Process Defects and Failure Analysis Methods of Crystal Oscillator

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Abstract. The common failure modes of crystal oscillators are vibration stop, waveform abnormality and frequency drift, there are many failure mechanisms, some of which are related to process defects, such as chip process defects, module packaging process defects and crystal process defects. In order to discover the process defects, summarize the performance, appearance, reason and failure analysis methods of its common process defects is necessary. Introduced several common process defects of current SMD crystal oscillators and corresponding analysis methods through specific case analysis.

1. Introduction
SMD crystal oscillator (hereinafter referred to as crystal oscillator) is an airtight module composed of a quartz crystal resonator and a bare chip of a peripheral circuit, which is often used as a clock source for electronic equipment. At present, there are many crystal oscillator manufacturers, and their process quality reliability guarantee ability is uneven. The main failure modes of crystal oscillators are vibration stop, abnormal waveform and frequency drift. Among them, failures caused by various process defects account for about 47%. Process defects have become the main source of crystal oscillator failure mechanisms. Common process defects of crystal oscillators mainly include quartz crystal defects, missing electrodes on the surface of the quartz crystal, and other defects related to the quartz crystal, crack of the conductive adhesive between the quartz crystal and the electrode column, chip bonding defects, chip surface scratches, and other defects related to the packaging process defects, chip breakage, interlayer dielectric defects of the chip surface metallization, chip passivation layer defects and other chip-related process defects. These process defects will cause such as local mechanical stress or electrical stress damage, fracture, quartz chip circuit open circuit and other manifestations, and these final failure characterization usually has covered the original defect morphology, therefore, it is relatively difficult to define the original defect through the final characterization. Through specific failure analysis cases, this paper introduces how to extract the essence from the analysis methods such as electrical testing and destructive analysis, so as to finally define the initial process defects that lead to failure.

2. Classification and proportion of common process defects of crystal oscillator
According to the statistics of failure analysis cases of a certain type of crystal oscillator, process defects can be divided into the following three categories: crystal process defects, packaging process defects, and chip process defects. The number and percentage of failures of these three types of process defects are shown in Table 1.
3. Analysis method of crystal oscillator failure caused by process defects

This section specifically introduces the analysis methods of crystal oscillator failure caused by these three types of process defects.

3.1. Crystal process defects

As the core element of the crystal oscillator, the crystal is composed of a precision-processed quartz crystal and the surface electrodes attached to both sides. According to the piezoelectric effect, the alternating voltage between the surface electrodes causes the quartz crystal to oscillate. The shape and size of the quartz crystal and the mass distribution of the vertical intersection of the surface electrodes play a key role in the oscillation frequency. Crystal defects or missing surface electrodes will cause the oscillation function to fail, which is a common type of crystal defects, and its failure is generally characterized by vibration stop and frequency drift.

The missing crystal and the missing surface electrode can generally be analyzed by optical microscopy. The following specific failure cases will introduce the analysis method of the crystal oscillator failure caused by the missing surface electrode.

A certain crystal oscillator has no oscillation waveform output. Test the volt-ampere characteristics (IV) of power supply (VDD), output (OUT) and standby (NC) to ground (VSS) at each port of the failed crystal oscillator, and no significant difference was found compared with the normal sample.

The crystal oscillator is opened, and the method of opening is to use sandpaper to polish and thin it and then cut with a sharp blade to ensure that it does not pollute the inside of the metal shell and minimize the mechanical stress of opening. Glue the bottom of the crystal oscillator to the fixed seat, and use 400# sandpaper to repeatedly polish the four edges of the metal cover on the crystal until the edges of the metal cover are obviously thinner. Be careful not to grind through to prevent particles from entering. Repeatedly spray alcohol during polishing. Clean and lubricate. After the metal cover becomes thin, use a utility blade to cut the upper cover. After opening the crystal oscillator, the crystal and surface electrodes can be seen, as shown in Figure 1. Using an optical microscope for internal inspection, it can be seen that the surface electrode of the quartz crystal in the failed crystal oscillator is missing at the junction and lead part, which causes the voltage of the surface electrode in this area to be abnormal, causing the crystal oscillator to stop vibration.

Table 1. Classification and proportion of process defect

| Process defects          | Number of failures | Percentage of failures |
|-------------------------|--------------------|------------------------|
| Crystal process defects | 21                 | 45.7%                  |
| Packaging process defects | 11               | 23.9%                  |
| Chip process defects    | 14                 | 30.4%                  |
The lack of surface electrode mainly comes from poor adhesion during the surface electrode sputtering process. Process defects such as crystal surface contamination before sputtering lead to a decrease in electrode adhesion, and partial electrode shedding occurs in the early stage, which may cause a change in the charge-to-mass ratio of the front and back of the crystal. The frequency misalignment will cause the electrode to open and stop vibration. The missing chip is mainly due to the bad stress in the quartz processing and subsequent processes, which can cause the vibration frequency to be inaccurate or even stop the vibration. The microscopic inspection method of the crystal after the crystal oscillator is opened can well identify the root cause of the crystal process defects.

3.2. Packaging process defects
The crystal oscillator of the hybrid structure package usually sinters the chip on the bottom, and leads the chip bonding pad to the external electrode through the bonding wire, and then connects the chip and the electrode through the electrode column. Packaging defects mainly include cracking of the conductive adhesive of the electrode column, wire bonding defects, scratches on the chip surface, etc. The failure mode caused by such defects is uncertain.

The packaging process defect analysis is generally judged by the optical microscope inspection of the internal appearance of the crystal after opening. The following specific cases will introduce the analysis methods of wire bonding defects and chip surface scratches.

Examples of wire bonding defects are as follows.
A certain failed crystal oscillator showed an abnormal waveform, the high level dropped to 1.10V, the high level of the output waveform of the normal sample was 5.12V, and the low level was -0.16V. Measure the IV characteristics of VDD, OUT, NC and VSS of each port of the failed crystal oscillator. Compared with the normal sample, the positive characteristic curve of VCC-VSS shifts to the left, and the forward voltage drop becomes smaller, and the positive characteristic curve of OUT-VSS shifts to the right, and the forward voltage drop becomes larger.

The metal casing is removed by the above-mentioned unsealing method, checking the quartz crystal, surface electrode and electrode column, no abnormalities were found, and the crystal failure was preliminarily ruled out. Remove the chip, the leads and the integrated circuit chip are visible. Check the bonding wire and internal and external bonding points under a microscope. It can be seen that the inner bond ball has different degrees of deviation and hits outside the bond pad and covers the active circuit area, as shown in Figure 3. The bonding point of the OUT port severely exceeds the bonding pad and covers the external circuit and transistors, causing stress damage to the circuit outside the bonding pad, causing failure of the shaping and amplifying circuit, resulting in abnormal output waveforms. Defects in the bonding process will not only cause bonding failures, but serious process problems such as the above-mentioned biased bonding points may even affect the circuit outside the bonding pad, damage the passivation layer or even the metalization layer of the chip, and cause circuit failure.

![Figure 3. Bonding point offset](image1)

![Figure 4. Transistor damage](image2)
Examples of chip surface scratches are as follows.

The performance of a failed crystal is abnormal waveform, the high level drops to 4.16V, the low level rises to 1.88V, the high level of the output waveform of the normal sample is 5.12V, and the low level is -0.16V. Measure the IV characteristics of VDD, OUT, NC and VSS of each port of the failed crystal oscillator. Compared with the normal sample, the positive characteristic curve of VCC vs. VSS shifts to the left, and the forward voltage drop becomes smaller, and the positive characteristic curve of OUT vs. VSS shifts to the right, and the forward voltage drop becomes larger.

Use the same method to open the package until the chip is exposed, and check the appearance of the circuit chip under a microscope. It can be seen that overvoltage breakdown and burnout occurred at the transistor position. There are obvious mechanical damage marks on the surface of the passivation layer near the burned circuit, as shown in Figure 4. Check the layout, this burnt-out transistor belongs to the part of the shaping amplifier circuit. Therefore, it is speculated that the root cause is that the chip is severely damaged by mechanical stress during the packaging process, which causes the circuit to leak and causes the damaged transistor to burn out after power-on.

Wire bonding defects originate from poor bonding process, mainly manifested as bonding craters and bonding position shift. The main source of chip surface scratches is abnormal stress damage during packaging. The cracking of conductive adhesive mainly comes from defects in the sticking process, and its sticking effect is directly related to the composition of the adhesive, the surface treatment state of the bonding surface, the pretreatment conditions, the curing conditions and the exposure environment. This type of defect also requires a microscope appearance inspection of the defect area after opening the cover to determine the source of the defect. If the microscope cannot determine it, a scanning electron microscope and an energy spectrum analyzer need to be used for further inspection to determine the morphology and foreign matter composition of the defect, identify the source of packaging process defects.

### 3.3. Chip process defects

The chip is a crystal oscillator integrated circuit component. The crystal oscillator circuit includes an oscillating circuit, a shaping amplifying circuit, and can be integrated with a voltage control circuit, a temperature control circuit, etc. according to requirements. Chip defects generally include chip structure breakage, dielectric defects between surface metallization layers, passivation layer defects, etc., resulting in uncertain failure modes, which mainly come from the chip production process. Chip structure breakage can cause circuit failure such as short circuit, leakage or open circuit. Dielectric defects and passivation layer defects usually cause circuit overheating damage. Chip structure breakage defects are generally judged by optical microscope inspection of the internal chip appearance of the crystal oscillator after opening. The analysis of the latter two defects is more complicated. Defective chips usually have different degrees of electrical damage after the crystal oscillator is powered on. The chip morphology after electrical damage may have covered the previous failure origin, so it is difficult to judge by the failure morphology Original defect.

The analysis and judgment of chip process defects are more complicated, and the following specific cases will introduce the analysis methods of chip defects.

A certain crystal oscillator exhibits an abnormal waveform, the low level floats to 4.04V, the high level of the output waveform of the normal sample is 5.12V, and the low level is -0.16V. Measure the IV characteristics of VDD, OUT, NC to VSS of each port of the failed crystal oscillator. Compared with the normal sample, the positive characteristic curve of VCC vs. VSS shifts to the left, the forward voltage drop becomes smaller, and the positive characteristic curve of OUT vs. VSS shifts to the right. The forward pressure drop becomes larger.

The metal casing is removed by the above-mentioned unsealing method, and the quartz crystal is mechanically removed, and the chip part can be seen. The appearance of the chip was inspected with an optical microscope, and it can be seen that overheating and carbonization morphology occurred on the internal chip VSS circuit of the failed crystal oscillator, as shown in Figure 5. It is speculated that the possible causes of overheating are: First, the cross-sectional area of the ground wire here is too small,
so that the resistance becomes larger, causing power loss and thermal damage; Second, the circuit under the bottom line has over-electric stress, and the ground wire is damaged; third, the dielectric defect between the ground wire and the lower circuit causes leakage between the upper and lower metallization circuits, and then overheat damage occurs.

The damage location is further analyzed using the method of grinding and delaminating. When grinding and removing the layer, glue the bottom of the chip to the fixed seat, polish it on a grinding and polishing machine. The polishing disc uses velvet polishing cloth with a rotating speed of 100 rpm and 1.0um diamond polishing agent. Use alcohol to lubricate and clean when polishing. Check the surface topography under a microscope every 10 rounds of polishing until it reaches the level to be analyzed.

After removing the passivation layer on the ground wire of the above chip, it can be seen that the carbonized area of the ground wire metalization layer is reduced, and the damage degree is reduced, as shown in FIG. 6. Further grinding to remove the layer, it can be seen that the damage on the ground metallization layer is further reduced, as shown in Figure 7. After further grinding, the ground metallization layer of the first layer was completely removed. It was found that the medium between the first metallization layer and the lower metallization layer did not have overheated or carbonized morphology, and the metallization of the lower layer did not overheat, only smaller cracks, and with the deepening of the grinding, the cracks below decrease, as shown in Figure 8, Figure 9, Figure 10. It is judged that the damage of the ground wire mainly occurs in the metallization layer of the ground wire on the outermost surface. The damage is caused by overheating of the ground wire, no leakage between the ground wire and the underlying circuit, and the underlying circuit and metallization are not hot spots for damage.
It is inferred that the failure mechanism of this sample is ground wire overheating, and the source of overheating is the power loss caused by the excessively small partial cross-sectional area of the ground wire metallization layer and the increase of resistance. The reason why the cross-sectional area of the ground wire metallization is too small here may be caused by the unevenness of the interlayer dielectric here. When there is a defect in the dielectric layer or the passivation layer, the metallization layer between the two will also be affected. When the cross-sectional area of the metallization layer is significantly reduced at the defect location, the resistance here will increase. After power-on, due to the increase of resistance, local power is too high and a lot of heat is generated, which causes damage to the surface and surrounding circuits. Capacitor cracking is a joint failure caused by medium squeezing after local overheating.

It can be seen that the source of chip defects cannot be determined only by microscopic inspection after opening. Only by further de-layering the chip with surface damage, and comparing the damage morphology of the passivation layer, metallization layer and dielectric layer, can the root cause of failure and the source of process defects be finally determined.

4. Conclusion
The failure mode of the crystal oscillator seems simple, but the corresponding failure mechanism and root cause are quite complicated. The above case analysis shows that some manufacturers have defects in crystal manufacturing, module packaging and chip manufacturing processes, which have led to the early failure of crystals in the customer link. This puts a severe test on the production and selection of domestic crystal oscillators. When the electrical measurement method cannot determine the root cause of the failure, the destructive analysis of the crystal oscillator, such as opening the cover, microscopic inspection, and chip delamination analysis, can effectively determine the failure mechanism and lock the root cause of the failure. At the same time, through the above destructive analysis methods, reasonable judgments can be made on the process defects and product quality of the crystal oscillator.

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