A1 (Schena) 28 June 2007 (28.06.2007), entire document, especially abstract, para [0003], [0071], [0076], [0079], [0087], [0093], [0097], [0109], [0112], [0115], [0121], [0128].	1-24
Y	US 2008/0116764 A1 (Heim) 22 May 2008 (22.05.2008), entire document, especially abstract, para [0003], [0004], [0009], [0011], [0046], [0047], [0093], [0100], [0103], [0105], [0110], [0122], [0123], [0133], [0135], [0139], [0150], [0153].	1-24

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

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Date of the actual completion of the international search	Date of mailing of the international search report
28 February 2010 (28.02.2010)	12 MAR 2010

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