Aug. 22, 1939.

W. G. CADY

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PIEZOELECTRIC CRYSTAL DEVIÇE

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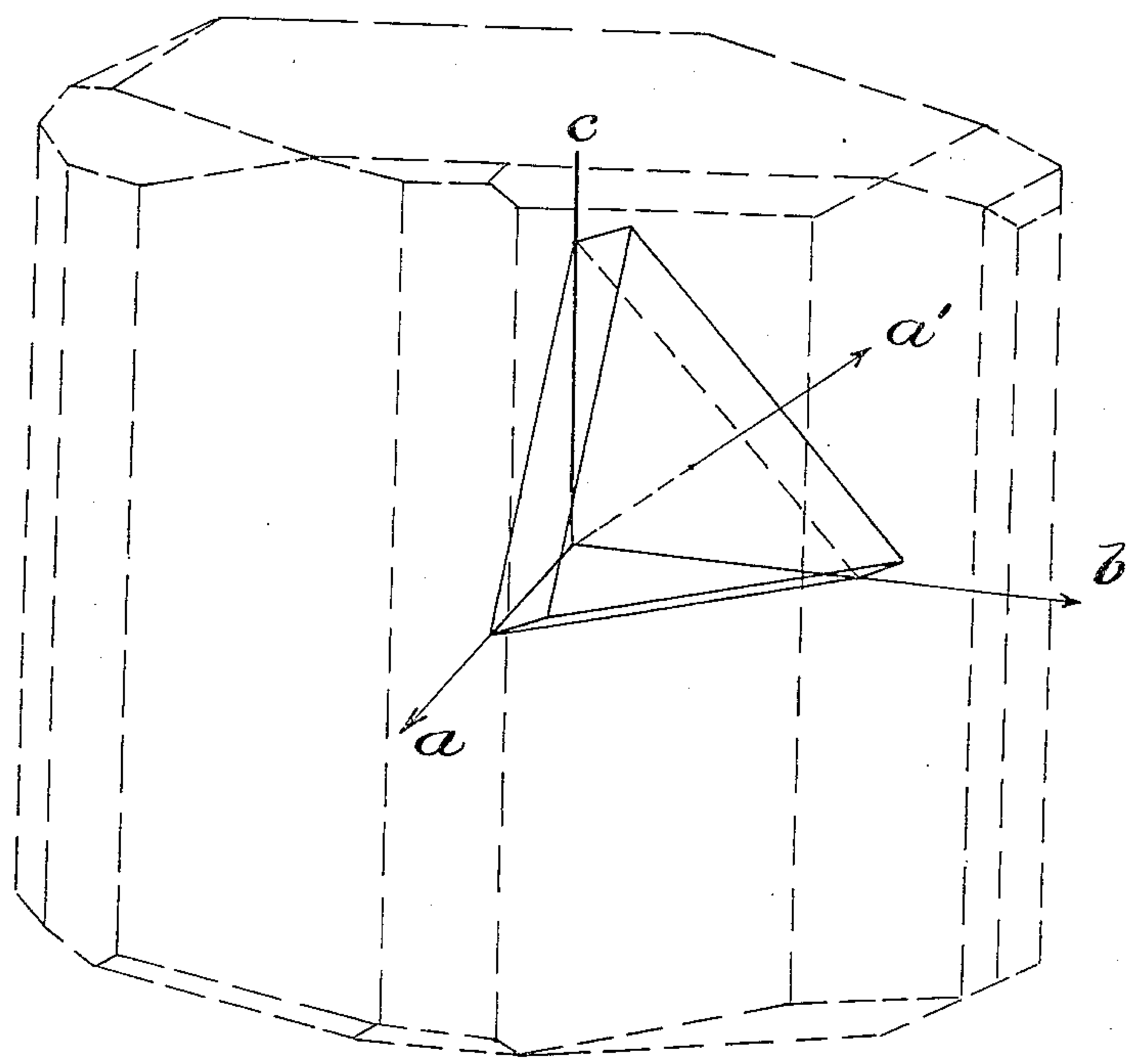

Fig. 1.

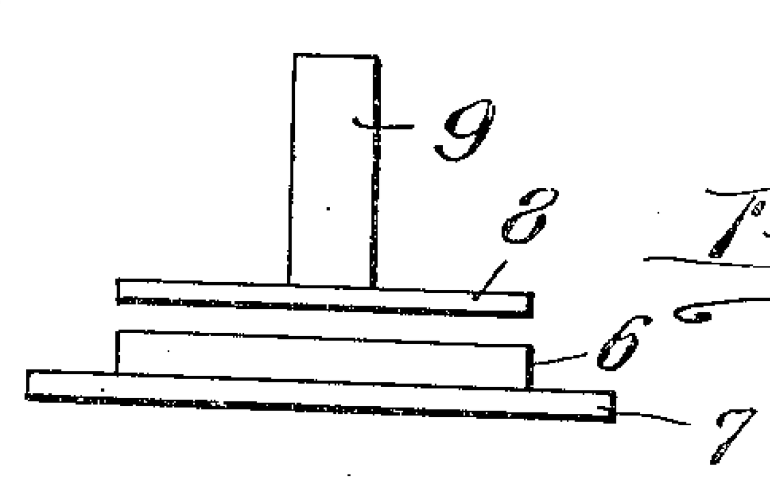

Fig. 2.

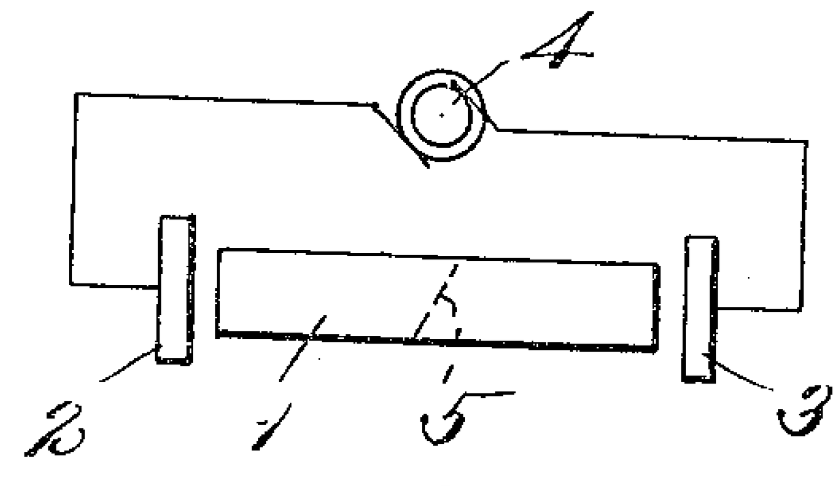

Fig. 3.

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PIEZOELECTRIC CRYSTAL DEVICE

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9 Claims. (Cl. 171—327)

The present invention relates to piezo-electric crystal compression devices.

As explained in my Patents 1,450,246, issued April 3, 1923, and 1,472,583, issued October 30, 1923, piezo-electric crystals have the property of becoming electrically polarized when compressed or otherwise mechanically deformed, the electric polarization giving rise to electric charges which can be utilized in various ways. A flat plate or rod cut from a crystal of quartz or tourmaline in a direction perpendicular to an electric axis, for example, when compressed in the direction of its thickness, develops opposite electric charges on its oppositely disposed faces; and, conversely, when a voltage is applied to the said two faces by means of suitable electrodes, the crystal plate or rod becomes thicker or thinner, according to the direction in which the voltage is applied.

The only crystals heretofore commonly used for this purpose have been quartz and tourmaline. Prior to the present invention, it has been commonly believed that crystals of Rochelle salt, which would be far more useful, because they are many times more strongly piezoelectric than either quarts or tourmaline, do not possess the very desirable property described above of becoming electrified in the direction of the mechanical pressure, or vice versa. It has generally been supposed, up to now, that the piezo-electric nature of Rochelle salt is not such as to cause a plate of this subsance, when compressed, to take on opposite electric charges on its two faces.

Since the earliest investigations on piezo-electricity in the last century, it has been known that compressional piezoelectric effects are of two general types, known as longitudinal and transverse. These terms have reference to the relation between the direction of the applied electric field and the resulting deformation of the crystal; or, conversely, the relation between the direction of an applied force and that of the resulting electric polarization. When a mechanical pressure is associated with a field in the same direction, the effect is termed longitudinal; when the field is at right angles to the pressure, it is called the transverse effect. Many piezoelectric crystals exhibit one effect in one direction and another in some other direction, or both effects may be present for the same direction of field, as is the case, for example, with quartz. The term "crystallographic axes" is employed in this specification in the generally accepted sense, denoting an orthogonal system of axes based on the symmetry characteristics of the crystal. The term "piezoelectric moduli", or its equivalent, denotes the moduli referred to this system of axes. Nine of the eighteen possible piezoelectric moduli yield shears in various directions. In some crystal classes, including that to which Rochelle salt belongs, the only compressional effect, for an electric field parallel to one of the crystallographic axes a, b and c of the crystal, is the transverse effect. In the case of the Rochelle-salt class, this may be expressed by the statement that the only piezoelectric moduli are shear moduli, denoted by d_{14}, d_{25} and d_{36}. In other words, the only type of strain that is produced piezoelectrically by an electric field in the crystal is a shear with respect to one or more of the three said orthogonal axes of the crystal. In my Patent 1,977,169 of October 16, 1934, I have discussed the nature of these moduli and pointed out some practical applications.

It has heretofore been considered, as before stated, that in Rochelle salt and other crystals possessing only piezoelectric shear moduli, the longitudinal effect does not exist; and this notwithstanding the account which J. and P. Curie, the discoverers of piezoelectricity, give of their first experiment on Rochelle salt (Comptes Rendues, vol. 91, p. 383, 1880) and notwithstanding the equations derived by Voigt, in his "Lehrbuch der Kristallphysik", Leipzig, 1910, pp. 849 and 872.

Hitherto, all piezoelectric devices for producing electric effects from mechanical pressure, in which the longitudinal effect was employed, have made use of plates cut at right angles to one of the crystallographic axes. In this invention, I show that similar devices can be made using plates cut from crystals in which there is no longitudinal effect with respect to any single crystallographic axis. Even if there is a longitudinal effect with respect to one or more of the crystallographic axes, it may be of advantage, for mechanical or electrical reasons, to cut plates according to the present invention in such direction with respect to the crystallographic axes as to make possible a more effective use of the longitudinal effect.

It is therefore an object of the present invention to provide a compression piezoelectric device constituted of Rochelle salt or other crystal of piezoelectric properties and exhibiting the longitudinal effect.

Other and further objects will be explained hereinafter and will be particularly pointed out in the appended claims.

The invention will now be described in connection with the accompanying drawing, in which Fig. 1 is a diagrammatic perspective view of a Rochelle salt crystal, shown in broken lines, with the so-called hemihedral (oblique) faces somewhat exaggerated, since, as is well known to those versed in crystal physics, these are the faces that indicate the piezoelectric properties of the crystal, the said Fig. 1 showing also the three crystallographic axes *a*, *b* and *c*, together with an obliquely cut plate which, for clearness, is drawn in full lines, in the form of a triangle; Fig. 2 is a view of a plate cut in the orientation indicated in Fig. 1, with electrodes; and Fig. 3 is a view similar to Fig. 2 of a modification.

The flat triangular crystal plate is assumed, in Fig. 1, to be so cut from the mother crystal that its normal, which, for convenience, I call the a'-axis, makes equal angles with the three crystallographic axes *a*, *b* and *c* of the crystal. The plate is shown in the form of a triangle merely to make the principle clear; it may have any suitable shape, such as rectangular. The dimensions of a suitable, rectangular plate 6 may for example, be approximately 3.5 mms. thick in the a' direction, with parallel faces 35 mm. x 27 mm. Instead of a plate, a bar or rod 1 may be employed, as in Fig. 3, say, approximately 19 mm. long in the a' direction, with rectangular cross section 7.15 mm. x 5.70 mm., the length of the bar or rod 1 being disposed in the same direction before described.

It is not essential that the axis a' make equal angles with the crystallographic axes, but, for maximum piezoelectric effect, the three angles should, in the case of Rochelle salt, theoretically be equal. This is not necessarily true, however, concerning crystals of classes possessing a longitudinal effect with respect to one or more of the crystallographic axes, and which may also be within the present invention, as hereinafter described. For mechanical reasons, it may be desirable to depart somewhat from this particular angle.

The longitudinal effect with the flat plate may be exhibited as illustrated in Fig. 2, in which the piezoelectric plate 6 is shown resting on a lower metal electrode 7, with an upper metal electrode 8 held by a stem 9 by means of which the position of the electrode 8 can be regulated. If the electrode 8 is allowed to press with a known force upon the crystal plate 6 and the electrode 7, then, when the electrodes 7 and 8 are connected to a calibrated ballistic galvanometer, a deflection will be observed due to the charges liberated on the electrodes 7 and 8 by the longitudinal effect. When the plate 6 is compressed in the direction of its thickness, therefore, it also becomes polarized in the same direction, so that electric charges appear upon the opposite faces. The converse is also true.

From this deflection the piezoelectric modulus, which I designate by d' for the longitudinal effect, can be calculated. In my experiments, the value d' was found to be about 3×10^{-5} electrostatic units, which is in satisfactory agreement with the value expected from theory.

This value of the piezoelectric modulus d' is about five hundred times as great as that of quartz or tourmaline. Herein lies the advantage in the use of the longitudinal effect of Rochelle salt. Though quartz and tourmaline are much stronger mechanically and less affected by pressure, temperature and moisture than Rochelle salt, nevertheless, flat plates of Rochelle salt can be subjected without injury to very considerable mechanical pressure, and their great superiority in the intensity of the piezoelectric effect compensates in large measure for their mechanical inferiority.

The plate shown in Figs. 1 and 2, as also the rod of Fig. 3, may serve as a piezoelectric resonator, according to the principles set forth in my said Patents 1,450,246 and 1,472,583. In order that the resonator may vibrate freely, the upper electrode 8 is raised sufficiently to leave a small gap between it and the plate 8, as illustrated in Fig. 2; or, the crystal plate may be coated on both sides with thin metal foil, for example, gold foil, serving as electrodes. The electrodes 7 and 8 may be connected to an electric oscillating circuit of the right frequency, as illustrated in Fig. 3, and the presence of resonant vibrations may be detected by the reaction upon the electric circuit. This may be indicated by an audible "click", which may be heard in a telephone receiver when the frequency passes through the resonant value; by a sudden change in the reading of an ammeter; or by the controlling effect which the crystal exerts upon the frequency of the circuit. These are illustrated in the said patents and need not, therefore, be illustrated here. The observed resonant frequency with a plate 1.93 mm. thick was observed to be 1070 kilocycles per second, while the frequency for longitudinal thickness vibrations calculated from theory was 1060 kilocycles per second. With plates of different thickness the frequency is found to be inversely proportional to the thickness, which is further proof that the vibrations are in the direction of the thickness.

The rod 1 of Fig. 3 may be employed to demonstrate and confirm the existence of the longitudinal effect. Though the apparatus indicated in Fig. 3 is suitable for demonstration purposes, it is to be borne in mind that, since the electric field is parallel to the length of the rod, the metal electrodes 2 and 3 must be located at the extreme ends, thereby making the electric field comparatively weak. The electrodes 2 and 3, slightly separated from the ends of the rod, are supplied with high-frequency alternating current from a suitable source 4. Under the action of the longitudinal effect, the rod becomes alternately lengthened and shortened by the alternating electric field, resulting in longitudinal vibrations which, at the resonant frequency, cause fine metallic particles sprinkled on the surface to be shaken off, except along the nodal line 5, which, in a particular experiment, was found to be disposed obliquely to the direction of the length of the rod. The existence of a node at the central portion of the rod demonstrates the reality of the longitudinal effect. The obliquity of the nodal line indicates, as is well known to those versed in the art, that, while the length of the rod was in the proper direction for maximum longitudinal excitation, the direction of maximum elastic constant, along which the vibrations tend to take place, made a certain angle with the direction of the length. This is due to the well-known peculiar elastic properties of Rochelle salt. It is possible that more effective vibrations may be secured, even if at a slight sacrifice of piezoelectric activity, by cutting the rod or plate in a slightly different direction, so as to make the nodal line at right angles to the direction of the length.

The fact that the rod is vibrating in resonance is further shown by its reaction on the driving circuit, which reaction may be observed either by the sudden change in the reading of a meter, or by the "click" produced in a telephone receiver, as before described. The rod, in other words, through the action of the longitudinal effect, becomes a piezo-electric resonator, according to the principles described in my abovementioned Patents 1,450,246 and 1,472,583.

Just as with other well-known types of resonator depending upon the longitudinal piezoelectric effect, so also in the case of a plate cut according to the present invention, it is possible, by application of a voltage of the proper frequency, to excite the plate so that it will vibrate at an overtone of its fundamental frequency. At the fundamental frequency the thickness of the plate is a half wavelength of the compressional wave. When the plate vibrates at the first overtone frequency, the thickness of the plate is approximately three half wavelengths; or, in general, it is approximately equal to an odd number of half wavelengths. Thus, a plate cut according to the present invention may be used at overtone frequencies for the generation of ultrasonic waves in air or in any other gas, liquid or solid.

It follows from the theoretical considerations mentioned above that such a plate as that represented in Fig. 2, cut according to the present invention, should function either as a microphone or as a reproducer for acoustic waves, whether sonic or ultrasonic. This I have found experimentally to be the case. A Rochelle-salt plate of this type was provided with tinfoil electrodes and connected to the input of an amplifier, the output of which was connected to a loud speaker. When sound waves from the human voice or other sources fell upon the surface of the plate, it was found that the plate was set into vibration so that, through the longitudinal piezoelectric effect, electric currents were generated which caused the sound to be reproduced in the loud speaker. A diaphragm having a central opening was placed in front of the crystal in some of these tests, to make sure that the sound energy fell upon the surface of the plate and not upon the edges.

It was also found that when the crystal plate was connected to the output of an amplifier, the input of which was provided with a current of audio frequency, said plate was set into vibration and served as an emitter or reproducer of sound over a very wide range of frequencies. As is usually the case with crystal reproducers and microphones, this device was more effective at high than at low frequencies.

In the course of these reproducer tests a stethoscope was used to explore the sound field close to the vibrating crystal plate. Owing to the transverse effect, which theoretically is present along with the longitudinal effect, some sound was emitted laterally from two opposite corners of the plate, but most of it was given off uniformly from the flat tin-foil-coated face in a direction at right angles to the face.

The present invention thus provides a means for generating substantially plane waves of sound, especially sound of high frequency. This is made possible by the fact that the type of device herein described consists of a flat plate, the entire major surface of which moves in and out in accordance with electric impulses supplied to it, in contrast to other types of crystal sound-generators such as have been used hitherto, in which the moving portion of the crystal is relatively small. If a still larger vibrating area is desired than can be secured with a single plate of the type herein described, a plurality of plates can be assembled covering a surface of any desired area, all connected to a common source of electric power.

In a similar manner, a single plate or a plurality of plates can be made to serve as receivers of sonic or utrasonic waves by allowing such waves to fall upon the surface of the plate or plates, the electrodes attached to the plates being connected to any suitable amplifying and recording or reproducing system.

It will be understood that the same technique and methods of mounting heretofore in use in various piezoelectric crystal applications are equally applicable to the device of the present invention.

The invention is not, of course, restricted to Rochelle salt; it is applicable to any piezoelectric crystal. A plate, bar, rod or the like, cut from any such crystal, in an orientation, oblique with respect to the said axes, such as to become electrically polarized to substantially the maximum extent in the direction of its thickness when a mechanical pressure is applied in that direction, is within the invention. By having the device cut at an angle oblique to all the crystallographic axes, the longitudinal effect will be secured through the cooperation of all the piezoelectric moduli that the crystal may possess. The invention may, as stated above, be employed with plates or other devices cut from piezoelectric crystals of any class, even those possessing longitudinal effects with respect to one or more of their crystallographic axes—which is not true of Rochelle salt—provided that the plate or other device is suitably oriented with respect to the said axes. It may also be employed with those crystal classes having no longitudinal effect with respect to any crystallographic axis, and yet possessing moduli that are not shear piezoelectric moduli. In many, if not most, cases where the crystal possesses a longitudinal effect with respect to one or more of its crystallographic axes, the total longitudinal effect with an oblique cut cannot be expected to be materially greater than if the plate were cut in the usual way, perpendicular to one of the crystallographic axes. Hence the invention applies more particularly to crystals possessing only shear piezoelectric moduli. In all such cases, if the plate, bar, rod or the like is suitably oriented, it will become polarized in a direction having a component parallel to the direction of compression in the thickness direction of the device and, conversely, will undergo extensional strain in the thickness direction when an electric field is applied in this direction.

Though the invention is most useful when maximum effects are obtained, as described above, it will be understood that its distinguishing feature consists in cutting from the piezoelectric crystal a plate, rod, or other suitably shaped specimen, in such a manner as to be at an oblique angle to all of the crystallographic axes. By this means the various piezoelectric moduli, even in a crystal possessing no longitudinal effect with respect to any of its crystallographic axes, may be caused to cooperate in such a way as to realize the above-mentioned longitudinal effect. By proper choice of angular orientation, of course, this effect may be made to assume a maximum value, as before described.

When the piezoelectric moduli of any crystal are known, the proper direction of cut for maximum longitudinal effect may be calculated from well known equations, such, for example, as given in the above-mentioned book by Voigt, on pages 838 and 849. For crystals belonging to the cubic hemihedral or tetartohedral classes, the tetragonal trapezohedral hemihedral and sphenoidal-hemihedral class, the rhombic hemihedral classes (which includes Rochelle salt), and the hexagonal enantiomorphic-hemihedral class, the following equation holds:

$$P=-F(d_{14}+d_{25}+d_{36})lmn$$

wherein the polarization P, in the direction specified by the direction cosines l, m and n, is expressed in terms of the pressure F in this direction, and the three piezoelectric moduli. Crystals of these six classes all have shear moduli, and only shear moduli, with respect to the crystallographic axes. For convenience, they will be referred to in the claims under the terminology the "six piezoelectric shear classes", or its equivalent. The maximum value of P for these classes is obtained by making l, m and n all equal, that is, by cutting the specimen so that the applied force makes equal angles with the three crystallographic axes. For most of the other piezoelectric crystal classes, the formulas are more complicated, but the direction for maximum longitudinal effect can always be determined. It may, for example, be derived from the following general formula (83) on page 849 of the above-mentioned book by Voigt:

$$\begin{aligned}P=-F[d_{11}l^3+d_{22}m^3+d_{33}n^3+l^2&\{(d_{21}+d_{16})m+(d_{31}+d_{15})n\}\\ +m^2\{(d_{32}+d_{24})n+(d_{12}+d_{26})l\}&\\ +n^2\{(d_{13}+d_{35})l+(d_{23}+d_{34})m\}&\\ +lmn(d_{14}+d_{25}+d_{36})]&\end{aligned}$$

In this formula, the d's are the various piezoelectric moduli (some of which are usually equal to zero for any particular crystal), and l, m and n are, as before, the direction cosines. As is obvious to those versed in this field, the maximum value of P will in general not be such that l, m and n are all equal, hence for such crystal classes the maximum polarization, while lying in a direction oblique to all three crystallographic axes, will not make equal angles with these axes. Nevertheless, there is always a certain particular direction, specified by certain values, of l, m and n, for which the polarization is a maximum.

It is well known that, in the past, for certain special purposes, plates have been cut, making an oblique angle with one or more of the crystallographic axes. However, heretofore no such cuts have been made for the purpos eof obtaining a maximum longitudinal effect. It is true that, in general, every oblique cut may be expected accidentally to contain a trace of the longitudinal effect, to some slight extent. In general, however, the effect will be small unless the angle of cut is properly chosen, as above described, within certain limits.

The invention has many uses, such as in acoustics, the generation of supersonic waves, underwater signalling, in piezoelectric devices for testing or measuring various mechanical effects, such as pressures and vibrations in machinery and explosives, and the control or measurement of high-frequency electric currents.

Other modifications will occur to persons skilled in the art, and all such are considered to fall within the spirit and scope of the invention, as defined in the appended claims.

What is claimed is:

1. A device cut from a piezoelectric crystal of the rhombic-sphenoidal class, the device being cut at substantially equal angles to the crystallographic axes of the crystal.

2. A Rochelle-salt crystal device cut at substantially equal angles to the crystallographic axes of the crystal.

3. A Rochelle-salt crystal resonator cut at substantially equal angles to the crystallographic axes of the crystal and provided with electrodes disposed substantially perpendicular to the normal to the resonator, the resonator having a nodal plane disposed substantially at right angles to the direction of the length of the resonator.

4. A piezoelectric device for producing electric effects from mechanical pressures, consisting of a plate cut from a Rochelle-salt crystal in a direction making substantially equal angles with all of the crystallographic axes, provided with suitable electrodes and employing the longitudinal effect.

5. A piezoelectric generator of sonic or ultrasonic waves, consisting of one or more plates cut from a piezoelectric crystal belonging to one of the classes that do not posses the longitudinal piezoelectric effect with respect to any one of the crystallographic axes, the plate being cut from the piezo electric crystal in a direction making substantially equal angles with all the crystallographic axes and capable of being set into thickness vibration through the longitudinal piezoelectric effect when excited by an alternating current of sonic or ultrasonic frequency.

6. A piezoelectric generator of sonic or ultrasonic waves, consisting of one or more plates, provided with suitable electrodes cut from a Rochelle-salt crystal in a direction making substantially equal angles with all the crystallographic axes and capable of being set into thickness vibration through the longitudinal piezoelectric effect when excited by an alternating current of sonic or ultrasonic frequency.

7. An acoustic device for emitting or receiving sound waves, consisting of a plate cut from a piezoelectric crystal belonging to one of the classes that do not possess the longitudinal piezoelectric effect with respect to any one of the crystallographic axes, the plate being cut from the piezoelectric crystal in a direction making substantially equal angles with all the crystallographic axes so as to exhibit to substantially a maximum degree the longitudinal effect.

8. An acoustic device for emitting or receiving sound waves, consisting of a plate cut from a Rochelle-salt crystal in a direction making substantially equal angles with all the crystallographic axes, provided with suitable electrodes and employing the longitudinal effect.

9. A piezoelectric device comprising a plate cut from a piezoelectric crystal belonging to one of the classes that do not possess the longitudinal piezoelectric effect with respect to any one of the crystallographic axes, the plate being cut from the piezoelectric crystal in a direction making substantially equal angles with all the crystallographic axes so as to exhibit to substantially a a maximum degree the longitudinal piezoelectric effect.

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