Stack-type piezoelectric element and process for production thereof.

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Description

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

The present invention relates to a stack-type piezoelectric element, and relates to the structure of an overall stacked piezoelectric actuator which is excellent in moisture durability, reliability and productivity and particularly can work at low operating voltage.

DESCRIPTION OF THE PRIOR ART

Piezoelectric ceramics have a property to perform mutual conversion of mechanical energy and electrical energy, so that the application of the ceramics to sensors and actuators for detecting dynamical quantities has been actively developed. However, since the percentage of elongation of piezoelectric ceramics per unit voltage applied is low, very high voltage must be applied to obtain a practically useful displacement. Accordingly, a method is frequently used to lower the voltage to be applied which uses a structure wherein a large number of piezoelectric ceramic sheets of as small a thickness as possible are stacked. Piezoelectric elements having such a structure are called stack-type piezoelectric elements.

One of the most advanced technology for production of stack-type piezoelectric elements is the green sheet method. In this method, powders of a piezoelectric material are dispersed in a suitable solvent, the resultant slurry is made up into the form of sheet, and a metal paste is coated on the sheet to serve as an electrode by means of screen printing, etc. A large number of the sheets thus obtained are stacked and pressure bonded, then dried and sintered. By virtue of the above method of production, it has become possible to lower the applied voltage necessary to obtain a maximum elongation of 0.1% down to 100 V, which value is commercially accepted as the maximum elongation of piezoelectric elements. Stack-type piezoelectric elements obtained by such prior art green sheet method are already known, for example, from Japanese Patent Publication No. 59-32040 and the article described in Sensor Gijutsu (Technology) 3, No. 12, p. 31 (1983).

Further, as an electrode structure which reduces the internal stress of a stack-type piezoelectric element and improves its reliability, there is described a system wherein the area of the piezoelectric ceramic and that of the electrode are made equal (hereinafter referred to as overall stacked system) in Japanese Patent Publication No. 63-17354. The cross-section of the overall stacked piezoelectric element is shown in Figs. 8 and 9, Fig. 9 is the A-A sectional view of the element of Fig. 8.

As other examples of prior arts related to the present invention, mention may be made of Japanese Patent Application Kokai Nos. (Laid-open) 62-62,571, and No. 61-27,868 etc.

In the former of the prior art methods described above, the sintering of the green sheet of the piezoelectric ceramic sheet 1 and the stacking thereof with the electrode 2 are simultaneously performed at about 1300°C. Therefore, noble metals stable at high temperature, particularly silver-palladium (AgPd) alloy, have been commonly used as the material for the electrode 2. However, piezoelectric elements using said silver-palladium alloy electrode have the problem of short-circuit between electrodes occurring during operation in humid atmosphere. The cause for this is conceivably that water permeates the molding resin 5 which is to protect the side face of the piezoelectric element, and a layer of water is formed between the stacked body and the resin 5, resulting in a low contact resistance between electrodes, or causing silver to dissolve out as ions (Ag+) thereinto, which are attracted by the electric field and deposited in the vicinity of neighboring electrodes, forming a current-carrying path. This phenomenon is generally called "migration" and is a problem common to all electrical parts using silver or silver-base alloy electrodes.

On the other hand, in overall stacked piezoelectric elements, the latter of the prior art technologies, a method is employed wherein the insulator 4 is coated along the end face of the electrode 2 in order that the electrode 2 and the lead-out terminal 3 are connected alternately, as shown in Fig. 8. In this method, however, the width and the thickness of the insulator 4 must be sufficiently large as compared with the thickness of the electrode 2 so as to ensure necessary dielectric strength, which becomes an obstruct in decreasing the distance between electrodes or the thickness of the piezoelectric ceramic sheet 1, resulting in difficulty in decreasing the operating voltage. Further, since the terminal 3 is formed on the rugged surface of the insulator 4, it causes a problem in its reliability. Another problem is that since the production steps are complicated, the yield of the product is low and the cost of production is high.

SUMMARY OF THE INVENTION

The object of the present invention is to provide a structure of an overall stacked piezoelectric element which undergoes no short-circuit of electrodes even in humid atmosphere, operates particularly at low voltage, and is excellent in reliability and of low cost, and to provide a method for producing such a piezoelectric element.

The above objects are solved by a stack-type piezoelectric element according to claim 1 and a process for production of a stack-type piezoelectric element according to claim 6, respectively. The dependent claims are directed to particular embodiments of the
invention.

It is particularly effective but not restrictive to assemble a so-called overall stacked system, wherein the area of the piezoelectric ceramic sheet is equal to that of the metal sheet for electrode.

In claim 1 the term "the electrical insulating compound substitution composed of the oxide and/or nitride of the material of said metal sheet" means a product formed by converting at least a portion of the metal sheet into an electrical insulating compound by suitable means, for example, subjecting at least a part of the sheet to an oxidation treatment, thereby converting at least a portion of the part into the oxide of the metal, an insulating compound. By such a treatment, the metal of said portion is, so to speak, replaced by the insulating compound or in other words, the insulating compound is substituted for the metal, not coated onto the metal.

Further advantages and particular embodiments of the invention shall briefly be outlined below.

The side face of the stacked body is preferably coated with a molding resin.

The planar dimension of the piezoelectric ceramic sheet is preferably approximately equal to that of the metal sheet.

A heater is preferably provided on the outside of the stacked body.

Electrical insulating compound substitution products are preferably positioned alternately for every metal sheet.

A stack-type piezoelectric device (e.g., actuator and sensor) is preferably provided with an external lead which collects, among the respective electrodes of the above-mentioned piezoelectric elements, the positive electrodes and with an external lead which collects the negative electrodes.

The piezoelectric element is produced according to claim 6 with the piezoelectric ceramic sheet and the metal sheet preferably having the same dimension except for the thickness. The metal sheet is preferably formed of aluminum or an alloy of solid solution of aluminum with silicon, magnesium or germanium. Further, an effective metal sheet comprises preferably an aluminum alloy core material and a skin material of an aluminum alloy having a lower melting point than that of the core material formed on the both sides of the core material. In this case, the heat-forming temperature (of the element) is for example 580-650 °C.

The process at least comprises a step of forming a metal film on at least one side surface of a sintered piezoelectric ceramic sheet and a step of stacking the piezoelectric ceramic sheets and heating them while applying pressure thereto to bond them.

Instead of merely piezoelectric ceramic sheets also piezoelectric ceramic sheets with metal layers lying between respective ceramic sheets can be stacked, with the metal layer being optionally formed of any one metallic material selected from nickel and copper.

To sum up, the process for preparation of stack-type piezoelectric elements of the present invention comprises stacking layers of a sintered piezoelectric ceramic material and electrode layers alternately, and then heating, or heating under pressure, them at a temperature lower than the sintering temperature of the piezoelectric ceramic material and keeping them at the condition for a predetermined time to effect bonding, particularly preferably diffusion bonding, of the stacked layers.

The term "sintered piezoelectric ceramic" referred to herein means the product obtained by sintering a piezoelectric ceramic green sheet.

It is preferable that after the bonding step the bonded body is cooled without removal of applied pressure. Particularly in the course of cooling after the bonding step, it is desirable to apply a voltage at a temperature higher by 20-70°C than the Curie point of the piezoelectric ceramic to effect the polarization of the ceramic. The "Curie point" referred to herein means the temperature at which the piezoelectric ceramic loses its characteristic property, and the "polarization" means one step of treating the ceramic to convert it into a piezoelectric element.

In general, a piezoelectric ceramic material is a ferroelectric material having a crystal structure of perovskite type. At a temperature higher than the Curie point it exists as a crystal of cubic system, whereas at a temperature lower than the Curie point it assumes a crystalline phase deformed from the cubic system, resulting in development of dislocation in the crystal structure, that is, polarity (or orientation). The piezoelectric ceramic immediately after sintering is the aggregate of crystal particles, and parts of different polarities are present mingled with each other in each crystal particle. In a piezoelectric ceramic which has undergone sintering alone, the sum of polarity vectors for respective crystal particles is zero, and the ceramic is nonpolar as a whole. By application of a predetermined electric field to the ceramic, the direction of polarity is determined for each individual crystal particle. This is called polarization and such a treatment is called polarization treatment.

The material for electrodes may be used in any desired form including film, foil and paste. Particularly preferable as the material are pure aluminum, nickel, aluminum-base alloys and nickel-base alloys, because they do not cause migration unlike silver or silver-base alloy. From the same viewpoint, platinum and palladium may also be used. When an aluminum electrode used, it preferably has a three layer structure wherein the both skin materials are aluminum-silicon alloy and the core material is aluminum.

The form of stacking is not limited to planar stacking; it may also be a cylindrical one. 

Polarization causes the piezoelectric ceramic it-
self to increase its volume, resulting in development of large internal stress. Accordingly, when the polar-
ization treatment is applied in the course of cooling, the internal strain (in other word, internal stress) is re-
leased as the result of compensation between the vol-
ume contraction due to cooling and the volume in-
crease due to polarization, and hence the strength re-
liability of the piezoelectric ceramic is improved.

When pure aluminum or aluminum-base alloys are used as the electrode metal, the stacking tempera-
ture (bonding temperature) can be greatly lowered, so that the thermal stress developed is small. Further, since aluminum is an active metal, the bonding of the electrode with the piezoelectric ceramic is improved.

Further, in the present invention, the insert mate-
rual used for bonding the piezoelectric layers with each other serves also as the electrode material, so that the operations for production are simple.

The main point in the present invention is the use of aluminum, nickel are the like as the electrode ma-
terial. Aluminum, nickel and the like are a very active metal when they have a clean surface, but they change into a chemically stable, so-called passive state when the surface is oxidized or nitrided. Therefore, it is possible to stack sintered piezoelectric ceramic sheets by bonding them with each other utilizing the active surfaces of the above-mentioned metallic materials and to use the metallic material as it is as the electrode. In this case, when the part of the elec-
trode which exposes itself on the side face of the stacked body is subjected to stabilization treatment, lowering of insulation resistance does not occur even when the side face comes to be wet with water during the operation in humid atmosphere, nor does migra-
tion due to dissolving out of the electrode into water as ions.

Particularly when the present invention is applied to an overall stacked piezoelectric element in which the electrode is formed over the whole face of the pie-
zolectric ceramic sheet, an insulator can be formed without producing irregularities on the side face of the element. Accordingly, the thickness of the piezoelec-
tric ceramic sheet can be reduced and hence the oper-
ating voltage can be lowered. Further, since the lead terminal is formed on a flat side face, its reliabil-
ity is improved. Moreover, since the production steps become simple, productivity is also improved.

The above-mentioned stabilization treatment can be achieved, for example, by oxidizing that part of the aluminum electrode exposed on the side face of the stacked body which part is not connected with the lead terminal by means of anodic oxidation and further filling remaining holes by electrophoresis, there-
by forming a dense electrical insulator. As the result of the treatment, lowering of insulation resistance is prevented from occurring even when the side face comes to be wet with water during the operation in hu-
mid atmosphere.

According to the present invention, the moisture resistance of a stack-type piezoelectric element can be improved, and the operating voltage can be lowered and the reliability can be improved of an overall stacked piezoelectric element.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a perspective view of the stacked body before being coated with a molding resin, of the stack-
type piezoelectric element of one embodiment of the present invention. Fig. 2 is a sectional view of the stacked body of Fig. 1 taken along the plane ABC. Fig. 3 is a perspective view showing the most effective structure of an electrode for stacking. Fig. 4 is a process flow diagram showing the steps for producing the stack-type piezoelectric element of one embodiment of the present invention. Fig. 5 is a sectional view showing one form of the end face of an electrode. Fig. 6 is a process flow diagram showing the steps for pro-
ducing the stack-type piezoelectric element of an-
other embodiment of the present invention. Fig. 7 is a diagram for illustrating an apparatus used for form-
ing an insulator layer. Fig. 8 is a two-directional sec-
tional view of an overall stacked piezoelectric element of the prior art. Fig. 9 is the A-A section of the element of Fig. 8. Fig. 10 is a longitudinal section of a mass flow controller relating to an application example. Fig. 11 is a longitudinal section of an injection valve relating to an application example. Fig. 12 is a longitudinal section of a movable stage for precision positioning relating to an application example. Fig. 13 is a longi-
tudinal section of the printing head of a printer relating to an application example.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

One embodiment of the present invention will be described below with reference to Fig. 1.

Fig. 1 is a perspective view of a stack-type pie-
zolectric element according to the present invention before being coated on the side face with a molding resin. Fig. 2 is a sectional view of the element shown in Fig. 2 taken along the plane ABC.

Dielectric ceramics which have a property to de-
velop electric polarization when pressure is applied there to, namely piezoelectricity, are called a piezo-
electric ceramic, among which barium titanate (Ba
TiO₃), lead titanate (PbTiO₃), lead titanate zirconate (Pb(Zr, Ti)O₃) etc. are in wide use.

The powders of these piezoelectric ceramics are mixed with a solvent to obtain a paste, and green sheets are obtained by forming the paste. Piezoelec-
tric ceramic sheets 1 are obtained by sintering the green sheets. A stacked body is obtained by using a plural number of the piezoelectric ceramic sheets 1 thus obtained, as shown in Figs. 1 and 2, arranging
between the respective layers electrode plates 2a and 2b, and then applying heat and pressure.

Lead-out terminals 3a and 3b for electrode plates 2a and 2b are formed at the two places on the side face of the stacked body obtained above, and the electrode plates 2a and 2b of every other layer are connected alternately with the lead terminals 3a and 3b. In this time, the end faces of the electrodes 2a and 2b which are not covered with the lead terminals 3a and 3b and expose themselves on the side face of the stacked body are converted into electrically insulating compounds 4a and 4b, for example, oxides or nitrides.

Further, as shown in Fig. 2, the electrode 2a connected to the lead terminal 3a is converted, at the part bordering to the lead terminal 3b, into an electrical insulating compound 4a to prevent electric contact with the terminal 3b, and the electrode 2b connected to the lead terminal 3b is converted, at the part bordering to the lead terminal 3a, into an electrical insulating compound 4b to prevent electric contact with the terminal 3a. The material of respective electrodes 2a and 2b is selected from aluminum, alloys of solid solution of aluminum with silicon, magnesium, or germanium, nickel, and alloys of solid solution of nickel with chromium, palladium, or copper or phosphorus, copper, and alloys of solid solution of copper with phosphorus or zinc.

A particularly preferable structure of an electrode is as shown in Fig. 3, wherein a skin material 22 of aluminum alloy, nickel alloy or copper alloy is formed on the both sides of a core material of aluminum, nickel, or copper.

The adoption of the electrode materials and the insulation structures described above offers the following advantages.

First, when an electrode containing aluminum as the main component is used, only the skin layer of the electrode turns to the liquid phase at a heating temperature of 580-660°C (melting point of aluminum) used in forming a stacked body by heating and application of pressure, so that the oxide film of the aluminum alloy electrode surface is broken and the above-mentioned liquid phase of active alloy promotes the close adhesion and the reaction of the alloy with the piezoelectric ceramic. On the other hand, aluminum of the core material remains as the solid phase, thus forming a dense electrode and keeping a constant thickness of electrode. Also when a nickel electrode or copper electrode is used, the same principle as that for aluminum applies except that the appropriate heating temperature is different.

Nextly, by converting the end face of the electrode used for stacking the piezoelectric ceramic sheets into an insulator, the restriction to the thickness of piezoelectric ceramic sheet 1 imposed in the prior art example (Fig. 8) is removed and the lowering of operating voltage becomes possible. Furthermore, since the side face of the stacked body is flat unlike in prior art examples, the form of the lead terminal 3 is smooth and the occurrence rate of breaking of wire is low. Further, the occurrence rate of migration and of the short-circuit between electrode 2 are low even when water permeates molding resin 5 during operation in humid atmosphere.

A process for production of a stack-type piezoelectric element will be described below with reference to Fig. 4.

a) Formed and sintered piezoelectric ceramic sheets 1 and aluminum alloy electrodes 2a and 2b were stacked alternately, and then heated up to about 600°C and held at the condition for 1 hour or less while a pressure of 1 kg/mm² or less was being applied thereto by using a hot press in an argon atmosphere, to form a stacked body. The side face of the stacked body was polished and then an electrode 3' was formed on the side face where electrodes 2a of every other layer exposed themselves.

b) The electrode 3' was subjected to anodic oxidation treatment, whereby the end faces of the electrodes 2a in contact with the electrode 3' were converted to an oxide 4a.

c) The electrode resulting stacked body was divided longitudinally by cutting so as to give an overall stacked structure wherein the electrode 2a and the electrode 2b had the same area. The Figure shows above-mentioned b) viewed from the right side, and shows the oxide 4a as if it is protruding to make its position clear.

d) A lead terminal 3a was formed on the side face where the oxides 4a and the electrodes 2b were alternately present, and was made to contact electrically with the electrodes 2b.

e) The lead terminal 3a was subjected to anodic oxidation treatment, whereby the end faces of the electrodes 2b in contact with the lead terminal 3a were converted into an oxide 4b.

f) A lead terminal 3b was formed on the side face where the electrodes 2a having a metallic surface exposed and the oxides 4b were present alternately, and was made to contact electrically with the electrodes 2b.

Although succeeding steps are not shown in the Figure, a lead wire for application of voltage was bonded to the lead terminal 3, and the side face of the stacked body was coated with molding resin. Finally, polarization treatment was conducted to give an intended piezoelectricity, whereby a stack-type piezoelectric element was obtained.

When nickel alloys are used for the electrode 2, the heating temperature is 850-1300°C, and when copper alloys are used, the heating temperature is 700-1000°C.

Even when the selective oxidation of electrodes by means of anodic oxidation is not conducted and an
insulation structure of prior art method is adopted, the effect of preventing the short-circuit of electrodes during operation in humid atmosphere can be attained by nitriding oxidizing, for example by means of glow discharge plasma, the end faces of the electrodes exposing themselves on the side face of the stacked body before the stacked body is coated with molding resin.

In the embodiment shown above, the end face of electrode was flat. Another embodiment wherein the situation is different will be described below with reference to Fig. 5. When the heating in stacking the piezoelectric ceramic sheets 1 and the electrodes 2 is above the melting temperature of the electrode 2, the electrode 2 will melt and be forced out to the side face of the stacked body as shown in Fig. 5. The electrode 2 of such a form is subjected to anodic oxidation treatment to form an oxide 4. By adopting such a form, the adhesion between the piezoelectric ceramic sheet 1 and the electrode 2 is enhanced and the strength of the stacked body is improved. Moreover, a thick insulator as used in the prior art example is not necessary, so that this method is suited for decreasing the thickness of the piezoelectric ceramic sheet 1.

Another process for production of a stack-type piezoelectric element will be described below with reference to Fig. 6.

a) Formed and sintered piezoelectric ceramic sheets 1 and aluminum alloy electrodes 2a and 2b whose areas are different for every other layer were stacked alternately, and heated up to 600°C or less and held at the condition for 1 hour or less while a pressure of 1 kg/mm² or less was being applied thereto by using a hot press in argon atmosphere, to form a stacked body. The side face of the stacked body was polished and then an electrode 3′ was formed on the side face where only the electrodes with a larger area expose themselves.

b) The electrode 3′ was subjected to anodic oxidation treatment, whereby the end faces of the electrodes 2a in contact with the electrode 3′ were converted to an oxide 4a. Though the Figure shows the oxide 4 as if it is protruding on the face opposite to the electrode 3′ in order to emphasize that said opposite face is also converted to oxide, actually the face is flat.

c) The stacked body was subjected to a cutting work such that the electrodes 2a and 2b become of the same area and an overall stacked structure is obtained.

d) A lead terminal 3a was formed on the electrodes 2a of which every other layer have been subjected to oxidation treatment, and was made to contact electrically with the electrode 2b.

e) The lead terminal 3b was subjected to anodic oxidation treatment, whereby the end faces of the electrodes 2b were converted to an oxide 4b.

f) A lead terminal 3b was formed on the side face where the electrodes 2a having a metallic surface exposed and the oxides 4b were present alternately, and was made to contact electrically with the electrodes 2a.

Succeeding steps are the same as those in the embodiment described before.

The process described above is suited to production of stack-type piezoelectric elements which use electrodes of relatively large area and require no cutting of the stacked body.

In each of the embodiments described above, such measures may also be adopted as improving the water permeability of molding resin which coats the outermost layer of the piezoelectric element to prevent water from coming into the element, or covering the element completely with a metallic cover. Examples of suitable molding resins include epoxy resins (which are used for molding most of the semiconductor elements), or epoxy resins incorporated with phenol-novolak resin as a cure accelerator, silicone rubber as a flexibility-imparting agent or powders of silica or alumina as a filler for improving the strength; and further polyimide resins, fluorocarbon resins, etc.

As examples of active metals which can be chemically stabilized by oxidation or nitriding, mention may be made, besides aluminum, aluminum-base alloys, nickel, and nickel-base alloys, of tin, tin-base alloys, indium, indium-base alloys, titanium, titanium-base alloys, zirconium, zirconium-base alloys, iron, iron-base alloys, zinc, zinc-base alloys, etc.

Then, an embodiment regarding the method for insulation treatment of electrode end faces will be described further with reference to Fig. 7. Piezoelectric ceramic sheets 1 and aluminum alloy electrodes 2 having a smaller area than the former are stacked to obtain an alternately stacked body 6 as shown in the Figure. A temporary electrode 10 is formed at the positions in the side face of the body obtained above where the end faces of electrodes of every other layer expose themselves. Then the stacked body is immersed in an electrolytic solution 9 while a direct current is being connected such that the temporary electrode acts as the anode and a metal 7 having a stronger ionization tendency than has the temporary electrode 10 acts as the cathode. With this apparatus, the surface of the electrode 2 in contact with the temporary electrode 10 is anodically oxidized and a porous oxide layer is formed. The electrolytic solution used here is, for example, a dilute aqueous solution of sulfuric acid, oxalic acid, boric acid, etc. Then the stacked body is subjected to electrophoresis wherein the body is immersed in a dilute electrolytic solution containing a resin dispersed therein in place of the electrolytic solution, whereby the resin is impregnated or attached to the inside and the surface of the holes of the porous oxide layer present on the surface of the anodically oxidized electrode 2; thus the hole-
filling treatment is attained and a dense electrical insulating compound layer is formed on the end face of the electrode 2. The insulating layer thus formed insulates the lead-out terminal and the internal electrode from each other.

The above embodiments were described mainly with aluminum electrodes as examples. When a nickel electrode is used, a combination of a core material 121 of nickel and a skin material of nickel-phosphorus alloy is preferable, and when a copper electrode is used a combination of a core material 121 of copper and a skin material 122 of copper-phosphorus alloy or copper-zinc alloy is preferable.

When an electrode plate comprising nickel as the main component is used and the heating temperature for forming the stacked body by heat and pressure is 900–1050°C, only the skin layer of the electrode plate turns to the liquid phase, so that the oxide film on the nickel-phosphorus alloy electrode plate surface is broken, and the liquid phase of active nickel-phosphorus alloy promotes the close adhesion and reaction with the piezoelectric ceramic. On the other hand, nickel of the core material remains solid and thus a predetermined thickness of the electrode plate is maintained.

When an electrode plate comprising copper as the main component is used, the same effect as that obtained in using nickel as the main component can be obtained at heating temperature of 700–1000°C.

As to the method for forming an electrode metal on the piezoelectric ceramic, besides those described above, the following methods are effective: coating of a paste of metallic material followed by baking, plating, physico-chemical vapor deposition methods such as evaporation and sputtering, etc.

Stacked bodies were formed by stacking piezoelectric ceramic sheets coated with metal films as described above and heating them while applying pressure thereto. The applied pressure was, for example, 0.5 kgf/mm² and the bonding atmosphere was air or an inert gas (e.g., Ar). A high bonding strength was obtained by setting the heating temperature at 850–1050°C for nickel-phosphorus alloys, about 1060°C for copper, 700–950°C for copper-phosphorus alloys, and 800–950°C for copper-zinc alloys.

When an electrode plate of plural layers is used, the stacked body may be formed, for example, by alternately stacking a piezoelectric ceramic sheet 1 coated with a metal film 22 comprising as the main component a nickel-phosphorus alloy, copper-phosphorus alloy or copper-zinc alloy and a nickel or copper plate 21, and heating them under applied pressure. Through the use of this method, only the metal layer of alloy turns to the liquid phase and the metal film 2 remains solid, keeping a predetermined electrode plate thickness, so that the respective layers of the stacked body are formed parallel to one another, no bending stress develops in the piezoelectric cer-amic sheets, and resultantly a stacked body with little of strain can be obtained.

Fig. 10 is a longitudinal section showing one example of a mass flow controller using the stack-type piezoelectric element of the present invention. In Fig. 10, a piezoelectric element 11 is elongated or contracted by applying a voltage thereto, the motion is transmitted to a diaphragm 12, whereby the opening of an orifice 13 provided in the passage of a fluid (e.g., gas) to be controlled is adjusted and the flow rate is controlled.

Such a mass flow controller shows a response behavior drastically improved as compared with the prior art controller using a solenoid. Further, a short life and a high operating voltage, which are serious problems in using piezoelectric element of prior art structures, can be improved.

Fig. 11 is a longitudinal section showing one example of the structure of an injection valve using the stack-type piezoelectric element of the present invention. In Fig. 11, a piezoelectric element 21 is elongated or contracted by applying a voltage thereto, the motion is transmitted to a cylinder 22, whereby a passage 23 of fuel inlet side is connected with a passage 24 provided to the cylinder. The amount of injected fuel is controlled by adjusting the length of time of voltage application to the piezoelectric element.

Such an injection valve does not require a step-up transformer for high voltage impression unlike in the use of piezoelectric elements of prior art structures and is free from such problems as shortening of life due to adhesion of fuel mists. Thus, the most efficient use can be made of the advantage of the use of piezoelectric elements, namely improvement in the response and accuracy of fuel injection.

Fig. 12 is a side view showing one example of a movable stage for precision positioning using the stack-type piezoelectric element of the present invention. In Fig. 12, a stage 34 is a coarse adjustment stage which is moved by a linear actuator 33 such as a ball screw. A fine adjustment stage 32 provided on the former stage is moved by means of a piezoelectric element 31.

The use of the piezoelectric element of the present invention in such a movable stage makes it possible to improve the moisture resistance and the reliability of movable stages using piezoelectric elements having a more excellent response behavior and accuracy than those of the prior art and to construct a movable stage capable of operating with excellent reliability even in humid atmosphere.

Fig. 13 is a side view showing one example of the structure of the printing head of a printer using the stack-type piezoelectric element of the present invention. In Fig. 13, a displacement produced by a piezoelectric element 41 is transmitted via a lever of a plate spring 42 to a printing pin 43 to perform printing.

Such a printing head has not only an excellent re-
sponse behavior but also an advantage of exhibiting a strong printing power with a very small size. Further, it exhibits a high performance of keeping a sufficient reliability even in humid atmosphere.

Claims

1. A stack-type piezoelectric element comprising a stacked body of plural piezoelectric ceramic sheets (1) and metal sheets (2a, 2b) lying between the respective piezoelectric ceramic sheets (1) and a pair of lead-out terminals (3a, 3b) provided to the side face of the stacked body, said metal sheet (2a, 2b) being a plate of a metallic material of single or plural layers selected from the group consisting of aluminum, aluminum-base alloys, nickel, nickel-base alloys, copper, copper-base alloys and active metals capable of being made chemically stable by oxidation and/or nitriding, wherein said metal sheets (2a, 2b) are alternately contacted electrically with one of said lead terminals (3a, 3b), the other lead terminal is rendered electrically non-contact with the metal sheets (2a, 2b), and the non-contact end parts of the metal sheets (2a, 2b) are formed of an electrical insulating compound substitution (4a, 4b) composed of the oxide and/or nitride of the material of said metal sheets (2a, 2b).

2. A stack-type piezoelectric element according to claim 1 wherein said electrical insulating compound (4a, 4b) is selected from anodically oxidized aluminum, anodically oxidized nickel, plasma discharge-nitrided aluminum and plasma discharge-nitrided nickel.

3. A stack-type piezoelectric element according to claim 1 wherein the alloy used in said metal sheet (2a, 2b) is a solid solution of aluminum with any one of silicon, magnesium and germanium or a mixture thereof.

4. A stack-type piezoelectric element according to claim 1 wherein the alloy used for said metal sheet (2a, 2b) is a solid solution of nickel with any one of chromium, palladium and copper or a mixture thereof.

5. A stack-type piezoelectric element according to claim 1 wherein the alloy used for said metal sheet (2a, 2b) is at least one metallic material selected from the group consisting of nickel-phosphorus alloys, copper-phosphorus alloys and copper-zinc alloys.

6. A process for production of a stack-type piezoelectric element comprising forming a stacked body by stacking plural piezoelectric ceramic sheets (1) and metal sheets (2a, 2b) lying between the respective piezoelectric ceramic sheets (1) and then providing a pair of lead-out terminals (3a, 3b) to the side face of said stacked body, a material used for said metal sheets mainly containing aluminum, nickel or copper, which process comprises, after stacking said metal sheets (2a, 2b) between said piezoelectric ceramic sheets (1), subjecting the end parts of every other said metal sheet (2a) to an anodic oxidation treatment and a hole-filling treatment by means of electrophoresis or plasma discharge nitriding treatment, followed by dividing the stacked body by cutting, forming one of the terminals (3a, 3b) such that it directly covers the treated parts and the untreated metal sheet end parts, then subjecting the other end faces of the untreated metal sheet and parts to an anodic oxidation treatment and a hole-filling treatment by means of electrophoresis or plasma discharge nitriding treatment and subsequently forming the other lead terminal.

7. A process according to claim 6, wherein said piezoelectric ceramic sheets (1) and said metal sheets (2a, 2b) are of the same dimension except for thickness.

8. A process according to claim 6, wherein an alloy used for said metal sheets (2a, 2b) is aluminum or a solid solution of aluminum with any one of silicon, magnesium and germanium or a mixture thereof.

9. A process according to claim 6, wherein an alloy used for said metal sheets (2a, 2b) is nickel or a solid solution of nickel with any one of chromium, palladium and copper or a mixture thereof.

10. A process according to claim 6, wherein a material used for said metal sheets (2a, 2b) is a member selected from the group consisting of nickel-phosphorus alloys, copper-phosphorus alloys and copper-zinc alloys.

Patentansprüche

1. Piezoelektrisches Stapelelement, das einen Stapelaufbau von mehreren piezoelektrischen Keramikschichten (1) und Metallschichten (2a, 2b) zwischen den jeweiligen piezoelektrischen Keramikschichten (1) und ein Paar von Außenanschlüssen (3a, 3b) auf der Seitenfläche des Stapelaufbaus umfaßt, wobei die besagte Metallschicht (2a, 2b) eine Platte aus metallischem Ma-
terial aus einer einzelnen oder mehreren Schichten ist, die aus der Gruppe von Aluminium, Aluminiumbasis-Legierungen, Nickel, Nickelbasis-Legierungen, Kupfer, Kupferbasis-Legierungen und aktiven Metallen, die chemisch durch Oxidation und/oder Nitrierung stabilisierbar sind, besteht, wobei die besagten Metallschichten (2a, 2b) elektrisch alternativ mit einem der Außenanschlüsse (3a, 3b) verbunden sind, wobei der andere Außenanschluß elektrisch keinen Kontakt mit den Metallschichten (2a, 2b) hat und die nicht kontaktierten Endabschnitte der Metallschichten (2a, 2b) aus einem elektrisch isolierenden Bestandteilsstoff (4a, 4b) aus dem Oxid und/oder Nitrid des Materials der besagten Metallschichten (2a, 2b) besteht.

2. Piezoelektrisches Stapelelement nach Anspruch 1, wobei der elektrisch isolierende Bestandteil (4a, 4b) ausgewählt wird unter anodisch oxidiertem Aluminium, anodisch oxidiertem Nickel, plasmaentladungsgekörntem Aluminium und plasmaentladungsgekörntem Nickel.

3. Piezoelektrisches Stapelelement nach Anspruch 1, wobei die für die Metallschicht (2a, 2b) benutzte Legierung eine feste Lösung von Aluminium mit entweder Silicium, Magnesium oder Germanium oder einer Mischung davon ist.

4. Piezoelektrisches Stapelelement nach Anspruch 1, wobei die für die Metallschicht (2a, 2b) verwendete Legierung eine feste Lösung von Nickel mit entweder Chrom, Palladium oder Kupfer oder einer Mischung daraus ist.

5. Piezoelektrisches Stapelelement nach Anspruch 1, wobei die für die Metallschicht (2a, 2b) verwendete Legierung wenigstens ein metallisches Material aus der Gruppe der Nickel-Phosphor-Legierungen, Kupfer-Phosphor-Legierungen und Kupfer-Zink-Legierungen ist.

6. Verfahren zur Herstellung eines piezoelektrischen Stapelelementes, das die Bildung eines Stapelaufbaus durch Stapelung mehrerer piezoelektrischer Keramikschichten (1) und Metallschichten (2a, 2b) zwischen den jeweiligen piezoelektrischen Keramikschichten (1) und dann die Anbringung eines Paars von Außenanschlüssen (3a, 3b) an der Seitenfläche des besagten Stapelaufbaus, umfaßt, wobei ein Material für die besagten Metallschichten hauptsächlich Aluminium, Nickel oder Kupfer enthält, wobei der Prozeß umfaßt:

Verfahren nach Anspruch 6, wobei die besagten piezoelektrischen Keramikschichten (1) und die besagten Metallschichten (2a, 2b) bis auf ihre Dicke dieselben Abmessungen haben.

8. Verfahren nach Anspruch 6, wobei eine für die besagten Metallschichten (2a, 2b) verwendete Legierung Aluminium oder eine feste Lösung von Aluminium mit entweder Silicium, Magnesium oder Germanium oder einer Mischung daraus ist.

9. Verfahren nach Anspruch 6, wobei eine für die besagten Metallschichten (2a, 2b) verwendete Legierung Nickel oder eine feste Lösung aus Nickel mit entweder Chrom, Palladium oder Kupfer oder einer Mischung daraus ist.


Revindications

1. Élément piezoelectrique de type empilage comprenant un corps emplié de plusieurs feuilles céramiques piezoelectriques (1) et de feuilles métalliques (2a, 2b) se trouvant entre les feuilles céramiques piezoelectriques respectives (1) et une paire de bornes conductrices de sortie (3a, 3b) fournie sur les faces latérales du corps empillé, ladite feuille métallique (2a, 2b) étant une plaque d’un matériau métallique monobloc multicouche choisi dans le groupe constitué d’aluminium, d’alliages à base d’aluminium, de nickel, d’alliages à base de nickel, de cuivre, d’alliages à base de cuivre et de métaux actifs pouvant être rendus chimiquement stables par oxydation et/ou nitration, dans lequel lesdites feuilles métalliques
(2a, 2b) sont alternativement mises en contact électrique avec une desdites bornes conductrices (3a, 3b), l’autre borne conductrice n’est pas mise en contact électrique avec les feuilles métalliques (2a, 2b) et les parties terminales sans contact des feuilles métalliques (2a, 2b) sont formées d’une substitution de composé isolant électrique (4a, 4b) constituée de l’oxyde et/ou du nitrate du matériau desdites feuilles métalliques (2a, 2b).

2. Élément piézoélectrique de type empilage selon la revendication 1, dans lequel l’élément isolant électrique (4a, 4b) est choisi parmi l’aluminium anodiquement oxydé, le nickel anodiquement oxydé, l’aluminium nitruré par décharge au plasma et le nickel nitruré par décharge au plasma.

3. Élément piézoélectrique de type empilage selon la revendication 1, dans lequel l’alliage utilisé dans ladite feuille métallique (2a, 2b) est une solution solide d’aluminium avec un quelconque des éléments choisis parmi le silicium, le magnésium et le germanium ou un mélange de ceux-ci.

4. Élément piézoélectrique de type empilage selon la revendication 1, dans lequel l’alliage utilisé pour ladite feuille métallique (2a, 2b) est une solution solide de nickel avec un quelconque des éléments choisis parmi le chrome, le palladium et le cuivre ou un mélange de ceux-ci.

5. Élément piézoélectrique de type empilage selon la revendication 1, dans lequel l’alliage utilisé pour ladite feuille métallique (2a, 2b) est au moins un matériau métallique choisi dans le groupe constitué des alliages de nickel-phosphore, des alliages de cuivre-phosphore et des alliages de cuivre-zinc.

6. Procédé pour la production d’un élément piézoélectrique de type empilage consistant à former un corps empilé en empilant plusieurs feuilles ceramiques piézoélectriques (1) et des feuilles métalliques (2a, 2b) se trouvant entre les feuilles céramiques piézoélectriques respectives (1) et à fournir ensuite une paire de bornes conductrices de sortie (3a, 3b) sur les faces latérales dudit corps empilé, un matériau utilisé pour lesdites feuilles métalliques contenant principalement de l’aluminium, du nickel ou du cuivre, lequel procédé consiste après l’empilage desdites feuilles métalliques (2a, 2b) entre lesdites feuilles céramiques piézoélectriques (1) à soumettre les parties terminales de chacune des autres dites feuilles métalliques (2a) à un traitement d’oxydation anodique et à un traitement de remplissage de trous au moyen d’une électrophorèse ou d’un traitement de nitration par décharge au plasma, puis à diviser le corps empilé par découpe, à former une des bornes (3a, 3b) de telle sorte qu’elle couvre directement les parties traitées et les parties terminales de feuilles métalliques non traitées, à soumettre ensuite les autres faces terminales et parties de la feuille métallique non traitée à un traitement d’oxydation anodique et à un traitement de remplissage de trous au moyen d’une électrophorèse ou d’un traitement de nitration par décharge au plasma et à former ensuite l’autre borne conductrice.

7. Procédé selon la revendication 6, dans lequel lesdites feuilles céramiques piézoélectriques (1) et lesdites feuilles métalliques (2a, 2b) ont la même dimension à l’exception de l’épaisseur.

8. Procédé selon la revendication 6, dans lequel un alliage utilisé pour lesdites feuilles métalliques (2a, 2b) est l’aluminium ou une solution solide d’aluminium avec un quelconque des éléments choisis parmi le silicium, le magnésium et le germanium ou un mélange de ceux-ci.

9. Procédé selon la revendication 6, dans lequel un alliage utilisé pour lesdites feuilles métalliques (2a, 2b) est le nickel ou une solution solide de nickel avec un quelconque des éléments choisis parmi le chrome, le palladium et le cuivre ou un mélange de ceux-ci.

10. Procédé selon la revendication 6, dans lequel un matériau utilisé pour lesdites feuilles métalliques (2a, 2b) est un élément choisi dans le groupe constitué des alliages de nickel-phosphore, des alliages de cuivre-phosphore et des alliages de cuivre-zinc.