

Jan. 1, 1946.

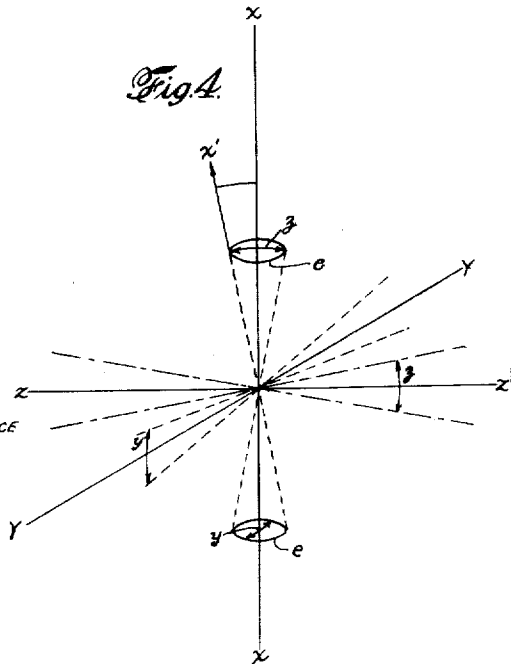
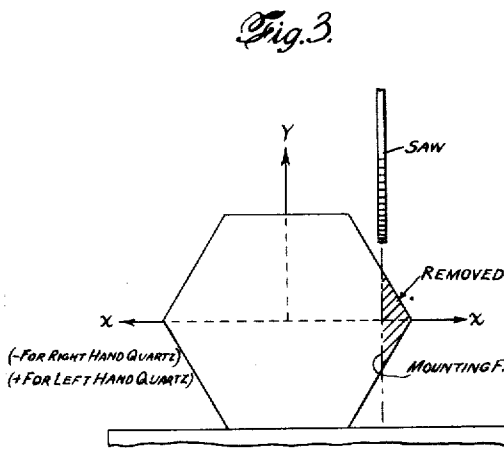
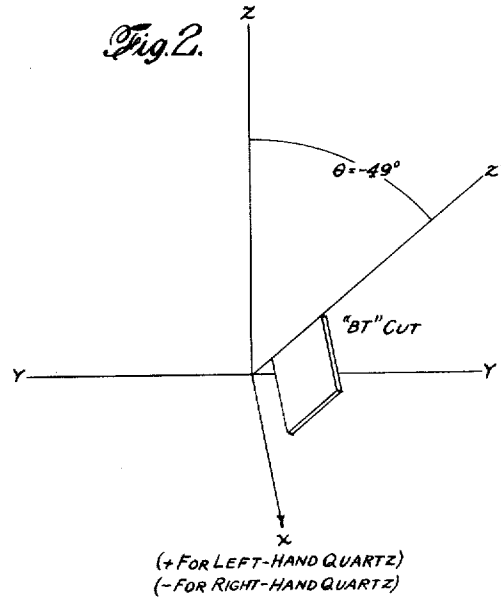
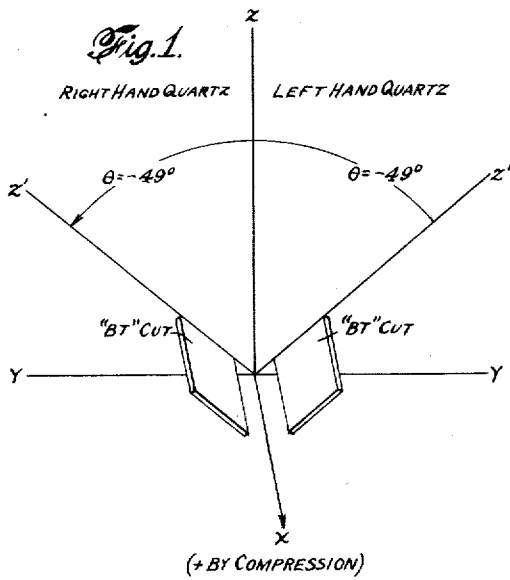
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2,392,271

MANUFACTURE OF PIEZOELECTRIC ELEMENTS

Filed Nov. 20, 1943

4 Sheets-Sheet 1



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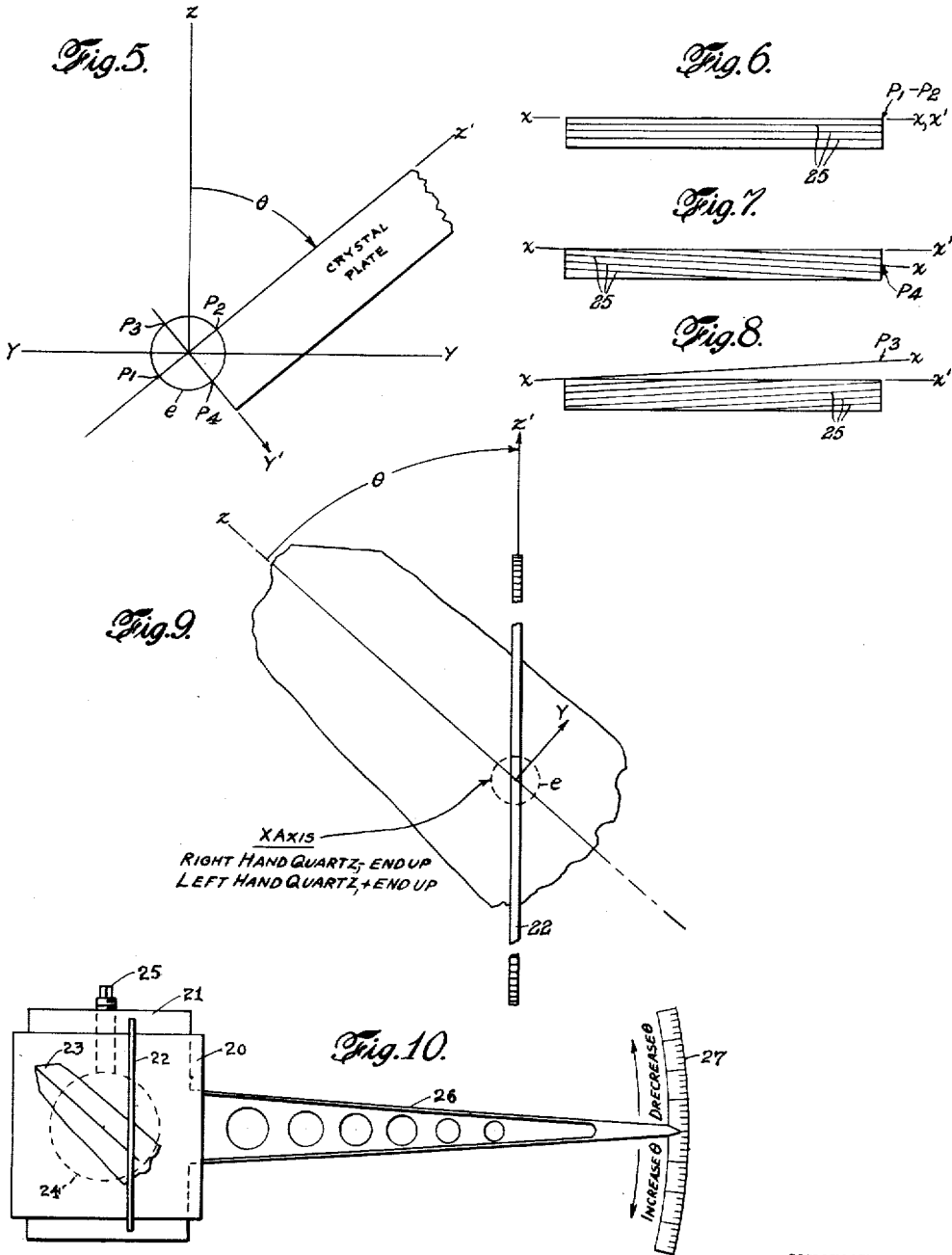
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MANUFACTURE OF PIEZOELECTRIC ELEMENTS

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4 Sheets-Sheet 2



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MANUFACTURE OF PIEZOELECTRIC ELEMENTS

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4 Sheets-Sheet 3

Fig. 11.

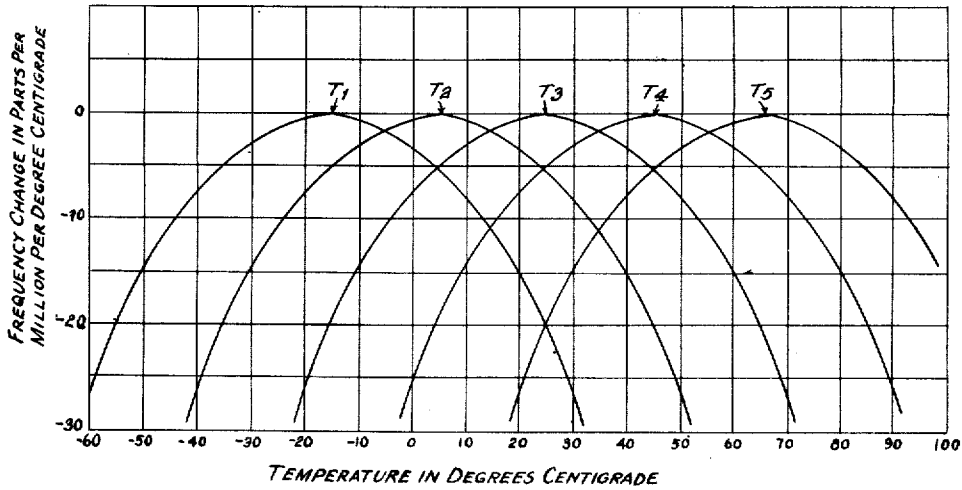
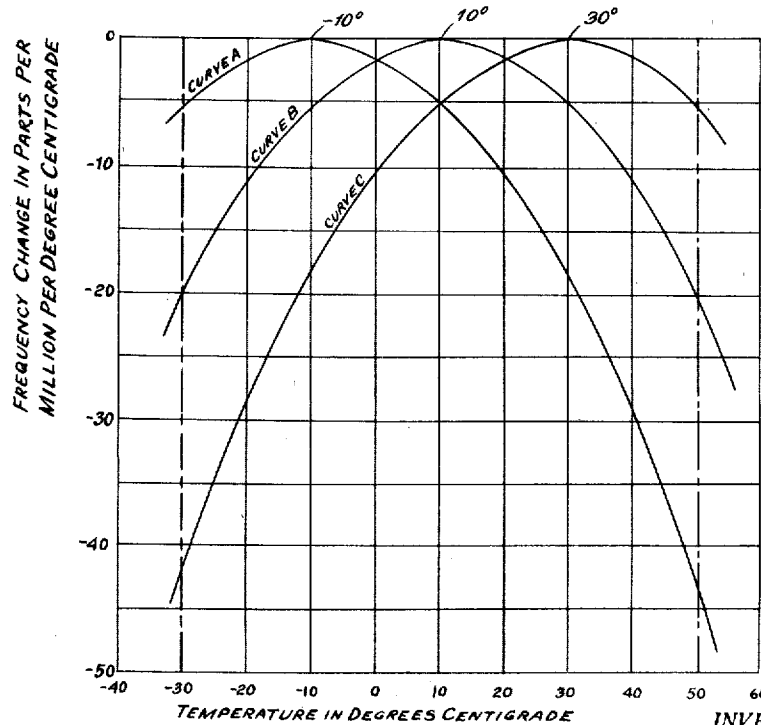


Fig. 12.



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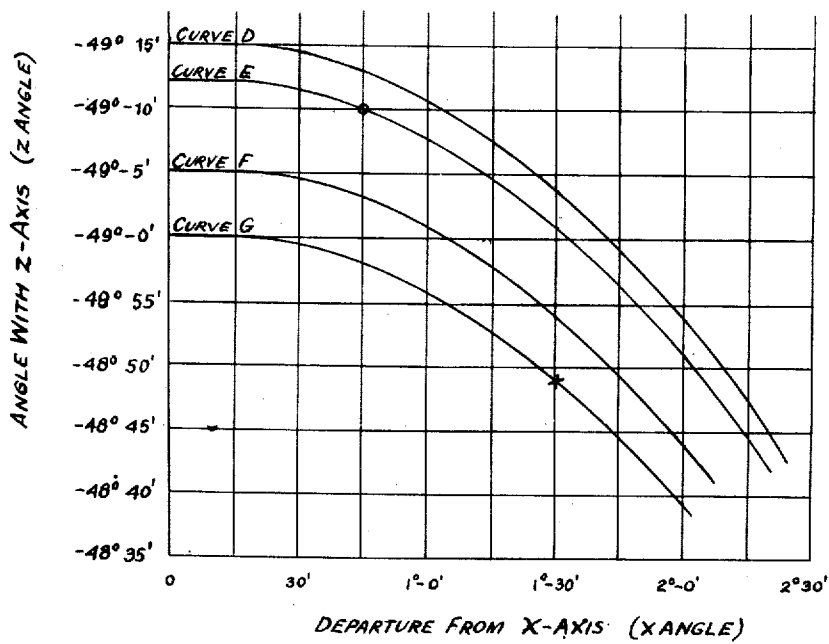
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4 Sheets-Sheet 4

Fig. 13.



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UNITED STATES PATENT OFFICE

2,392,271

MANUFACTURE OF PIEZOELECTRIC
ELEMENTS

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Application November 20, 1943, Serial No. 511,035

8 Claims. (Cl. 171—327)

This invention relates to piezoelectric crystals and more particularly to the art of cutting blanks or plates from piezoelectric crystals, such as quartz, for use as frequency-determining elements in oscillation generators or in other electrical systems or networks.

This specification will follow the standard terminology as applied to quartz which employs the orthogonal axes X, Y and Z to designate the electric, the mechanical and the optic crystallographic axes, respectively, of piezoelectric crystal material and which employs the orthogonal axes X', Y' and Z' to designate the directions of axes or surfaces of a piezoelectric body angularly oriented with respect to any or all of the X, Y and Z crystallographic axes thereof. Where the orientation is obtained by rotation principally about an X axis, as particularly illustrated herein, the orientation angle θ designates the effective angular position of the crystal in degrees as measured between the Z axis and the Z' axis. This angle will also be referred to as the "Z angle." An angle between an X axis of the mother crystal and the X' axis of a slab or plate cut therefrom, which is angularly disposed with respect to an X axis, will be referred to as the "X angle."

Quartz crystals occur in two forms, right-hand and left-hand. A crystal is designated as right-hand if it rotates the plane of polarization of plane polarized light traveling along the Z axis in a right-hand direction and is designated as left-hand if it rotates the plane of polarization to the left.

If a compressional stress be applied to the ends of an electric or X axis of a quartz crystal and not removed, a charge will be developed which is positive at the positive end of the X axis and negative at the negative end of that axis, for either right-hand or left-hand crystals. The sign of the charge and hence the polarity of an X axis may be determined by means well known in the art.

In specifying the orientation of a plate cut from a right-hand crystal, the angle θ which the Z' axis makes with the Z axis, as the crystal plate is rotated about the X axis, is deemed positive when, with the positive end of the X axis pointed toward the observer, the rotation is in a clockwise direction. A counter-clockwise rotation of such a crystal gives rise to a negative orientation angle. Conversely, the orientation angle of a plate cut from a left-hand crystal is positive when, with the positive end of the electric axis pointed toward the observer, the rotation is coun-

ter-clockwise and is negative when the rotation is clockwise.

It is well known that the frequency, temperature-coefficient, activity and other properties of oscillating quartz crystals are dependent not only on the dimensions of the plate but upon the orientation of the plate relative to the crystallographic axes of the raw crystal. Many different cuts have been devised, in order to secure quartz crystal plates meeting a wide variety of requirements. Thus there are the parallel face cuts known as X-cut, Y-cut and Z-cut crystals, each of which has a major face normal to the crystallographic axis from which it derives its name. They are little used today because of various well known deficiencies. Crystal plates more commonly used at the present time are cut with their X', Y' and Z' axes at specified angles to the X, Y and Z crystallographic axes, most of them having one edge parallel to one crystallographic axis, about which they are rotated by certain angles with reference to another axis. Such for example, are the cuts known as AT and BT, used for high frequencies, and CT and DT used for lower frequencies. The AT cut is rotated about the X axis at an angle of substantially $+35^{\circ} 15'$ and the BT cut is rotated, in the opposite direction, at an angle of substantially -49° , both measured from the Z or optical axis of the crystal.

It is well recognized that the frequency of oscillation of a crystal plate is influenced by the temperature at which it is operated, changes in temperature causing changes in the natural frequency of oscillation. Any such change is an obvious disadvantage since the crystals are used for the purpose of stabilizing or controlling frequencies in electrical systems. The magnitude of the change in frequency caused by change in temperature is determined very largely by the orientation of the plate, that is to say by the type of cut. It is expressed as the number of cycles change per million cycles of crystal frequency per degree variation in temperature and is termed the temperature coefficient of oscillation frequency, or more briefly the frequency-temperature coefficient. A positive coefficient indicates that crystal frequency increases with increasing temperature and a negative coefficient that crystal frequency decreases with increase in temperature.

The AT, BT, CT and DT cuts referred to above have a zero frequency-temperature coefficient at a specified temperature. On either side of that temperature, which is referred to herein as the "turning point," the frequency increases or decreases in a generally parabolic curve with tem-

perature, which curves will be more particularly described hereinafter. Because of this characteristic these cuts are known as "zero temperature coefficient crystals," although obviously the designation is accurate only with respect to a single temperature, or at best with respect to a very narrow range of temperatures. It is this characteristic, however, that is largely responsible for the present widespread use of crystal cuts of this type.

The present invention is concerned with improvements in the method of manufacturing zero temperature coefficient crystals generally of the type referred to above and to the crystal cuts produced thereby which, as will hereinafter appear, may differ from the specific cuts mentioned.

The problems involved and the manner in which they are solved in accordance with the invention will be more readily understood from the following detailed description, taken in connection with the drawings, in which:

Fig. 1 is a diagrammatic showing of a BT cut plate as cut either from right-hand or left-hand quartz;

Fig. 2 is a similar showing of a BT cut, illustrating how the Z angle, or θ , may be measured in the same direction from the Z axis, with reference to the observer's position, for either right-hand or left-hand quartz, by turning the raw crystal so that the end of the X axis toward the observer has one polarity for right-hand quartz and the opposite polarity for left-hand quartz;

Fig. 3 shows diagrammatically the cutting of a mounting face on a raw crystal, by means of which it may be mounted, for cutting into wafers, with the desired orientation with respect to two axes;

Fig. 4 illustrates, with reference to the X, Y and Z axes, the errors which may occur in cutting the mounting face and in mounting the crystal for sawing into wafers;

Fig. 5 relates the errors shown in Fig. 4 to a crystal plate, showing how the X axis may be thrown out of the plane of the plate;

Figs. 6, 7 and 8 are schematic edge views of the plate partially shown in Fig. 5, and looking at the X'Y' plane thereof, showing in exaggerated scale the angular displacement of the X' axis from the X axis and the corresponding angular relation between the atomic planes of the crystal and the face of the plate;

Fig. 9 is a detailed view looking down on a raw crystal in position under a vertical rotary saw for cutting into wafers, showing one angle of cut and the positions of the X axis for right-hand and left-hand quartz;

Fig. 10 shows a table on which the crystal may be mounted under the saw, which table is rotatable in a single horizontal plane for changing the angle θ , or Z angle;

Fig. 11 is a graph showing frequency-temperature curves of BT cut quartz plates for different orientation angles giving turning points at various temperatures from -15° to $+65^{\circ}$ C.;

Fig. 12 is a comparison of three frequency-temperature curves having different turning points over a temperature range from -30° to $+50^{\circ}$ C., showing the effect of shifting the turning point on frequency change over that range of temperature; and

Fig. 13 is a graph showing a series of curves each of which represents a series of orientation angles which will give crystal plates the temperature-frequency curves of which will have the same turning point.

In order to illustrate the invention, the cutting of BT type plates will be considered in detail, by way of example, but it is to be understood that the invention is not limited thereto and that its principles may be applied to other cuts. For purposes of discussion a standard BT cut will be assumed to be one, as shown in Figs. 1 and 2, which is rotated about an X axis at an angle of -49° as measured in the plane perpendicular to the X axis, or YZ plane. Hence the plate will have its major faces parallel to the X axis and the X' axis of the plate is parallel to the X axis.

It is obvious that to cut such a plate accurate orientation in three planes is required. Crystals are cut by rotary diamond saws operating in fixed planes and heretofore it has been the practice to mount the raw crystal under the saw on a three-way orientation table requiring three adjustments. The opportunity for error in such methods is large since there is the possibility of human and mechanical error in each adjustment, the adjustments are time-consuming and relatively difficult to make, and error may also result from wear in the several necessary moving parts of the orientation table which cannot be as ruggedly constructed as a table having only a single movement. It is, of course, well known that relatively small errors in orientation affect the performance characteristics of the plates.

In the cutting of zero frequency-temperature coefficient crystals the ultimate requirements, from the standpoint of performance, are the production of plates having zero coefficients and also having the proper turning points. This will be clear from a consideration of Figs. 11 and 12. Fig. 11 shows a series of frequency-temperature coefficient curves for a BT cut plate. The turning point for each curve is the temperature at which the said coefficient is zero. The turning points are shown at T_1 , T_2 , T_3 , T_4 and T_5 and these values may be selected by varying θ , the angle of rotation of the plate about the X axis, by very small amounts.

The practical importance of the proper location of the turning point may be seen from a consideration of Fig. 12 where the frequency-temperature coefficient curves for three plates having different turning points are plotted with reference to a desired operating range of from -30° to $+150^{\circ}$ C.

Such crystal plates may be used, for example, as frequency controls in radio apparatus in aircraft where they will be subjected to wide fluctuations in temperature and in which it is desired that the change in frequency with change in temperature be kept to a minimum. If the plate is cut to have a turning point at -10° C., as shown by curve A, or at $+30^{\circ}$ C. as shown by curve C, it will be seen that the frequency change at either end of the temperature range may be in excess of 40 cycles per megacycle, at -30° C. for curve C and at $+50^{\circ}$ C. for curve A. If, however, the turning point is at $+10^{\circ}$ C., as shown by curve B, the maximum frequency change will be a decrease of only 20 cycles per megacycle at either extreme of temperature.

The principal objects of the present invention are:

(a) To provide a simplified method of cutting raw quartz into wafers in the manufacture of zero frequency-temperature coefficient plates;

(b) To eliminate the necessity for accurate three-plane orientation of the crystal preparatory to cutting;

(c) To provide a method whereby final orienta-

tion, which will give the desired characteristics, may be accomplished in a single plane;

(d) To eliminate several sources of possible error in orientation and to simplify the training of operators;

(e) To produce zero frequency-temperature coefficient crystal plates having turning points giving minimum frequency changes with changes in temperature;

(f) To make crystal plates of more accurate operating characteristics; and

(g) To save time, labor and expense and simplify the apparatus required in fabricating piezoelectric bodies.

The invention pertains to that part of the complete process of making finished crystal plates which consists of orienting the raw crystal with respect to the saw and slicing it up into wafers having the proper orientation with reference to the crystallographic axes. Thereafter the wafers are further processed by cutting them into blanks, lapping to the desired thickness, edging, and finishing according to well known procedures. In general, the invention comprises the steps of mounting the raw crystal with approximate orientation with reference to its axes, making a test cut, determining the angle between the face of the wafer so cut and the X axis of the crystal, and compensating for that angular difference by a single plane reorientation of the crystal which changes primarily only the Z angle or θ . It has been discovered, contrary to generally held views, that by following the procedures hereinafter described plates having the desired operating characteristics can be produced by methods which are greatly simplified over those generally followed.

In order to position the crystal for sawing into wafers, a mounting face is first cut on it. Ideally this face should be in the YZ plane so that when the crystal rests on it the X axis will be normal to the support. Ideally such support, for example the saw table, or a block attached to it, should be perpendicular to the plane of the saw. Neither of these ideals, especially the former, is easy to attain by simple, practical manufacturing methods. In cutting the mounting face according to the method of the invention it is first determined, by means of a Conoscope, whether the crystal is right-hand or left-hand and the polarity of an X axis is determined by known means. As shown in Fig. 3, if it is right-hand the face will be cut so that the negative end of an X axis will be uppermost when the crystal rests on the face and a positive end uppermost if the crystal is left-hand. (The opposite poles could equally well be uppermost, in each case, but one method or the other should be adopted as standard practice.) The YZ plane is then approximately determined, as to the Y axis by merely resting the crystal on a natural face, which places the YZ plane approximately perpendicular to the support, and as to the direction of the Z axis by means of a photoelectric Polariscopes, and the mounting face is cut.

The crystal is then mounted with optical wax on a block 20 (Fig. 10), adapted to be secured to the saw table 21, with the Z axis, determined in the Polariscopes as just explained, at the desired angle to the plane of the saw 22. In the case of a BT cut this would be -49° . According to the present method this need be only approximate in making the test cut.

Referring to Fig. 4, if the mounting face were precisely in the plane determined by the Y and Z axes and in mounting the crystal on the saw this plane were maintained perpendicular to the

plane of the saw, the cut made by the saw would be parallel to the X axis and the X axis would also be normal to the mounting face. But such a condition would be fortuitous, using the methods described. The Y axis may not have been accurately determined due to irregular or poor natural faces on the crystal. Error in reading the Polariscopes will result in erroneous determination of the Z axis. The film of optical wax by which the crystal is mounted on the saw table may be of uneven thickness. The saw blade may not be truly vertical. The possible cumulative effect of these errors is shown on an exaggerated scale in Fig. 4. The crystal may have been rotated about its Y axis through the angle z or about its Z axis by the angle y , either of which would move the X axis through corresponding angles. Obviously any combination of both of these movements may have taken place in locating and cutting the mounting face and in mounting the crystal. Assuming equal values for y and z , the X axis might pass from the intersection of the Y and Z axes through any part of the circle of error e , as shown at X'. As may be seen from Figs. 5 and 9, if the X axis, due to tilting of the YZ plane is caused to fall anywhere off of the Z' line, the saw will not cut the crystal parallel of the X axis. Thus if the X axis passes through the point P₁ or the point P₂ or through any point on the line joining them, the plane of the crystal plate or wafer cut by the saw will be parallel to the X axis, as shown in Fig. 6. The atomic planes 25 of the crystal will be parallel to its major faces. However, if the X axis passes through point P₁, the atomic planes will be angularly disposed relative to the plane of the plate as shown in Fig. 7 and similarly if it passes through P₂ they will be disposed as shown in Fig. 8. The points chosen for explanation are those for the minimum and maximum deviations of the X axis from the plane of the cut and it should be evident that for other positions of the X axis, passing through other points on the circle e , the angle will have some intermediate value. This angle is referred to herein as the X angle.

The methods of mounting described, if followed with reasonable care, will result in relatively small values for the X angle, of the order of one or two degrees. Even such small deviations, however, are sufficient to materially change the operating characteristics of the plates as frequency control elements, for example by shifting the turning point and increasing the frequency drift over a given range of temperature.

Determination of the X angle is made by cutting a wafer from the crystal after it is mounted under the saw and measuring the angle by established X-ray techniques which it is unnecessary to describe in detail, it being well known that under proper conditions X-rays impinging on a crystal plate reflect from its atomic planes, rather than its mechanical surface, and consequently their direction may be determined relative to the surface of the plate.

In order to correct for values of the X angle, as measured, resort is had to the data represented by the curves of Fig. 13. The four curves D, E, F and G, given by way of example, were derived as follows: A number of crystal plates known to have the same turning point were examined by X-ray to determine their X angles. They were then similarly examined to determine for each the angle θ , that is their rotation with respect to the Z axis (designated "Z angle" in Fig. 13). The values of these two angles were

then plotted, giving the curves shown. Curve G, for example, gives the values of the X angle and the Z angle for plates having the same turning point as a plate having an X angle of 0 and a rotation about the X axis relative to the Z axis $-49^{\circ}-0'$. Hence if the X angle of a trial cut is found to be $1^{\circ}-30'$ (either plus or minus) and a plate having the same turning point is desired, the Z angle will be $-48^{\circ}-49'$, as shown by point "X" on curve G. It will be observed that the curves are very similar and as a practical matter it is possible to plot a few curves for different turning points and draw in additional curves by interpolation.

The application of the data given by the curves of Fig. 13 is made as follows: The X angle of the test slab has been determined by X-ray. Its Z angle is next measured by X-ray. Knowing the turning point which it is desired the final plate should have, and knowing the X angle and the Z angle existing in the test cut, it is then necessary only to increase or decrease the Z angle to obtain a Z angle which will give the desired turning point. For example the X angle is found to be $0^{\circ}-45'$ and the Z angle $-48^{\circ}-55'$. A turning point is desired which is the same as that of a true BT cut having an X angle of 0 and a Z angle of $-49^{\circ}-12'$. From curve E it may be seen (at the point circled) that the Z angle for the measured X angle should be $-49^{\circ}-10'$. The crystal is therefore rotated under the saw to increase the Z angle by $0^{\circ}-15'$. If the X angle should turn out to be zero, then it is only necessary to correct the Z angle.

Fig. 10 shows the preferred manner of effecting this single plane reorientation. The saw table 21, carrying the block 20 on which the crystal 23 is mounted, is rotatable in a horizontal plane on a firm pivot 24 and can be locked in position by screw 25. A long scale-arm 26 is attached to the table for taking accurate readings on a scale 27, on which changes in the Z angle are measured. From Fig. 10 may also be seen the advantage of mounting crystal 23 so that, whether it is right-hand or left-hand, movement of arm 26 in a given direction will always change the Z angle in the same sense, that is either decrease it or increase it. Production procedure can thus be standardized.

After reorienting the table in the manner described one more wafer may be cut for a final check if desired and then the entire crystal is sliced up into wafers from which plates are cut and finished in the usual way. Wafers having their faces cut at different angles in the process of reorientation, so that their faces are not parallel, should of course be discarded.

It will thus be seen that the invention provides a very simple and expeditious method of cutting quartz crystal plates having orientations which give zero frequency-temperature coefficients, the turning points of the frequency-temperature curves being determined with a high degree of accuracy, yet without necessitating the accurate orientation of the crystal, after mounting in the cutting device, in more than one plane.

The method may be applied with good results where the orientation methods used in fixing the plane of the mounting face and the errors in mounting do not result in throwing the X axis out more than about four degrees from being normal to the plane of mounting, that is where the cumulative errors represented by the circle of error e (Figs. 4 and 5) do not give it a radius subtending an angle at the intersection point

of the axes of more than about four degrees. However, it is preferred that such angle should not be more than about two degrees for accurate work as the curves (Fig. 13) increase in slope rapidly for X angles between two and four degrees and relatively small increases in the X angle will require progressively larger changes in the Z angle.

According to the provisions of the patent statutes, the principles and procedures of the invention have been explained and have been illustrated and described by reference to a specific embodiment thereof. However, it is to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically illustrated and described.

What is claimed is:

1. The method of cutting from a crystal having X, Y and Z axes a piezoelectric plate having a zero frequency-temperature coefficient at a specified temperature which comprises, making an approximate determination of the Y and Z axes, mounting the crystal for cutting in a plane which is substantially perpendicular to the plane of the Y and Z axes as thus determined and is at a predetermined angle to the Z axis, cutting a piece from the crystal, measuring the angles of the cut face with the X axis and the Z axis of the crystal, and reorienting the crystal in a single plane to give the angle between the plane of the cut and the Z axis a value which, for the angle of said plane to the X axis, will place said zero coefficient at the specified temperature.

2. The method of cutting from a crystal having X, Y and Z axes a piezoelectric element having a zero frequency-temperature coefficient at a desired temperature which comprises, making an approximate determination of the Y and Z axes by optical means, cutting a mounting face substantially in the plane of the Y and Z axes as thus determined, mounting the crystal on said face for cutting into wafers with the Z axis as thus determined at approximately the desired angle to a fixed plane of cutting, cutting a sample piece from the crystal, measuring by X-ray reflection the true angles between the plane of the cut and the X and Z axes, and reorienting the mounted crystal in a single plane with reference only to the angle of the plane of the cut to the Z axis to give that angle a value which, for the angle of said plane to the X axis, will place said zero frequency-temperature coefficient at the desired temperature.

3. In the cutting of piezoelectric plates from quartz crystals, the method of adjusting the turning point of the frequency-temperature curve of the plate to a specified value which comprises cutting a sample piece from the crystal in a plane approximately parallel to an X axis of the crystal and at an angle to the Z axis thereof known to produce a zero frequency-temperature coefficient at some temperature when the angle of the plate with the X axis is zero, measuring the angle between the plane of the cut and the X axis, and then finally orienting the crystal in a single plane to adjust the angle of cut to the Z axis to a value which, for the measured angle of the cut to the X axis, will give an orientation producing the specified turning point.

4. The method of accurately adjusting to desired values the turning point of the frequency-temperature coefficient curve of a piezoelectric quartz crystal element having a zero frequency-temperature coefficient which comprises, cutting a sample piece from a raw crystal at approxi-

mately the desired orientation with respect to the crystallographic axes, measuring the angles between the cut face of the sample and the X and Z axes of the crystal, and reorienting the crystal in a single plane with reference to the angle between the plane of the cut and said Z axis to give that angle such value as will cause it to fall on a curved plotted for the angles with the X and Z axes of crystal elements known to have the desired turning point.

5. The method of cutting from a crystal having X, Y and Z axes a zero temperature coefficient piezoelectric element whose frequency-temperature coefficient curve has its turning point at a specified temperature which comprises, making an approximate determination of the Y and Z axes, cutting a mounting face on the crystal substantially in the YZ plane as thus determined, mounting the crystal on said face for cutting with the Z axis as thus determined at an angle of substantially -49° to the plane of cutting, cutting a test piece from said crystal, accurately determining the angle of the cut face with the X and Z axes, and reorienting the mounted crystal in a single plane with reference to the angle of the plane of cut to the Z axis to give that angle a value which, for the angle of said plane to the X axis, will cause said turning point to be at said specified temperature.

6. The method of cutting from a crystal having X, Y and Z axes a piezoelectric element having a zero frequency-temperature coefficient at a specified temperature or turning point and other coefficients at temperature different therefrom which comprises, plotting a curve giving the angles of orientation with respect to the Z axis and small angles with respect to the X axis which result in elements having the same turning points, making an approximate determination of the YZ plane of the crystal, cutting a mounting face substantially parallel to the YZ plane as so determined, mounting the crystal on said face for cutting with its Z axis at an angle to the plane of cutting which falls within the plotted range, cutting a test piece, measuring accurately the angles of the plane of the cut with the X and Z axes, and reorienting the crystal by rotation in a single plane to give the angle of cut with the Z axis a value as shown by said curve for the measured value of the angle with the X axis.

7. The method of claim 6 wherein the small angle of orientation with respect to the X axis is four degrees or less.

8. The method of claim 6 wherein the small angle of orientation with respect to the X axis is two degrees or less.

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CERTIFICATE OF CORRECTION.

Patent No. 2,392,271.

January 1, 1946.

MELVIN L. SMITH.

It is hereby certified that error appears in the printed specification of the above numbered patent requiring correction as follows: Page 1, second column, line 21, for "wihch" read --which--; page 2, second column, line 49, for "150^o" read --50^o--; page 3, second column, line 27, for "of" read --to--; and page 5, first column, line 8, claim 4, for "curved" read --curve--; and that the said Letters Patent should be read with this correction therein that the same may conform to the record of the case in the Patent Office.

Signed and sealed this 26th day of February, A. D. 1946.

Leslie Frazer

(Seal)

First Assistant Commissioner of Patents.

mately the desired orientation with respect to the crystallographic axes, measuring the angles between the cut face of the sample and the X and Z axes of the crystal, and reorienting the crystal in a single plane with reference to the angle between the plane of the cut and said Z axis to give that angle such value as will cause it to fall on a curved plotted for the angles with the X and Z axes of crystal elements known to have the desired turning point.

5. The method of cutting from a crystal having X, Y and Z axes a zero temperature coefficient piezoelectric element whose frequency-temperature coefficient curve has its turning point at a specified temperature which comprises, making an approximate determination of the Y and Z axes, cutting a mounting face on the crystal substantially in the YZ plane as thus determined, mounting the crystal on said face for cutting with the Z axis as thus determined at an angle of substantially -49° to the plane of cutting, cutting a test piece from said crystal, accurately determining the angle of the cut face with the X and Z axes, and reorienting the mounted crystal in a single plane with reference to the angle of the plane of cut to the Z axis to give that angle a value which, for the angle of said plane to the X axis, will cause said turning point to be at said specified temperature.

6. The method of cutting from a crystal having X, Y and Z axes a piezoelectric element having a zero frequency-temperature coefficient at a specified temperature or turning point and other coefficients at temperature different therefrom which comprises, plotting a curve giving the angles of orientation with respect to the Z axis and small angles with respect to the X axis which result in elements having the same turning points, making an approximate determination of the YZ plane of the crystal, cutting a mounting face substantially parallel to the YZ plane as so determined, mounting the crystal on said face for cutting with its Z axis at an angle to the plane of cutting which falls within the plotted range, cutting a test piece, measuring accurately the angles of the plane of the cut with the X and Z axes, and reorienting the crystal by rotation in a single plane to give the angle of cut with the Z axis a value as shown by said curve for the measured value of the angle with the X axis.

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