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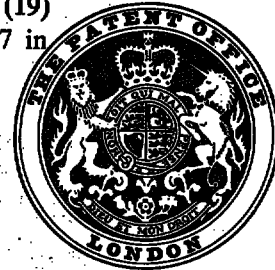
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(54) QUARTZ OSCILLATOR

(71) We, KABUSHIKI KAISHA SEIKOSHA, a Japanese Company of 6-21, 2-chome, Kyobshi, Chuo-ku, Tokyo, Japan, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

This invention relates to a thickness-shear mode quartz oscillator such as an AT-cut or a BT-cut quartz oscillator.

It has experimentally been confirmed by the inventors of this invention that in thickness-shear mode quartz oscillators there is an "abnormal frequency phenomenon" which is different from the well-known "jump phenomenon", the latter phenomenon being one in which the main vibration of the thickness-shear is drawn into sub-vibrations so that its mode is different from the mode of the main vibration. If this "abnormal frequency phenomenon" is present at the working temperatures and frequencies of the quartz oscillator, this gives rise to various problems such as unsatisfactory performance and unstable operation of the quartz oscillator.

According to the present invention, there is provided a thickness-shear mode quartz oscillator consisting of a thickness-shear mode quartz slice, driving electrodes formed on opposite surfaces of said quartz slice, and at least one additional mass formed on at least one of said driving electrodes, the shape of the or each said additional mass being non-circular, and/or the centre of the or each said additional mass being spaced from that of the slice, so that, at working temperatures and load capacitances, the frequency f_0 of the fundamental main vibration of the oscillator and the frequencies f_{ns} of a group of n -fold harmonics (where n is an odd number of 3 or more) satisfy the following relationships:-

$$f_0 \neq \frac{f_{ns}}{n}$$

The said quartz slice may have a convex lens-like shape having a larger thickness at its centre than at its peripheral portion.

Moreover, said additional mass may be transversely elongated, the longitudinal direction thereof being substantially parallel to the direction of the Z' axis or the X axis of said quartz slice.

Additionally, each of said driving electrodes may have an outwardly extending electrode which is formed to extend in a direction intersecting at right angles the longitudinal direction of the or each said additional mass.

In one embodiment, the quartz slice has a plano-convex shape and the or each said additional mass is formed on the plane surface of said quartz slice.

The invention is illustrated, merely by way of example, in the accompanying drawings, in which:-

Figures 1 and 2 are respectively a front view and a longitudinal sectional view at the centre of a conventional AT-cut quartz oscillator,

Figure 3 is a diagram of a driving circuit incorporating the oscillator of Figures 1 and 2, Figure 4 is a frequency-temperature characteristic diagram of the conventional AT-cut quartz oscillator,

Figure 5 shows side views of various types of quartz oscillators,

Figure 6 is a frequency-phase characteristic diagram of the conventional AT-cut quartz oscillator,

Figure 7 is a load capacitance characteristic diagram of the conventional AT-cut quartz oscillator,

Figures 8 and 9 are respectively a front view and a longitudinal sectional view at the centre of an AT-cut quartz oscillator of a first embodiment of an oscillator in accordance with the present invention,

Figure 10 is a frequency phase characteristic diagram of the AT-cut quartz oscillator of Figures 8 and 9,

Figure 11 is a load capacitance characteristic diagram of the AT-cut quartz oscillator of Figures 8 and 9,

Figure 12 is a frequency-temperature characteristic diagram of the AT-cut quartz oscillator of Figures 8 and 9,

Figure 13 is a front view of a second embodiment of an AT-cut quartz oscillator in accordance with the present invention,

Figure 14 is a front view of a third embodiment of an AT-cut quartz oscillator in accordance with the present invention,

Figure 15 is a schematic view showing the shape of various additional masses which may be used on an oscillator in accordance with the present invention,

Figure 16 is a schematic view showing the positions of various additional masses on oscillators in accordance with the present invention,

Figure 17 is a front view of a fourth embodiment of an AT-cut quartz oscillator in accordance with the present invention, and

Figure 18 is a diagram showing the relationship between the "plate-back quantity" of the additional mass of an oscillator of the present invention and the crystal impedance CI thereof, and between the "plate-back quantity" of the additional mass and the expression

$$\frac{f_{3s}}{3} - f_0$$

Figures 1 and 2 illustrate an example of a heretofore known plano-convex type AT-cut quartz oscillator (frequency $f_0 = 4.2$ MHz). Driving electrodes 2, 2, having a diameter of 5.20 mm, are formed on the opposite surfaces of a quartz slice 1 having a diameter of 8.00 mm and a centre thickness of 0.41 mm by evaporation or other methods. Outwardly extending electrodes 2a, 2a are formed to extend from the driving electrodes 2, 2 in the radial direction and are connected to supporting springs (not shown). An additional mass 3, in the form of a film, is formed on one of the driving electrodes 2 by evaporation or other method in order to adjust the the oscillation frequency f_0 . The additional mass 3 has a truly circular form and its centre is coaxial with that of the driving electrodes 2. The additional mass 3 is generally made of the same material as that of the driving electrodes (e.g. Au, Ag). If desired, an additional mass 3 may be fitted to each of the driving electrodes 2, 2. The quantity of material evaporated to form this additional mass 3 is referred to as a "plate-back quantity" and is expressed in terms of the frequency drop (KHz) caused by the addition of the same.

A number of quartz oscillators having the above-described construction are driven, as indicated at 4 in Figure 3, by a driving circuit consisting of a C-MOS type integrated circuit 5 not having a frequency selection circuit in its oscillation loop, the circuit having load capacitances C_1 , C_2 and C_3 to measure its frequency-temperature characteristics. The results of such measurement are shown in Figure 4 which is a graph whose ordinate represents the frequency 4(KHz) and whose abscissa represents the temperature $T(^{\circ}\text{C})$. Those portions of the graph which are circled represent the positions at which the above-mentioned, "abnormal frequency phenomenon" occurs.

It has been found that this "abnormal frequency phenomenon" arises from the mutual interference between a fundamental wave current, fed back by the fundamental main vibration, and a harmonic wave current fed back by the harmonic vibrations, and that this "abnormal frequency phenomenon" is different from the conventional "jump phenomenon". It has also been ascertained that this "abnormal frequency phenomenon" is more likely to occur in oscillators, as shown in Figures 1 and 2, having an additional mass 3 on a driving electrode 2 for the fine adjustment of the frequency. Moreover, this "abnormal frequency phenomenon" occurs more strikingly in convex lens type AT-cut quartz oscillators such as the plano-convex type of Figure 5(b), in the bi-convex type of Figures 5(c), and in the bevelled types of Figures 5(d) and 5(e), than in the plate type of Figure 5(a). It has also been confirmed that the "abnormal frequency phenomenon" takes place even in oscillators not having the additional mass 3.

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Figure 6 illustrates the frequency-phase characteristics (resonance characteristics) of a sample of conventional plano-convex type AT-cut quartz oscillators (in which the plate-back quantity of the additional mass 3 is 4 KHz) where f_0 is the fundamental frequency and f_{31} and f_{32} are a group of harmonics that are present near the triple d frequency of the fundamental frequency f_0 . As shown in the load capacitance characteristic curve of Figure 7, the fundamental frequency f_0 varies in accordance with the load capacitance C_L . (The frequency adjustment of the quartz oscillator uses this phenomenon). However, $f_{31}/3$ and $f_{32}/3$ hardly cause any change. In a practical application, the load capacitance C_L is mostly set by 10 PF or below because a smaller load capacitance generally provides a wider range for the frequency adjustment. Accordingly, in the working range of the load capacitance C_L , it sometimes occurs that the fundamental frequency f_0 coincides with the frequency $f_{32}/3$. Even when these frequencies do not coincide, they become coincident with each other in certain temperature conditions, because the frequencies are extremely close to each other. In this instance, the frequency $f_{32}/3$ exerts an influence on the fundamental frequency f_0 and thus causes the "abnormal frequency phenomenon". This generally applies to a group of harmonics of a multiple of an odd number of the fundamental frequency f_0 .

In other words, in an AT-cut quartz oscillator, depending upon the way in which the quartz oscillator was produced the driving circuit used and other factors, there are almost always present a series of groups of harmonics in the range of frequency n ($n = \text{odd number}$) times the fundamental frequency f_0 and the harmonic wave f_{ns} which satisfy the following equation (1):-

$$f_0 = \frac{f_{ns}}{n} \dots\dots\dots(1)$$

For the above-mentioned reason, the "abnormal frequency phenomenon" shown in Figure 4 is very likely to occur. The magnitude H of the "abnormal frequency phenomenon" (see Figure 4) becomes greater as the degree n of the harmonic wave f_{ns} becomes smaller.

The reason why this "abnormal frequency phenomenon" has not so far been a serious problem is that the occurrence of the phenomenon depends in particular upon the kind and performance of the driving circuit used therefor. This "abnormal frequency phenomenon" does not occur, for example, when an AT-cut quartz oscillator is driven by an oscillation circuit having one kind of frequency selection/tuning circuit such as a tank circuit. Moreover, when a C-MOS type integrated circuit not having a frequency selection circuit in its oscillation loop as shown in Figure 3 is used, the "abnormal frequency phenomenon" does not occur, or is small even when it does, if the high frequency response characteristics of the integrated circuit are not very good. As the high frequency response characteristics of the integrated circuit 5 become better, however, the "abnormal frequency phenomenon" is more noticeable and more likely to occur. Hence, the "abnormal frequency phenomenon" will become a serious problem in the future when the development of the integrated circuit proceeds further and its high frequency response characteristics are enhanced.

In Figures 8 and 9 there is therefore shown a first embodiment of an oscillator according to the present invention in which the "abnormal frequency phenomenon" is avoided.

As shown in Figures 8 and 9, an additional mass 3a in said first embodiment of the present invention is characterized in that it has a non-circular shape, that is to say, it is elongated in the direction of the Z' axis. In this embodiment, the quartz plate or slice 1, the driving electrodes 2, 2 and the outwardly extending electrodes 2a, 2a have the same shape and size as those in the conventional device. Figure 10 illustrates the frequency-phase characteristics of a sample whose additional mass 3a has a plate-back quantity of 4 KHz, and Figure 11 illustrates its load capacitance characteristics. As can be clearly seen from Figure 11, the fundamental frequency f_0 is sufficiently separated from the frequencies $f_{31}/3$ and $f_{32}/3$ that are one-third frequencies of a group of the tripled harmonics. Hence, these frequencies do not cross each other even when the load capacitance C_L is varied. As previously described, this results from the fact that the piezo-electric effect and the effects of the addition of the additional mass 3a are different between the fundamental vibration and the harmonic sub-vibrations, so that the rate of change in the respective frequency becomes different. It has been found that this also applies as such to other samples. Using the same driving circuit as the conventional circuit shown in Figure 3, the frequency-temperature characteristics of the oscillator is measured in the range of temperature of from -30°C to $+70^\circ\text{C}$. As shown in Figure 12, the characteristic curve continuously changes and the "abnormal frequency phenomenon" cannot be seen at all.

This generally holds good also for the non-circular additional masses 3b -3f shown in

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Figures 15(a)–(e). Various other shapes may also be employed.

Although the longitudinal direction of the additional mass 3a of Figures 8 and 9 is substantially in conformity with the Z' direction of the quartz slice 1, it may be substantially in conformity with the X direction as shown in Figure 13. In this case, the space between the additional mass 3a and the respective outwardly extending electrode 2a can be made sufficiently large, thereby eliminating a short-circuit with the supporting spring even if the position of the additional mass 3a varies considerably during evaporation. In comparison with the embodiment wherein the longitudinal direction of the additional mass 3a coincides with the direction of X axis of the quartz slice shown in Figure 13, the embodiment wherein the longitudinal direction of the additional mass 3a coincides with the direction of Z' axis shown in Figure 8 provides a greater effect in preventing the "abnormal frequency phenomenon".

It is customary to arrange the outwardly extending electrodes 2a, 2a of the driving electrodes 2 in the direction of the Z' axis in view of the ageing characteristics. In order to reliably eliminate the "abnormal frequency phenomenon" at the sacrifice of the ageing characteristics to a certain extent, the outwardly extending electrodes 2a, 2a are formed in the direction of the X axis and the additional mass 3a is formed in the direction of the Z' axis. In comparison with the case where the longitudinal direction of the additional mass 3a is in conformity with the X axis (as shown in Figure 13), the prevention of the "abnormal frequency phenomenon" is further reduced when the longitudinal direction of the additional mass 3a is positioned at an angle of 45° with respect to the Z' axis or to the X axis.

In the embodiments shown in Figures 8, 9, 13 and 14, the additional mass 3a is formed at the central position of the quartz slice 1. However, the same effect can be obtained, as illustrated in Figure 16, by forming the additional mass 3a at positions 4a – 4d such that the centre of the additional mass 3a does not coincide with the centre 0 of the quartz slice 1. In this case, the additional mass 3a may have a single circular shape as in the conventional addition mass 3 (shown in Figure 1). It is also possible to combine additional masses 3a – 3f, as shown in Figures 8, 9 and 13-15 of various non-circular shapes with the above-mentioned positions 4a – 4d.

Furthermore, the same effect as in the embodiment of Figure 16 can be obtained by disposing a plurality of completely separated additional masses 3g, 3g at positions each of which is spaced from the centre 0 of the quartz slice 1 as shown in Figure 17. In this case, the additional masses 3g, 3g may have any desired shape including a true circle.

The additional mass 3a shown in Figure 8, the additional mass 3c shown in Figure 15(b), and the additional masses 3g, 3g shown in Figure 17 are respectively fitted at the centre 0 of a quartz slice 1 having the same shape and size as the quartz slice 1 of the above-mentioned embodiments by respectively varying the plate-back quantity m to form thereby quartz oscillators having a 4.2 MHz band. Each of the oscillators thus produced is driven at a load capacitance $CL = \infty$, and the crystal impedance CI and the value

$$\frac{f_{3s}}{3} - f_0$$

are measured. The results of the measurement are shown in Figure 18.

It has been found from the experimental results that when the load capacitance C_L is ∞ in the 4.2 MHz band, the occurrence of the "abnormal frequency phenomenon" can be reliably restrained even by setting the load capacitance C_L in the ordinary working range (10 pF or below) if the following relationship is satisfied:-

$$\frac{f_{3s}}{3} - f_0 > 1.7 \text{ KHz} \quad \dots\dots\dots(2)$$

Next, observation is made on each of the additional masses 3a, 3c and 3g. In the case of the additional mass 3a, the crystal impedance CI tends to become excessively large when the plate-back quantity m becomes great, whereas the additional mass 3g tends to fail to satisfy the above-mentioned relationship (2) due to production errors etc., when the plate-back quantity m is small. Hence, the additional mass 3c is preferable.

In the case of the plano-convex type, the additional masses 3a etc are preferably formed on the plane surface rather than on the curved surface because it has been experimentally confirmed that undulation tends to occur in the frequency-temperature characteristic curve when the additional masses 3a etc. are formed in the curved surface.

Although the foregoing embodiment of the present invention relate to AT-cut oscillators, the explanation applies also to other thickness-shear modes such as BT-cut oscillators.

As described in detail in the fore-going paragraphs, the additional mass in accordance with the present invention has a non-circular shape or its centre is spaced from the centre of the quartz slice or both these features are combined together, in order to sufficiently separate the frequency

$$\frac{f_{ns}}{n_f}$$

from the fundamental frequency f_o and thus always to satisfy the relationship

$$f_o \neq \frac{f_{ns}}{n}$$

under varying conditions by utilizing the fact that the piezo-electric effect and the effect of addition of the additional mass over the fundamental main vibration are different from those over a group of n -times the harmonics having frequencies f_{ns} . In consequence, it is possible to reliably prevent the occurrence of the "abnormal frequency phenomenon" simultaneously with the fine adjustment of frequency. Accordingly, the operation of the quartz oscillator is stabilized and its characteristics become excellent. The prevention of the "abnormal frequency phenomenon" can be effected merely by changing the shape or the position of the evaporation mask. Hence, the carrying out of the present invention never requires any change in the conventional production process and is therefore extremely simple. In particular, an AT-cut quartz oscillator in accordance with the present invention works extremely well when connected in a C-MOS type integrated circuit not having a frequency selection circuit in its oscillation loop, and this fact will become more noticeable as the high frequency response characteristics of the integrated circuit are further improved.

WHAT WE CLAIM IS:-

1. A thickness-shear mode quartz oscillator consisting of a thickness-shear mode quartz slice, driving electrodes formed on opposite surfaces of said quartz slice, and at least one additional mass formed on at least one of said driving electrodes, the shape of the or each said additional mass being non-circular, and/or the centre of the or each said additional mass being spaced from that of the slice, so that, at working temperatures and load capacitances, the frequency f_o of the fundamental main vibration of the oscillator and the frequencies f_{ns} of a group of n -fold harmonics (where n is an odd number of 3 or more) satisfy the following relationship:-

$$f_o \neq \frac{f_{ns}}{n}$$

2. An oscillator as claimed in claim 1 wherein said quartz slice has a convex lens-like shape having a larger thickness at its centre than at its peripheral portion.

3. An oscillator as claimed in claim 1 or 2 wherein said additional mass is transversely elongated, the longitudinal direction thereof being substantially parallel to the direction of the Z' axis of the X axis of said quartz slice.

4. An oscillator as claimed in claim 3 wherein each of said driving electrodes has an outwardly extending electrode which is formed to extend in a direction intersecting at right angles the longitudinal direction of the or each said additional mass.

5. An oscillator as claimed in claim 1 wherein said quartz slice has a plano-convex shape and the or each said additional mass is formed on the plane surface of said quartz slice.

6. A thickness-shear mode quartz oscillator substantially as hereinbefore described with reference to any of Figures 8, 9 and 13-17 of the accompanying drawings.

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As described in detail in the fore-going paragraphs, the additional mass in accordance with the present invention has a non-circular shape or its centre is spaced from the centre of the quartz slice or both these features are combined together, in order to sufficiently separate the frequency

$$\frac{f_{ns}}{n}$$

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$$f_0 \neq \frac{f_{ns}}{n}$$

2. An oscillator as claimed in claim 1 wherein said quartz slice has a convex lens-like shape having a larger thickness at its centre than at its peripheral portion.

3. An oscillator as claimed in claim 1 or 2 wherein said additional mass is transversely elongated, the longitudinal direction thereof being substantially parallel to the direction of the Z' axis of the X axis of said quartz slice.

4. An oscillator as claimed in claim 3 wherein each of said driving electrodes has an outwardly extending electrode which is formed to extend in a direction intersecting at right angles the longitudinal direction of the or each said additional mass.

5. An oscillator as claimed in claim 1 wherein said quartz slice has a plano-convex shape and the or each said additional mass is formed on the plane surface of said quartz slice.

6. A thickness-shear mode quartz oscillator substantially as hereinbefore described with reference to any of Figures 8, 9 and 13-17 of the accompanying drawings.

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