During the war X-ray diffraction, which had been used only in research in some scientific and technical laboratories, also proved its usefulness as an aid in mass production manufacturing. It was introduced into the quartz oscillator-plate industry for the measurement of the crystallographic angles of cuts from quartz crystals. The diffraction apparatus developed for this purpose makes it possible for unskilled people to measure deviations with respect to specified crystallographic angles with an accuracy of a few minutes of arc in a time of 10 to 15 seconds.

The tolerances of oscillator plates

As an introduction to this second article on the manufacture of oscillator plates it is desirable to consider more closely the question of tolerances in the orientation and dimensions of these plates.

It has been stated 1 that the deviations in the crystallographic angles with respect to the prescribed values for a low temperature coefficient cut, a BT cut for example, may not amount to more than 10 minutes, while the thickness of a plate is restricted to a tolerance of, for instance, $10^{-5}$ mm. Furthermore the length of the sides is often also prescribed, with a tolerance of 0.03 mm or less.

The crystallographic angles involved are illustrated in fig. 1, for the case of the square AT and BT plates. This figure shows how these two cuts are orientated in a quartz crystal. An edge $X'$ of the plate must be parallel to an $X$-axis (electrical axis) of the quartz, thus the angle $XX' = 0^\circ$. The projection $Z'$ of the Z-axis (optic axis) on the face of the plate must make an angle $ZZ'$ with the Z-axis amounting to $35^\circ$ $15'$ in the case of the AT cut and of $-49^\circ$ $20'$ in that of the BT cut. Generally the tolerance for $XX'$ is somewhat larger than for $ZZ'$. During the war it was in most cases $20'$ for $XX'$ and $10'$ for $ZZ'$. In the case of the higher precision AT plates made today, the $ZZ'$ angle is often held to smaller tolerances, perhaps 3 or 4 minutes.

These tolerances in the crystallographic angles are dependent upon the requirements regarding the variation of the resonance frequency as a function of the temperature. The turning point of this curve may be displaced to an undesirable temperature region or it may disappear due to a slightly incorrect orientation of the cut. This is illustrated by fig. 2. The tolerance in the thickness depends upon the accuracy with which the desired resonance frequency must be realized. In the case of AT and BT plates where the desired mode of vibration involves a thickness shear, the frequency is inversely proportional to the thickness. The tolerance in the length of the sides is finally prescribed by the requirement that a coupling of the desired vibration with undesired modes of vibration of the plate must be avoided as much as possible. In the case of AT and BT plates, the high

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1) W. Parrish, The manufacture of quartz oscillator-plates, I. How the required cuts are obtained, Philips Techn. Rev. 11, 1949 (No. 11). This article is referred to in the following as I.
harmonics of a fundamental low frequency flexural mode about a Y-axis, which runs diagonally through the plate, often cause the most trouble.

Fig. 2. Variation of resonance frequency with temperature, for a number of BT cuts with slightly differing crystallographic angles. The ordinate scale gives the deviation of the resonant frequency from the maximum value, in $10^{-3}$ cps. The turning points (maxima) of the curves lie near 42, 16, 16, 2 and $-10^\circ$ to $-10^\circ$ respectively. Besides the position of the turning point, the steepness of the curve must be taken into account, in order to get a broad range of working temperatures.

The check on whether the plate has been brought within the tolerances of thickness and length is not carried out by measuring directly these dimensions but indirectly (or rather even more directly) by investigation of the behaviour of the plate in the oscillator circuit of a valve oscillator. In this way it is easy to determine the mechanical resonance frequency of the plate. The “activity” of the plate, i.e., the amplitude at which the plate vibrates, is also measured and serves as a criterion of an adequate limitation of undesired couplings: excessive couplings cause activity “dips” at some frequencies. The lapping (and etching) of the plate is continued until it satisfies the specifications as to frequency and activity. In the last article of this series we shall have an opportunity of going into this more deeply.

The proportionality constant in the relation between resonance frequency and thickness (i.e. the product of frequency times thickness) depends closely upon the orientation of the cut in the crystal. The dimensions required for the avoidance of couplings are also very much influenced by the orientation. In the case of the “indirect” empirical process of finishing the oscillator plates little attention was given to these influences. Nevertheless, the last mentioned influence is of practical importance. Several manufacturers endeavor to minimize the coupling with undesired modes of vibration by giving the plates well defined and previously determined optimal dimensions (predimensioning). These dimensions vary with the cutting angles and hence it is necessary to maintain small tolerances for these angles to make the scheme practical.

During the war predimensioning was not widely practiced in production. Activity dips over the temperature range were then one of the principal causes of rejection of plates.

The checking and correction of the cutting angles was formerly accomplished by a similar “indirect” procedure: a plate was cut from the crystal and lapped to the desired resonance frequency. The frequency was measured as a function of the temperature and from the curve obtained it was deduced as best one could by what amount the cutting angles were incorrect. It was not possible from this method to separate the corrections for ZZ' and XX', but, moreover, it was a quite lengthy and elaborate test. To be sure, checking the orientation is not required for every blank separately; it is to be performed on a test piece, parallel to which a whole series of wafers or blanks can be cut out of a crystal block. The result of the former test method would however be that after cutting the test piece the quartz saw would be idle for quite a long time during the lapping and performance of the test.

An economical mass production of oscillator plates with the present extremely strict specifications only became possible upon the introduction of the X-ray diffraction method, with which the crystallographic angles such as XX' of ZZ' can be measured directly, rapidly and very accurately. With the apparatus designed for this purpose by the North American Phillips Co., which was used on a large scale in the American quartz industry during the war, the required corrections for a test cut could be determined by relatively unskilled help with an accuracy of a few minutes of arc and the whole measurement required only 10 to 15 seconds time 3).

Principle of the angle measurement by X-ray diffraction

The phenomenon of X-ray diffraction in a crystal can be described as a reflection of an X-ray beam at the lattice planes, an appreciable reflection at a set

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3) W. Parrish and S. C. Gordon, Precise angular control of quartz-cutting by X-rays, Amer. Mineralogist 30, 326-346, 1945. See also W. L. Bond and E. J. Armstrong, Use of X-rays for determining the orientation of quartz crystals, Bell System Tech. J. 22, 293-337, 1943; V. Petružilka and J. Boneš, A method for the determination of crystal cuts by applying the reflection of X-rays from a known lattice plane, Phil. Mag. (7) 37, 399-410, 1946.
of parallel lattice planes only being possible when Bragg's condition,

\[ \sin \Theta = \frac{n \lambda}{2d} \]

is satisfied (see fig. 3). In this relation \( d \) is the spacing of the parallel lattice planes, \( \Theta \) the angle of incidence and emergence between X-ray beam and lattice plane, \( \lambda \) the wavelength of the X-rays, \( n \) a whole number (order of the reflection).

Each set of lattice planes in a quartz crystal makes definite angles with the crystallographic axes (X, Y, Z-axes), with the natural faces of the crystal (prism faces \( m \), major and minor rhombohedron faces \( r \) and \( z \), respectively, etc.) and therefore also with the various low-temperature coefficient cuts and any auxiliary planes used in the manufacture. Hence, the orientation of a test cut can be checked by measuring the angle between the plane of that cut and a suitably chosen lattice plane. The principle of the arrangement used for this purpose is shown in fig. 4.

The freshly cut flat surface of the piece or wafer cut from the quartz crystal is pressed against the reference surface of the specimen holder which has been ground perfectly plane. The holder has an opening which exposes part of the cut surface. A narrow beam of nearly monochromatic X-rays from the X-ray tube \( B \) passes through collimator slits \( S_1 \) and \( S_2 \) and impinges on the exposed surface of the wafer. The specimen holder can be rotated about the vertical axis \( P \). The angle \( \alpha \) between the reference surface and a chosen fiducial or reference position, which for the sake of convenience in this discussion may be chosen in the extension of the primary X-ray beam, can be read off on the goniometer scale. After a lattice plane whose spacing \( d \) and orientation are known has been chosen as a plane of reference, the crystal holder is turned until at the point \( 2 \Theta \) in the goniometer scale (\( \Theta \) being calculated according to (1) from the known values of \( d \) and \( \lambda \)) a reflected X-ray beam is observed. The difference between the position \( \alpha \) of the crystal holder and the angle \( \Theta \) is, as may be seen immediately in fig. 4, the angle between the cutting plane and the lattice plane of reference. (This is rigorously correct only if the lattice plane of reference also is perpendicular to the plane of the drawing; we shall return later to this essential condition.)

The X-ray diffraction apparatus

In the practical execution of the measurement by this principle the way in which the reflected X-ray beam is observed requires the most attention. In the Philips apparatus a Geiger counter tube is used, in a form which was developed by Friedman\(^3\), and is shown in fig. 5. The slit in front of the window of the tube is brought to the desired position of the goniometer scale (\( 2 \Theta \)) and the tube remains fixed during the measurement. The X-ray quanta entering the slit are detected by current pulses in the tube and the X-ray intensity is indicated directly by use of circuits measuring the average current developed in the tube. We need not go more deeply into the construction or mechanism of the counter tube since these

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have already been discussed by Friedman \(^3\)) and in this periodical \(^4\).

This method of indication has been essential for the success of the apparatus. Photographic detection of the diffraction (which would have required a different X-ray method) would have meant a serious obstruction in the smooth flow of the mass production process because of the time lost in regulating the magnitude of the average current obtained through the counter tube simply by changing the supply voltage. This is a convenience in this application because it makes it possible to keep the response to the wide range of reflection intensities from different lattice planes within the range of the meter. In practice it is not necessary to adjust the voltage when making successive measurements on the same type of cut, using always the same lattice plane of reference.

This method of operation is possible here because a single crystal produces very intense reflections, making it unnecessary to resort to the maximum gain of the counter tube, which is attained when working on the “plateau”. (Strictly speaking, the name “Geiger counter” is historically correct only under the latter working condition.) Moreover, in this problem it is only a question of detection of a single diffraction peak. For the apparatus described in \(^4\), with which intensities of a number of (much weaker) diffraction lines of powder specimens must be compared, it is important not only to have maximum gain but also to keep the gain of the counter as constant as possible, and hence the “plateau” is used.

Incidentally, it should be noted that the proportional counter has a much shorter “dead time” than has the Geiger counter proper. Therefore, individual quanta may be detected at much higher counting rates, which means that the response of the proportional counter is linear to higher X-ray intensities than that of the Geiger counter.

The slit mounted in front of the window of the counter tube, through which the X-rays pass, is quite wide, so that the setting of the counter tube on the goniometer scale is not critical. This is important because the diffraction spots given by the quartz crystals are very sharp (compared with the diffraction lines of powders) and thus with a slightly incorrect placing of a narrow slit the operator would run the risk of turning the crystal holder past the reflecting position without observing any reflection at all. The slit may not of course be so wide that in certain positions it would allow the passage of two neighboring diffraction spots simultaneously and thus lead to mistakes as to the reflecting lattice plane. But a slit width of \(1/4\)\(^\circ\), measured along the goniometer scale, is quite permissible for the lattice planes normally used in this work, as may be seen from the diffraction spectrum of a quartz sample given in fig. 6.

The apparatus is equipped with an X-ray tube of low power, operating with 3 to 4 mA at a peak voltage of 35 kV, and is air cooled. This is feasible because the intensities of the diffraction spots of single crystal plates are considerably higher than those of the diffraction lines of a polycrystalline specimen. Moreover, the counter tube is much more sensitive than the photographic film usually used in dif-

\(4)\) J. Bleeksma, G. Kloos and H. J. Di Giovanni, An X-ray spectrometer with Geiger counter for measuring powder diffraction patterns, Philips Tech. Rev. 10, 1-12, 1948 (No. 1). The spectrometer described in this article was developed from the special apparatus designed for quartz oscillator-plate manufacture.
fraction research, so that a relatively low intensity of the primary X-ray beam is sufficient. A copper anode is used giving the characteristic copper radiation, of which the \( K\alpha \) lines are used: \( K\alpha_1 = 1.54050 \) Å, \( K\alpha_2 = 1.54434 \) Å; \( K\alpha \) (weighted) = 1.5418 Å. The CuK\( \beta \)-radiation, which gives diffraction spots at slightly different angles, is sufficiently weakened by a nickel foil in front of the window of the X-ray tube, so that it is not detected.

The opening in the specimen holder must be large enough that the metal edges are not struck by the primary X-ray beam, otherwise X-radiation scattered at the edges would cause a troublesome background intensity in all positions of the counter tube. Furthermore it is important that the reference surface, against which in a smoothly running manufacturing process a block of extremely hard quartz is laid several hundred times daily, should not gradually be worn off and lose its plane surface or its precise setting with respect to the goniometer arm. The holder is therefore made of the hardest available hardened tool steel or of boron carbide, and the reference surface is checked every few days.

The goniometer scale is graduated in whole degrees, and a fine-adjustment knob which drives the arm of the specimen holder carries a scale graduated in minutes. In order to avoid repeated subtraction of the angle \( \Theta \) for a reference lattice plane the goniometer has a second sliding scale whose zero point can be set at the angle \( \Theta \) or any other desired fiducial point; this is best done empirically, by means of a standard crystal which has a face lapped parallel to the desired lattice plane. The minute scale on the adjustment knob can be set at the desired position at 0' by temporarily uncoupling it from the driving gear. The specimen holder can also be unlocked and rotated to any position with respect to the arm which rocks it on the goniometer scale so that one can make measurements on any convenient part of the scale.

A photograph of the arrangement, including the X-ray tube, slit system, shutter, specimen holder, counter tube, direct beam shield, goniometer, meter for reading the X-ray intensity, and supply voltage control for counter tube is shown in fig. 7. The X-ray tube has two windows. Two complete measuring setups can therefore be used, one on either side of the tube. The complete apparatus is shown in fig. 8.

\[ K\alpha_1 = 1.54050 \text{ Å}, \quad K\alpha_2 = 1.54434 \text{ Å}; \quad K\alpha \text{ (weighted)} = 1.5418 \text{ Å}. \]

Fig. 6. X-ray diffraction spectrum of the front reflection region of a quartz powder sample made with the Geiger counter X-ray spectrometer 5) (improved form of the instrument previously described in this periodical 4)). The diffraction spots from single crystal quartz plates are even sharper than the lines of the polycrystalline specimen. This pattern was recorded automatically at a rate of \( \frac{1}{4} \) of 26 per minute, with the copper target X-ray tube operated with full-wave rectification at 40 kVp, 20 mA, 0.015 mm nickel filter. The goniometer radius was 170 mm, the angular aperture of the incident beam 1' and width of the receiving slit 0.08 mm. (The 1011-peak is far off the chart.)
Fig. 7. Measuring table of the X-ray diffraction apparatus. On the right is the X-ray tube housing B with slits S and a hinged shutter in front of the X-ray tube window. When this shutter is opened a cover C descends in front of the crystal holder, so that the operator cannot place his hands in the path of the X-ray beam. On the left is the goniometer scale G along which the Geiger counter tube T and the goniometer arm A bearing the specimen holder H can be rocked. The counter tube remains radially directed since it is fastened to an arm which rotates around the same axis (P in fig. 4) as the goniometer arm. The crystal holder visible in the middle is intended for measuring blanks for Y-Z test cuts or for test wafers from an X-block, etc. Different holders are used. The undiffracted portion of the primary beam is absorbed by a lead plate L behind the crystal holder. On the goniometer scale there is a short sliding auxiliary scale whose position is set with a standard crystal and which permits direct reading of the desired angles. At the end of the goniometer arm is the knob D for fine adjustment with scale in minutes. In front is the milliammeter mA which indicates the intensity by reading the average current flowing through the counter tube. (The arrangement in this case is the mirror image of that in fig. 4.)

Recently, a number of refinements have been incorporated in the instrument that markedly increase the precision. The width of the diffraction spot and hence the accuracy of the angle measurement, in case of a nearly perfect crystal such as quartz, depends on the width of the source slit $S_1$ (fig. 4) and the divergence of the X-ray beam falling on the crystal surface. In the instrument described above the slit-width was 0.39 mm and the divergence 0.9°. In the improved arrangement an X-ray tube with a smaller focal spot is used so that it can assume the function of the source slit. This focal spot is 3 mm wide and the beam is obtained at an angle of $1/4^\circ$ with the anode surface, the projected width thus being 0.04 mm. The divergence is limited to less than 1°.

These changes make it possible to measure angles accurately to within 0.002° to 0.003°, i.e. about 10 seconds. In order to enable the angles to be read with such a precision, the minute scale has been provided with a vernier.

This great accuracy is not necessary for the production of quartz plates. However, it affords the possibility of using the instrument for studying the degree of perfection of crystalline surfaces, say the effect of lapping a crystal plate, and for similar problems.

Performance of the measurements

In article I it was shown that the desired low-temperature coefficient cut in a quartz block was not obtained in a single operation but in several
steps. We shall briefly review the way in which the angle measurement with X-ray diffraction enters into the procedure, using the X-block method as an example.

**Fig. 9.** a) Cutting a Y-Z-plane from a raw quartz crystal to make an X-block. A prism face (XZ-plane) of the crystal lies on the saw table, thus an X-axis is horizontal. The Z-axis must be orientated so that it is parallel to the saw blade. An inaccuracy in this orientation leads to a deviation \(XX'\) of the oscillator-plates to be cut out of the block.

b) The AT and BT plates are sawn out of the X-block perpendicular to the Y-Z plane which lies in the plane of the drawing. The horizontal Z-axis must be orientated at the prescribed angle to the saw blade. Any inaccuracy in this angle causes deviations of the angle \(ZZ'\) of the oscillator plates.

In the X-block method a plane which should be perpendicular to an X-axis (YZ-plane) is first cut off the quartz crystal. One of the prism faces of the crystal (XZ-plane) is laid on the horizontal saw table (so that an X-axis is horizontal) and a segment is sawn off as nearly as possible parallel to the Z-axis, see fig. 9a. A deviation of parallelism to Z entails a deviation of the normal of the cut surface from the X-axis in the horizontal plane and is found later as angle \(XX'\) in all the blanks obtained from this X-block. It is thus necessary even at this stage to measure the cutting direction accurately and to correct according to the results of the measurement.

The cut YZ-plane of the quartz block is then laid on the saw table (X-axis vertical), which is rotated through an angle read from the degree scale on the table until the saw blade makes the desired angle with the horizontal Z-axis of the quartz block; see fig. 9b. The inaccuracy of this angle setting, when the block is cut into parallel wafers, would occur in all the blanks as an error in the angle \(ZZ'\). Therefore in this step a test wafer must also be cut, the angle in question measured and the saw should be corrected if necessary.

**Checking a YZ-plane.**

The YZ-plane which is first cut in the X-block method itself a lattice plane of the crystal, namely the 1120-plane; see fig. 10. The measurement is in this case relatively simple. The counter tube is set at the Bragg angle on the goniometer scale \(2\theta = 36^\circ 34'\) for this reference plane. When reflection occurs (more precisely: when maximum reflection occurs), the reflecting 1120-plane will be oriented so as to intersect the goniometer scale at the point \(\theta = 18^\circ 17'\), whatever may be the orientation of the actual cut we have made. If the surface was cut exactly parallel to a 1120-plane the goniometer arm which bears the specimen holder will be found at the angle \(\alpha = \theta\) and it will be independent of any rotation of the cut crystal segment in the holder (with the cut surface always against the vertical reference surface). If the cut plane deviates by a small angle \(\epsilon\) from the 1120-plane, an angle \(\alpha\) is found which is not in general equal to \(\theta\) (deviation \(\Delta \alpha\)) and which more-

**Fig. 10.** Position of the 1010, 1120, and 0003-planes in a quartz crystal: these lattice planes are identical, respectively, with an X-Z plane (prism face), Y-Z plane and X-Y-plane. In the cross-section dotted lines show the direction of incidence and emergence of X-rays upon reflection for each set of lattice planes.
over varies upon turning the crystal in the holder. In turning the crystal the normal of the reflecting 1120-plane describes a cone of half apex angle $\varepsilon$ about the horizontally directed normal to the cutting plane (reference surface). For the highest and lowest positions of the normal, $\Delta a$ equals 0 (unless $\varepsilon$ is so large that in these positions no reflected intensity at all is observed in the goniometer plane and hence measurement is impossible); for the extreme right- and left-hand horizontal positions of the normal (thus where the 1120-plane of reference is vertical), $\Delta a = +\varepsilon$ and $-\varepsilon$ respectively (fig. 11).

Fig. 11. X-ray reflection is observed when the lattice plane of reference is in the position $\Theta$. This corresponds to a position $\alpha$ of the cut surface of the crystal segment (reference surface of the crystal holder), if the cut surface does not coincide with the lattice plane. The deviation $\Delta a$, by which $\alpha$ differs from $\Theta$, varies when the crystal is rotated in the holder; the maximum value of $\Delta a$, which is found in two opposite positions of the crystal, equals the correction $\varepsilon$ of the cutting angle required under the saw to make the cut coincide with the lattice plane.

From the above it will be clear that the angle $\Delta a$, which is read off the scale, is equal to the required horizontal correction angle under the saw only when the test cut is placed in the specimen holder in the same orientation it had on the saw table. This is most easily accomplished by drawing a vertical arrow pointed up on the outer surface of the test cut before removing it from the saw table. The test cut is placed in the specimen holder with the fresh cut surface toward the X-ray beam and the arrow again vertical and pointed up. It is then easy also to correlate the direction of the correction: if the goniometer arm must be rotated clockwise from the position $\Theta$ in order to bring the 1120 reference plane of the test cut into a reflecting position, the crystal on the saw table must also be rotated clockwise in order to make the 1120-plane parallel to the saw block.

It is easy to verify that the correlation thus expressed is valid for the right-hand as well as for the left-hand goniometer in fig. 8, the two scales of which are mirror images of each other.

If in cutting a crystal for making an X-block the saw blade was not exactly perpendicular to the saw table, the normal of the cut surface will deviate from the X-axis in the vertical plane. This vertical deviation can be measured in exactly the same way as above, with the only difference that the arrow painted vertically on the test cut must be placed in a horizontal position. Correlation of the direction of the measured deviation and the required correction is simple also in this case, provided care is taken to note if the test cut was made from the right or left side of the crystal.

Such simple correlation rules, which apply to all types of test cuts, are of great importance for mass production, where the saws and X-ray machines are operated by relatively unskilled persons.

**Checking AT and BT cuts**

In the previous section the desired cutting plane coincided with a lattice plane, but in checking the low temperature coefficient cuts proper this is not the case. In checking the $Z'Z'$ angle of an AT or BT test cut from an X-block therefore a choice must first be made of the lattice plane to be used as plane of reference.

For AT test cuts the 0111-plane (minor rhombohedron face) is chosen as plane of reference. This plane, like the AT cut and most other low-temperature coefficient cuts, is perpendicular to the YZ-plane (see fig. 12), and makes an angle of $+38^\circ 13'$ with the Z-axis. The ideal AT cut, with $Z'Z' = +35^\circ 15'$, thus deviates by the angle $\gamma = -2^\circ 58'$ from the plane of reference. The fact that this deviation

![Fig. 12. Position in the quartz crystal of a number of lattice planes all of which are perpendicular to a YZ-plane. The 1011-plane is the major rhombohedron face, the 0111-plane the minor rhombohedron face. The latter is suitable as lattice plane of reference for AT cuts. For BT cuts the 2023-plane is usually used for reference, since it is almost parallel to the BT cut.](image)
is so small is very important for the practical measurements, as will be seen below. The chief advantages are that even fairly large errors in the cutting plane become accessible to measurement and the accuracy with which the correction can be determined is high.

Imagine the test cut turned in all directions in the crystal holder, as in the previous section, with the cut surface always against the reference surface and with the counter tube fixed in the $2\theta$ position corresponding to the reflection of the chosen lattice plane of reference. The normal to this reflecting plane again describes a cone but now with a half apex angle $|\gamma - \varepsilon|$, where $\varepsilon$ is the error in $ZZ'$ of the test cut. The position $\alpha$ of the goniometer arm necessary for maximum reflection then varies around the theoretical angle $\Theta$ to an amount between the maximum values $+|\gamma - \varepsilon|$ and $-|\gamma - \varepsilon|$. In order to measure the correct value of $|\gamma - \varepsilon|$, an arrow must be used again to preserve the orientation of the test wafer in transferring it from the saw table to the specimen holder of the X-ray machine. On placing the arrow point in the same direction in the holder as under the saw, the simple correlation rule for the direction of the required correction may also be applied 3). Since, however, the half apex angle $|\gamma - \varepsilon|$ of the cone may be much larger (nearly equal to $\gamma$ in the case of small $\varepsilon$) than that with which we were concerned in the previous section, small inaccuracies in the position of the arrow when measuring have greater consequences and may cause appreciable errors in the derived correction, errors increasing as $\gamma$ becomes larger. Moreover, if $\gamma$ is large, the normal to the lattice plane of reference may deviate so far from the horizontal plane when the arrow is slightly oblique that no reflection is observed in the horizontal goniometer plane and thus no measurement can be made.

From this it follows that it is important to have a small $\gamma$, and thus to choose a lattice plane of reference that is as nearly as possible parallel to the cut being checked. For BT cuts, the 2023-plane is excellently suited, as this has an angle $ZZ' = -49^\circ 44'$; thus $\gamma$ is only $0^\circ 24'$. Some other lattice planes of reference used for different types of cuts are indicated in Table I.

Primarily, the X-ray measurement described above gives only the angle $|\gamma - \varepsilon|$, indicating the amount and, by the correlation rule, the direction of the correction $\Delta\alpha$ that would be necessary under the saw to make the test cut coincide with the lattice plane of reference. Now, in order to be able to make the test cut coincide with the ideal AT cut, we must calculate the angle $\varepsilon$. This is not possible unambiguously from the data obtained: although the value of the angle $\gamma$ between lattice plane and AT cut is known ($\gamma = -2^\circ 58'$ in our case), we do not know whether $\gamma$ should be added to or subtracted from $\Delta\alpha$, as the measurement cannot reveal whether $\varepsilon > \gamma$ or $\gamma < \varepsilon$. This difficulty, which is illustrated by fig. 13 a, b, does not present itself in the case that $\gamma$ is rather large (lattice plane of reference far from parallelism to AT and to test cut), as in that case there will be no doubt that the orientation error $\varepsilon$ is smaller than $\gamma$. If, however, for the sake of precision as explained above, $\gamma$ is chosen rather small, the ambiguity can be solved only by repeating the measurement of the test cut (in a rough way) using another

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* Based upon CuKα = 1.5418 Å. Calculated from the dimensions $a = 4.9131$ Å and $c = 5.4046$ Å of the unit cell of the quartz crystal, at $18.0^\circ$ C (measurements by A. J. C. Wilson and H. Lipson, Proc. Phys. Soc. 53, 245-250, 1941).

Table I. Crystallographic and X-ray data for checking various cuts.

<table>
<thead>
<tr>
<th>Name of cut</th>
<th>ZZ' of cut</th>
<th>Reference lattice plane</th>
<th>ZZ' of reference lattice plane</th>
<th>Angle γ</th>
<th>Counter tube setting (2θ) for CuKα *)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XZ-plane</td>
<td>0°</td>
<td>1010</td>
<td>0°</td>
<td>0°</td>
<td>20° 52'</td>
</tr>
<tr>
<td>YZ-plane</td>
<td>0°</td>
<td>1120</td>
<td>0°</td>
<td>0°</td>
<td>36° 34'</td>
</tr>
<tr>
<td>AT</td>
<td>+35°15'</td>
<td>0111</td>
<td>+38°13'</td>
<td>-2°58'</td>
<td>26° 39'</td>
</tr>
<tr>
<td>BT</td>
<td>-49°20'</td>
<td>1011</td>
<td>-38°13'</td>
<td>-11°07'</td>
<td>26° 39'</td>
</tr>
<tr>
<td>BT</td>
<td>-49°20'</td>
<td>2023</td>
<td>-49°44'</td>
<td>+0°24'</td>
<td>68° 12'</td>
</tr>
<tr>
<td>CT</td>
<td>+38°9'</td>
<td>0111</td>
<td>+38°13'</td>
<td>-0°13'</td>
<td>26° 39'</td>
</tr>
<tr>
<td>DT</td>
<td>-51°58'</td>
<td>2023</td>
<td>-49°44'</td>
<td>-2°14'</td>
<td>68° 12'</td>
</tr>
<tr>
<td>GT</td>
<td>+51°08'</td>
<td>0223</td>
<td>+49°44'</td>
<td>+1°24'</td>
<td>68° 12'</td>
</tr>
</tbody>
</table>

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*) This is the reason for determining on the test wafer—the line of the X-axis, which is vertical in the process of cutting, and the direction of the Z-axis, indicating the latter by an arrowhead, as was mentioned in article I. The line of the X-axis is made to stand vertically in the crystal holder, while the Z-arrowhead pointing to the right or to the left gives the correct direction. (The separate blanks are marked in the same way and may be similarly measured to make certain that the blanks to be lapped have an orientation within the desired tolerances.)
The X-ray measurement gives the value and direction of the correction angle \(\Delta \alpha = |\gamma - \varepsilon|\) that is required to make a test cut coincide with the lattice plane of reference. In order to find the correction \(\varepsilon\) necessary for obtaining the desired AT cut, it must moreover be known whether \(\gamma > \varepsilon\) or \(\gamma < \varepsilon\), which is not revealed by the X-ray measurement.

lattice plane of reference, for instance the \(02\overline{2}3\)-plane \((\gamma' = 35^\circ 15' - 49^\circ 44' = -14^\circ 29')\), the two conditions \(\varepsilon = \Delta \alpha \pm \gamma'\) and \(\varepsilon = \Delta \alpha' \pm \gamma'\) together leaving only one possible value for \(\varepsilon\).

There are various other procedures possible with this equipment which are adaptable to the particular method of cutting (the previously discussed “strategy” of the cutting). For example in cases where it is desired to have a surface either parallel to or making some small angle with a chosen lattice plane, and the degree of precision required is beyond the accuracy easily attainable with the saw, the following method has proven useful. The crystal mounted in a special jig which is adjustable in two mutually perpendicular planes is placed in the X-ray beam and by manipulation of the setting screws of the jig it is tilted until the desired reflection occurs. The crystal is then correctly oriented with respect to the reference edges of the jig. The latter is then transferred to a lapping machine and the crystal surface ground to the orientation set by the X-ray machine. This procedure was used for wafering before accurate sawing methods were introduced. It is apparent that, if large numbers of wafers were cut in this manner, the method would waste a large amount of quartz, because thicker cuts are required than in direct sawing.

The method of measuring crystallographic angles by X-ray diffraction has also assumed some importance in other fields. With some modification it may be applied in the orientation of diamonds for wire drawing; and of sapphire needles used in gramophone pick-ups, in the cutting of barium titanate crystals, etc.  


Summary. After an introductory discussion of the tolerances in the manufacture of quartz oscillator-plates, the X-ray diffraction apparatus is described which was constructed by the North American Philips Co., Inc. during the war to make possible a rapid and accurate check of the crystallographic angles of test cuts. A Geiger counter tube is used in this apparatus to detect the reflected X-ray beam. After placing the counter tube in the position \(2\theta\) (\(\theta = B r a g g\) angle) on a goniometer scale, the holder in which the test piece, test wafer or blank to be examined is clamped is turned until reflection occurs. The reflecting lattice plane is then oriented according to the angle \(\theta\) on the goniometer scale and from this the angles between this lattice plane and the reference surface of the crystal holder (cutting plane of the test cut) can be derived. The execution of the measurements, in particular the choice of a suitable lattice plane of reference is explained by means of several examples: checking the \(YZ\)-cut in making an \(X\)-block and checking \(AT\) and \(BT\) cuts.
When a small piece of zinc is burnt in a flame a white cloud of zinc-oxide is seen to rise, from which flakes up to a few mm in size are precipitated. A very minute flake collected along the edge of a specimen plate shows under the electron microscope a picture of small crystals with a large number of needle-like spurs loosely intertwined. Photograph taken with the Philips 100 kV electron microscope with a magnification of about 32,000 times.