Dec. 1, 1953 J. E. MUMPER 2,661,432

PIEZOELECTRIC DEVICE

Filed May 14, 1951

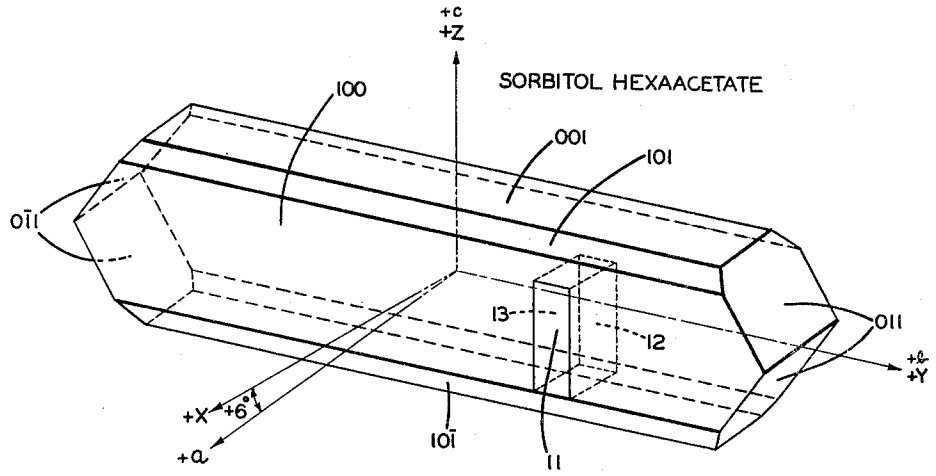


FIG. 1

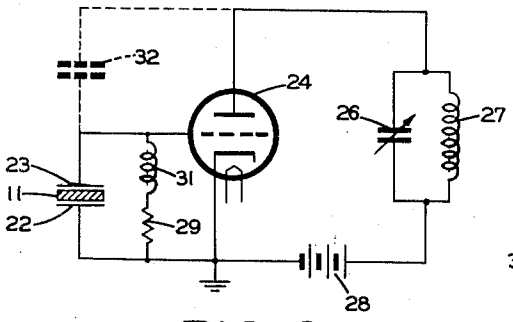


FIG. 2

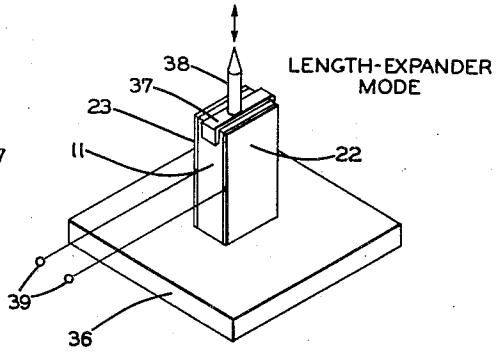


FIG. 4

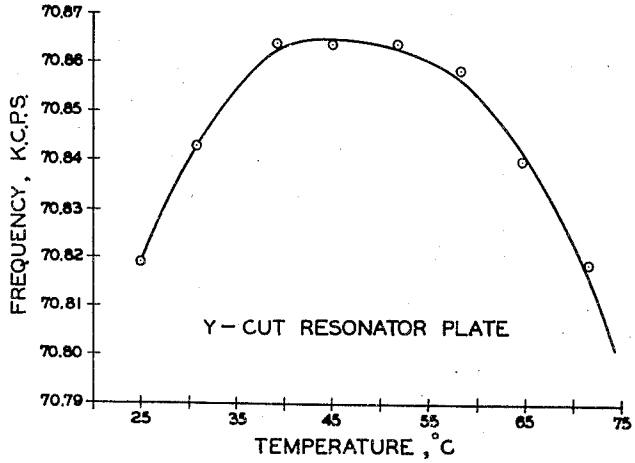


FIG. 3

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PIEZOELECTRIC DEVICE

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8 Claims. (Cl. 310—8.1)

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This invention relates to piezoelectric devices, and more particularly to such a device comprising a piezoelectrically sensitive section having an especially advantageous crystallographic orientation and cut from a single crystal of sorbitol hexaacetate.

Sorbitol hexaacetate,

$CH_3.CO.O.CH_2(CH.O.CO.CH_3)_4CH_2.O.CO.CH_3$

is an article of commerce, ordinarily available in the form of small crystallites. It may be identified by its melting point of 98–100° C. and by its other physical and chemical properties. Sorbitol hexaacetate is optically active and rotates the plane of plane-polarized light when in suitable solutions. The ordinarily available compound may be termed *d*-sorbitol hexaacetate and is prepared by the complete esterification of the commonly available sorbitol, which is obtained by reduction of *d*-glucose and in like manner may be termed *d*-sorbitol. The other enantiomorphic form of the ester, *l*-sorbitol hexaacetate, also may be included in piezoelectric devices in accordance with the invention described hereinbelow. The piezoelectric responses of the two forms of the ester are the same except for a reversal of the electric polarity. Accordingly the term sorbitol hexaacetate is used in this specification and in the appended claims to identify either of the two enantiomorphic esters.

Piezoelectric devices of the type comprising a piezoelectrically sensitive section cut from a single crystal of sorbitol hexaacetate are described and broadly claimed in an application Ser. No. 226,182, filed concurrently herewith in the name of Hans Jaffe and assigned to the same assignee as the present invention. This concurrently filed application also discloses and claims certain crystal sections cut from a single crystal of sorbitol hexaacetate in such a way that the major faces of the crystal sections are roughly perpendicular to the X-axis of the crystalline substance. Such crystal sections are particularly desirable when use is to be made of a thickness-shear mode of motion of the section, and properly oriented crystal sections of the type specifically described in the aforementioned Jaffe application exhibit quite small variations of resonant frequency over appreciable ranges of temperature.

It now has been discovered that certain other crystal sections cut from sorbitol hexaacetate crystals have unexpected and desirable piezoelectric response characteristics.

Accordingly it is an object of the present invention to provide a novel and useful piezoelectric device including a section cut from a single crystal of sorbitol hexaacetate.

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It is another object of the invention to provide a useful piezoelectric device comprising a section cut with a novel crystallographic orientation from a single crystal of sorbitol hexaacetate.

It is a further object of the invention to provide a new and improved piezoelectric device having a substantial piezoelectric sensitivity.

It is yet another object of the invention to provide a new and improved piezoelectric device exhibiting response characteristics not greatly affected by moderate changes of temperature within the limits of ordinarily useful temperatures.

In accordance with the invention, a piezoelectric device comprises a piezoelectrically sensitive section cut from a single crystal of sorbitol hexaacetate and having a pair of electroded surfaces with the normal to the plane of each of these surfaces extending approximately in the direction of the Y-axis of the crystalline substance.

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 sorbitol hexaacetate, including an outline view of a portion or section of the crystal which may be cut therefrom and which is of a type particularly useful in a piezoelectric device in accordance with the invention;

Fig. 2 is a schematic circuit diagram representing an oscillator which includes a resonator crystal section of the type shown in outline in Fig. 1;

Fig. 3 is a graphical representation of the natural resonant properties of crystal sections of this type; and

Fig. 4 is a perspective view of a transducer device comprising a similar piezoelectrically sensitive crystal section.

Referring to Fig. 1, there is represented in perspective a single crystal of sorbitol hexaacetate with relation to crystallographic axes *a*, *b*, and *c*. The crystallographic axes *b* and *c* are made to coincide with the respective coordinate axes Y and Z in the manner which has become conventional in representing crystals of the monoclinic system, to which sorbitol hexaacetate crystals belong. More specifically, this substance crystallizes in a lattice structure of the hemimorphic or polar crystal class, also designated class C_2, of the monoclinic system. The positive directions of the crys-

tallographic and coordinate axes are represented in Fig. 1 by arrows. It will be observed also that the crystallographic $+a$-axis makes an angle of essentially $+6°$ with the coordinate $+X$-axis, this angle in the XZ-plane being positive in accordance with convention, since it is rotated counterclockwise from the $+X$-axis as viewed looking into the positive direction of the Y-axis. The crystallographic indices of various crystal faces are indicated in Fig. 1. A somewhat more detailed discussion of the crystallography of this crystalline substance and of the identification of the faces and axes of single crystals thereof is included in the aforementioned Jaffe application.

A crystal section 11 is represented in outline in the crystal of Fig. 1. One of the narrower surfaces of the section 11 is shown lying in a (100) face of the single crystal, that is, parallel to the Y- and Z-axes. As shown in Fig. 1, the three pairs of opposed surfaces of the section 11 are related approximately orthogonally to each other. The largest of these surfaces, designated 12 and 13, are oriented approximately parallel to the XZ-plane. Thus the section 11 has a pair of major opposed surfaces with the normal to the plane of each of these surfaces extending approximately in the direction of the Y-axis of the crystalline substance.

The schematic circuit diagram of Fig. 2 represents a piezoelectric device in accordance with the invention which comprises the piezoelectrically sensitive section 11 cut from a single crystal of sorbitol hexaacetate. Each of the pair of surfaces 12 and 13 of the section 11 is provided with electrodes, so that the crystal section has a pair of respective electroded surfaces 22 and 23 the normal to which extends at least approximately in the direction of the Y-axis. The term "electroded surfaces," 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. Crystal holders which provide an air gap between the electrode and the crystal surface are known to the art. In general, the electrodes or electroded surfaces 22 and 23 may be provided on or near the faces of the crystal section in any convenient manner. Ordinarily these electrodes are formed by applying thin coatings or layers of metal or other conductive material directly to the crystal surfaces 12 and 13 in a well known manner.

In the device of Fig. 2 the electroded section 11 is a piezoelectrically sensitive resonator section having the pair of electroded surfaces 22 and 23, preferably with the normal to the plane of each of these surfaces substantially coinciding with the Y-axis of the crystalline substance. Such a crystal section may be designated a Y-cut section and is especially desirable in a frequency-controlling arrangement because of its frequency stability, as will be explained hereinbelow. The remainder of the device of Fig. 2 comprises electrical oscillatory circuit means for exciting the resonator section 11 so as to utilize the frequency-selective or control characteristics thereof. This oscillatory circuit is a crystal-controlled circuit of a modified tuned-plate tuned-grid type having a triode vacuum tube 24. The tuned-plate portion of the circuit includes a variable capacitor 26 suitable for resonating a parallel inductor 27. The parallel resonant circuit 26, 27 is connected in the anode-cathode circuit of the triode 24 with a source of anode potential 28 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 11, the electrodes 22 and 23 of which are connected to the cathode and control electrodes respectively of the triode 24. The crystal element 11 is shunted by a resistor 29 and a series choke inductor 31 to provide a suitable bias voltage. A capacitor 32 may be connected between the anode and control electrodes of the triode 24, but this capacitor is shown in dotted lines because the interelectrode capacitance of the triode ordinarily supplies the desired regenerative coupling between these electrodes.

A substantially Y-cut crystal section of the type designated 11 in Fig. 2 is adapted particularly well to be excited in an expander mode of motion so as to utilize the frequency-selective characteristics of that mode of motion of the crystal section. Specifically, it is preferred to utilize in the Fig. 2 device a resonant condition of the crystal section associated with the propagation of elastic energy in the direction of the Z-axis of the crystalline substance.

Referring to Fig. 3, there is illustrated graphically a curve in which the abscissas represent the temperature of a Y-cut crystal section and the ordinates represent the natural fundamental resonant frequency associated wtih strains of the expansion and contraction type parallel to the Z-axis at these temperatures. It appears from the graph that good frequency stability with temperature changes is obtained over a substantial range of temperatures centering upon about 45° C. As an example, a Y-cut section of sorbitol hexaacetate crystal had a length of 13.45 mm. parallel to the Z-axis, a width of 6.81 mm. parallel to the X-axis, and a thickness of 4.64 mm. parallel to the Y-axis. The frequency constant of the length expander mode at about 45° C. has a maximum value of 953 kcps.-mm.; measurements show that the resonant frequency in the length expander mode decreases from its maximum by less than one part in 10,000 as the temperature is lowered to 37° C. or raised to 58° C.

In the operation of the circuit of Fig. 2, the capacitor 26 may be adjusted so that the circuit 26, 27 resonates at a frequency which is at or near the frequency of a length-controlled expander mode resonance of the section 11 having a shape such as that illustrated in outline in Fig. 1. Any excitation in the anode-cathode circuit of the triode 24 tends to produce oscillations at the frequency of resonance of the tuned circuit 26, 27. The resulting oscillatory voltage appears across the capacitance 32 and the impedance of crystal element 11, 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 charateristic of the crystal element 11.

Ordinarily the crystal section, having the normal to the plane of each of its electroded surfaces extending approximately in the direction of the Y-axis, is cut so that these electroded surfaces are substantially rectangular. This shape tends to cause the section to exhibit a definite resonant frequency and in most cases is the preferred shape for frequency-controlling purposes.

Corresponding to resonance associated with expander motion in the direction of the Z-axis, which ordinarily is a length dimension or possibly a width dimension of a section electroded to respond to electrical fields in the approximate

direction of the Y-axis, there is another resonance associated with expander motion in the direction of the Y-axis, which ordinarily is the thickness direction of such a section. The extent of the electromechanical excitation of these expander responses, which involve motion in the length and thickness directions respectively of the crystal section 11 as shown specifically in Fig. 1, is indicated by the respective piezoelectric coefficients d_{23}, which has a value of about 4.7×10^{-12} meters per volt, and d_{22}, which has a value of about 4.4×10^{-12} meters per volt. These coefficients have opposite signs. Some motion also occurs in the width direction, but the value of the d_{21} coefficient is only about 0.6×10^{-12} meters per volt.

The thickness expander mode of such a crystal section has a frequency constant of about 1995 kcps.-mm. While the thickness expander mode may be utilized in electromechanical transducer devices, the relatively high frequency of the fundamental resonance and the smaller absolute motion obtainable in this mode with reasonable electrical signal voltages usually make the length-expander mode of motion more attractive. Consequently, a transducer for utilizing directly the motion in the latter mode is shown and described herein for purposes of illustration. Fig. 4 is a representation in perspective of such a piezoelectric device for transducing between the types of energy which are classified as electrical and mechanical, and serves to illustrate a useful application of the generally Y-cut sections of sorbitol hexaacetate single crystals to devices other than frequency-controlling devices. Such a transducer device may be used for transducing from electrical energy to mechanical energy, or vice versa.

The device of Fig. 4 includes a piezoelectrically sensitive section, such as the section 11, cut from a single crystal of sorbitol hexaacetate and having a pair of surfaces with the normal to the plane of each of these surfaces extending approximately in the direction of the Y-axis of the crystalline substance. In this connection it should be noted that substantial deviations from the crystallographic orientation corresponding precisely to a Y-cut section may be tolerated in many cases. Such deviations ordinarily produce only minor changes in the piezoelectric response until the angular deviation is quite considerable. Thus deviations of 5° to 10° have only a slight effect, especially where special characteristics such as the frequency-temperature characteristics are of no great moment. Accordingly, in this specification and in the claims appended thereto, the phrase "extending approximately in the direction of the Y-axis" is intended to indicate a permissible angular relationship of 5° to 10° between the direction of the normal to the plane of the appropriate surface of the crystal section and the direction of the Y-axis.

The section 11 is seen in Fig. 4 in a similar perspective to that as shown in outline in Fig. 1. The length direction is vertical, and the electroded surfaces 22 and 23 are arranged to carry electrical charges corresponding to an electrical signal field in the thickness or Y-direction. The bottom surface of the section 11 is fastened to a base 36. A yoke 37 is cemented to the top surface and carries a stylus 38. A pair of terminals 39 is connected to the individual electrodes 22 and 23.

The device of Fig. 4 may be used for transducing from electrical to mechanical energy by connecting to the terminals 39 the output circuit of a source, not shown, of electrical signals, for example, audio frequency signals. The resulting electrical field developed in the direction of the Y-axis of the crystalline substance causes expansions and contractions lengthwise of the section 11, causing the stylus point to vibrate vertically, as indicated by the double arrow. The stylus point may press against a moving deformable record medium, not shown, to impress therein undulations of the hill-and-dale or vertical type corresponding to the audio frequency electrical signal impressed on the device. Thus the terminals 39 and the source of electrical signals connected thereto, together with the electrodes 22 and 23 and the interconnecting wires, constitute means for applying to the crystal section 11 energy of one of the two types mentioned hereinabove, in this case electrical energy. The base 36, providing a mounting surface, and the yoke 37 and stylus 38 constitute means dependent upon the effect of the applied energy upon the crystal section 11 for deriving and utilizing energy of the other type, that is, mechanical energy.

It will be evident to those familiar with piezoelectric phenomena that the reciprocal transducer response also may be obtained. For example, a record medium or other surface having undulations may be moved relative to the stylus 38 to impart vertical forces through the stylus 38 and yoke 37, causing coresponding strains in the form of expansions and contractions lengthwise of the section 11. Corresponding electrical charges then appear at the electrodes. The resulting electrical signals at the terminals 39 may be utilized, for example, by applying the signals to the input circuit of an amplifier, not shown, to drive a loud speaker or a signal-displaying arrangement such as an oscillograph. In this case the stylus 38 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. The electrodes 22 and 23, the terminals 39, the interconnecting wiring, and any amplifying and other apparatus coupled to the electrodes then constitute means dependent upon the effect of the applied mechanical energy for deriving and utilizing electrical energy.

When the crystal section 11 is intended to operate in the so-called length expander mode of motion, as described particularly hereinabove, it is preferable that two edges of each of the electroded surfaces be oriented substantially parallel to the Z-axis of the crystalline substance. Usually these two edges extend in the length direction of the section. Whether or not these edges are so oriented, the crystal section 11 in the device of Fig. 4 is piezoelectrically sensitive to an expander mode of motion of the crystal section in the approximate direction of the Z-axis of the crystal substance. The mechanical energy involved in the electromechanical transducing in the Fig. 4 device thus is associated with motion of the crystal section in an expander mode in this approximate direction.

It has been shown hereinabove that sections cut from sorbitol hexaacetate single crystals with surfaces having the approximate orientation of Y-cut surfaces exhibit useful piezoelectric sensitivity in the piezoelectric devices of the present invention. The piezoelectric device illustrated in Fig. 2 and including a Y-cut resonator section

is particularly useful in view of the frequency-temperature characteristic indicated in Fig. 3. Devices utilizing these crystal sections are particularly attractive for frequency-controlling purposes. Thus novel and unexpectedly useful cuts of this crystalline material are provided as components of piezoelectric devices in addition to the cuts specifically disclosed in the copending application of Hans Jaffe, identified hereinabove. The practical utility of the devices of the present invention is enhanced by the fact that crystals of this substance appear to be stable at temperatures as high as 90° C. and are suitable for continuous use in piezoelectric devices at a temperature of at least 75° C.

As discussed in the aforementioned Jaffe application, the preparation of a sizeable single crystal of sorbitol hexaacetate, such as that illustrated in Fig. 1, presents no very unusual difficulties to those skilled in the art. The solubility of this substance in water is quite low, which is an advantage since crystal plates thereof are not subject to rapid attack by atmospheric moisture. Substantial amounts of sorbitol hexaacetate, however, may be dissolved at somewhat elevated temperatures in substantially anhydrous acetic acid, which if desired may be diluted with water up to about 50% of the volume of acetic acid. A seed crystal of the substance is placed in the solution, which is rocked gently to bathe the surfaces of the growing crystal in a solution of uniform composition. The temperature of the solution is lowered slowly to cause moderate supersaturation of the solution with reference to the crystal faces. As an example, a saturated solution in two liters of glacial acetic acid deposits about 115 grams of crystalline substance with a temperature drop of 7° C. After the crystal has grown to the desired dimensions, it conveniently may be cut into rough sections by the use of a string saw, the string being passed through methanol, which acts as a solvent. The rough sections then are milled to the desired dimensions. It is noted that crystals of this substance have a perfect cleavage along the (100) plane.

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 aimed, therefore, in the appended claims to cover all such changes and modifications as fall within the true spirit and scope of the invention.

What is claimed is:

1. A piezoelectric device comprising: a piezoelectrically sensitive section cut from a single crystal of sorbitol hexaacetate and having a pair of electroded surfaces with the normal to the plane of each of said surfaces extending approximately in the direction of the Y-axis of the crystalline substance.

2. A piezoelectric device comprising: a piezoelectrically sensitive section cut from a single crystal of sorbitol hexaacetate and having a pair of electroded surfaces with the normal to the plane of each of said surfaces substantially coinciding with the direction of the Y-axis of the crystalline substance.

3. A piezoelectric device comprising: a piezoelectrically sensitive section cut from a single crystal of sorbitol hexaacetate and having a pair of substantially rectangular electroded surfaces with the normal to the plane of each of said surfaces extending approximately in the direction of the Y-axis of the crystalline substance.

4. A piezoelectric device comprising: a piezoelectrically sensitive section, cut from a single crystal of sorbitol hexaacetate, and having a pair of electroded surfaces, with the normal to the plane of each of said surfaces extending approximately in the direction of the Y-axis of the crystalline substance, and with two edges of each of said surfaces substantially parallel to the Z-axis of said crystalline substance.

5. A piezoelectric device comprising: a section cut from a single crystal of sorbitol hexaacetate, having a pair of electroded surfaces with the normal to the plane of each of said surfaces extending approximately in the direction of the Y-axis of the crystalline substance, and piezoelectrically sensitive to an expander mode of motion of said crystal section in the approximate direction of the Z-axis of said crystalline substance.

6. A piezoelectric device for transducing between the types of energy which are classified as electrical and mechanical, comprising: a piezoelectrically sensitive section cut from a single crystal of sorbitol hexaacetate and having a pair of surfaces with the normal to the plane of each of said surfaces extending approximately in the direction of the Y-axis of the crystalline substance; 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.

7. A piezoelectric device for transducing between the types of energy which are classified as electrical and mechanical, comprising: a piezoelectrically sensitive section cut from a single crystal of sorbitol hexaacetate and having a pair of surfaces with the normal to the plane of each of said surfaces extending approximately in the direction of the Y-axis of the crystalline substance; 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 an expander mode in the approximate direction of the Z-axis of said crystalline substance.

8. A piezoelectric device comprising: a piezoelectrically sensitive resonator section cut from a single crystal of sorbitol hexaacetate and having a pair of electroded surfaces with the normal to the plane of each of said surfaces substantially coinciding with the direction of the Y-axis of the crystalline substance, and electrical circuit means for exciting said resonator section so as to utilize the frequency-selective characteristics thereof.

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