Clamped-Clamped Beam Micro-Mechanical Resonators in Thick-Film Epitaxial Polysilicon Technology

Dimitri Galayko
IEMN-ISEN (Lille, France), UMR CNRS 8520
dimitri.galayko@isen.fr

Andreas Kaiser
IEMN-ISEN (Lille, France), UMR CNRS 8520
andreas.kaiser@isen.fr

Bernard Legrand
IEMN-ISEN (Lille, France), UMR CNRS 8520
bernard.legrand@isen.fr

Lionel Buchaillot
IEMN-ISEN (Lille, France), UMR CNRS 8520
lionel.buchaillot@isen.fr

Chantal Combi
ST Microelectronics (Milan, Italy)
chantal.combi@st.com

Dominique Collard
CIRMM / ISS-The University of Tokyo
dominique.collard@isen.iemn.univ-lille1.fr

Abstract

This paper presents design and test results of clamped-clamped beam resonators fabricated in thick-film epitaxial polysilicon technology. A new technique is used to achieve a 0.2 µm sensing electrod-to-resonator lateral gap in a structural polysilicon layer of 15 µm thickness. The frequencies of the designed resonators belong to the range of 2.3-16.4 MHz, the measured quality factors are of 450-15500 for different resonance frequencies.

1. Introduction

Clamped-clamped beam resonators are base components of micro-mechanical filters. Although providing a second-order frequency response, that is not enough for achievement of filtering needed in IF stages, use of several resonators of this type in coupled-resonator architecture allows to achieve a high-order filter, satisfying complex passband specifications. In this paper we present the results of design of different clamped-clamped beam resonators in thick-film epitaxial polysilicon technology.

Almost in all work presented up to now micro-mechanical resonators and filters were designed in thin-film technologies [1-3]. One of the key advantages of thin-film technology is the possibility to achieve a sub-micronic capacitive transducer gap, that is the most crucial issue in the micro-mechanical filter design. The common approach to obtain a narrow 0.1-0.2 µm electrode-to-resonator gap is to define it by a silicon oxide layer, that is removed once the electrodes and resonator are manufactured. The disadvantage of this technique is a relative complexity of the fabrication process.

The thick-film technologies allows to create capacitive transducers with large area, that partly compensates the difficulty of a narrow gap implementation. From the other side, thick-film silicon technologies have recently been developed in the industry, and used for big-volume MEMS devices fabrication (accelerometers, etc.). The goal of our study is to explore the ability of a thick-film polysilicon technology, called THELMA, developed at ST Microelectronics (Italy) for micro-mechanical filter design.

The main limitation of the technology for our application was the impossibility to realize narrow transducer-to-resonator gaps. We overcame this difficulty by employing an electrostatical motor that reduces the gap from 3.1 to 0.2 µm once the device is fabricated. Several resonators were fabricated and tested with resonance frequencies of 2-16 MHz. The quality factor has shown a strong dependence from the resonance frequency, and for tested resonators belongs to range 500-12000.

2. ST Microelectronics thick epipoly technology

High thickness of the structural layer provides ability to design lateral vibrational mode resonators and encourages the employment of complex architectures. Structures designed in THELMA technology have only two silicon layers: the structural layer (epitaxial polysilicon) and thin polysilicon layer used for anchoring and biasing of epitaxial layer structures. These two layers are separated from each other and from the substrate by two oxide layers. The structure of a device in THELMA technology and its main characteristics are shown in the fig. 1 and in the table 1. The thick structural layer is patterned by dry anisotropic etching, that provides merely vertical walls of etched trenches (89° over 15 µm layer).

This technology has the following advantages for the MEMS filter design: (1) favorable mechanical properties of epitaxial polysilicon, that translates into lower mechanical losses, and consequently higher quality factor of resonators, (2) high thickness of structures allowing to increase the capacitive transducers efficiency and so to reduce the motional resistance Rx [3]. The drawback is

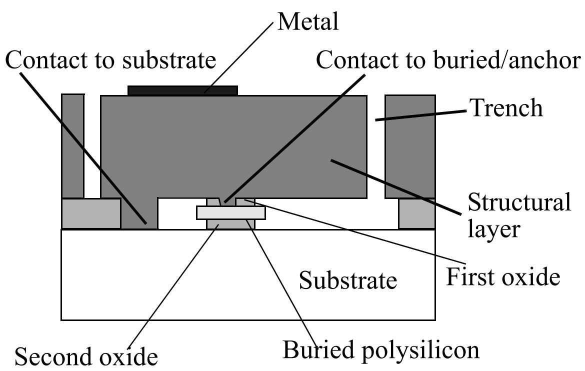

Figure 1. Structure of a device in THELMA technology

Table 1. THELMA technology parameters

	Structural layer	1st oxide	Buried poly	2nd oxide	Substrate
Thick-ness, µm	15	1.6	0.45	2.5	-
Resistance	10 Ω/ square	-	25 Ω/ square	-	1 Ω/cm

the difficulty to achieve sufficiently low gap values necessary to reinforce the coupling between sensing electrodes and resonator. This constraint is imposed by the actual pattern etching of the structural layer: only relatively wide trenches can be achieved by etching through 15 µm thickness epitaxial layer. In addition the actual trench width is increased by 1.0-1.2 µm by under-etching (0.5-0.6 µm for each side) compared to the designed width (defined at mask level). This yields a minimal trench width of 2.9-3.1 µm, that is far too much for an achievement of a good capacitive transducer (<0.5 µm values are necessary, <0.2 µm are desirable). Since the motional resistance of micro-mechanical resonator is inversely proportional to the forth power of the gap width, it would be too high for 3 µm gap, and the transmission level at resonance frequency would be too weak.

3. Post-process gap reducing

To get submicronic gap width without any modification at the technology level, we proposed a post-process gap reducing technique. We use an electrostatic motor to approach the input and output electrodes (sensing electrodes) to the resonator. A schematic representation of the electrostatic motor for one of the signal electrodes is shown in the fig. 2. The second one being identical. Figure 2a) depicts the fabricated non-biased motor state. The sensing electrode is fixed to a rigid beam, which is suspended by a soft spring . The spring is anchored to the substrate at the other end. The fixed motor electrodes are placed near the rigid beam. The device is biased in the following way: the resonator and motor electrodes are positively biased (these bias voltages are different in the general case), the sensing electrodes are only connected to the signal source and to the output load, therefore the DC bias is zero (fig. 2b). The bias voltage of the motor electrodes creates a mechanical force that attracts the beam to the motor electrodes. This force is sufficiently high to deform the spring, and the beam with signal electrode fixed on it moves towards the motor electrode. The geometry of the device is designed in such a way that this displacement approaches the signal electrode to the resonator, and so the signal electrode-to-resonator gap reduces.

The photo SEM of a clamped-clamped beam resonator with motor electrodes is shown in the fig. 3. The electrostatical motor has shown excellent performances and reliability of operating over several tens of tested devices. The activation voltage is 25-30 V, without any power consumption.

The big advantage of the proposed gap reducing method is a very low sensitivity toward the variation of under-etching width. Since the actual gap width is

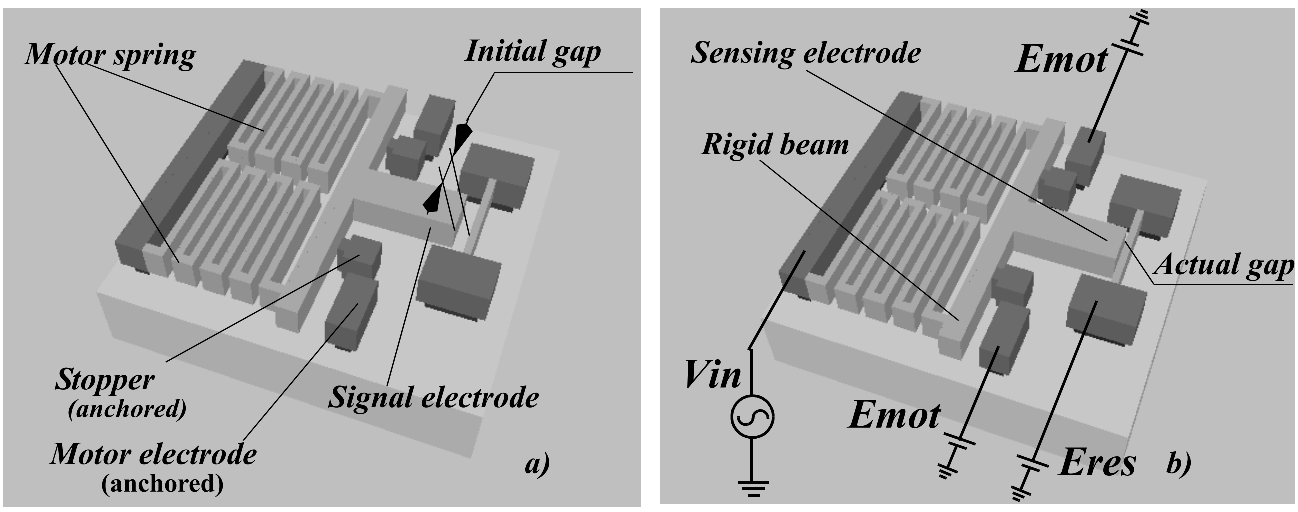

Figure 2. a) The unbiased state of the resonator; b) the resonator with a biased motor: gap is reduced

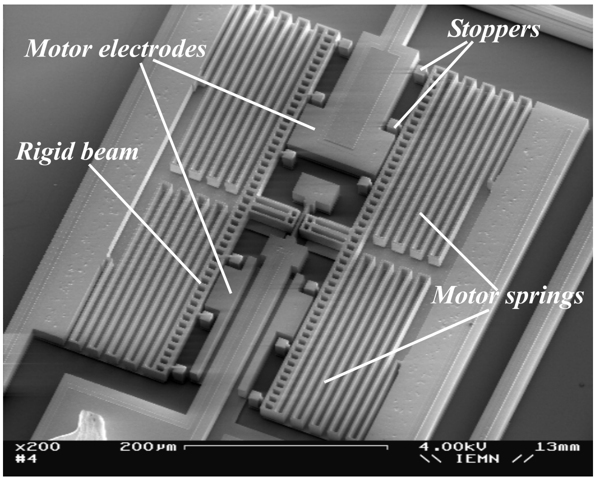

Figure 3. Photomicrographs of the device.

defined as a difference between two widths of fabricated gaps (resonator-to-sensing electrode and stopper-to-sensing electrode), the under-etching presented in the both is cancelled and the actual gap width is mostly defined by mask dimensions. The accuracy of the actual gap definition is limited by the litography resolution and by the irregularity of the over-etching width at one module. We observed a maximal dispersion of the gap value of 0.1 μm over all measured resonators.

4. Clamped-clamped beam resonator test results

We fabricated clamped-clamped beam resonators with length from 30 to 80 μm, with different width. For all resonator the designed gap width was 0.2 μm. Below we present different characteristics of resonator performances.

4.1. Evolution of quality factor versus resonance frequency

We present the measured resonance frequencies and maximal quality factors in the table 2. In fact, the quality factor of a mechanical resonator depends on the vacuum level. It increases as the pressure decreases and reach a saturation at the pressure, starting from which intristic mechanical losses in the resonator dominate the air damping.

From this table one can see a tendency of the quality factor evolution versus frequency, whatever the ratio between the length and the width is: the quality factor drops with increasing of the resonance frequency. This is more evident when these data are presented in graphic form (fig. 4). One can notice that the dependance of the quality from the frequency is hyperbolic. The fitting of the experimental plot yields the formula $Q \approx \frac{50000}{fo^{3/2}}$.

The quality factor of the clamped-clamped beam resonators decreases strongly with resonance frequency, taking values of 500 for 16 MHz. We couldn't detect a

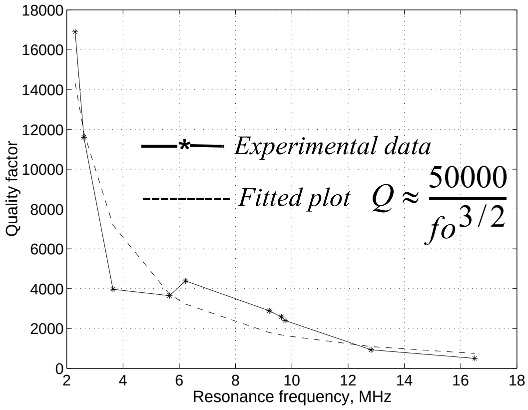

Figure 4. Quality factor versus resonance frequency plot.

Table 2. Resonance freqiencies and quality factors of different resonators

N***	1	2	3	4	5	6	7
Length, μm	30	40	50	50	80	80	80
Width, μm	1.8	1.8	1.8	4.8	1.8	2.8	4.8
Resonance frequency, MHz	16.4	9.8	6.23	12.82	2.30	3.65	5.65
Quality factor	530	2400	4390	924	15500	4000	3645

responses of clamped-clamped beam resonators with higher resonance frequencies. From the plot of the fig. 4 we can suppose that the quality factor of these resonators was even lower, and the amplitude of oscillation was too weak to be detected. It is known that the quality factor is strongly influenced by the anchor geometry. The subject of our ongoing work is an amelioration of the anchoring of the resonators and to qualify its influence on the quality factor.

4.2. Evolution of quality factor versus air pressure

In the fig. 5 we show the plot of quality factor value versus air pressure for two different resonators. As we can see, the quality factor is constant for low pressure. Nevertheless, the threshold pressure, from which the saturation is observed is different for two resonators.

4.3. Resonance frequency versus bias voltage and resonator-to-electrode gap measurement

A very relevant characteristic is the evolution of the resonance frequency versus bias voltage. The frequency variation with bias voltage comes from the non-linearity of the parallel-plate capacitive transducer: the force generated by it depends not only from the applied voltage, but also from the resonator position. Thus the transducer

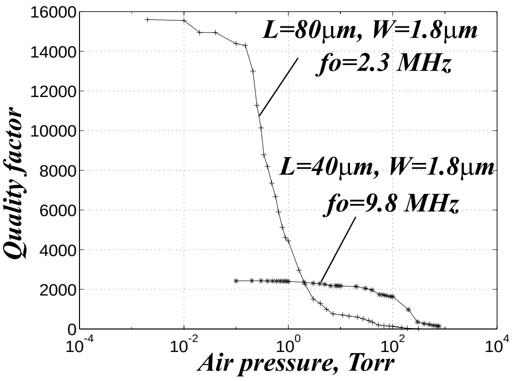

Figure 5. Plot of quality factor versus operating air pressure.

behaves as an additional spring with a negative stiffness that is joined to the resonator [3]. Thank to this property, a resonance frequency tuning is possible.

For the resonators with designed gap of 0.2 μm the maximum possible bias voltage was 15-20V. Past this voltage we systematically observed a shorting between one of the electrodes and the resonator. This is probably due to a pull-in phenomenon for flexible resonators (long beams), and to electrode bending, for more rigid resonators (short beams). This considerably limits the performances that one can get from the resonator, since the transmission at the resonance frequency is proportional to the square of bias voltage.

In the fig. 6 we show the plot of the resonance frequency evolution for two equal resonators of 40 μm length and 1.8 μm width with different designed gap values of 0.4 and 0.2 μm.

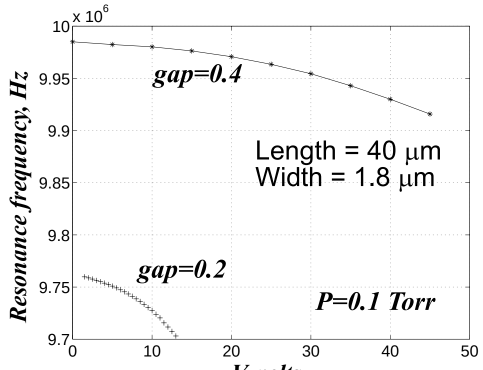

Figure 6. Resonance frequency versus bias voltage

As we can see, although the bias voltage variation was different for this two resonators (because of different maximal bias voltages for resonators with different gaps), the tuning ranges are equal. The resonances frequencies differ slightly, this is due to manufacturing tolerances. From this plots we could extract the real gap values [2]. They are 0.27 and 0.57 μm, slightly larger than the designed 0.2 and 0.4 μm.

4.4. Parameter dispersion over equally designed resonators fabricated on different modules

The main source of the resonance frequency dispersion is a variation of the under-etched width over the position on the wafer. In fact, we observed up to 5% of spread of the resonance frequency. Theoretically the actual (adjusted) gap value is not sensitive to the under-etching width. Nevertheless, in the reality the under-etching is slightly different for different geometries of trenches, and is bigger in open areas, where the chemical etching products can easily be evacuated. Over all fabricated samples we observed up to 0.1 μm of error on the corrected gap value.

5. Conclusion

Clamped-clamped beam micro-mechanical resonators designed in thick-epipoly technology with different dimensions were presented with resonance frequencies of 2.5-16 MHz. The difficulty of obtaining of submicornic gap values is overcome by using of an electrostatical motor, that approaches electrodes to the resonator. The gap is so reduced from 3.1μm down to 0.2 μm (ratio of 15).

To design micro-mechanical filter for IF stages of RF receivers, higher resonance frequencies should be obtained for elementary resonators. It can be achieved from one side, by improvement of the anchoring of the beams, and so by reducing of losses at high frequencies, and from other side, by using more complex vibrational modes (volume modes etc.).

6. References

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