INTRODUCTION
TO
QUARTZ CRYSTAL UNIT DESIGN

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THE ELECTROMAGNETIC SPECTRUM

The radio frequency spectrum extends from about 15,000 cycles per second (15 kHz) to at least 100,000,000,000 cycles per second (100,000 MHz). Over this entire range of frequencies, it is essential that the frequency be accurately controlled to avoid interference between transmitters operating in the same geographical area or on adjacent channels. The continuing demand for space in the available radio-frequency spectrum has resulted in closer and closer spacing of the assigned frequencies with accompanying requirements for better frequency control. Maximum utilization of the limited frequency spectrum requires the highest possible stability of the transmitted frequency and the maximum selectivity at the receiver.

The use of single-sideband and suppressed-carrier communication systems allows more communication channels in a given frequency band but imposes severe requirements on the frequency stability of both transmitter and receiver. Many navigation and ranging systems depend upon precise frequency control and accurate time measurements.

Over much of the frequency spectrum, all these purposes are best accomplished by the use of quartz crystal units as active elements in oscillator circuits and as passive elements in electrical wave filters.

OTHER APPLICATIONS OF THE QUARTZ CRYSTAL UNIT

The ability of the vibrating quartz element to mark off equal intervals of time makes it a natural choice as the isochronous element in timekeeping devices. The development of suitable electronic components to use with the vibrating quartz element now makes quartz clocks and watches practical and it appears that the torsional pendulum which has been the basis of the watch industry for over three centuries has now been superceded by the quartz piezoid.

The temperature-frequency dependence of a specially designed quartz piezoid is used in a thermometer of great convenience and accuracy. The quartz thermometer is capable of providing almost instantaneous digital temperature information from remote locations. The frequency-stress dependence of a vibrating piezoid of quartz has been used as a pressure indicator and as an accelerometer. New applications of the vibrating quartz piezoid are continually being found and doubtless many remain yet undiscovered.

THE PIEZOELECTRIC EFFECT

The word *piezoelectricity* literally means "pressure electricity"; the prefix *piezo* (pronounced pi-e-zo) is derived from the Greek word *piezein*, "to press." The word has been generally defined by Cady as follows: "piezoelectricity is electric polarization produced by mechanical strain in crystals belonging to certain classes, the polarization being proportional to the strain and changing direction with it." The production of an electric polarization by mechanically inducing a strain in a crystal is called the direct piezoelectric effect. The converse effect, whereby a mechanical strain is produced in a crystal by a polarizing electric field, also exists. The converse piezoelectric effect has sometimes been confused with the electrostrictive effect which occurs in solid dielectrics such as glass. The two effects differ in two important respects. The piezoelectric strain is usually larger by several orders of magnitude than the electrostrictive strain, and the piezoelectric strain is proportional to the electric-field intensity and changes sign with it, whereas the electrostrictive strain is proportional to the square of the field intensity and therefore independent of its direction. The electrostrictive effect occurs simultaneously with the piezoelectric effect but (at least in quartz) may be ignored for practical purposes.

In some crystals, electric polarization is produced by simply squeezing the crystal along a certain axis, for example, by clamping it in a vice. Other types of strain such as bending, shearing, and torsion also produce polarization in crystals of certain types. Often several effects occur simultaneously. Conversely, the application of polarizing electric fields may cause the crystal to experience a longitudinal or shearing stress and under certain conditions bending, torsion, and flexure may be produced. This is called the *converse piezoelectric effect.*

The term piezoelectricity is also used with reference to materials such as barium titanate in which electric fields produce mechanical strains. These materials are polycrystalline, however, and have a permanent dipole moment induced in them during manufacture. They also exhibit a domain structure. Their behavior is analogous to that of ferromagnetic materials in which magnetic fields produce mechanical contraction called *magnetostriction.* These materials are not considered in this book.

CRYSTALS

In the physical sense, a crystal is a set of atoms, molecules, or ions arranged in a definite geometric pattern in three dimensions. The ideal crystal is made up of unit cells which are the smallest parallelepipeds that can be fitted together to form the crystal. Each unit cell of a given crystal is identical to every other unit cell of the crystal in that each one contains the same set of atoms, molecules, or ions, arranged in exactly the same way.

The atoms, molecules, or ions which make up the crystal are arranged in rows, columns, and planes. The natural faces and the cleavage planes of the crystal tend to be parallel to planes of atoms. The distances between the planes of atoms and the dihedral angles between the nonparallel planes are as characteristic of the crystal as its density or its chemical composition. Crystallographers long ago deduced much about the internal structure of crystals by studying their external forms.

Crystallographers recognize 32 classes of crystals- of which 20 exhibit the piezoelectric effect. It is thus apparent that piezoelectricity is not a particularly rare phenomena. Although many crystals exhibit the piezoelectric effect, very few are useful, and quartz alone provides the necessary combination of mechanical, electrical, chemical, and thermal properties required for making piezoelectric elements for the electrical communication field.

QUARTZ

Crystalline quartz is composed of two elements, silicon and oxygen. The chemical formula is SiO_2. In the amorphous form SiO_2 is a major constituent of many rocks and most sand. The crystalline form of SiO_2, or quartz, is also relatively abundant in nature; but in the highly perfect form required for the manufacture of quartz crystal units, the supply is not large. Most of the high-quality crystals of natural quartz are obtained from Brazil. Some domestic sources of quartz are known, but the low quality and high cost of production make their use prohibitive.

Natural quartz crystals were grown from water solutions containing dissolved SiO_2. The crystals were probably grown at moderate temperatures over long periods of time. Sometimes the crystals are found in their original formations but more often the cavities, or "vugs," in which the crystals grew, have weathered away and the harder quartz crystals are now found in the debris or in river beds where they have been deposited.

The limited supply and the high cost of natural quartz have resulted in the development of a cultured quartz industry. By improving on the work done in Germany half a century ago, it is now possible to produce crystals of quartz which can be used in most applications.

Silicon dioxide is only slightly soluble in water at ordinary temperatures. However, in alkaline solutions at elevated temperatures, the solubility is increased appreciably. Crystals of cultured quartz are grown by dissolving SiO_2 in an alkaline solution of water at temperatures near the critical temperature of water. Very strong autoclaves are required to withstand the pressures, which may exceed 1000 atm. Seed crystals are placed in the cooler part of the autoclave and nutrient in the form of chunks of SiO_2 is placed in the warmer portion. The temperatures and temperature gradients are controlled by computer programs. The solution moves by convection from the hotter to the cooler region dissolving the nutrient and depositing on the seed crystals. Crystals having masses of several hundred grams can be grown in a few weeks. The quality of the quartz is critically dependent upon the conditions of growth; in general, the slower the growth, the higher the quality. Most of the quartz processed in the United States (1980) is cultured (man-made) quartz. The crystals are grown in such shapes and sizes that the labor and loss of material in processing are minimized.

The quality of the quartz for piezoelectric use can be predicted by measurements of its infrared absorption. It is customary to inspect the quartz in this way and to grade it for specific applications. Natural quartz is still preferred for a few of the most severe requirements. The differences between samples of quartz crystals are due to crystalline imperfections. These may include such defects as lattice vacancies, interstitial atoms, impurity atoms, and growth dislocations. The common defects of twinning in natural quartz are not present in cultured quartz.

The crystalline form of SiO_2 at temperatures below 573°C is called *alpha quartz*, or simply *quartz*, and it is with this material that we will be exclusively concerned. Much of the information may be applicable to other materials, of course, but the direct application will be to the use of quartz in the design and fabrication of oscillator and resonator elements. No distinction is required between natural and cultured quartz and none will be made in the material which follows.

HISTORICAL REVIEW

The discovery of the piezoelectric effect is usually ascribed to Jacques and Pierre Curie, who announced their discovery in 1880. Not only did they demonstrate the phenomenon, but they also established the criteria for its existence in a given crystal. The Curie brothers measured the values of the piezoelectric constants in several crystals, including quartz, and devised a few instruments utilizing the phenomena.

Except for an isolated instance here and there, the phenomenon of piezoelectricity was not exploited until the period of World War I, when Langevin (France) used piezoelectrically excited quartz plates to generate sound waves in water for use in submarine detection. Langevin later used quartz plates as receivers of sound waves, thus employing both the direct and converse piezoelectric effects. Langevin's work, of course, was the forerunner of sonar. Interest in piezoelectricity was revived by the work of Langevin, and among those who became interested in the field were Cady at Wesleyan University and Nicholson of the Bell Telephone Laboratories. Their work led to the development of the piezoelectric resonator as a frequency-controlling element.

An oscillator employing a Rochelle salt crystal was patented by Nicholson of the Bell Telephone Laboratories in 1918. It is not altogether clear whether or not he conceived the function of the crystal as being primarily a frequency-controlling element; but in any case, the control could not have been very effective. In 1920 Cady patented an oscillator circuit, the frequency of which was definitely controlled by a quartz resonator. Cady's oscillator consisted of a three-stage amplifier with the quartz resonator in the feedback path. A little later, Pierce showed that a crystal-controlled oscillator could be built using only one vacuum tube.

The first broadcast station to be crystal-controlled was WEAF in New York City. It was placed in operation in 1926, and soon thereafter most broadcast stations began to utilize quartz crystals for frequency control. Throughout the period from 1926 to 1939, quartz crystal units were used by amateurs, broadcast stations, and some manufacturers of two-way radio-communication equipment. These units were made by a small number of suppliers, often on a custom basis. No industry, as such, existed.

The use of crystal control in military communication equipment did not become common until immediately prior to World War II. The armed services were in the process of converting to crystal control when the United States entered the war. In 1940 it was estimated that in the event of a major war, the armed services might require as many as 100,000 units. This seemed like a fantastic quantity at a time when all crystal units were made in a few small shops where a skilled worker might be able to make as many as 10 units in a day. During the war, however, over 30 million quartz crystal units were produced through a crash program costing over $1 billion. At the peak of the war effort over 125 factories were engaged in the production of quartz crystal units for the armed services of the United States and the Allies.

THE PIEZOELECTRIC RESONATOR

The first quartz resonators were simply quartz plates cut from the crystal in such a way that the normal to the plate is parallel to the *X*-axis of the crystal.[1] Such a piezoid, called an *X*-cut, has a temperature coefficient of frequency of about −20 Hz/(MHz)(°C). In other words, the frequency decreases 20 Hz/MHz for each degree rise in temperature.

The *Y*-cut plate, which was introduced by E. D. Tillyer in the late 1920s, has certain advantages over the *X*-cut plate. It is only about two-thirds as thick as an *X*-cut plate of the same frequency. It also has fewer undesirable modes of vibration and is less affected by air damping. Fabrication is also somewhat simpler. Its most important advantage is that it can be clamped for mounting. The *Y*-cut has two disadvantages, however. The temperature coefficient of frequency is about +100 Hz/(MHz)(°C) and the device often refuses to operate or changes frequency abruptly as the temperature is changed.

It was discovered by groups in Germany, Japan, and America in 1929 that the temperature coefficient of the *Y*-cut plate could be improved and in fact made to become zero at certain temperatures by rotating the plane of the *Y*-cut about the *X*-axis. The first of the zero temperature coefficient cuts to be discovered was named the *AT-cut*. It is still the most widely used of all the quartz piezoids. The second zero-temperature-coefficient orientation to be discovered was named the *BT-cut*. The BT-cut, which is 50 percent thicker than the AT-cut for a given frequency, was widely used during World War II, but it has been largely replaced by the AT-cut, which can be made to have a smaller frequency excursion over the wide temperature ranges required by modern communication systems.

Quartz piezoids can be made in many different forms. Quartz bars, vibrating in flexure modes (like xylophone bars), are used from the audio range to some tens of kilohertz. Such elements are used as the isochronous elements in wristwatches. Small piezoids in the form of tuning forks, operating around 30 kHz, have also been developed for use in wristwatches. Quartz bars vibrating longitudinally

[1] The terms *X-cut*, *X-axis*, etc., are defined in Chap. 2.

and quartz rings vibrating radially have been used as frequency standards at frequencies from 50 to 100 kHz. In the range from 100 to 1000 kHz, quartz plates vibrating in the face-shear mode have been widely used.

Piezoids of many other configurations have been developed for special applications. Most are designed to make the frequency as nearly independent of temperature as possible. Most of the material covered in this book relates directly to piezoids of the thickness-shear mode type, i.e., Y-cut, AT-cut, and BT-cut plates. However, with suitable interpretation nearly all the material is applicable to piezoids of any orientation.

FABRICATION TECHNIQUES

In the early days, quartz crystal units were fabricated by hand methods which were very crude and primitive in comparison with present-day manufacturing techniques. Originally the quartz plates were cut with "muck saws," which were simply metal discs running in a slurry of abrasive and oil or water. The orientation of the plates was determined by reference to the natural faces of the quartz crystal. Orientation was therefore inaccurate, and rarely were two finished units found to perform in the same way. The quartz plates were mounted between two metal plates which served as electrodes and also to support the quartz plate.

During the past four decades, enormous improvements have been made in fabrication techniques. The muck saw was replaced by the diamond saw, which is capable of cutting thin wafers of quartz with extraordinary speed and accuracy. The use of x-ray diffraction replaced orientation by reference to natural faces. Precision machinery for lapping and controlling the dimensions of the plates with precise orientation now make it possible to fabricate units to a given design with such accuracy that the mechanical and electrical characteristics are substantially identical.

In the past few years a new type of slurry saw has replaced the diamond saw, especially for sawing cultured quartz. This saw consists of a set of 100 or more fine, stretched metal bands moving back and forth across a number of bars of quartz in a flood of abrasive slurry. These "gang saws" are capable of cutting several hundred crystal blanks per hour with very little cost for labor.

The electrodes of modern crystal units are metal films deposited directly on the quartz by vacuum evaporation. Not only does this provide a more convenient method of adjusting the frequency but it also eliminates the air gap between the quartz and the electrode which is a principle source of difference between units of a given type. A further advantage is that the units are more rugged and less susceptible to the effects of shock and vibration. The units are also lighter and less expensive.

While improvements in the temperature coefficients, mechanical stability, and reliability of the quartz crystal unit were being made, the frequencies realizable were also being increased. Prior to World War II most crystal units operated in or a little above the broadcast band. A few units operating at frequencies of 3 to 4 MHz were made for "short-wave" enthusiasts. During the war the practical limit was pushed to approximately 10 MHz but not without serious difficulties, especially with "aging." Today (1980) it is possible to purchase reliable crystal units operating at frequencies above 150 MHz. This appears to be approaching the upper practical limit for direct control of frequency by the use of vibrating plates. Direct methods of controlling frequencies in the gigahertz range with the precision of quartz resonators are sorely needed. Recent developments in the area of surface (Rayleigh) waves may result in devices which will help to meet this need.

SUMMARY

The quartz crystal unit is one of the most remarkable devices made by human beings. Whether considered from the standpoint of the complexity of the physical phenomena involved; the delicate operations required in the fabrication of the device; the unique properties of the basic material, the precision, reliability, or low cost of the device; the quartz crystal unit holds a place which is almost unique among manufactured articles.

A typical crystal unit is specified to operate at a frequency of 50 MHz over a temperature range of −55 to +105°C with a maximum frequency excursion of ±0.005 percent of its nominal frequency. It is specified to operate continuously under severe conditions of shock or vibration in any position over long periods of time. It may not be generally appreciated that a tolerance of ±0.005 percent is equivalent to about 4 sec in 24 hr or about 3 in/mi (or 5 cm/km). Yet the typical crystal unit is expected to maintain this precision under any combination of the adverse conditions described while executing 50 million mechanical vibrations per second. Furthermore, it is required to continue this performance over long periods of time without change of frequency or failure. The number of mechanical vibrations executed by a 12-MHz quartz plate reaches the astounding total of 10^{12} per day!

Note the forces involved in the vibration of the quartz. The actual displacement of a point on the surface of the quartz is, of course, quite small – generally only a few atomic distances. Even this small displacement results in tremendous forces, however. It can easily be shown[2] that a point on the surface of a quartz plate vibrating at 50 MHz experiences accelerations of several million "g's." It can also be shown[3] that the loss of an amount of quartz from the surface of the plate, equivalent in thickness to one layer of atoms, would result in an increase of several hundred cycles per second in the resonant frequency. This is an appreciable part of the total frequency change allowed for all effects including temperature and aging.

It is indeed fortunate for the communication art that nature has provided a material with the piezoelectric, mechanical, and electrical properties required to meet such exacting conditions.

It is not surprising that in order to achieve such results in a manufactured article, a high order of scientific and engineering skill plus meticulous care at every step in the fabrication process are required.

Considering all the factors involved, it appears that quartz, in the words of W. P. Mason, will remain "the cornerstone of the communication art."

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[2] The displacement of a point vibrating with simple harmonic motion may be described as $x = A \sin(\omega t)$, where A is the amplitude and ω is the angular frequency. The acceleration $\ddot{x} = -\omega^2 A \sin(\omega t)$. Hence, the maximum value of the acceleration is $\omega^2 A$. If we assume that A is only one lattice spacing, i.e., about 5×10^{-10} m and $\omega = 2\pi f = 3 \times 10^8$ sec^{-1}, then the acceleration is 45×10^6 m sec^{-2}, or about 5 million 'g's.

[3] The resonant frequency of a plate vibrating in a thickness-shear mode is given by $f = n\nu/2e$, where e is the thickness, ν is the wave velocity, and $n = 1, 3, 5, \ldots$. Differentiating the expression for f gives $df = -(f/e)de$. A 50-MHz plate vibrating in its third-overtone mode ($n = 3$) has a thickness of approximately 1.0×10^{-2} cm. A change of thickness of 5×10^{-8} cm (about one atomic layer) therefore results in a change of frequency of about 250 Hz.