Microfabrication and characterization of thin-film amorphous Silicon MEMS membranes

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Abstract— MEMS resonators nowadays offer promising alternatives for timing, mass sensing and filtering purposes. Using doped a-Si:H thin-films for MEMS applications is an attractive choice as these films are associated with low processing temperatures, low residual stress and good electrical conductivity.

The work performed within this dissertation focused on surface micromachining microfabricating and characterizing square-shaped MEMS membranes, with side length between 80 µm and 250 µm, on both glass and crystalline silicon substrates at temperature below 300 ºC. The first process to be carried out used an all-in-one approach using RIE etching in order to define lateral gaps and the structural layer, while the second one made use of a lateral sacrificial layer. Aluminium and silicon dioxide deposition conformity was also investigated towards the usage in the latter process, yielding step coverage of about 40% and 80% for Al and SiO₂, respectively. Some resonators exhibited multiple higher order peaks, up to 26 modes for one 250 µm structure. Quality factors up to 4500 resonance frequencies up to 8 MHz were measured. While voltage bias sweep tests commonly induced electrical spring softening on tested resonators, one structure displayed an intermediate effect between mechanical stiffening and electrical softening. Pressure tests for one structure indicated a critical pressure point at 80 Pa, along with reasonably well defined free molecular flow and viscous flow regimens. A visible crossover between those two regimens happened at about 1000 Pa. Displacement up to 180 pm for the first resonance flexural mode was obtained via LDV measurements.

Keywords— MEMS, square-shaped membranes, surface micromachining, thin-films, amorphous silicon

1. INTRODUCTION

In the last decades, miniaturized systems have progressively gained more attention from the scientific community, media and even popular culture. “There’s plenty of room at the bottom”, quoting the Nobel awarded world renowned theoretical physicist Richard Feynman [1], is a sentence that illustrates the on-going path of miniaturization in the sense that potential applications increase as the technology shrinks down in size. It is impressive to look back and realize the evolution of electronics, since the invention of the first MOSFET transistor to nowadays.

Advances in fabrication techniques, like bulk micromachining, were key factors to the development of microelectromechanical system [2]. These systems are composed by micro-scaled mechanical and electrical components that will interact with each other. One simple way to imagine such devices is to consider a system composed by a 100 µm silicon composed cantilever and a metallic electrode gate that suffer electrostatic actuation. The actuation force applied will cause the cantilever to move, implying transduction between the electric energy applied and the mechanical energy.

MEMS resonators are currently especially interesting towards substituting crystals like quartz [3] in timing applications, mass sensing [4] for biological or non-biological purposes and radio frequency filtering [5]. Resonators designed and fabricated within this work are structurally composed of n-type amorphous silicon. This material is reported to be compatible with monolithic integration, while not being expensive [6] but most importantly providing optimal characteristics for MEMS such as good electrical conductivity and low mechanical stress.

Amorphous silicon will be deposited by a RF-PECVD method which allows tuning electrical and mechanical proprieties along with the deposition rate by adjusting simply deposition conditions. Thin-Film’s INESC MN group has years of experience on RF-PECVD amorphous silicon for MEMS applications [7], [8], [9]. Besides cantilever-beams and bridges [10], [11] thin-film amorphous silicon plate resonators have been produced within the group [12]. Flexible substrates such as plastic [13] and DNA sensing [14] has also been accomplished by the group.

Surface micromachining has also been associated with in-plane high-frequency 6.3 µm centrally-anchored radius disk resonators with quality factors over 20000 [15]. In fact, Clark et al [15] successfully fabricated a ultra-high frequency laterally vibrating sub-micron gapped disk resonator combining surface microfabrication, metal coating and sacrificial-spacing techniques in order to overcome usual lithographic and etching limitations. The sidewall sacrificial layer is deposited around the patterned resonator, similarly to what was done in this work in the sacrificial process (see Section 3). Clark et al use a 100 nm thick LPCVD silicon oxide layer for sacrificial layering means, later released with HF acid. Specifically, this process yielded a laterally vibrating resonator characterized by exhibiting both high resonance frequency, 193 MHz, and high...
quality factor, 23000 in vacuum and 8880 at atmospheric pressure. Besides that, higher order modes were actuated up to 829 MHz, answering the need of operating at ultra-high frequencies without needing to fabricate smaller structures. Same group also reports the fabrication and characterization of four-anchored disk resonators exhibiting capacitively detectable in-plane resonance [16] with and without an additional anchor at the centre. As with exclusively centre-anchored structures, four anchored disks are characterized by high frequency and high quality factor.

Gualdino, working within INESC MN’s thin-film group, also succeeded in fabricating sub-micron in-plane vibrating a-Si:H square resonators by making use of a ion milling patterning and DRIE etching process [17]. The Lamé mode of these resonators was successfully detected by capacitive sensing by one-port and two-port sensing schemes. Finally, bulk mode acoustic silicon resonators, have been long associated with high quality factors, over 10^7 in some works [18] making use of Silicon on Insulator techniques to fabricate two armed structures vibrating at tens of MHz with sub-micron gaps. Matilla et al deep reactive ion etched the SOI wafer using an oxide etchable by HF acid as the sacrificial layer. The authors of the aforementioned study used capacitive sensing as the characterization setup.

2. OPTICAL CHARACTERIZATION

The experimental setup is composed by four main components which are a laser, a vacuum chamber (10^-2 Torr was considered vacuum) in which the microchip is inserted, an avalanche photodiode module with an integrated amplifier and a network analyser (HP4195) used in spectrum mode. The laser beam is focused on the microresonator, which is effectively actuated using electrostatic actuation, and the deviation caused by the resonance movement will be measured by the photodetector as \( \text{Response}_{\text{APD}} \propto \text{deflection} \). Figure 2.1 illustrates the optical characterization setup used by Thin-film’s INESC MN group, well described by previous works [19].

The data regarding the deflection in order to frequency can be extracted and as the resonance peak resembles a Lorentzian curve, one can fit that to that type of curve in order to fit the experimental data. According to Gualdino [17], if the height of the resonator’s peak exceeds 6 dB, the quality factor can be successfully estimated by:

\[
Q = \frac{\omega_r}{\Delta \omega_{3dB}}
\]  

The network analyser will sweep the frequency of the actuation in the range of MHz. The laser is characterized by emitting 658 nm wavelength light and by having a spot diameter close to 50 µm. With the help of an optical microscope, the red spot will be focused on the microresonator, which upon excitation will vibrate producing a displacement of the laser light that is reflected by the microdevice. That displacement is captured by the photodetector, which in its turn must be well aligned with the reflected laser light, producing an output signal which is seen as a spectrum on the network analyser.

3. FABRICATION OF THIN-FILM AMORPHOUS SILICON RESONATORS

In the first process, the gap between the plate and the resonator is defined by lithographically patterning and etching, thus it is diminutively called etching process. This process is limited to gaps as small as 1 µm. The second process solves the gap problem removing a sacrificial layer. Gap size can be controlled by the thickness of that layer, therefore sub-micron gaps are easily achievable. Second process is often called sacrificial process. All the fabrication was executed in INESC MN’s cleanroom facilities.

Fabrication of square-shaped resonators whose gap is defined via etching

Present subsection will present the sequence of techniques used in order to fabricate structures whose gap was defined via etching, built by surface micromachining on a glass substrate (see Figure 3.1 for a cross-sectional view).

The first step on this process is to clean carefully the 2 inch per 1 inch and 0.7 mm thick glass substrate in order to remove
contaminants and other particles on the surface of the substrate, as their presence can compromise the fabrication of the device. Cleaning is performed by immersing the substrate in a glass tub containing a detergent solution (Alconox) and placing the glass tub in ultrasounds at about 60 ºC for 30 minutes. After the detergent, isopropyl alcohol and DI water were used to finish the cleaning of the substrates. Twelve 6.5 mm x 6.5 mm dies will be fabricated per substrate.

Posteriorly to the preparation of the glass substrates, a 1 µm thick Aluminium layer was deposited via DC Magnetron Sputtering on a Nordiko 7000 machine (Figure 3.2 a) to b)). Aluminium will serve as the sacrificial layer of this structure, holding temporarily the structural layer in place while the process is being completed. This layer has to be thick enough so the resonator does not collapse by colliding with the substrate when at resonance. Stiction effects also become more prominent for reduced gaps. The sacrificial layer will be futurely removed in order to release the structure. After depositing, the layer was patterned in several squares via direct write lithography (Figure 3.2 c) and d)) and etched with aluminium etchant. The etching time for a 1µm thick layer is about 15 minutes. Each one of the squares patterned represents one structure to be fabricated, and it’s vital that the etching step removes all the silicon from the substrate. If not, the amorphous silicon thin-film can be compromised during the release of the resonator.

The deposition of the n-type hydrogenated amorphous Silicon structural 2 µm thick layer via RF-PECVD follows the definition of the sacrificial layer (Figure 3.2 e)). This layer will form both the structure (hence called structural layer) and the electrodes, being an all-in-one process composed of simply two lithographies. In order to increase the conductivity of the n-type doped a-Si:H structural layer, 100 nm of TiW was deposited on its top by magnetron sputtering using the Nordiko 7000 system. Once both depositions are complete, the patterning and etching of the structural layer ensues (Figure 3.29 f) and g)). Patterning is accomplished by lithographic procedure, while the etching of both the a-Si:H and TiW layers occurs via Reactive Ion Etching on a LAM machine. Etching time for both layers ascends up to 400-500s in several temporal steps. These steps are used in order to maximize the control of the etching process, as over etching can have detrimental effects on feature size increasing the real length of the resonator to electrode gap. Although the reactive ion etching performed on a LAM machine is anisotropic, it becomes more isotropic when etching deep holes. In fact, according to SEM examination, real gap length was about 0.5 µm higher than what was designed in the software mask and the bottom of the electrode to resonator gap exhibits a slightly isotropic etching profile. This etching penetrates through amorphous silicon until the substrate is clearly visible, being crucial for the device’s performance that it is not stopped before meeting that condition. After etching the sample is covered fully with photoresist and diced in twelve 6.5 mm x 6.5 mm dies. A Disco DAD 321 machine was used.

Once the structure and the lateral electrodes are defined, the release of the structure ensues (Figure 3.2 i)). The release is performed by the removal of the aluminium sacrificial layer with aluminium etchant and is the most critical step in this microfabrication. Releasing the structure is a time-consuming process, as big structures (such as 250 µm) necessitate about 32 hours at 1 µm/15 min etch rate. Aluminium etchant did not affect significantly the amorphous silicon thin-film even in such long etches. After releasing, the dies are mounted on a dual-in-line chip carrier.

Most fabrication problems were subsequent to the release of the structures, as about 40% of the structures did not withstand the release being visibly either partially broken or even missing as a result of complete anchor destruction. Besides that, many successfully fabricated structures showed no resonance, which can be attributed to release-related problems such as stiction or incomplete release. Incomplete release can also interfere with the resonance frequency of the structure, as the real length at resonance can be greatly reduced.
Fabrication of square-shaped resonators whose gap is defined via the removal of a sacrificial layer.

Fabricating resonators whose gaps are defined by removing a sacrificial layer is a more delicate, intricate, complex and longer process than fabricating a resonator using the etching process. The sacrificial process encompasses two sacrificial layers. For this work, both aluminium and silicon dioxide were considered to be competent choices for those layers and as such Al/SiO$_2$ and SiO$_2$/SiO$_2$ was used as sacrificial layer combinations in the fabrication. Using Aluminium for first layer and Silicon Dioxide for the second one choice proved to be the best choice, as no resonator with dual silicon dioxide sacrificial layering could be successfully fabricated.

Figure 3.4 – Cross-section view of square-shaped membrane whose electrode to gap was defined by removing a sacrificial layer. The square resonator is in the center and electrodes are placed in the sides

A 0.6 µm thick Aluminium layer will be deposited by DC magnetron sputtering on a Nordiko 7000 machine (Figure 3.5 b)). This layer is thinner than in the etching process as the deposition stack of the process currently being described is considerably taller (see Figure 3.4). Then, direct write lithography ensues, followed by etching the aluminium layer with aluminium etchant for about 10 minutes Figure 3.5 c), d) and e)). The result of this etch is the patterning of several aluminium squares.

The deposition of the 2 µm n$^+$-type amorphous silicon structural layer is the next step, followed by depositing 100 nm of TiW. This is the point where the etching process and the sacrificial process differ greatly, as the following lithographic step and RIE etch of both films will define just the structural layer and not the electrodes (Figure 3.5 f) and g)). This etch must be well controlled, as the crystalline silicon substrate is etched by the gas mixture used and substantial over etch will affect the relative height between the resonator and the electrodes. However, optical inspection is not totally reliable, profilometer measurements cannot be used directly as photoresist is also etched by RIE. The best single indicator proved out to be fabrication experience, but all the samples presented at least slight substrate overetching. Figure 3.6 a) and c) show clearly the unintended substrate etching. The second part of the fabrication of these resonators will be the deposition of a 400 nm/600 nm Silicon Dioxide layer, which is the sacrificial layer that will originate the sub-micron gap (400 – 500 nm). As always, following the deposition there will be a lithographic step. This particular lithography has the intent of opening holes as deep as the substrate, which will accommodate the future deposition of the electrodes. The etching of this silicon dioxide layer will be performed either with 7:1 Buffered Oxide Etch (BOE) for 7 minutes or by RIE on the LAM machine for 100s (see Figure 3.5 h) summarizing deposition-lithography-etching process). This etch is absolutely critical in the fabrication of the device, as three problematic scenarios that can arise:

- a) Incomplete etching causes the lift-off of the electrodes when releasing the structure;
- b) Overetching the silicon layer surrounding the gap, i.e. protected by photoresist, affecting gap size. Wet etching is particularly dangerous as it is considerably isotropic;
- c) Substantially overetching the crystalline silicon substrate, causing the electrodes to be lower than the electrode to structure gap accounts and possibly being in direct contact with the structure – present in reactive ion etching.

All three scenarios greatly compromise the fabrication of the resonator. During this work, scenarios b) and c) were probably the cause of many malfunctioning and/or non-working devices. In order to optimize BOE etching, some indicative tests were performed by consecutive etching of a silicon dioxide 600 nm thick layer, deposited on a crystalline silicon substrate and marked in a lined fashion, followed by measuring the height of the SiO$_2$ layer until it is totally etched. The lined pattern on the silicon dioxide was done by drawing several lines with an acetate pen on the silicon substrate and then removing them with acetone after the oxide’s deposition. This test indicated that the etch occurs at about 600 nm/3.5 min. BOE etching was chosen instead of HF at 49% (diluted in water) because it offers superior control over the etching process.

Reactive ion etching was only considered as a mean to open the aforementioned holes in a later stage of this work. As such, it was used in just one sample of Al/SiO$_2$, sacrificial layering and the process proved to be more comfortable health-wise, simple and relatively controlled. Unfortunately, no structures were successfully produced while using RIE on this step, because the further deposition of amorphous silicon went wrong irreversibly damaging the sample. Figure 3.8 b) and c) clearly show that buffered HF acid etching occurs isotropically as silicon dioxide on the edges of the patterned holes is also removed, and that RIE etching is isotropic as it doesn’t exhibit that phenomenon.

The next step in the microfabrication process is to deposit a second amorphous silicon thin-film, slightly thicker than the structural layer at about 2.5 µm, and 100 nm of TiW on top of it (Figure 3.5 i)); this dual layer will originate the electrodes after performing the following lithography and etching via RIE on the LAM machine (Figure 3.5 j)). This step is also important as the electrodes must overlap slightly the surface of the resonator in a L-like fashion (see Figure 3.4). Some structures had problems regarding the TiW layer deposited on top of electrode layer, as that same layer was often either
completely or partially removed (Figure 3.6 c)). That can be explained by incidental excessive etching through the photoresist layer down to the thin metallic alloy layer; or even, although less likely, weak adhesion of the TiW layer with the a-Si:H layer. SEM inspection also shows that the desired L-pattern for the electrodes was not well performed as there is a clear disconnection between the electrode’s top and bottom. Just one die fabricated by the sacrificial process was examined by SEM, so this problem could be punctual and coincidental, although actuating difficulties (see Section 5) were common with these resonators. Then, the samples are covered with photoresist diced in 6.5 mm x 6.5 mm squares in a Disco DAD 341 machine. Finally, the photoresist is removed and the release of the structures ensues. Similarly to the etching process, releasing the structures is a critical step that will be determinant towards the successful fabrication of the resonators. The release was performed by immersing the sample firstly on BOE acid for ~20 minutes (and then immediately immersing it on aluminium etchant for up to 32 hours (Figure 3.5 m)). After the release the dies are mounted on a dual-in-line chip carrier. Figure 3.8 comprises several fabrication micrographs taken along the process, showing several fabrication steps of different structures. Films deposited within this fabrication were generally stress-free, but some exceptions were encountered upon SEM examination (see Figure 3.7 b)). Figure 3.6 illustrate the top view of the fabrication.

Figure 3.6 – Top view of the fabrication process flow. Dashed lines represent layers buried underneath the oxide layer. a) to b) represent the sacrificial and structural layer definition. c) and d) represent oxide layer patterning and electrode definition. e) depicts the release

Figure 3.5 – Cross-section view of the process flow. Drawings are not at scale. Lithographies and etches are represented by dotted arrows from f) on.

Figure 3.7 – SEM micrograph – sacrificial process. a) partially successful released structure. b) buckled resonator. c) Incomplete release and attacked TiW on electrodes

4. SQUARE-SHAPED RESONATORS WITH 1.5 µM LATERAL GAP PRODUCED BY ETCHING

The structures designed and produced in this work were a-Si:H square membranes produced by a sequential surface micromachining process. The structures produced were 2 µm thick with a vast set of different widths: 120, 150, 200 and 250 µm, fixed by four 15 µm long and 7 µm wide anchors, placed at the vertexes of the square. In order to successfully design a resonator it’s important to understand how a given structure will respond to electrostatic actuation, namely what will be the general shape of the vibration mode and in what frequency the structure will resonate. As such, several structures with different widths were modelled in a FEM based software (Figure 4.1). Eigenmode analysis was performed in order to
assess and predict the range of natural frequencies intrinsically associated with each structure.

<table>
<thead>
<tr>
<th>L (µm)</th>
<th>120</th>
<th>150</th>
<th>200</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (GPa)</td>
<td>f₀ (kHz)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>247</td>
<td>176</td>
<td>997</td>
<td>70</td>
</tr>
<tr>
<td>115</td>
<td>274</td>
<td>194</td>
<td>109</td>
<td>77</td>
</tr>
<tr>
<td>150</td>
<td>314</td>
<td>221</td>
<td>122</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 4.1 – FEM simulation result for the first out-of-plane vibrational mode

In this section, all the measurements were done applying Vₐc directly to the resonator via the anchor and V₇dc to one of the electrodes. The choice of using just one electrode to actuate the structure instead of two or even all of the four electrodes is justified as one of the goals of this first characterization step was to select suitable structures for further capacitive detection.

In some structures several flexural modes of resonance beyond the first one were easily actuated, producing in a rich spectrum such as the one seen in Figure 4.2. In the spectrum hereby shown, six resonance peaks are detected from roughly 150 kHz to 900 kHz. As expected, the first peak shows the highest amplitude among them all, with an overall decrease in amplitude in the subsequent modes. Structures with such a rich spectrum are promising, as these peaks are easily actuated. An even more remarkable structure in the context of the number of resonance modes actuated is seen in Figure 4.2. This particular structure’s first three resonance modes were excited with very low voltages, but with the gradual increase of voltage and broadening of the frequency spectrum, a multitude of peaks, exactly 26, could be actuated to frequencies as high as 3.8 MHz. As optical detection is highly sensitive on laser position, it is possible to argue that even more resonance peaks could be actuated than the ones found in this work.

Figure 4.1 – Illustration of the three first flexural resonance modes of a square plate with four t-shaped anchors

Figure 4.2 – Frequency spectrums of 250 µm side square resonator

Frequency Spectrums in Vacuum

Plotting the data from the two runs (generation 2 has wider electrodes than generation 2) performed shows the accordance of the experimental data of the shorter structures with the respective simulation, and the obvious discrepancy in the longer resonators (Figure 4.3). The discrepancy observed precludes the hypothetical fitting of the experimental data to a given function in order to extract parameters such as the Young’s Modulus and even the thickness. In order to be able to infer more meaningful insights on the relationship between the resonance frequency of the first out-of-plane mode and the length of the square’s side one would have to possess bigger set of data, which can be obtained by simply repeating the microfabrication and characterization steps.

The second generation of devices also exhibit generally higher quality factors than the first gen (Figure 4.4), achieving acceptable quality factors of over 2000. First generation’s quality factors were capped at 1000 and were as low as about 100. This finding indicates that the broader design of the electrodes is accompanied with smaller energy dissipation. Although longer devices have slightly higher quality factors due to the discrepancy in the results it is not clear that, as reported for similar membrane-like resonators [20], the quality increases unequivocally for wider structures. That phenomenon is justified by higher clamping losses and higher surface to volume ratio in shorter structures [21].

Plotting the resonance frequency from all the measured
peaks against the frequency and comparing with the theoretical limitation imposed by thermoelastic damping one concludes that such constraint is negligible in this case (Figure 4.5).

Figure 4.3 – Resonance frequency of the first mode versus the side’s length – both generations

Figure 4.4 – Quality factor of the first vibrational mode versus the side length – a) all of the structures; b) highest Q structures

Figure 4.5 – Quality factor dependence on frequency and TED

Vibrometer measurements performed in vacuum

In vacuum Laser-Doppler vibrometry (LDV) was also performed in order to supplement the characterization of the square-shaped out-of-plane vibrating resonators fabricated in this work. Experiments were carried out at the Iberian Nanotechnology Laboratory (INL) facilities. The vibrometer used in this characterization was Polytec’s UHF-120 Ultra High Frequency Vibrometer. The working principle behind LDV is the Doppler effect, which describes the change of a wave’s frequency when the observer is moving relatively to the wave’s source. In the case of a resonator, as the plate vibrates there will be a shift in the backscattered laser’s light and by making use of a interferometry apparatus it is possible to estimate both the velocity and the displacement induced by the motion [17], [22], [23]. Modal shape is depicted in Figure 4.6.

Figure 4.6 – a) Top: vibrometer’s RMS software generated 3D representation of the modal shape. Bottom: 3D FEM simulated modal shape for the first flexural mode. b) Top: matrix definition and magnitude in each point. Bottom: 2D FEM simulated Modal shape

5. SQUARE-SHAPED RESONATORS WITH SUB-MICRON LATERAL GAPS

Step coverage testing

Structures whose gaps are defined by the removal of a sacrificial layer, like the aforementioned ones, rely greatly on the dimension of that same layer, as it will be the foundation of the gap between the electrodes and the resonator. Gap length will depend directly on how conformal the deposition of the second sacrificial layer and quantifying that process is advantageous. Gap size plays a major role in the sensing (mainly capacitive) but also in its electrostatic actuation. The materials chosen to be competent suitors for forming the second sacrificial layer were Aluminium and Silicon Dioxide. These materials are commonly used for sacrificial layering purposes in Thin-Film’s INESC MN group [24], [17], [25], although their usage is more common on bottom-gate MEMS. The removal of these materials is a well known process, leaving three possibilities in the open for the sacrificial layer duo: first layer of Aluminium and second of Silicon Dioxide, both first and second layers composed of Silicon Dioxide and both first and second layer composed of Aluminium. The experiment consisted in depositing a 2 µm hydrogenated amorphous silicon layer via PECVD followed by direct write photolithography and etching by reactive ion etching, on a LAM machine. Aluminium and silicon dioxide are then
deposited by magnetron sputtering on a Nordiko 7000 machine and by an Electrotech Delta chemical vapour deposition system, respectively. Tests indicated step coverage of about 40% for Aluminium and 80% for silicon dioxide.

Optical characterization at resonance induced by single electrode actuation

Structures whose gaps were produced by the removal of a Silicon Dioxide sacrificial layer showed to be less easily actuated than etching structures. Fewer structures exhibited multi-peak spectrums and generally required much higher voltages in order to be measurable.

Quality factors tend to increase with the mode’s number in the structure produced in the second run, behaviour similar to what was observed with the resonators whose lateral gaps were defined by etching. Table 5.1 summarizes the information gathered regarding the first mode of vibration. It is clear to see that the results are not coherent with the length of the structure which indicates that are underlying problems in the microfabrication procedure.

As such it is possible to say that the electrical spring constant will be increasingly more negative with higher bias voltage. The effect is called electrostatic spring softening as the spring constant will be diminished by the electrically induced spring constant. In fact, the rise of $V_{DC}$ is expected to force the centre of the resonance peak to shift leftwards to the smaller side, as the resonance frequency is given by $f = \sqrt{\frac{k}{m}}$.

Table 5.1 – Structures optically measurable produced. A, B, and C refer to equally lengthy structures in different dies

<table>
<thead>
<tr>
<th>Length (μm)</th>
<th>Natural Frequency (Hz)</th>
<th>Quality factor</th>
<th>$V_{DC}, V_{AC}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>120 - A</td>
<td>909k</td>
<td>1249</td>
<td>20, 1.26</td>
</tr>
<tr>
<td>120 - B</td>
<td>229k</td>
<td>285</td>
<td>30, 1.26</td>
</tr>
<tr>
<td>150</td>
<td>2.5M</td>
<td>296</td>
<td>40, 1.26</td>
</tr>
<tr>
<td>200 - A</td>
<td>762k</td>
<td>1751</td>
<td>20, 1.26</td>
</tr>
<tr>
<td>200 - B</td>
<td>1.47M</td>
<td>1296</td>
<td>10, 1.26</td>
</tr>
<tr>
<td>200 - C</td>
<td>168 kHz</td>
<td>450</td>
<td>10, 1.26</td>
</tr>
</tbody>
</table>

Nonlinearities in MEMS can be either electrically or mechanically induced. Typically, on silicon electrical nonlinearities dominate over mechanical ones, which are often be neglected [27]. Additionally, electrical nonlinearities in silicon resonators are more deeply understood than mechanical ones, being described in several works [18], [17].

The electrical spring constant $k_e$ will be the result of the sum of a zero order term with several higher order corrections depending on the displacement $x$:

$$k_e(x) = V_{DC}^2 \left( \frac{d^2}{dx^2} - \frac{3ex^2}{2d^4} - \frac{2ex^4}{d^6} + \cdots \right)$$

As such it is possible to say that the electrical spring constant will be increasingly more negative with higher bias voltage. The effect is called electrostatic spring softening as the spring constant $k$ will be diminished by the electrically induced spring constant. In fact, the rise of $V_{DC}$ is expected to force the centre of the resonance peak to shift leftwards to the smaller side, as the resonance frequency is given by $f = \sqrt{\frac{k}{m}}$. Voltage bias sweeps were performed in order to assess its effect on the resonance frequency and energy dissipation (via quality factor estimation) of a resonator. This
particular effect was investigated in detail for multiple structures and modes of vibration beyond the first.

It is clear that all structures do not respond to DC voltage with the same magnitude. The maximum shift measured was about -1.3% of the natural frequency. All of the structures in Figure 5.4 suffered the electrical softening of their spring constant, as a result of the increasing bias voltage. Although the vast majority of structures suffered electrical spring softening with the increase of bias voltage, higher modes have been reported to have their stiffness increased with [25]. This effect is called mechanical stiffening. Figure 5.5 depicts the third vibrational mode of a 200 μm square resonator. It is visible that there are two effects at play, at first the electrical spring softening with the increase of voltage from 10V to 15V and then, on the transition from 15V and 20V, the opposite happens. As such, the third vibrational mode of this particular resonator exhibits both electrical softening and mechanical stiffening, known as an intermediate effect [28].

Besides affecting resonance peaks, bias voltage also considerably causes an increase in the dissipation of the resonator’s energy. This effect is non-negligible and losses in the quality factor can amount up to 80% in some cases. The behaviour of the quality factor is visible on Figure 5.6.

Figure 5.4 – Frequency shift with sweeping voltage bias. A and B represent different structures of equal length

Figure 5.5 – Mechanical stiffening and electrical softening effects

Figure 5.6– Quality factor loss versus bias voltage. The initial quality factor, correspondent to 0% \( \frac{Q}{Q_0} \), is placed next to each set of points with the respective matching color.

Effect of pressure on the dynamic properties of resonators

Dynamic properties of a resonator are affected by the dissipative media than surrounds the structure. The effect of pressure on MEMS’ vibration has been thoroughly reported and studied [29], making these structures suitable candidates to serve as pressure sensors [30]. Even more fluidic environments have been explored [25], such as water, and tested for potential applications [31]. Specifically regarding the measure of energy dissipation of a given structure, quality factor will be heavily affected by the surrounding environment. In response to rising pressure there will two regimens. Firstly, there will be abrupt drop in the quality factor by \( \frac{1}{p} \). This is the moment where damping losses greatly overcome intrinsic losses entering the realm of molecular free flow, and its starting pressure is designated as the critical pressure. The quality factor will now be given by [29]:

\[
Q_{fmf} = \frac{1}{p}
\]

where \( p \) is the mass density of the plate, \( f \) the frequency, \( h \) the thickness, \( M \) the molecular mass of the gas medium. The ongoing increase in pressure can possibly originate a further crossover for the viscous flow regimen where the quality factor will depend on \( \frac{1}{\sqrt{p}} \), being approximately given by

\[
Q_{fmf} = \frac{m_0}{6\pi\mu a^2 \sqrt{p}} \left( \frac{RT}{2\pi M} \right)
\]

where \( m_0 \) is the mass of the resonator, \( a \) is the characteristic linear dimension, in this specific case it is the radius of the spherical nitrogen molecules dragged in the fluid, \( \mu \) is the viscosity of fluid and \( f_0 \) the resonators’ natural frequency. Besides affecting energy dissipation, pressure will interfere with the resonance frequency of the resonator, via a phenomenon known as squeeze-film damping. Such effect has
been thoroughly reviewed and studied on MEMS [32, 17, 25]. Briefly, higher pressures will enable the formation of a thin gas film which will increase the stiffness of the resonator by mimicking a spring affecting considerably high surface structures. However, this trend is expected to be reverted as the transition from the free molecular flow regimen to the viscous flow regimen occurs [17].

![Figure 5.7 – Quality factor versus chamber pressure](image)

![Figure 5.8 – Resonance frequency changes induced by squeeze-film damping. Orange dashed circle flags the cross over region between free molecular flow and viscous flow](image)

Figure 5.7 exhibits the continuous decrease in the quality factor as predicted. The critical pressure point was determined to be at about 80 Pa. From above that point, quality factor drops approximately by $P^1$, according to equation 3 entering the realm of molecular free flow. There is a visible cross over between the free molecular flow regimen and the viscous flow regimen, as was predicted. The transaction appears to be about 1000 Pa, although the exact value is impossible to determine from the data. From above that pressure, the quality factor decreases by a factor of $P^{-1/2}$, characteristic of the viscous flow regimen (equation 4). Figure 5.8 summarizes the effect of squeeze-film damping on the resonance frequency of the resonator. Squeeze-film damping effect on the resonator natural frequency is below 3% for the highest pressure which is similar to values reported for the first out-of-plane vibrational mode of similar sized structures [29]. The resonance frequency’s right-oriented shift is present even at lower voltages, although just one point of data was acquired at low pressures below 10$^5$ Pa. At first the shift is approximately linear, but when the pressure crosses 1000 Pa and enters the viscous flow regimen realm, marked out by the dashed circle, there’s a mitigation of the slope and the natural frequency changes become less prominent. It is expectable that, if the structure could be measurable at higher pressure, there would be a downward shift in the resonance frequency of the first out-of-plane vibrational mode following the measured slope mitigation [17]. Data shows good agreement with the theoretical predictions and what was reported for in the literature for similar sized plate resonators. Unfortunately, none of the structures micro fabricated within this work showed resonance in air, precluding further experiments.

6. Conclusions and Future Work

The focus of this dissertation was designing, fabricating and characterizing square-shaped MEMS thin-film amorphous silicon membranes through two different processes at considerably low processing temperatures – less than 300 °C. The first fabrication process to be used took advantage of an all-in-one approach to fabricate both the square structure and lateral electrodes simultaneously. Lateral gaps were defined directly by RIE, being in the 1.5 µm – 2 µm range, hence calling this process the etching process. It was found that smaller structures showed good agreement with the simulation, whereas bigger structures did not, indicating fabrication problems. Highest quality factor measured was about 4500, well below the theoretical limit imposed by TED. One of the structures showed up to 26 vibrational modes.

Devices were fabricated by the sacrificial process using Al/SiO2 and SiO2/SiO2 as sacrificial layering combinations. Only Al/SiO2 structures were optically characterized.. Sacrificial structures showed less agreement with FEM simulation than the structures produced by the etching process indicating fabrication problems. As expected, both the resonance frequency and the quality factor shifted to the lower side as the voltage increased, however one 200 µm structure exhibited an intermediate effect between electrical spring softening and mechanical stiffening.

Finally, one 120 µm square-shaped resonator produced by the sacrificial process was characterized in function of chamber pressure. A critical pressure point was identified at about 80 Pa. Free molecular flow and viscous flow regimens were also clearly identified with a crossover point at about 1000 Pa. Lowest quality factor measured was 20.

Regarding future work, the next immediate step is to fabricate structures via the sacrificial process with the double aluminum layering as the wet etch of aluminum is a less aggressive procedure than using HF acid and its deposition step coverage is adequate for sub-micron structures. The etching process using RIE produced transduction gaps too large for capacitive sensing, thus it was rendered inappropriate for fabricating in-plane vibrating bulk resonators. Future work could be devoted to using a technique that allows the patterning and etching of sub-micron narrow gaps, similar to Gualdino’s DRIE etching process that successfully fabricated bulk resonators [17].
REFERENCES

[28] Manu Agarwal et al., "Nonlinear Characterization of Electrostatic MEMS Resonators," Departments of Electrical and Mechanical Engineering , Stanford University, Stanford, California, USA ..