March 15, 1938.

S. A. BOKOVOY

2,111,383

PIEZOELECTRIC QUARTZ ELEMENT

Filed Sept. 30, 1935

2 Sheets-Sheet 1

Fig. 1.

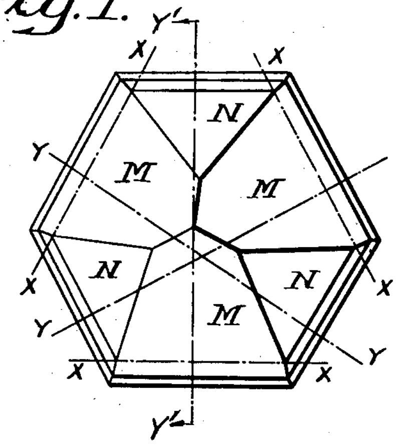


Fig. 2.

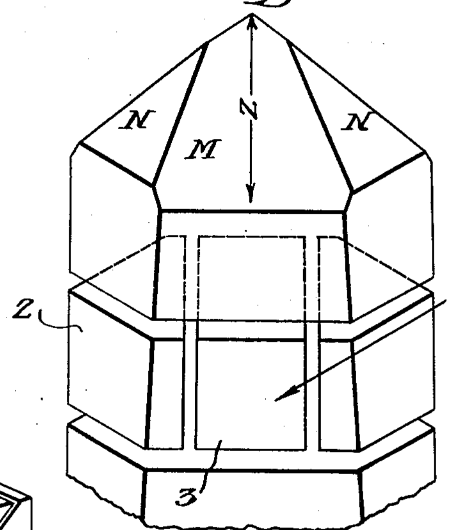


Fig. 3.

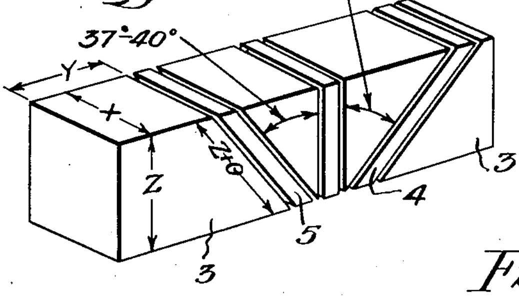


Fig. 4

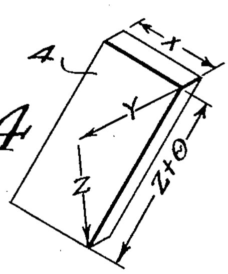


Fig. 6.

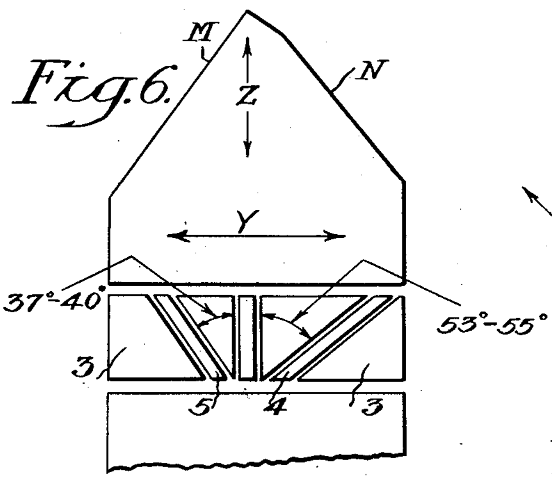
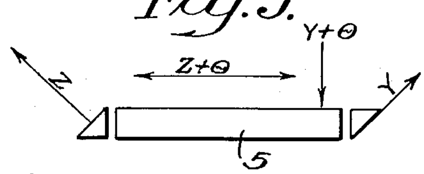


Fig. 5.



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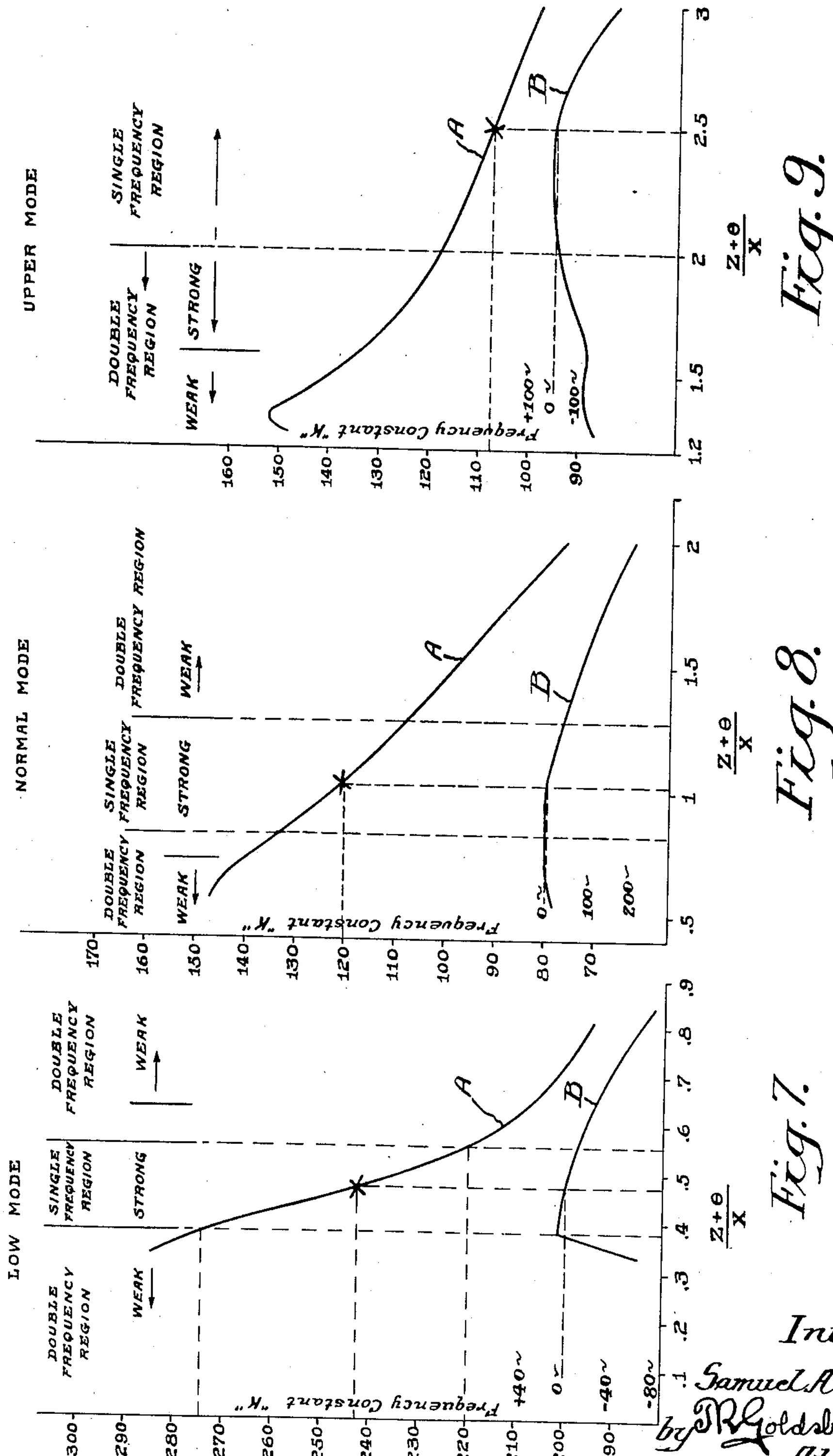
March 15, 1938. S. A. BOKOVOY 2,111,383

PIEZOELECTRIC QUARTZ ELEMENT

Filed Sept. 30, 1935 2 Sheets-Sheet 2



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UNITED STATES PATENT OFFICE

2,111,383

PIEZOELECTRIC QUARTZ ELEMENT

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Application September 30 1935, Serial No. 42,915

13 Claims. (Cl. 171—327)

This 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 process 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-wide ratio for the low, normal and upper modes of frequency response along the X-axis.

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*) A 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 k. c. 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.

(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 k. c. and also at 1000 k. c., 200 k. c. and 2000 k. c., 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/or 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 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 surfaces 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"* or *"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 53°–55°, say 54° towards parallelism with a major apex face, it will possess a zero or some other low temperature coefficient of frequency.

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 from the Z axis toward parallelism with a minor apex face and that of the 53°–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 lie 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 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.

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

Example 1

Given a blank cut with its principal surfaces tilted at an angle of substantially 38.6° towards parallelism with the plane of a minor apex face (blank 5 of Figs. 3, 5 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, 100 k. c.

(c) a second frequency response of, say, 10 times that of the 100 k. c. frequency.

Assuming further, for purposes of illustration, that the 100 k. c. 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 (100 k. c.) expressed in megacycles divided into any constant (K) between substantially 218 and 275 and that the other of the two greater dimensions of the crystal (i. e. the $Z+\theta$ dimension Fig. 5) should be substantially .36 to .55 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. 7 that a random selection of a constant within the 218–275 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 38.6° towards parallelism with a minor apex face of the mother crystal. For this angle of orientation the zero temperature coefficient is achieved when the constant (K) selected is substantially 242.1 and the ratio of the Z+Θ dimension to that of the X-axis dimension is substantially .463.

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

$$X=\frac{242.1}{.1}$$

thus, the X-axis dimension will be 2421 mils of an inch.

The Z+Θ dimension will be 2421 mils times .463 (the

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

ratio) or substantially 1,120.9 mils of an inch.

The formula required to achieve the third (*c*) desired characteristic i. e. a "thickness" or Y+Θ mode frequency response of 1000 k. c., is

$$d=\frac{K'}{f'} \qquad (2)$$

where *d* is the dimension along the Y+Θ axis, *f'* is the Y+Θ mode frequency expressed in megacycles and K' is equal to substantially 67.

As the second frequency required in this instance is 1000 k. c. it is apparent that the element should be ground or lapped to a thickness of substantially 67 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 109–133 and the

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

dimensional ratio is .8–1.3. The preferred constant K is 120 and the preferred

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

ratio is 1.02 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 100 k. c. will be 1200 mils of an inch, and the Z+Θ dimension will be 1200 mils of an inch times 1.02 or 1224 mils of an inch. The thickness required to achieve a Y+Θ frequency response of 1000 k. c. will be, as in the earlier example, 67 mils of an inch.

Example 3

Curve A of Fig. 9 shows clearly that the range of constants K for an element cut to respond to a single "upper" mode frequency is substantially 97–118 and the

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

length-width ratio between 2 and 3. For the 38.6° zero temperature tilt the preferred constant K is 107.5 and the dimensional ratio is 2.5. Accordingly, the dimension along the X-axis for 100 k. c. response will be 1075 mils of an inch and the Z+Θ dimension 2687.5 mils of an inch. The thickness of the element for the Y+Θ 1000 k. c. response, as in the two prior examples, should be 67 mils of an inch.

The formula for the single frequency X-mode of response holds true for all frequencies between substantially 20 k. c. and 750 k. c. The thickness or Y+Θ frequency range is substantially 400 k. c. to, say, 10 megacycles depending to some extent upon practical limits of lapping thin plates.

The curves of Figs. 7, 8 and 9 are for the 37°–40° tilt about the X-axis toward parallelism with a minor apex face. The constants therein disclosed do not hold good for the 53°–55° blank.

All of the examples set forth are for a 38.6° angle of rotation, the permissible range of angles, however, is that stated, i. e. 37°–40°. If, whether through accident or design, the element is given a tilt other than 38.6° and within this range it will not exhibit an exactly zero temperature coefficient of frequency, however this desired operating characteristic may be achieved for a specific angle by altering the

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

ratio in a direction corresponding to the direction of departure from 38.6°. That is to say assuming a blank to be cut at 39.5°, the

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

ratio should be slightly increased to retain the zero temperature coefficient. The curves B of Figs. 7, 8 and 9 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 present invention to oscillate at a single X-mode frequency and at a desired Y+Θ mode frequency will ordinarily exhibit an exactly zero temperature coefficient only while operating at its X-mode frequency, the temperature coefficient of frequency of the element while vibrating at its Y+Θ frequency will, however, be quite low, usually within −15 cycles per million per degree C.

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 37° to 40° from the Z-axis toward parallelism with the plane of a minor 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 the element expressed in megacycles and K is equal to 218 to 275, and the other dimension of said surfaces, similarly expressed, is equal to substantially .55 to .36 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 to substantially 67.

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 38.6° from the Z-axis toward parallelism with the plane of a minor apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

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

in which f is a frequency of the element expressed in megacycles and K is equal to 242.1 and the other dimension of said surfaces, similarly expressed, is equal to substantially .463 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 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 to substantially 67.

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 37° to 40° from the Z-axis toward parallelism with the plane of a minor 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 the element expressed in megacycles and K is equal to 109 to 133, and the other dimension of said surfaces, similarly expressed, is equal to substantially 1.3 to .8 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.

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 to substantially 67.

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 38.6° from the Z-axis toward parallelism with the plane of a minor apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

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

in which f is a frequency of the element expressed in megacycles and K is equal to 120, and the other dimension of said surfaces, similarly expressed, is equal to substantially 1.02 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 to substantially 67.

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 37° to 40° from the Z-axis toward parallelism with the plane of a minor 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 the element expressed in megacycles and K is equal to 97 to 118, and the other dimension of said surfaces, similarly expressed, is equal to substantially 3 to 2 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.

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 to substantially 67.

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 38.6° from the Z-axis toward parallelism with the plane of a minor apex face, the dimension of each of said surfaces along the X-axis expressed in mils of an inch being equal to

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

in which f is a frequency of the element expressed in megacycles and K is equal to 107.5, and the other dimension of said surfaces, similarly expressed, being equal to substantially 2.5 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 to substantially 67.

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 from substantially 37° to substantially 40° with respect to the Z-axis in a direction towards parallelism with the plane of a minor 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.

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