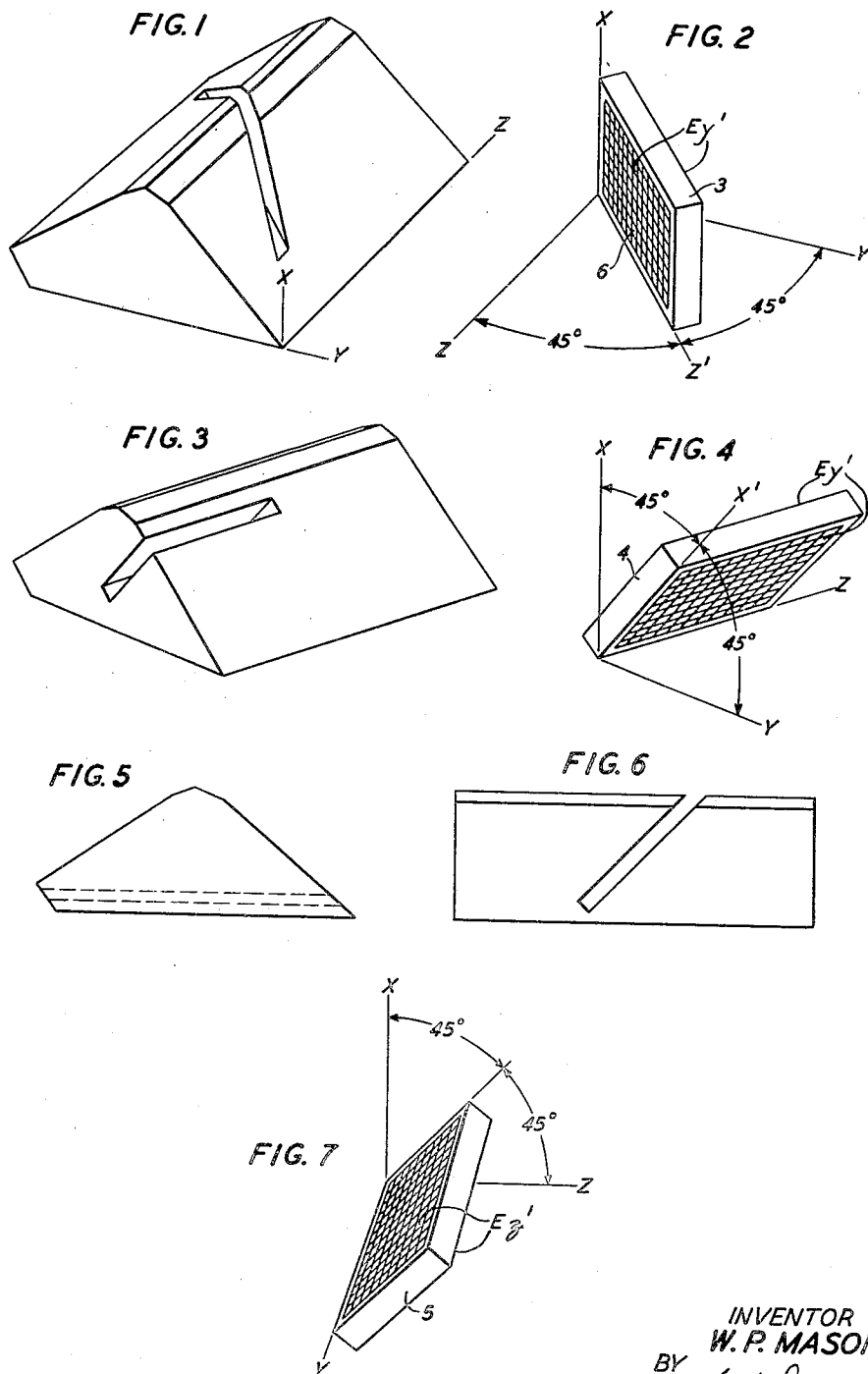


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PIEZOELECTRIC ELEMENT

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PIEZOELECTRIC ELEMENT

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This invention relates to piezoelectric elements comprising Rochelle salt and other isomorphous crystalline substances having such electrical resonance characteristics as to render them suitable for use as reactances in tuned circuits, filters and other electrical networks.

An object of the invention is to provide piezoelectric elements which may take advantage of the high piezoelectric activity of Rochelle salt and which may be sufficiently free from coupling to other modes of vibration at closely adjacent frequencies to enable vibration in a single mode.

A further object of the invention is to provide piezoelectric elements having the high piezoelectric activity characteristic of Rochelle salt and having a smaller dissipation factor or as it is commonly termed a higher selectivity or "Q" than elements of that type hitherto available to enable their employment in electric wave filters.

An additional object of the invention is to provide a piezoelectric element of the Rochelle salt type, the piezoelectric constant of which is substantially invariable with varying temperature.

As is well known, piezoelectric elements are, in general, capable of vibrations which may be extensional, shear or flexural in various directions depending upon the relative dimensions of the piezoelectric element and, also, upon the frequency and the direction of the impressed electric field. If the exciting force for a desired mode of vibration is capable of setting up vibrations of any other mode at some neighboring frequency the resultant vibration of the piezoelectric element may partake of both the desired and the undesired vibrations. For frequency control of oscillators the electrical reaction of such a piezoelectric element is, accordingly, not that of a simple tuned circuit of a single resonance frequency which tends to hold the oscillation frequency closely to one fixed frequency but rather that of two coupled circuits with a double-peaked resonance characteristic. Moreover, for use in filters, in which it is often essential to approximate the characteristics of a simple tuned circuit such double resonance elements are particularly undesirable.

In accordance with the present invention, piezoelectric elements having a high piezoelectric constant, and in general a high "Q" that is, ratio of reactance to resistance, together with a natural mode of vibration relatively free from coupling to any extraneous vibrations of closely adjacent frequencies, are obtained by utilizing

novel combinations of the orientations of the principal faces of the piezoelectric elements and of the mode of vibration in which the elements are excited. By orientation is meant the angular positioning of the plane of the principal faces of the piezoelectric element with respect to the orthogonal faces of the virgin material and the angular positioning of the margins of the principal faces in that plane. In the course of the study leading up to this invention it has been discovered that particularly desirable orientations may be secured using a sodium potassium tartrate type piezoelectric element with its principal plane faces parallel to any one of the three orthogonal axes X, Y or Z, the planes of these faces being rotated about that one axis to an angle of 45 degrees with the remaining two axes. Elements having these latter orientations may be operated in a high frequency shear vibration along their smallest dimension and exhibit piezoelectric and dielectric constants which are relatively stable with varying temperature.

Other aspects and features of the invention will be apparent from a consideration of the following detailed description taken in connection with the accompanying drawing in which:

Figs. 1 and 2 show respectively a sodium tartrate or Rochelle salt crystal from which a piezoelectric element is cut and the piezoelectric element, the principal faces of which include the X axis and substantially bisect the angle between the Y and Z axes.

Figs. 3 and 4 illustrate respectively a Rochelle salt crystal from which an element is cut, and the element itself having its principal parallel faces extending in the direction of the Z axis and rotated thereabout to a position midway between the X and Y axes.

Figs. 5, 6 and 7 show respectively, an end view of a Rochelle salt crystal, a side view and an element cut from a crystal with the plane of its principal faces parallel to the Y axis and bisecting the angle between the Y and Z axes.

Rochelle salt and isomorphous substances belong to the rhombic hemihedral class of crystals and have three orthogonal crystallographic axes sometimes designated as *a*, *b* and *c* axes but which in this specification will be called the X, Y and Z axes. Piezoelectric elements of the so-called *x* cut having their principal faces perpendicular to the X axis and with their length dimension oriented at an angle of 45 degrees to the Y and Z axes have been rather widely used. Cady has also suggested (U. S. Patent 1,977,169, October 16, 1934) the use of X, Y and Z cut Ro-

chelle salt elements having their lengths parallel to one of the orthogonal axes of the virgin material. However, due, no doubt, in part to the lack of an accurate determination of the dynamical constants of Rochelle salt there has been relatively little development of its possibilities and it has not hitherto been possible in the absence of such data to predict the resonance frequency of "oriented" piezoelectric elements except in a very few directions of orientation.

A study of sodium tartrate piezoelectric elements leading up to the present invention has shown that the resonant and anti-resonant electrical reactance frequencies of the crystal are both considerably below the natural mechanical resonance frequencies of the crystal. This fact is in disagreement with the customary assumption made in deriving the frequencies of a piezoelectric crystal. By assuming that the piezoelectric force is proportional to the applied charge rather than the applied potential as is usually assumed, theoretical frequencies are obtained which are in substantial agreement with the actual frequencies of vibration.

The elastic constants of sodium tartrate elements measured dynamically, that is, with the crystal excited in mechanical oscillation show large differences from those measured statically. It is believed that this may be fairly attributed to the large relaxation time for these piezoelectric elements which does not allow them to attain their static conditions when an alternating voltage is applied.

A systematic design of a piezoelectric element to serve as a vibrating member involves a knowledge of a number of characteristics. First, it must be known what modes of vibration, extensional, shear, flexural, etc., may be induced with respect to a given set of axes of the piezoelectric material and how they are related to the stresses or forces by which they may be induced. For the Rochelle salt system these relationships are indicated by the stress-strain equations

$$\begin{aligned} x_x &= s_{11}X_x + s_{12}Y_y + s_{13}Z_z \\ y_y &= s_{12}X_x + s_{22}Y_y + s_{23}Z_z \\ z_z &= s_{13}X_x + s_{23}Y_y + s_{33}Z_z \\ y_z &= s_{44}Y_z \\ z_x &= s_{55}Z_x \\ x_y &= s_{66}X_y \end{aligned} \quad (1)$$

in which the stresses are represented by the capital letters, X_x being an extensional stress along the X axis and Y_z a shear stress in the YZ plane; the strains or displacements are represented by small letters, y_y being an extensional displacement, namely, compression or lengthening along the Y axis and z_x , a shear displacement in the ZX plane. The compliances are designated by s with an appropriate positional subscript, the positional subscript being shown in parentheses beneath its numerical equivalent in certain terms of the equations.

From the foregoing equations it is apparent that extensional displacements may be produced along all three axes by a force parallel to any one axis and that a shear displacement may be set up in a plane of any two axes by a shear stress in that plane. It is also evident that an alternating extensional force which is able to induce any extensional vibration along the X, Y and Z axes will set up extensional vibrations along all three. In other words the three extensional modes of vibration are coupled. It is also apparent that the shear modes of vibration

are not coupled to any other mode or to each other.

Having considered the elastic constants of Equation 1 we may now turn to the piezoelectric equations to ascertain which of the mechanical stresses may be induced piezoelectrically. The piezoelectric equations are:

$$\begin{aligned} P_x &= d_{14}Y_z \\ P_y &= d_{25}Z_x \\ P_z &= d_{36}X_y \end{aligned} \quad (2)$$

where P_x , P_y and P_z represent electric charges applied to impress an electric field parallel respectively to the X, Y and Z axes and d_{14} , d_{25} and d_{36} are the appropriate piezoelectric constants relating electrical charge to mechanical stress.

The resonance frequencies of elements of sodium tartrate material can be predicted by using certain formulae involving the dimensions of the elements and the compliance or s constants. Although magnitudes of these constants have been previously published they have, so far as any substantially complete table is known, been based on static determinations. The discrepancies between the published magnitudes and the actual dynamic characteristics are such as to render the hitherto available data unsuitable for calculations with respect to the dynamic behavior of piezoelectric elements consisting of Rochelle salt. The magnitudes as determined by applicant are

$$\begin{array}{ccccccccccc} s_{11} & s_{22} & s_{33} & s_{44} & s_{55} & s_{66} & s_{12} & s_{13} & s_{23} \\ 5.14 \times 10^{-12} & 3.46 & 3.31 & 7.91 & 32.55 & 10.99 & -1.52 & -2.09 & -1.02 \end{array}$$

it being understood that in each instance the constant includes the factor 10^{-12} as in the case of s_{11} .

A brief perusal of the piezoelectric Equation 2 makes it apparent that for piezoelectric elements of Rochelle salt having edges all parallel to the orthogonal crystallographic axes so that the impressed electric field is in the direction of one such crystallographic axis no extensional stresses are set up but only shears and, moreover, that the shears are not coupled to each other.

The compliance factor, as for example, s_{11}' , of an oriented element indicated by a primed subscript may be derived from that of its corresponding unprimed or orthogonal compliance factor s_{11} by use of the proper one of a series of transformation equations. The transformation equation for rotation about the Z axis is

$$s_{11}' = [s_{11} \cos^4 \theta + (2s_{12} + s_{66}) \sin^2 \theta \cos^2 \theta + s_{22} \sin^4 \theta] \quad (4)$$

in which θ represents the angle by which the length direction has been oriented about the Z axis. Hence s_{11}' may be readily determined from Equation 4.

Referring to the drawing Figs. 1 and 2 illustrate the manner of cutting an element 3 which has its principal faces lying in planes parallel to the X axis of the virgin sodium tartrate and rotated about the X axis to a position at 45 degrees with respect to the Y and Z axes. The element 3 is provided with a pair of conducting electrodes 6 between which an exciting electromotive force E_y' may be applied. The element 3 may be excited in an X_y' shear mode of vibration by an alternating piezoelectric force of proper frequency and the magnitude of which is a function of the piezoelectric constant

$$d_{26}' = \left(\frac{d_{25} + d_{36}}{2} \right) \sin 2\theta \quad (5)$$

where θ is the angle between the Y axis and a

normal to the major face. Hence, if θ were either zero degrees or 90 degrees so that the marginal edges of the crystal coincided with the crystallographic axes no effect would be obtained. The elastic constant for this mode of motion is

$$c_{66}' = c_{66} \cos^2 \theta + c_{55} \sin^2 \theta \quad (5)$$

and the frequency

$$f = \frac{1}{2t} \sqrt{\frac{c_{66}'}{\rho}} \quad (7)$$

where t is the thickness of the plate and ρ is the density of the material. The piezoelectric constant of this orientation does not depend appreciably on the temperature.

Figs. 3 and 4 illustrate a different orientation in which the piezoelectric element 4 is cut parallel to the Z axis and with its principal faces at an angle of 45 degrees with respect to the X and Y axes. It may be excited by a Zy' shear the piezoelectric constant having a magnitude

$$d_{24}' = \left(\frac{d_{14} + d_{25}}{2} \right) \sin 2\theta \quad (8)$$

The elastic constant is

$$c_{55}' = c_{44} \cos^2 \theta + c_{55} \sin^2 \theta \quad (9)$$

The resonance frequency is given by the formula

$$f = \frac{1}{2t} \sqrt{\frac{c_{44}'}{\rho}} \quad (10)$$

This orientation is characterized by a large piezoelectric coupling.

Figs. 6, 7 and 8 indicate the manner of deriving another useful orientation of Rochelle salt piezoelectric element. The element 5 is cut parallel to the Y axis and midway between or 45 degrees from the X and Z axes. It is capable of oscillation in a high frequency Yz' mode at a frequency determined by

$$f = \frac{1}{2t} \sqrt{\frac{c_{44}'}{\rho}} \quad (11)$$

where

$$c_{44}' = c_{44} \sin^2 \theta + c_{66} \cos^2 \theta \quad (12)$$

This orientation possesses a large piezoelectric coupling.

It will be understood that the principles presented are applicable to the design not only of Rochelle salt elements but also to the design of piezoelectric elements of all isomorphous crystals. It will be appreciated, however, that the magnitudes of the constants of density, elasticity and piezoelectricity vary for different materials and that it will be necessary in the use of the elastic and piezoelectric equations to be careful to introduce the correct magnitudes of each.

What is claimed is:

1. A piezoelectric plate of sodium potassium tartrate type having two parallel plane boundary faces, the parallel planes including one of the three orthogonal axes and being effectively rotated thereabouts to a position intermediate the other two orthogonal axes and means for subjecting the element to an alternating electric field in its thickness direction of a frequency corresponding effectively to the shear mode of vibration in the plane which includes the thickness direction and an element of the two parallel planes.

2. A piezoelectric plate of Rochelle salt type having two parallel plane boundary faces, the plane of the faces extending parallel to one of the three orthogonal axes of the virgin material and bisecting the angle between the other two axes.

3. A piezoelectric element comprising a rectangular plate of Rochelle salt having two parallel plane boundary faces of dimensions several times the thickness of the plate between the faces, the plane of the faces being parallel to the X axis and positioned at an angle of substantially 45° with respect to the Z axis and means for subjecting the element to an alternating electric field in its thickness direction of a frequency corresponding effectively to the XY' shear mode of vibration of the element.

4. A piezoelectric plate in accordance with claim 1, characterized in this, that the plane of its principal faces is parallel to the Y axis of the virgin material.

5. A piezoelectric plate in accordance with claim 1, characterized in this, that the plane of its principal faces is parallel to the Z axis of the virgin material.

6. A piezoelectric plate of Rochelle salt having two parallel plane boundary faces of dimensions several times the thickness of the plate between the faces, the plane of the parallel faces including the X axis of the virgin material and being effectively rotated thereabout to a position midway between the Y and Z axes.

7. A piezoelectric plate of Rochelle salt having two parallel plane boundary faces of dimensions several times the thickness of the plate between the faces, the plane of the parallel faces including the Y axis of the virgin material and being effectively rotated thereabout to a position midway between the X and Z axes.

8. A piezoelectric plate of Rochelle salt having two parallel plane boundary faces of dimensions several times the thickness of the plate between the faces, the plane of the parallel faces including the Z axis of the virgin material and being effectively rotated thereabout to a position midway between the X and Y axes.

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