HIGH-FREQUENCY HIGH-Q MICRO-MECHANICAL RESONATORS IN THICK EPIPOLY TECHNOLOGY WITH POST-PROCESS GAP AJUSTEMENT

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ABSTRACT

This paper presents high-Q high-frequency lateral-mode clamped-clamped beam micro-resonators driven by parallel-plate electrostatic transducers fabricated in a thick epipoly michromachining technology. An innovative approach is employed to reduce an intrinsically high transducer gap value of more then 3.0 μm (determined by the need of 15 μm thickness structural layer etching) down to 0.2-0.4 μm after the fabrication. This is achieved by employing an electrostatic motor that approaches actuating and sensing electrodes close to the resonator. The electrode motor is driven with 30 V DC voltage, without any DC current consumption. Two resonators having a resonance frequency of 10 MHz have been fabricated with gap values of respectively 0.2 and 0.4 μm. A comparative analysis of performances of the two resonators is given in the paper.

INTRODUCTION

High frequency micro-mechanical resonators have recently gained considerable attention. Vibrating micro-mechanical elements are considered for use in filters and oscillators in SOC applications [2]. Nevertheless, considerable work has yet to be done to make the fabrication and the use of these devices compatible with industrial and commercial constraints. One of the main industrial requirements for resonators is the simplicity and reliability of the fabrication technology.

To use a VHF micro-mechanical resonators in electronic systems, the resonator's motional resistance should be as low as possible for an effective impedance adaptation. This resistance is determined by internal losses of the resonator and by the coupling coefficient of the input and output electrostatic transducers, that is inversely proportional to the square of the electrode-to-resonator gap value. Therefore the latter should be as low as possible, and practically should have sub-micron dimensions (less then 0.3-0.5 μm), that is generally much lower than the resolution of the lithography. So far, most of the proposed methods of gap reduction have been based on the definition of the sub-micron gap by an oxid layer that is deposited on the resonator or on the electrodes [1, 2]. This approach requires complex and expensive technologies.

In this paper we demonstrate a VHF 10 MHz micro-mechanical resonator fabricated in a thick-layer epipoly technology with an original post-fabrication gap reduction method. The fabrication technology is provided by ST Microelectronics, where it is commericialized and used for fabrication of low frequency MEMS devices such as accelerometers, etc. The technology uses one structural polysilicon layer of 15 μm thickness, where elements are patterned by dry etching. The minimum distance between two elements authorized by the lithography is 1.6-1.8 μm, and the over-etching on the structural element edges is of 0.6 μm. Therefore the minimally possible electrode-to-resonator gap value is about 3.0 μm (1.8μm+2x0.6μm). As shown by simulations and measurement results, VHF resonators with such a large gap have a motional resistance that is too high for use in electronic circuits. The goal of our work was to find a method for gap reduction without any modification on the technology level.

ELECTROSTATIC MOTOR

To reduce the electrode-to resonator gap we propose to use an electrostatic motor to approach the input and output electrodes ("signal electrodes") to the resonator. A schematic representation of the electrostatic motor for one of

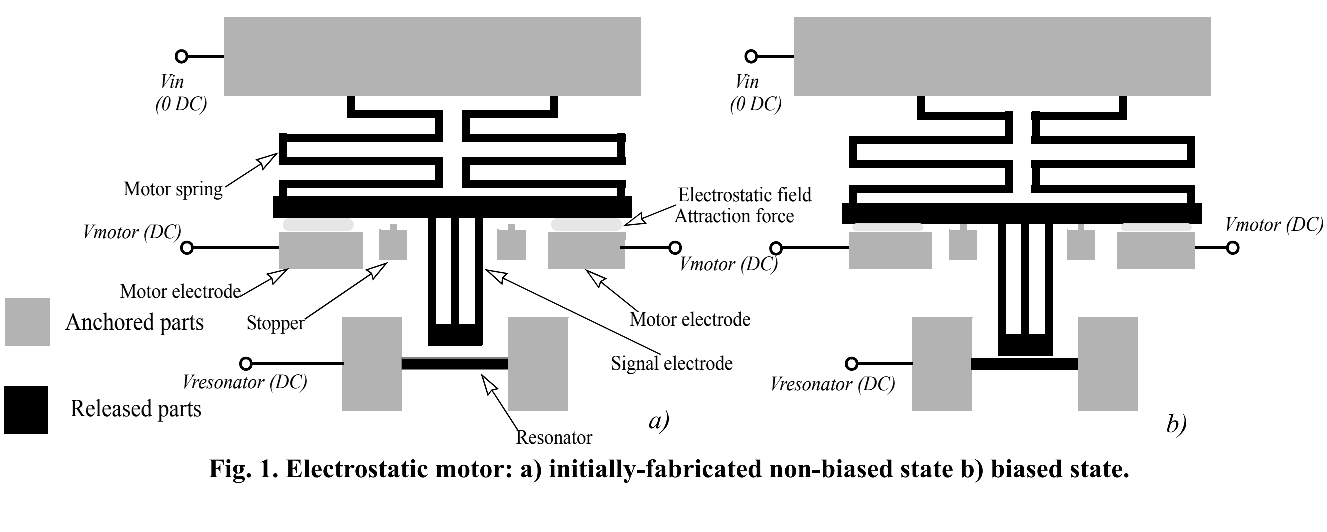

Fig. 1. Electrostatic motor: a) initially-fabricated non-biased state b) biased state.

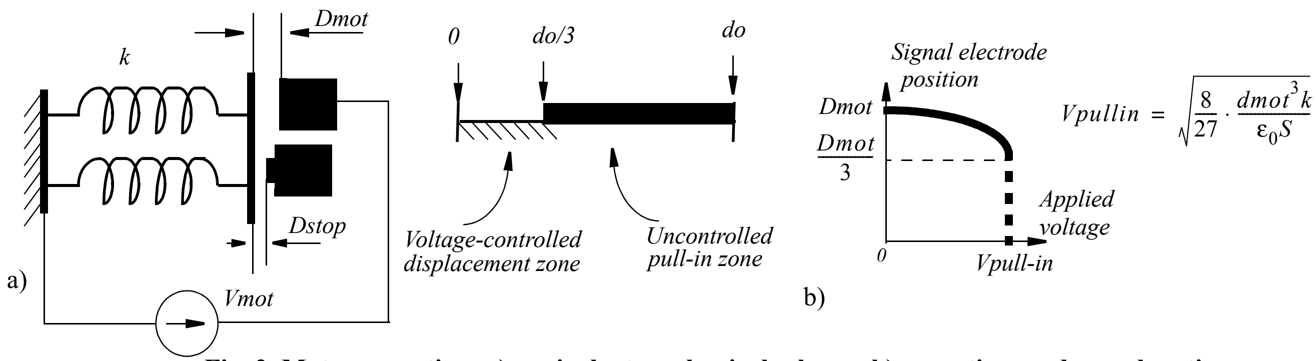

Fig. 2. Motor operation: a) equivalent mechanical scheme, b) operating modes explanation.

the signal electrodes is shown in the fig. 1. The second one being identical. Fig. 1 a) depicts the initially fabricated non-biased motor state. The signal electrode is fixed to a rigid beam, which is suspended by a soft spring (parallel to the silicon surface). 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 signal electrodes are only connected to the signal source and to the output load, therefore the DC bias is zero. The bias voltage of the motor electrodes creates a mechanical force that attracts the beam to the motor electrodes. If the force is sufficiently high, the spring deforms and the beam with the 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.

In order to limit the displacement (to avoid mechanical and electrical contact between the signal electrode and the motor electrodes or the resonator), stoppers are put near the beam. The beam with the signal electrode is clamped to the stoppers and remains in this state as long as the bias voltage on the motor electrodes is applied (fig. 1 b)). The gap between the signal electrode and the resonator is reduced by the displacement value, that is equal to the initial (fabricated) distance between the signal electrode and the stoppers. The stoppers are electrically isolated from the substrate and have a floating potential.

If *Dres* is the initial (fabricated) signal electrode-to-resonator gap, *Dstop* is the initial (fabricated) distance from the signal electrode to the stoppers, the final signal electrode-to-resonator gap (*Dfinal*) is equal to: *Dfinal=Dres-Dstop*.

We would like to note two advantages of the proposed method. (1) On the initially fabricated, non-biased device any gaps between elements can be of values authorized by the lithography, (greater than 3 μm in our case), so the device can be fabricated by a simple etching of the structural layer. Since the actual signal electrode-to-resonator gap is determined by the *difference* between two fabricated distances, the actual gap can have very small values much smaller that initially fabricated ones. (2) The actual gap value doesn't depend on the over-etching of the structural layer. Since the actual gap value is defined by the difference between two fabricated gap values, the error due to over-etching present in each of them is cancelled, so the actual gap value is defined only by *designed* dimensions. This is very advantageous for the industrial use, because the over-etching depends on numerous fabrication process parameters (etching method, etching time, etc.), and thanks to the differential nature of the gap value definition, these technological parameters need not to be taken into account for the design.

ELECTROSTATIC MOTOR DESIGN

It is obvious that the voltage applied to the motor should be as low as possible, in order to avoid the need of using high DC voltages in low-voltage electronic systems. This voltage depends on the initial (fabricated) distance between the motor electrodes and the signal electrode (*Vmot*), the surface of the active area of the motor electrodes, and the needed displacement value (the signal electrode-to-stoppers distance *Dstop*). The equivalent mechanical scheme of the system is presented in the fig. 2 a). Depending on the relative position of the stoppers and motor electrodes with regard to the signal electrode, two cases are possible. (1) The final position of the signal electrode is situated in the voltage-controlled position zone, where an equilibrium between the electrostatical force and the mechanical spring force is possible, or (2) it is situated in the pull-in zone, where such an equilibrium is not possible (for a fixed *Vmot*), and as soon as the voltage *Vmot* exceeds *Vpull-in*, the signal electrode moves toward the motor electrode until touching the stoper (fig. 2 b)). The border between these zones is approximately situated at the point $\frac{Dmot}{3}$ from the zero position of the signal electrode, as shown in the fig. 2 b). To reduce the needed actuating voltage, the initial distance between the motor electrodes and the signal electrode should be as small as possible. The lower limit is of cause determined by the needed displacement, i.e. by the (fabricated) distance between the stopper and the signal electrode. We choose it 3.1 μm, close to the minimum gap value allowed by the lithography (2.8 μm for the used technology). So the fabricated distance between

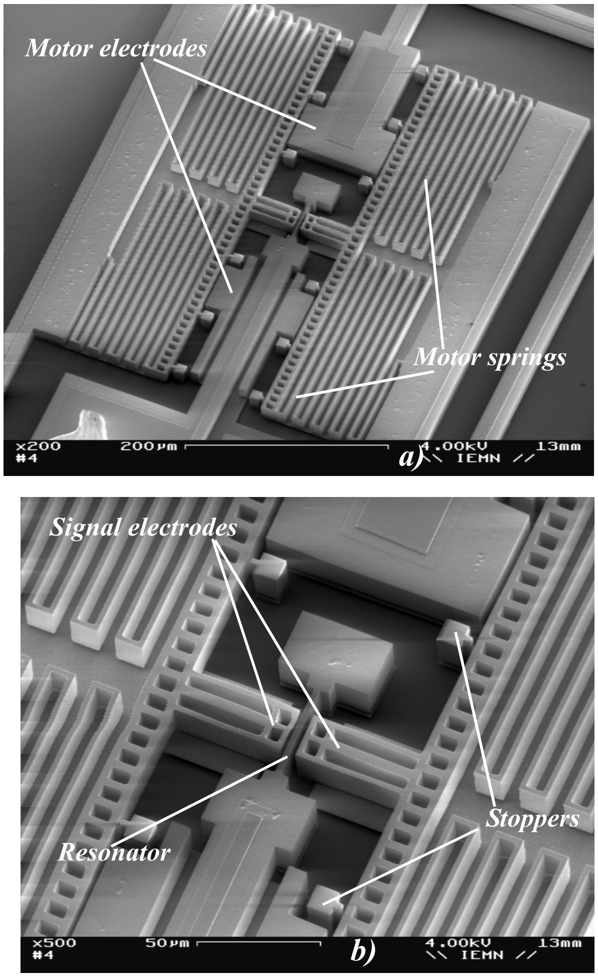

Fig. 3. Photomicrographs of the device.

the signal electrode and the motor electrodes should be larger. We also have to consider the residual distance (after the displacement) between the signal electrode and the motor electrode. It should not be very low, since it adds a signal electrode-to-ground parasitic capacitance. We have chosen this residual gap to be equal to 1.5 µm for our devices. It means that the final displacement point of the signal electrodes is situated in pull-in zone, and therefore to activate the motor, at least the system's pull-in voltage should be applied.

To calculate the pull-in voltage of the system, we use the formula found for a linear-spring case (fig. 2). It is possible because the displacements of the motor are very small compared to the spring dimensions, and so the spring can be considered linear. The calculated pull-in voltage of the system is 37V.

Table 1. Basic motor and resonator's *designed* dimensions.

Parameter's name	Value	Parameter's name	Value
Beam length, µm	40	Dres, µm	1.8, 2.0
Beam width, µm	3	Dstop, µm	1.6
Structural layer-thickness, µm	15	Dmot, µm	3.1

DEVICE FABRICATION

Two resonators with the same beam dimensions have been fabricated, with different initial gaps between the resonator and the signal electrodes, in the way to get the final gaps equal to 0.4 and 0.2 µm. The essential dimensions of motor elements and resonators are given in the table 1. Fig. 3 a) and 3 b) show photomicrographs with an overall view of the manufactured device and a zoom on the resonator.

MOTOR TEST

The test of the motor has shown that the pull-in phenomenon occurs at Vmot=30V, close to the theoretically estimated 37V. After the gap is reduced, the motor bias voltage can be reduced to 20V, and electrodes are still maintained close to the resonator. The motor does not consume any DC power.

RESONATOR TEST

We have especially been interested by characteristics that emphasize the signal electrodes-to-resonator gap reduction effects. For this the most informative is the resonance frequency shift versus bias voltage characteristic (fig. 4). From this plot the real value of the gap can be extracted by curve-fitting [3]. The extracted gap values for the fabricated resonators are 0.27 µm and 0.57 µm, slightly larger than the designed values of 0.2 and 0.4 µm. The difference between the designed and the extracted gap values can be due to the fabrication mismatch: the over-etching width can be slightly different for areas with different geometry, and 0.1 µm of tolerance is possible.

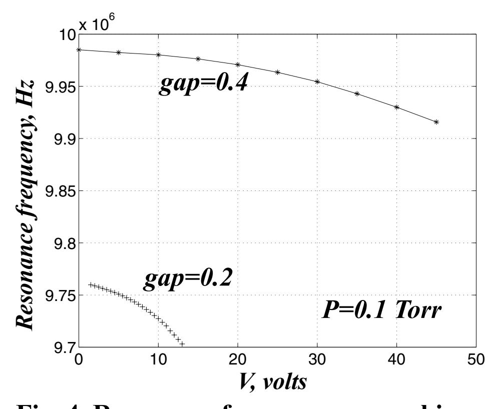

Fig. 4. Resonance frequency versus bias voltage characteristics.

Although the both resonators have been designed with the same dimensions, their resonance frequencies are different as we can see from the fig. 4 (9.98MHz and 9.77 MHz). This is due to fabrication tolerances.

The following characteristic shows the influence of the gap value on the resonator's performance. Two transmission characteristics have been measured for two resonators (fig. 5). The bias voltages are chosen in the way to get

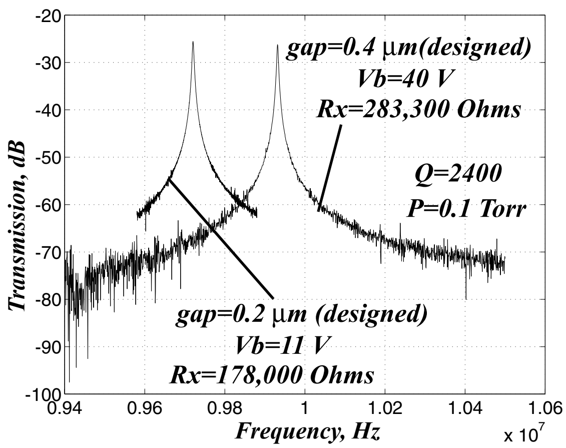

Fig. 5. Comparison of the performance of two resonators.

equal transmission at the resonance frequencies (and so an identical motional resistance). The ratio of the bias voltages of the resonators is 40/11=3.6, close to 4, that proves the ratio for the gaps to be close to 2 ($Rx \sim \frac{do^4}{Vb^2}$). To achieve the same transmission level without the gap reduction, the bias voltage would have to be close to 2500V!

The values of motional resistances of two resonators mentioned in the fig. 5 have been obtained from the extracted gap values and simulated mechanical parameters of the resonators. They are not equal as were expected from the equality of the transmission levels at the resonance frequency (37% difference). It can be explained by the inaccuracy of the extraction operation: since the motional resistance value is very sensible to the extracted gap value ($\sim d_o^4$), even low errors of the latter considerably affect the calculated value of the motional resistance.

TEST SET-UP

To test the resonators' performances, we have used the set-up depicted in fig. 6.

This measurement scheme doesn't allow to eliminate the parasitic capacitive coupling between the input and output electrodes from measurement results. This coupling creates a feedthrough current that is added to the motional current at the input. Since the both signals are complex, their superposition gives a characteristic different from one of a single resonator (fig. 7, plot a)). To separate the motional resonator response from the parasitic coupling signal, we have adapted the method described in [4]. Using the set-up shown in the fig. 6, we first measure the resonator with $Vb=0$, i. e. only parasitic feedthrough current, and save the measured data in the network analyzer memory. We then measure the biased resonator, and subtract the memory data from the new measured signal containing both the feedthrough and the motional component. In this way an accurate measurement of the motional signal has been achieved (fig. 7, plot b), and also plots in fig. 5).

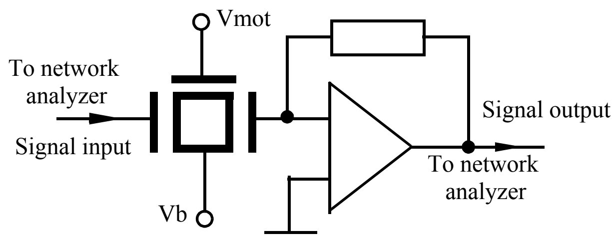

Fig. 6. Resonator test set-up.

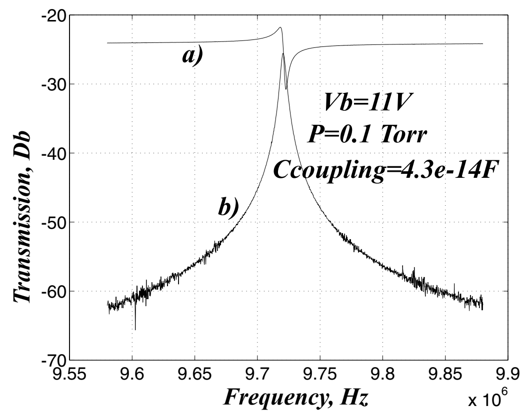

Fig. 7. Demonstration of the parasitic coupling influence on the resonator characteristic.

CONCLUSIONS

Test results have proven the effectiveness of the proposed method of the gap adjustment. It offers a possibility to design micro-mechanical VHF filters in thick-layer silicon technology, where up to now the main difficulty was to achieve a sufficiently narrow gap without a complex technology. To drive the gap correction electrostatical motor, only 30 V DC without any current consumption is needed, that can be generated even in mobile systems. This issue contributes to the use MEMS filters in commercial wireless applications. In the paper we have presented resonators with 10 MHz center frequency, but the method should allow the design of resonators and filters working at much higher frequencies approaching the intermediate frequency band. Also, by appropriately modifying the geometrical parameters of the motor, the reduction of the motor actuating voltage is possible.

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