Collective Fabrication of 20 MHz Resonators by Deep Reactive Ion Etching on 3 ” Quartz Wafers

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Abstract— **High quality resonators for spatial and military applications are only made by unitary way and high speed directional etching of piezoelectric material is yet insufficiently developed to produce high aspect ratio microstructures.**
So, in this paper, we report on the theoretical definition and on the realization of BAW resonators, working at 20 and 40 MHz. Part of mechanical process is made by deep Reactive Ion Etching of AT- and SC-cut quartz crystal wafers. To avoid edge effects such as mechanical stresses induced by mounting structure or leakage of the vibration mode, we have to realize a good energy trapping of the selected resonant frequency. Several trapping methods can be used depending on the frequency, thereby changing the resonator design, such as mass loading by electrodes themselves, mesa forms (i.e. 1 to 3 µm circular or elliptical steps), or radius of curvature on one face of the resonator at least. Here, for question of manufacturing, we choose to trap the energy by a mesa form.
Fabrication of complete mesa architecture with bridges aperture (like in a bva structure) requires combining high depth (about 140 µm for a 40 MHz 3rd overtone resonator), high aspect ratios, good uniformity over the entire wafer (for about 40 resonators), vertical wall profiles and reasonable etching selectivity.
After describing different RIE processes, we analyze the quality of the realization through the surface roughness, the geometry, the homogeneity of the mesa-step, the wall profile.

I. Introduction

Within the framework of a french project aimed achieving quartz resonators for Time and Frequency applications, and entitled "*Crystal resonators modeling and innovative process for miniaturization*", we investigate several manufacturing processes compatible with 3 or 4" wafers. Indeed, innovative technological processes, such as micromachining, multi-layers assembly or wafer bonding can be successfully applied to quartz, in order to minimize packaged resonators while optimizing their performances. Our challenge is summarized in the following sentence:

"Smaller, cheaper and better performances"

Unfortunately, current manufacturing technology for BAW quartz resonators does not allow reducing the size and the cost. We therefore have to study collective processes, which are well-known in the Silicon industry.

II. Presentation of our procedure

In this paper, we present the manufacturing process of small resonators designed to vibrate at 20 MHz on their 3rd overtone (corresponding to a thickness of about 280 µm, which is a standard value for the purchased quartz wafers). Among different collective etching techniques (chemical etching, UltraSonic Machining or grinding and polishing…), we study the realization of resonators using the DRIE technique which is described in [1]. This technique has already proved that it is conceivable to realize mesa on the active part of the resonator and the apertures defining the links (or bridges) between active and dormant parts. Indeed, previously, we have fabricated few resonators in a 140 µm thick quartz wafer of 1.5 x 1.5 square inches using DRIE. The apertures were completely opened at least in the resonator made in the center as shown in the Fig. 1. We see here that the etching depth is not exactly the same in the entire surface of the wafer, but it is very difficult to measure it due to the strains (and fractures) induced by the thermal expansion created during the etching.

Fig. 1: DRIE of a small quartz wafer (1.5 x 1.5'' square)

So hereafter, we describe two different procedures in order to manufacture resonators with a "double step" on one face as shown in Fig. 2. This succession of steps on the surface is necessary if we want to discretize correctly the radius of curvature realized on resonators working at a few MHz in the way to correctly trap the energy of vibration. Therefore, we will first realize 2 steps with a size of few tens of µm each. After the machining of the apertures, we plan to implement the full procedure for manufacturing 37 resonators on a 3" AT-cut quartz wafer.

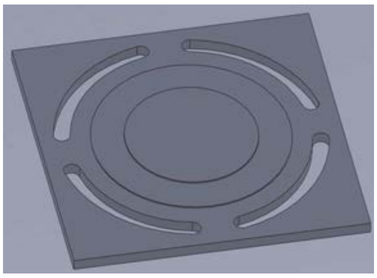

Fig. 2: design of the desired resonator

III. FIRST DRIE QUARTZ ETCHING PROCESS

In this first test procedure, we realize a succession of wet etchings in order to structure layers of Nickel. The total thickness has first been deposited to allow the total etching of about 140 µm. To etch 150 µm of quartz, we have to coat 8 µm of Nickel using the "electrolytic" method (selectivity 1:20). These two preliminary etching operations are separated by a coating of photoresist, exposed to light through a mask defining our pattern. Another etch of about 2 µm of Ni by *Ferric Chloride* is performed. The last etching operation is made to remove the last 4 µm of Ni at the level of the apertures.

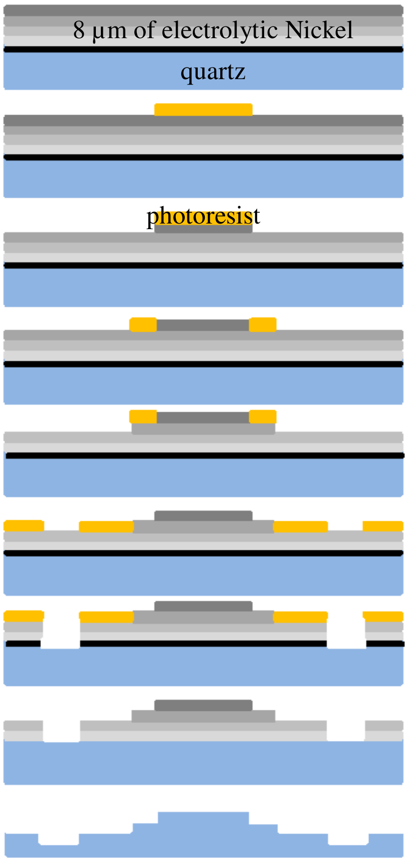

Fig. 3: procedure to structure layers of Nickel

Unfortunately, the chemical etching process of the Ni by Ferric Chloride is very inhomogeneous. Up to now, it is impossible to calibrate the thickness to be removed. Furthermore, the thickness of Ni on the quartz wafer is too thick and cracks appear systematically during the ionic etching which generates very high stresses.

IV. SECOND PROCEDURE

We have then tested a second procedure, which is more "classical" and consists in 3 successive phases with 3 different masks (Fig. 4): the first one realizes the apertures (first mask on the left) with the coating of 4 µm of electrolytic Ni allowing the dry etching of 80 µm of quartz.

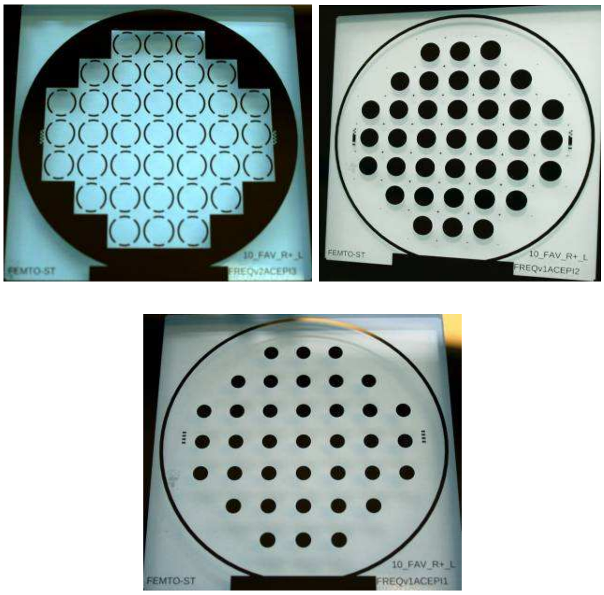

Fig. 4: Three successive masks for our second procedure

Then, coating of a new layer (about 2µm) corresponding to the pattern defining the biggest mesa and dry etching for a 40 µm step is performed. Finally, the third coating defines the small mesa with also 2 µm of Ni. Unfortunately, here also, the mechanical stresses induced by the layer of electrolytic Ni submitted to high temperatures during the DRIE process deform the quartz wafer up to cracks (see Fig. 5). Several tests have been realized in changing the temperature in the back of the substrate, but the problem remains the same: the wafers still break down.

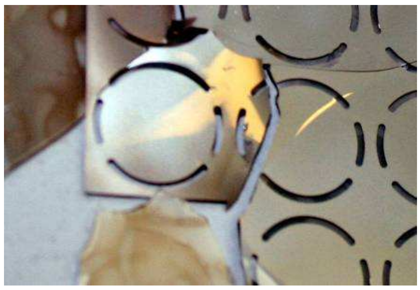

Fig. 5: photography of an example of crack after DRIE

Nevertheless, we have observed MESAs on the AT-cut quartz wafer and we have measured the height of some steps.

Classically, on our STS machine, the etching process is faster on the edges than on the center. Here, we have etched 27 µm in the edges and only 17 µm in the middle.

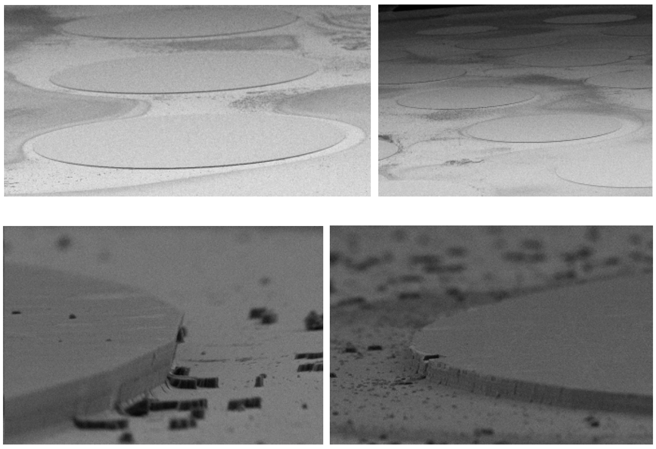

Fig. 6: MESAs observed by BEM… and details of the steps

V. THIRD PROCEDURE

The last procedure described here aims to prove that it is possible to chain 2 realizations of mesa one after another; the apertures (defining the bridges) may be made, at the end, using Ultrasonic Machining [2].

Considering the small heights of the steps to realize (see Fig. 7 below), we have finally chained here 2 Reactive Ion Etching processes, allowing etching 2 to 2.5 µm thick on quartz. Indeed, our wafer is 280 µm thick, processed to realize resonators working at about 20 MHz on their 3[rd] overtones. So, a 1000 mm radius of curvature seems satisfactory to trap correctly the vibrating energy and the 2 corresponding steps have to be of about 2 to 2.5 µm height.

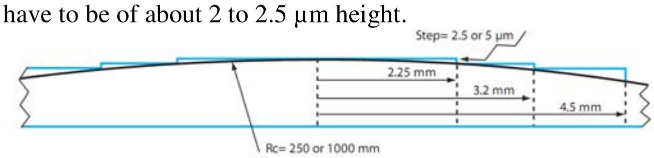

Fig. 7: example of discretization of a given radius of curvature

If the photoresist has been deposited by spin coating for the first step, we have coated it by spray coating for the second one, the relief of the first deposit being too high. We see in Fig. 8 that the quality of the pattern is the same than previously.

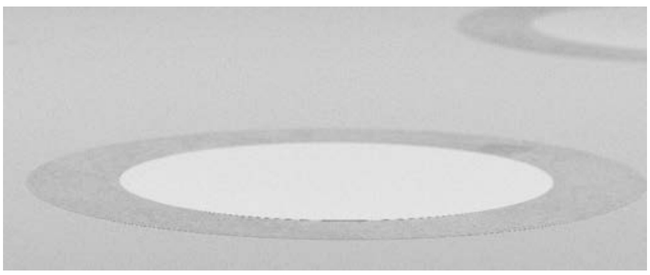

Fig. 8: The 2 MESAs with 4.5 and 6.4 mm of diameters

But, if the surface roughness does not depend on the number of the manufacturing process, the quality of the edge of the pattern is highly dependent on how the photoresist is deposited. Indeed, a thickness of the resin deposited by spin coating is uniform only if the surface of the wafer is uniform, a pattern higher than 2 µm creating a kind of bulge in the thickness of the coating. And consequently, the edge of the pattern will have the quality of the deposition, this defined by the spray coating being linked to the microbubble size of the spray. The 2 Fig. 9 below illustrate this difference.

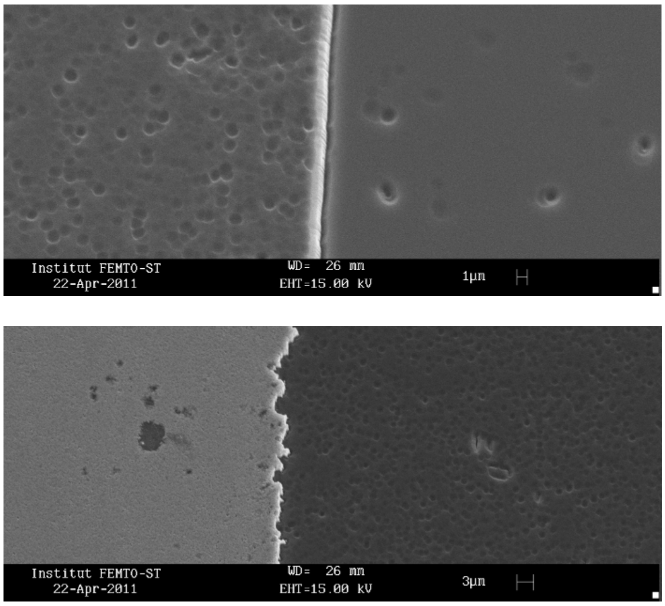

Fig. 9a and 9b: definition of the edges of the first and second MESA, linked to the quality of the deposition to the Nickel (spin coating for the first one and spray coating after).

And so, the height of the step is not uniform as shown in the Fig. 10 where we indicate 2 different values of steps: 2 and 3 µm which are the minimum and the maximum of the step heights.

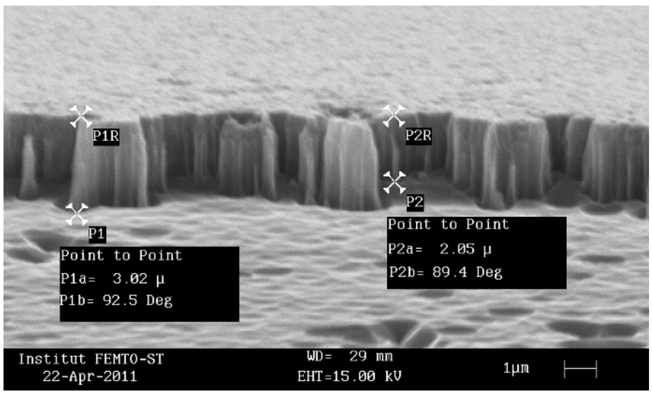

Fig. 10: second MESA: its height ranged between 2 to 3 µm (etching time: 70 min)

We note, at least, the second pattern has been obtained with the following conditions of Reactive Ion Etching:

- deposition of 320 nm of Ni/Cr
- spray coating of S1813 photoresist (4.2 µm)
- photolithography with the given mask,
- annealing at 120°C during 1 min,
- Cr etch / Ni etch and finally
- 7 steps of 10 min with SF_6 gas at 2mT and 220 W.

This work will be followed by the deposition of the metallization allowed to excite the chosen mode of vibration, which is the C-mode 3rd overtone, working at about 20 MHz for a 280 µm thick wafer (in fact 17.68 MHz, the required value of thickness being not reached). Then, we will open the apertures by UltraSonic Machining (USM) before bonding the covers on each side.

VI. FEM SIMULATION OF THE RESONATORS

Previously to this technical work, we have initiated efforts in the calculation of the best design to well trap the vibration energy of the C-mode, 3rd overtone. For that, we use the Finite Element Method allowing calculating resonant frequency and Q-factor for a single-step-mesa resonator and a stepped bi-mesa structure. Below, we compare these calculated values with the output frequency characteristics of a beveled “standard” quartz crystal resonator working at about 20 MHz. Finally, this tool should help us to simulate the complete behavior of any resonator, including the mounting structure and its influence on the resonant frequency.
Few works have been done in this area [3-4], completed by the realization of QCM resonators (Quartz Crystal Microbalance) for which the goal is not to reach very high Q-factors, dedicated to frequency and time applications [5], but only to measure mass loading effect.
So, to evaluate our simulation, we have modeled a resonator with an external diameter of 9 mm, a diameter of 3 mm for the electrodes (constituted by 200 nm of gold) and 6 layers in the thickness of quadratic elements (see Fig. 11).
At least, to calculate the acoustic loss of the desired resonant frequency, we have introduced the tensor of the viscosity constant measured by Lamb and Richter [6]. And so, the displacement along the X-axis for different designs is as indicated in the following figures (Fig. 12a to Fig. 12d).

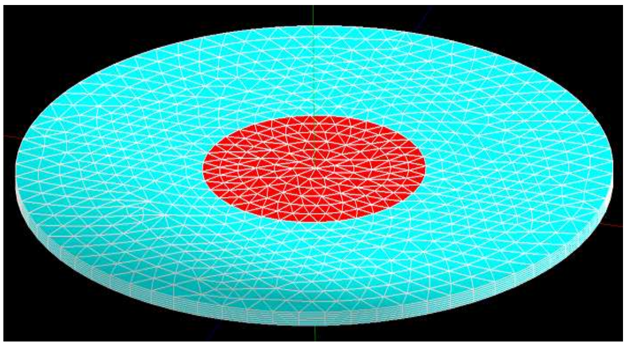

Fig. 11: finite elements model of the resonator and its electrode

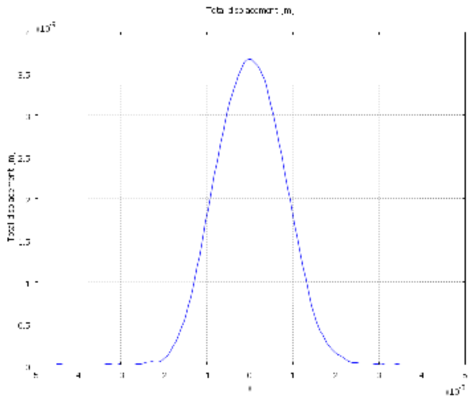

Fig. 12a: displacement along X-axis for a plano-convex resonator

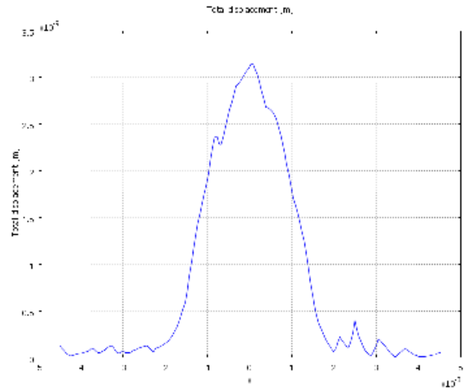

Fig. 12b: displacement along X-axis for a plano-plano resonator

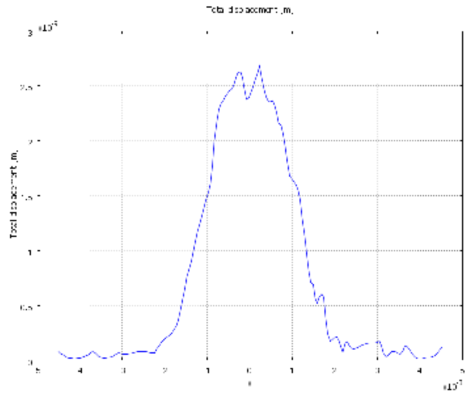

Fig. 12c: displacement along X-axis for a “1 MESA” resonator

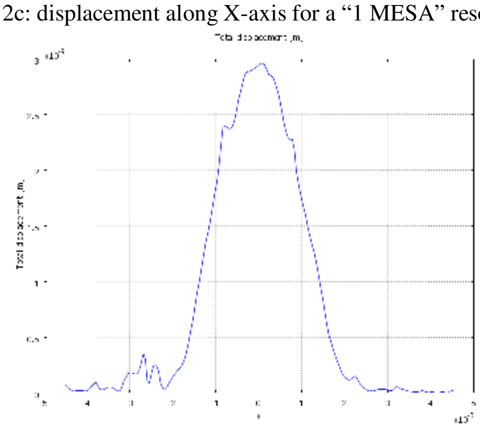

Fig. 12d: displacement along X-axis for a “2 MESAs” resonator

The Q-factor of the C-mode 3rd overtone has been calculated for each design. They are indicated in the following table:

design	Q-factor
Flat resonator	771,000
with Rc = 1000 mm	766,000
with 1 MESA	767,500
with 2 MESA	767,200

Table 1: Q-factor calculated by Finite Element Modeling

We observe that the design has a very little influence on Q values. It is not surprising because the working frequency of 20 MHz corresponds to the point for which a curvature or the mass loading have almost the same influence on the energy trapping.

VII. CONCLUSION

Our test vehicle is not achieved and we have to develop:

Metallization, wafer bonding, dicing,
Chemical etching,
ultrasonic machining of the covers,
…

and to realize 3 and 4'' SC-cut quartz wafers.

Nevertheless, we have demonstrated several points:

- ✓ DRIE shall be an efficient tool to realize deep patterns if we anneal the thermal stresses induced by the electrolytic Ni layer (by deposition of new Ni layer on the other side of the wafer, for example). So, we hope to etch more than 80 µm deep currently,
- ✓ we are able to chain 2 or more RIE processes on the same wafer,
- ✓ …

and we own an efficient tool to calculate the motional parameters of a given resonant frequency of a resonator with particular design.

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