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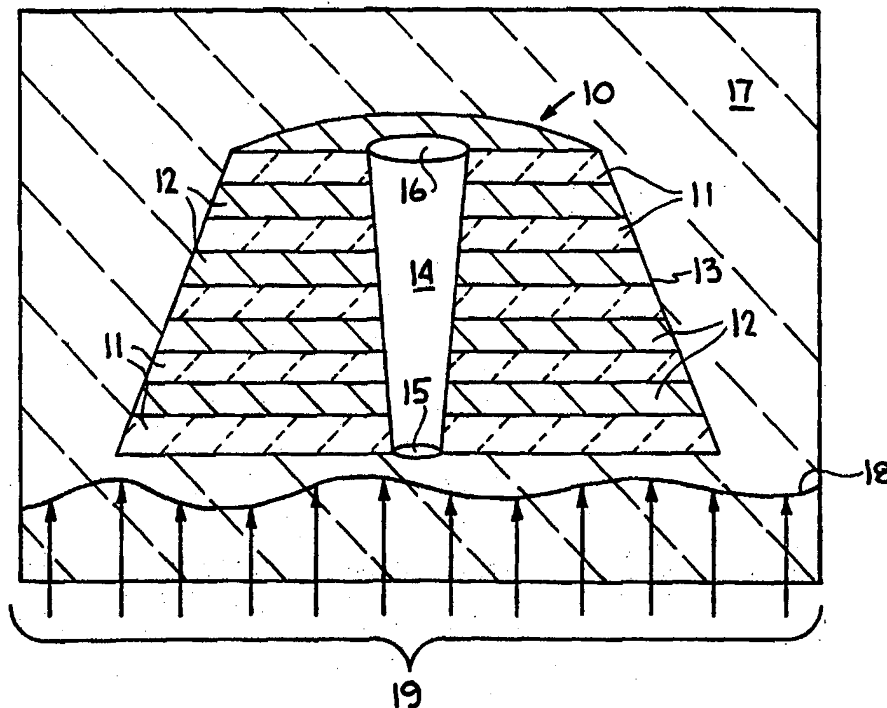
(57) Abstract



A shock or strain driven multilaminate piezoelectric high voltage stack, and fabrication process. The nanostructure includes alternating layers of piezoelectric and conductor materials forming a cylinder or similarly shaped stack of piezoelectric layers. For accelerator application the piezoelectric layers have a coaxial cavity. Very high voltages or high voltage waves can be generated when the piezoelectric stack is subjected to mechanical stock, which may be the result of a high explosive detonation or a more conventional mechanism. As the shock propagates through the piezoelectric stack, each layer of piezoelectric material generates a voltage potential between its two adjacent conductor layers. The voltage of each conductor layer is the sum of the voltages of preceding piezoelectric layers, as in batteries in series. For accelerator applications, charged particles at one end of the cavity in the stack are accelerated through the cavity to a target. The piezoelectric stack can be fabricated with discrete layers of piezoelectric and conductor materials stacked and mechanically bound within packaging or support material. Alternatively, integrated solid state piezoelectric stacks can be fabricated by the successive masked deposition of piezoelectric and conductor materials. Deposition of the materials can be carried out by physical or chemical vapor deposition, including RF sputtering and similar techniques.

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MULTILAMINATE PIEZOELECTRIC HIGH VOLTAGE STACK

The United States Government has rights in this invention pursuant to Contract No. W-7405-ENG-48 between the United States Department of Energy and the University of California for the operation of Lawrence Livermore National Laboratory.

RELATED APPLICATION

5 This application relates to U.S. Provisional Application No. 60/031,465 filed November 20, 1996, and claims priority thereof.

BACKGROUND OF THE INVENTION

The present invention relates to the generation of high voltages, particularly to a piezoelectric stack for high voltage applications, and more particularly to a shock driven solid state nanostructure high
10 voltage piezoelectric stack and process for fabricating same.

High voltage (100-300 Kv) acceleration is needed for many scientific and defense applications. Further, inexpensive, rugged and compact accelerators are in demand. The higher the voltage gradient across the accelerator the shorter the stack can be to achieve the same
15 particle acceleration. High voltage compact accelerator are currently limited by their power source, the voltage holdoff of dielectric materials, and their design and construction.

The present invention provides an all solid state multilaminate high voltage piezoelectric stack as an alternative to large high voltage
20 power supplies and even the newest dielectric materials. Applications for the multilaminate piezoelectric stack include compact accelerator configurations, compact high power microwave sources, and other short duration, high voltage sources. In the multilaminate piezoelectric stack a voltage is generated proportional to the mechanical strain of the

piezoelectric material. The multilaminate stack utilizes alternating layers of piezoelectric and conductor materials fabricated to form, for example, a cylinder shaped stack of piezoelectric layers, and as the shock or strain propagates through the stack, each layer of piezoelectric material
5 generates a voltage potential between its two adjacent conductive layers, and the voltage of each conductor layer is the sum of the voltages of preceding piezoelectric layers. The piezoelectric stack can be fabricated using conventional deposition techniques.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a means for
10 generating very high voltages or high voltage waves.

A further object of the invention is to provide a piezoelectric stack for high voltage applications.

A further object of the invention is to provide a method for fabricating a piezoelectric stack.

15 Another object of the invention is to fabricate a solid state multilaminate piezoelectric stack utilizing alternate layers of piezoelectric and conductor materials surrounded by a support material.

Another object of the invention is to provide a multilaminate piezoelectric high voltage stack that responds to imposed stress and
20 resulting strain on the stack.

Another object of the invention is to provide a shock driven piezoelectric high voltage stack.

Another object of the invention is to provide a multilaminate piezoelectric high voltage stack having alternating layers of piezoelectric
25 and conductor materials fabricated to form a cylinder or shaped stack of piezoelectric layers, and for accelerator application provide the stack of piezoelectric layers with a coaxial cavity.

Another object of the invention is to provide a shock driven compact particle accelerator utilizing a stack of piezoelectric layers having
30 a cavity therein, wherein charged particles at one end of the cavity are accelerated through the cavity to a target.

Other objects and advantages of the present invention will become apparent from the following description and accompanying drawing. The invention is a shock or strain driven multilaminate

piezoelectric high voltage stack for generating very high voltages or high voltage waves when the piezoelectric stack is subjected to mechanical shock or stress, which may be the result of a high explosive detonation or a more conventional mechanism. As the shock or stress propagates through the piezoelectric stack, each layer of piezoelectric material generates a voltage potential between its two adjacent conductor layers. The voltage of each conductor layer is the sum of the voltages of preceding piezoelectric layers, as in batteries in series.

Applications include, but are not limited to, the acceleration of charged particles. The piezoelectric stack includes alternating layers of piezoelectric and conductor materials fabricated to form a cylinder or similarly shaped stack of piezoelectric layers, and for accelerator application the stack includes a coaxial cavity. For accelerator applications, charged particles produced from a source at one end of the cavity are accelerated through the cavity to a target.

The multilaminate high voltage piezoelectric stack is fabricated as a solid state device. The stack can be fabricated with discrete layers of piezoelectric and conductor materials stacked and mechanically bound with packing, using conventional deposition techniques. Alternatively, integrated solid state high voltage piezoelectric stacks can be fabricated by the successive masked deposition of the piezoelectric and conductor materials.

BRIEF DESCRIPTION OF THE DRAWING

The accompanying drawing, which is incorporated into and forms a part of the disclosure illustrates an embodiment of the invention and, together with the description, serves to explain the principles thereof.

The single figure illustrates in cross-section an embodiment of a solid state multilaminate high voltage piezoelectric stack configured as a compact particle accelerator.

DETAILED DESCRIPTION OF THE INVENTION

The invention is directed to a shock or strain driven multilaminate piezoelectric high voltage stack. The piezoelectric stack is capable of generating 200-300 Kv and high acceleration voltages needed

for many scientific and defense applications. The invention provides a high voltage, inexpensive, rugged, and compact accelerator. When the piezoelectric stack is subjected to mechanical shock, very high voltages or high voltage waves are generated. As the shock or strain propagates through the piezoelectric stack, each layer of piezoelectric material generates a voltage potential due to the resulting strain between its two adjacent conductor layers. The voltage of each conductor layer is the sum of the voltages of preceding piezoelectric layers, as in batteries in series. Extraordinary short duration voltage gradients can be achieved, particularly when subjected to detonation shock in applications that result in destruction of the stack.

The multilaminate piezoelectric stack includes alternating layers of piezoelectric and conductor materials fabricated to form a cylinder or similarly shaped stack of piezoelectric layers, the stack being mechanically bound with packaging or support materials. For accelerator applications the cylindrical stack of piezoelectric layers is provided with a coaxial cavity. Charged particles from a source located at one end of the cavity are accelerated through the cavity to a target located at the other end of the cavity.

The invention has the potential for a wide variety of applications, such as for compact accelerators and compact high voltage and microwave sources. Inexpensive, explosive driven compact sources have applications such as particle accelerator for physics effects and diagnostics, and high power microwave use. Also, there are applications for inexpensive shock or strain driven compact sources and particle accelerators which vary from small, portable high energy x-ray sources for industrial and medical applications.

The multilaminate high voltage piezoelectric stacks can be fabricated with discrete layers of piezoelectric and conductor materials stacked and mechanically bound with packing. Alternatively, integrated solid state high voltage piezoelectric stacks can be fabricated by the successive deposition of piezoelectric and conductor materials. Deposition of the materials can occur by physical or chemical vapor deposition, including RF and DC sputtering and similar techniques.

By matching fully dense crystal lattice structures of the piezoelectric and conductor materials one can fabricate stacks capable of

functioning under extraordinary stress. The deposition process of fabrication also provides the opportunity to engineer-in piezoelectric characteristics well suit for accelerator or other applications matching the open circuit voltage or short circuit current required in response to an anticipated shock. For example, piezoelectric and conductor materials, such as zinc-oxide and gold, provide well matched crystal lattice structures in that they have the ability to form a close packed lattice with nearly identical interatomic distances. Fully dense single crystal materials have a significant advantage in withstanding high stress. Other piezoelectric materials suitable for high power stack applications include zirconium titanate, lead zirconate titanate (PZt), or $PbNb_2O_7$, while other conductor materials include Al, Cu, Pt, Rd, and indium tin oxide (ITO), or $In_2Sn_3O_2$.

The piezoelectric effect relies on the deformation of the material's crystal lattice and creation of domains as the temperature falls below the Curie temperature. Domains are aligned (polarized) by an imposed electric field and an electric double layer is created with the conductor materials bounding the piezoelectric material.

The voltage (v) developed across a piezoelectric material is

$$V = Q/C = g_{33}pt$$

where g_{33} is a constant for a piezoelectric material, p is the mechanical stress, and t is the thickness of the piezoelectric material. For bulk lead zirconate titanate (PZT) piezoelectric material $g_{33} = 20 \times 10 - 3$ v-m/n. A 5 K bar stress on a 1cm thick PZT device can generate a 100 Kv open loop potential to the limit of the materials dielectric strength and lattice integrity. The trick is to increase g_{33} and the dielectric strength, and defer failure of the piezoelectric effect. A multilaminate superlattice with a high density of interlaced piezoelectric double layers and equipotential conductor planes will accomplish all three.

Multilaminate materials fabrication is a well established technology at the Lawrence Livermore National Laboratory, as exemplified by U.S. Patent No. 5,486,277 issued January 23, 1966. Facilities and equipment capable of proof-of-principal and small scale device fabrication and testing are currently available. Thus, multilaminate manufacturing technologies are available for fabricating the solid state piezoelectric high voltage stacks, using precision deposition techniques

capable of synthesizing extraordinary smooth submicron thick layers of piezoelectric and conductor materials. The fabrication process for producing and testing a multilaminate piezoelectric high voltage stack utilizing these existing technologies will be set forth hereinafter. The multilaminate high voltage piezoelectric stack is fabricated as a solid state device. Physical vapor deposition techniques are employed to deposit alternating layers of piezoelectric materials, such as zinc oxide, and conductor materials (e.g., aluminum). Typical layer thicknesses can vary from 0.1 micron to 10s of microns. Tens to thousands of alternating piezoelectric-conductor layers may be deposited to generate very high voltages in response to mechanical stress or a shock wave. Shadow masks of various shapes and sizes may be used in depositing layers and fabricating stacks with tapered inner and outer surfaces. These solid state stacks may themselves be stacked and fused to form cascaded high voltage accelerators and sources.

The all solid state multilaminate high voltage stack of the present invention is an alternative to high voltage power supplies and even the newest dielectric materials. A voltage is generated proportional to the mechanical strain on the piezoelectric material. When layers of piezoelectric and conductor materials are stacked in submicron thicknesses, extraordinary voltage gradients may be produced. In response to detonation shock or mechanical stress, the multilaminate high voltage piezoelectric stack will generate very high voltages approaching the structural limit of the piezoelectric's lattice. As pointed out above, the voltage at each conductor layer is the sum of the voltages of preceding piezoelectric layers. Extraordinary short duration voltage gradients can be achieved, particularly when subjected to detonation shock.

The drawing illustrates in cross-section an embodiment of a solid state nanostructure high voltage piezoelectric stack configured as a compact particle accelerator. The piezoelectric stack, generally indicated at 10, includes a plurality of conductor material or metal equipotential plane layers 11 between which are piezoelectric material 12, formed in this embodiment as a tapered cylinder having an outer surface 13 and provided with a coaxial tapering opening or accelerator cavity 14. A particle source 15 is located at the bottom of cavity 14 and a target 16 is

located at the top of cavity 14. A support material 17 surrounds the piezoelectric stack 10, is similar in density and mechanical properties to the piezoelectric material 12, and is in close contact with the stack 10 to avoid reflecting transverse shock (voltage reversal is to be avoided). By
5 way of example, the stack 10 may be composed of 10 to 4,000 layers 11 and 12, with one more layer 11 than 12, the conductor material layers 11 may be composed of gold having a thickness of 0.05μ to 0.1μ; the piezoelectric material layers 12 may be composed of zinc oxide having a thickness of 1.0 to 100 microns; the support material may be composed of ZrO_2. In this
10 embodiment, for example, the tapered stack 10 may have an overall height of 10μ to 2mm, a lower diameter of 10 to 100mm, an upper diameter of 1 to 25mm, with the tapered outer surface 13 extending at a taper of 0.1° to 45°; and the tapering accelerator cavity 14 having a lower diameter of 0.1 to 0.5mm, and upper diameter of 0.1 to 1mm, tapering at
15 0.1° to 45° from bottom to top. The particle source 15 may be, for example, composed of tungsten or loaded europeum, and the target 16 composed of tungsten. The support material may, for example, have an overall height of 1 to 10mm, with a thickness of 10 to 100mm below and above the stack 10, and a thickness varying from 10 to 100mm along the tapered surface 13
20 of the stack 10.

As shown in the drawing, a shock front 18, produced by a detonation shock or mechanical stress indicated by arrows 19, propagates through the support material 17 towards the accelerator stack 10, wherein successive piezoelectric layers 11 erect with mechanical strain, the
25 accelerator voltage generated in the stack 10 is the instantaneous sum of voltage generated by each piezoelectric layer 11.

The following is an example of the fabrication process for manufacturing the accelerator stack 10 illustrated in the drawing using gold as the conducting material and zinc oxide as the dielectric material.
30 The operational steps of the process are as follows:

1. Using gold target in a 2 mTorr argon atmosphere and a magnetron source (DC powered to 600 watts and operating voltage of 700-750 V with current of 0.9 amps), the conducting electrode layer (gold) is deposited on a substrate, such as float
35 glass, at a deposition rate greater than 30 Å per second to a thickness of 0.1-0.2 μm (1000Å) for example, using a deposition

time of 30-70 seconds. It is desired to maintain the substrate temperature at 40°-50°C during processing.

2. Mask the thus deposited gold layer for electrode geometry, using nickle alloy as the maskant.

3. Position masked electrode in a second source using an argon atmosphere at 3-4 mTorr for depositing the ZnO layer.

4. Deposit the piezoelectric ZnO by reactive sputtering on the non-masked areas of the gold layer by magnetron sputtering in a reactive gas (O_2 at 0.5-1.0 mTorr), providing a deposition rate of 8 Å/sec. and thickness of 0.5 μm. This allows control of pressure at substrate stoichiometry of deposited ZnO to be controlled.

5. The maskant is removed, and the electrode is again placed in the first source (or an equivalent third source).

6. The maskant is applied to put on the next electrode, whereafter a layer of gold is applied.

7. The electrode is returned to the second source (or an equivalent fourth source).

8. An appropriate maskant is applied to enable deposition of a second layer of ZnO piezoelectric.

9. Thereafter the electrode is moved between sources and masked to provide the desired layers of gold and ZnO.

It should be noted that the substrate quality is important, high quality thin-uniform substrates with roughness of less than 1/20 of the thickness of the thinnest layer is preferred.

It has thus been shown that the present invention provides an inexpensive, rugged, and compact device capable of generating high voltages or high voltage waves. The shock or strain driven piezoelectric high voltage stack of the present invention has application for use in compact accelerators, compact high voltage and microwave sources, explosive driven compact sources for particle acceleration for studies relating to physics effects and diagnostics, as well as for portable high energy x-ray sources for industrial and medical applications.

While a particular embodiment, along with materials, parameters, and fabrication steps have been set forth to exemplify and explain the principles of the invention, such are not intended to be

limiting. Modifications and changes may become apparent to those skilled in the art, and it is intended that the invention be limited only by the scope of the appended claims.

THE INVENTION CLAIMED IS

1. A shock or strain driven multilaminate piezoelectric high voltage stack, comprising:

a plurality of layers of conductor material;

a plurality of layers of piezoelectric material, each of said
5 plurality of layers of piezoelectric material being positioned between a pair of said plurality of layers of conductor material; and

support material for said layers of conductor and piezoelectric materials.

2. The stack of Claim 1, additionally including an opening extending through said layers of conductor and piezoelectric materials.

3. The stack of Claim 2, additionally including a particle source and a target located in different areas of said opening.

4. The stack of Claim 1, wherein said conductor material is selected from the group consisting of Au, Al, Pt, Pd, ITO, and $In_2Sn_3O_2$.

5. The stack of Claim 1, wherein said piezoelectric material is selected from the group consisting of zinc-oxide, zirconium titanate, lead zirconate titanate, and $PbNb_2O_7$.

6. The stack of Claim 1, wherein said support material is selected from the group consisting of ZrO_2 and zirconia.

7. The stack of Claim 1, wherein said plurality of layers of conductor and piezoelectric materials are constructed to have a thickness of 0.05 to 0.1μ.

8. The stack of Claim 1, wherein said plurality of layers of conductor and piezoelectric material consist of a number of layers each having a thickness in the range of 1.0 to 100μ.

9. The stack of Claim 1, wherein said plurality of layers of conductor and piezoelectric material are constructed to have an externally extending tapered surface and an internal opening having a longitudinal taper.

10. The stack of Claim 9, additionally including a particle source located at one end of said internal opening, and a target located at an opposite end of said opening.

11. A shock driven apparatus for generating very high voltages or high voltage waves when subject to a mechanical or detonation shock, comprising:

a stack of alternating layers of conductor material and
5 piezoelectric material.

12. The apparatus of Claim 11, additionally including a material for packages said stack.

13. The apparatus of Claim 11, wherein said stack includes a coaxial cavity.

14. The apparatus of Claim 11, wherein said alternating layers have a thickness in the range of 1.0 to 100μ.

15. The apparatus of Claim 11, wherein said layers of piezoelectric material comprise a number of layers in the range of 10 to 4000.

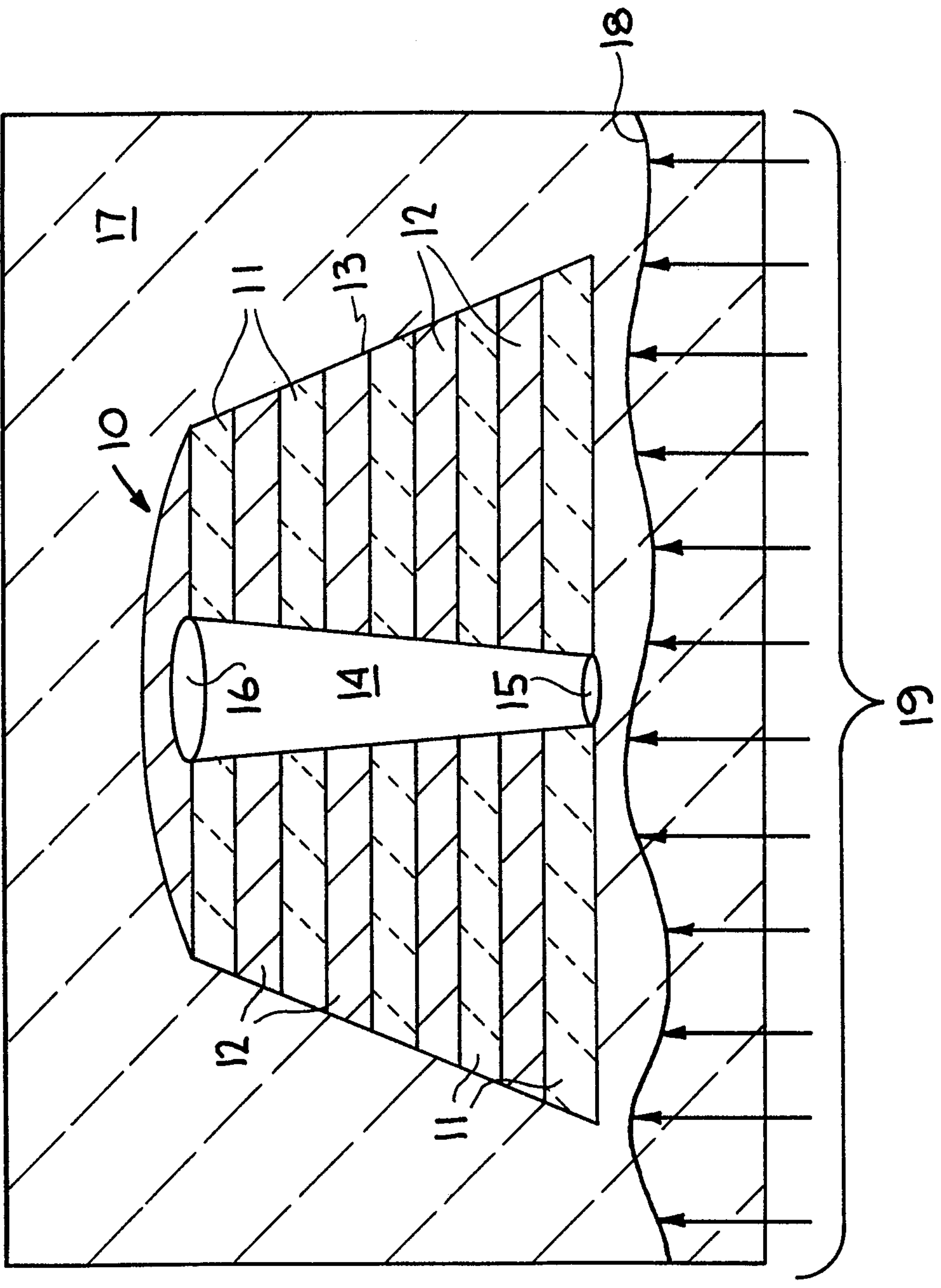
16. A process for producing a piezoelectric high voltage stack which includes forming alternating layers of conductor material and piezoelectric material by a technique selected from the group consisting of

physical or chemical vapor deposition of the individual alternating
5 layers, and successive masked deposition of the alternating layers.

17. The process of Claim 16, wherein the deposition is carried out by magnetron sputtering.

18. The process of Claim 16, wherein forming the alternating layers is carried out by forming layers of gold and zinc oxide.

19. The process of Claim 16 additionally including forming the conductor material from the group consisting of Au, Al, Pt, Pd, ITO, and $In_2Sn_3O_2$.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