Oct. 4, 1949. H. JAFFE 2,483,641

PIEZOELECTRIC CRYSTAL ELEMENT

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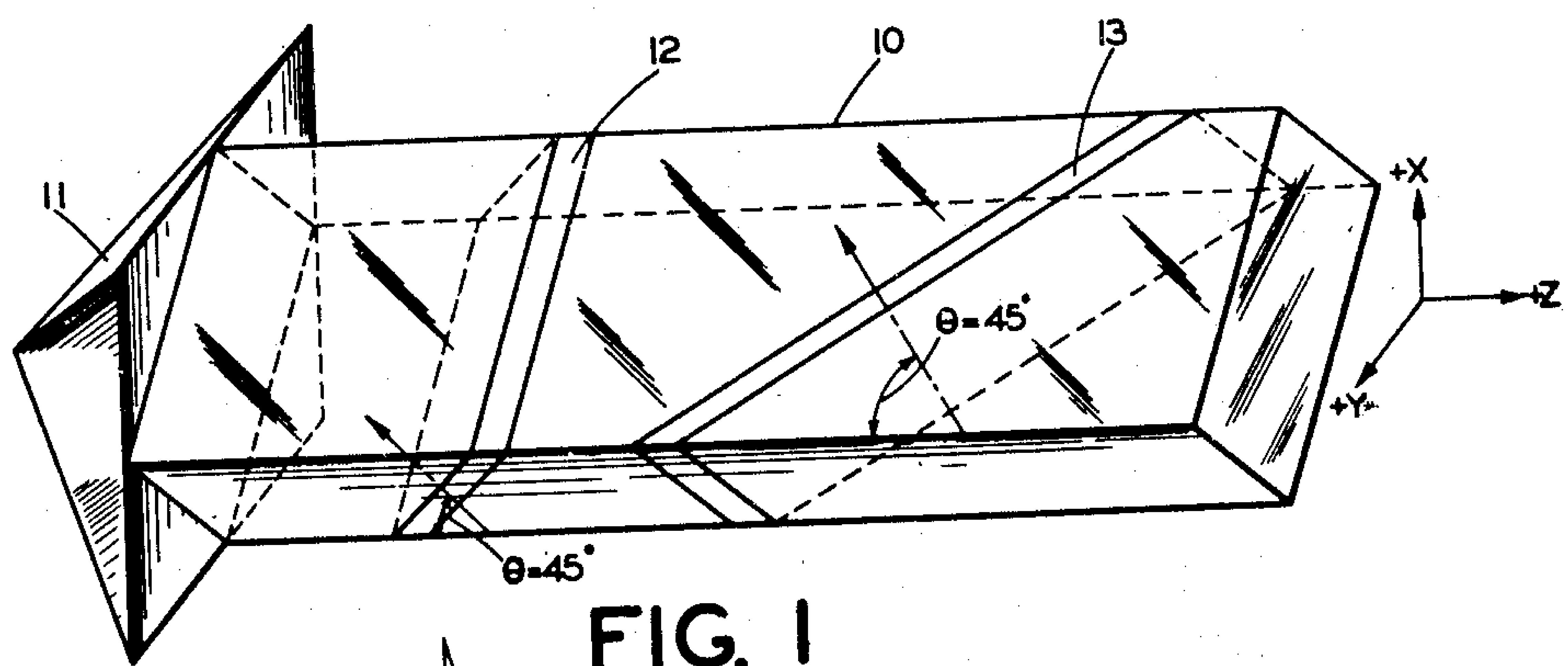

FIG. 1

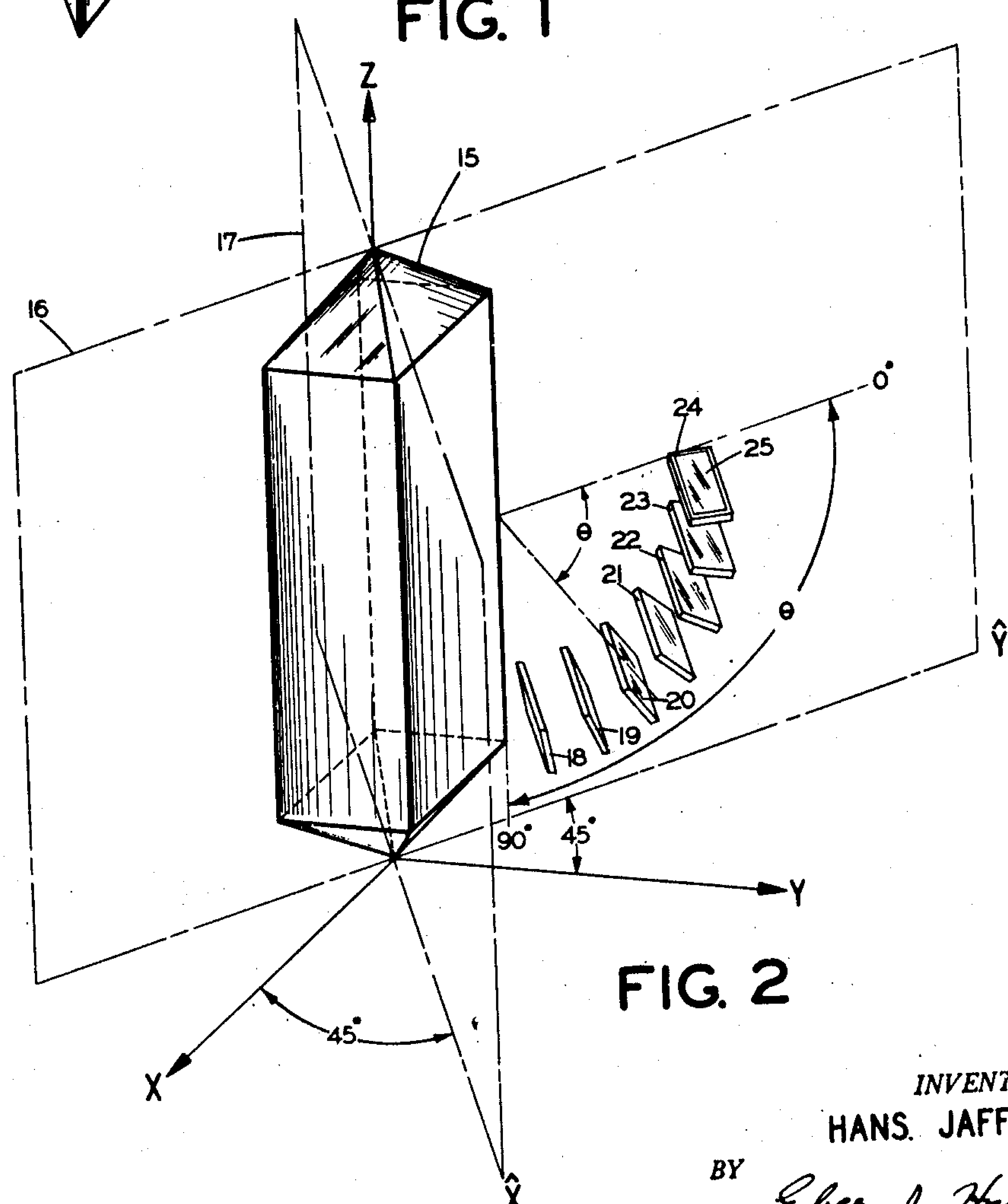

FIG. 2

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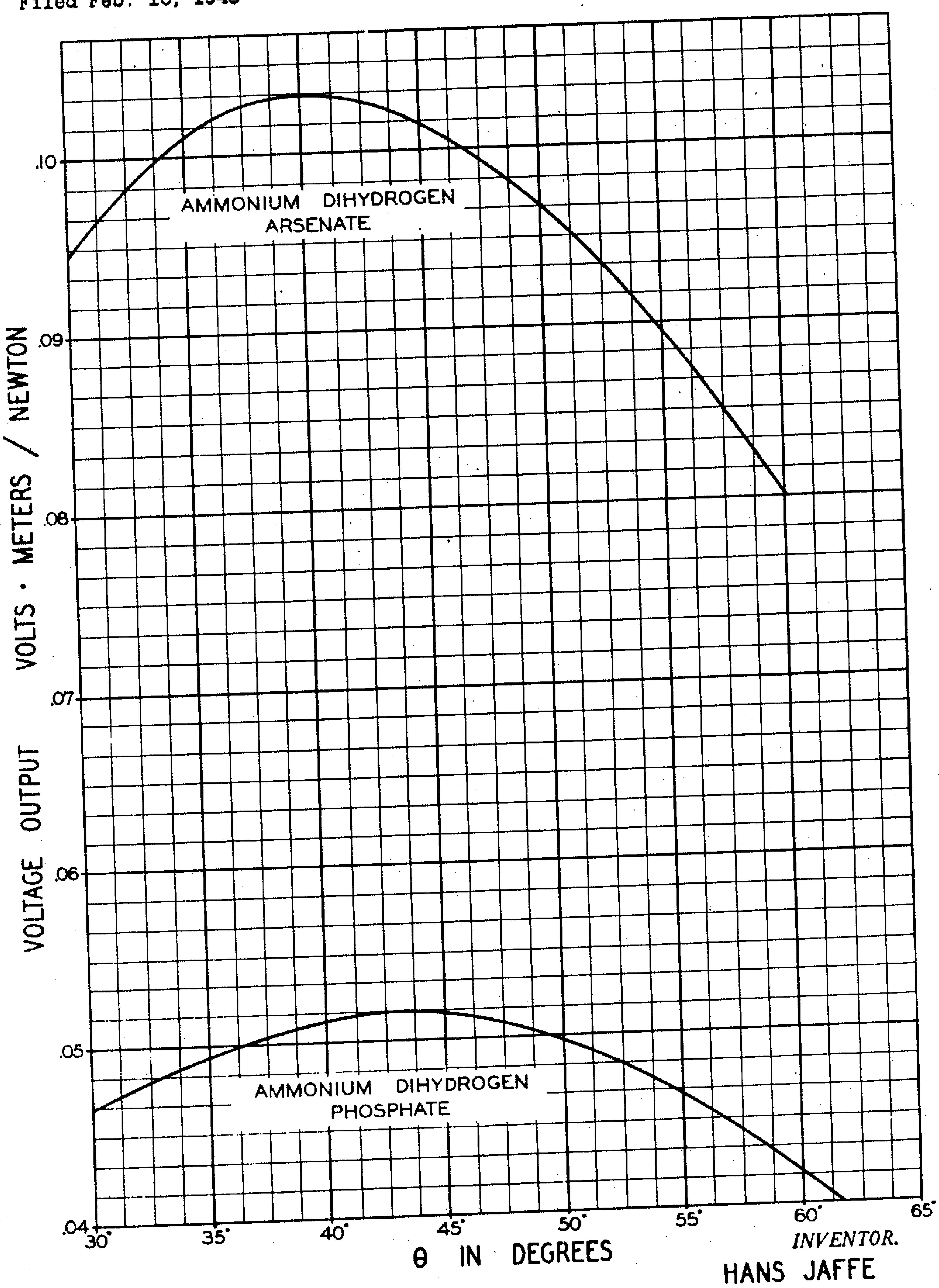

FIG. 3

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PIEZOELECTRIC CRYSTAL ELEMENT

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Application February 16, 1948, Serial No. 8,678

4 Claims. (Cl. 171—327)

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This invention pertains to a piezoelectric crystal element cut with particular orientation from any one of a number of representatives of a family of crystals.

This application is a continuation-in-part of a copending application filed June 8, 1944, in the name of Hans Jaffe, Serial Number 539,312, now Patent No. 2,463,109, for Piezoelectric crystal means and method of using same, and assigned to the same assignee as the present application.

In the piezoelectric art useful applications have been found for crystals offering several distinct types of relationship between a mechanical strain and a dielectric polarization or electric field. One well-known type is the 45 degree X-cut plate of Rochelle salt, also known as an expander plate. In this crystal plate the mechanical strain is in a direction at right angles to the direction of the electric field. Such a relationship in a highly useful amount is also exhibited by the 45 degree Z-cuts of P-type crystals, described and claimed in Patent No. 2,463,109. Another type of useful relationship between strain and polarization is that between a polarization and an expansion strain component parallel to this polarization. A crystal plate having such a relationship for a polarization in its thickness direction is known as a thickness expander plate, such as the X-cut plate of quartz.

It has been shown in U. S. Patent 2,170,318 issued to W. G. Cady that thickness expander plates can also be obtained from crystals of Rochelle salt, and other crystals of the same or related symmetry, by cutting plates at angles substantially different from zero to their three axes X, Y, Z, the latter being orthogonal axes defined for the various crystals by accepted rules. These thickness expander plates are useful in several applications such as, for instance, the production or the detection of compressional waves, in particular such waves in liquids, and for the maintenance of resonant vibrations of comparatively high frequency in oscillating circuits.

The present invention pertains to thickness expander plates of the P-type group of crystals which are superior to such thickness expander plates cut from Rochelle salt due to their ability to withstand temperatures as high as about 120 degrees centigrade compared to 55 degrees centigrade for Rochelle salt, and the smaller temperature dependence of their dielectric and piezoelectric coefficients. Their ability to withstand higher temperatures than Rochelle salt enables

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them to deliver higher levels of power when used as a transmitter of ultrasonic waves.

In accordance with this invention there is provided a plate-like thickness expander piezoelectric crystal element cut from a P-type crystal. The plate has its thickness direction in a direction substantially parallel to a symmetry plane of the crystal and inclined at an angle greater than zero degrees and less than ninety degrees from the Z-axis of the P-type crystal.

The term "P-type crystal" is to be understood as comprising primary ammonium phosphate ($NH_4H_2PO_4$), primary potassium phosphate, primary rubidium phosphate, the primary arsenates of ammonium, potassium and rubidium, isomorphous mixtures of any of these named compounds, and all other piezoelectrically active crystalline materials isomorphous therewith. All of these crystals belong to the crystallographic symmetry class V_d, also known as the di-tetragonal alternating crystal class, and as the tetragonal sphenoidal class. It is characterized by the presence of three two-fold axes of symmetry perpendicular to each other and two planes of symmetry at right angles to each other and intersecting in one of the two-fold axes. The planes cut the other two two-fold axes at angles of 45 degrees. This combination of symmetry elements makes that axis which is parallel to the two planes of symmetry a four-fold alternating symmetry axis which is also the optic axis of the crystal.

For the symmetry class of the P-type crystals there exist, according to general principles of piezoelectricity, two separate and independent piezoelectric actions. One of these actions is that due to an electric field or field component parallel to the optic axis. If a coordinate system X, Y, Z is used which has its Z-axis parallel to the optic axis of the crystal and the X and Y axes parallel to the two-fold axes of symmetry respectively, then this piezoelectric action appears as an interaction between an electric field parallel to the Z-axis and a shearing deformation about the Z-axis. With such a choice of coordinates the piezoelectric coefficients describing this interaction are characterized by the subscript 36.

Of the several P-type crystals, primary ammonium phosphate ($NH_4H_2PO_4$) has been found to be of particular merit, and a certain cut thereof is claimed in Patent No. 2,463,109. For the family of cuts herein claimed, primary ammonium phosphate and primary ammonium arsenate are of particular merit. Both of these crystals are stable up to at least 120 degrees centigrade. They contain no water of crystallization so that they may be subjected to a vacuum for long periods of time without detrimental effects. A further advantage of using an element cut from a crystal of the P-type is that when it is used in an enclosed transducer housing, an amount of an extreme drying agent such as phosphorous pentoxide may be added to prevent moisture from establishing shunt circuits across the element faces between the electrodes. Previously, when silica gel or the like was put into a transducer housing containing a Rochelle salt element, care had to be exercised to see that the silica gel was only partially dry, as completely dehydrated silica gel would rob the Rochelle salt of its water of crystallization, thereby rendering the unit inoperative. Another important advantage gained by using an element of the P-type instead of using a Rochelle salt element is that the P-type element may be coated with a thermo-setting material such as a phenolic condensate product ("Bakelite"), methyl methacrylate, or any other material which will form a moisture-resistant coating upon being heated over a period of time at a temperature of 120 degrees centigrade, or less. A further distinct advantage is realized when affixing an element of primary ammonium phosphate to a base, such for example as a glass base, as a thermo-setting elastomer may be utilized since the element will withstand the heat necessary for vulcanization.

It is an object of the invention to provide a suitably oriented plate of synthetic piezoelectric crystalline material which has no water of crystallization and which has sufficiently high piezoelectric activity that the plate is highly useful in a piezoelectric transducer device.

A further object of the invention is to provide a suitably oriented plate of synthetic piezoelectric crystalline material useful in the production or the detection of compressional waves, particularly in the high frequency range, which is not severely limited in its use by temperature conditions, and which will handle large amounts of power compared to Rochelle salt plates.

It is also an object of the invention to provide a suitably oriented plate of synthetic piezoelectric crystalline material for maintaining resonant high frequency vibrations in oscillating circuits.

For a better understanding of the present invention, together with other and further objects thereof, reference is had to the following description taken in connection with the accompanying drawings, and its scope will be pointed out in the appended claims.

In the two sheets of drawing Fig. 1 is a schematic isometric view of a P-type crystal showing two crystal elements cut in accordance with a preferred orientation; Fig. 2 is a schematic view showing a family of plates cut in accordance with the invention; and Fig. 3 is a graph showing the voltage output of the family of plates shown in Fig. 2 as a function of the angle of their cut.

The orientation of a plate-like piezoelectric crystal element with respect to the orthogonal axes of the crystalline material from which it is cut depends upon the characteristics which are desired. A plate may be cut from a P-type crystal with such orientation that its thickness direction lies in one of the symmetry planes of the crystal and is at an angle to the Z axis of the crystalline material. If the highest possible electric charge is to be produced in the plate by a given pressure applied to the plate, the angle should be chosen so that the piezoelectric modulus d'_{33} is at its

maximum. This modulus d'_{33} determines the piezoelectric charge produced on a crystal per unit applied compressional stress in the thickness direction. The value of the piezoelectric modulus d'_{33} for an inclined plate of a P-type crystal having its thickness direction in a symmetry plane is given by the formula:

$$d'_{33}=(2d_{14}+d_{36})\sin^2\theta\cos\theta$$

where θ is the angle between the thickness direction of the plate and the direction of the Z-axis. In many applications, however, this modulus is not a true measure of the piezoelectric usefulness of a crystal. For instance, when operating as a microphone acting at high frequencies, such as one megacycle or more, at which thickness expander plates are particularly useful, the most important piezoelectric magnitude is the open-circuit voltage output per unit applied stress. In a plate whose thickness direction is perpendicular to a symmetry axis of a P-type crystal this voltage output is given by a piezoelectric coefficient termed the elasto-electric coefficient and designated by the letter "g" in Patent No. 2,463,109. The rules for transforming this coefficient g to inclined axes are the same as for the transformation of the modulus d. It would therefore appear that the value $\theta=55°$ would give the preferred plate in respect to voltage output. This is not so, however, as the coefficient g is not the true measure of the voltage output in case of plates whose thickness direction is inclined to the Z-axis of a P-type crystal. A more accurate measure of this voltage output is given by

$$\frac{d_{33}'}{K'}$$

where K' is the effective dielectric constant of the inclined plate. This ratio for inclined plates is not identical with the g coefficient. The reason for the difference is found in the fact that the electric field and dielectric polarization in these inclined plates are not parallel to each other. The effective dielectric constant (that is the capacity compared to an air condenser of the same dimensions) of a plate with its thickness direction inclined by an angle θ to the Z-axis of a P-type crystal is given by the relation:

$$K'=K_z\cdot\cos^2\theta+K_x\cdot\sin^2\theta$$

where K_z and K_x are, respectively, the dielectric constants for the Z and X directions.

In this relation the clamped values for the dielectric constants should be used because in typical applications of these thickness expander plates the crystal is prevented from lateral motions.

The voltage output is thus given by the "effective voltage output coefficient"

$$\frac{(2d_{14}+d_{36})\sin^2\theta\cos\theta}{\epsilon_0 Kz(\cos^2\theta+\sin^2\theta\cdot K_x/K_z)}$$

where $\epsilon_0=8.9\cdot10^{-12}$ farad/meter and is the dielectric constant of air.

The voltage, in volts, obtained from a crystal plate is given by the effective voltage output coefficient multiplied by the thickness of the plate in meter and the applied pressure in newton/meter^2.

For the crystal primary ammonium phosphate, the clamped dielectric constants are $K_z=14$ and $K_x=56$, giving a ratio

$$\frac{K_x}{K_z}=4.0$$

The piezoelectric moduli are $d_{14}=-1.5$ and

$d_{36}=+48.0$, the unit being 10^{-12} coulomb/newton.

For the crystal primary ammonium arsenate, the clamped dielectric constants are $K_z=14.0$ and $K_x=75$, giving a ratio of 5.36. Further I have found $d_{14}=+41$ and $d_{36}=+31\cdot10^{-12}$ coulomb/newton.

In Fig. 1 there is shown a bar **10** of P-type crystalline material with its X, Y and Z orthogonal axes indicated. The bar **10** is obtained from a synthetically grown crystal (not shown in its entirety) by cutting the edges of the bar at 45 degrees to the natural prism faces of the crystal. The pyramidal and cap **11** of the grown crystal may be used to orient the crystal bar during cutting. Plate **12** is obtained by slicing the bar **10** at an angle of 45 degrees to one of the edges, and plate **13** is obtained by slicing the bar at an angle of 45 degrees to another of the edges. The thickness direction of both of the plates is at an angle of 45 degrees to the Z axis, and the two plates are equivalent to each other.

Fig. 2 shows schematically a P-type crystal **15** with its mutually perpendicular symmetry planes **16**, **17** intersecting in the Z axis. A family of thickness expander plates 18 to 24 is indicated with the angle θ varying from greater than zero degrees to less than ninety degrees. The crystal plate **24** is shown with an electrode **25** on one of its major faces. It is to be understood that its other major face is to be electroded, and it is to be further understood that each of the other plates **12**, **13** and **18—23** may be similarly electroded.

In Fig. 3 there is shown in curve form the voltage output versus angle θ. It is seen that the maximum voltage output is obtained at an angle θ of about 42 degrees for ammonium dihydrogen phosphate and 40 degrees for ammonium dihydrogen arsenate. The curves are rather flat in the vicinity of the maximum, permitting to choose an angle θ several degrees away from the theoretical optimum without noticeable loss in output. In the particular case of ammonium dihydrogen phosphate, the output for the angle $\theta=45°$ is extremely close to the maximum theoretical output. The practical convenience of cutting plates at an angle of 45 degrees to the Z-axis compared to cutting at an odd angle, such as 42 degrees, has led to the preference of the value $\theta=45$ for this crystal.

The angle θ giving maximum voltage output depends only on the ratio of the dielectric constants K_x and K_z and satisfies the equation:

$$2(K_x/K_z-1)\ \sin^2\theta=-3+\sqrt{8K_x/K_z+1}$$

The specified angles of orientation θ lie between zero and 90 degrees. It may be noted that the equation given to derive the value of θ for maximum voltage output will lead to two values which are supplementary in respect to 180 degrees. The two angles so obtained are identical in terms of crystal symmetry.

While there have been described what are at present considered to be the preferred embodiments of this invention, it will be obvious to those skilled in the art that various changes and modifications may be made therein without departing from the invention, and it is, therefore, aimed in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

I claim:

1. A plate-like thickness expander piezoelectric crystal element cut from an arsenate P-type crystal, said plate having its thickness direction in a direction substantially parallel to a symmetry plane of said crystal and inclined at an angle greater than zero degrees and less than ninety degrees from the Z-axis of said P-type crystal.

2. A plate-like thickness expander piezoelectric crystal element cut from a P-type crystal, said plate having its thickness direction in a direction substantially parallel to a symmetry plane of said crystal and inclined to the Z-axis by an angle θ satisfying the equation

$$2(K_x/K_z-1)\ \sin^2\theta=-3+\sqrt{8K_x/K_z+1}$$

whereby the voltage output for compression in the thickness direction is substantially a maximum.

3. A plate-like thickness expander piezoelectric crystal element cut from a P-type crystal as set forth in claim 2, in which said crystal is a primary ammonium phosphate crystal, and said angle of inclination is substantially 45 degrees.

4. A plate-like thickness expander crystal element cut from a P-type crystal as set forth in claim 2, in which said crystal is a primary ammonium arsenate crystal, and said angle of inclination is substantially 40 degrees.

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No references cited.