

METHOD OF PRODUCING ELECTROMECHANICAL POLYMER MULTILAYER STRUCTURE AND RESULTING DEVICES

Field of the Invention

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The present invention relates to a method of producing an electromechanical polymer multilayer structure and resulting devices. In particular, the invention relates to a powder-based method of producing electromechanical polymer multilayer structure and resulting devices.

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Background

Research results have shown that electromechanical polymer multilayer structures can significantly enhance device performance as compared to single layer of the same material. The multilayer structures with thinner individual electromechanical polymer layer and higher effective area attributed to the multilayer configuration are ideal for electromechanical sensing and transduction applications due to the improved electrical power transfer efficiency as compared to single layer structure. Such features are even more attractive for miniaturized electromechanical devices applications, including acoustic sensors and ultrasonic transducer arrays. The high electrical impedance of polymer single layer due to the small element size in these electrical mechanical devices causes electrical impedance mismatch with external circuitry. This results in low power transfer efficiency and in turn, degrades device performance. Hence, electromechanical polymer multilayer structures with significantly lowered electrical impedance due to the thinner individual layer and larger effective area can lead to better electrical impedance matching for enhanced power transfer efficiency and improved performance for electromechanical devices.

Several methods have been attempted to produce electromechanical polymer multilayer structures. One such methods include fabricating electromechanical polymer multilayer structures by stacking polymer sheets and bonding them with adhesive. Due to the inherently high electrical impedance of electromechanical polymers, a large number of thin electromechanical polymer layers is desired for improving electrical matching with external circuitry to maximize electrical power transfer. However,

stacking of a large number of electromechanical polymers layers with adhesive is a challenging process particularly when the thickness of the sheets reduces to below 100µm due to the requirement for very thin bonding adhesive layer. The bonding adhesive is an electromechanically inactive layer between the electromechanical polymer sheets and this layer decreases the overall electromechanical coupling efficiency of the multilayer structures. The inactive layers also introduce local clamping effect on the electromechanical polymer layers and further degrade the electromechanical performance of the multilayer structures. Hence, such fabrication method is unsuitable for producing high-performance and miniaturized electromechanical multilayer structures.

Electromechanical polymer multilayer structures can also be produced by successive depositions of electromechanical polymers and electrodes on a substrate. Such deposition methods eliminate the requirement of inactive adhesive layers between the electromechanical polymer layers, with promise for higher electromechanical performance. However, repeated depositions of electromechanical polymer to form multilayer structures through vapour deposition methods are complex, costly and have low productivity, with many unsolved processing issues including effective multiple electrode connection.

Another method of producing electromechanical polymer multilayer structure is by forming electromechanical polymer multilayer structure on a substrate using solution-based spin-coating and dip-coating methods. Such method causes re-dissolution of the deposited polymer layer during repeated solution deposition processes. During solution-based deposition process, the polymer multilayer is immersed in the solution containing both the dissolved polymer and the corresponding solvent for the polymer, in which the solvent can dissolve or damage the top polymer layer of the multilayer structure. The re-dissolution introduces defects in the electromechanical polymer layers after the deposition process and causes dielectric breakdown during electrical poling process. Hence, the yield of fabricating the electromechanical multilayer structures by vapour- or solution-based process is low, and these methods have not been adopted to produce electromechanical polymer multilayer devices in industry.

A further method is reported in the prior art and this method uses powder-based electrophoretic deposition method for producing electromechanical polymer single

layer, but no feasible method has been disclosed for producing electromechanical polymer multilayer structures with complex structures and electrical connections, which are significantly different from single layer structure. The electrophoretic deposition is performed by applying an electrical field across a conductive substrate and a counter
5 electrode. In the electrophoretic deposition process, the electromechanical polymer powder particles dispersed in the suspension is driven by the electrical field and deposited on the conductive substrate. However, usually one is not motivated to apply such an approach for forming electromechanical polymer multilayer structures since the deposited polymer layer is electrical insulator and the electrical potential applied on
10 the bottom conductive substrate is unable to attract the dispersed polymer powder particles. Hence, conventional electrophoretic deposition method has only been used for producing electromechanical polymer single layer structure.

It is therefore desirable to provide a method for producing electromechanical polymer
15 multilayer structure and resulting devices that seek to address at least one of the problems described hereinabove, or at least to provide an alternative.

Summary of Invention

20 In accordance with a first aspect of this invention, a method of producing an electromechanical polymer multilayer structure is provided. The method comprises (a) depositing a first suspension of electromechanical polymer powder particles on a conductive surface of a substrate to form a first polymer layer; (b) depositing a first electrode layer on the first polymer layer; (c) depositing a second suspension of
25 electromechanical polymer powder particles on the first electrode layer to form a second polymer layer; (d) depositing a second electrode layer on the second polymer layer; (e) depositing a third suspension of electromechanical polymer powder particles on the second electrode layer to form a third polymer layer; (f) repeating steps (b)-(e) to form an electromechanical polymer multilayer structure comprising a plurality of
30 polymer layers, a plurality of first electrode layers and a plurality of second electrode layers, wherein each of the polymer layers is disposed between two adjacent electrode layers; and wherein the plurality of first electrode layers are interconnected to form a first electrode group of a first type and the plurality of second electrode layers are interconnected to form a second electrode group of a second type; and wherein the

first electrode layers of the first electrode group are electrically insulated from the second electrode layers of the second electrode group.

In accordance with one embodiment of this invention, the electromechanical polymer powder particles are deposited on the conductive surface of the substrate by electrophoretic deposition. The electrophoretic deposition comprises immersing the conductive surface of the substrate into the first suspension of electromechanical polymer powder particles; and applying an electrical potential across the conductive surface of the substrate and a counter electrode.

In accordance with one embodiment of this invention, the electromechanical polymer powder particles are deposited on the first electrode layer and the second electrode layer by electrophoretic deposition. The electrophoretic deposition comprises immersing the first electrode layer and the second electrode layer into the second suspension of electromechanical polymer powder particles and the third suspension of electromechanical polymer powder particles, respectively; and applying an electrical potential across each of the first electrode layer and the second electrode layer, and a counter electrode.

In accordance with one embodiment of this invention, a portion of the first electrode layer and a portion of the second electrode layer are not immersed in the suspension of electromechanical polymer powder particles during the electrophoretic deposition and the portions are exposed for realizing the electrical connection.

In accordance with one embodiment of this invention, the method further comprises treating the electromechanical polymer powder particles deposited on the substrate, on the first electrode layer and on the second electrode layer with heat above melting temperature of the electromechanical polymer powder particles to form continuous polymer layers.

In accordance with one embodiment of this invention, the method further comprises patterning the plurality of first electrode layers and the plurality of second electrode layers to form an array of a plurality of electromechanical elements.

In accordance with a second aspect of this invention, an electromechanical polymer multilayer structure is provided. The electromechanical polymer multilayer structure comprises at least one unit of successive layers, each unit comprises a first polymer layer; a first electrode layer deposited on the first polymer layer; a second polymer layer deposited on the first electrode layer; and a second electrode layer deposited on the second polymer layer; wherein each of the polymer layers is formed from a suspension of electromechanical polymer powder particles, and each of the polymer layers is disposed between two adjacent electrode layers; wherein the first electrode layers of the successive layers are interconnected to form a first electrode group of a first type and the second electrode layers of the successive layers are interconnected to form a second electrode group of a second type; and wherein the first electrode layers of the first electrode group are electrically insulated from the second electrode layers for the second electrode group.

In accordance with one embodiment of this invention, the first electrode layers are interconnected at a portion not exposed to the electromechanical polymer powder particles to form the first electrode group of the first type; and the second electrode layers are interconnected at another portion not exposed to the electromechanical polymer powder particles to form the second electrode group of the second type.

In accordance with one embodiment of this invention, the first electrode layers and the second electrode layers are patterned to form an array of a plurality of electromechanical elements.

In accordance with a third aspect of this invention, an electromechanical device comprising an electromechanical polymer multilayer structure of the present invention is provided.

In accordance with one embodiment of this invention, the electromechanical polymer multilayer structure is configured to convert acoustic wave into electrical signal for acoustic wave sensing. In accordance with another embodiment of this invention, the electromechanical polymer multilayer structure is configured to convert applied voltage into acoustic wave for acoustic wave generation.

Brief Description of the Drawings

The above advantages and features of a method and resulting devices in accordance with this invention are described in the following detailed description and are shown in the drawings:

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Figure 1 is a schematic illustration of a powder-based electrophoretic deposition process in accordance with an embodiment of the present invention.

10 Figure 2 is a schematic illustration of (a) electromechanical polymer powder particles deposited on a conductive substrate through electrophoretic deposition; (b) formation of a continuous polymer layer after heat treatment above melting temperature; (c) deposition of a first electrode layer on the polymer layer; and (d) a photo of a polymer layer with deposited aluminium layer.

15 Figure 3 is a schematic illustration of (a) deposition of a second suspension of electromechanical polymer powder particles on the first electrode layer through electrophoretic deposition; (b) electromechanical polymer powder particles deposited on the immersed first electrode layer after electrophoretic deposition; and (c) formation of a second polymer layer after heat treatment and deposition of a second electrode
20 layer.

Figure 4 is a schematic illustration of an electrical connection and polarization configuration of the electromechanical polymer multilayer structure after electric poling. Figure 4(a) shows the top view of the multilayer structure and Figure 4(b) shows the
25 side view of the multilayer structure.

Figure 5 (a) is a graph showing the experimental results of the voltage output vs number of layers for multilayer ultrasonic transducers with same overall thickness and central frequency. Figure 5(b) is a graph showing the time-domain signals of multilayer
30 ultrasonic transducers with different total number of layers.

Figure 6(a) is a schematic illustration of a 32-element array formed on a polymer insulating layer, directly deposited on an aluminium substrate. Figure 6(b) is a photo showing an electro-polished aluminium substrate before electrophoretic deposition.

Figure 6(c) shows a patterned first electrode layer deposited on the polymer insulating layer on the aluminium substrate.

Figures 7(a)-(c) are schematic diagrams showing (a) the first electrode layer for the 32 elements formed on the insulating polymer layer and a close-up view of the selected area; (b) the electromechanical polymer powder particles deposited on the immersed area of the electrode layer through electrophoretic deposition and a close-up view of the selected area; and (c) formation of a second polymer layer after heat treatment and a close-up view of the selected area

Figures 8(a)-(c) are schematic diagrams showing (a) the second electrode layer formed on the second polymer layer and a close-up view of the selected area; (b) the electromechanical polymer powder particles deposited on the immersed area of the second electrode layer through electrophoretic deposition to form a third polymer layer and a close-up view of the selected area; and (c) formation of the third polymer layer after heat treatment and a close-up view of the selected area.

Figure 9(a) is a graph showing the relationship between capacitance vs number of layer. Figure 9(b) is a graph showing polarization – electric field (P-E) hysteresis loops for all the 32 elements in a 6-layer multi-element electromechanical polymer structure. Figure 9(c) is a 3-D drawing of the displacement data under the sine-wave driving electrical signal of 20 V.

Figures 10(a)-(b) are photos showing the (a) front view, and (b) back view of the 32-element ultrasonic transducer array design using the electromechanical polymer multilayer structure of the present invention.

Figure 11(a) is a schematic illustration of a photoacoustic imaging setup. Figure 11(b) is a photoacoustic image obtained by the 32-element electromechanical polymer multilayer transducer array in a commercial photoacoustic imaging system (MSOT).

Figure 12(a) is a schematic diagram showing the cross-sectional view of a curved multi-element electromechanical polymer multilayer structure on aluminium substrate. Figure 12(b) shows a photo of the curved multi-element electromechanical polymer multilayer structure on aluminium substrate.

Figure 13(a) is a schematic illustration of a photoacoustic imaging setup for focused 32-element transducer array. Figure 13(b) shows a photoacoustic image obtained by the focused 32-element electromechanical polymer multilayer transducer array in a commercial photoacoustic imaging system (MSOT).

Detailed Description

The present invention relates to a method of producing electromechanical polymer multilayer structure and resulting devices. In particular, the invention relates to a powder-based method of producing electromechanical polymer multilayer structure. The powder-based method as disclosed in this invention utilizes electrophoretic deposition process to form electromechanical polymer multilayer structure and electromechanical devices.

In one aspect of the present invention, a method of producing an electromechanical polymer multilayer structure is provided. The method comprises (a) depositing a first suspension of electromechanical polymer powder particles on a conductive surface of a substrate to form a first polymer layer; (b) depositing a first electrode layer on the first polymer layer; (c) depositing a second suspension of electromechanical polymer powder particles on the first electrode layer to form a second polymer layer; (d) depositing a second electrode layer on the second polymer layer; (e) depositing a third suspension of electromechanical polymer powder particles on the second electrode layer to form a third polymer layer; (f) repeating steps (b)-(e) to form an electromechanical polymer multilayer structure comprising a plurality of polymer layers, a plurality of first electrode layers and a plurality of second electrode layers, wherein each of the polymer layers is disposed between two adjacent electrode layers; and wherein the plurality of first electrode layers are interconnected to form a first electrode group of a first type and the plurality of second electrode layers are interconnected to form a second electrode group of a second type; and wherein the first electrode layers of the first electrode group are electrically insulated from the second electrode layers of the second electrode group.

The electromechanical materials used to form the electromechanical polymer multilayer structure of the present invention are piezoelectric polymers. Such polymers

include, but are not limited to, poly(vinylidene fluoride) (PVDF), poly(vinylidene fluoride-trifluoroethylene) (P(VDF/TrFE) or any other piezoelectric polymers. The piezoelectric polymers are in powder form, with particle sizes in the nanometer range.

- 5 In one embodiment, the first suspension of electromechanical polymer powder particles is prepared by dispersing the electromechanical polymer powder particles in a liquid that does not substantially dissolve the powder particles, to form a stable suspension. Suitable liquid includes, but is not limited to, isopropyl alcohol and other liquids with similar dispersion property as isopropyl alcohol, such as ethanol, butanol,
10 etc.

The substrate on which the suspension of electromechanical polymer powder particles deposited has at least one electrical conductive surface. The conductive surface may cover the entire surface of the substrate, a substantial area of the substrate or one
15 major surface of the substrate. The conductive surface is provided for the deposition of the electromechanical polymer powder particles. Any suitable substrate may be used. The substrate may be made of any materials including, but not limited to, any electrical conductive metals, such as aluminium, copper, etc., alloy, polymer with at least one electrical conductive surface or composite. In one embodiment, the substrate is a
20 polished aluminium film. One skilled in the art will appreciate that the substrate can be of any suitable shape and size, depending on the required application of the electromechanical polymer multilayer structure. In an exemplary embodiment as shown in Figure 12, a curved substrate is used to produce a curved electromechanical polymer multilayer structure.

25 Figure 1 shows an exemplary set up of an apparatus for use in the method of the present invention. In one embodiment, the electromechanical polymer powder particles **100** in the first suspension **102** are deposited on the conductive surface of the substrate **104** by electrophoretic deposition wherein the substrate is immersed in the first suspension of electromechanical polymer powder particles as an anode and an
30 electrical potential **106** is applied across the conductive surface of the substrate **104** and a counter electrode **108** that functions as a cathode. The electrical potential applied across the anode and the cathode allows electrical current to flow for sufficient period of time to allow the electromechanical polymer powder particles **100** to move
35 towards the anode to be deposited on the conductive surface of the substrate **104** to

obtain a deposited electromechanical polymer particles **110** of desired thickness. The arrow **112** shows the movement of the electromechanical polymer particles **100** towards the anode.

5 “Electrophoretic deposition” as used herein refers to a process of coating a conductive surface of a material with particles suspended in a liquid medium under the influence of an electric field applied between the conductive material which acts as an electrode and a counter electrode. Electrophoretic deposition utilises electrically charged particles that move through the liquid medium between the two electrode (an anode
10 and a cathode) immersed in the liquid medium.

The deposited electromechanical polymer powder particles **110** on the substrate are subjected to heat treatment above the melting temperature of the electromechanical polymer powder particles for a time sufficient to melt the electromechanical polymer
15 powder particles and form a continuous first polymer layer **114**. The melting temperature employed for the heat treatment varies depending on the type of electromechanical polymer powder particles used.

In step (b), a first electrode layer **116** is deposited on the first polymer layer **114**. In one
20 embodiment, the first electrode layer is deposited by physical vapour deposition.

“Physical vapour deposition” as used herein refers to a process used to produce a metal vapour that can be deposited on electrically conductive materials as a thin film or coating. Some examples of physical vapour deposition processes include, but are not
25 limited to, electron-beam physical vapour deposition, evaporative deposition, sputter deposition, pulsed laser deposition, etc.

The electrode layer is an electrical conductive layer that may comprise material independently selected from the group consisting of conductive metal, metal oxide and
30 polymer. Preferably, the conductive metal, metal oxide and polymer are selected from the group of metals, metal oxides and polymers that can be deposited through physical vapour deposition. Examples of such conductive metals include, but not limited to, aluminium and gold. In one embodiment, the electrode layer is a layer of aluminium. The first electrode layer functions as a conductive substrate for subsequent

electrophoretic deposition of the electromechanical polymer powder particles and also as the device electrode.

Step (c) involves depositing a second suspension **202** of electromechanical polymer powder particles on the first electrode layer **116** to form a second polymer layer **204**. Step (d) involves depositing a second electrode layer **206** on the second polymer layer **204**. Figure 3 is a schematic diagram showing how the first electrode layer **116**, the second polymer layer **204** and the second electrode layer **206** are arranged on the substrate **104** in accordance with an embodiment of the present invention.

Referring to Figure 3, the first electrode layer **116** is connected to the electrical power supply as an anode and immersed in the second suspension **202** of electromechanical polymer powder particles for electrophoretic deposition of the electromechanical polymer powder particles **100** on the first electrode layer **116**. A portion **310** of the first electrode layer **116** is not immersed in the second suspension of electromechanical polymer powder particles during the electrophoretic deposition process so that the portion **310** of the first electrode layer **116** is not covered by the electromechanical polymer powder particles **100**. The deposited electromechanical polymer powder particles **110** on the first electrode layer **116** are subjected to heat treatment above the melting temperature of the electromechanical polymer powder particles for a time sufficient to melt the electromechanical polymer powder particles and form a continuous second polymer layer **204**.

A second electrode layer **206** is deposited on the second polymer layer **204** in the same manner as described herein for depositing the first electrode layer. The second electrode layer may be comprised of a different material or the same material as the first electrode layer. The second electrode layer functions as a conductive substrate for subsequent electrophoretic deposition of electromechanical polymer powder particles and also as the device electrode.

In step (e), a third suspension **302** (not shown) of electromechanical polymer powder particles is deposited on the second electrode layer **206** to form a third polymer layer **304**. A portion **312** of the second electrode layer **206** is not immersed in the third suspension of electromechanical polymer powder particles during the electrophoretic process so that the portion **312** of the second electrode layer **206** is not covered by the

electromechanical polymer powder particles **100**. Figure 3(c) shows an exemplary embodiment wherein the portion **310** of the first electrode layer **116** and the portion **312** of the second electrode layer **206** do not overlap. The portion **310** and the portion **312** can be arranged in any suitable manner so long as the two portions are spaced apart and do not overlap.

The third suspension of electromechanical polymer powder particles is deposited on the second electrode layer in the same manner as described hereinabove for the second suspension of electromechanical polymer powder particles. The electromechanical polymer powder particles deposited on the second electrode layer are subjected to heat treatment above the melting temperature of the electromechanical polymer powder particles for a time sufficient to melt the electromechanical polymer powder particles and form a continuous third polymer layer **314**.

Steps (b) to (e) are repeated until an electromechanical polymer multilayer structure comprising a plurality of polymer layers, a plurality of first electrode layers and a plurality of second electrode layers is formed.

“Electromechanical polymer multilayer structure” as used herein refers to a structure comprising more than one electromechanical polymer layer in which each of the individual electromechanical polymer layer is sandwiched between two electrode layers.

In the present invention, the electrode layers are separated into two groups, namely, the first electrode layers and the second electrode layers. The plurality of first electrode layers (or the odd-numbered electrode layers) are interconnected to form a first electrode group **416** of a first type and the plurality of second electrode layers (or the even-numbered electrode layers) are interconnected to form a second electrode group **406** of a second type. The electrodes within the same electrode group, that is, the first electrode group **416** and the second electrode group **406** are aligned to overlap at the same area to achieve an electrical connectivity within the same electrode group. The first electrode layers of the first electrode group are electrically insulated from the second electrode layers of the second electrode group. Figure 4(b) shows an embodiment on how the plurality of polymer layers **404**, the plurality of first

electrode layers **416** and the plurality of second electrode layers **406** can be arranged in an electromechanical polymer multilayer structure.

5 The term “electromechanical” as used herein refers to converting electrical signal to mechanical signal, and vice-versa. In the present invention, the electromechanical polymer multilayer structure is electrically poled by applying an electric field across the first electrode group and the second electrode group. Figure 4(b) shows an exemplary embodiment of the poling direction **408** of the electromechanical polymer multilayer structure. The poling electric field direction, and also the resulting polarization
10 directions of each polymer layer, points at an opposite direction as compared to adjacent piezoelectric layers. When a tensile or compressive force (such as from an acoustic wave) exerts on the normal direction of the electromechanical polymer multilayer structure, the piezoelectric outputs of all the polymer layers are constructively summed.

15 The second suspension and the third suspension of electromechanical polymer powder particles used to fabricate the various polymer layers can be prepared in the same manner as the first suspension of electromechanical polymer powder particles. The second suspension and the third suspension of electromechanical polymer
20 powder particles can be obtained from the same batch of suspension of electromechanical polymer powder particles prepared for use as the first suspension of electromechanical polymer powder particles or each suspension can be prepared separately. The second suspension and the third suspension may comprise the same or a different type of electromechanical polymer powder particles. The second
25 suspension and the third suspension may comprise the same or a different type of electromechanical polymer powder particles as the first suspension.

In various embodiments, the suspensions of electromechanical polymer powder particles are subjected to sonication to break up the agglomeration of the
30 electromechanical polymer powder particles to ensure even dispersion of the polymer powder particles in the liquid.

The polymer layers formed by the method of the present invention are substantially crack-free and this is critical in improving the yield of device fabrications as cracks and
35 other defects increase the chance of dielectric breakdown during the subsequent

electrical poling process. The thickness of the deposited polymer layers can be controlled by the electrical potential applied to the layers, the concentration of the suspension and the duration of the deposition process. In some embodiments, the electrophoretic deposition is performed for a period of 2 to 10 mins per polymer layer.

5 In various embodiments, each deposited polymer layer has a thickness between 1 and 50 μm .

In one embodiment, the first polymer layer is an insulating layer. The insulating layer is for the purpose of electrically separates the conductive substrate and the electrode
10 layers of the electromechanical multilayer structure.

In one embodiment, the plurality of first electrode layers and the plurality of second electrode layers are patterned to form an array of a plurality of electromechanical elements. An exemplary embodiment of a patterned electrode layers is shown in
15 Figure 7. One skilled in the art will appreciate that the electrode layers may be patterned in any suitable manner without departing from the scope of the present invention. In all embodiments, the plurality of first electrode layers are interconnected to form a first electrode group of a first type and the plurality of second electrode layers are interconnected to form a second electrode group of a second type, wherein the
20 first electrode layers of the first electrode group are electrically insulated from the second electrode layers of the second electrode group. In one embodiment, the multi-element array comprises 32 or more elements per array.

In various embodiments, the electrode layers of the present invention each has a
25 thickness ranging from 50 to 500 nm.

The method of the present invention may further include removing the substrate **104** by chemical etching after the electromechanical polymer multilayer structure is formed. In some embodiments, the etching comprises immersing the electromechanical
30 polymer multilayer structure in a chemical etchant including, but not limited to, acids such as hydrochloric acid, or bases, such as sodium hydroxide.

The electromechanical polymer multilayer structure of the present invention has a thickness between 1 and 100 μm .

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The method of the present invention employs an electrode configuration uniquely designed for producing electromechanical polymer multilayer structures through powder-based electrophoretic method. Electrical conductive layers (or electrode layers) deposited on the electromechanical polymer layers function as conductive substrate for subsequent electrophoretic deposition and also as the device electrode. The electrical conductive layer that is exposed to the suspension of electromechanical polymer powder particles is capable of attracting the polymer powder particles during electrophoretic deposition. This allows subsequent electrophoretic polymer layer deposition to take place on the electrical conductive layer to form the next electromechanical polymer layer. The power supply for the electrophoretic deposition needs to be connected only to the electrical conductive layer that is positioned at the topmost layer of the multilayer structure during every deposition cycle. By repeating the alternate electrical conductive layer deposition and electrophoretic deposition of the polymer layer on the electrical conductive layer positioned at the topmost layer of the multilayer structure, an electromechanical polymer multilayer structure with desired thickness can be produced using the powder-based electrophoretic method.

In addition, the electrode layers of the electromechanical polymer multilayer structure are separated into two electrically insulated groups which function as device electrodes. The conventional electrophoretic deposition for single layer structure does not provide any method to produce the electrical connections required for multilayer devices. The method as disclosed in the present invention forms two electrode groups in a unique way by offsetting the exposed portions of the electrode layers to avoid short-circuit between the two electrode groups.

In a second aspect of the present invention, an electromechanical polymer multilayer structure is provided. The electromechanical polymer multilayer structure comprises at least one unit of successive layers, each unit comprises: a first polymer layer; a first electrode layer deposited on the first polymer layer; a second polymer layer deposited on the first electrode layer; and a second electrode layer deposited on the second polymer layer. Each of the polymer layers is formed from suspension of electromechanical polymer powder particles, and each of the polymer layers is disposed between two adjacent electrode layers. The first electrode layers of the successive layers are interconnected to form a first electrode group of a first type and the second electrode layers of the successive layers are interconnected to form a

second electrode group of a second type; and wherein the first electrode layers of the first electrode group are electrically insulated from the second electrode layers for the second electrode group.

- 5 In some embodiments, the first electrode layers and the second electrode layers are patterned to form an array of a plurality of electromechanical elements. One skilled in the art will appreciate that the first electrode layers and the second electrode layers may be patterned in any suitable manner without departing from the scope of the present invention. In one embodiment, the first electrode layers and the second
10 electrode layers are patterned to form a multi-element array comprises 32 or more elements per array.

The electromechanical polymer multilayer structure of the present invention can take the form of any suitable shape and size, depending on the required application of the
15 electromechanical polymer multilayer structure. The method of the present invention allows various shapes and sizes of the electromechanical polymer multilayer structure to be formed. In an exemplary embodiment as shown in Figure 12, the electromechanical polymer multilayer structure is curved with a radius of curvature.

The electromechanical polymer multilayer structure produced by the method of the
20 present invention may be used in several applications and devices. In one embodiment, electromechanical devices including a piezoelectric ultrasonic transducer with multi-element array configuration is obtained. Photoacoustic imaging application can be demonstrated using the piezoelectric ultrasonic transducer with multi-element array configuration.

25 In a third aspect of the present invention, an electromechanical device comprising an electromechanical polymer multilayer structure of the present invention is provided. In one embodiment, the electromechanical polymer multilayer structure is configured to convert acoustic wave into electrical signal for acoustic wave sensing, and/or convert
30 applied voltage into acoustic wave for acoustic wave generation.

In one embodiment, the electromechanical device is for use as a focused acoustic transducer with focal length equal to the radius of curvature of the multilayer structure. In some embodiments, the electromechanical device is for use as acoustic transducer
35 to sense acoustic waves generated by light for photoacoustic sensing and imaging.

The method, the multilayer structures and the devices of the present invention have several advantages. The electromechanical polymer multilayer structures of the present invention significantly enhance device performance as compared to a device using a single layer structure of the same material. This is due to the improved impedance match and electromechanical response output that are achieved by the electromechanical polymer multilayer structures of the present invention. Theoretical analysis shows there a correlation between increasing sensitivity with increasing the number of layers.

The method of the present invention is of lower cost and with higher fabrication yield as compared to vapour-based and solution-based fabrication methods known in the state of the art. One of the reasons for the higher yield is that the powder-based method as disclosed herein ensures good electrical insulation between the two electrode groups without generating any defects in the polymer layers. The present invention has a higher electromechanical performance as compared to the conventional stacking method that is limited by layers thickness and adhesive clamping. The method of the present invention allows effective control on the deposition area of the electromechanical multilayer layer and the number of polymer layers and electrode layers to be deposited since the desired area and layers can be controlled by specifying the electrical conductive surface to be exposed in electrophoretic deposition, the electrical potential to be applied during electrophoretic deposition and the duration of application of the electrical potential.

The method and multilayer structures of the present invention can be employed for use in several different applications including, but are not limited to, ultrasonic sensor for high performance photoacoustic imaging, ultrasonic transducer for real-time in-vivo biomedical ultrasonic imaging, and non-destructive testing for quality control and structural health monitoring (semiconductors, automobiles, infrastructures, and industrial equipment) and mechanical energy harvesting. The electromechanical devices comprising the electromechanical polymer multilayer structures of the present invention also demonstrate a higher performance (such as ultrasonic transducer output) as compared to electromechanical devices using single layer of the same material.

To facilitate a better understanding of the present invention, the following examples of specific embodiments are given. In no way should the following examples be read to limit or define the entire scope of the invention. One skilled in the art will recognize that the examples set out below are not an exhaustive list of the embodiments of this invention.

EXAMPLES

Example 1

In this example, the powder-based method is demonstrated to form electromechanical polymer multilayer structure through an electrophoretic deposition.

In this example, the powder of piezoelectric polymer, poly(vinylidene fluoride-trifluoroethylene) (P(VDF/TrFE)), with particle size of approximately 200 nm was used. The P(VDF/TrFE) powder particles were first dispersed in isopropyl alcohol (IPA) to form a suspension. The suspension was sonicated to break up the agglomeration of the P(VDF/TrFE) particles to ensure even dispersion of the piezoelectric polymer powder particles in IPA. A substrate with an electrical conductive surface, such as a polished aluminium film, was connected to an electrical power supply as anode, while another electrical conductive film was connected to the electrical power supply as cathode. The substrate was immersed in the suspension P(VDF/TrFE) powder particles and a constant voltage of 20 V was applied for electrophoretic deposition of the P(VDF/TrFE) powder particles on the substrate.

The particles of P(VDF/TrFE) had a negative zeta potential in the IPA solution. Hence, the particles of P(VDF/TrFE) dispersed in the IPA solution were driven by the electric field toward the anode, which was the substrate for the multilayer structures (see Figure 1). The P(VDF/TrFE) particles deposited on the substrate were dried in air at room temperature. Heat treatment above the melting point of the P(VDF/TrFE), at 160°C was performed to melt the P(VDF/TrFE) particles and form a continuous deposited polymer layer (see Figure 2(b)). The thickness of the deposited polymer layer can be controlled by the electrical potential applied to the layer and the duration of the electrophoretic deposition process. In this example, the electrophoretic

deposition was performed for 5 mins to form a polymer layer with a thickness of about 20 μm .

A layer of electrical conductive layer was then formed on the deposited polymer layer (see Figure 2(c)). This was done by depositing a layer of aluminium with a thickness of 200 nm on the deposited polymer layer using e-beam evaporation. A crack-free continuous P(VDF/TrFE) layer with deposited aluminium layer was obtained as shown in Figure 2(d).

10 The P(VDF/TrFE) layer previously deposited directly on the aluminium substrate functioned as an insulating layer to electrically separate the conductive substrate and the electrode layers of the electromechanical multilayer structure. The first layer of the deposited electrical conductive layer (also known as the first electrode layer) functioned as the electrical conductive substrate for subsequent electrophoretic
15 deposition of a first working piezoelectric P(VDF/TrFE) layer (also known as the second polymer layer) to build the multilayer structure.

The first electrode layer was then connected to the electrical power supply as anode. The first electrode layer was immersed in the suspension of P(VDF/TrFE) for
20 electrophoretic deposition of the first working piezoelectric P(VDF/TrFE) layer (or the second polymer layer). Similar to how the first suspension of P(VDF/TrFE) particles was deposited on the conductive substrate, the P(VDF/TrFE) particles dispersed in the IPA suspension were drawn to the first electrode layer which was now an anode and deposited on the conductive surface of the first electrode layer. An area of the first
25 electrode layer was not immersed in the suspension during the electrophoretic process so that the area was not covered by the P(VDF/TrFE) particles (see Figure 3(b)). This was to allow subsequent electrical conductive layers to be deposited and overlapped on the same area so as to establish an electrical connection within the same electrical terminal group of the same electrode layers for forming the electromechanical polymer
30 multilayer structure. The deposited P(VDF/TrFE) particles were dried and heat treated under the same conditions as the insulating layer (also known as the first polymer layer) to form the first working layer (also known as the second polymer layer).

After the second polymer layer is formed, a second electrode layer was deposited on
35 the second polymer layer. This was done by depositing another layer of aluminium

with a thickness of 200nm on the deposited second polymer layer using e-beam evaporation. The second electrode layer had an exposed area (312) that did not overlap with the exposed area (310) of the first electrode layer (see Figure 3(c)).

- 5 The second electrode layer was connected to the electrical power supply as anode. The second electrode layer was immersed in the suspension of P(VDF/TrFE) for electrophoretic deposition of a second working piezoelectric P(VDF/TrFE) layer (also known as the third polymer layer). The P(VDF/TrFE) particles dispersed in the IPA suspension were drawn to the second electrode layer which was now an anode and
10 deposited on the conductive surface of the second electrode layer.

The steps for depositing the first electrode layers, the polymer layers and the second electrode layers were repeated until an electromechanical polymer multilayer structure comprising a plurality of first electrode layers, a plurality of polymer layers and a
15 plurality of second electrode layers of desired thickness was formed. The plurality of first electrode layers formed the odd-numbered electrode layers and the plurality of second electrode layers formed the even-numbered electrode layers. The odd- and even-numbered electrode layers formed two electrical insulated electrode groups. The electrodes within the same electrode group, that is, the first electrode group (416) were
20 aligned to overlap on the same exposed area (310) to achieve an electrical connectivity within the same electrode group, while the second electrode group (406) were aligned to overlap on the same exposed area (312) to achieve an electrical connectivity within the same electrode group.

- 25 The P(VDF/TrFE) polymer multilayer structure was electrically poled by applying an electric field across the two electrode groups (see Figure 4(b)). The poling electric field direction, and also the resulting polarization directions of each piezoelectric polymer layer, points at the opposite direction as compared to adjacent piezoelectric layers.

30 **Example 2**

In this example, electromechanical devices for ultrasonic transducing is demonstrated using the electromechanical polymer multilayer structures.

Electromechanical devices, such as ultrasonic transducers, were fabricated using the P(VDF/TrFE) piezoelectric multilayer structure formed by the method of the present invention. Multilayer ultrasonic transducers using the P(VDF/TrFE) multilayer structures with different number of layers (1, 2, 4, and 8 layers) were produced to demonstrate the effect of electromechanical polymer multilayer structure on the performance of the multilayer ultrasonic transducer.

The multilayer ultrasonic transducer comprises a P(VDF/TrFE) multilayer structure as the electromechanical element, a backing layer, a housing and electrical connections. The P(VDF/TrFE) multilayer structures were fabricated with the powder-based method using the electrophoretic deposition process as described hereinabove in Example 1. The aluminium substrate used in the electrophoretic deposition process for the formation of the multilayer structure was chemically etched off and replaced by an epoxy backing layer for the piezoelectric polymer multilayer structure. Epoxy was selected because a backing material having an acoustic impedance similar to the piezoelectric polymer multilayer structure was preferred. This is for improving the transducer bandwidth and imaging resolution. A watertight housing was provided to enclose the backing and the electrical connections to minimize signal noise. The electrical connections may comprise electrical wires or printed-circuit board, to conduct the electrical signal between the P(VDF/TrFE) multilayer structure and the connectors for the communication with external circuitry.

The multilayer ultrasonic transducer was used as the ultrasound sensor wherein another immersion ultrasonic transducer with nominal center frequency of 10 MHz was used as the pulser to investigate the ultrasonic transducer performance. The total thickness of the P(VDF/TrFE) multilayer structure was designed to be around 100 μm to match the center frequency of the pulser at 10 MHz. Ultrasonic wave was generated by the pulser in water and sensed by the P(VDF/TrFE) multilayer ultrasonic transducer which worked as a sensor, with the pulser and the sensor being placed at a distance of 10 mm apart.

Figures 5(a) and (b) show that the voltage output of the P(VDF/TrFE) multilayer ultrasonic transducer increases with the number of layers. The results show the enhanced sensitivity of the multilayer ultrasonic transducer as compared to a single layer ultrasonic transducer.

Example 3

In this example, a multi-element array with each of the electromechanical element
5 comprising the P(VDF/TrFE) multilayer structure was fabricated using the powder-
based method of the present invention. The electrode layers were patterned to form a
multi-element array as shown in Figure 6(a). The individual elements of the same
electrode group in the multi-element array were electrically insulated from each other.
The electromechanical device comprising the said multi-element electromechanical
10 array, with each element comprising the multilayer structure, was demonstrated for
photoacoustic imaging.

A P(VDF/TrFE) polymer layer was deposited on the aluminium substrate as the
insulating layer to ensure electrical insulation between the electromechanical elements.
15 P(VDF/TrFE) polymer powder with particle size of approximately 200 nm were
dispersed in IPA. The P(VDF/TrFE) suspension was sonicated to break up the
agglomeration of the P(VDF/TrFE) particles. A polished aluminium foil as shown in
Figure 6(b) was used as the substrate for forming the multilayer structure.
Electrophoretic deposition was performed by applying a constant voltage of 20 V to the
20 anode (substrate) and the cathode (counter electrode), which were both immersed in
the P(VDF/TrFE) suspension for 5 mins. The sample was dried in air at room-
temperature and heated at 160°C to melt the deposited P(VDF/TrFE) particles and
form a continuous insulating layer. Aluminium layer with a thickness of 200 nm was
deposited on the insulating P(VDF/TrFE) layer using a shadow mask to form the first
25 electrode layer for a 32-element array as shown in Figure 6(c).

The first electrode layer functions as the anode for the next electrophoretic deposition
to form a first working piezoelectric polymer layer as shown in Figure 7(a). All the first
electrode layers (116) for the 32 elements were connected to the electrical power
30 supply as anode and the electrode layers were partly immersed in the suspension of
piezoelectric polymer powder particles for the subsequent electrophoretic deposition.
As mentioned hereinabove, the P(VDF/TrFE) particles dispersed in the suspension
were drawn to the anode and deposited on the immersed area of the first electrode
layer (see Figure 7(b)). The deposited P(VDF/TrFE) powder particles (110) were dried
35 in air at room temperature and heat treated at 160°C to form the first working

P(VDF/TrFE) polymer layer (204) (also known as the second polymer layer) as illustrated in Figure 7(c). The conductive pads (610) of the first electrode layers, which were not immersed in the suspension of piezoelectric polymer powder particles were not coated with the P(VDF-TrFE) particles. The conductive pads (610) were used to
5 establish electrical connections with external circuitry.

A second electrode layer (206) was deposited on the first working P(VDF/TrFE) layer as a common electrode for all the 32 elements (see Figure 8(a)). The second electrode layer was electrically insulated from the first electrode layer as the conductive pad or
10 the exposed area (712) of the second electrode layer that was not immersed in the suspension did not overlap with the conductive pads or exposed areas (710) of the first electrode layer. The second electrode layer was connected to an electrical power supply as anode and it was partially immersed in the suspension of piezoelectric P(VDF/TrFE) powder particles for electrophoretic deposition of the P(VDF/TrFE)
15 powder particles on the second electrode layer (see Figure 8(b)). The deposited P(VDF/TrFE) powder particles (110) were dried and heat treated under the same conditions as the first working P(VDF/TrFE) layer to form a second working P(VDF/TrFE) layer (314) (also known as the third polymer layer) as shown in Figure 8(c).

20 A third electrode layer with the same pattern as the first electrode layer for the 32 elements was deposited on the second working P(VDF/TrFE) layer. The third electrode layer was aligned to overlap with the first electrode layer to ensure electrical connectivity within the same electrode group. Depositions of subsequent polymer
25 layers and electrode layers were repeated alternately to form a multilayer structure with desired number of layers. The odd- and even-numbered electrode layers formed two electrically insulated electrode groups.

The dielectric, ferroelectric and piezoelectric properties of the multi-element
30 P(VDF/TrFE) multilayer structure were evaluated for device applications. The graph in figure 9(a) shows that the capacitance of multilayer structures increases linearly with increasing number of deposited layers. This indicates good electrical connectivity for all the electrode layers within the same group.

Figure 9(b) shows that all the 32 elements of the P(VDF/TrFE) multilayer structure exhibit similar magnitude of polarization in the polarization - electric field (P-E) hysteresis loop. This indicates a uniform quality in the layers. The 32-element P(VDF/TrFE) multilayer structure was electrically poled in the same manner as described in Example 1. The piezoelectric response of a single element P(VDF/TrFE) multilayer structure as measured by Laser Scanning Vibrometer (LSV) is as shown in Figure 9(c). The piezoelectric strain constant d_{33} of 16.1 pm/V was recorded for a 6-layer P(VDF/TrFE) multilayer structure.

10 **Example 4**

An ultrasonic transducer array comprising the multi-element P(VDF/TrFE) multilayer structure fabricated using the powder-based method of the present invention was demonstrated for photoacoustic imaging. In this example, the 32-element P(VDF/TrFE) multilayer (6-layer) structure was used as the electromechanical element (500) for the ultrasonic transducer array as shown in Figure 10.

The ultrasonic transducer array has a casing (502) and the conductive pads of the 32-element multilayer structure were connected to a flexible printed-circuit board (Flex PCB) (504) using an anisotropic conductive adhesive (ACF), mounted on top of the casing. The ACF establishes the electrical connectivity for the 32 elements to an external circuit without electrical shorting between the 32 elements. An epoxy backing (506) was formed on one side of the multilayer structure as described in Example 2. The Flex PCB was connected to a 64-pin connector (508) for integration with commercial ultrasonic receiver system. The 64-pin connector was required for interfacing with external circuitry.

The photoacoustic imaging capability of the 32-element P(VDF/TrFE) multilayer ultrasonic transducer array (510) was demonstrated using a commercial system (MSOT, Ithera Medical) as shown in Figure 11(a). A graphite rod (512) with diameter of 0.3 mm was used as the imaging target and a pulsed laser (514) with pulse duration of 10 ns at wavelength of 700 nm was used to excite the photoacoustic signal on the graphite rod. The photoacoustic signal generated by the graphite rod was sensed by the 32-element P(VDF/TrFE) multilayer ultrasonic transducer and processed by the MSOT system. The graphite rod was clearly visible in the photoacoustic image

obtained by the 32-element P(VDF/TrFE) multilayer transducer array on a commercial photoacoustic imaging system (MSOT) as shown in Figure 11(b).

Example 5

5

In this example, acoustic sensing performances of the multilayer electromechanical devices are evaluated.

10 A curved P(VDF/TrFE) multilayer structure fabricated using a powder-based method of the present invention was used as the electromechanical elements for the focused 32-element multilayer transducer array in photoacoustic imaging.

15 A P(VDF/TrFE) multilayer structure was fabricated using the powder-based method as described in Example 1. The electrode layers of the multilayer structure were connected to a flexible printed circuit board (Flex PCB) using an anisotropic conductive adhesive (ACF). The P(VDF/TrFE) multilayer structure was curved by pressing it against a mold with desired curvature. In this example, the P(VDF-TrFE) multilayer structure was shaped by a curved mold with radius of 1.5 cm to produce a focal length of 1.5 cm (see Figures 12(a) and (b)). An epoxy backing was formed on one side of
20 the multilayer structure and attached to a casing as described in Example 2. The Flex PCB was connected to a 64-pin connector for integration with commercial photoacoustic imaging system (MSOT, Ithera Medical).

25 The photoacoustic imaging capability of the focused 32-element P(VDF/TrFE) multilayer transducer array was demonstrated using a commercial system (MSOT, Ithera Medical) as shown in Figure 13(a). A hollow polyethylene tube (516) was used as the imaging target and a pulsed laser (514) with pulse duration of 10 ns at wavelength of 940 nm was used to excite the photoacoustic signal on the polyethylene tube.

30

The polyethylene tube (516) was placed at the focal point of the curved transducer array (518) for optimum imaging quality.

35 The photoacoustic signal generated by the polyethylene tube was sensed by the focused 32-element P(VDF/TrFE) multilayer transducer array and processed by the

MSOT system. The hollow polyethylene tube structure can be resolved clearly in the photoacoustic image obtained by the focused 32-element P(VDF/TrFE) multilayer transducer array on the commercial photoacoustic imaging system (MSOT) as shown in Figure 13(b).

5

Although an embodiment of the present invention have been shown and described, the present invention is not limited to the described embodiments. Instead, it would be appreciated by those skilled in the art that changes may be made to the embodiments without departing from the scope of the invention, the scope of which is set forth in the following claims.

10

CLAIMS

1. A method of producing an electromechanical polymer multilayer structure, the method comprising:

5 a) depositing a first suspension of electromechanical polymer powder particles on a conductive surface of a substrate connected to a power supply to form a first polymer layer;

b) depositing a first electrode layer on the first polymer layer;

10 c) connecting the first electrode layer to the power supply and depositing a second suspension of electromechanical polymer powder particles on the first electrode layer to form a second polymer layer;

d) depositing a second electrode layer on the second polymer layer;

15 e) connecting the second electrode layer to the power supply and depositing a third suspension of electromechanical polymer powder particles on the second electrode layer to form a third polymer layer;

f) repeating steps (b)-(e) to form an electromechanical polymer multilayer structure comprising a plurality of polymer layers, a plurality of first electrode layers and a plurality of second electrode layers, wherein each of the polymer layers is disposed between two adjacent electrode layers; and

20 wherein the plurality of first electrode layers are interconnected to form a first electrode group of a first type and the plurality of second electrode layers are interconnected to form a second electrode group of a second type; and

wherein the first electrode layers of the first electrode group are electrically insulated from the second electrode layers of the second electrode group.

25

2. The method according to claim 1, wherein the electromechanical polymer powder particles are deposited on the conductive surface of the substrate by electrophoretic deposition, the electrophoretic deposition comprising:

30 immersing the conductive surface of the substrate into the first suspension of electromechanical polymer powder particles; and

applying an electrical potential across the conductive surface of the substrate and a counter electrode.

3. The method according to claim 1, wherein the electromechanical polymer powder particles are deposited on the first electrode layer and the second electrode layer by electrophoretic deposition, the electrophoretic deposition comprising:

immersing the first electrode layer and the second electrode layer into the second suspension of electromechanical polymer powder particles and the third suspension of electromechanical polymer powder particles, respectively; and

applying an electrical potential across each of the first electrode layer and the second electrode layer, respectively, and a counter electrode.

4. The method according to claim 3, wherein a portion of the first electrode layer and a portion of the second electrode layer are each not immersed in the suspension of electromechanical polymer powder particles during the electrophoretic deposition and the portions are exposed for realizing the electrical connection.

5. The method according to claim 1, further comprising:

treating the electromechanical polymer powder particles deposited on the substrate, on the first electrode layer and on the second electrode layer with heat above melting temperature of the electromechanical polymer powder particles to form continuous polymer layers.

6. The method according to claim 1, wherein the electromechanical polymer powder particles are selected from a group of piezoelectric polymers, including poly(vinylidene fluoride) (PVDF) and poly(vinylidene fluoride and trifluoroethylene) P(VDF/TrFE).

7. The method according to claim 1, wherein all the first, the second and the third suspensions of electromechanical polymer powder particles are prepared by dispersing the electromechanical polymer powder particles in isopropyl alcohol to form a stable suspension.

8. The method according to claim 1, wherein the first electrode layer and the second electrode layer are each deposited on the first polymer layer and the second polymer layer, respectively, by physical vapour deposition of a conductive layer on the first polymer layer and the second polymer layer.

9. The method according to claim 1, further comprising:
patterning the plurality of first electrode layers and the plurality of second electrode layers to form an array of a plurality of electromechanical elements.
- 5 10. The method according to claim 1, wherein the substrate is a curved substrate with a focal point.
11. The method according to claim 1, further comprising:
removing the substrate by chemical etching after the electromechanical polymer
10 multilayer structure is formed.
12. The method according to claim 1, wherein the electromechanical polymer multilayer structure having a thickness ranging from 1 to 100 μm .
- 15 13. An electromechanical polymer multilayer structure comprising:
at least one unit of successive layers, each unit comprises:
a first polymer layer;
a first electrode layer deposited on the first polymer layer;
a second polymer layer deposited on the first electrode layer; and
20 a second electrode layer deposited on the second polymer layer;
wherein each of the polymer layers is formed from a suspension of electromechanical polymer powder particles through connecting each of the electrode layers to a power supply to allow deposition of the polymer powder particles on each of the electrode layers, and each of the polymer layers is disposed between two adjacent
25 electrode layers;
wherein the first electrode layers of the successive layers are interconnected to form a first electrode group of a first type and the second electrode layers of the successive layers are interconnected to form a second electrode group of a second type;
and
30 wherein the first electrode layers of the first electrode group are electrically insulated from the second electrode layers for the second electrode group.
14. The electromechanical polymer multilayer structure according to claim 13, wherein the first electrode layers are interconnected at a portion not exposed to the
35 electromechanical polymer powder particles to form the first electrode group of the first

type; and the second electrode layers are interconnected at another portion not exposed to the electromechanical polymer powder particles to form the second electrode group of the second type.

5 15. The electromechanical polymer multilayer structure according to claim 13, wherein the first electrode layers and the second electrode layers are patterned to form an array of a plurality of electromechanical elements.

10 16. The electromechanical polymer multilayer structure according to claim 13, wherein the electromechanical polymer multilayer structure is curved with a radius of curvature.

15 17. An electromechanical device comprising an electromechanical polymer multilayer structure as described in claims 13-16.

18. An electromechanical device according to claim 17, wherein the electromechanical polymer multilayer structure is configured to convert acoustic wave into electrical signal for acoustic wave sensing, and/or convert applied voltage into acoustic wave for acoustic wave generation.

20 19. The electromechanical device according to claim 17, for use as a focused acoustic transducer with focal length equal to the radius of curvature of the multilayer structure.

25 20. The electromechanical device according to claim 17, for use as acoustic transducer to sense acoustic waves generated by light for photoacoustic sensing and imaging.