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(54) **PIEZOELECTRIC COMPOSITE APPARATUS AND A METHOD FOR FABRICATING THE SAME**

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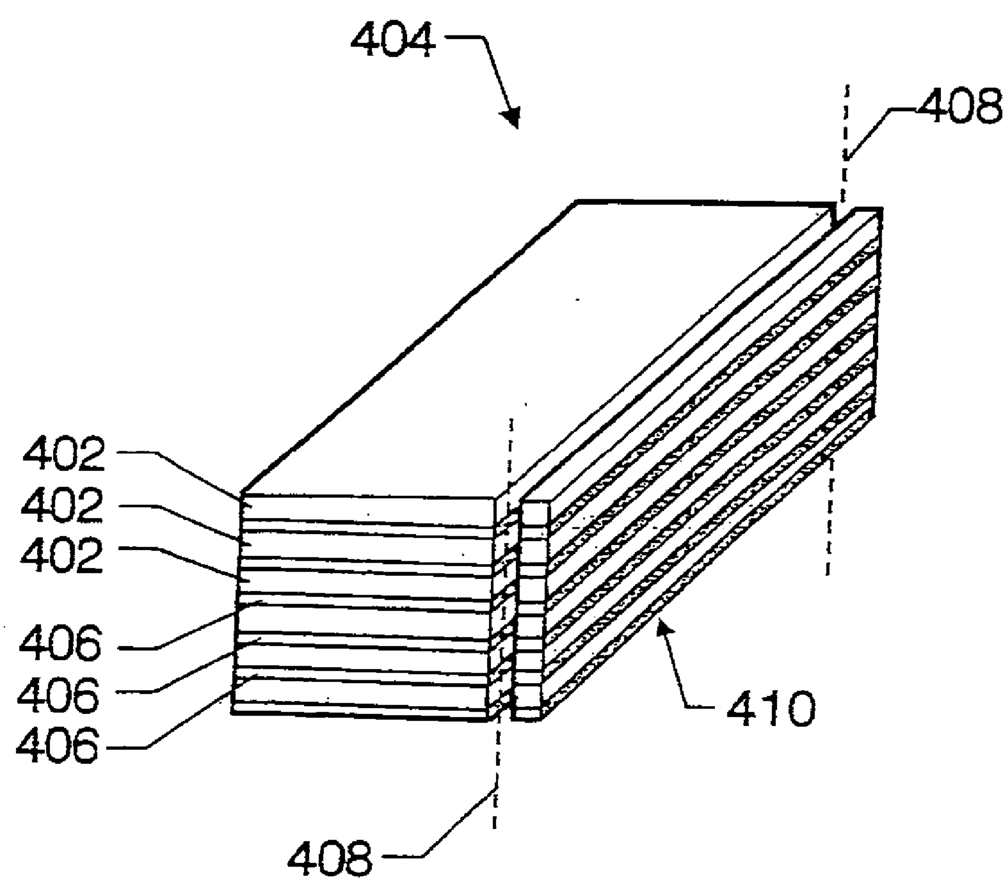
(57) **ABSTRACT**

A method for fabricating a piezoelectric fiber sheet comprises providing a plurality of wafers of piezoelectric material, bonding the wafers together with an adhesive material to form a stack of alternating layers of piezoelectric material and adhesive material, and cutting through the stack in a direction substantially parallel to the thickness of the stack and across the alternating layers of piezoelectric material and adhesive material to provide at least one piezoelectric fiber sheet having two sides comprising a plurality of piezoelectric fibers in juxtaposition to the adhesive material.



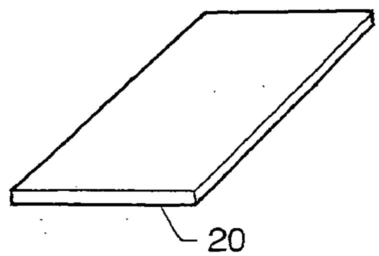


FIG. 1

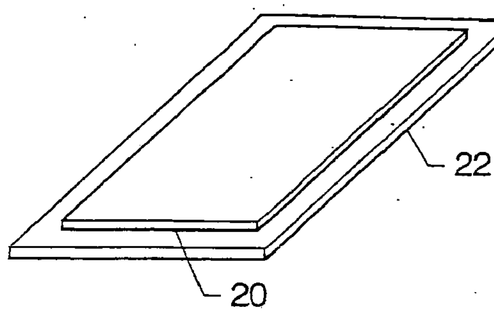


FIG. 2

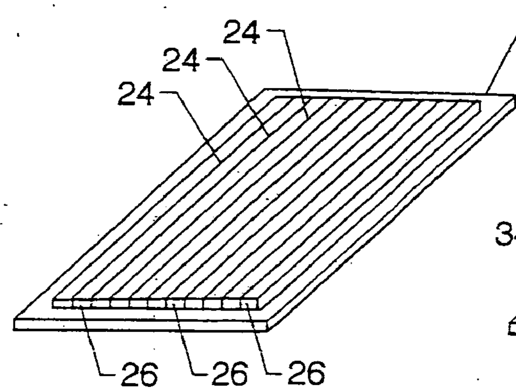


FIG. 3

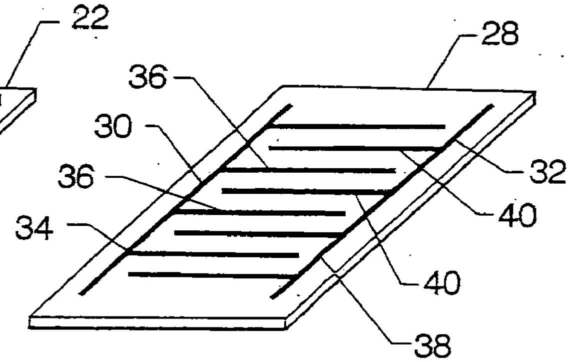


FIG. 4

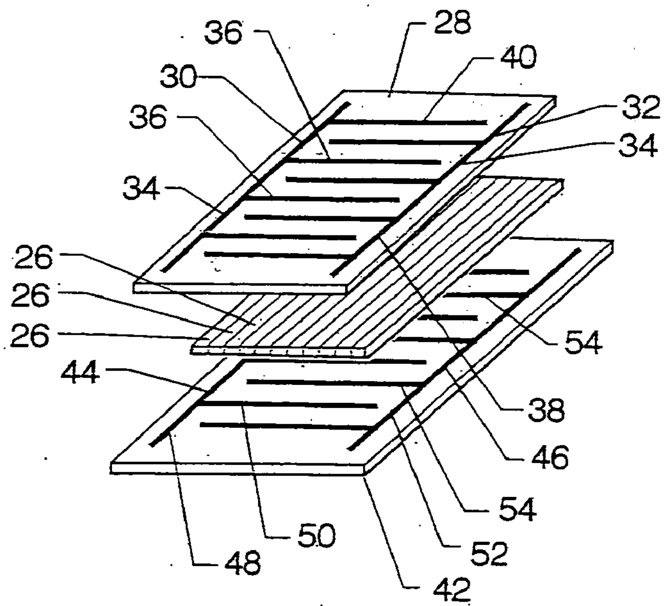
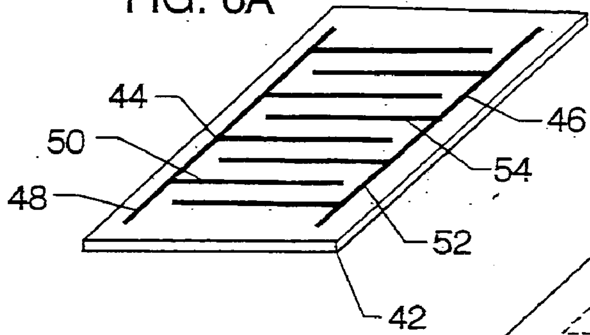


FIG. 5

FIG. 6A



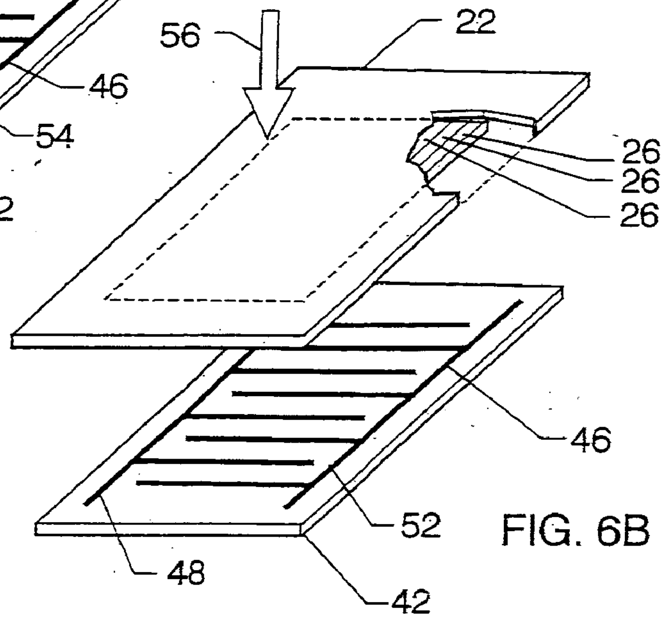
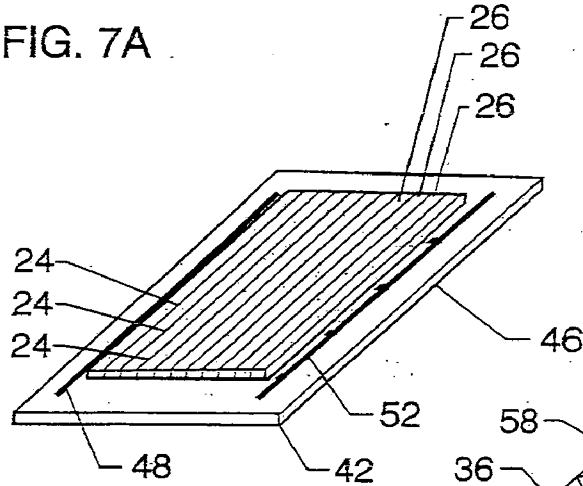


FIG. 6B

FIG. 7A



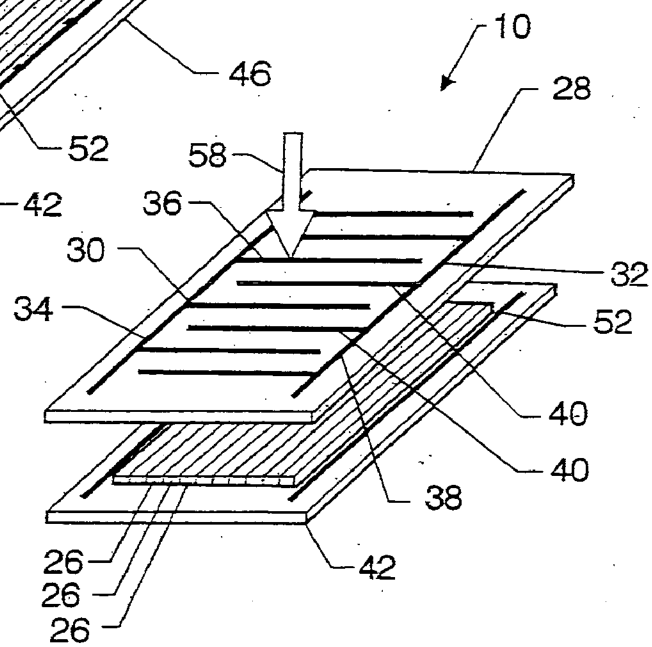


FIG. 7B

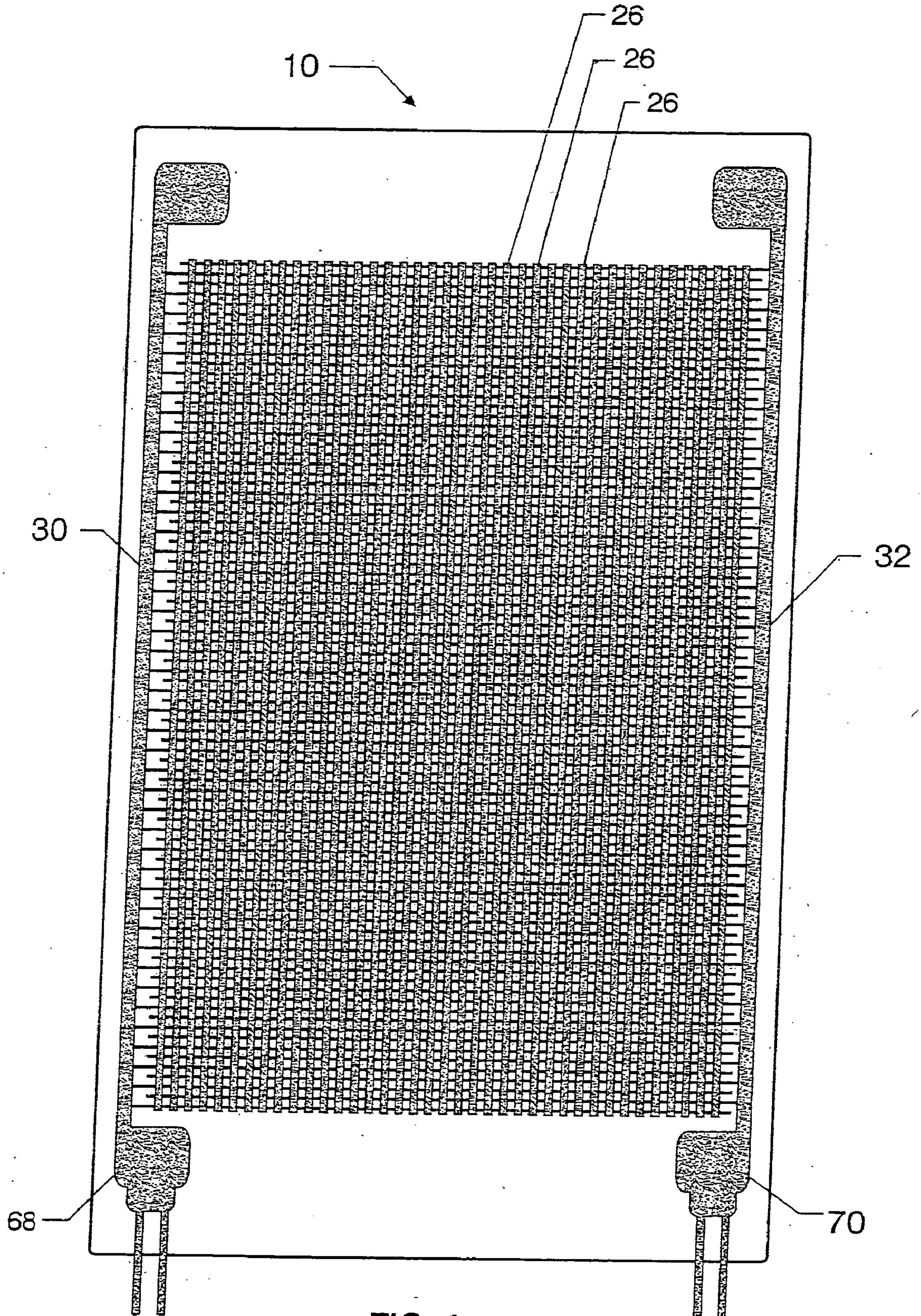
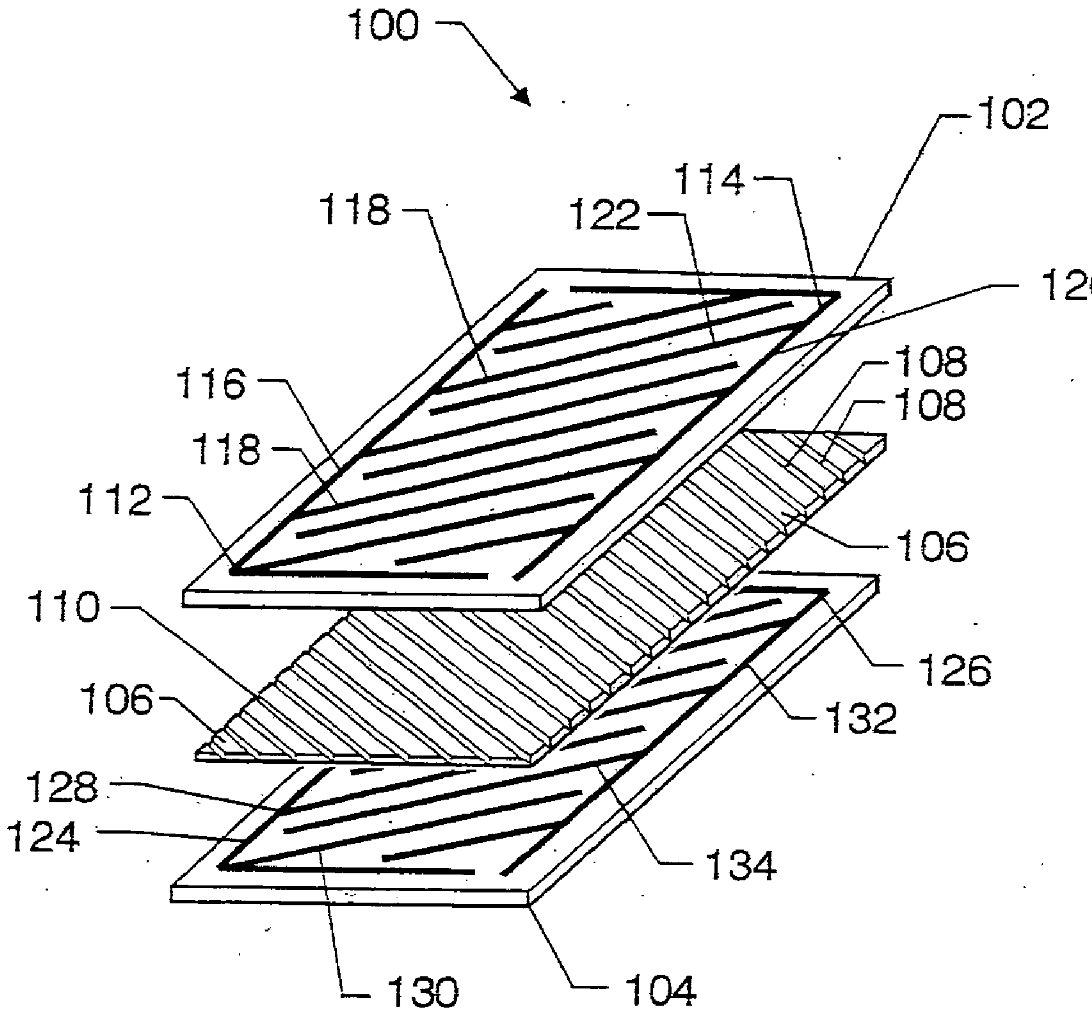


FIG. 8


100
102
114
118
122
120
116
108
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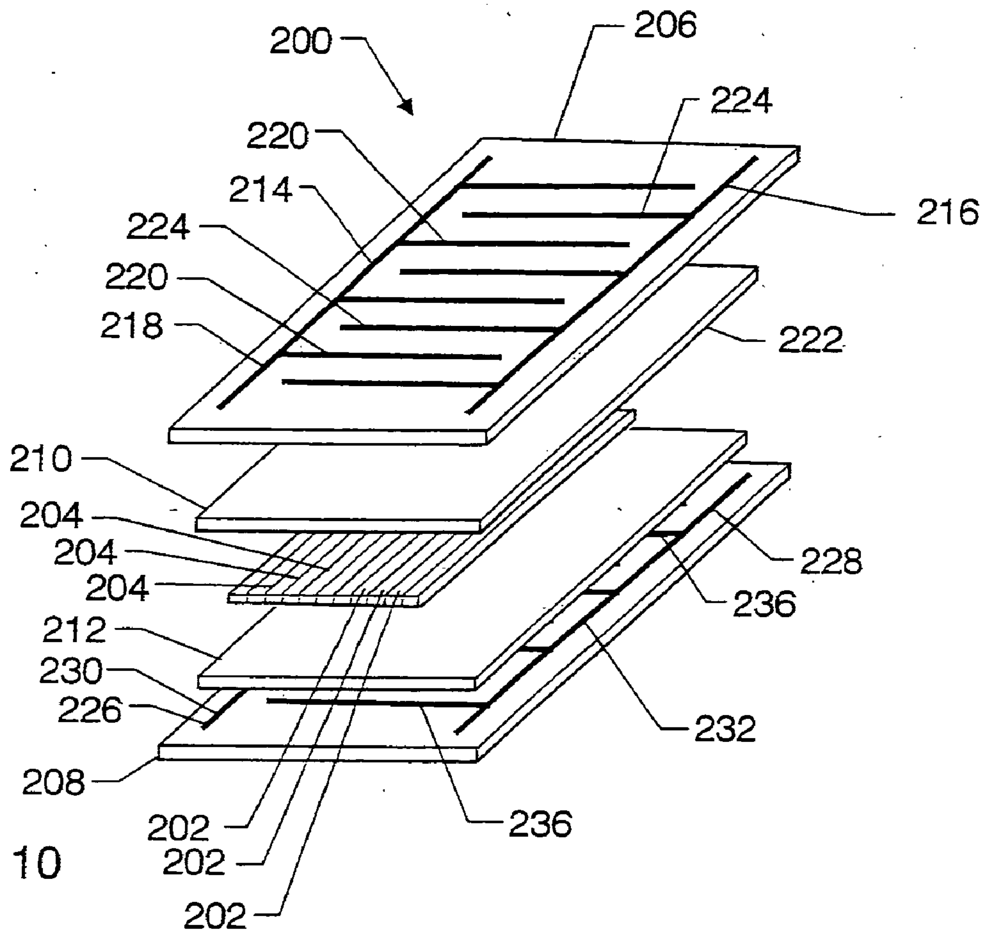
118
112
106
110
126
106
132
128
124
134
130
104

FIG. 9


200
206
224
220
216
214
224
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222
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210
204
204
228
204
236
212
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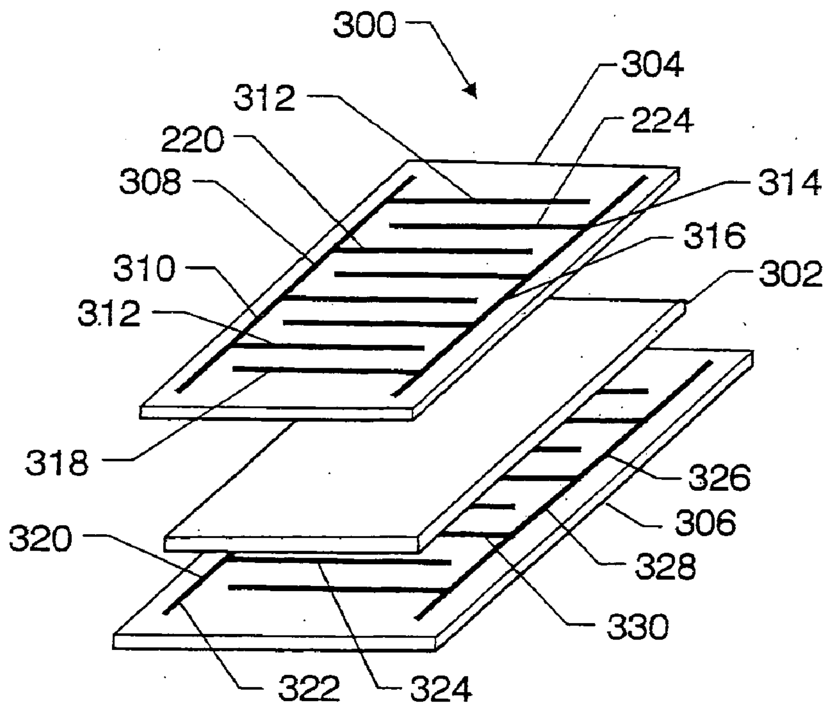
226
232
208
236
202
202
202

FIG. 10


300
304
312
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302
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312
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324

FIG. 11

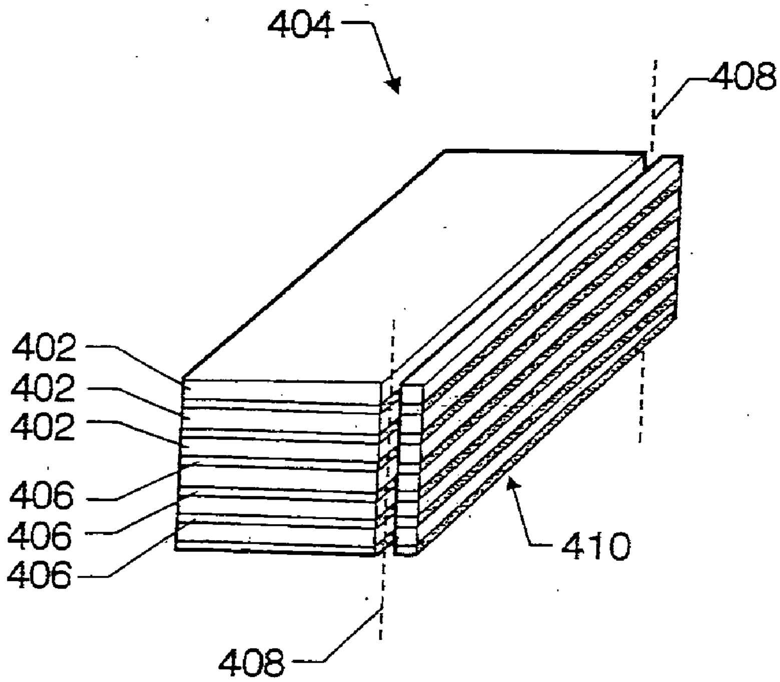

FIG. 12A

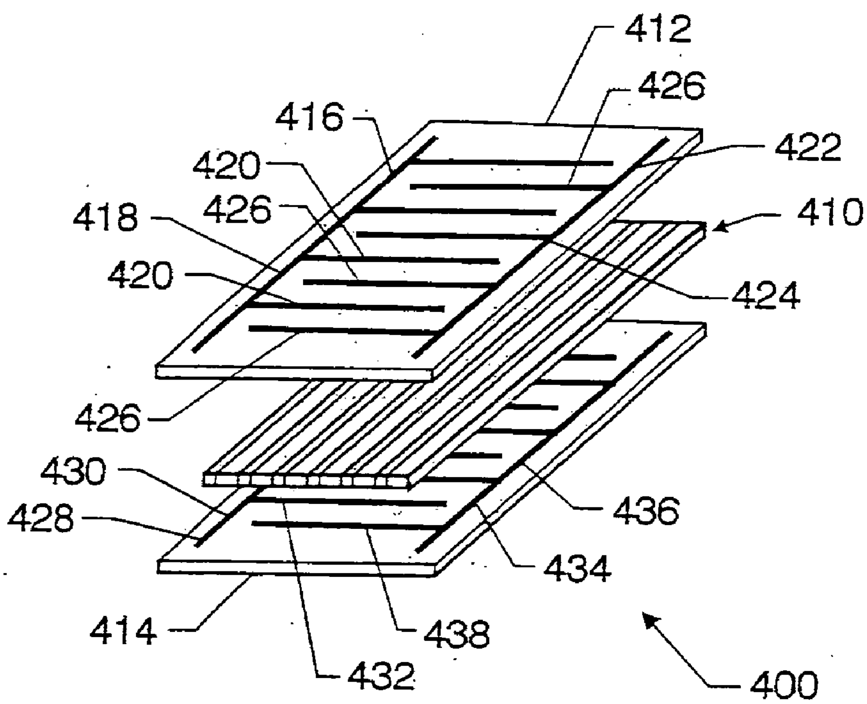

FIG. 12B

PIEZOELECTRIC COMPOSITE APPARATUS AND A METHOD FOR FABRICATING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a divisional of pending U.S. patent application Ser. No. 10/653824, filed Sep. 3, 2003.

ORIGIN OF THE INVENTION

[0002] The invention described herein was made by employees of the United States Government and may be used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

[0003] 1. Field of the Invention

[0004] The present invention is generally related to piezoelectric fiber composite strain actuators.

[0005] 2. Description of the Related Art

[0006] Conventional piezoelectric fiber composite actuators are typically manufactured using a layer of extruded piezoelectric fibers encased in protective polymer matrix material. Interdigitated electrodes etched or deposited onto polymer film layers are placed on the top and bottom of the fibers to form a relatively thin actuator laminate. Protecting the fibers in a matrix polymer strengthens and protects the piezoelectric material. The resulting package is more flexible and conformable than actuators formed from monolithic piezoelectric wafers. These actuators can be easily embedded within or placed upon non-planar structures using conventional manufacturing techniques. In addition, the use of interdigitated electrode poling permits production of relatively large, directional in-plane actuation strains. The directional nature of this actuation is particularly useful for inducing shear (twisting) deformations in structures.

[0007] Unfortunately, the methods of manufacturing conventional piezoelectric fiber composites typically use relatively high cost, extruded, round piezoelectric fibers. Moreover, alternative methods of manufacture using square fibers, which are milled from lower cost monolithic piezoelectric wafers, have been unsuccessful due to the difficulty of aligning individual square fibers during actuator assembly without shifting and rolling. Rolled square fibers tend to expose sharp corners and edges which can sever the interdigitated electrode layers during the final process of actuator assembly. Both the round and square fiber approaches require individual handling of piezoelectric fibers during assembly, thereby resulting in relatively high manufacturing costs.

[0008] Another disadvantage of conventional piezoelectric fiber composite actuators is the requirement of relatively high operating voltages. High operating voltages are needed to produce electric fields which are sufficiently strong to propagate through the protective polymer material encasing the piezoelectric fibers. These electrode voltages are several times higher than those theoretically required to produce a given strain in the unprotected piezoelectric material. Additionally, round fibers have a low contact area with the electrode, thereby causing losses and decreased efficiency. To compensate for these losses, increased voltages are required. Conventional techniques for applying electrodes directly in contact with the piezoelectric fibers have thus far not been practical.

[0009] It is therefore an object of the present invention to provide an improved piezoelectric fiber composite strain actuator and a method for making same.

[0010] Still other objects and advantages of the present invention will in part be obvious and will in part be apparent from the specification.

SUMMARY OF THE INVENTION

[0011] The above and other objects and advantages, which will be apparent to one of skill in the art, are achieved in the present invention which is directed to, in one aspect, a method for fabricating a piezoelectric macro-fiber composite actuator. The first step comprises providing a structure comprising piezo-electric material which has a first side and a second side. First and second films are then adhesively bonded to the first and second sides, respectively, of the piezo-electric material. The first film has first and second conductive patterns formed thereon which are electrically isolated from one another and in electrical contact with the piezo-electric material. In one embodiment, the second film does not have any conductive patterns. The first and second conductive patterns of the first film each have a plurality of electrodes that cooperate to form a pattern of interdigitated electrodes. In another embodiment, the second film has a pair of conductive patterns similar to the conductive patterns of the first film.

[0012] In a related aspect, the present invention is directed to a piezoelectric macro-fiber composite actuator, comprising:

[0013] a structure consisting of piezo-electric material having a first side and a second side;

[0014] a first film bonded to the first side of the structure, the film further including first and second conductive patterns formed thereon, the first conductive pattern being electrically isolated from the second conductive pattern, both conductive patterns being in electrical contact with the piezo-electric material structure, the first and second conductive patterns each having a plurality of electrodes that cooperate to form a pattern of interdigitated electrodes; and

[0015] a second film bonded to the second side of the structure.

[0016] In a further aspect, the present invention is directed to a piezoelectric macro-fiber composite actuator, comprising:

[0017] a plurality of piezoelectric fibers in juxtaposition, each fiber having a first side and a second side, each pair of adjacent fibers being separated by a channel;

[0018] a first adhesive layer disposed over the first sides of the fibers and in the channel;

[0019] a first film bonded to the first sides of the fibers, the film further including first and second conductive patterns formed thereon, the first conductive pattern being electrically isolated from the second conductive pattern, both conductive patterns being in electrical contact with the piezo-electric material structure, the first and second conductive patterns each having a plurality of electrodes that cooperate to form a pattern of interdigitated electrodes;

[0020] a second adhesive layer disposed over the second sides of the fibers and into the channels; and

[0021] a second film bonded to the second sides of the fibers, the second film having a first conductive pattern and a second conductive pattern electrically isolated from the first conductive pattern of the second film, the first and second conductive patterns of the second film being in electrical contact with the fibers, the first and second conductive patterns of the second film each having a plurality of electrodes that cooperate to form a pattern of interdigitated electrodes.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022] The features of the invention are believed to be novel and the elements characteristic of the invention are set forth with particularity in the appended claims. The figures are for illustration purposes only and are not drawn to scale. The invention itself, however, both as to organization and method of operation, may best be understood by reference to the detailed description which follows taken in conjunction with the accompanying drawings in which:

[0023] **FIG. 1** is a perspective view of a typical piezoelectric wafer.

[0024] **FIGS. 2-7B** are perspective views illustrating preferred method steps of the present invention for making a piezoelectric macro-fiber composite actuator.

[0025] **FIG. 8** is a top plan view of the assembled piezoelectric macro-fiber composite actuator having electrically conductive extensions attached thereto.

[0026] **FIG. 9** is an exploded, perspective view illustrating an actuator fabricated in accordance with an alternate embodiment of the method of the present invention.

[0027] **FIG. 10** is an exploded, perspective view illustrating an actuator fabricated in accordance with a further embodiment of the method of the present invention.

[0028] **FIG. 11** is an exploded, perspective view illustrating an actuator fabricated in accordance with yet another embodiment of the method of the present invention.

[0029] **FIGS. 12A and 12B** are perspective views illustrating an actuator fabricated in accordance with yet a further embodiment of the method of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0030] In describing the preferred embodiments of the present invention, reference will be made herein to **FIGS. 1-12B** of the drawings in which like numerals refer to like features of the invention.

(1) Preferred Embodiment

[0031] Referring to **FIG. 1**, the first step of the method of the present invention entails providing a ferro-electric wafer **20**. For example, wafer **20** is fabricated from unelectroded, piezoelectric material. In one embodiment, PZT-5 piezoelectric ceramic material is used to fabricate the wafer **20**. However, it is to be understood that any piezo-electric material may be used to fabricate wafer **20**. In a preferred embodiment, piezoelectric wafer **20** has a thickness between about 0.002 and 0.010 inches.

[0032] Referring to **FIG. 2**, the next step entails disposing piezoelectric wafer **20** on a relatively thin polymer backing sheet **22**. In a preferred embodiment, the polymer backing sheet is moderately adhesive so as to facilitate handling during the subsequent steps of the fabrication method of the present invention.

[0033] Referring to **FIG. 3**, the next step comprises forming a plurality of slots or channels **24** on piezoelectric wafer **20**. While the slots **24** extend through substantially the entire thickness of wafer **20**, they do not completely slice the underlying polymer backing sheet **22**. This step results in the creation of a sheet of side-by-side piezoelectric macro-fibers **26** attached to the polymer backing layer **22**. In a preferred embodiment, slots **24** are formed by a machining process that uses a commercially available computer-controlled dicing saw. However, other cutting methods may be used, e.g. lasers. In a preferred embodiment, each slot **24** has substantially the same width, which is between about 0.001 and 0.005 inches. However, each slot **24** can have a width less than 0.001 inch or greater than 0.005 inch. In a preferred embodiment, each macro-fiber **26** has a width between about one (1) and (2) two times the thickness of piezoelectric wafer **20**. However, each macro-fiber **26** can have a width that is less than the thickness of piezoelectric wafer **20** or greater than twice the thickness of piezoelectric wafer **20**.

[0034] Referring to **FIG. 4**, the next step is to fabricate electrically a pair of non-conducting film elements that will be bonded to macro-fibers **26**. One such film element is film **28**. Film **28** can be fabricated from any type of electrically non-conducting material. In one embodiment, the electrically non-conducting material is fabricated from a polyimide. One suitable material is Kapton® manufactured and marketed by Dupont®. In a preferred embodiment, film **28** has a thickness between about 0.0005 and 0.001 inches. Preferably, film **28** has width and length dimensions which are larger than the width and length of piezoelectric wafer **20**. The reasons for this configuration will be discussed below.

[0035] Referring to **FIG. 4**, film **28** comprises two electrically conductive patterns **30** and **32**. Conductive pattern **30** comprises a longitudinally extending portion **34** and interdigiiated electrode fingers **36**. Conductive pattern **32** comprises a longitudinally extending portion **38** and interdigitated electrode fingers **40**. In one embodiment, conductive patterns or electrodes **30** and **32** are formed on film **28** using a photo-resist-and-etch process and pre-bonded polyimide-copper sheet laminate (e.g. Dupont® Pyralux® copper clad laminates). In a preferred embodiment, the thickness of the copper sheet material is between about 0.0005 and 0.001 inches. For example, a copper sheet having a thickness of about 0.0007 inch has provided good results. Although the foregoing description is in terms of conductive patterns **30** and **32** being fabricated from copper-sheet material, other types of sheet materials, e.g. gold, silver, etc, may also be used. The polyimide-conductive material laminate may also utilize an electro-deposited conductive layer instead of a pre-bonded conductive sheet, such as rolled and annealed copper.

[0036] Referring to **FIG. 4**, in a preferred embodiment, the center-to-center spacing of longitudinally extending portions **34** and **38** is about six times the thickness of piezoelectric wafer **20**, and the spacing between interdigitated electrodes or "fingers"**36** and **40** is about equal to the thickness of piezoelectric wafer **20**. The center-to-center spacing of longitudinally extending portions **34** and **38** and interdigitated electrodes or fingers **36** and **40**, however, can be other than described above. Furthermore, the width of conductive patterns **30** and **32** may have any suitable width.

[0037] Referring to **FIGS. 2-4**, film **28** has width and length dimensions that are larger than the width and length of piezoelectric wafer **20** so as to permit the placement of longitudinally extending portions **34** and **38** of conductive patterns **30** and **32**, respectively, away from piezoelectric wafer **20**. This configuration significantly lessens the potential for cracking of macro-fibers **26** caused by highly non-uniform electrical field distribution in regions beneath and adjacent to the longitudinally extending portions **34** and **38**. Additionally, this packaging concept affords a sealed electrical system protected from the environment.

[0038] Referring to **FIGS. 4 and 5**, a second film **42** is fabricated in accordance with the steps described above. In one embodiment, film **42** comprises conductive patterns or electrodes **44** and **46**. Conductive pattern **44** comprises longitudinally extending portion **48** and interdigitated electrodes or fingers **50**. Similarly, conductive pattern **46** comprises longitudinally extending portion **52** and interdigitated electrodes or fingers **54**. Conductive patterns **44** and **46** of film **42** are "mirror images" of conductive patterns **30** and **32**, respectively, of film **28**. The next step comprises positioning films **28** and **42** as shown in **FIG. 5** such that film **28** confronts one side or face of macro-fibers **26** and film **42** confronts the other side of macro-fibers **26**. Conductive patterns **30** and **32** of film **28** are directly aligned with conductive patterns **44** and **46** of film **42**. Thus, conductive patterns **30** and **32** are in "mirror-image" alignment with conductive patterns **44** and **46** across the thickness of macro-fibers **26**. Although film **42** has been described in the foregoing description as having conductive patterns thereon, film **42** may be configured without any conductive patterns.

[0039] 0019]Referring to **FIGS. 6A, 6B,** 7A, and 7B, films **28** and **42** are bonded with an adhesive to macro-fibers **26** to form a flexible laminate. In a preferred embodiment, the adhesive is a two-part liquid epoxy to bond films **28** and **42** to macro-fibers **26**. An example of such a liquid epoxy is Scotchweld DP-460 epoxy manufactured by 3M Company. However, other types of bonding materials can be used, e.g. urethane, acrylic, etc. Referring to **FIG. 6A**, the first step in the bonding process is to coat the electrode face of film **42** with a relatively thin layer of liquid epoxy. Referring to **FIG. 6B**, sheet **22** and macro-fibers **26** are then placed on film **42** such that macro-fiber **26** contacts the epoxy-coated face of electrode film **42**. Light pressure, indicated by arrow **56**, and heat are applied in a vacuum to partially cure the epoxy layer to affix the macro-fibers to electrode film **42**. After the partial cure is complete, polymer backing sheet **22**, previously used for handling of macro-fibers **26**, is peeled away and discarded. Referring to **FIG. 7A**, macro-fibers **26** are now attached to the bottom electrode film **42** by the epoxy. An additional coat of liquid epoxy is now applied to macro-fibers **26** in order to fill all machined slots **24** between adjacent fibers **26**. Application of epoxy in this manner serves to substantially eliminate air pockets between adjacent, alternately charged electrode fingers **36**, **40**, **50** and **54** in the final assembly. The elimination of these air pockets substantially reduces the probability of electrical arcing or permanent shorts which would render the actuator inoperable.

[0040] Referring to **FIGS. 6B, 7A**, and 7B, after slots **24** are filled with the epoxy, the next step is to apply a relatively thin coat of epoxy to the electroded face of upper film **28**. Next, film **28** is placed epoxy side down onto the previously coated surface of macro-fibers **26** such that conductive electrode patterns **30**, **32** and **44**, **46** of films **28** and **42**, respectively, are substantially aligned. The next step entails applying moderate pressure, indicated by arrow **58**, and heat to the assembly of films **28**, **42** and macro-fibers **26**. The heat and pressure are applied in a vacuum until a substantially complete, void-free cure of the epoxy is attained. Application of this pressure also forces the relatively thick copper conductive patterns or electrodes **30**, **32** and **44**, **46** to contact and rest upon the flat surfaces of the macro-fibers **26**. Such contact between the relatively thick copper conductive patterns or electrodes **30**, **32** and **44**, **46** and the flat surfaces of macro-fibers **26** creates a bond line between the conductive patterns or electrodes **30**, **32** and **44**, **46** and fiber **26** that is extremely thin or "starved," resulting in only a minimal attenuation of the actuator's electric field produced when voltage is applied. The bond line between the unelectroded portions of films **28** and **42** (i.e. the portions of films **28** and **42** having no conductive pattern) and fibers **26** is sufficiently thick to keep films **28** and **42** attached. This process results in a longitudinal mode piezoelectric fiber actuator **10**.

[0041] As shown in **FIG. 8**, conductive patterns **30** and **32** are provided with electrically conductive extensions **68** and **70**, respectively. During operation, an external power supply (not shown) is electrically connected to the extensions **68** and **70** in a manner such that at any one moment in time, opposite electrical polarity is supplied to interdigitated fingers **36**, **40** and **50**, **54**. This polarity generates electric fields directed along the length of fibers **26** in the regions between adjacent interdigitated electrode fingers **36** and **40** and between fingers **50** and **54**.

[0042] The interdigitated electrodes **36**, **40** and **50**, **54** are also used for polarizing the piezoelectric fibers **26**. Polarization of the macro-fibers **26** is typically required before operating the device as an actuator. Polarization is performed by applying a steady voltage across alternate electrode fingers **36**, **40** and **50**, **54**. In one embodiment, a voltage which generates an average electric field intensity of approximately 300% of the room temperature coercive electric field of the macro-fibers **26** is used. Such voltage is applied to the actuator for approximately 20 minutes at room temperature. Other poling techniques, as are well understood in the art, may also be used.

[0043] Subsequent application of a voltage to conductive patterns **30**, **32**, **44**, and **46** produces an induced strain in macro-fibers **26**. The largest strain produced occurs along the fiber length direction, with a contractile strain occurring in the transverse direction.

(2) Alternate Embodiments

[0044] **FIG. 9** depicts an alternate piezoelectric fiber actuator **100** of the present invention. Shear-mode actuator

100 is configured to allow continuous twisting moments to be easily produced in a host structure, e.g. high aspect ratio structures, beams, spars, etc. Shear-mode actuator **100** generally comprises films **102**, **104** and piezoelectric fibers **106**. Films **102**, **104** and fibers **106** are adhesively bonded together using an epoxy as described above. Piezoelectric fibers **106** have separated slots **108** which are the result of a cutting or slicing process as has been previously described. Fibers **106** define a longitudinally extending edge **110**. Slots **108** are formed at an angle with respect to longitudinally extending edge **110**. Preferably, each slot **108** is formed at a 45° angle with respect to the longitudinal extending edge **110** because such an angular orientation provides optimum results in inducing piezoelectric shear stresses within a host structure. However, slots **108** may be formed at a different set of angles with respect to the longitudinally extending edge **110**.

[**0045**] Film **102** includes two conductive patterns **112** and **114** formed thereon. Conductive pattern **112** includes a longitudinally extending portion **116** and interdigitated electrodes or fingers **118**. Similarly, conductive pattern **114** includes a longitudinally extending portion **120** and interdigitated electrodes or fingers **122**. As shown in **FIG. 9**, fingers **118** are angulated with respect to longitudinally extending portion **116**. Similarly, fingers **122** are angulated with respect to longitudinally extending portion **120**. In a preferred embodiment, fingers **118** and **122** are formed at a 45° angle with respect to portions **116** and **120**, respectively, so that fingers **118** and **120** are substantially perpendicular to the fibers **106**.

[**0046**] In one embodiment, film **104** includes two conductive patterns **124** and **126** formed thereon. Conductive pattern **124** includes a longitudinally extending portion **128** and interdigitated electrodes or fingers **130**. Similarly, conductive pattern **126** includes a longitudinally extending portion **132** and interdigitated electrodes or fingers **134**. As shown in **FIG. 9**, fingers **130** are angulated with respect to longitudinally extending portion **128**. Similarly, fingers **134** are angulated with respect to longitudinally extending portion **132**. In a preferred embodiment, fingers **130** and **134** are formed at a **450** angle with respect to portions **128** and **132**, respectively, so that fingers **130** and **134** are substantially perpendicular to the fibers **106**. Although film **104** has been described in the foregoing description as having conductive patterns thereon, film **104** may also be configured without any conductive patterns. Films **102** and **104** are bonded with an adhesive to macro-fibers **106** in a process similar to the process previously described for assembly of piezoelectric fiber actuator **10** and shown by **FIGS. 6A, 6B**, 7A, and 7B.

[**0047**] Actuator **100** further includes four electrical conductors (not shown) wherein each electrical conductor is electrically connected to a corresponding one of conductive patterns **112**, **114**, **124**, and **126**. In a preferred embodiment, each of the electrical conductors are positioned near the edge of films **102**, **104** and function to electrically connect actuator **100** to external electronic circuitry (not shown). The four electrical conductors apply electrical power to actuator **100** in the same manner as described above.

[**0048**] **FIG. 10** illustrates a further embodiment of the actuator of the present invention. Actuator **200** generally comprises a plurality of piezoelectric macro-fibers **202** separated by slots **204**, and films **206**, **208**, **210**, and **212**. Slots **204** are formed by the slicing or cutting methods previously described herein. Films **206** and **208** are generally the same in construction as films **28** and **42**, respectively, discussed above.

[**0049**] Film **206** includes two conductive patterns **214** and **216** formed thereon. Conductive pattern **214** includes a longitudinally extending portion **218** and interdigitated electrodes or fingers **220**. Similarly, conductive pattern **216** includes a longitudinally extending portion **222** and interdigitated electrodes or fingers **224**. As shown in **FIG. 10**, fingers **220** and **224** are substantially perpendicular to longitudinally extending portions **218** and **222**, respectively.

[**0050**] In one embodiment, film **208** comprises two conductive patterns **226** and **228**. Conductive pattern **226** includes a longitudinally extending portion **230** and interdigitated electrodes or fingers (not shown). Similarly, conductive pattern **228** includes a longitudinally extending portion **232** and interdigitated electrodes or fingers **236**. The fingers of film **208** are substantially perpendicular to longitudinally extending portions **230** and **232**. Film **208** may also be configured without any conductive patterns.

[**0051**] Actuator **200** further comprises anisotropically conductive films or sheets **210** and **212** positioned on the top and bottom of piezoelectric macro-fibers **202**. Each film **210** and **212** has generally the same surface area as the total surface area of piezoelectric macro-fibers **202**. Films **210** and **212** are used to bond films **206** and **208** to the piezoelectric macro-fibers **202**. Each film **210** and **212** comprises a thermoset/thermoplastic adhesive matrix. In one embodiment, the adhesive matrix has a thickness between about 0.0001 and 0.002 inches. The adhesive matrix has randomly loaded conductive particles. These conductive particles provide conductive paths through the thickness of the adhesive film, but not through the plane of the film. This pathing arrangement permits the fingers of films **206** and **208** to be in direct electrical contact with the underlying piezoelectric fibers **202** while remaining electrically isolated from adjacent, oppositely charged fingers. In one embodiment, the conductive particles have a diameter of about 0.0005 inch. Films **210** and **212** comprise Z-Axis Film, product no. 3M 5303R, manufactured by 3M Company, Inc. However, other films having generally the same anisotropically conductive characteristics as the aforementioned Z-Axis Film may be used.

[**0052**] Referring to **FIG. 10**, before final assembly of actuator **200**, slots **204** are filled with an electrically non-conductive matrix epoxy to prevent the development of air pockets. The application of the epoxy is implemented in generally the same manner as previously described for assembly of actuator **10**.

[**0053**] Referring to **FIG. 10**, the use of films **210**, **212** to bond films **206** and **208** to piezoelectric macro-fibers **202** creates relatively strong bond lines that are maintained beneath and between fingers of films **206** and **208**. In an alternate embodiment, films **206** and **208** may be added during the fabrication of the shear-mode actuator previously described and shown in **FIG. 9**.

[**0054**] **FIG. 11** shows another embodiment of the actuator of the present invention. Actuator **300** generally comprises a monolithic piezoelectric wafer **302** and films **304** and **306**. Wafer **302** may be produced as a longitudinal-mode or shear-mode actuator. Films **304** and **306** have electrode patterns and are generally the same in construction as films **28** and **42** described above and shown in **FIGS. 4 and 5**.

[**0055**] Film **304** comprises a conductive pattern **308** which has a longitudinally extending portion **310** and interdigitated electrodes or fingers **312**. Film **304** further comprises conductive pattern **314**, which has a longitudinally extending portion **316** and interdigitated electrodes or fingers **318**. As shown in **FIG. 11**, fingers **312** and **318** are substantially perpendicular to longitudinally extending portions **310** and **316**, respectively.

[**0056**] In one embodiment, film **306** comprises a conductive pattern **320** having a longitudinally extending portion **322** and interdigitated electrodes or fingers **324**. Film **306** further comprises a conductive pattern **326** having a longitudinally extending portion **328** and interdigitated electrodes or fingers **330**. As shown in **FIG. 11**, fingers **324** and **330** are substantially perpendicular to the longitudinally extending portions **322** and **328**, respectively. Film **306** may also be configured without any conductive patterns.

[**0057**] Films **304** and **306** may be bonded to wafer **302** by any of the methods previously described. The omission of the machined slots in wafer **302** significantly reduces the per-unit cost of actuator **300** and provides a relatively high actuation-efficiency device. Additionally, the lamination effect of the attached electrode films **304** and **306** provides actuator **300** with a predetermined degree of flexibility and conformability which, although not as great as actuators **10**, **100** and **200**, makes actuator **300** suitable for applications wherein endurance and fatigue life are not major considerations, for example, launch vehicle payload shrouds, torpedo bodies, missile stabilizer fins, etc.

[**0058**] A further embodiment of the actuator of the present invention is given in **FIGS. 12A and 12B**. The first step in fabricating actuator **400** is to bond together a plurality of relatively thin piezoelectric wafers **402** to form a stack **404**. In a preferred embodiment, a liquid epoxy as previously described is used to bond together the wafers **402**. Stack **404** may be of almost any height. In one embodiment, the height of stack **404** is about 0.25 inch. In a preferred embodiment, the thickness of bond lines **406** between adjacent wafers **402** is between about 0.125 and 0.25 times the nominal thickness of the individual piezoelectric wafers **402**. After stack **404** is bonded, it is cured at relatively moderate pressure and temperature to form a substantially void-free bonded stack. In a preferred embodiment, the aforementioned pressure and temperature are applied under a vacuum.

[**0059**] Next, stack **404** is sliced parallel to the thickness direction and along the length direction, as indicated by dotted lines **408**, to provide a plurality of relatively thin, piezoelectric sheets **410**. In one embodiment, a wafer dicing saw is used to cut fiber sheets **410**. However, other cutting methods may be used. Fiber sheets **410** may be handled and packaged in the same manner as monolithic piezoelectric wafers. In one embodiment, the thickness of each sheet **410** is about equal to the thickness of one of the piezoelectric wafers **402** used to form stack **404**. However, each sheet **410** may have a thickness that is less than or greater than the thickness of one of the piezoelectric wafers **402**.

[**0060**] Referring to **FIG. 12B**, sheet **410** is positioned between films **412** and **414**. Film **412** comprises a conductive pattern **416**, which has a longitudinally extending portion **418** and interdigitated electrodes or fingers **420**, and a conductive pattern **422**, which has a longitudinally extending portion **424** and interdigitated electrodes or fingers **426**. As shown in **FIG. 12B**, fingers **420** and **426** are substantially perpendicular to longitudinally extending portions **418** and **424**, respectively.

[**0061**] Film **414** comprises a conductive pattern **428** having a longitudinally extending portion **430** and interdigitated electrodes or fingers **432**. Film **414** further comprises a conductive pattern **434** having a longitudinally extending portion **436** and interdigitated electrodes or fingers **438**. Fingers **432** and **438** are substantially perpendicular to longitudinally extending portions **430** and **436**, respectively. Film **414** may also be configured without any conductive patterns. Films **412** and **414** are adhesively bonded to sheet **410** via a liquid epoxy or using an anisotropically conductive film as previously described.

[**0062**] The configuration shown in **FIGS. 12A and 12B** has two significant advantages. First, the possibility of bonding to a surface skin is virtually eliminated. Second, all the macro-fibers of sheets **410** are pre-aligned.

(3) Advantages Over Prior Art Actuators And Methods

[**0063**] The method of the present invention substantially eliminates the need to manufacture and individually handle large numbers of piezoelectric fibers. Thus, production time and handling costs associated with packaging piezoelectric fiber composite actuators are significantly reduced. The method of the present invention is easily controlled and precise, which greatly enhances the repeatability and uniformity of the actuators produced. The method of the present invention permits square fibers to be manufactured and easily aligned within the actuator package without the possibility of damage to the actuator electrodes. Thus, the difficulties associated with the use of square cross-section piezoelectric fibers are virtually eliminated. The use of square fibers in accordance with the present invention instead of round fibers allows the volume fraction of piezoelectric material within the actuator package to be increased, thereby improving the actuation stress capability of the actuator. The use of the relatively thick copper conductive patterns, which are attached via liquid epoxy or anisotropically conductive adhesive, also provide for an unimpeded electrical connection to be made between the piezoelectric material and the electrodes. As a result, the electric field transfer efficiency of the actuator electrodes is significantly improved, which in turn increases the strain produced per unit applied voltage. A further advantage is that the square or rectangular fibers have a substantially flat contact area with the electrodes. This flat contact area is relatively greater than the contact area achieved with round fibers.

[**0064**] The polyimide films each have width and length dimensions that are larger than the width and length of piezoelectric wafer so as to permit the placement of longitudinally extending portions of the conductive patterns (e.g. portions **34** and **38** of conductive patterns **30** and **32**, respectively) away from the piezoelectric wafer. This configuration significantly lessens the potential for cracking of the macro-fibers caused by highly non-uniform electrical field distribution in regions beneath and adjacent to the longitudinally extending portions of the conductive patterns. Additionally, this packaging concept affords a sealed electrical system that is protected from the environment.

[0065] While the present invention has been particularly described, in conjunction with a specific preferred embodiment, it is evident that many alternatives, modifications, and variations will be apparent to those skilled in the art in light of the foregoing description. It is therefore contemplated that the appended claims will embrace any such alternatives, modifications, and variations as falling within the true scope and spirit of the present invention.

What is claimed is:

1. A method of fabricating a plurality of piezoelectric fibers, comprising the steps of:

providing a plurality of wafers of piezoelectric material;

bonding the wafers together with an adhesive material between each wafer to form a stack of alternating layers of piezoelectric material and adhesive material, the stack having a thickness; and

cutting through the stack in a direction substantially parallel to the thickness of the stack and across the alternating layers of piezoelectric material and adhesive material to provide at least one piezoelectric fiber sheet comprising a plurality of piezoelectric fibers in juxtaposition to the adhesive material.

2. The method according to claim 1 wherein the wafer of piezoelectric material comprises a monolithic piezoelectric material.

3. The method according to claim 1 wherein each piezoelectric fiber has a substantially rectangular cross-section.

4. A plurality of piezoelectric fibers made by a process comprising:

providing a plurality of wafers of piezoelectric material;

bonding the wafers together with an adhesive material between each wafer to form a stack of alternating layers of piezoelectric material and adhesive material, the stack having a thickness; and

cutting through the stack in a direction substantially parallel to the thickness of the stack and across the alternating layers of piezoelectric material and adhesive material to provide at least one piezoelectric fiber sheet.

5. The plurality of piezoelectric fibers according to claim 4 wherein the wafer of piezoelectric material comprises a monolithic piezoelectric material.

6. The plurality of piezoelectric fibers according to claim 4 wherein each piezoelectric fiber has a substantially rectangular cross-section.

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