HIGH FREQUENCY QUARTZ RESONATORS AND FILTERS OPERATING AT FUNDAMENTAL MODE

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Abstract

This paper describes firstly a high frequency fundamental (HFF) quartz resonator in the frequency range from 80MHz to nearly 1GHz operating at fundamental mode, which fabricated by an industrial photolithographic batch manufacturing process with chemical etching, secondly HFF monolithic crystal filter (MCF) developed for 1st intermediate frequency (IF) filter of mobile communication systems such as cellular phones.

We describe here in detail, the design approach including batch process etching technology. Through photolithography, 56 patterns are chemically etched on one wafer. Then, a similar etching process automatically adjusts the wafer thickness in accordance with frequency. Further, we describe technology for miniaturization, realizing higher frequency and suppression of the spurious response.

By our above developed technology, we achieved miniaturized 1st IF filters at center frequency range of 70MHz to 300MHz with sharp selectivity for mobile communication systems such as cellular phones.

1. Introduction

New development in mobile communication systems requires higher operating frequencies, and smaller size and lighter weight of equipment. Therefore, resonators and MCFs are required to be miniature models with higher operating frequencies. In resonators and MCFs using the fundamental mode of thickness shear AT-cut crystals with excellent temperature characteristics, obtaining high operating frequencies involves to thin the wafer thickness. With the mechanical restrictions on fabricating, 50MHz has been the upper limit for the fundamental operating frequency at thickness of about 33µm. Even if it were possible to lap and polish to a thinner wafer, it would be difficult to implement mass production and ensure high reliability. Because it would have insufficient mechanical strength and, as a result, such problems as damage in assembly process, by vibration and mechanical shock.

In recent years, several studies have suggested that the problems mentioned above may be eliminated by etching technology which employs photolithography and that higher frequencies may be achieved by milling only the central portion of the wafer to a minimum thickness[1]-[7].

In this paper, we reported that we have accordingly employed a batch processing method with chemical etching that has not been previously attempted, in order to achieve high frequency. We have produced HFF quartz resonators in the frequency range from 80MHz to nearly 1GHz operating at fundamental mode[8]-[10]. Further, we described further miniaturization, achieve higher frequency and suppression of the spurious response. We have developed HFF-MCFs at center frequency range of 70MHz to 300MHz with sharp selectivity for 1st IF filter of cellular phones.

2. Structure of HFF quartz resonator

Figure 1 shows the structure of one such HFF quartz resonator that we have developed.
Since the resonance frequency of thickness shear AT-cut crystal, which provides excellent temperature characteristics, is in reverse proportion to the thickness of the substrate, the substrate must be extremely thin, at approximately 17\(\mu\text{m}\) to achieve 100MHz or approximately 3\(\mu\text{m}\) to achieve 500MHz in the fundamental mode. Thus, mass production has not been possible with conventional mechanical fabricating, which employs a lapping and polishing method. Higher frequencies are achieved by chemical etching the central area of an AT-cut crystal substrate with a thickness of 80\(\mu\text{m}\), which is relatively easy to handle, through etching from one side.

Aluminum with low density was used for main electrode and ground electrode was formed by vacuum evaporation on the entire surface of the crystal wafer on the side that had been etched. On the flat surface on the other side, main electrode was formed through photolithography.

The main electrode is located on the flat surface, with the reverse side electrode on the etched concave surface. Since the plate back ratio, which determines the extent of energy trapping, depends solely on the film thickness of the main electrode in this structure, the structure therefore has an advantage in that it allows the film thickness of the conventional resonator to be doubled when the film thickness of the electrode is reduced with a higher frequency.

### 3. Fabrication process of HFF quartz resonator

The fabrication process for the HFF quartz resonators is shown in Figure 2. The AT-cut crystal wafer to be used for fabrication is a polished wafer (25mm x 20mm x 0.08mm), cut out from a synthetic quartz which has etch channel density 3 or less of per sq.cm. The crystal wafer is formed through surface treatment with a hydrofluoric acid solution in order to completely remove machining distortions on the surface and vacuum evaporation of gold with chrome as a base for enhancing the strength of the bond with the crystal. A crystal etching pattern is formed through photolithography, which makes it possible to form 56 elements at a time on a wafer.

A hydrofluoric acid solution which is heated to approximately +85 \(^\circ\text{C}\) is used during the crystal etching process to etch only the vibration area to the thickness which corresponds to the desired frequency.

All the frequencies of the individual elements in the vibration area on the crystal wafer thus etched are measured, and adjustment is performed using a final etching equipment, which etches only the vibration area through computer control so that all the elements will achieve the target frequency. Figure 3 and 4 shows the measurement system of wafer thickness and the adjustment system of wafer thickness.

After aluminum vacuum evaporation, the main electrode pattern is formed through photolithography on the flat side, which is not etched. The entire surface of the etched side is covered by a ground electrode. Because of this, an electrode pattern is achieved with higher dimensional accuracy than mask evaporation methods, which have been conventionally used for electrode formation.

The 56 elements on the crystal wafer for which the frequency adjustment has been performed are then cut out in segments of approximately 2.4mm x 2.4mm and these are mounted in a ceramic package with conductive paste. Then, the main electrode is connected to terminal of the ceramic package through wire bonding with aluminum.
The final frequency adjustment is performed from the split electrode side through silver vacuum evaporation. After the adjustment is complete, it is sealed within a nitrogen gas atmosphere, employing the seam welding method, which offers a high degree of reliability since the temperature at the time of sealing does not affect the elements.

4. Characteristics of HFF quartz resonator

We prepared prototypes of HFF quartz resonators with resonance frequencies from 80MHz to 930MHz to investigate their potential for application in oscillators or filters.

Note that the prototypes of the resonators were constituted from a crystal wafer obtained from synthetic quartz with a material Q value at 2 million. Aluminum was used to constitute electrodes with the sizes of the main electrodes at 0.6mm x 0.6mm, 0.3mm x 0.3mm and 0.15mm x 0.15mm and the thickness of the electrode film at 0.1nm both at the front and the rear. The prototype resonators were mounted in TO-5, which is a standard package, and the S-parameter method using a Hewlett Packard (HP) 8753C Network Analyzer was employed to measure the equivalent circuit parameters. Typical equivalent circuit parameters of the resonators thus measured are shown in Table 1 while the relationships along the resonance frequencies at 159MHz through 931MHz, the obtained Q values and the material Q value of the synthetic quartz used are shown in Figure 5. The obtained Q value of the HFF quartz resonators is approximately 30 % of the material Q value.

Figure 6 shows the frequency temperature characteristics of the HFF quartz resonator in the resonance frequency of 130MHz. Figure 6 shows that the cubic curve characteristics particular to the AT-cut resonator are achieved.

Table 1 Measured equivalent circuit constant of the HFF quartz resonators.

<table>
<thead>
<tr>
<th>Fs [MHz]</th>
<th>158.1</th>
<th>319.04</th>
<th>754.62</th>
<th>931.47</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 [Ω]</td>
<td>11.2</td>
<td>14.7</td>
<td>16.3</td>
<td>15.4</td>
</tr>
<tr>
<td>L1 [μH]</td>
<td>154</td>
<td>77</td>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>C0 [pF]</td>
<td>2.5</td>
<td>2.0</td>
<td>2.0</td>
<td>2.3</td>
</tr>
<tr>
<td>C1 [fF]</td>
<td>6.6</td>
<td>3.3</td>
<td>3.1</td>
<td>4.7</td>
</tr>
<tr>
<td>C0/C1</td>
<td>387</td>
<td>607</td>
<td>642</td>
<td>475</td>
</tr>
<tr>
<td>Electrode size</td>
<td>0.60</td>
<td>0.30</td>
<td>0.15</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Figure 5 Frequency vs. measured Q values of HFF quartz resonators.
Consequently, it is verified that the manufacturing method for the HFF quartz resonators using chemical etching does not present any problems.

5. Application for cellular phone IF filters

5.1 Further miniaturization of HFF-MCF

On the basis of the basic structure of the HFF-MCF chip as above, the miniaturized HFF-MCF is constructed, however, details of its structure is different from that of the conventional HFF-MCF. For comparing the details, the structure of a conventional HFF-MCF is shown in Figure 7(a), while that of the miniaturized HFF-MCF is shown in Figure 7(b). In the structure of a conventional HFF-MCF, the wire-bonding and single-fixed-point die-bonding method are utilized, while a face-down method is utilized as a bonding method for achieving the miniaturization, whereby the HFF-MCF chip is placed with the sprit electrode facing down, and the three points on the input/output electrodes and ground electrode are connected to the ceramic package by a silicone-based conductive paste and held cantilevered.

Since the wire-bonding space of the package which was necessary with conventional structures is no longer needed with the face-down method, now it is possible to house the HFF-MCF chip in a miniaturized ceramic package with external dimensions of 3.8mm x 3.8mm x 0.9mm becomes possible even though the same-sized conventional HFF-MCF chip (2.4mm x 2.3mm x 0.08mm) is used here as well.

The passband characteristics and the group delay characteristics of a 130MHz 2-pole HFF-MCF are shown in Figure 8 and its stopband attenuation characteristics are shown in Figure 9.

5.2 Higher frequency of HFF-MCF

High productivity in the mass production is achieved by batch processing performed in the wafer state from electrode pattern formation through frequency adjustment. In this manufacturing method, it is important to ensure uniform thickness for each of the chips on the wafer. Adjustment of thickness is made to within approximately ±30nm or less by additional and individual etching on each chip after the main etching process. With this method, HFF-MCF with a center frequency of 150MHz can be produced with the precision of frequency within ±30ppm.
In case of realizing the frequencies beyond 150MHz, it is difficult to achieve the desired filter characteristics, because the thickness of vibration area is extremely thin, and as the amount of frequency adjustment by evaporation after a single individual etching process excessively increase, compared to the thickness of vibration area. However, by repeating individual etching using the dilution etchant for high-precision thickness adjustment etching, the thickness distribution for individual chips in the wafer was reduced to within ±10nm, and this makes the filter characteristics demanded realizable.

The passband characteristics and the group delay characteristics of a 250MHz 2-pole HFF-MCF are shown in Figure 10 and its stopband attenuation characteristics are shown in Figure 11. HFF-MCFs up to approximately 300MHz are thought to be practically realizable by batch process manufacturing using this method.
5.3 Better performance of HFF-MCF

We produced of 130MHz filter in 4-pole configuration in which two 2-pole HFF-MCF elements are connected in cascade. Its passband characteristics and group delay characteristics are shown in Figure 12 and its stopband attenuation characteristics are shown in Figure 13.

So, we examined methods for suppressing spurious responses generated in the higher side stopband. The method which is normally used to suppress spurious responses in MCF involves determining the dimensions of the electrode and the volume of plateback based upon the theory of energy trapping. However, it is very difficult to suppress more than 80dB. We solved the problem with a 4-pole configuration in which two elements are connected in cascade and by suppressing spurious responses generated at the individual elements by shifting the frequency positions of these spurious responses in relation to each other. We attempted an improvement in the attenuation by designing a pattern in which the ratio (W/L) in the electrode dimensions is varied. The design parameters are shown in Table 2.

The electrode patterns A and B shown in Table 2 have different ratio (W/L) and different distance (D) dividing the split electrode. In order to match the terminal impedance and the passband width between the input and the output, the electrode area (WxL) and the electrode film thickness were made the same in patterns A and B.

Figures 14 and 15 show the spurious response characteristics of the 2-pole filter with the electrode patterns A and B respectively in the prototypes. The results clearly reveal that the spurious responses generating positions are offset.

Therefore, we made a 4-pole configuration with two elements connected in cascade, using the 2-pole filters in which the spurious response characteristics are different from each other.

<table>
<thead>
<tr>
<th>Pattern A</th>
<th>Pattern B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension [mm]</td>
<td>W</td>
</tr>
<tr>
<td>0.35</td>
<td>0.22</td>
</tr>
<tr>
<td>Ratio (W/L)</td>
<td>1.6</td>
</tr>
<tr>
<td>Area (WxL) [mm²]</td>
<td>0.08</td>
</tr>
<tr>
<td>Film thickness [nm]</td>
<td>0.10</td>
</tr>
</tbody>
</table>
Figure 14  Spurious response characteristics of 130MHz 2-pole HFF-MCF (electrode pattern A).

Figure 15  Spurious response characteristics of 130MHz 2-pole HFF-MCF (electrode pattern B).

Figure 16 shows its stopband attenuation characteristics. In the attenuation, the spurious response is suppressed at both high and low center frequencies, while permitting attenuation characteristics greater than 75dB for more than f0±200kHz. In addition, characteristics for the passband and the group delay were achieved that are completely identical to those described earlier.

Featuring excellent attenuation characteristics, the filter works as the 1st IF filter in the RF section of cellular phones, helping to cut down on the number of orders of 2nd IF ceramic filter. This helps decrease the height of ceramic filters, contributing greatly to achieving thin designs in cellular phones.

6. Conclusion

We established the etching technology of a batch processing system effective in mass production. The high frequency quartz resonators to about 1GHz which operating at fundamental mode were fabricated by this method. The HFF quartz resonators having the value of measured equivalent circuit constant and the cubic curve with the frequency temperature characteristic particular to an AT-cut crystal was obtained. Consequently, it was verified that the manufacturing method for the HFF crystal resonators using chemical etching does not present any problems.

Further, we described further miniaturization, achieve higher frequency and suppression of the spurious response. We realized miniaturization HFF-MCF with low loss, sharp selectivity and low impedance for 1st IF filter of cellular phones which has a center frequency range of 70MHz to 300MHz.
References