PROCEEDINGS
OF THE
32nd ANNUAL SYMPOSIUM ON FREQUENCY CONTROL

1978

② PROCEEDINGS

of the

THIRTY SECOND ANNUAL FREQUENCY CONTROL SYMPOSIUM

1978

Sponsored by

① U.S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT COMMAND
Major General Charles D. Daniel, Jr.
Commanding

ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY
Dr. C. G. Thornton
Director

Printed in U.S.A.

Copies of the Proceedings are available from:

Electronic Industries Association
2001 Eye Street, N.W.
Washington, D.C. 20006

PRICE PER COPY $10.00

31 MAY - 2 JUNE 1978

Howard Johnson's Regency Hotel
Atlantic City, New Jersey

THIRTY SECOND ANNUAL FREQUENCY CONTROL SYMPOSIUM

Sponsored By

U.S. ARMY ELECTRONICS RESEARCH AND DEVELOPMENT COMMAND
ELECTRONICS TECHNOLOGY AND DEVICES LABORATORY
Fort Monmouth, New Jersey

31 MAY - 2 JUNE 1978
Howard Johnson's Regency Hotel
Atlantic City, New Jersey

SYMPOSIUM EXECUTIVE COMMITTEE

Chairman	Dr. Erich Hafner
Executive Assistant	Dr. John Vig
Executive Secretary	Mrs. Lee Hildebrandt

TECHNICAL PROGRAM COMMITTEE

Dr. Erich Hafner-Chairman
U.S. Army Electronics Technology and Devices Laboratory

Mr. E. J. Alexander
Bell Laboratories

Dr. A. Ballato
U.S. Army ERADCOM

Dr. M. Bloch
Frequency Electronics, Inc.

Mr. A. R. Chi
NASA — Goddard Space Flight Center

Dr. L. T. Claiborne
Texas Instruments

Dr. L. S. Cutler
Hewlett-Packard

Mr. M. E. Frerking
Rockwell International

Mr. V. L. Friedrich
OFC, Asst Secy of the Army (R&D)

Dr. H. Hellwig
National Bureau of Standards

Mr. J. D. Holmbeck
Northern Engineering Laboratories

Dr. W. H. Horton
Piezo Technology, Inc.

Mr. E. Kentley
Hi-Q Quartz Products Limited

Mr. T. Kesolits
U.S. Army, CORADCOM

Dr. J. C. King
Sandia Laboratories

Mr. J. A. Kusters
Hewlett-Packard

Mr. T. Lukaszek
U.S. Army, ERADCOM

Dr. T. M. Reeder
United Technology Research Center

Mr. D. Reifel
Motorola, Inc.

Mr. L. J. Rueger
APL, Johns Hopkins University

Mr. S. S. Schodowski
U.S. Army, ERADCOM

Mr. J. H. Sherman, Jr.
General Electric Company

Prof. J. Vanier
Laval University

Dr. J. R. Vig
U.S. Army, ERADCOM

Dr. G. M. R. Winkler
U.S. Naval Observatory

Dr. N. F. Yannoni
U.S. Air Force, RADC

CHAIRMEN FOR TECHNICAL SESSIONS

FUNDAMENTAL PROPERTIES OF QUARTZ

Dr. J. deKlerk, Westinghouse R&D Center

SURFACE ACOUSTIC WAVE DEVICES PROPERTIES AND APPLICATIONS

Dr. L. T. Claiborne, Texas Instruments

RESONATOR THEORY

Dr. R. D. Mindlin, Professor Emeritus, Columbia University

SAW MATERIALS AND RESONATOR OBSERVATIONS
CRYSTAL FILTERS

Mr. T. R. Meeker, Bell Laboratories

RESONATOR DESIGN
RESONATOR PROCESSING

Mr. D. Reifel, Motorola

RESONATOR PROCESSING Continued
SPECIFICATION AND MEASUREMENT

Mr. W. Samuelson, Piezo Crystal Co., retired

FREQUENCY GENERATION
CRYSTAL OSCILLATORS

Dr. M. Bloch, Frequency Electronics, Inc.

ATOMIC AND MOLECULAR FREQUENCY STANDARDS
NEW CONCEPTS AND DEVICES

Dr. L. S. Cutler, Hewlett-Packard

THE PRECISION FREQUENCY STANDARD AS A SYSTEM
A & M DEVICES - APPLICATION AND EVALUATION

Dr. H. Hellwig, National Bureau of Standards

BANQUET SPEAKER

Mr. James Randi
Member Inner Magic Circle, London
51 Lennox Avenue
Rumson, N.J. 07760

SPECIFICATIONS AND STANDARDS GERMANE TO FREQUENCY CONTROL

Institute of Electrical and Electronic Engineers

Order through: Institute of Electrical and
Electronic Engineers
345 E. 47th Street
New York, New York 10017

176-1949 Piezoelectric Crystals, Terminology for (ANSI C83.3-1951) (Reaff 1971) $ 4.00

177-1966 Piezoelectric Vibrators, Definitions and Methods of Measurement for (ANSI C83.17-1970) $ 4.00

178-1959 Piezoelectric Crystals, Determination of the Elastic, Piezoelectric, and Dielectric Constants of, also, the Electromechanical Coupling Factor (ANSI C83.23-1960) $ 3.50

179-1961 Piezoelectric Ceramics, Methods of Measurement of (ANSI C83.24-1962) (Reaff 1971) $ 3.50

180-1962 Ferroelectric Crystal Terms, Definitions of $ 3.00

319-1971 Piezomagnetic Nomenclature $ 4.00

Electronic Industries Association

Order through: Electronic Industries Assn.
2001 Eye Street, N. W.
Washington, D.C. 20006

(a) Holders and Sockets

RS-192-A, Holder Outlines and Pin Connections for Quartz Crystal Units. (Standard Dimensions for older types.) $ 5.00

RS-367, Dimensional and Electrical Characteristics Defining Receiver Type Sockets. (Including crystal sockets.) $15.00

RS-417, Crystal Outlines (Standard dimensions and pin connections for current quartz crystal units - 1974) $ 5.80

(b) Production Tests

RS-186-D, Standard Test Methods for Electronic Component Parts $ 5.20

(c) Application Information

Components Bulletin #6, Guide for the Use of Quartz Crystal Units for Frequency Control $ 3.60

International Electrotechnical Commission

Order through: American National Standards
Institute
1430 Broadway
New York, New York 10018

IEC Publication 122-1 (1962) Quartz Crystal Units for Oscillators
Section 1, Standard Values and Conditions.
Section 2, Test Conditions
including Amendments 1, 2 and 3 $16.20
Amendment 1 (1967) $ 1.40
Amendment 2 (1969) $ 1.00
Amendment 3 (1971) $ 1.80

IEC Publication 122-2 (1962) Section 3, Guide in the Use of Quartz Oscillator Crystals, including Amendment 1 $15.40
Amendment 1 (1969) $ 1.40

IEC Publication 122-3 (1962) Section 4, Standard Outlines, including Supplements 122-3A, 122-3B and 122-3C $23.60

IEC Publication 283 (1968) Methods for the Measurement of Frequency and Equivalent Resistance of Unwanted Resonances of Filter Crystal Unit $ 6.00

IEC Publication 302 (1969) Standard Definitions and Methods of Measurement for Piezoelectric Vibrators Operating Over the Frequency Range up to 30 MHz $10.80

IEC Publication 314 (1970) Temperature Control Devices for Quartz Crystal Units, including Supplement 314A $25.00
Contents. General Characteristics & Standards;
Test Conditions; Pin Connections

IEC Publication 314A (1971) First Supplement to Publication 314 (1970) $12.60
Contents. Guide to the Use of Temperature Control Devices for Quartz Crystal Units.

IEC Publication 368 (1971) Piezoelectric Filters, including Amendment 1 and Supplement 368A and 368B $45.80
Contents. General Information & Standard Values; Test Conditions

IEC Publication 368A (1973) Supplement to Publication 368 (1971) $17.40
Contents. Guide to the Use of Piezoelectric Filters

IEC Publication 368B (1975) Second Supplement to Publication 368 (1971) $16.00
Contents. Piezoelectric Ceramic Filters

IEC Publication 444 (1973) Basic Method for the Measurement of Resonance Frequency and Equivalent Series Resistance of Quartz Crystal Units by Zero Phase Technique in a π - Network $13.80

IEC Publication 483 (1976) Guide to Dynamic Measurements of Piezoelectric Ceramics with High Electromechanical Coupling

Department of Defense

Order through: Naval Publication & Form Center
5801 Tabor Avenue
Philadelphia, PA 19120

MIL-C-3098 Crystal Unit, Quartz, General Specification For

MIL-H-10056 Holders (Enclosures), Crystal, General Specification For

MIL-STD-683 Crystal Units, Quartz; And Holders, Crystal

MIL-C-39020 Crystal Units, Quartz Established Reliability, General Specification For

MIL-F-28734 Frequency Standards, Cesium Beam, General Specifications For

MIL-0-55310 Oscillators, Crystal, General Specification For

MIL-F-18327 Filters, High Pass, Low Pass, Band Pass Suppression and Dual Functioning, General Specification For

MIL-0-39021 Oven, Crystal, General Specification For

Table of Contents

Fundamental Properties of Quartz

Page No.

Surface Acoustic Wave Devices, Properties and Applications

Resonator Theory

SAW Materials and Resonator Observations

Crystal Filters

Resonator Design

Resonator Processing

Page No.

Resonator Processing Continued

Specification and Measurement

Frequency Generation

Crystal Oscillators

Atomic and Molecular Frequency Standards - New Concepts and Devices

The Precision Frequency Standard as a System

A & M Devices - Application and Evaluation

THE CHARACTERIZATION OF SYNTHETIC QUARTZ BY USING INFRA-RED ABSORPTION

J.C. Brice and A.M. Cole

Philips Research Laboratories,
Redhill, Surrey, RH1 5HA, England

Summary

Samples of quartz obtained over several years from 12 suppliers have been examined. Hydrogen is found to be the major impurity. Infra-red measurements show that there are linear relations between the absorption due to hydrogen at 3585, 3500, 3410, 3300 and 3200 cm^{-1}. A consideration of the intrinsic and practical problems of using each of these absorptions suggests that it is advantageous to use the absorption at 3410 cm^{-1} and a simple reciprocal relation between Q and the appropriately corrected extinction coefficient is suggested.

Measurements of infra-red Q at various positions in a crystal show that significant changes only occur in general due to changing the position of the measured sample in the Z direction. These changes become large as the average Q falls. Similarly comparing the mean Q's of crystals from one batch shows that deviations from the batch mean increase as the batch mean falls. It is also shown that there is an inverse correlation between dislocation density and Q.

Introduction

The electromechanical Q of a quartz crystal is a useful guide to its suitability for various applications. Because high Q material must be grown slowly [1-4], it is expensive and should not be used unnecessarily. Direct measurements of Q are difficult to make. Thus a simple indirect method of measurement is needed. Dodd and Fraser [5] showed that there is a good correlation between electromechanical Q and infra-red absorption and this method is now used by most workers in the field. Sawyer [6] showed that the relation took the form

$$Q^{-1} = Q_o^{-1} + A\alpha + B\alpha^2 \qquad (1)$$

where α is the extinction coefficient. Strictly, α is defined so that the fractional intensity of light transmitted through a parallel sided sample of thickness t is

$$T = \frac{(1 - R)^2 \, 10^{-\alpha t}}{1 - R^2 \, 10^{-2\alpha t}} \qquad (2)$$

where R is the reflection coefficient of the sample surfaces and the denominator allows for the effect of multiple internal reflections. For quartz in the near infra-red, R is about 4% so that the term $R^2 \, 10^{-2\alpha t}$ has a maximum value of less than 2×10^{-3} and can be neglected. However a reliable estimate of α still required measurements to be made on samples with different thicknesses. This was done by Lias et al [2] but other workers [6-10] compare measurements at two wave numbers, one of which is chosen to have negligible absorption but essentially the same reflection coefficient as the frequency of interest. Then

$$\alpha = \left[\log_{10} (T_{ref}/T_\nu) \right] / t \qquad (3)$$

where T_{ref} is the transmitted intensity at the reference wave number (usually 3800 or 3900 cm^{-1}) and T_ν is the transmission at the wavenumber of interest. Table 1 summarizes the data in the literature in terms of coefficients in equation (1). Lias et al [3] give data which relates α and hydroxyl content. At 3500 cm^{-1} they find that $\alpha = 1$ cm^{-1} corresponds to 4800 ppm H measured relative to silicon. Sawyer [6] suggests a figure of 6000 ppm $(cm^{-1})^{-1}$.

This paper compares results obtained at the various wavenumbers sensitive to the presence of OH and shows that there are significant effects due to finite absorption independent of the hydroxyl content and that apparatus parameters (resolving power and polarization) can appreciably alter the results obtained. From the results obtained it is also shown that the variations of Q within a crystal and between crystals in a batch both increase as Q falls and that there seems to be an inverse correlation between Q and dislocation density.

Experimental

Samples were cut from crystals with Y-bar or Y-plate seeds obtained over a six year period from 12 suppliers (3 in the USA, 4 in Europe, 2 in Japan and one each in Russia, China and South America). From each supplier we obtained as many grades of material as possible. Thus the samples should be a representative selection of materials grown from various raw materials with a reasonable range of growth parameters. Table 2 gives the impurity contents found and shows that hydrogen is always the major impurity on an atomic basis. The only other significant trends observed were that high Q crystals tended to have less of all the impurities than low Q crystals (the upper quartile data are typical of crystals with a Q of about 1×10^6 and the lower quartile figures are typical of samples with a Q of 2×10^6). Note also the effect of mineralizer on carbon content.

The samples for infra-red measurements were usually plates with faces including the X and Z axes and the radiation was propagated parallel to Y. The samples were polished usually finishing with Syton but for some samples we used cerirouge. If these samples were repolished on Syton, no significant differences were seen optically but double crystal reflection topographs showed that the cerirouge finish left some surface strains.

The measurements were made at room temperature (20 ± 5°C) generally using a Perkin-Elmer 337 double beam spectrometer. The beam size was stopped down to 5mm diameter. Because of the use of a reflecting optical system the radiation was polarized so that about 70% of the electric vector lay in a horizontal plane. We measured the crystals with the optic axis horizontal and vertical and deduced values of respectively α_{11} and $\alpha_{\perp}$ as discussed later. The symbol α is used to imply the mean of these measurements. Similarly T implies the mean of the two transmitted intensities. Comparing our results with those obtained on the same samples with 3 other spectrometers showed that in general the T values agreed to within ± 0.5% and results were reproducible to about 0.2%. Thus we believe that our measurements of the product αt (equation 3) are accurate to ± 0.005, i.e. for a 10mm thick sample we can measure α to $\pm$ 0.005 cm^{-1}. The only exception to this was the measurement of α_{3585}. For this parameter we found that the resolving power of the instrument was important. Other spectrometers with resolving powers of about 4 cm^{-1} like ours gave the same result but instruments with better resolving power ($<$ 1.5 cm^{-1}) gave values which were higher by 15% on average. Thus for this line instrument resolving power is important. Other workers find the same effect. Thus due to a change in resolving power the calibration curves given in references 9 and 10 differ by a factor 2.

We measured plates between 1 and 20 mm thick but discarded results on plates less than 7 mm thick except for measurements of absolute absorption. We also discarded measurements on crystals which reflection topographs showed to be highly strained. These crystals could have values of $\alpha_{11}:\alpha_{\perp}$ which were radically different from the average e.g. 2.

Attention was concentrated on the Z growth zone and only these results are discussed in the next section. Values of α in the +X zone were usually larger than in the Z zone. This would be expected from the greater segregation coefficients (see reference 11 for a discussion of this).

Results and Discussion

Figure 1 shows the general features of the transmission spectrum of a typical sample. The two curves are for the same area but the upper curve is $T_{\perp}$ and the lower curve is T_{11}. Kats [12] observed a similar sensitivity to polarization. His results taken at a temperature of 78K with 100% polarization show larger ratios than our data for about 300K with 70% polarization, see Table 3, which indicates that polarization effects can be significant.

Most workers use absorption at 3500 cm^{-1} as a measure of the quality of the crystals. Kats [12] has shown that much of the absorption in the near infra-red is due to hydrogen. Thus the lines at 3517, 3510 and 3485 are associated with hydrogen alone and the lines at 3513, 3510 and 3500 are associated with hydrogen and Na, Li and Ag respectively. Figure 1 shows that the absorption changes rapidly with wavenumber in this region. Typically a 1 cm^{-1} change in wave number changes α by 1%. Few spectrometers are reproducibly accurate to more than a few cm^{-1} so that errors of a few per cent can occur from using this absorption. A self locating line is therefore desirable but as was shown in the last section the line at 3585 cm^{-1} is so narrow that the result obtained depends to a large extent on the instrument resolving power. Kats [12] shows that this line is associated with H alone or H + K. The absorptions at 3410, 3300 and 3200 cm^{-1} are similarly associated with hydrogen with possible components due to hydrogen plus Na, Ag, Li and Cu. Kats [12] shows that there are lattice absorptions at 3396, 3300, 3220 and 3204 cm^{-1} and the half widths of these absorptions are typically 20 cm^{-1} so that a combined H and lattice effect is likely to be seen. However the lines at 3410, 3300 and 3200 cm^{-1} are easily located and the line at 3410 is very broad and therefore easy to locate and measure with any spectrometer.

Figure 2 gives data comparing α_{3410} with α_{3500} which from the published data [2, 13] seems to be linearly proportional to hydroxyl content. (The value of α_{3585} is similarly linearly related to hydroxyl content [13]). The average data spread on Figure 2 is ± 7% about the line

$$\alpha_{3410} = 0.050 + 1.25\alpha_{3500} \qquad (4).$$

This data spread is expected on the basis of experimental errors. Similarly we find that with spreads of ± 8% the other relative extinction coefficients (equation 3) can be given by

$$\alpha_{3300} = 0.125 + 0.80\alpha_{3500} \qquad (5)$$

and

$$\alpha_{3200} = 0.110 + 0.60\alpha_{3500} \qquad (6).$$

Our measurements of $\alpha_{3585}:\alpha_{3500}$ show that the average value is 1.03 ± 0.08. It is possible that the ratio is slightly dependent on α. We find a ratio of 0.97 ± 0.05 for $\alpha < 0.1$ cm^{-1} and 1.07 ± 0.05 for $\alpha > 0.1$ cm^{-1}. These differences are probably due to the resolving power effect already discussed. The uncertainties quoted in all these instances are spreads of the data points. Uncertainties in the mean values are much less.

In general our data show that for unstrained samples there is little variation in the transmission of any sample in the range 4000 to 3760 cm^{-1}. (Badly strained samples show reproducible variations in this range.) However we did observe that the values of T varied with thickness from about 83 to 94%. Figure 3 plots the average values as a function of sample thickness. The slope of the line on this figure suggests an intrinsic extinction coefficient of 0.025 ± 0.002 cm^{-1} in this range. Kats [12] suggests that there may be lattice absorptions. If this is the case then the relative extinction coefficients (equation 3) will be smaller than the absolute ones (equation 2) and to convert from relative to absolute we must add 0.025 cm^{-1}. If this is done, equations (4) to (6) become

$$\alpha_{3410} = 0.044 + 1.25\alpha_{3500} \qquad (7)$$

$$\alpha_{3300} = 0.130 + 0.80\alpha_{3500} \qquad (8)$$

and $$\alpha_{3200} = 0.120 + 0.60\alpha_{3500} \qquad (9)$$

Thus the intrinsic lattice absorptions at these frequencies correspond to absolute extinction coefficients of 0.044, 0.120 and 0.110 cm^{-1}. To obtain the hydroxyl related extinction coefficient from a relative one we must allow both for these absorptions and the intrinsic absorption at the reference frequency. Thus we add 0.025 cm^{-1} at 3500 and 3585 cm^{-1} and subtract 0.019, 0.105 and 0.095 cm^{-1} at 3410, 3300 and 3200 cm^{-1} respectively. Values treated in this way are denoted by α^*.

Figure 4 shows a plot of Q against α^* using the published data. It can be seen that for 3500 cm^{-1} the data are well represented by

$$Q = C \times 10^5/\alpha^*_{3500} \qquad (10)$$

where C = 1.35. The spread is that expected from experimental errors. The Toyo data for 3585 cm^{-1} seem to be well represented by the same equation but from our measurements we expect $C_{3585} = 1.39$ or for a spectrometer with a resolving power of better than 1.5 cm^{-1}, C_{3585} should be 1.60. Similarly at the other wavenumbers we can derive values of C from equations (7) to (9) which are $C_{3410} = 1.69$, $C_{3300} = 1.08$ and $C_{3200} = 0.81$. In practice only the absorption at 3410 cm^{-1} offers any appreciable advantage and we recommend the use of this line and the relation

$$= 1.69 \times 10^5/\alpha^*_{3410} \qquad (11)$$

There seems little doubt that a relation like (10) or (11) can be used with at least the same degree of confidence as any of the relations given in Table 1.

Now that we have a measurement technique, there is still a sampling problem: one measurement of Q does not characterize a crystal and measurements on one crystal do not characterize a batch grown in the same autoclave at the same time. Looking first at the variations in one crystal, we find that moving the beam in the X direction does not change α significantly unless there is a subboundary (Figure 5) and such regions give large polarization effects: $\alpha_{11}:\alpha_{\perp}$ ratios of 1.5 or even 2. Similarly, if we measure another slice from the same crystal and make our measurement at the same distance from the seed, the changes are barely significant 15% for a Q of 1.0 x 10^6, 10% for a Q of 1.5 x 10^6 and perhaps 5% for a Q of 2.5 x 10^6. However when the beam is moved parallel to the Z axis large changes occur. Figure 6 shows the average change $\overline{\Delta\alpha^*}$ obtained by moving a 5mm diameter beam in the Z direction by 5mm. The value of α decreases by an amount $\overline{\Delta\alpha^*}$ on moving outwards. The figure gives the mean value of $\overline{\Delta\alpha^*}$ as a function of the average of the two measured values of α^*. For most purposes the values of $\overline{\Delta\alpha^*}$ and $\overline{\alpha^*}$ probably characterize the crystal adequately. If we now examine the variations within a batch of Q deduced from $\overline{\alpha^*}$ we find the relation shown on Figure 7. The values obtained for batches with the same mean Q are surprisingly constant. The standard error of the standard deviation is only about 20%. Thus we can use Figure 7 to deduce confidence limits based on measurements of a relatively small sample of crystals from one batch.

Because we had topographs of samples from crystals with known Q we could correlate dislocation densities with Q as shown on Figure 8. On this figure, open circles are median values and the filled circles and triangles represent respectively the maximum and minimum values found in batches of 8 to 12 samples. Thus it appears that a Q specification also fixes the likely range of dislocation densities. A relation between dislocation density and Q or α is reasonable on the model proposed by Griggs [14] who suggests that dislocations are surrounded by a cloud of hydroxyl ions and Ayensu and Ashbee [15] have proposed that dislocation movement requires OH ions. (Dislocation generation requires dislocation movement.)

Conclusions

This paper has shown that infra-red measurements can be used to characterize quartz. In order to obtain reasonable accuracy a relatively thick sample must be examined: for measurement of high Q's a sample 10mm or more thick must be used. Account must be taken of polarization effects and intrinsic absorptions but if these are treated correctly a simple reciprocal relation gives Q. It is specifically recommended that when comparable results are required from different instruments the absorption at 3410 cm^{-1} should be used. Absorption at this wave number has the following advantages:

(a) It shows the maximum sensitivity to hydroxyl concentration.

(b) The line is easily located.

(c) The line is broad so that no problems are experienced with resolution or instrument calibration.

(d) The correction needed to convert relative extinction to absolute extinction due to hydroxyl is the smallest of any line considered.

(e) The polarization effect is small.

It is also necessary to measure at more than one location relative to the seed. If all these factors are taken into account then a batch can be characterized by measurements on a relatively few specimens. The polarization effect can be used to detect strained crystals and it appears that a measurement of Q fixes the range of dislocation densities likely to be found.

Acknowledgements

The analytical data given in Table 2 was provided by Messrs. J.A. Roberts and J.B. Clegg. Mrs. R.S. Cosier and Ir. B. Oppedijk took the X-ray topographs used to determine strain and dislocation densities. Mr. J. Dowsett and Ir. D.J. Grevink provided most of the crystals on which measurements were performed.

References

1. C.S. Brown; "Internal Friction in Synthetic Quartz", Proc. Phys. Soc., Vol. 75, 1960 pp. 459-460.

2. N.C. Lias, E.E. Grudenski, E.D. Kolb and R.A. Laudise; "The Growth of High Acoustic Q Quartz at High Growth Rates", J. Crystal Growth, Vol. 18, 1973 pp. 1-6.

3. R.L. Barns, E.D. Kolb, R.A. Laudise, E.E. Simpson and K.M. Kroupa; "Production and Perfection of z-Face Quartz ", J. Crystal Growth, Vol. 34, 1976 pp.189-197.

4. D. Chakraborty; "Dependence of Mechanical Q on Growth Rate of Quartz Single Crystals", J. Crystal Growth, Vol. 41, 1977 pp. 177-180.

5. D.M. Dodd and D.B. Fraser; "Infra-red Studies of the Variation of H-Bonded OH in Synthetic α-Quartz", J. Phys. Chem. Solids, Vol. 26, 1965 pp. 673-686.

6. B. Sawyer; "Q Capability Indications from Infra-red Absorption Measurements for Na_2CO_3 Process Cultured Quartz", IEEE Trans SUS, Vol. SU-19, 1972 pp. 41-44.

7. D.B. Fraser, D.M. Dodd, D.W. Rudd and W.J. Carroll; "Using Infra-red to Find Mechanical Q of α-Quartz", Frequency, Vol. 4, 1966 pp. 18-21.

8. D.W. Rudd and E.E. Houghton; "Mechanical W of Alpha-Quartz Rapidly Evaluated", Western Electric Engineer, Vol. 10, 1966 pp. 22-29.

9. Toyo Technical Bulletin B-1; "Quality of Quartz Crystal Blanks for Pieco-electric Applications", October 1975.

10. Toyo Technical Paper No. 77-03; "Evaluation of Synthetic Quartz by Infra-red Absorption", May 1977.

11. J.C. Brice; "The Growth of Insulating Crystals", Rep. Prog. Phys. Vol. 40, 1977, pp. 567-602.

12. A. Kats; "Distribution of OH in Synthetic and Natural Quartz Crystals", Philips Res. Repts., Vol. 17, 1962 pp. 133-195 and 201-279.

13. D. Chakraborty and G. Lehmann; "Hydrogen in Alpha-Quartz", J. Solid State Chem., Vol. 17, 1976, pp. 305-311.

14. D. Griggs; "A Model of Hydrolytic Weakening in Quartz", J. Geophys. Res., Vol. 79, 1974, pp. 1653-1661.

15. A. Ayensu and K.H.G. Ashbee; "The Creep of Quartz Single Crystals", Phil. Mag., Vol. 36, 1977, pp. 713-723.

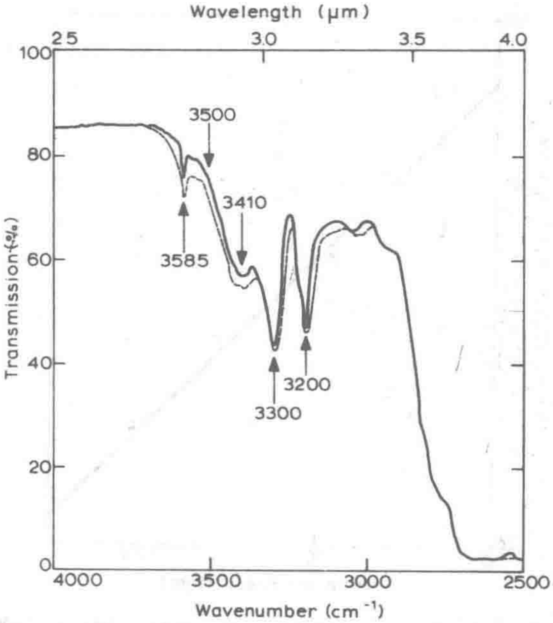

Figure 1. The transmission spectrum of a 20mm thick sample. The full line is obtained when the major part of the electric vector is parallel to Z. The broken line is the result obtained with the sample rotated 90° about Y.

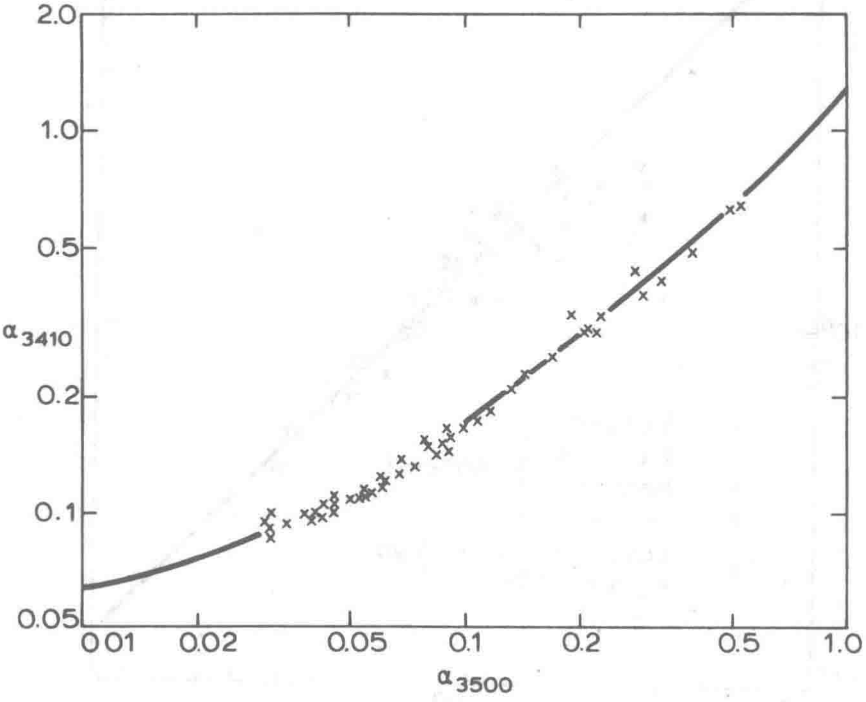

Figure 2. The comparison of α_{3410} with α_{3500}.

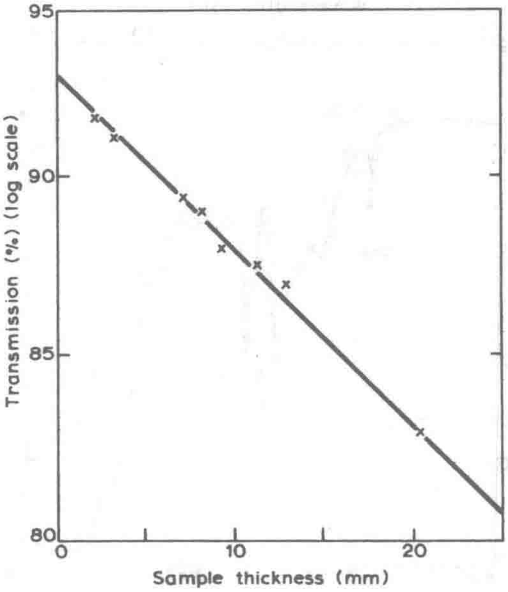

Figure 3. Average transmission in the range 3800 to 3900 cm^{-1} as a function of sample thickness.

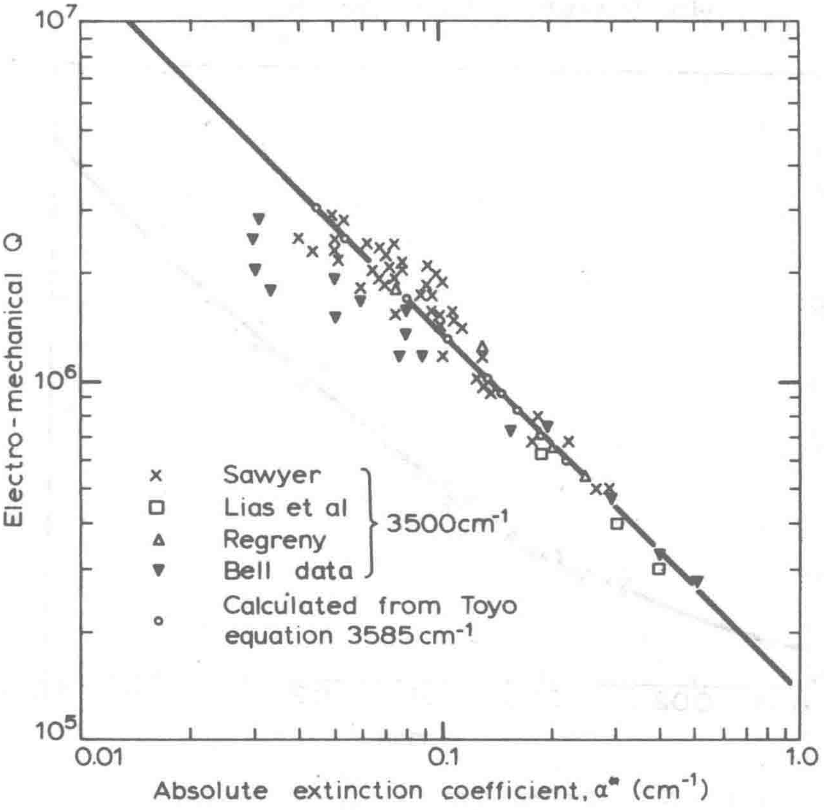

Figure 4. Published data on Q plotted as a function of α^*.

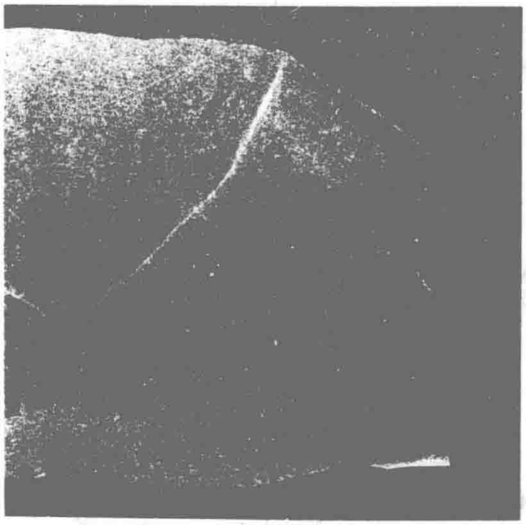

Figure 5. A double reflection X-ray topograph showing a "sub-boundary" in the Z zone.

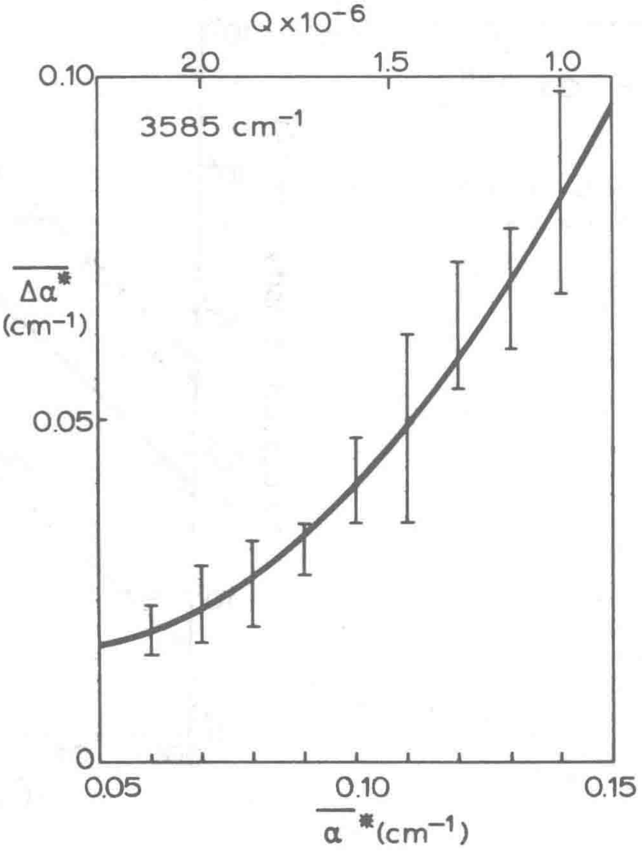

Figure 6. The change in α^* found on moving 5mm in the Z direction as a function of the mean value of α^*.

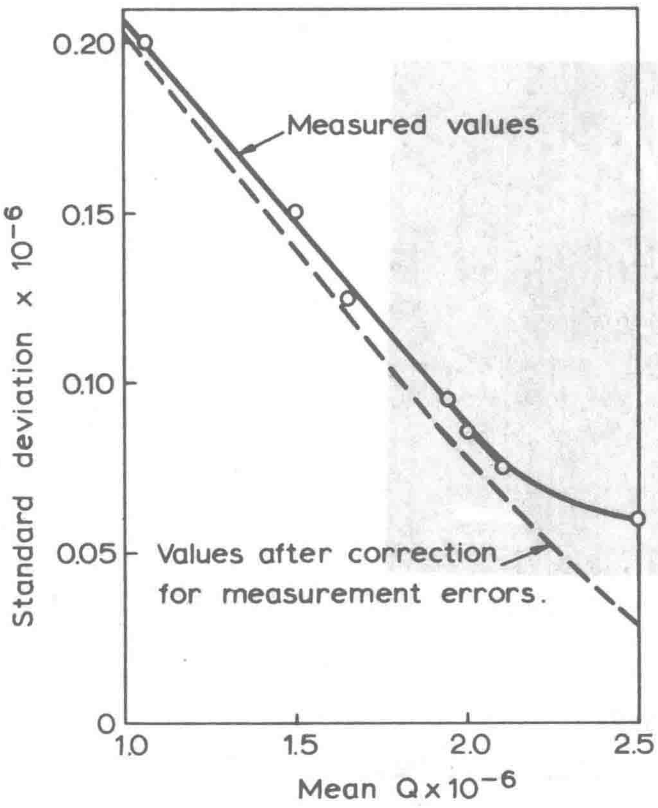

Figure 7. The standard deviation of Q in batches with different mean Q's.

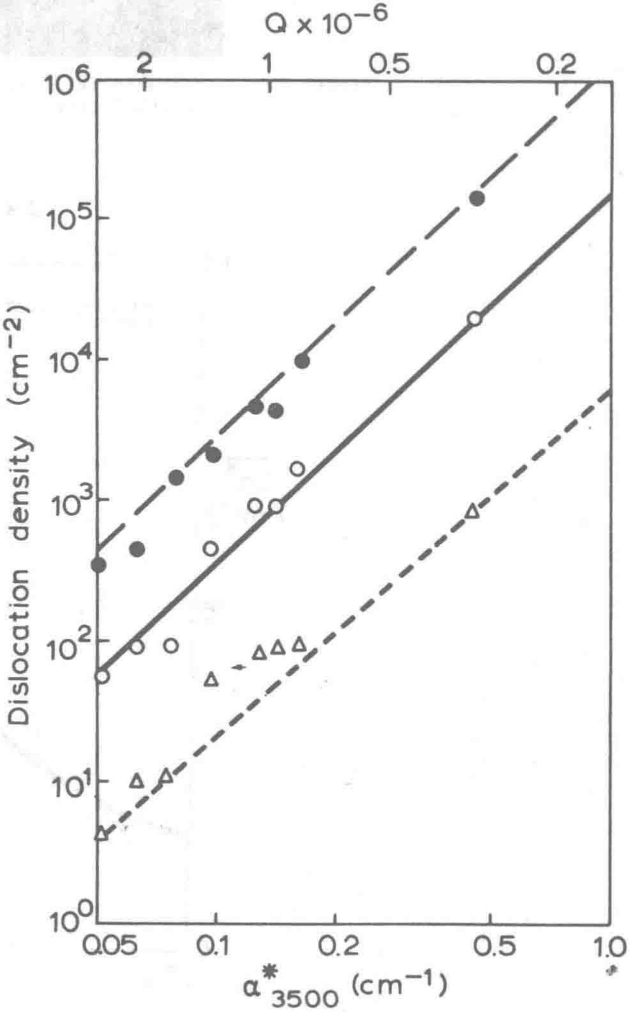

Figure 8. Dislocation density as a function of α^*. The full line is median values. The broken lines represent maximum and minimum observed values.