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PIEZOELECTRIC DEVICE CONSTRUCTED OF
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This invention relates to piezoelectric devices, and more particularly to such a device comprising piezoelectrically sensitive sections cut from single crystals of a type of material heretofore unknown in the piezoelectric art.

It is well known that every crystal belongs to one of thirty-two crystal symmetry classes. It also is well known that certain of these crystal classes, notably those having the highest symmetry, cannot exhibit piezoelectricity. Concerning the remaining crystal classes, all that can be said on theoretical grounds is that piezoelectric responses, as between electric fields having predetermined orientations with respect to the crystallographic axes and mechanical strains of predetermined types, of such crystals are not prohibited by the symmetry characteristics of the crystalline material. However, it has not been found possible to predict the magnitude of any such responses, and the magnitude may be substantially zero or entirely negligible in any particular case, even though the substance under consideration belongs to one of the so-called piezoelectric crystal classes.

There are a number of crystal classes which are represented individually by one or more crystalline substances whose elastic, dielectric, and piezoelectric properties have been investigated rather thoroughly. However, no detailed or quantitative piezoelectric data heretofore were available with regard to any crystal of the crystal class known as the hemimorphic or pyramidal class of the orthorhombic system, also designated class C_{2v} . Nevertheless, it has been determined that a plate suitably cut from a crystalline material of the class C_{2v} may exhibit a piezoelectric response in regard to a thickness-controlled shear mode and that such a thickness-shear mode response is free of undesired coupling to other modes. Piezoelectric thickness-controlled shear crystal plates of this type are described and claimed in the copending application Serial No. 20,173, filed April 10, 1948, in the name of Hans G. Baerwald and assigned to the same assignee as the present invention which issued on October 18, 1949, as Patent No. 2,485,130.

A number of compounds were known to crystallographers to conform to the crystalline structure of the hemimorphic orthorhombic class, class C_{2v} . Notable among these substances is hemimorphite (calamine), which, however, seems to be of no practical use in the piezoelectric art.

Small crystals of the substance known as potassium pentaborate tetrahydrate were investigated and the lattice parameters of this crystal-

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line substance were measured as long ago as 1901. This work indicated that the substance did not belong to the hemimorphic orthorhombic crystal class. More recent work on this same compound yielded revised information on its crystalline structure. The early investigations were found to be in error, and the substance was assigned properly to the hemimorphic orthorhombic class. The more recent work also indicated that the hydrogen atoms present in this substance are more closely bound in the crystal lattice than is indicated by the tetrahydrate formula, and it was concluded that the true structure is represented more accurately by the formula potassium dihydrogen dihydronium pentaborate. Even these detailed investigations, however, failed to give any indication that the substance under investigation exhibits a measurable piezoelectric response. In fact, it may be concluded that, prior to the present invention, no substance was known in the crystal class C_{2v} which could be obtained in single-crystalline plates of a convenient size and chemical stability and which also was known to afford a piezoelectric response of any commercially significant magnitude.

Accordingly, it is an object of this invention to provide a piezoelectric device comprising a piezoelectrically sensitive section cut from a single crystal and having novel and useful piezoelectric properties.

It is another object of the present invention to provide a new and improved piezoelectric device comprising a section cut from a substance of the hemimorphic orthorhombic crystal class.

It is a further object of the invention to provide a new and improved piezoelectric device comprising a piezoelectrically sensitive section cut from a crystalline material which is stable to temperatures higher than those usually encountered during the operation of such devices.

It is yet another object of the invention to provide a new and improved piezoelectric device comprising a piezoelectrically sensitive resonator section having a desirably low frequency-temperature coefficient.

It is a still further object of the invention to provide a new and improved piezoelectric device comprising a synthetic crystal plate having a high piezoelectric response in a thickness-shear mode.

In accordance with the invention, a piezoelectric device comprises a piezoelectrically sensitive section having electroded major surfaces cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetra-

hydrate, and isomorphous mixtures of these potassium and rubidium pentaborate hydrates. While these pentaborate compositions are referred to herein as tetrahydrates, it will be understood that the compounds intended to be designated are those commonly identified as tetrahydrates and given the formula $MB_5O_8 \cdot 4H_2O$, where M is the univalent metal, although some or all of the water of hydration apparently is bound more closely within the pentaborate molecule, so that the formula more accurately might be written $MH_2(H_3O)_2B_5O_{10}$, an acid dihydronium pentaborate. For convenience the designated compounds will be referred to in this specification and in the appended claims as pentaborate tetrahydrates. Furthermore, the term "electroded surface" as used in this specification and in the appended claims is intended to include an electrode arranged so as to be spaced by an air gap from the crystal surface and closely capacitively coupled thereto, as frequently practiced in the piezoelectric art.

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 drawing, and its scope will be pointed out in the appended claims.

In the drawing, Fig. 1 is a perspective view of a typical single crystal of potassium pentaborate tetrahydrate, or of an isomorphous composition containing rubidium pentaborate tetrahydrate, which is useful in a piezoelectric device in accordance with the invention;

Fig. 2 is a representation in the same perspective as that of Fig. 1 of a thin plate cut from the crystal of Fig. 1 with a predetermined crystallographic orientation and showing the outline within a portion of this plate of a piezoelectrically sensitive section having a rectangular shape which may be cut from the plate;

Fig. 3 is a plan view of the plate of Fig. 2 showing the same piezoelectrically sensitive rectangular section;

Fig. 4 is a schematic circuit diagram representing an oscillator which includes a resonator section prepared from the rectangular section illustrated in Figs. 2 and 3; and

Fig. 5 is a view, partly schematic, of a transducer device comprising a similar piezoelectrically sensitive section.

Referring to Fig. 1, there is represented in perspective a single crystal of a composition which may be any composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of the potassium and rubidium pentaborate hydrates, the latter type also being known as mixed crystals. While any of the isomorphous compositions of this group may have the external structure and development illustrated by way of example in Fig. 1, the crystal habit represented by Fig. 1 is particularly common with potassium pentaborate tetrahydrate. The pentaborate crystal is represented in Fig. 1 with relation to crystallographic axes a , b , and c . These three crystallographic axes are made to coincide in the conventional manner with the respective coordinate axes X , Y , and Z of a right-handed system of rectangular coordinates. The positive directions of the crystallographic and coordinate axes are represented by arrows. The crystallographic index of each of the crystal faces is designated in Fig. 1 in the conventional manner.

The piezoelectric phenomena discussed hereinbelow are described with reference to the coordinate axes X , Y , and Z . In order to clarify the manner of locating these coordinate axes in the crystalline material, a discussion of some crystallographic characteristics of these pentaborate materials is desirable. In accordance with accepted practice, the two-fold rotational axis present in class C_{2v} is chosen as the c -axis, while the a - and b -axes are perpendicular to the two symmetry planes. Axial ratios are determined by measurement of angles between the inclined crystal faces of index (111) and are found to be $a:b:c=1.00:1.00:0.80$. A distinction between the a - and b -axes by means of angular measurement is made difficult by the tendency of the aforementioned inclined faces to be curved.

The axes herein used, however, are readily identified on any crystal of potassium or rubidium pentaborate by the description of crystal properties which follows: In terms of my axes, crystals of potassium pentaborate and isomorphous compositions containing rubidium ordinarily are characterized by the presence of a pair of faces perpendicular to the b -axis, these faces having the crystallographic index (010). There is also a well developed face usually found at one end of the c -axis. I have chosen this end of the c -axis and the coinciding Z -axis as the positive end; hence the well developed face referred to has the index (001⁺). I have found that an extensional stress applied parallel to the Z -axis produces a positive piezoelectric charge on the aforementioned positive end of this axis.

These pentaborate crystals are further characterized by a pronounced tendency to develop twinning during growth; the twinning plane is (101⁻) in terms of the crystallographic axes described hereinabove. The typical crystal illustrated in Fig. 1 has relatively small twinned portions at each end of the crystal, and the twin boundaries are represented by wavy lines.

On a piece of potassium pentaborate crystal devoid of well developed faces, the crystallographic a -, b -, and c -axes are readily identified by means of polarized light. The two optic axes are found to lie in the plane perpendicular to the a -axis, while the b -axis is the bisectrix of the acute angle between the optic axes.

The single crystals from which the piezoelectrically sensitive sections of the device of the present invention are obtained show a pronounced cleavage along YZ -planes, which also may be designated as (100) planes. Accordingly the major surfaces of an X -cut section or plate of these substances, particularly of potassium pentaborate tetrahydrate, lie on cleavage planes, which greatly facilitates the production of X -cut sections of these materials. One such cleavage plane 11 is shown in Fig. 1, passing more or less centrally through the crystal. This same plane 11 is illustrated in the same perspective in Fig. 2, which also shows another plane 12 which would be obtained by cutting through the crystal of Fig. 1 a short distance from the plane 11 and parallel thereto. For simplicity of illustration the plane 12 is not indicated in the view of Fig. 1. The crystalline material between the planes 11 and 12 has the shape of a thin plate 13 with two major surfaces normal to the direction of the X -axis and with edge portions which are portions of the original faces of the single crystal through which the cuts were passed along the planes 11 and 12. The crystallographic indices of these edge portions also are indicated in Fig. 2. In some cases

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deviations of the normal to the plate 13 from the direction of the X-axis are permissible, and alternative directions of the normal also are indicated in Fig. 2, as discussed hereinbelow.

Reference to Fig. 1 reveals at the top of the crystal a large (001) face, normal to the Z-axis. Although a small face parallel thereto and designated (001-) appears at the bottom of the crystal, it should be noted that the latter face ordinarily does not develop during the unimpeded growth of a crystal of the type described. To identify the (001-) face as artificial its outlines appear as dot-dash lines in the views of Figs. 1-3. The portions of the crystal of Fig. 1 which ordinarily might develop in the region beneath the artificial (001-) face as shown in the drawing would tend to be imperfect and twinned, and thus unfit for use in the preparation of piezoelectrically sensitive sections.

Referring again to Fig. 2, there is shown within a portion of the plate 13 the outline of a section 14 having a rectangular shape which may be removed from the plate 13 as by a sawing operation. The section 14 has two major surfaces in the planes 11 and 12 respectively and is then relative to its length and width. The section is rectangular in outline, as seen more clearly in the plan view of Fig. 3, in which the X-direction is normal to the plane of the drawing. The longer edges of the section 14 extend in the Z-direction, while the shorter edges extend in the Y-direction. As mentioned hereinabove, however, in some cases the normal may deviate somewhat from the X-direction, in which case at least one of the edges no longer extends in the direction of a coordinate axis.

A suitable section, such as the section 14 of Figs. 2 and 3, taken from the original single crystal advantageously may be incorporated as a resonator element in a frequency-selective piezoelectric device. X-cut sections are well adapted for resonator operation in the approximate frequency range 0.4 mc. to 5 mc. While such a frequency-selective device may take the form of a crystal filter, in which these X-cut sections have the advantage of providing an unusually wide transmission bandwidth due to their high piezoelectric coupling coefficient, it will be convenient to describe a frequency-selective oscillator device. Thus the crystal section 14 may be incorporated in an oscillator device of the type illustrated schematically in Fig. 4. The crystal section 14 has electroded major surfaces 16 and 17, illustrated schematically, these electroded surfaces being portions of the respective planes 11 and 12 as seen in Fig. 2. The electrodes or electroded surfaces 16 and 17 may be provided on the faces of the crystal section in any convenient manner. For example, various methods of applying thin coatings or layers of metal or other conductive material are well known. Alternatively, a crystal holder may be used which provides an air gap between the electrode and the crystal surface. Thus, as described above, the resonator section 14 may be cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of such potassium and rubidium pentaborate hydrates. Ordinarily it is preferred to cut the section from a crystal of potassium pentaborate tetrahydrate, since this substance is readily available and has desirable elastic and piezoelectric properties, as mentioned hereinbelow. However, sections cut

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from a crystal of rubidium pentaborate tetrahydrate or from a mixed crystal of the two pentaborate hydrates may have somewhat different properties which may be desirable in certain cases.

The remainder of the device of Fig. 4 comprises electrical oscillatory circuit means for exciting the resonator section 14 so as to utilize the frequency-selective characteristics thereof. This oscillatory circuit is a crystal-controlled circuit of a modified tuned-plate tuned-grid type having a triode vacuum tube 18. The tuned plate portion of the circuit includes a variable capacitor 19 suitable for resonating a parallel inductor 21. The parallel resonant circuit 19, 21 is connected across the anode-cathode circuit of the triode 18 with a source of anode potential 22 inserted between the resonant circuit and the grounded cathode of the triode. The essential element of the tuned grid portion of the circuit is the crystal resonator 14, the electrodes 16 and 17 of which are connected to the cathode and control electrode respectively of the triode 18. The crystal element 14 is shunted by a resistor 23 and a series choke inductor 24 to provide a suitable bias voltage. A capacitor 25 may be connected between the anode and control electrodes of the triode 18, but this capacitor is shown in dotted lines because the interelectrode capacitance of the triode ordinarily supplies the desired coupling between these electrodes.

The X-cut crystal section 14, having the shape illustrated in Figs. 2 and 3, is adapted particularly well to be excited in a thickness-shear mode of motion so as to utilize the frequency-selective characteristics of that mode of motion of the crystal section. In the operation of the circuit of Fig. 4, capacitor 19 may be adjusted so that the circuit 19, 21 resonates at a frequency which is at or near the frequency of a thickness-shear resonance of the section 14. Any excitation in the anode-cathode circuit of the triode 18 tends to produce oscillations at the frequency of resonance of the tuned circuit 19, 21. The resulting oscillatory voltage appears across the capacitance 26 and the impedance of the crystal element 14, and stabilizes at such a frequency that it is applied regeneratively to the control-electrode circuit of the triode. This tends to set up oscillations, the frequency of which is determined in a well-known manner by the steep impedance-frequency characteristic of the crystal element 14.

The piezoelectrically sensitive crystal section included in the piezoelectric device of the present invention preferably is cut from the pentaborate material and electroded so as to have a pair of electroded surfaces with the normal to the plane of each of these surfaces inclined not more than 15° from the X-axis of the crystalline substance. When cut in this way from a single crystal of the pentaborate, preferably of potassium pentaborate tetrahydrate, the crystal section is piezoelectrically sensitive to a thickness-shear mode of motion. The true X-cut section 14 illustrated specifically in Figs. 2 and 3, which has a pair of electroded major surfaces 16 and 17 as shown in Fig. 4 with the normal to the plane of each of these surfaces substantially coinciding with the X-axis of the crystalline substance, has the advantage that its major surfaces are cut substantially along natural cleavage planes of the original crystal. When an X-cut section, such as the section 14, of potassium or rubidium pentaborate tetrahydrate has its thickness dimension,

parallel to the X-axis, much smaller than its length dimension, parallel to the Z-axis, the natural frequency of a thickness shear mode of motion of the section is determined by the thickness dimension. The symmetry of this crystalline material is such that a field applied in the X-direction produces a shear in the plane perpendicular to the Y-axis, that is, the XZ-plane. The width dimension, parallel to the Y-axis, may be chosen to provide a desirable capacitance for the electroded section. It will be understood that operative piezoelectric devices may include X-cut sections the edges of which are not parallel to the Y-direction or Z-direction or which are not rectangular in shape. Modifications of the frequency constant or changes in the frequency-temperature characteristics may be effected by cutting or grinding the major surfaces of the crystal section so that the normal to each surface is inclined somewhat from the X-axis of the crystalline substance, but, as indicated hereinabove, inclinations of more than 15° from the X-axis may be expected to cause serious deterioration of the desired piezoelectric response.

The orientation of such crystal plates deviating not more than 15° from the X-cut plates is indicated in Fig. 2 by the use of dashed lines representing the direction of the normal to the plate relative to the direction of the X-axis. It will be seen that the locus of the normal forms a cone with the axis of the cone in the X-direction. The angle θ between the normal and the X-axis may lie between 0° and 15°, this angle being 0°, of course, for a true X-cut section. It will be clear that the X-direction and one or both of the Y- and Z-directions no longer can coincide with edges of the crystal plate when θ is greater than zero, but for simplicity of illustration the edges are shown in Fig. 2 in coincidence with the directions of the coordinate axes, as is the case with X-cut plates having rectangular major faces and the preferred orientation of the edges.

The thickness shear response of X-cut sections is not the only useful piezoelectric response obtainable with potassium or rubidium pentaborate tetrahydrate crystals. The capabilities of, for example, the potassium salt may be seen from the following approximate values of the piezoelectric coefficients in units of 10⁻¹² meters per volt:

d_{15} -----	9.5
d_{24} -----	1.7
d_{31} -----	5.4
d_{32} -----	Small
d_{33} -----	5.6

The coupling coefficients are given by these piezoelectric coefficients in conjunction with dielectric and elastic data. The dielectric constants for these materials are all about 5. A noteworthy feature of the elastic coefficients is the unusually high shear stiffness in the XZ-plane combined with unusually low compressional stiffness. The density of the crystallized potassium salt is 1.74.

Three of the piezoelectric coefficients given hereinabove have sufficiently high values to permit strong excitation of resonances. These are the coefficients d_{15} , exciting the high frequency shear mode around the Y-axis in the X-cut section as described hereinabove, the coefficient d_{31} providing a lateral expander mode in Z-cut sections, and the coefficient d_{33} , which ordinarily might be expected to excite thickness expander modes of motion in Z-cut sections. Thickness expander resonances of Z-cut sections have not

been observed, however, presumably due to the opposite signs and almost equal value of the coefficients d_{33} and d_{31} and strong elastic coupling between expansion in the Z-direction and X-direction.

The X-cut thickness shear section 14 of Figs. 2 and 3 exhibits a frequency constant of about 1550 kc.-mm. at about 27° C., and either increase or decrease of temperature causes the frequency constant to decrease, but only to the extent that the frequency is decreased by 0.1% at +2° C. and at +53° C. The coupling coefficient for the X-cut thickness shear section is about 0.20. In the case of a thickness-shear mode, such as discussed herein, the coupling coefficient is related to the ratio of series capacitance C_s to parallel capacitance C_p in the well known equivalent circuit for piezoelectric crystal plates by the formula (coupling coefficient)² = $(\pi^2/8) (C_s/C_p)$.

In addition to the Z-cut lateral expander mode mentioned hereinabove, useful piezoelectric responses may be obtained in length expander and thickness modes with crystal sections or bars the thickness direction of which is inclined at an angle of about 45° to both the Z-axis and X-axis. Another bar with the thickness direction at about 45° to the Z- and Y-axes exhibits an expander mode response attributable to the d_{33} coefficient, but this response is not strong. With a bar having its length direction inclined at 45° to the X- and Y-axes a lengthwise expander mode is obtained. A doubly inclined section, parallel to the (111) face, also acts as a piezoelectric resonator in several modes. Negative temperature coefficients of the frequency constant may be expected with most of these inclined cuts. Additionally, Y-cut plates may be excited in a thickness-shear mode by virtue of the piezoelectric coefficient d_{24} .

In addition to the perfect cleavage exhibited by the potassium pentaborate tetrahydrate in YZ-planes, it may be remarked that the materials show a good cleavage along XZ-planes. These materials have an advantageously high stability at rather elevated temperatures; for example, potassium pentaborate is stable to about 125° C. It also may be mentioned that the rubidium pentaborate tetrahydrate, the properties of which closely resemble those of the potassium salt, has a maximum frequency constant at about 5° C. Again, as with the potassium salt, an increase or decrease in temperature of about 25° C. causes a decrease in frequency of about 0.1%.

Fig. 5 is a partially schematic representation of a piezoelectric device for transducing between the types of energy which are classified as electrical and mechanical. Such a device may be used for transducing from electrical energy to mechanical energy, or vice versa. This device also utilizes a piezoelectrically sensitive section 14 cut from a single crystal of potassium or rubidium pentaborate hydrate. This section is seen in Fig. 5 mounted as if looking at the left hand edge of the section 14 as shown in Fig. 2. In other words, the edge surface of the section 14 as seen in Fig. 5 lies in an XZ-plane. The electroded surface 16 of the section 14 is fastened securely to a supporting surface 30. The other electroded surface 17 of the section 14 is fastened securely to a solid rod 31, only the left hand end portion of which is shown in the drawing. A pair of terminals 32 is connected to the individual electrodes 16 and 17.

The arrangement of Fig. 5 may be used for transducing from electrical to mechanical en-

ergy by connecting to the terminals 32 the output circuit of an electrical signal generator, for example an ultrasonic frequency signal generator. The resulting electrical field developed in the direction of the X-axis of the crystalline substance causes shear distortions of the XZ-planes within the section 14. Such a distortion at a given instant appears as a downward motion of the unmounted or right hand face of the section 14, as represented in Fig. 5 by the arrows 33. These shear motions alternate upward and downward as seen in Fig. 5 and propagate to the right along the rod 31. There also appear in Fig. 5 several additional sets of arrows 34, 35, and 36, representing for the given instant the positions of regions of maximum deformation in upward and downward directions due to motion of the element 14 previous to that represented by the arrows 33. These additional sets of arrows, of course, are spaced one half wave length apart along the rod, the wave length being determined by the velocity of propagation of ultrasonic energy along the rod 31. Thus the terminals 32 and the electrical circuit apparatus connected thereto, together with the electrodes 16 and 17 and the interconnecting wires, constitute means for applying to the crystal section 14 energy of one of the two types mentioned hereinabove, in this case electrical energy. The mounting surface 30, the rod 31, and the arrangement fastening the section 14 between the surface 30 and the rod 31 constitute means dependent upon the effect of the applied energy upon the crystal section 14 for deriving and utilizing energy of the other type, that is, mechanical energy. This mechanical energy is derived in the form of shear deformations propagating along the rod 31 as described above, and the propagation of the ultrasonic energy along the rod 31 is a utilization of the mechanical energy so derived. The ultimate utilization of the mechanical energy may be the testing of the rod 31 for flaws. The energy propagated along the rod 31 may be reflected from the distant right hand end of the rod, not shown, and thus returned to the left hand end after the round trip time of propagation of the energy along the rod has elapsed. For this purpose the vibrational energy should be developed in the rod 31 in short pulses of ultrasonic frequency energy, which can be generated in a well-known manner. If reflected pulses appear at the left end of the rod before this round trip period of time has elapsed, a structural flaw in the rod is indicated. In another application of the Fig. 5 device the rod 31, of predetermined length and elastic properties, may be used as a mechanical delay line for storing energy during the period of time required for round trip propagation of shear vibrations along the rod. It is noted that the mechanical energy transduced in the device is associated with motion of the crystal section 14 in a thickness shear mode.

In the utilizations just discussed of the piezoelectric device of Fig. 5, it was implied that shear vibrations propagating in the leftward direction along the rod 31 may be picked up by the element. In this case the rod 31 and its mechanical connection to the mounted crystal section constitute means for applying mechanical energy to the section, wherein this energy is transduced to electrical signal energy. Suitable electrical receiving and display devices, well known in the art, may be connected across

the terminals 32, in which case such devices, the electrodes 16 and 17, and the interconnecting wiring constitute means dependent upon the effect of the applied mechanical energy for deriving and utilizing electrical energy.

As mentioned hereinabove, certain crystallographic investigations of potassium pentaborate had been made by others prior to the work leading to the present invention. This prior work established that single crystals may be grown by slow cooling of a saturated aqueous solution. This has been confirmed, and the same procedure has been found suitable for growing the isomorphous materials which may be incorporated in the devices of the present invention.

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 with the true spirit and scope of the invention.

What is claimed is:

1. A piezoelectric device comprising: a piezoelectrically sensitive section having electroded major surfaces cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates.

2. A piezoelectric device comprising: a piezoelectrically sensitive section having electroded major surfaces cut from a single crystal of potassium pentaborate tetrahydrate.

3. A piezoelectric device comprising: a piezoelectrically sensitive section having electroded major surfaces cut from a single crystal of rubidium pentaborate tetrahydrate.

4. A piezoelectric device comprising: a section having electroded major surfaces, cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates, and piezoelectrically sensitive to a thickness-shear mode of motion of said crystal section.

5. A piezoelectric device comprising: a piezoelectrically sensitive section, cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates, and which has a pair of electroded surfaces with the normal to the plane of each of said surfaces inclined not more than 15° from the X-axis of the crystalline substance.

6. A piezoelectric device comprising: a section, piezoelectrically sensitive to a thickness-shear mode of motion, cut from a single crystal of potassium pentaborate tetrahydrate, and having a pair of electroded surfaces with the normal to the plane of each of said surfaces inclined not more than 15° from the X-axis of the crystalline substance.

7. A piezoelectric device comprising: a piezoelectrically sensitive section, cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium

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pentaborate hydrates, and which has a pair of electroded surfaces with the normal to the plane of each of said surfaces substantially coinciding with the X-axis of the crystalline substance.

8. A piezoelectric device comprising: a piezo-electrically sensitive section, cut substantially along natural cleavage planes from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates, and which has a pair of electroded major surfaces with the normal to the plane of each of said surfaces substantially coinciding with the X-axis of the crystalline substance.

9. A piezoelectric device comprising: a piezo-electrically sensitive resonator section having electroded major surfaces cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates; and electrical circuit means for exciting said resonator section so as to utilize the frequency-selective characteristics thereof.

10. A piezoelectric device comprising: a piezo-electrically sensitive resonator section having electroded major surfaces cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates; and electrical circuit means for exciting said resonator section in a thickness-shear mode of motion so as to utilize the frequency-selective characteristics of said mode of motion of said section.

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11. A piezoelectric device for transducing between the types of energy which are classified as electrical and mechanical comprising: a piezo-electrically sensitive section cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates; means for applying energy of one of said types to said crystal section; and means dependent upon the effect of said applied energy upon said crystal section for deriving and utilizing energy of said other type.

12. A piezoelectric device for transducing between the types of energy which are classified as electrical and mechanical comprising: a piezo-electrically sensitive section cut from a single crystal of a composition selected from the group consisting of potassium pentaborate tetrahydrate, rubidium pentaborate tetrahydrate, and isomorphous mixtures of said potassium and rubidium pentaborate hydrates; means for applying energy of one of said types to said crystal section; and means dependent upon the effect of said applied energy upon said crystal section for deriving and utilizing energy of said other type; said mechanical energy being associated with motion of said crystal section in a thickness-shear mode.

HANS JAFFE.

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The following references are of record in the file of this patent:

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