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THE EFFECT OF BONDING ON THE FREQUENCY VS. TEMPERATURE CHARACTERISTICS OF AT-CUT RESONATORS

Raymond L. Filler
John R. Vig

Electronics Technology & Devices Laboratory

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US ARMY ELECTRONICS COMMAND FORT MONMOUTH, NEW JERSEY 07703

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Although the frequency vs. temperature (f vs. t) characteristics of quartz resonators depend primarily on the angle of cut of the quartz plate with respect to the natural crystallographic axes, processing variables such as the stresses due to the mounting clips, bonding agents, and electrodes can also have important effects. For thin resonator plates, in particular, it has been found that the bonding technique employed can produce large rotations in the f vs. t characteristics. Changes in the f vs. t characteristics which correspond to shifts in apparent angle of several minutes have been observed. This paper discusses

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) experiments which have defined the effect of bonding on the apparent angle.

Nickel electrobonding was used throughout these experiments because this technique permits precise control of the bonded area, the thickness of the bonding film, and the intrinsic stress in the film. The experiments were performed on 6.4 mm (0.250 in.) diameter, 20 MHz AT-cut plates. The bonding areas were small (1 square mm) ovals placed along a blank diameter. The shift in apparent angle was measured as a function of the orientation of this diameter with respect to XX'. Downward shifts in apparent angles were observed when the bonding areas were oriented along the ZZ' direction; upward shifts were observed along the XX' direction. For a 50 μm (2 mils) thick bonding film, a change in bonding orientation from ZZ' to XX' produces an apparent angle shift of over 6 minutes.

The shifts in apparent angle were found to be a function of the shape, area and thickness of the bonding agent, and of the orientation of the bonding area with respect to the crystallographic axes of the plate. By carefully controlling the geometry and orientation of the bonding spots, the effect of bonding on resonator frequency can be minimized, or alternately, predictable shifts in apparent angle can be produced. Thus the bonding method can possibly serve as a convenient means of 'angle correcting'.

TABLE OF CONTENTS

Introduction

The frequency versus temperature (f vs. T) characteristic of a quartz resonator depends primarily on the angle of cut of the resonator blank. There are, however, secondary factors introduced during the processing which can also influence this characteristic. Among these are the stresses due to mounting, bonding and the electrodes.

Young, et al., have demonstrated by an X-ray source image distortion technique the existence of process-induced strains, including "cement-strains" due to the bonding agent[1]. The effects of such "cement strains" on resonator performance have not, however, been measured previously. This paper discusses experiments which show that the bonding technique employed can significantly change the f vs. T characteristics of AT-cut resonators.

Bonding Experiments

During the fabrication of 20 MHz resonators, a poor correlation was noted between the angle of cut, as measured by X-ray diffraction, and the apparent angle, as determined from the f vs. T characteristic. This poor correlation persisted even after the incorporation of a highly accurate laser assisted X-ray goniometer[2] into the fabrication process.

At the time of these observations, two different 20 MHz resonator designs were under development. For both resonator designs, the nickel electrobonding technique was used to bond the blanks to the mounting clips. The bonded areas of the two designs are shown as the blackened portions in Figure 1. One design was

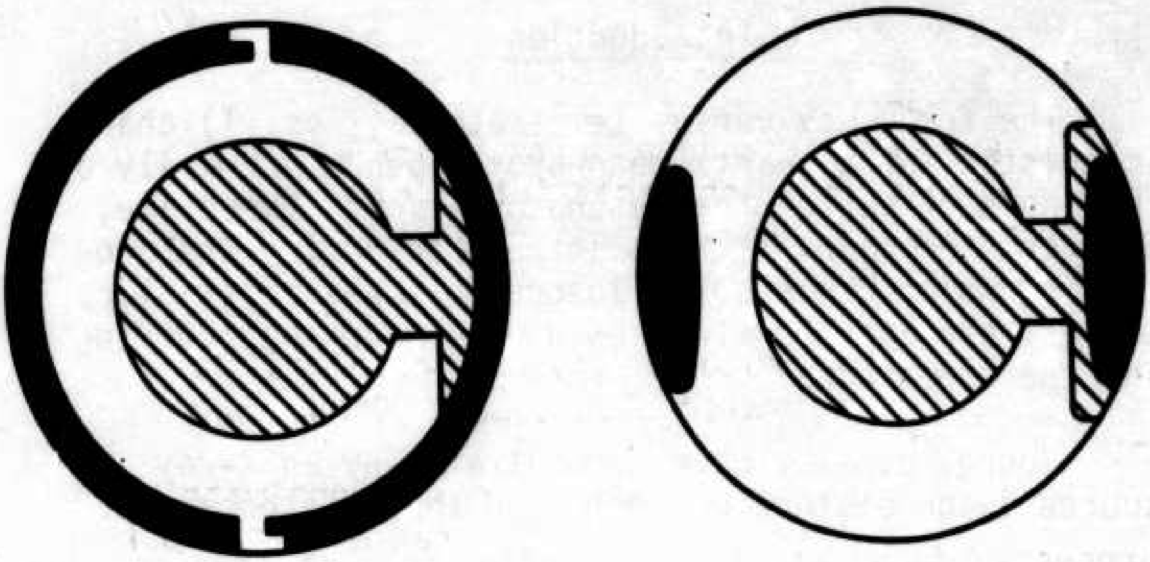

Figure 1. Bonding Areas on Low Shock and High Shock Resistant Crystals

for a high shock resistant Temperature Compensated Crystal Oscillator (TCXO) application in which the edges of the blank were strengthened by extending the nickel plating around nearly the whole circumference of the blank. Two small diametrically opposed gaps in the plating serve to prevent electrical shorts between the two semicircular halves of the edge plating. The second design, with the small bonded areas, was for a low shock TCXO application. The centers of the bonded areas in both designs were oriented along the ZZ' crystallographic direction of the blanks.

Resonators of the high shock design were found to have a f vs. T characteristic which one would normally associate with blanks whose angles of cut are higher than the measured X-ray angles. Resonators of the low shock design, however, had apparent angles which were consistently lower than the X-ray angles. Moreover, the discrepancies between apparent angles and X-ray angles increased as the thickness of the the nickel film used for bonding was increased.

These observations suggested that the poor correlations between the apparent angles and X-ray angles were related to the bonding films. The tight tolerances on the f vs. T characteristics of these TCXO crystals made a better understanding of these observations essential.

A group of resonators were fabricated as shown in Figure 2. The resonator blanks were 20 MHz fundamental, plano-plano, AT cut, natural quartz, with a diameter of 6.35 mm (0.250 inch), final lapped with 5 μm aluminum oxide abrasive, beveled, then etched 800 kHz. After measuring the angles of cut carefully, chromium-gold tabs were vacuum evaporated onto the blanks near the edges. The tabs, which consisted of 200 Å of Cr + 120 Å of Cr-Au mixture + 600 Å of Au, define the areas on the blanks to be plated during nickel electrobonding. These areas, indicated as the "bonded areas" in Figure 2, are 0.5 mm wide and 2 mm long (0.020" X 0.080"). The bonding orientation angle, ψ, between the diameter defined by the centers of the tabs and the XX' crystallographic orientation of the blanks was measured by conoscopic observation in a polarizing microscrope[4].

The mounting clips were 0.76 mm wide, 5.1 mm long, 51 μm thick (0.030" X 0.200" X 0.002") steel. The clips were positioned on the base (HC-25) in such a manner that when the resonators were mounted, the radial force exerted by the clips was near the minimum required to hold the crystals in place. An area on each clip was masked to assure that the clips were not stiffened by the nickel during electrobonding. One of these areas is labeled as the "hinge" in Figure 2.

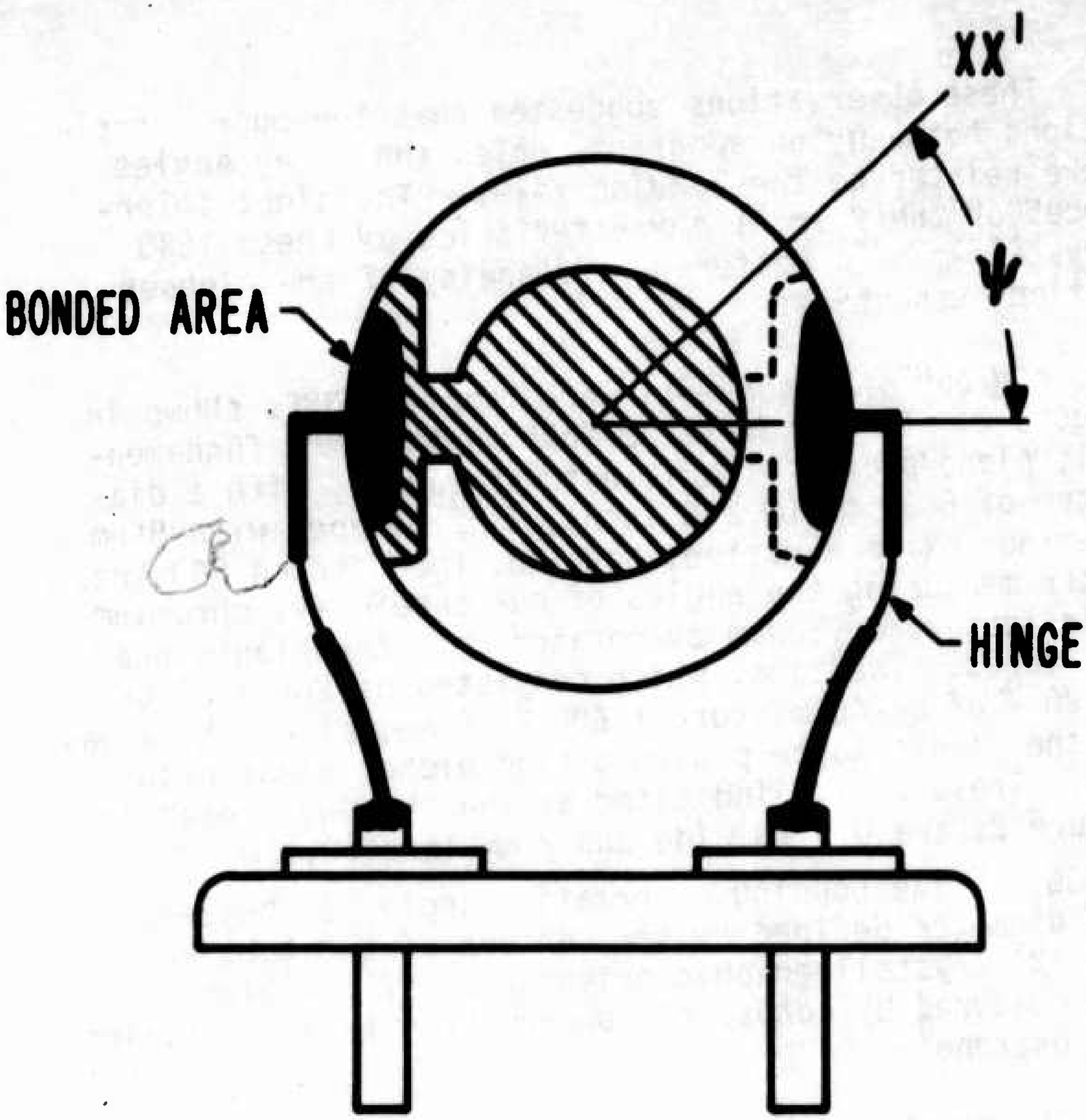

Figure 2. Resonator with Bonding Area Orientation, ψ, Shown.

The crystals were bonded into the bases using the nickel electrobonding process described previously[3]. The nickel plating took place in a temperature controlled plating bath at 48°C. The thickness of nickel deposited during bonding was a constant 50 μm (2 mils) throughout this experiment. The thickness was controlled by using a constant plating current density and a constant plating time, and was checked by measuring the thickness on a control sample. The circular electrodes had a 3.2 mm diameter, and consisted of vacuum evaporated gold, with a plateback of 350 kHz. The resonators were sealed with a dry nitrogen atmosphere inside the enclosures.

The f vs. T characteristic was measured, and the apparent angle was determined from the curve relating the normalized difference between turning point frequencies, δF, to the angle of cut, as shown in Figure 3.

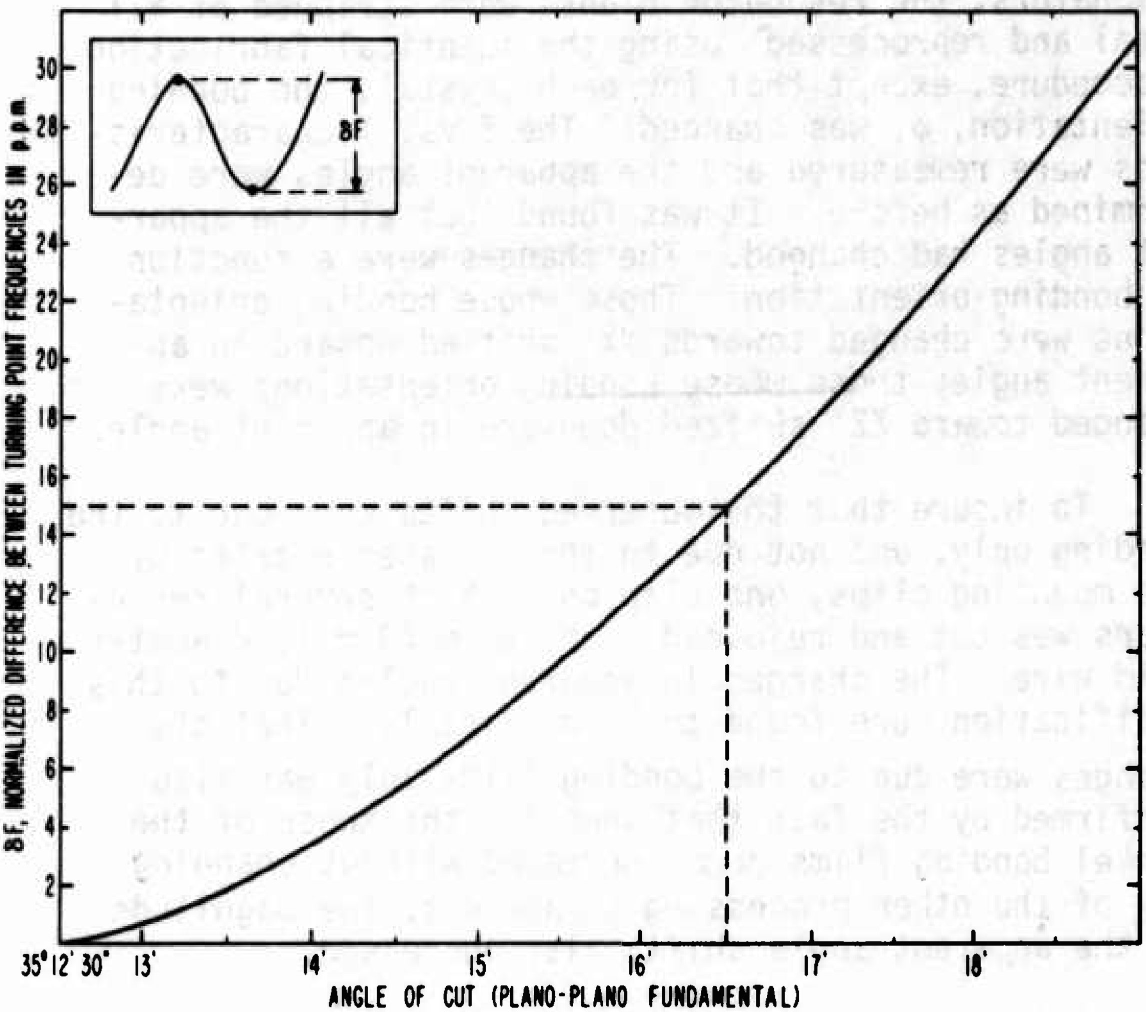

Figure 3. Difference Between Turning Point Frequencies vs. Angle of Cut

The curve is a plot of the relationship[5]

$$\delta F = \frac{4(b^2 - 3\,ac)^{3/2}}{27c^3} \qquad (1)$$

where a, b and c are the usual temperature coefficients of the first, second and third order, respectively. For example, as shown by the dashed line in Figure 3, when $\delta F = 15$ ppm, the apparent angle is 35° 16' 30". After so determining the apparent angles of a group of resonators, the resonator blanks were stripped of all metal and reprocessed using the identical fabrication proceedure, except that for each crystal, the bonding orientation, ψ, was changed. The f vs. T characteristics were remeasured and the apparent angles were determined as before. It was found that all the apparent angles had changed. The changes were a function of bonding orientation. Those whose bonding orientations were changed towards XX' shifted upward in apparent angle; those whose bonding orientations were changed toward ZZ' shifted downward in apparent angle.

To insure that the observed shifts were due to the bonding only, and not due to the stresses exerted by the mounting clips, one clip on each of several resonators was cut and rejoined with 76 μm (3 mil) diameter gold wire. The changes in apparent angles due to this modification were found to be negligible. That the changes were due to the bonding films only was also confirmed by the fact that when the thickness of the nickel bonding films WAS increased without changing any of the other processing parameters, the magnitude of the apparent angle shifts also increased.

The reprocessing of resonators was repeated until a curve of apparent angle shift vs. bonding orientation was obtained, as shown in Figure 4. The vertical

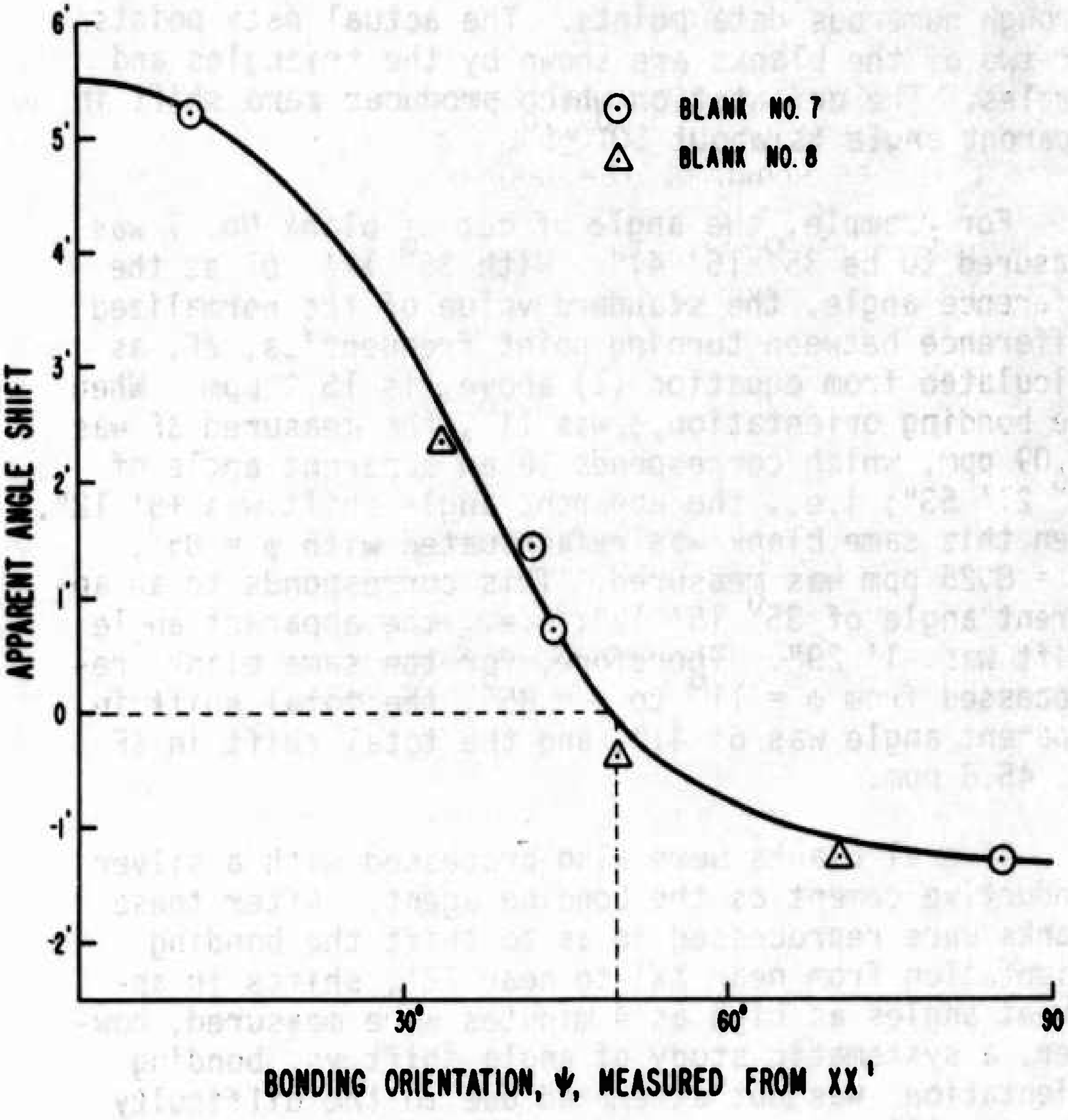

Figure 4. Apparent Angle Shift vs. Bonding Orientation

axis is the apparent angle shift, in minutes, measured from the angle of cut of the blank (as determined by X-ray diffraction). The curve shown is the best fit through numerous data points. The actual data points for two of the blanks are shown by the triangles and circles. The orientation which produces zero shift in apparent angle is about 50° ±5°.

For example, the angle of cut of blank No. 7 was measured to be 35° 16' 41". With 35° 12' 30" as the reference angle, the standard value of the normalized difference between turning point frequencies, δF, as calculated from equation (1) above, is 15.9 ppm. When the bonding orientation, ψ, was 11°, the measured δF was 54.09 ppm, which corresponds to an apparent angle of 35° 21' 53"; i.e., the apparent angle shift was +5' 12". When this same blank was refabricated with $\psi = 85°$, $\delta F = 8.25$ ppm was measured. This corresponds to an apparent angle of 35° 15' 12"; i.e., the apparent angle shift was -1' 29". Therefore, for the same blank reprocessed from $\psi = 11°$ to $\psi = 85°$, the total shift in apparent angle was 6' 41", and the total shift in δF was 45.8 ppm.

Several blanks were also processed with a silver conductive cement as the bonding agent. After these blanks were reprocessed so as to shift the bonding orientation from near XX' to near ZZ', shifts in apparent angles as high as 4 minutes were measured, however, a systematic study of angle shift vs. bonding orientation was not attempted due to the difficulty of controlling the area and thickness of the cement applied.

Discussion of Results

The curve in Figure 4 explains the seemingly anomalous behavior of the two TCXO crystal designs mentioned earlier. For both designs, the blanks were mounted along ZZ'. The low shock design produced a downward shift in apparent angle, as would be expected from Figure 4. The upward shift in angle produced by the high shock design is also explained by Figure 4, because when the angle shifts are summed over all bonding orientations encompassed by the edge plating on the high shock design, the net angle shift is clearly upward.

The angle shifts are believed to be due to the temperature dependent stresses produced by the bonding agent. As the temperature of the resonator is changed, the stresses due to the difference in thermal expansion coefficients between the bonding agent and the quartz also change. For a given bonding procedure, the shifts in δF due to these thermal stresses are expected to be proportional to the difference in thermal expansion coefficients, the difference in elastic constants, and to the stress sensitivity coefficient of quartz.

The thermal expansion coefficient of quartz in the tangential and radial directions is plotted as a function of the orientation, ψ, in Figure 5. Since the bonding agents are generally isotropic, it is not possible to achieve an exact match to the thermal expansion coefficient of quartz.

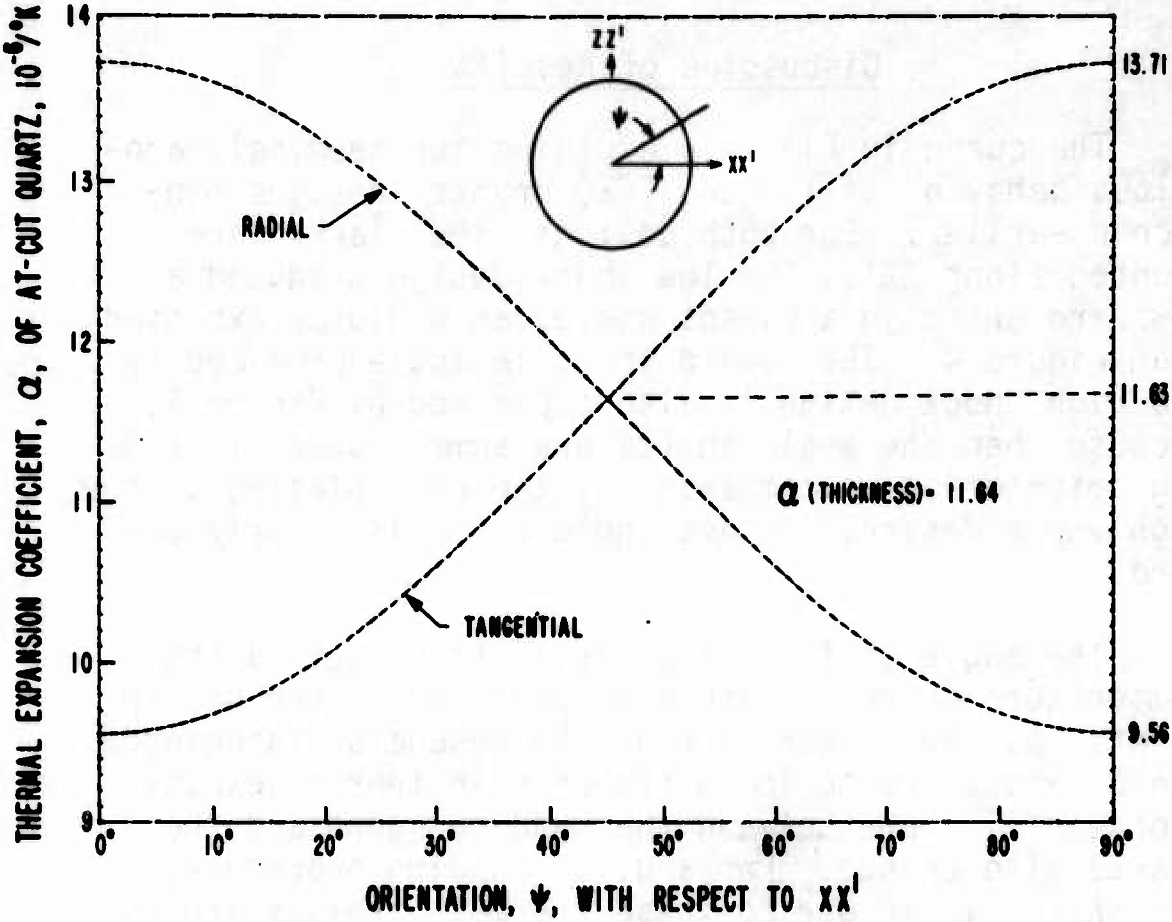

Figure 5. Thermal Expansion Coefficient of AT-cut Quartz vs. Orientation

The stress sensitivity coefficient of quartz for an isotropic stress in the active area of the resonator has been calculated by EerNisse[6] for the rotated Y-cut family. To explain the angle shift data of Figure 4, however, the stress sensitivity coefficient for an anisotropic stress applied in the plane of the blank near the edges would be needed as a function of orientation, ψ. Such information is not currently available.

Applications

1. Aging and Thermal Hysteresis

We have seen that the bonding agent can produce significant shifts in f vs. T characteristics. For example, as was discussed previously, when blank No. 7 of Figure 4 was bonded near the XX' orientation, the measured δF differed from the value one would normally expect from the angle of cut by nearly 40 ppm. At the upper turning point, for example, a relaxation of the thermal stresses could produce a frequency change, i.e., aging, of over 10 ppm. Similarly, if the frequency of this resonator is measured at a given temperature, then remeasured at the same temperature after having experienced a temperature excursion, the frequency will be different if during the temperature excursion the stresses at the quartz-bonding agent interface change. Therefore, the stresses due to the bonding agent may lead to significant aging and thermal hysteresis effects.

To minimize the contribution of the bonding agent to aging and thermal hysteresis, resonators should be bonded along the orientation which produces zero shift in apparent angle. Interestingly, and perhaps not coincidentally, the optimum orientation for minimizing the effects of bonding, about 50^{o} from XX', is near the optimum orientation for minimizing the effects of mounting stresses. Ballato[7] has shown that for a radial force applied to the edge of an AT-cut plate, the force-frequency coefficient is zero when the force is applied at about 60^{o} from XX'.

2. Angle Correction

The effect of bonding on the f vs. T characteristic can be utilized to intentionally change the apparent angles of blanks whose angles of cut would normally place them outside the usable range. For example, for the bonding configuration described above, according to the results presented in Figure 4, the range of "angle correction" is from 5.5 minutes up to 1.5 minutes down. Of course, this range can be varied by varying the bonding configuration, i.e., the area, shape and thickness of the bonding agent applied. To minimize the effect of angle correction on resonator stability, the bonding agent used should be one which shows minimum stress relief at the normal operating temperatures of the resonator.

3. High Shock Resistant Resonators

Among the requirements on a shock resistant TCXO crystal under development is a f vs. T characteristic in which the frequency excursion between turning points is 18 ± 5 ppm, and that the resonator survive a 15,000g shock of 6 msec duration, with minimal change in frequency. These two requirements seemed for a long time to be incompatible. The high shock bonding configuration shown in Figure 1 strengthened the resonator sufficiently to allow it to survive the 15,000g shock. The bonding, however, also shifted the apparent angle to such an extent, that the yield on high shock crystals with acceptable f vs. T characteristics was extremely low.

The results presented in Figure 4 allowed us to redesign the high shock crystals in a manner which now permits a much higher yield on the f vs. T characteristics. In Figure 4, the upward angle shift at the XX' bonding orientation is about four times as large as the downward shift at the ZZ' orientation. The bonded area was therefore made wider in the vicinity of the ZZ' orientation so as to compensate for the greater shift produced by the bonding near XX'. The new bonding configuration is shown in black in Figure 6. The shift in apparent angle due to this bonding configuration is near zero.

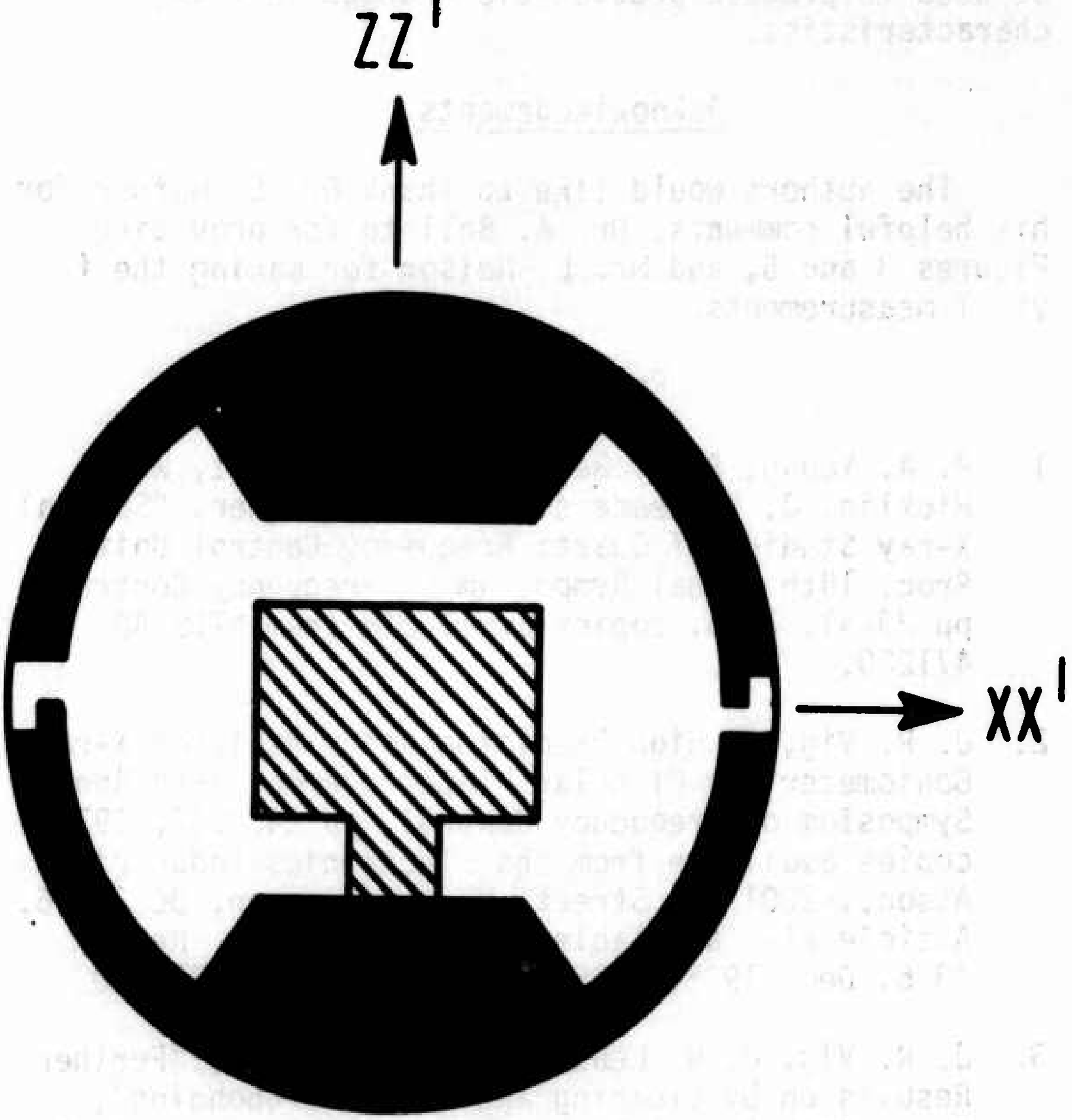

Figure 6. Angle Shift Compensated Bonding Area on High Shock Resistant Resonator

Conclusions

The bonding has been shown to be capable of producing significant changes in the f vs. T characteristics of AT-cut resonators. The effect of bonding on resonator frequency can be minimized by a careful choice of bonding configuration. The effect can also be used to produce predictable changes in f vs. T characteristics.

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