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March 15, 1938. S. A. BOKOVOY 2,111,384

PIEZOELECTRIC QUARTZ ELEMENT

Filed Sept. 30, 1936 2 Sheets-Sheet 1

Fig.1.

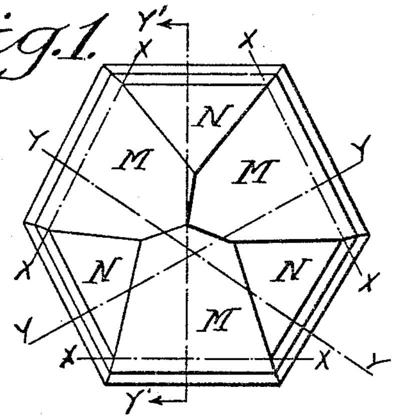


Fig.2.

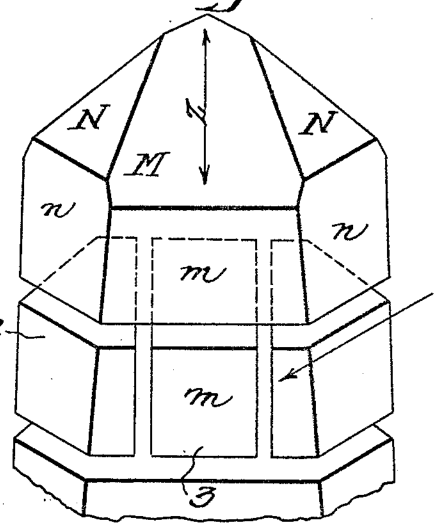


Fig.3.

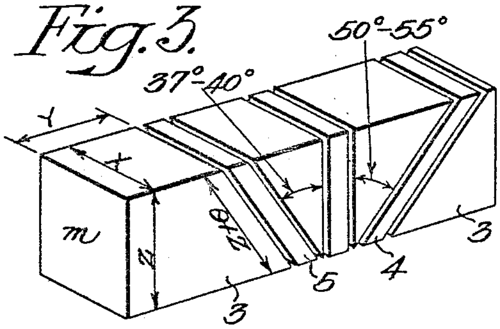


Fig.4.

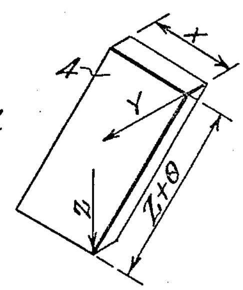


Fig.6.

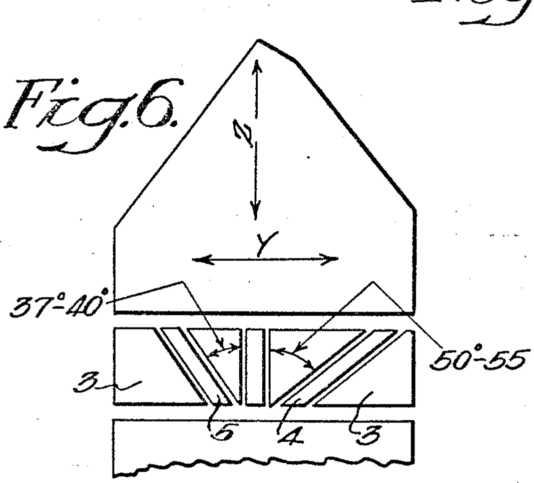
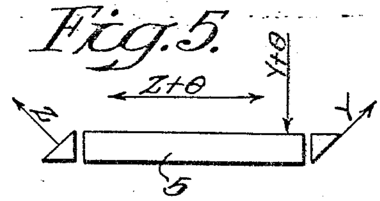


Fig.5.



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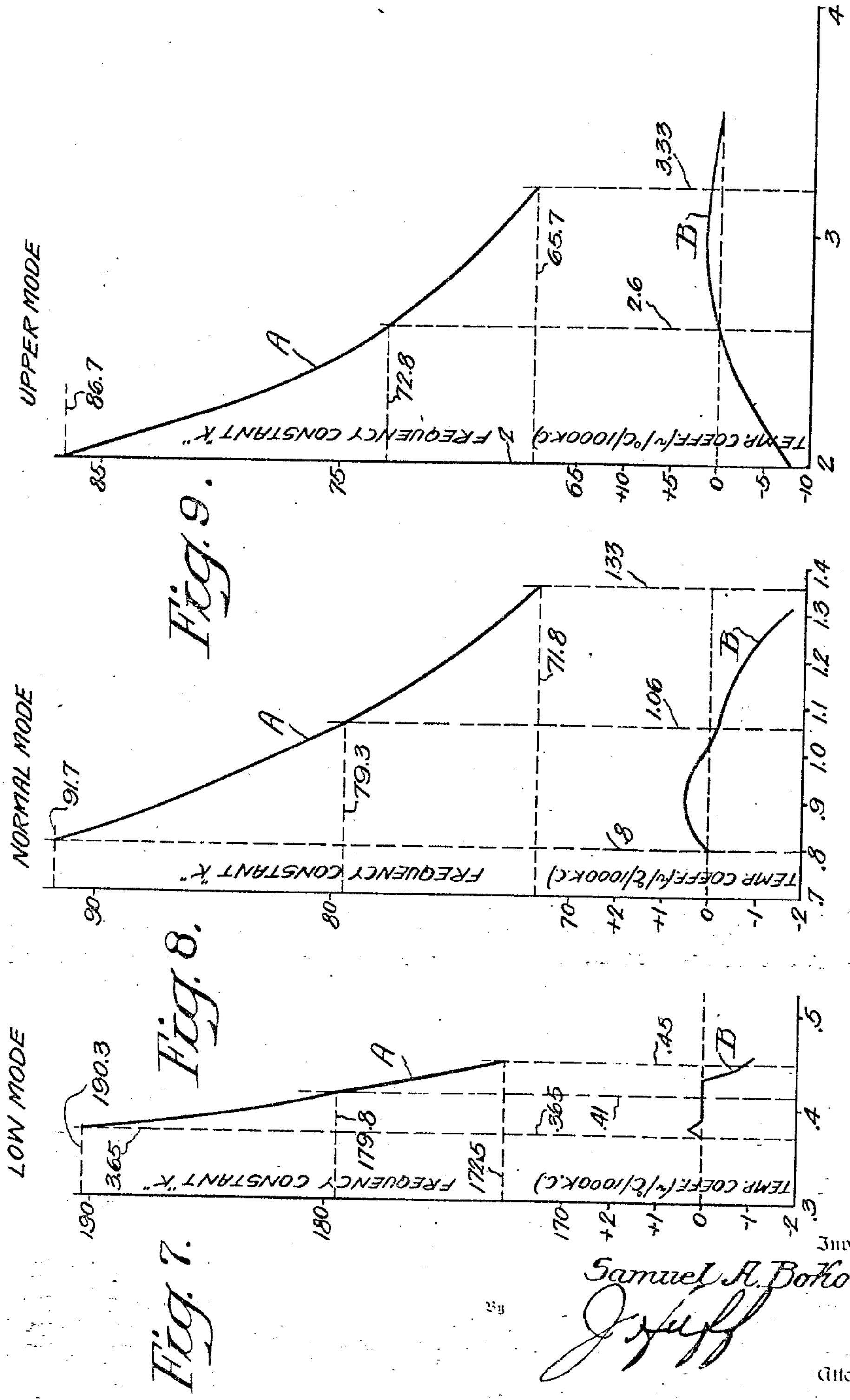
PIEZOELECTRIC QUARTZ ELEMENT

Filed Sept. 30, 1936 2 Sheets-Sheet 2



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Patented Mar. 15, 1938

2,111,384

UNITED STATES PATENT OFFICE

2,111,384

PIEZOELECTRIC QUARTZ ELEMENT

Samuel A. Bokovoy, West Collingswood, N. J., assignor to Radio Corporation of America, a corporation of Delaware

Application September 30, 1936, Serial No. 103,292

13 Claims. (Cl. 171—327)

This case is a continuation in part of application Serial No. 42,915, filed September 30, 1935.

The invention relates to the piezo-electric art and particularly to the cutting of quartz piezo-electric elements.

An object of the invention is to provide a quartz piezo-electric element possessing a unitary freedom for its X-axis mode of vibration.

Another object of the invention is to provide a method for cutting a quartz crystal to procure a piezo-electric element that will oscillate efficiently at but one of several "X" or contour-mode frequencies originally present.

Another object of the invention is to provide a crystal of the type described which, when vibrated at its single contour-mode frequency will exhibit a substantially zero temperature coefficient of frequency.

Another object of the invention is to provide a quartz piezo-electric element free to oscillate at only two fundamental frequencies, one of the frequencies bearing a multiple or other desired relationship to the other, the lower frequency being a function of the X-axis dimension of the element and the higher frequency being a function of its thickness dimension.

Another object of the invention is to provide a crystal of the type described which, when vibrated at its higher (i. e., its thickness-mode) frequency will exhibit a temperature coefficient of frequency no greater than substantially minus 15 cycles per million per degree centigrade.

Another object of the invention is to provide a simple, accurate and efficient mode of procedure in the cutting of quartz crystals to eliminate as far as possible any uncertainties with regard to the oscillatory characteristics of the finished piezo-electric elements.

Other objects and advantages will be apparent and the invention will be best understood by reference to the following specification and to the accompanying drawings wherein:

Fig. 1 is a plan view of a natural or "mother" quartz crystal, the optic (Z) axis of which is perpendicular to the plane of projection; the relative location of the major and minor faces, the apex, the electric (X) axes and the mechanical (Y) axes being here illustrated as an aid to a clear understanding of the system of orientation followed in producing piezo-electric elements within the present invention.

Fig. 2 shows in outline and in perspective a piece of natural quartz having a section cut and divided to provide a rough bar having top and bottom surfaces lying in planes which are normal to the optic (Z) axis.

Fig. 3 is an elevational view looking in the direction of the arrow in Fig. 2 showing the position of a number of blanks cut from the bar of Fig. 2.

Fig. 4 shows the right hand blank of Fig. 3 removed.

Fig. 5 shows the left-hand blank of Fig. 3 removed, the plane of projection being perpendicular to the plane of the paper.

Fig. 6 is a cross-sectional view taken on the line Y'—Y' of Fig. 1 showing the rotation of the blanks about an X-axis of a mother crystal and with respect to the major and minor apex faces.

Figs. 7, 8 and 9 are, respectively, families of curves, empirically obtained, each showing the single frequency region, the corresponding frequency constant and characteristic temperature coefficient for a variable length-width ratio for the low, normal and upper modes of frequency response along the X-axis when the quartz element or blank is tilted about an X-axis towards parallelism with a major apex face of the mother crystal.

The present invention contemplates and its practice provides a piezo-electric element having all, or, if desired, less than all, of the following operating characteristics:

(a) A zero temperature coefficient of frequency or a temperature coefficient of either sign and of a desired low value.

This desired operating characteristic obtains, in accordance with the present invention, by reason of a predetermined orientation of the principal surfaces of the element with respect to the plane of a minor, or conversely, a major apex face of the mother crystal from which the element is cut.

(b) Unitary freedom for its X-axis mode of vibration. The significance of this feature of the invention will perhaps be best understood when it is recalled that with known piezo-electric elements several modes of vibration and consequently several frequencies (which may be within 50 kc. or so of each other) are possible of achievement even when the crystal is employed in a non-regenerative circuit. Another mode of vibration, namely, the thickness-mode is present in any case but because, in a given crystal, the frequency characteristic of this mode is so much higher than that of any of the X-mode frequencies, it is not disturbing.

The single frequency which is a function of that one of the greater dimensions of the element which coincides with an electric (X) axis of the mother crystal obtains, in accordance with the invention, by reason of a predetermined length-width ratio. As will hereinafter more fully appear, this frequency may be characteristic of any of the natural modes of vibration but is preferably characteristic of one of the stronger modes, i. e., the "upper", "normal" or "low" X-modes of vibration. The length-width ratio is given for each mode, and for each direction of tilt.

(c) A crystal may be so cut in accordance with the present invention that the second or "thickness-mode" frequency, which is always present, will bear a predetermined useful relation to the single X-mode frequency previously mentioned. Thus it is practical to so cut a quartz crystal that the finished element will oscillate at a frequency of, say 100 kc. and also at 1000 kc., 200 kc. and 2000 kc., or at any two other desired widely separated frequencies. This characteristic is achieved by correlating the length, the width and the thickness of the element in accordance with a given formula.

Since the present invention involves a system of orientation in which the major and minor apex faces of the mother crystal are employed as reference planes, it is first necessary to locate and identify these faces. As all unbroken quartz crystals are substantially uniformly shaped hexagonal bi-pyramids, this is a relatively simple step.

Referring to Figs. 1 and 2 of the drawings, it will be seen that certain of the terminal faces of the quartz extend to the apex of the pyramid. These faces are designated M and are the major apex faces. Those terminal faces which do not touch the apex are designated N and are the minor apex faces of the crystal. Occasionally, a mother crystal will be found in which more than three of the cap or apex faces extend to the tip of the pyramid, other crystals may have their pyramid ends broken off. No confusion, however, need exist as to the virtual location of the major and minor apex faces of a broken or otherwise abnormal crystal providing that the side faces, *m* and *n*, or one of them, is intact, for it will be apparent from an inspection of Fig. 2 that those side edges of the mother crystal which approach each other in the direction of its ends terminate in a major apex face, while those which diverge in this direction terminate in a minor apex face. This is so in the case of both "left-hand" and "right-hand" quartz.

Fig. 1 is further marked to show the electric (X) axes and mechanical or crystallographic (Y) axes of the mother crystal. The optic (Z) axis, marked in Fig. 2, is perpendicular to the plane of projection in Fig. 1.

If the element is so cut in accordance with the invention that its principal surfaces (i. e., top and bottom) fall in planes which are substantially parallel to an X (electric) axis and inclined at an angle of between 37°–40°, say 38.6°, toward parallelism with the plane of a minor apex face, or at an angle of between 50°–55°, say 52.5° or 53.5° towards parallelism with a major apex face, it will possess a zero or some other low temperature coefficient of frequency for contour mode vibrations.

The preliminary steps in the cutting of a crystal may proceed in the manner usual in the cutting of a standard Y-cut blank. Thus, referring to Fig. 2, a section **2**, say one inch thick, should first be sliced from the body of the crystal and a bar **3** in turn cut from the section. As indicated in Fig. 3, the thickness dimension of this bar **3** is parallel to the Z (optic) axis, the width is parallel to an X (electric) axis, and the length is parallel to a Y (mechanical) axis.

The blanks **4** and **5**, from which the finished elements of the present invention are formed, are then sliced from this bar at an angle within the indicated range. As previously set forth and as indicated in Fig. 6, the 37°–40° low temperature coefficient tilt is in a direction away from parallelism with the Z axis toward parallelism with a minor apex face and that of the 50°–55° low temperature coefficient tilt is in a direction toward parallelism with a major apex face.

In the interest of clearness and brevity, that dimension of the blanks and of the finished elements which lies in a plane tilted from parallelism with the Z-axis will hereinafter be referred to in the drawings and in the specification as the $Z+\theta$ dimension. The other of the two greater dimensions of the element is parallel to an X-axis and is designated the X-axis dimension. The thickness dimension lies in a plane which intersects a Y-axis and is occasionally referred to as the $Y+\theta$ dimension.

When the blanks **4** and **5** of the correspondingly numbered figures are correctly proportioned as to width and length and are properly finished, it will be found that they possess a zero or some low temperature coefficient of frequency and further will, unless strongly excited, respond to but a single X-mode of vibration.

Regardless of which of the two described blanks is selected for finishing, the dimension of the finished element should first be determined in accordance with the formula

$$X=\frac{K}{f} \qquad (1)$$

where X is the dimension of the element along the X-axis expressed in mils of an inch,

f is the desired single frequency in megacycles,
K is a constant which is the same for all frequencies characteristic of a given mode, but differs for each of the available modes and the direction of tilt.

The constants and ratios for the various X-axis modes of vibration of a crystal element tilted from 37° to 40° about an X-axis toward parallelism with the plane of a minor apex face of a mother crystal are disclosed in copending application Serial No. 42,915 filed September 30, 1935, in the name of the present applicant.

The constants and ratios for the various X-axis modes of vibration of a crystal element tilted from 50° to 55° about an X-axis toward parallelism with the plane of a major apex face of a mother crystal are shown in Figs. 7, 8 and 9, and described in connection with Examples 1, 2 and 3, below.

It may here be noted that while the broad objects of the invention may be achieved in a crystal element tilted in either direction (i. e. towards a major or towards a minor apex face) there are certain advantages peculiar to each direction of tilt. Thus, it may be said generally that a finished crystal element which has been cut from a blank tilted towards parallelism with a minor apex face will oscillate at least slightly more vigorously than one cut from a blank tilted in the opposite direction. On the other hand a finished element cut from a blank orientated with respect to a major apex face will usually be physically smaller than one obtained from a blank tilted with respect to a minor apex face. Smallness is an advantage since a small element can ordinarily be accommodated in a holder of standard type and dimensions. Accordingly, a technician in selecting a blank for finishing should weigh the advantages peculiar to each direction of tilt.

Example 1

Given a blank cut with its principal surfaces tilted at an angle of substantially 52.5° towards parallelism with the plane of a major apex face (blank 4 of Figs. 3, 4 and 6) and assuming that a finished element possessing the following operating characteristics is required

(*a*) zero temperature coefficient of frequency

(*b*) a single X-mode frequency response of, say, 200 kc.

(*c*) a second or "thickness-mode" frequency response of, say, 500 kc.

Assuming further, for purposes of illustration, that the 200 kc. frequency to be achieved is to be a "low"-mode frequency.

Referring then to Fig. 7 of the drawings and particularly to curve A, it will be seen that the dimension of the element along its X-axis dimension expressed in mils of an inch should be equal to the desired low-mode frequency (200 kc.) expressed in megacycles divided into any constant (K) between substantially 172.5 and 190.3, and that the other of the two greater dimensions of the crystal (i. e. the $Z+\theta$ dimension Fig. 4) should be substantially .45 to .365 times that of the X-axis dimension, depending upon the X-axis constant selected.

It will be noted, however, by reference to curve B of this Fig. 10 that a random selection of a constant within the 172.5 to 190.3 K single frequency range will not ensure a finished element having an exactly zero temperature coefficient of frequency when the $Z+\theta$ dimension, as in the example given, is tilted precisely 52.5° towards parallelism with a major apex face of the mother crystal. For this angle of orientation the zero temperature coefficient is achieved when the constant (K) selected is substantially 179.8 and the ratio of the $Z+\theta$ dimension to that of the X-axis dimension is substantially .41.

Applying Formula 1, it will be seen that the dimensions of a piezo-electric element filling requirements "*a*" and "*b*" will be

$$X=\frac{179.8}{.2}$$

thus, the X-axis dimension will be 899 mils of an inch.

The $Z+\theta$ dimension will be 899 mils times .41 (the

$$\frac{Z+\theta}{X} \text{ ratio)}$$

or substantially 368.6 mils of an inch.

The formula required to achieve the third (*c*) desired characteristic, i. e., a "thickness" or $Y+\theta$ mode frequency response of 500 kc., is

$$d=\frac{K'}{f'}$$

where d is the dimension along the $Y+\theta$ axis

f' is the $Y+\theta$ mode frequency expressed in megacycles and

K' is equal to substantially 98.7.

As the second frequency required in this instance is 500 kc., it is apparent that the element should be ground or lapped to a thickness of substantially 197.4 mils of an inch.

Example 2

Referring to curve A of Fig. 8, it will be seen that the single frequency range of constants (K) for the "normal" X-mode of vibration is substantially 71.8 to 91.7 and the

$$\frac{Z+\theta}{X}$$

dimensional ratio is 1.33 to .8. The preferred constant (K) is 79.3 and the preferred

$$\frac{Z+\theta}{X}$$

ratio is 1.06 for, as will be seen by reference to curve B, these values will ensure a substantially zero temperature coefficient of frequency.

Applying Formula 1, the X-axis dimension of a piezo-electric element having a single "normal" X-mode frequency response of 200 kc. will be 396.5 mils of an inch, and the $Z+\theta$ dimension will be 396.5 mils of an inch multiplied by 1.06, which substantially equals 420.3 mils of an inch. The thickness required to achieve a $Y+\theta$ frequency response of 500 kc. will be, as in Example 1, 197.4 mils of an inch.

Example 3

Curve A of Fig. 9 shows that the range of constants (K) for an element (tilted with respect to a major apex face) cut to respond to a single "upper" mode frequency, is substantially 65.7 to 86.7 and the

$$\frac{Z+\theta}{X}$$

length-width ratio to be between 3.33 and 2. The preferred zero temperature angle of tilt in this case is 53.5° away from the Z-axis towards parallelism with the plane of a major apex face (instead of 52.5° as in Examples 1 and 2). The preferred constant (K) is 72.8 and the preferred ratio of length to width is 2.6. Accordingly, the dimension along the X-axis for 200 kc. response is 364 mils of an inch and the $Z+\theta$ dimension 946.4 mils of an inch.

While the formula required to achieve a desired "thickness" or $Y+\theta$ mode frequency response is the same as that obtaining in each of the prior examples, the constant (K') is different. In this case

$$d=\frac{K'}{f'}$$

where d is the dimension along the $Y+\theta$ axis

f' is the $Y+\theta$ mode frequency expressed in megacycles, and

K' is equal to substantially 98.9 (instead of 67 as in Examples 1, 2 and 3, or 98.7 as in Examples 4 and 5).

As the $Y+\theta$ or "second" frequency required in this instance is 500 kc., it is apparent that the element should be ground or lapped to a thickness of substantially 197.8 mils of an inch.

In Examples 1 and 2, the preferred "zero temperature angle of cut" is 52.5°, in Example 3 the preferred angle is 53.5°. The permissible range of angles, however, is that stated, i. e., 50° to 55°. A zero or substantially zero temperature coefficient of frequency may be achieved at any angle within this range in the manner described in connection with Examples 1, 2 and 3, that is to say, by altering the

$$\frac{Z+\theta}{X}$$

ratio in a direction corresponding to the direction of departure from the above-specified "preferred" angles.

The curves B of Figs. 7 to 9, inclusive, are intended primarily to indicate the direction of frequency drift (that is, in a positive or negative direction) with respect to the effects of temperature change rather than the amount of change per degree of temperature. The exact shift per degree C will be found to vary with the frequency for which the element is cut.

A crystal cut in accordance with the teachings of the invention and designed to oscillate at both a single X-mode frequency and at a desired $Y+\theta$ mode frequency will ordinarily exhibit an exactly zero temperature coefficient while operating at its X-mode frequency. The temperature coefficient of frequency of the element while vibrating at its $Y+\theta$ mode frequency will, however, be quite low, usually within −15 cycles per million per degree C. For example, in a crystal element cut in accordance with either Example 1 or 2, the frequency change per million cycles, per degree C (when vibrating at its $Y+\theta$ mode frequency) will be substantially −6.8 cycles and in the case of Example 3, −8.5 cycles.

Although certain specific ways and means for accomplishing the object of the invention have been set forth, it will be understood that they have been given by way of example and should not be construed as limitations to the scope of the invention. Neither is it to be understood that any statements herein made in regard to the values or relationships between dimensions and frequency are other than close approximations. It is well known in the art that, in order to obtain the frequency characteristics of a piezo-electric plate with the precision that is required, frequent tests of frequency characteristics should be made between successive stages of the grinding operation. The invention, therefore, is not to be limited except insofar as is necessitated by the prior art and by the spirit of the appended claims.

What is claimed is:

1. A quartz piezo-electric element cut from a mother crystal having major and minor apex faces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 50° to 55° from the Z-axis toward parallelism with the plane of a major apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

$$\frac{K}{f}$$

where f is a frequency of said element expressed in megacycles and K is equal to 172.5 to 190.3, and the other dimension of said surfaces similarly expressed is equal to substantially .45 to .365 times said first mentioned dimension, said element being characterized by exhibiting a substantially unitary freedom for its X-axis mode of vibration and a low temperature coefficient of frequency.

2. The invention as set forth in claim 1 further characterized in that the thickness of said element expressed in mils of an inch is equal to

$$\frac{K'}{f'}$$

where f' is a second frequency of said element expressed in megacycles and K' is equal substantially to 98.7.

3. A quartz piezo-electric element cut from a mother crystal having major and minor apex faces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 52.5° from the Z-axis toward parallelism with the plane of a major apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

$$\frac{K}{f}$$

where f is a frequency of said element expressed in megacycles and K is equal to 179.8, and the other dimension of said surfaces similarly expressed is equal to substantially .41 times said first mentioned dimension, said element being characterized by exhibiting a substantially unitary freedom for its X-axis mode of vibration and a substantially zero temperature coefficient of frequency.

4. The invention as set forth in claim 3 further characterized in that the thickness of said element expressed in mils of an inch is equal to

$$\frac{K'}{f'}$$

where f' is a second frequency of said element expressed in megacycles and K' is equal substantially to 98.7.

5. A quartz piezo-electric element cut from a mother crystal having major and minor apex faces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 50° to 55° from the Z-axis toward parallelism with the plane of a major apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

$$\frac{K}{f}$$

where f is a frequency of said element expressed in megacycles and K is equal to 71.8 to 91.7, and the other dimension of said surfaces similarly expressed is equal to substantially 1.33 to .8 times said first mentioned dimension, said element being characterized by exhibiting a substantially unitary freedom for its Z-axis mode of vibration and a low temperature coefficient of frequency.

6. The invention as set forth in claim 5 further characterized in that the thickness of said element expressed in mils of an inch is equal to

$$\frac{K'}{f'}$$

where f' is a second frequency of said element expressed in megacycles and K' is equal substantially to 98.7.

7. A quartz piezo-electric element cut from a mother crystal having major and minor apex faces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 52.5° from the Z-axis toward parallelism with the plane of a major apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

$$\frac{K}{f}$$

where f is a frequency of said element expressed in megacycles and K is equal to 79.3, and the other dimension of said surfaces similarly expressed is equal to substantially 1.06 times said first mentioned dimension, said element being characterized by exhibiting a substantially unitary freedom for its X-axis mode of vibration and a substantially zero temperature coefficient of frequency.

8. The invention as set forth in claim 7 further characterized in that the thickness of said element expressed in mils of an inch is equal to

$$\frac{K'}{f'}$$

where f' is a second frequency of said element expressed in megacycles and K' is equal substantially to 98.7.

9. A quartz piezo-electric element cut from a mother crystal having major and minor apex faces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 50° to 55° from the Z-axis toward parallelism with the plane of a major apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

$$\frac{K}{f}$$

where f is a frequency of said element expressed in megacycles and K is equal to 65.7 to 86.7, and the other dimension of said surfaces similarly expressed is equal to substantially 3.33 to 2 times said first mentioned dimension, said element being characterized by exhibiting a substantially unitary freedom for its Z-axis mode of vibration and a low temperature coefficient of frequency.

10. The invention as set forth in claim 9 further characterized in that the thickness of said element expressed in mils of an inch is equal to

$$\frac{K'}{f'}$$

where f' is a second frequency of said element expressed in megacycles and K' is equal substantially to 98.7.

11. A quartz piezo-electric element cut from a mother crystal having major and minor apex faces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 53.5° from the Z-axis toward parallelism with the plane of a major apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

$$\frac{K}{f}$$

where f is a frequency of said element expressed in megacycles and K is equal to 72.8, and the other dimension of said surfaces similarly expressed is equal to substantially 2.6 times said first mentioned dimension, said element being characterized by exhibiting a substantially unitary freedom for its X-axis mode of vibration and a substantially zero temperature coefficient of frequency.

12. The invention as set forth in claim 11 further characterized in that the thickness of said element expressed in mils of an inch is equal to

$$\frac{K'}{f'}$$

where f' is a second frequency of said element expressed in megacycles and K' is equal substantially to 98.9.

13. A quartz piezo-electric element cut from a mother crystal having major and minor apex surfaces, said element having its principal surfaces in planes which are substantially parallel to an X-axis and inclined at an angle of substantially 50° to substantially 55° with respect to the Z-axis in a direction towards parallelism with the plane of a major apex surface, said element having its length and width relatively so proportioned with respect to the angle formed by the intersection of said surfaces with said Z-axis that it possesses a unitary freedom for its X-axis mode of vibration.

SAMUEL A. BOKOVOY.

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DISCLAIMER

2,111,384.—*Samuel A. Bokovoy*, West Collingswood, N. J. PIEZOELECTRIC QUARTZ ELEMENT. Patent dated March 15, 1938. Disclaimer filed December 12, 1940, by the assignee, *Radio Corporation of America*.

Hereby enters this disclaimer to claim 7.

[*Official Gazette January 21, 1941.*]