A generator includes a thin first contact charging layer and a thin second contact charging layer. The thin first contact charging layer includes a first material that has a first rating on a triboelectric series. The thin first contact charging layer has a first side with a first conductive electrode applied thereto and an opposite second side. The thin second contact charging layer includes a second material that has a second rating on a triboelectric series that is more negative than the first rating. The thin first contact charging layer has a first side with a first conductive electrode applied thereto and an opposite second side. The thin second contact charging layer is disposed adjacent to the first contact charging layer so that the second side of the second contact charging layer is in contact with the second side of the first contact charging layer.

13 Claims, 5 Drawing Sheets
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TRIBOELECTRIC GENERATOR

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application claims the benefit of U.S. Provisional Patent Application Ser. No. 61/528,981, filed Aug. 30, 2011, the entirety of which is hereby incorporated herein by reference. This application also claims the benefit of U.S. Provisional Patent Application Ser. No. 61/621,114, filed Apr. 6, 2012, the entirety of which is hereby incorporated herein by reference.

STATEMENT OF GOVERNMENT INTEREST

This invention was made with government support under agreement No. DE-FG02-07ER46394, awarded by the Department of Energy. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to generators and, more specifically, to a system for generating voltage and current using the triboelectric effect.

2. Description of the Related Art

Energy harvesting by converting ambient energy into electricity may offset the reliance of small portable electronics on traditional power supplies, such as batteries. When long-term operation of a large number of electronic devices in dispersed locations is required, energy harvesting has the advantages of outstanding longevity, relatively little maintenance, minimal disposal and contamination. Despite of these benefits, superior performance, miniaturized size and competitive prices are still to be sought after in order for energy harvesting technology becoming prevalent.

The triboelectric effect is a type of contact electrification in which certain materials become electrically charged after they come into contact with another such as through friction. It is the mechanism though which static electricity is generated. Triboelectric effect associated electrostatic phenomena are the most common electrical phenomena in our daily life, from walking to driving, but the triboelectric effect has been largely ignored as an energy source for electricity. Some electrostatic microgenerators have been developed and used in research relating to microelectromechanical systems (MEMS), but such designs tend to be based on inorganic materials and the fabrication of such devices requires complex processes.

Therefore, there is a need for a reliable, small and easily manufactured system for harvesting triboelectric energy.

SUMMARY OF THE INVENTION

The disadvantages of the prior art are overcome by the present invention which, in one aspect, is a generator that includes a thin first contact charging layer and a thin second contact charging layer. The thin first contact charging layer includes a first material that has a first rating on a triboelectric series. The thin first contact charging layer has a first side with a first conductive electrode applied thereto and an opposite second side. The thin second contact charging layer includes a second material that has a second rating on a triboelectric series that is more negative than the first rating. The thin first contact charging layer has a first side with a first conductive electrode applied thereto and an opposite second side. The thin second contact charging layer is disposed adjacent to the first contact charging layer so that the second side of the second contact charging layer is in contact with the second side of the first contact charging layer.

In another aspect, the invention is a triboelectric generator that includes a first conductive electrode layer, a second conductive electrode layer, a first contact charging layer and a second contact charging layer. The first contact charging layer has a first side and an opposite second side. The first conductive electrode layer is disposed on the first side of the first contact charging layer. The first contact charging layer includes a first material that has a first rating on a triboelectric series. The first contact charging layer has a thickness sufficiently thin so that a positive excess charge on the second side induces an electric field that induces negative charge carriers to form in the first conductive electrode layer. The second contact charging layer has a thickness sufficiently thin so that a second material that has a second rating on the triboelectric series wherein the second rating is more negative than the first rating. The second side of the second contact charging layer is disposed against the second side of the first contact charging layer. The second contact charging layer includes a second material that has a second rating on the triboelectric series wherein the second rating is more negative than the first rating. The second side of the second contact charging layer is disposed against the second side of the first contact charging layer. The second contact charging layer has a thickness sufficiently thin so that a negative excess charge on the second side induces an electric field that induces positive charge carriers to form in the second conductive electrode layer. Relative movement between contacting portions of the second side of the first contact charging layer and the second side of the second contact charging layer results in excess positive charge on the second side of the first contact charging layer and excess negative charge on the second side of the second contact charging layer.

In yet another aspect, the invention is a method of generating an electrical current and voltage in which a first contact charging layer is brought in contact with a second contact charging layer. The first contact charging layer has a first side and an opposite second side. A first conductive electrode layer is disposed on the first side of the first contact charging layer. The first contact charging layer includes a first material that has a first rating on a triboelectric series. The first contact charging layer has a thickness sufficiently thin so that a positive excess charge on the second side induces an electric field that induces negative charge carriers to form in the first conductive electrode layer. The second contact charging layer has a first side and an opposite second side. A second conductive electrode layer is disposed on the first side of the second contact charging layer. The second side of the second contact charging layer includes a second material that has a second rating on the triboelectric series wherein the second rating is more negative than the first rating. The second side of the second contact charging layer is disposed against the second side of the first contact charging layer. The second contact charging layer has a thickness sufficiently thin so that a negative excess charge on the second side induces an electric field that induces positive charge carriers to form in the second conductive electrode layer. Relative movement between the first contact charging layer and the second contact charging layer is caused. A load is applied between the first conductive electrode layer and the second electrode layer, thereby causing an electrical current to flow through the load.

These and other aspects of the invention will become apparent from the following description of the preferred embodiments taken in conjunction with the following drawings. As would be obvious to one skilled in the art, many
variations and modifications of the invention may be effected without departing from the spirit and scope of the novel concepts of the disclosure.

BRIEF DESCRIPTION OF THE FIGURES OF THE DRAWINGS

FIG. 1 is a schematic diagram of one representational embodiment.

FIG. 2 is a schematic diagram of several generating units stacked and coupled in series.

FIGS. 3A-3E is a plurality of schematic views showing a pressing-releasing sequence of one embodiment.

FIG. 3F is a graph demonstrating voltage relationships during the sequence shown in FIGS. 3A-3E.

FIG. 3G is a graph demonstrating current relationships during the sequence shown in FIGS. 3A-3E.

FIG. 4A is a micrograph of a contact charging layer having a surface with a rectangular prism texture.

FIG. 4B is a micrograph of a contact charging layer having a surface with a row texture.

FIG. 4C is a micrograph of a contact charging layer having a surface with a row texture.

Detaile Description of the Invention

A preferred embodiment of the invention is now described in detail. Referring to the drawings, like numbers indicate like parts throughout the views. Unless otherwise specifically indicated in the disclosure that follows, the drawings are not necessarily drawn to scale. As used in the description herein and throughout the claims, the following terms take the meanings explicitly associated herein, unless the context clearly dictates otherwise: the meaning of “a,” “an,” and “the” includes plural reference, the meaning of “in” includes “in” and “on.”

As shown in FIG. 1, a triboelectric energy harvesting system may be embodied as a generator or a sensor unit 100 that includes a first contact charging layer 110 that has a first conductive electrode layer 116 disposed on a first side 112 and that has an opposite second side 114 that has a textured surface. The first contact charging layer 110 includes a material with a relatively less negative triboelectric series rating. Examples of such materials can include: polyethylene terephthalate (PET), poly(methyl methacrylate) (PMMA), a conductor, a metal, an alloy and combinations thereof.

The operating principle of the system can be described by the coupling of contact charging and electrostatic induction, as shown in FIG. 3A-3G in an embodiment in which the first contact charging layer comprises a Kapton film and the second contact charging layer comprises PMMA. In FIG. 3A, at the original state, no charge is generated or induced, and no electric potential difference (EPD) exists between the two electrodes. When an externally introduced displacement is applied to the unit 110 in the direction of the arrows, as shown in FIG. 3B, the two contact charging layers are brought into contact with each other. Surface charge transfer then takes place at the contact area due to triboelectric effect. According to the triboelectric series, electrons are injected from PMMA into Kapton, resulting in net negative charges at the Kapton surface and net positive charges at the PMMA surface, respectively. The insulating property of these polymers allows a long-time retention of triboelectric charges for hours or even days.

Relative movement between the second sides 114 and 124 of the first contact charging layer 110 and the second contact charging layer 120 can be caused by applying a force to one of the layers. This causes electrons to be transferred from the second contact charging layer 120 to the first contact charging layer 110. This causes the second surface 114 of the first contact charging layer 110 to be negatively charged and the second surface 124 of the second contact charging layer 120 to be positively charged. The charges on the second sides 114 and 124 generate respective electric fields that induce charge accumulation in the electrode layers 116 and 126 and when a load 150 is coupled therebetween, electrons will flow through the load 150.
As the displacement decreases, the unit 100 starts to be released and the Kapton film begins to revert back to its original position due to its own resilience. Once the two polymers separate, an EPD is then established between the two electrodes, as shown in FIG. 3C. Defining electric potential of the bottom electrode \((U_{BE})\) to be zero, electric potential of the top electrode \((U_{TE})\) can be calculated by:

\[
U_{TE} = -\frac{\sigma d' \varepsilon_0}{\varepsilon_r} \tag{1}
\]

where \(\sigma\) is the triboelectric charge density, \(\varepsilon_0\) is the vacuum permittivity, and \(d'\) the interlayer distance at a given state.

Here, a forward connection is defined for measurement as a configuration with positive end of the electrometer 150 connected to the bottom electrode \((BE)\). (All electric measurements herein are based on the forward connection unless otherwise stated.) Therefore, as the unit 100 is being released, \(V_{oc}\) (as shown in FIG. 3F) keeps increasing until reaching the maximum value when the Kapton film fully reverts to the original position, as shown in FIG. 3D. Theoretically, such a voltage would remain constant provided that the input impedance of the electrometer is infinite. If renewed pressing is immediately followed, as shown in FIG. 3E, the EPD starts diminishing as the two polymer layers get closer to each other. As a result, \(V_{oc}\) drops from the maximum value to zero when a full contact is made again between the two polymers, as shown in FIG. 3F.

As shown in FIG. 3G, if the two electrodes are shorted, any established EPD shown in Equation (1) (as the two polymers separate) drives electrons from the top electrode \((TE)\) to the bottom electrode \((BE)\), resulting in a nearly instantaneous positive current during the releasing process. The net effect is that induced charges accumulate with positive sign on the \(TE\) and negative sign on the \(BE\). The induced charge density \(\sigma'\) when the generator is fully released can be expressed as below:

\[
\sigma' = \frac{\sigma d' \varepsilon_0 \varepsilon_r}{\delta_{TE} + d' \varepsilon_0 \varepsilon_r + d_2 \varepsilon_0} \tag{2}
\]

where \(\varepsilon_{r_1}\) and \(\varepsilon_{r_2}\) are the relative permittivity of Kapton and PMMA, respectively, \(d_1\) and \(d_2\) are the thickness of the Kapton film and the PMMA layer.

Once the unit 100 is pressed again, reduction of the interlayer distance makes the \(TE\) possess a higher electric potential than the \(BE\). As a consequence, electrons are driven from the \(BE\) back to the \(TE\), reducing the amount of induced charges. This process corresponds to the nearly instantaneous negative current shown in FIG. 3G. When the two polymers are in contact again, as shown in FIG. 3B, all induced charges are neutralized.

In one experimental embodiment, as triggered by a vibration source with controlled frequency and amplitude, the unit 100 produced an open circuit voltage and a short circuit current as predicted in the above analytical model. Electric output with opposite sign was obtained by switching the polarity for electric measurement. The peak value of the \(V_{oc}\) and \(I_{oc}\) were up to 110 V and 6 \(\mu\)A, respectively. Substituting the experimentally determined \(V_{oc}\) into Equation (1), a theoretical triboelectric charge density was obtained according to the following:

\[
\sigma = \frac{V_{oc\alpha}}{\varepsilon_0} = 97.39 \mu C/m^2 \tag{3}
\]

Then based on Equation (2), the maximum induced charge density \((\sigma'_{max})\) was theoretically calculated to be:

\[
\sigma'_{max} = \frac{\sigma d' \varepsilon_0 \varepsilon_r}{\delta_{TE} + d' \varepsilon_0 \varepsilon_r + d_2 \varepsilon_0} = 73.72 \mu C/m^2 \tag{4}
\]

Therefore, electrons are pumped back and forth between the two electrodes as a result of contact charging and electrostatic induction. For one cycle of contacting-sliding-separating the integration of current over time for releasing has the same value as that for pressing, indicating that equal amount of electrons flow in the opposite direction. The current peak corresponding to releasing has a smaller magnitude but lasts longer than that for pressing. Such an observation can be explained by the fact that pressing is caused by the external vibration source while it is the resilience of the Kapton film that leads to releasing. Therefore, it is likely that releasing corresponds to a slower process and thus a smaller but wider current signal. Having the maximum induced charge \((Q')\), the corresponding charge density was obtained as:

\[
\sigma'_{max} \frac{Q}{S} = 87.23 \mu C/m^2 \tag{6}
\]

where \(S\) is the electrode area. The experimental result in Equation (6) is only slightly larger than the theoretically calculated one in Equation (4), indicating that the model is fairly valid for explaining the working principle.

External load matching for the generator was studied in the experimental embodiment. With an increase in the load resistance, the maximum current decreases due to ohmic loss, while the maximum voltage across the load has an opposite trend. Accordingly, the electric power exhibited an instantaneous peak value of 110 \(\mu\)W, in correspondence to a power density of 31.2 mW/cm². The measurement results reveal that the generator is particularly efficient provided that the load has a resistance on the order of mega ohms.

One embodiment can be employed in a sensor system, such as a self-powered touch screen. To make the device transparent and improve the power generation density, three approaches were used in an experimental embodiment: (1) using a transparent PDMS film as one of the contact charging layers; (2) using transparent ITO for the electrode layers, resulting in a flexible and transparent structure; and (3) fabricating various PDMS pattern arrays to enhance the friction effect, resulting in a high-output generator unit.

Such an embodiment can be made of two sheets of polymers that have distinctly different triboelectric characteristics, with one easy to gain electrons and the other one easy to lose electrons. By stacking the two sheets together with flexibility of relative sliding, two insulating polymeric materials are touched and rubbed with each other when deformed by an external mechanical deformation. Thus, electrostatic charges with opposite signs are generated and distributed on the two surfaces of the polymer films due to the presence of the nanometer scale roughness, and an interface dipole layer is formed, which is called a triboelectric potential layer. Such a dipole layer induces an inner potential layer between the planar metal electrodes. The induced charges will not be
quickly conducted away or neutralized owing to the insulative nature of the polymer films. To minimize the energy created by the triboelectric potential, electrostatically induced free-charges will flow across the external load between the two electrodes coated on the top and bottom polymer sheets, respectively, to reach equilibrium. Once the structure is released and the triboelectric force is removed, the two polymer films recover their original shapes, and the triboelectrically generated positive and negative charges may neutralize, and the electrostatic induced charges across the two electrodes recombine.

As shown in FIGS. 4A-4E, patterns can be fabricated on the polymer surfaces to increase the triboelectric power output. To make patterned polydimethylsiloxane (PDMS) films, Si wafer molds 210 are fabricated by traditional photolithography methods, followed by a dry or wet etching process to fabricate different recessed features 212 on the surface, as shown in FIG. 4A. Examples of such features include pyramids 216, rectangular prisms 226 (as shown in FIG. 4A) and rows 236 (as shown in FIG. 4B). The surface of the molds is initially treated with trimethylchlorosilane to prevent the PDMS film from sticking to the recessed features 212. As shown in FIG. 4B, liquid PDMS elastomer and a cross-linker are mixed, degassed and uniformly spin-coated on the surface of the mold 210. As shown in FIG. 4C, after curing thermally, a uniform PDMS layer 214 is peeled off, including inverse 216 of the original pattern features 212 on the surface of the mold 210. As shown in FIG. 4D, the PDMS film was fixed on the insulation surface of a clean indium tin oxide (ITO)-coated 219 polyethylene terephthalate (PET) substrate 217 by a thin PDMS bonding layer, and then the entire structure was covered with another ITO-coated 215 PET film 213 to form a sandwich-structured device. A schematic view of a resulting structure is shown in FIG. 5.

The above described embodiments, while including the preferred embodiment and the best mode of the invention known to the inventor at the time of filing, are given as illustrative examples only. It will be readily appreciated that many deviations may be made from the specific embodiments disclosed in this specification without departing from the spirit and scope of the invention. Accordingly, the scope of the invention is to be determined by the claims below rather than being limited to the specifically described embodiments above.

What is claimed is:

1. A generator, comprising:
(a) a thin first contact charging layer including a first material that has a first rating on a triboelectric series, the thin first contact charging layer having a first side with a first conductive electrode layer applied thereto and an opposite second side;
(b) a thin second contact charging layer including a second material that has a second rating on a triboelectric series that is more negative than the first rating, the thin second contact charging layer having a second side with a second conductive electrode layer applied thereto and an opposite second side;
(c) a plurality of spaced apart shapes, each having a maximum length of 10 µm, extending outwardly from at least a selected one of the second side of the first contact charging layer and the second side of the second contact charging layer.

2. The generator of claim 1, wherein the first contact charging layer comprises a material selected from a list consisting of: polyethylene terephthalate, poly(methyl methacrylate), a conductor, a metal, an alloy and combinations thereof.
3. The generator of claim 1, wherein the second contact charging layer comprises a material selected from a list consisting of: poly-oxydiphenoxy-pyromellitamide, polydimethylsiloxane, a conductor, a metal, an alloy and combinations thereof.
4. The generator of claim 1, wherein the first conductive electrode layer and the second conductive electrode layer each comprise a material selected from a list consisting of: gold, silver, aluminum, a metal, indium tin oxide, and combinations thereof.
5. The generator of claim 1, wherein the plurality of spaced apart shapes includes a molded texture.
6. The generator of claim 5, wherein the molded texture comprises a texture that includes a plurality of evenly spaced shapes selected from a list consisting of: pyramids, rectangular prisms, rows and combinations thereof.

7. The generator of claim 1, wherein the plurality of spaced apart shapes includes a plurality of elongated vertically aligned nanowires extending outwardly therefrom.

8. A triboelectric generator, comprising:
   (a) a first conductive electrode layer;
   (b) a first contact charging layer having a first side and an opposite second side, the first conductive electrode layer disposed on the first side of the first contact charging layer, the first contact charging layer including a first material that has a first rating on a triboelectric series, the first contact charging layer having a thickness sufficiently thin so that a positive excess charge on the second side of the first contact charging layer induces an electric field that induces negative charge carriers to form in the first conductive electrode layer;
   (c) a second conductive electrode layer,
   (d) a second contact charging layer having a first side and an opposite second side, the second conductive electrode layer disposed on the first side of the second contact charging layer, the second contact charging layer including a second material that has a second rating on the triboelectric series wherein the second rating is more negative than the first rating, the second side of the second contact charging layer being disposed against the second side of the first contact charging layer, the second contact charging layer having a thickness sufficiently thin so that a negative excess charge on the second side of the second contact charging layer induces an electric field that induces positive charge carriers to form in the second conductive electrode layer; and
   (e) a plurality of spaced apart shapes, each having a maximum length of 10 µm, extending outwardly from at least a selected one of the second side of the first contact charging layer and the second side of the second contact charging layer, wherein relative movement between contacting portions of the second side of the first contact charging layer and the second side of the second contact charging layer results in excess positive charge on the second side of the first contact charging layer and excess negative charge on the second side of the second contact charging layer.

9. The triboelectric generator of claim 8, wherein the first contact charging layer comprises a material selected from a list consisting of: polyethylene terephthalate, poly(methyl methacrylate), a conductor, a metal, an alloy and combinations thereof.

10. The triboelectric generator of claim 8, wherein the second contact charging layer comprises a material selected from a list consisting of: poly-oxydiphenylene-pyromellitamide, polydimethylsiloxane, a conductor, a metal, an alloy and combinations thereof.

11. The triboelectric generator of claim 8, wherein the first conductive electrode and the second conductive electrode each comprise a material selected from a list consisting of: gold, silver, aluminum, a metal, indium tin oxide, and combinations thereof.

12. The triboelectric generator of claim 8, wherein the plurality of spaced apart shapes includes a molded texture including a plurality of evenly spaced shapes selected from a list consisting of: pyramids, rectangular prisms, rows and combinations thereof.

13. The triboelectric generator of claim 8, wherein the plurality of spaced apart shapes includes a plurality of elongated vertically aligned nanowires extending outwardly therefrom.