Oct. 11, 1949. W. P. MASON 2,484,635

PIEZOELECTRIC CRYSTAL APPARATUS

Original Filed Aug. 9, 1943

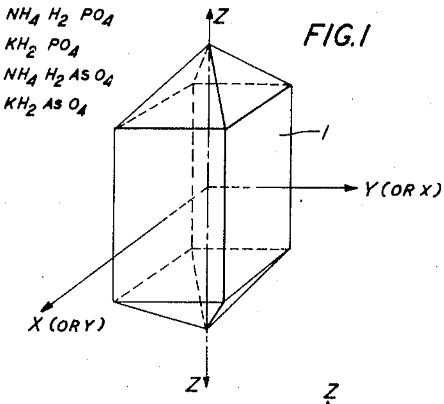

FIG. 1

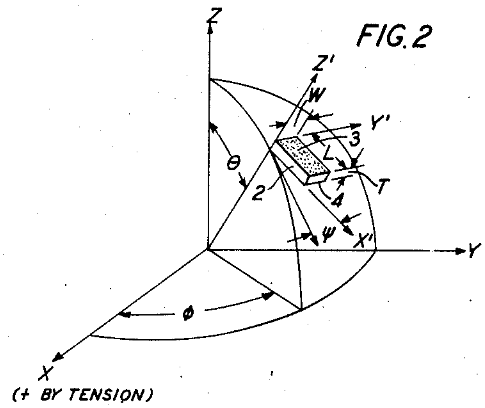

FIG. 2

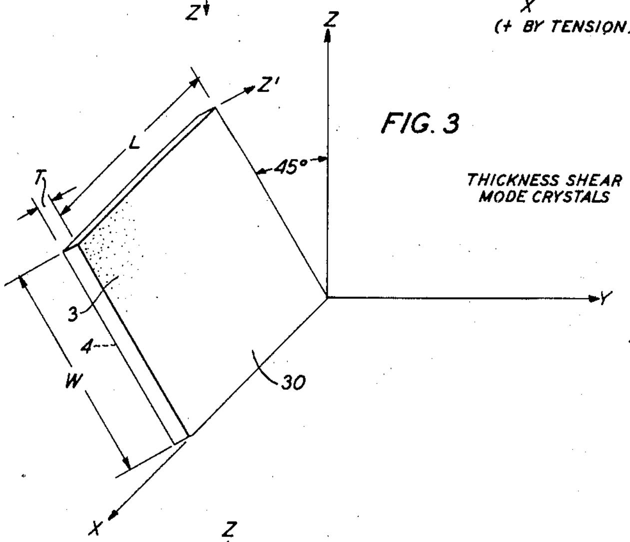

FIG. 3

THICKNESS SHEAR MODE CRYSTALS

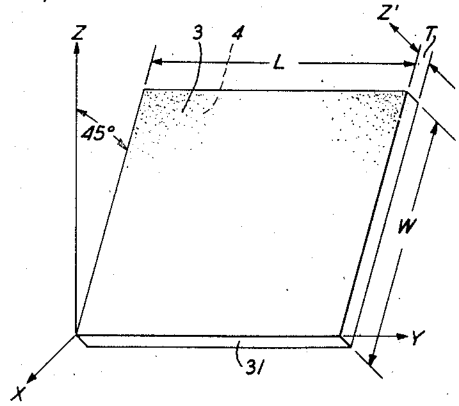

FIG. 4

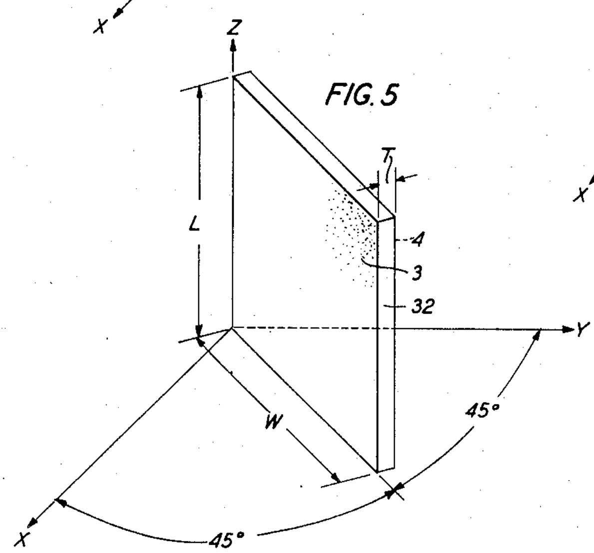

FIG. 5

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Patented Oct. 11, 1949

2,484,635

UNITED STATES PATENT OFFICE

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PIEZOELECTRIC CRYSTAL APPARATUS

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Original application August 9, 1943, Serial No. 497,883. Divided and this application December 24, 1945, Serial No. 637,127

9 Claims. (Cl. 171—327)

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This invention relates to piezoelectric crystal apparatus and particularly to thickness shear mode piezoelectric crystal elements comprising crystalline ammonium dihydrogen phosphate ($NH_4H_2PO_4$), potassium dihydrogen phosphate (KH_2PO_4), ammonium dihydrogen arsenate ($NH_4H_2ASO_4$), potassium dihydrogen arsenate (KH_2ASO_4) and isomorphous combinations.

This application is a division of my copending application for Piezoelectric crystal apparatus, Serial No. 497,883, filed August 9, 1943, now Patent No. 2,450,010. Such crystal elements are useful as electromechanical transducers utilized, for example, in sonic or supersonic projectors, microphones, pick-up devices and detectors. Also, they may be utilized as frequency control elements in electric wave filter systems, oscillation generator systems and amplifier systems. Other applications for such crystal elements may include harmonic producers, and, in general, any application where either a resonant or non-resonant piezoelectric crystal element may be utilized. The non-linear hysteresis loop characteristics of the non-resonant crystal may be made use of to produce overtones or harmonics therefrom.

One of the objects of this invention is to provide useful orientations and modes of motion in crystal elements made from crystalline ammonium dihydrogen phosphate, potassium dihydrogen phosphate, ammonium dihydrogen arsenate, potassium dihydrogen arsenate and isomorphous combinations.

Other objects of this invention are to provide crystal elements comprising dihydrogen phosphate and arsenate substances that may possess useful characteristics, such as large piezoelectric constants, large vibrational motion, minimum coupling of the desired mode of motion with undesired modes of motion therein, and temperature coefficients of frequency that may have the relatively lower values.

Another object of this invention is to take advantage of the high piezoelectric activity, the low cost and other advantages of crystalline ammonium dihydrogen phosphate and similar dihydrogen phosphate and arsenate crystals.

Crystal elements of suitable orientation cut from crystalline ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate, ammonium dihydrogen arsenate and isomorphous combinations thereof may be excited in different modes of motion, such as longitudinal length, longitudinal width or longitudinal thickness modes of motion, shear face modes of motion controlled mainly by the width and length major face dimensions, or thickness shear modes of motion controlled mainly by the thickness dimension. Also, low frequency flexural modes of motion of either the width bending flexure type or the thickness bending flexure type may be utilized. The contour or face modes of motion may be either the face shear mode of motion, or the width or length face longitudinal modes of motion, as disclosed and claimed in my parent application, Serial No. 497,883, hereinbefore referred to. The thickness modes of motion may be either the thickness longitudinal mode of motion as involved in my copending application, Serial No. 637,126, filed December 24, 1945 now Patent No. 2,450,011, or the thickness shear mode of motion as involved in the present application. These modes of motion are similar in the general form of their motion to those of corresponding names that are already known in connection with quartz, Rochelle salt, and other known piezoelectric crystals.

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Crystal elements composed of crystalline ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate, ammonium dihydrogen arsenate and isomorphous combinations may have piezoelectric and elastic constants or moduli of considerable interest for use in electromechanical transducers, filter systems and oscillator systems, for example. In accordance with this invention, a number of crystal orientations or cuts are provided that may be utilized for these purposes and others. The types of crystal cuts may be divided into several categories, such as (a) crystal cuts that have relatively large piezoelectric constants and hence may be driven strongly piezoelectrically, (b) crystal cuts that have advantageous elastic properties, such that the longitudinal face modes of motion therein are free from coupling to the face shear modes of motion therein, and face shear mode crystal elements that are free from coupling with other modes of motion therein, and (c) crystal cuts that may have the relatively lower values of temperature coefficients of frequency.

Crystal elements comprising ammonium dihydrogen phosphate, potassium dihydrogen phosphate, ammonium dihydrogen arsenate, potassium dihydrogen arsenate and isomorphous combinations also possess ferroelectric properties such as large dielectric constants, hysteresis loops and non-linearity of charge field relationships below their critical or Curie temperatures of about 115° K., 91° K., 155° K. and 220° K. respectively. These crystal substances also possess high piezoelectric constants at room temperatures, which, in general, are larger than those of most other piezoelectric crystals except Rochelle salt. Ammonium dihydrogen phosphate crystals have relatively the largest piezoelectric constants of any of the four isomorphic dihydrogen crystal substances mentioned, and are relatively easy to grow in shapes and sizes that are suitable for cutting useful plates or elements therefrom.

The ammonium dihydrogen phosphate crystals, for example, may have properties somewhat similar to 45-degree Y-cut type Rochelle salt crystals but will stand a much higher operating temperature which may be of the order of about 180° C. or much higher, and also have no water of crystallization and hence will not dehydrate when operated in air or in vacuum. The temperature coefficients of frequency for certain of the principal cuts are roughly of the order of 100 to 300 parts per million per degree centigrade. The dielectric constants decrease slightly with an increase in temperature while the piezoelectric constants relating charge and stress are nearly independent of temperature. Since the ammonium dihydrogen phosphate crystals have the relatively higher values of electromechanical coupling, and are free from water of crystallization which eliminates dehydration in the crystal, and will stand relatively high operating temperatures of the order of 180° C., or more, they are useful as driving elements for all transducer applications, such as projectors and microphones in underwater sound work, for example. Also, this type of crystal may be used as a substitute for quartz frequency control elements in filter and oscillator applications, especially when used with temperature control. For the lower frequency filter applications, the crystal cuts having the relatively lower temperature coefficients of frequency may be used at ordinary temperatures without temperature control.

Although all four of the crystalline dihydrogen substances particularly mentioned herein have relatively large piezoelectric constants and other useful characteristics, the ammonium dihydrogen phosphate crystal elements may be constructed to have the largest values of piezoelectric constants of the four crystalline dihydrogen phosphate and arsenate salts mentioned, and also generally, are relatively more easy to grow in the sizes and shapes that are useful for cutting crystal elements therefrom.

The crystal elements disclosed in this specification may have conductive electrode coatings on their major surfaces of any suitable composition, shape, and arrangement, such as those already known in connection with quartz, Rochelle salt and other piezoelectric crystals; and they may be mounted and electrically connected by any suitable means, such as for example, by pressure type clamping pins or by conductive supporting wires cemented by conductive cement to the crystal coatings at or near the nodal regions, as already known in connection with quartz, Rochelle salt and other crystals having similar or corresponding modes of motion.

Spurious modes of motion may be avoided in these crystal elements by a suitable dimensioning of the crystal element, such as by adjusting the thickness dimension thereof relative to the length and width dimensions thereof, in the case of face shear mode or face longitudinal mode crystals, and by adjusting the length and width dimensions relative to the thickness dimension in the case of thickness mode crystals, such as thickness shear mode crystals or thickness longitudinal mode crystals. Also the effect of spurious modes in these face mode and thickness mode dihydrogen crystals may be reduced by the use of centrally disposed electrodes partially covering the major faces of the crystals, in the manner of such partial electrodes as are now used in connection with quartz crystals, for example.

For a clearer understanding of the nature of this invention and the additional advantages, features and objects thereof, reference is made to the following description taken in connection with the accompanying drawings, in which like reference characters represent like or similar parts and in which:

Fig. 1 is a perspective view illustrating the prismatic tetragonal-scalenohedral form in which ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate, ammonium dihydrogen arsenate and isomorphous combinations thereof crystallizes, and also illustrating the relation of the prism faces and cap faces of such crystalline substances with respect to the mutually perpendicular electric axis X, mechanical axis Y, and optic axis Z thereof;

Fig. 2 is a perspective view illustrating the orientation, in terms of the angles φ, θ and ψ, of a crystal element cut from any of the dihydrogen crystalline substances illustrated in Fig. 1, and may be taken to illustrate the orientation of any dihydrogen salt crystal element disclosed in this specification; and

Figs. 3, 4 and 5 are perspective views illustrating the orientations of several types of thickness shear mode crystal elements cut from any of the substances ammonium dihydrogen phosphate, potassium dihydrogen phosphate and corresponding arsenate crystal substances, as illustrated in Fig. 1.

This specification follows the conventional terminology as applied to piezoelectric crystalline substances, which employs three mutually perpendicular X, Y and Z axes, as shown in the drawings, to designate an electric axis, a mechanical axis and an optic axis, respectively, of piezoelectric crystalline substances, and which employs three orthogonal axes X′, Y′ and Z′ to designate the directions of the axes of a crystalline piezoelectric body or element that is angularly oriented with respect to such X, Y and Z axes thereof.

This specification also follows the conventional terminology used to designate the elastic constants s and c, the piezoelectric constants d and other constants of piezoelectric crystalline substances. As an illustrative example, the d_{36} piezoelectric constant means that a Z axis field represented by the numeral **3** may produce XY shear motion represented by the numeral **6**. If the d_{36} piezoelectric constant of the substance has a large value, as it does in the case of the several dihydrogen salt crystals here considered, then a Z axis field applied thereto may produce a strong shear motion in the XY plane of the crystal body.

The value of the elastic compliance and shear stiffness for rotated crystal elements may be calculated from the fundamental elastic matrix given in Equation 1 in my parent application hereinbefore referred to. One method of doing this is by the short-hand matrix method discussed in a paper "The mathematics of crystal properties," by W. L. Bond, Bell System Technical Journal, January 1943, page 1, using the matrix where the axes X', Y' and Z' of the rotated crystals are related to the crystallographic axes X, Y and Z by the direction cosines l_1 to n_3, l_1 being the direction cosine between X' and X, n_3 the direction cosine between Z' and Z, etc. As shown by Bond, the elastic compliances of rotated crystals are given in terms of the elastic compliances of unrotated crystals by the product of the matrices.

The direction cosines that cause the length dimension L of the crystal element to point in the desired direction are used. For this purpose, the system of angles illustrated in Fig. 2 is used where the length L of the crystal is taken along the X' axis, the width W is taken along the Y' axis and the thickness T is taken along the Z' axis. The angle θ measures the angle between the Z crystallographic axis and the Z' thickness T axis. The angle φ measures the angle between the XZ plane and the ZZ' plane and ψ the skew angle, is the angle between the length dimension L of the crystal and the tangent to the great circle through the Z and Z' areas.

The elastic, dielectric and piezoelectric equations for crystalline ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate, ammonium dihydrogen arsenate and isomorphous combinations are given in my parent application hereinbefore referred to. These substances crystallize in the prismatic tetragonal-scalenohedral form shown in Fig. 1 and as a consequence have six elastic compliances, namely, s_{11}, s_{12}, s_{13}, s_{33}, s_{44}, and s_{66}, and two types of piezoelectric constants, namely, $d_{14}=d_{25}$, and d_{36}.

Referring to the drawing, Fig. 1 is a perspective view illustrating the form in which ammonium dihydrogen phosphate, potassium dihydrogen phosphate, ammonium dihydrogen arsenate, and potassium dihydrogen arsenate crystallizes. As illustrated in Fig. 1, such isomorphic dihydrogen crystal substances crystallize in the prismatic tetragonal scalenohedral form and are formed with four major prism faces and with four cap faces at each end. The optic axis Z extends between each apex of the cap faces, and the mutually perpendicular X and Y axes, extend perpendicular to the four major prism faces. The several cuts or orientations of dihydrogen phosphate and arsenate crystal elements hereinafter disclosed may be cut from the mother crystal **1** of the substances and form illustrated in Fig. 1.

The mother crystal **1** illustrated in Fig. 1 may be grown from any suitable substances, and in any suitable manner such as, for example, by either the circulation method or the rocking method. As an illustrative example, the potassium salts, used in growing the mother crystal **1** illustrated in Fig. 1, may be obtained from potassium hydroxide and phosphoric or arsenic acid, and the ammonium salts may be obtained from ammonium carbonate and the corresponding acids. Saturated solutions may be prepared from these salts and the crystal **1** grown from watery solutions at a gradually decreasing temperture in any suitable manner. The crystal shape illustrated in Fig. 1 may be varied somewhat to obtain either needle-shaped crystals, or the more compact or short prism form as illustrated in Fig. 1. Ammonium dihydrogen phosphate produces short and thick prismatic crystals at room temperature. If liquor is added in excess, all of these salts may be crystallized in short prisms at room temperature. The short thick form of crystal **1**, as illustrated in Fig. 1, is generally the more convenient form for cutting the various orientations of crystal plates therefrom.

Fig. 2 is a diagram illustrating the system, recently defined by the Institute of Radio Engineers, for specifying the orientation for a piezoelectric crystal element or body **2** in relation to its mutually perpendicular X, Y and Z axes. As shown in Fig. 2, the X' axis is taken along the length dimension L of the crystal element **2**, the Y' axis is taken along the width dimension W of the crystal element **2**, and the Z' axis is taken along the thickness or thin dimension T of the crystal element **2**. The angle θ is, as shown in Fig. 2, the angle between the optic axis Z and the plate normal or Z' axis, and the angle φ is the angle between the +X axis (+ by tension) and the intersection of the plane containing the Z and Z' axes with the XY plane, while ψ is the angle between the length L axis X' and the tangent of the great circle containing the Z and Z' axes as measured in a plane perpendicular to the Z' axis. All angles are positive when measured in a counterclockwise direction. Fig. 2 is applicable to a right-hand crystal, such as quartz, following the crystallographer's definition and the earlier Biot convention. The positive (+) X axis is the X axis for which a positive charge develops on a tension stress being applied thereto.

The crystal element **2** of Fig. 2 may be cut from any of the crystalline phosphate and arsenate substances illustrated in Fig. 1, and, by specifying the values for the three angles θ, φ and ψ of Fig. 2 may generally designate the orientation of any of the several crystal elements disclosed in this specification and illustrated in Figs. 3 to 5 of the drawing.

Suitable conductive electrodes such as the crystal electrodes **3** and **4** of Fig. 2 may be placed on or adjacent to or formed integral with the opposite major faces of any of the crystal plates disclosed herein in order to apply electric field excitation thereto. The crystal electrodes **3** and **4** when formed integral with the surfaces of any of the crystal elements **2** may consist of gold, platinum, aluminum, silver or other suitable conductive material deposited upon the crystal surfaces by evaporation in vacuum, painting, spraying, or by other suitable process. If desired, the crystal element **2** may be electroplated to the desired frequency by nickel plating or otherwise.

The thickness shear mode crystal elements illustrated in Figs. 3 to 5 may be utilized at the relatively high thickness mode frequencies, fundamental or harmonic, to generate high frequency waves in liquids for submarine detection and also may be used as frequency control elements in electric wave filter systems, oscillation generator systems and for other purposes where a relatively high frequency or thickness mode crystal element may be desired.

Figs. 3, 4 and 5 are perspective view of thickness shear mode crystal elements **30**, **31** and **32** which may be cut from crystalline ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate, ammonium dihydrogen arsenate and isomorphous combinations, and made into a plate of substantially rectangular parallelepiped shape with its major faces having a length dimension L and width dimension W which may be of equal dimensions or with one dimension either longer or shorter with respect to the other. The frequency determining thickness or thin dimension T between the major faces of the crystal elements **30**, **31** and **32** is perpendicular to the other two dimensions L and W, which may be dimensionally related to the thickness dimension T to remove spurious face mode frequencies from the region of the desired thickness mode frequency.

The thickness shear modes of motion in the piezoelectric crystal elements **30**, **31** and **32** of Figs. 3, 4 and 5 are similar to the same type of shear motion that obtains in quartz crystals and may be similarly utilized in filter systems and oscillator systems, for example.

The thickness shear modes in the four isomorphic dihydrogen crystal substances mentioned hereinbefore are generated by the piezoelectric constants

$$d'_{34} \text{ and } d'_{35}$$

The piezoelectric constants that have the larger values are obtained in the three orientations for the thickness shear mode crystal elements **30**, **31** and **32** illustrated in Figs. 3, 4 and 5. In the crystal elements **30**, **31**, **32** of Figs. 3, 4 and 5, the frequency is controlled mainly by the relatively thin thickness dimension T, and the major faces thereof may be of square or rectangular shape as illustrated in Figs. 3, 4 and 5, or of circular or other shape if desired.

As illustrated in Fig. 3, the crystal element **30** has one pair of its edges along or nearly along the X axis, the rectangular major faces thereof and the normal Z′ to the major faces being inclined at an angle of 45 degrees or nearly 45 degrees with respect to the Y and Z axes, which corresponds to the orientation angles, expressed in terms of the convention illustrated in Fig. 2, of $\varphi=0$ degrees, $\theta=45$ degrees and $\psi=0$ degrees.

The crystal element **31** of Fig. 4 has one edge along or nearly along the Y axis, the rectangular major faces and the normal Z′ to the major faces being inclined at an angle of 45 degrees or nearly 45 degrees with respect to the X and Z axes, which corresponds to the orientation angles of $\varphi=90$ degrees, $\theta=45$ degrees and $\psi=0$ degrees as expressed in terms of the convention illustrated in Fig. 2.

The crystal element **32** of Fig. 5 has one edge along or nearly along the Z axis, the rectangular major faces and the normal Z′ to the major faces being inclined at an angle of 45 degrees or nearly 45 degrees with respect to the X and Y axes, which corresponds to the orientation angles of $\varphi=45$ degrees, $\theta=90$ degrees and $\psi=90$ degrees as expressed in terms of the angles illustrated in Fig. 2.

The three thickness shear mode crystal elements **30**, **31** and **32** of Figs. 3, 4 and 5, respectively, when constructed from crystalline ammonium dihydrogen phosphate, have frequency constants of about 1040, 1040, and 1015, respectively, expressed in kilocycles per second per millimeter of thickness dimension T, and have temperature co-efficients of frequency of about −308, −308, and −184, respectively, expressed in parts per million per degree centigrade.

As an illustrative example of the characteristics of thickness shear mode crystals, an ammonium dihydrogen phosphate crystal element **30** of Fig. 3 having its width W or length L along the X axis and having its thickness axis T inclined 45 degrees from the Z axis and having a length L, a width W and a thickness T of about 1.25, 1.25 and 0.103 centimeters, respectively, has a fundamental thickness shear mode resonant frequency of about 1010 kilocycles per second and a frequency constant f_T of about 1040 kilocycles per second per millimeter of thickness dimentions T for its fundamental thickness shear mode frequency, a shear elastic constant

$$c^{E\prime}_{44}=\frac{c^E_{44}+c^E_{66}}{2}=\text{about } 7.79\times10^{10}$$

a temperature coefficient of thickness shear mode frequency of about −308 parts per million per degree centigrade and a temperature coefficient of about −666 for its shear elastic constant

$$c^{E\prime}_{44}$$

As another illustrative example of the characteristics of a thickness shear mode crystal element, an ammonium dihydrogen phosphate crystal element **32** of Fig. 5 having its width W or length L along the Z axis and having its thickness axis T inclined 45 degrees from the X axis and having a length L, a width W and a thickness T of about 1.848, 1.840 and 0.256 centimeters, respectively, has a fundamental resonant frequency of 396.81 kilocycles per second and a frequency constant f_T of about 1015 kilocycles per second per millimeter of thickness T for its fundamental thickness shear mode frequency, a shear elastic constant

$$c^E_{44}$$

of about 7.42×10^{10}, a temperature coefficient of thickness shear mode frequency of about −184 parts per million per degree centigrade, and a temperature coefficient of about −388 for its shear elastic constant

$$c^E_{44}$$

The thickness shear mode crystal element **30** of Fig. 3 having its width W or length L along the X axis and having its thickness axis T inclined at an angle of about 45 degrees from the Y and Z axes, corresponding to angles in Fig. 2 of $\psi=0$ degrees, $\varphi=90$ degrees and $\theta=45$ degrees, is controlled by the elastic constant:

$$c^{E\prime}_{44}=c^E_{44}\,[\sin^2\theta]+c^E_{66}\,[\cos^2\theta]=\frac{c^E_{44}+c^E_{66}}{2}$$

The thickness shear mode crystal element **32** of Fig. 5 having its width W or length L along the Z axis and having its thickness axis T inclined at an angle of 45 degrees from the X and Y axes, corresponding to angles in Fig 2 of $\theta=90$ degrees, $\psi=0$ degrees and $\varphi=45$ degrees, is controlled by the elastic constant

$$c^{E\prime}_{55}$$

and for all angles of rotation φ about the Z axis, the thickness shear modulus is given by:

$$c^{E\prime}_{55}=c^E_{44}\,[\cos^2\varphi+\sin^2\varphi]=c^E_{44}$$

The thickness shear mode frequency f of the crystal element **30** of Fig. 3, **31** of Fig. 4 and **32** of Fig. 5 is given by the following equations, respectively:

$$f=\frac{1}{2T}\sqrt{\frac{c^{E\prime}_{44}}{\rho}}=\frac{1}{2T}\sqrt{\frac{c^E_{44}+c^E_{66}}{2\rho}}$$

$$f=\frac{1}{2T}\sqrt{\frac{c^{E\prime}_{44}}{\rho}}=\frac{1}{2T}\sqrt{\frac{c^E_{44}+c^E_{66}}{2\rho}}$$

$$f=\frac{1}{2T}\sqrt{\frac{c^{E\prime}_{55}}{\rho}}=\frac{1}{2T}\sqrt{\frac{c^E_{44}}{2\rho}}$$

where:

T is the thickness T in millimeters

ρ is the density which in the case of ammonium dihydrogen phosphate is about 1.8

$$c^{E\prime}_{44},\ c^{E\prime}_{44},\ \text{and } c^{E\prime}_{55}$$

is the corresponding shearing elastic constant.

The thickness shear mode crystal elements **30**, **31** and **32** of Figs. 3, 4 and 5 may be adapted to vibrate alone or simultaneously in two thickness shear modes of motion, one being the fundamental thickness shear mode and the other the second thickness shear mode, in the manner as disclosed in W. P. Mason Patent 2,303,375 dated December 1, 1942. Both the first and second shear mode frequencies are controlled mainly by the thickness dimension T of the crystal element and vary inversely as the value of the thickness dimension T of the crystal element.

The coupling between the face shear mode of motion and the thickness shear mode of motion is controlled by the elastic constant

$$c'_{46}$$

The value of

$$c'_{46}$$

for the thickness shear mode crystal elements **30** and **31** of Figs. 3 and 4 rotated in effect about the X and Y axes, respectively, is given by:

$$c'_{46}=\left(\frac{c_{66}-c_{44}}{2}\right)\sin 2\theta$$

which goes to a zero value only at $\theta=0$ degrees and $\theta=90$ degrees where no piezoelectric thickness shear driving constant is present. On the other hand, for the orientation of Fig. 5,

$$c'_{46}$$

vanishes, and this crystal element **32** of Fig. 5 will have no coupling to a face shear mode of motion.

Although this invention has been described and illustrated in relation to specific arrangements, it is to be understood that it is capable of application in other organizations and is, therefore, not to be limited to the particular embodiments disclosed, but only by the scope of the appended claims and the state of the prior art.

What is claimed is:

1. A piezoelectric crystal element adapted for thickness shear motion at a frequency controlled mainly by its thickness dimension between its major faces, and comprising one of the substances ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate and ammonium dihydrogen arsenate, said major faces being substantially parallel to one of the three mutually perpendicular X, Y and Z axes and inclined at the bisecting angle of substantially 45 degrees with respect to the other two of said three X, Y and Z axes of said crystal element, said angle being a value corresponding to substantially the largest value of piezoelectric constant in said crystal substance for said thickness shear mode of motion.

2. A piezoelectric crystal element in accordance with claim 1 wherein said major faces are substantially parallel to said Z axis, and said bisecting angle of substantially 45 degrees with respect to said X and Y axes corresponds to a value where said thickness shear motion has substantially no coupling to a face shear mode of motion in said major faces.

3. A piezoelectric crystal element in accordance with claim 1 wherein said major faces are substantially parallel to said Y axis, and said bisecting angle is inclined substantially 45 degrees with respect to said X and Z axes and corresponds to a value where said thickness shear mode of motion has a high electromechanical coupling value.

4. A piezoelectric crystal element adapted for thickness shear motion at a frequency controlled mainly by its thickness dimension between its major faces, and comprising one of the substances ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate and ammonium dihydrogen arsenate, said major faces being substantially parallel to one of the three mutually perpendicular X, Y and Z axes and inclined at the bisecting angle of substantially 45 degrees with respect to the other two of said three X, Y and Z axes of said crystal element, said angle being a value corresponding to substantially the largest value of piezoelectric constant in said crystal substance for said thickness shear mode of motion, and means comprising electrodes cooperating with said major faces for operating said crystal element in said thickness shear mode of motion.

5. Piezoelectric crystal apparatus in accordance with claim 4 wherein said major faces are substantially parallel to said Y axis, and said bisecting angle is inclined substantially 45 degrees with respect to said X and Z axes and corresponds to a value where said thickness shear mode of motion has a high electromechanical coupling value, and said one of said substances is ammonium dihydrogen phosphate.

6. A piezoelectric crystal element adapted for thickness shear motion at a frequency controlled mainly by its thickness axis dimension between its major faces, and comprising one of the substances ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate and ammonium dihydrogen arsenate, said major faces being substantially parallel to the Z axis of the three mutually perpendicular X, Y and Z axes and inclined at the bisecting angle of substantially 45 degrees with respect to the other two X and Y axes of said three X, Y and Z axes of said crystal element, said angle being a value corresponding to substantially the largest value of piezoelectric constant in said crystal substance for said thickness shear mode of motion, and said angle being a value corresponding to a substantially zero value of coupling of said thickness shear motion with the face shear mode of motion in said major faces, said thickness dimension being a value corresponding to the value of said frequency for said thickness shear mode of motion, and means comprising electrodes cooperating with said major faces for operating said crystal element in said thickness shear mode of motion.

7. Piezoelectric apparatus in accordance with claim 6 wherein said one of said substances is ammonium dihydrogen phosphate.

8. A piezoelectric crystal element adapted for thickness shear motion at a frequency controlled mainly by its thickness axis dimension between its major faces, and comprising one of the substances ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate and ammoninum dihydrogen arsenate, said major faces being substantially parallel to the Z axis of the three mutually perpendicular X, Y and Z axes and inclined at the bisecting angle of substantially 45 degrees with respect to the other two X and Y axes of said three X, Y and Z axes of said crystal element, said angle being a value corresponding to substantially the largest value of piezoelectric constant in said crystal substance for said thickness shear mode of motion, and said angle being a value corresponding to a substantially zero value of coupling of said thickness shear motion with the face shear

mode of motion in said major faces, said thickness dimension being a value corresponding to the value of said frequency for said thickness shear mode of motion.

9. A piezoelectric crystal element adapted for thickness shear motion at a frequency controlled mainly by its thickness axis dimension between its major faces, and comprising one of the substances ammonium dihydrogen phosphate, potassium dihydrogen phosphate, potassium dihydrogen arsenate and ammonium dihydrogen arsenate, said major faces being substantially parallel to the Z axis of the three mutually perpendicular X, Y and Z axes and inclined at the bisecting angle of substantially 45 degrees with respect to the other two X and Y axes of said three X, Y and Z axes of said crystal element, said angle being a value corresponding to substantially the largest value of piezoelectric constant in said crystal substance for said thickness shear mode of motion, and said angle being a value corresponding to a substantially zero value of coupling of said thickness shear motion

with the face shear mode of motion in said major faces, said major faces being substantially rectangular, said thickness dimension being a value corresponding to the value of said frequency for said thickness shear mode of motion, and means comprising electrodes cooperating with said major faces for operating said crystal element in said thickness shear mode of motion.

WARREN P. MASON.

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Number	Country	Date
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