Designing and Manufacturing Quartz Crystal Oscillators

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Abstract. In this decade, the number of wireless devices grow significantly, caused the frequency stability is very important. Almost all wireless devices use the quartz crystal oscillator to generate stable frequency. To get good quality of quartz crystal oscillators, then it needs to be taken carefully from designing up to how to manufacture them. In this paper, we present the characteristic of quartz crystal oscillator and the factors that affect the frequency stability of quartz crystal oscillator. Knowing these factors to design crystal oscillator is essential. The characteristic of crystal oscillator will depend on the material purity, cutting angle, dimension, surface roughness and edges, thickness, material of electrode, and cleanliness. Crystal oscillator manufacturing process is very long, starting from row material angle marking, cutting, shaping, lapping, electrode evaporation, mounting, frequency adjusting, and aging. All these process will discuss in this paper, including the testing.

1 Introduction

In this decade, the numbers of devices that use wireless technologies grow significantly. Starting from the most simple such as TV's remote to highly complex equipment such as mobile phones or satellite. All these devices aim to transfer information or signals using radio waves. These radio waves have a frequency between 3 kHz to 300 GHz. Each range of frequency is used for specific purposes. For instance, 470 to 860 MHz for TV transmission, 1 to 2 GHz for GPS and mobile GSM phone, 2 to 4 GHz for wireless LAN and microwave ovens and so on. Because so many wireless devices, it is clear that the frequency stability is very important; if not there will be interference between the wireless devices. Almost all wireless devices use the quartz crystal oscillator to generate stable frequency. To get good quality of quartz crystal oscillators, then it needs to be taken carefully from designing up to how to manufacture them.

Quartz crystal has a unique characteristic that is the piezoelectric effect. The piezoelectric effect is the effect of material when we applied an action to it. In piezoelectric, the material will generate the electricity when we applied mechanical stress or pressure on it. Vice versa, the materials will response when we applied electricity to the material. This effect can be useful for many applications such as sensor, frequency generator, energy alternative, etc. In this paper we present the quartz crystal for generating frequency. In this paper we present designing and manufacturing quartz crystal oscillator starting from growing quartz crystal to final testing of quartz crystal oscillator.

2 Background

In this section presents the background related to the quartz crystal oscillator. First we will introduce the piezoelectric material and theory then explaining the application of the quartz crystal in many areas.

2.1 Piezoelectric

The piezoelectric effect found in some material in which the material will generate the electricity charge when the mechanical stress applied to the material. Vice versa, if the electricity field applied to the material, the material response by mechanical strain. The effect of piezoelectric was introduces at the first time by Coulomb in the year 1815 [1], [2]. He had a hypothesis and theory that some material can generated electricity when pressure applied on that material. Five year after Coulomb introduced his theory, and then Hauy and Becquerel tried to prove the Coulomb's theory. His experiment support the Coulomb's theory, he concluded that the electricity charge could be generated by stretching rubber. In 1880, the brothers Pierre Curie and Jacques Curie proved the piezoelectric effect in crystalline minerals such as tourmaline, quartz, topaz, cane sugar, and Rochelle salt. They made experiment to apply mechanical stress to those crystalline minerals and measured the voltage from electrical charge that resulted by those crystalline minerals.

Since Curie brothers found the effect of piezoelectric then many research had been done in this area including the theory, model and experiment. In the beginning of the 19^{th} century, Langevin started to make transducer from piezoelectric material. Until the frequency stability versus temperature change of quartz crystal oscillator was found by Born in 1933. Born found that the quartz crystal oscillator that made by 35 degree to the axis Z of quartz crystal had the best frequency stability to the temperature change. He gave the name AT cut for angle cutting 35 degree. He also introduces the BT cut that had cutting angle of 49 degree. After this finding, all of the precision frequency control was made by quartz crystal oscillator.

There are four type of piezoelectric material can be identified since Curie brothers discovered the effect of piezoelectric [3]. These types of piezoelectric materials are single crystal quartz, single crystal Rochelle salt, barium titanate ceramics, and lead zirconate titanate (PZT) ceramics. In this paper we focused on the single crystal quartz. The quartz crystal made by silicon and oxygen or silicon oxide (SiO_2). Its characteristic form is a result of the unit cells by which the crystal grows [4]. These unit cells are identical and consist of atoms arranged in a repetitive geometric pattern. In quartz crystal there are four axes of symmetric because of its geometrical shape. The first axis is optic axis. The other three axes lie in a plane perpendicular to the optic axis and separated by an angle of 120^0. These axes are known as electric axes because along the direction in which they lie the maximum piezoelectric effect is observed [5]. The properties of quartz crystal depend on direction of these axes. In order to describe the characteristic of quartz crystal easier, then different axial systems need to be familiarized. In figure 1, showed two coordinate axis system to explain different properties of quartz crystal. The Bravais – Miller axis system was used to explain atomic system in quartz crystal. The Orthogonal axis was used to explain the piezoelectric and mechanical properties of quartz crystal.

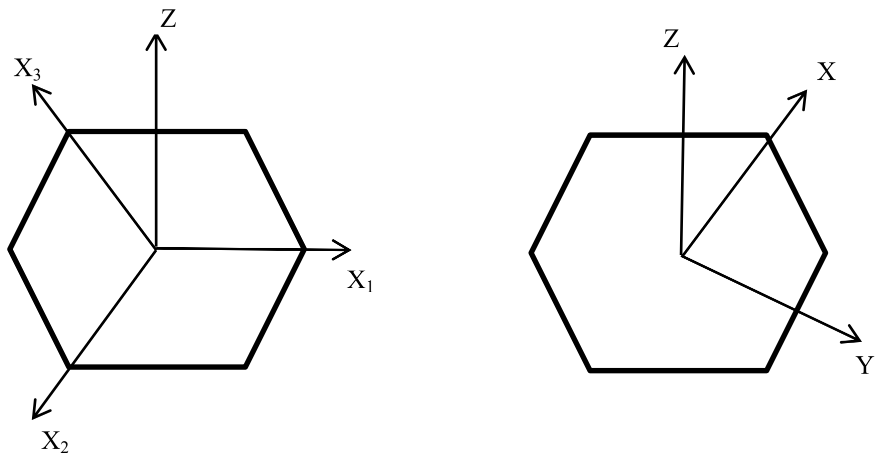


Fig. 1. On left is Bravais – Miller coordinate axis system and on the right is Orthogonal coordinate axis system.

Basically the application of quartz crystal can be divided into several groups: Sensor (microphones, pressure sensor, force sensor, strain gauge), Actuators (loudspeaker, piezoelectric motors, valves), Generator (energy harvesting, cigarette lighter), Transducer (ultrasonic sonar devices), and Frequency standard (oscillator).

2.2 Quartz Crystal Oscillator: History and Market

The research of quartz crystal oscillator initiated by A.M. Nicholson of the Bell Telephone Laboratories and W.G. Cady at Wesleyan University in 1917 [6]. Two year later, Cady used a quartz piezoid to control the frequency of an oscillator and in a series of papers during the next three years he described the use of quartz bars and plates as frequency standards and wave filters. It is generally accepted that Cady was the first to use a quartz piezoid to control the frequency of an oscillator circuit [6].

According to Virgil [6], Bell Telephone Laboratories established a quartz laboratory in 1923. And then one of individuals who recognized the potential of the quartz crystal unit was August E. Miller. Miller went to quartz crystal business, making quartz crystal oscillator for amateur radio operators. Quartz crystal was blank very expensive at that time. General Radio Company offered quartz crystal blank for sale at the price of $35 to $50. This was very large amount of money in 1925 [7]. Finally, in 1926, the AT&T radio station WEAF in New York City became the first radio station in the United States to control its frequency with a quartz crystal unit [8].

Efforts to develop a practical unit having a low frequency temperature coefficient were successful in 1934 when the AT and BT cuts were discovered independently by Koga from Japan, Bechmann and Straubel from Germany, and Lack, Willard, and Fair from United States [8].

According to Ji Wang [8], in 1943 there was 130 manufactures were engaged in the production of crystal units. They were scattered over 20 states from Oregon to Florida. Most of them were in the same area. There were twenty three factories that produced crystal units in Chicago, twenty in New York area, fifteen in Carlisle area, and fourteen in Kansas City area.

Quartz crystal unit market will be about more than 10 billion USD with growth rate of 7.5% annually. These because of more devices that work based on the wireless technique. In 2011, there are about 450 companies and suppliers globally that had business in quartz crystal units. 30% of crystal unit were installed in the telecommunication devices while the remaining 70% were installed in consumer electronics products. Japan is supplying the high-end products for telecommunications, while china is producing crystal units for the consumer markets with a global market share about 25% [8].

2.3 Quartz Crystal Synthetic

The quartz crystal is formed from silicon and oxygen, become SiO_2 (silicon dioxide) as shown in figure 2 [10]. At the beginning of producing crystal oscillator in 1920s, the manufacturer used natural quartz crystal. Many disadvantages used natural quartz crystal to make quartz crystal units. The number of natural quartz crystal is very limited and the purity is very low. The purity will have an impact to the impedance of quartz crystal unit and will drain the power resources. Besides that, the determination of axis is very difficult. All these make the price of crystal oscillator unit become very expensive in 1920s, $30 to $50 for a unit.

The research to make synthetic quartz crystal was started in the mid nineteenth century. The scientist attempted to create quartz crystal in laboratory with create the conditions in which the quartz crystal growth in nature. In 1845, the first person who tried to synthesize quartz crystal was a geologist, Karl Emil. He crated microscopic hexagonal quartz crystal in a pressure cooker for eight days. However, the quality and size of the crystals that were produced by these early efforts were poor [9]. Since 1930, all the telecommunications industry used the quartz crystal oscillator to control the frequency but the supply of quartz crystal is very limited. After the war many researcher and scientist attempted to make the synthetic quartz crystal. Finally in 1950s, synthetic quartz crystal were being produced and sold commercially.

Synthetic quartz crystal as shown in figure 2 is manufactured in a vertical-type autoclave (high-temperature and high-pressure oven) using the hydrothermal synthesis method. An autoclave is partitioned by a baffle into two compartments: an upper and lower [11]. Seed crystals are placed in the upper compartment (growth zone) and materials (lascas) in the lower (dissolution zone) as shown in figure 4. A dilute alkaline solution is then poured into the remaining 60 to 80 percent of free space and, after being covered the autoclave is heated with a heater. When the temperatures of the upper and lower compartments of the autoclave reach between 300 to 320 °C and 380 to 400 °C, respectively, the alkaline solution expands and is compressed; the pressure inside reaches 130 to 145 MPa.

Fig. 2. A cluster of natural quartz crystal. Adapted from the evolution of time measurement, part 2: Quartz Clocks by Michael A. Lombardi. In IEEE Instrumentation & Measurement Magazine, October 2011

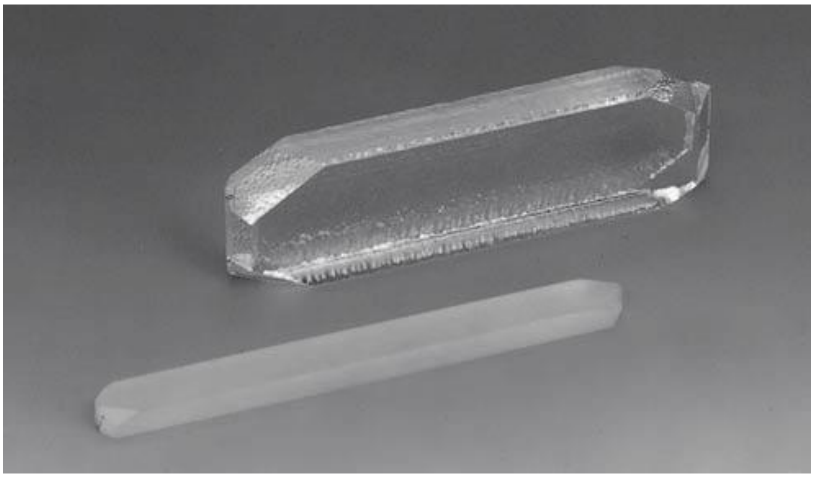


Fig. 3. Synthetic quartz crystal. Adapted from Synthetic Quartz Crystal by Nihon Dempa Kogyo Co., LTD.

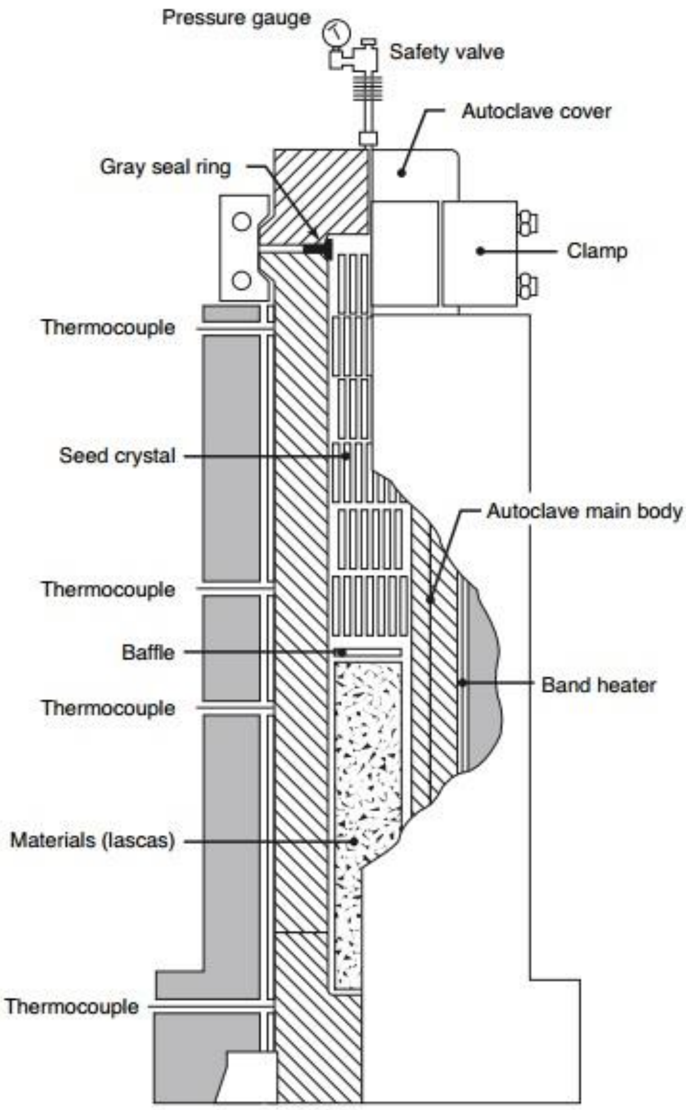


Fig. 4. One Schematic depiction of synthetic quartz crystal growth. Adapted from Synthetic Quartz Crystal by Nihon Dempa Kogyo Co., LTD.

According [11], under these high temperatures and pressures the materials in the lower compartment of the autoclave dissolve in the alkaline solution to become the SiO2 saturated solution. This saturated solution rises due to the convection caused by the temperature difference between the upper and lower compartments of the autoclave. When the solution reaches the upper compartment of the autoclave, it becomes supersaturated because of the lower temperature of the compartment, and according to the degree of the temperature difference SiO2 is crystallized on the seed crystal [11]. The solution then returns to the lower compartment of the autoclave and dissolves the materials, thereby becoming the SiO2 saturated solution, and due to convection it raises and the cycle repeats. The repetition of this process leads to the successive growth of synthetic quartz crystals [11].

Manufacture crystal oscillator unit from the synthetic quartz crystal is easier than natural quartz crystal. Synthetic quartz crystal has high purity or almost 100% pure. The axes are already determined in the growth process and it is very helpful in cutting process. We can easy to make AT, BT cut or others cutting angle. Synthetic quartz crystal available globally, we can order as much as we need them with variety size.

2.4 Thickness Vibration

There are several vibration modes in quartz crystal oscillator as shown in figure 5. Each angle cut will has its own vibration mode. For example, quartz crystal oscillator with AT and BT cut have thickness shear vibration mode, and CT, DT, and SL cut have face shear vibration mode.

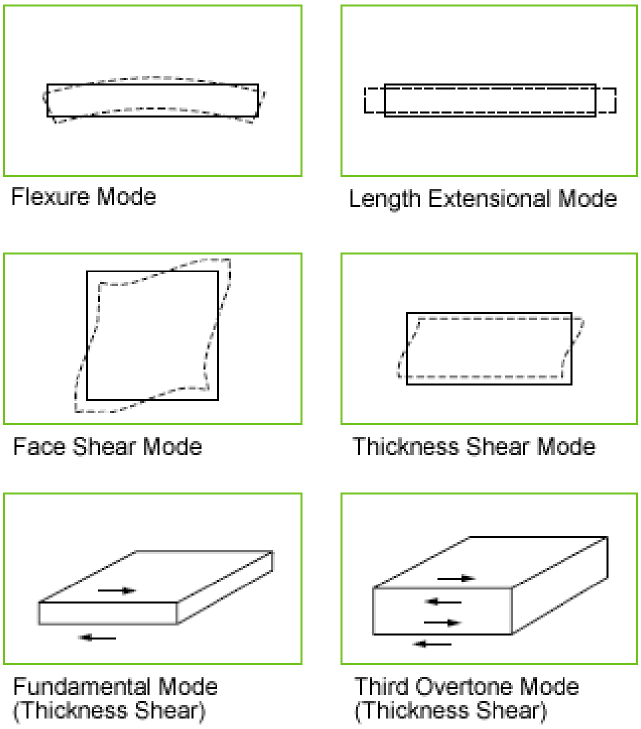


Fig. 5. Quartz crystal vibration mode. Adapted from Quartz Crystal Basic Theory by Token Passive Components.

AT cut with thickness shear vibration mode can be vibrate from 0.5 – 300 MHz. The orientation cut angle of AT cut between $35^{o}15$’ to $35^{o}18$’ and BT cut is - $49^{o}08$’ against Z axis. CT, DT, and SL cut with face shear vibration mode can generate frequency 75 – 900 kHz. The orientation cut angle of CT, DT, and SL cut are 38^{o}, -52^{o}, and -57^{o} consecutively.

3 Designing Quartz Crystal Oscillator

In designing quartz crystal oscillator, the first step is we have to know several electronic parameters and the environmental condition where the oscillator will be placed. The electronic parameters that we have to know are frequency, maximum resistance, load capacitance, and frequency tolerance. The environmental condition that we have to know is the temperature range where the crystal oscillator will be operated.

Base on those information we can decide the angle cut of quartz crystal follow the graphic shown in figure 6.

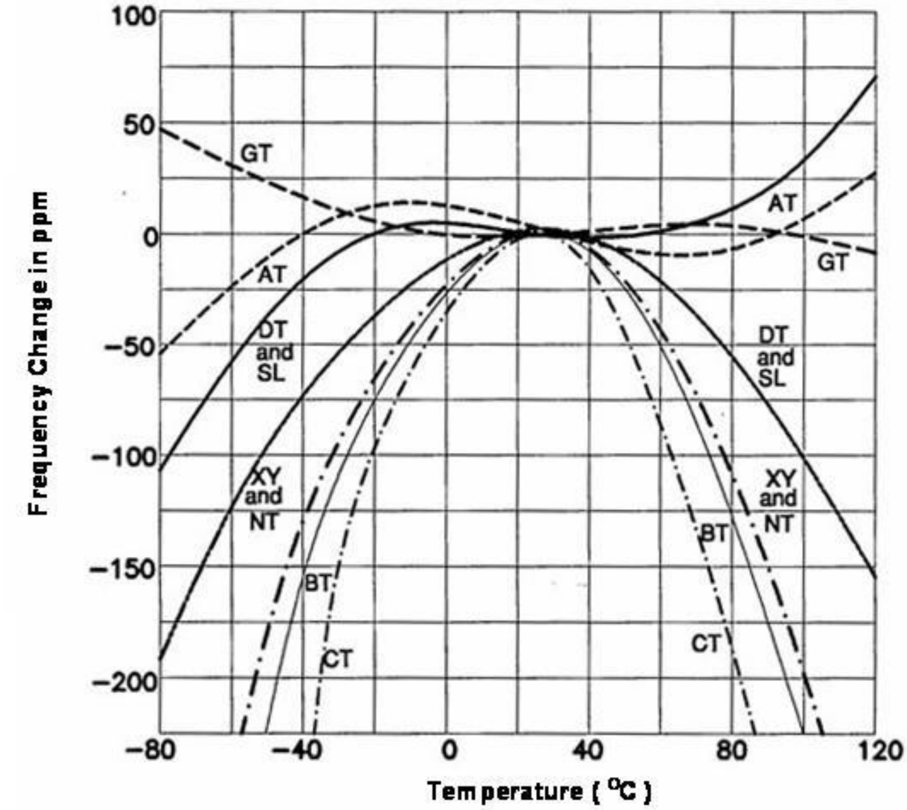


Fig. 6. Frequency vs. temperature characteristic of various quartz cutting angle. Adapted from Technical Terminology by TXC Corporation.

The most popular quartz cut is AT cut, because the most stable frequency to temperature changing is AT cut. The frequency is depending on the thickness of quartz blank. We can follow the equation 1 to determine the thickness of quartz blank with AT cut. Different cutting has different coefficient cutting.

$$f\ [kHz] = \frac{1670}{thickness\ [mm]} \quad (1)$$

For example, to produce quartz crystal oscillator 10 MHz or the thickness 0.167 mm, we must cut the synthetic quartz crystal about 0.24 mm. After cutting process, they will be lapped to the frequency closed to 10 MHz or 0.167 mm.

Next step is to determine the diameter of electrode. The electrode diameter depend on the load capacitance that the required by user. The load capacitance is an external capacitor in order to adjust the frequency to the specific frequency. It can put in parallel or series to the crystal unit.

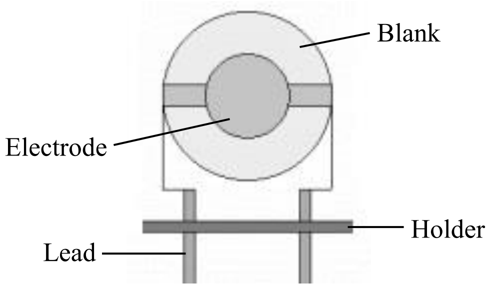


Fig. 7. Inside view of crystal unit.

Crystal unit has equivalent circuit as shown in figure 8. The Co is a shunt capacitance represents the capacitance of the crystal electrode including capacitance of the crystal holder and leads. C_1 is motional capacitance represents mechanical elasticity. L_1 is motional inductance represents mechanical inertia. R_1 is motional resistance represents mechanical losses.

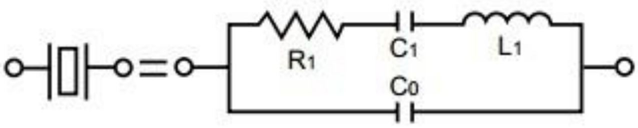


Fig. 8. Equivalent circuit of crystal unit

The quality factor Q of a crystal unit as shown in equation 2 is the quality factor of the motional arm at resonance. The maximum stability that can be attained by the crystal unit is directly related to Q, the higher Q the smaller the bandwidth.

$$Q = \frac{2\pi * fr * L_1}{R_1} \quad (2)$$

4 Manufacturing Quartz Crystal Oscillator

The raw material for manufacturing quartz crystal unit is synthetic quartz crystal. Quartz crystal unit manufacturing process is very long process. The processes start with lapping process or grinding the surface of synthetic quartz crystal to final test.

4.1 Lumbering Synthetic Quartz Crystal

The lumbering synthetic quartz crystal is a process to grind the surface of synthetic quartz crystal. This process use abrasive green silicon carbide powder #500. There are two purposes of this process. Firstly, is to make the size of synthetic quartz crystal to be the same. Secondly, is to be easy to propagate the x-ray in the next process. After process lumbering, the synthetic quartz crystal become lumbered bar.

4.2 Lumbered Bar Cutting

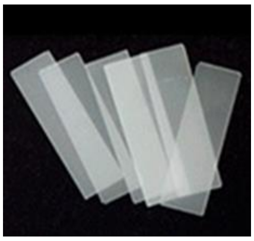
A steel board was placed on the x-ray machine, and the lumbered bar will be placed on a steel board using UV silicon glue. The x-ray was used to determine the right position of cutting angle lumbered bar. Depending on the size of steel board, one steel board can accommodate 4 to 6 lumbered bar per layer and it can be 3 layers maximum. After the lumbered bar placed in the right position then the steel board and lumbered bar will be placed in the UV lamp conveyor to dry the UV glue. Then the steel board and lumbered board placed on cutting machine. Normally, cutting machine uses blade to cut the lumbered bar. It will take about 10 to 12 hours to cut three layer of lumbered bar.

4.3 Wafer Lapping

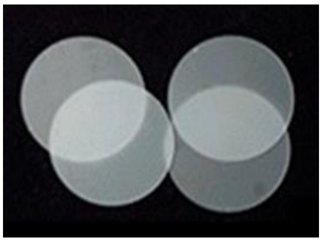
After process cutting the lumbered bar become a piece of quartz crystal with the thickness about 0.20 – 0.24 mm (use 0.25 mm spacer in cutting process), and size about 10 x 27 mm. The piece of quartz crystal was called the wafer. After cutting process, the thickness of wafers did not the same. The goal of lapping wafers is to make the wafer thickness be the same or in the range 0.19 – 0.21 mm.

4.4 Dimensioning or Shaping

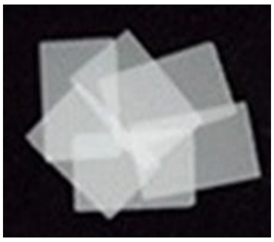
The next process is the process of dimensioning or shaping. In this process, wafers are shaped into a blank with the size and shape in accordance with the order. In this process wafers were stacked of one another and then glued together to form a wafer stick. Then the wafer stick is made round or cut according to the size of the order. After this process, the wafers quartz crystal become the blank quartz crystal. It can be round or rectangular as shown in figure 9.



Wafers



Round blanks



Rectangular blanks

Fig. 9. Wafers and blanks

4.5 Blank Lapping

In the blank lapping process, the thickness is no longer the target, but a frequency is a target, where the target frequency is in accordance with the order from user. In this case the thinner blank then the higher the frequency. The formula that connects between the frequency and the thickness is shown in equation 1. Frequency [kHz] = 1670 / thickness [mm]. In the blank lapping process used green silicon carbon powder. If we want the crystal oscillator work on the overtone frequency, then after lapping used green silicon carbon, the blank have to be polished.

4.6 Etching

It may have particles of green silicon and oil still stick on the surface of blank. The purpose of etching process is to clean the surface of the blank from the particles and smoothing the blank surface. The etching process is done by immersing the blank in fluorite acid or HF acid solution for a few seconds.

4.7 Cleaning

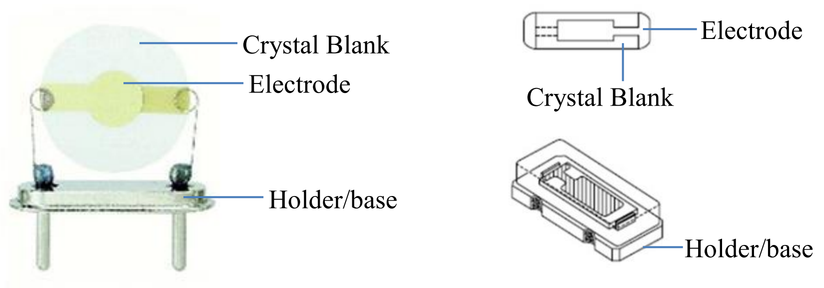
In this process, crystal blanks are washed in the ultrasonic washing machine with chemical liquid soap. The purpose of this cleaning process is to clean the surface of crystal blank from the particle and oil lapping that still attached to its surface. Cleanliness of the surface of the crystal blank will determine the quality of the crystal oscillator. In this process, crystal blank is inserted into the basket and then the basket placed into a stainless steel ultrasonic tub that was filled with solution of liquid detergent. Crystal blank was washed by ultrasonic machine approximately one to three minutes, depending on the thickness of the crystal blank to be washed and the number of blanks in the basket. When finished, the blank crystal soaked with alcohol and put them back to the ultrasonic machine in the basket with alcohol. After that, immerse the crystal blank with alcohol to absorb water. Once it's dry so no water spots on the surface of the crystal blank. After that, the crystal blank is inserted directly to the oven with a temperature between 80 -110 degrees Celsius for one hour. Once out of the oven then the crystal blank is ready to the next process, which is base plating process. If the blank do not clean, it will increase the motional resistance.

4.8 Base Plating

In this process, blank is given electrode on both sides by using silver or gold. When using gold it will be more resistant to corrosion or rust. But generally use silver. Blank will be placed on the mask, and the mask is inserted into the machine base coating. The process of base plating uses an evaporation technique at low pressure or vacuum. Actually, this low pressure just to lower the melting point of silver or gold, beside to pull out the oxygen gas trapped in the base plating machine.

4.9 Mounting

Mounting is the process to place the blank on the holder as shown in figure 10. The holders depend on the type of crystal. Some holder for round blank and some for rectangular blank.



Round blank and holder   Rectangular blank and holder

Fig. 10. Crystal blank on the holder

4.10 Frequency Adjustment

In this process frequency is adjusted so close to the target by adding silver to the electrode. Crystals are placed on a ring and covered by a mask in accordance with electrode diameter and is inserted into the vacuum machine. If the frequency more than 50 PPM from the target then silver will be sprayed on the electrode until the frequency range to 5 PPM.

4.11 Sealing

Sealing is process to cover crystal blank and holder. There are several techniques to seal between cover and holder. The most popular are resistance welding technique. Resistance welding is a process that use electrically to generated heat and force is applied to surface of material to bonds between holder and cover. The welding process is done in a chamber, fill in by nitrogen gas. The purpose of nitrogen is to pull out the oxygen gas, because the oxygen gas can make the electrode oxidation.

4.12 Final Test

The last process is final test. The quartz crystal unit is tested use the automated final test machine. Normally, the parameter which was measured as follow:

1. Frequency range.
2. Co (shunt capacitance), represents the capacitance of the crystal electrode including capacitance of the crystal holder and leads.
3. C_1 (motional capacitance), represents mechanical elasticity.
4. L_1 (motional inductance), represents mechanical inertia.
5. R_1 (motional resistance), represents mechanical losses.

5 Conclusion

Stability frequency on wireless devices became very important, because more and more the wireless devices used in daily life. From simple equipment such as TV remote, AC remote to complex equipment such as cell phone, access point, etc. These devices will not be able to function properly when the frequency interfering between the devices. Crystal oscillator unit is an electronic component that is responsible for frequency stability. Therefore all steps and processes in designing and manufacturing crystal oscillator must be considered carefully.

Orientation of cutting angle is very critical to the stability of frequency to change of temperature. Quartz crystal unit with the AT cut has the most stable frequency compare to others cutting angle.

The motional resistance R_1 will be higher if the surface of quartz blank is not clean or there are some particles on the surface. The higher motional resistance will need more energy to vibrate. In other word, it will drain the battery more if installed in the wireless devices.

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