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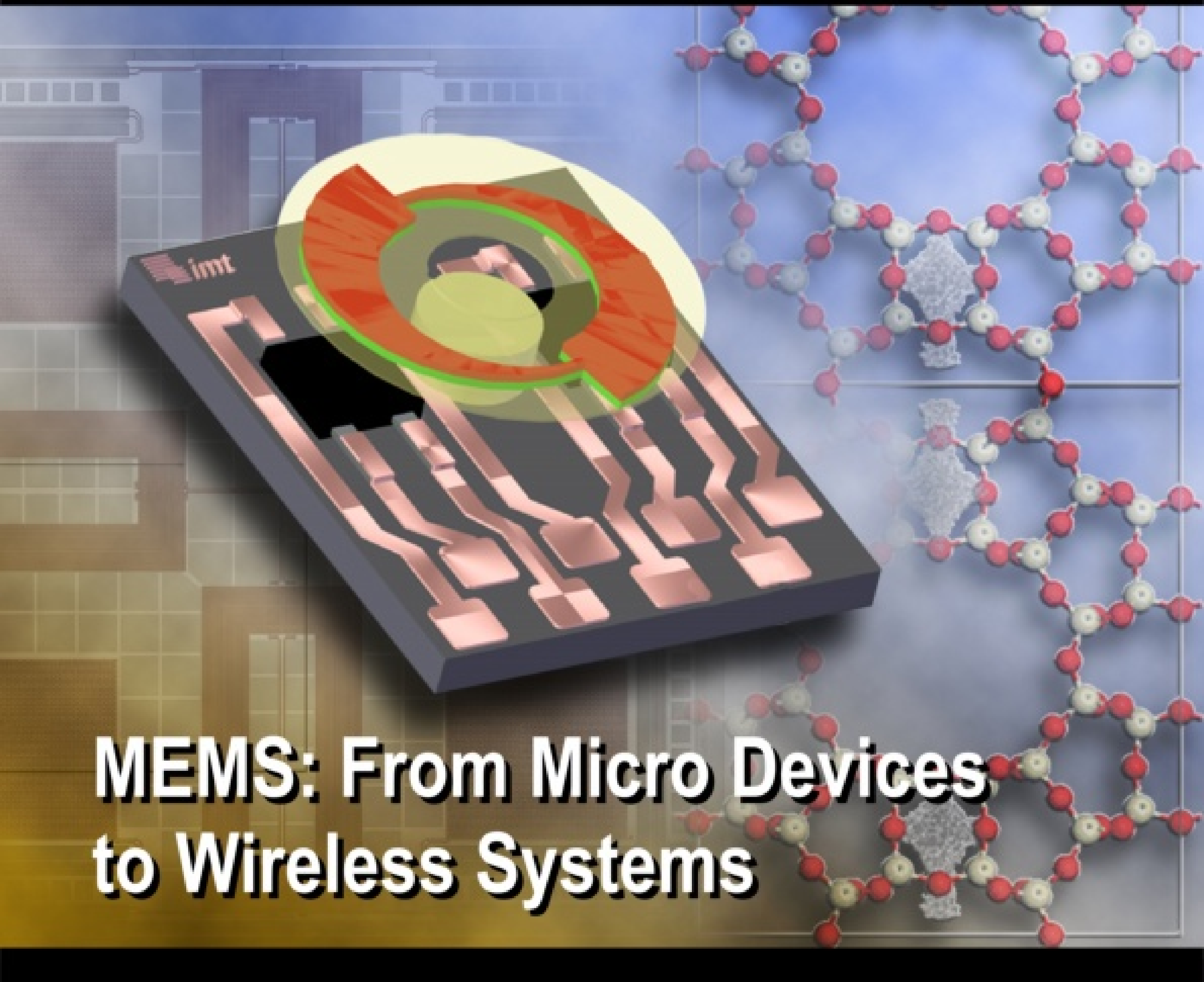

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Micro-fabricated Rotational Actuators for Electrical Voltage Measurements Employing the Principle of Electrostatic Force

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Abstract: In this paper, we present an advanced RMS voltage sensor based on rotating parallel-plate capacitors based on the principle of electrostatic force. The actuator is built using a micromechanical thin bulk silicon batch process yielding structures with a high sensitivity mainly due to a low mechanical spring constant, realized with thin and long beams. Metal layers provide separated excitation and sensing electrodes. The actuator is anodically bonded on a matching glass substrate with a shallow rectangular cavity in which the opposite electrodes are located and which defines the working distance to be as low as 2.5 µm. To avoid stiction, bumpers with a small contact area physically prevent short circuiting under pull-in conditions and thus improve the reliability. Finally design choices and the micromechanical fabrication process are explained. Moreover, DC and RF characterization results of the devices are presented showing successful operation from below 10 Hz up to more than 1 MHz. *Copyright © 2009 IFSA.*

Keywords: MEMS, Metrology, RMS voltage sensor, High-frequency Measurements, Bulk silicon, Anodic bonding, Batch process

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1. Introduction

In this paper, a micro machined silicon actuator for DC and RF voltage measurements is presented. The conventional method for traceable high-frequency voltage metrology is based on power dissipation measurement of ohmic resistances, allowing RMS voltage conversion by the square power law. Employing the principle of electrostatic force is an alternative method to solve this problem [1]. It takes advantage of a completely different physical principle. Due to the quadratically decreasing force as a function of distance it is necessary to utilize micromachining for the construction of such a sensor. Comb-like structures are often used in sensors and actuators for this task, allowing the use of surface micromachining technologies, but showing unwelcoming parasitic effects. For metrology applications it is preferable to have a well calculable structure with as few parasitic effects as possible. Therefore, a parallel plate setup is chosen for actuation and sensing. Voltage excitation leads to a rotation of the actuator which in turn is detected using either the integrated electrodes for capacitance measurement or by optical detection. By operating the device above its mechanical resonance frequency, the mean force is proportional to the RMS value of the voltage excitation.

The presented sensor allows rotational movement around an axis above the center of the electrodes. The actuated element is made of a 20 µm thick dry-etched silicon layer, combining the elastic, but stiff, properties of silicon with a very low spring constant, resulting in a high sensitivity with a low overall device footprint. In this paper we summarize the necessary theoretical foundation, present the optimized batch fabrication process, and finally show DC and RF measurement results. The process allows simultaneous production of 64 sensors in one production run on a standard 100 mm wafer resulting in devices with better mechanical properties compared to manual assembly. A similar but stiffer design based on bulk silicon is presented in [2]. Related work in this area involves non-rotating linear sensors [3] with a lower sensitivity and surface micromachined sensors for higher frequencies [4].

2. Theory of Operation

For the derivation of the analytical model, we consider a simplified model of the geometry as shown in Fig. 1. A movable plate of size B x $2L$ is suspended at its center with two beams of length l having a rectangular cross-section w x t. On each end of the plate an electrode is located with a non-movable counterpart at the initial distance h_0 on the opposite side forming the capacitors C_A and C_B.

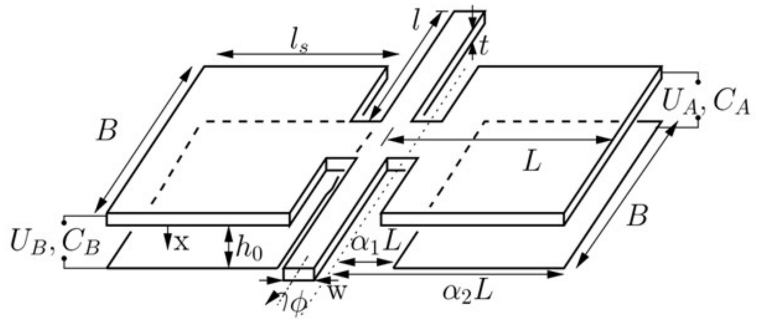


Fig. 1. Geometrical model of the torsional actuator showing the important dimensions of the actuator and of the capacitive electrodes.

Applying a voltage to a pair of electrodes creates a moment M_U around the tilting axis, leading to a deflection of the plate by the angle ϕ. This in turn leads to a counter moment M_k due to the twisted beams of the suspension. The attracting moment is increasing more than linearly with increasing deflection angle; the restoring moment is only proportional to the angle. When those moments cannot balance each other any more, the so called pull-in point is reached. The actuator moves to the mechanical end position $\phi\mathrm{max} = \sin^{-1}(h_0/L)$.

This pull-in voltage U_{pi} is commonly expressed as [5]:

$$U_{pi} = \sqrt{0.827 \frac{k_\phi h_0^3}{\varepsilon_0 B L^3}}, \tag{1}$$

with the restoring spring constant k_ϕ

$$k_\phi = \frac{E_{Si} \cdot \beta \cdot t \cdot w^3}{l(1+\nu_{Si})} \tag{2}$$

E, υ are the Young's modulus and Poisson's ratio of the material (Silicon in this case) respectively, and β is a numerical constant depending on the ratio t / w (typically 0.4).

To design a high sensitivity device, a large actuator with a long lever arm attached to the support by long and slender beams has to be chosen. The initial spacing h_0 between the electrodes has also to be as low as possible as well. This increases the capacitance of the structure, and thereby the load on the incident wave. By tuning the spring constant to be as low as possible the sensitivity can be increased without increasing the load.

For RMS voltage conversion the behavior of the device in the time-domain has to be considered as well. The sensor forms a 2nd order system with a mechanical resonance frequency f_r. With a DC excitation, the actuator will eventually settle to its equilibrium position. AC excitation with a frequency $f < f_r$ leads to a delayed response of the system. Only by operating the device at an AC frequency $f \gg f_r$ the desired root-mean-square shaping effect is achieved. The typical resonance frequency of the presented devices is tuned to be at about 1 kHz, making them ideally suited for measurements at electrical frequencies as low as 10 kHz. High damping and a low excessive force lead to a slow time response thereby decreasing the lower frequency range to about 100 Hz.

3. Design and Fabrication

Bearing in mind calculability, reproducibility and the need of superior non-deteriorating elastic properties, silicon is chosen as actuator material. Silicon is used to achieve maximum mass, to reduce mechanical noise, and to optimize the flatness of the devices. A low distance between the electrodes is essential according to Equation 1. The electrodes are therefore placed in wet-etched shallow rectangular cavities on a separate glass wafer. The initial distance between the electrodes is hence solely determined and controlled by the etching time and can be changed without modifying the lithographical masks. A typical device with the parameters in Table 1 has a pull-in voltage well below 10 V. A cross-section of the fabricated device is shown in Fig. 2. The overall device footprint is 6 x 6 mm^2, fitting around 100 different designs on a standard 100 mm wafer. The fabrication process involves processing three wafers in parallel and joining them to form a hybrid micro system. Press-on contacts allow electrical contact between the different wafers. Up to the dicing step, the whole fabrication is done in batch, giving uniform results and high throughput compared to manual assembly. An overview of the fabrication process is given in Fig. 3.

The fabrication process starts with a glass wafer (Corning 7740) which is coated with a thin chromium adhesion layer and a thick gold layer. Using standard thin photo-resist technology, first the gold is structured where later the press-on contacts are going to be located. In the next lithography step, the chromium is structured to define the location of the cavities. These are etched in a fluoric-acid based wet-etch solution to define the gap distance from 2.5 μm up to 5 μm. To prevent stiction and to improve long-term reliability of the devices bumpers are fabricated in this step by making use of isotropic under etching of small rectangles (Fig. 4a).

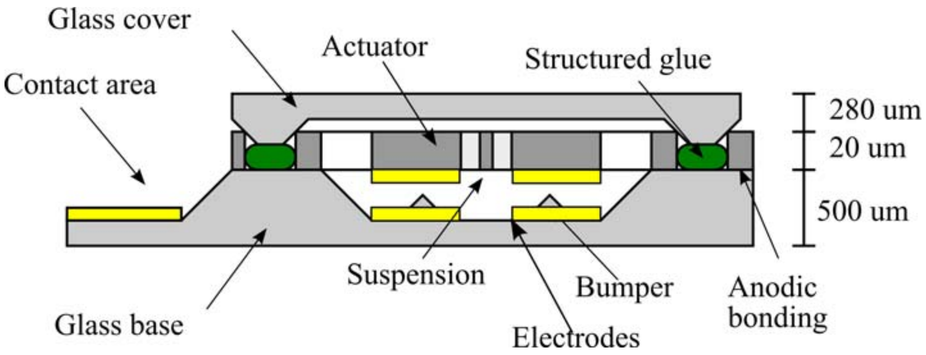


Fig. 2. Cross-section of the final sensor.

Table 1. Principle geometrical dimensions of the presented sensor.

Dimension	**Symbol**	**Value**	**Unit**
Overall device footprint		8 x 8	mm^2
Plate length	L	2000	µm
Plate width	B	1000	µm
Gap	h_0	5	µm
Plate thickness	t	20	µm
Length of torsion beam	l	1000	µm
Width of torsion beam	w	20	µm
Start of electrode	$\alpha_1 \cdot L$	1000	µm
End of electrode	$\alpha_2 \cdot L$	2000	µm

Afterwards, the gold and chromium layer from the press-on contacts is removed, while keeping the rest of the masking. In another wet-etch step the depth of these areas is defined to be about 500 nm – about 100 nm lower than the thickness of the combined electrode layers on the glass and silicon respectively (600 nm).

In parallel, a second wafer is prepared for the other side of the actuator. This is a SOI wafer having a 20 µm thick device layer and 1 µm buried oxide. On this wafer silicone-oxide is deposited as an isolation layer and on top of that, gold electrodes are lithographically defined. The thickness of these layers has to be carefully controlled, so that the internal mechanical stress of the layers is compensated. Otherwise deformation of the actuator would occur after release.

The glass and silicon wafer are subsequently anodically bonded together with voltages below 400 V and a temperature of 350 °C to prevent damage to the electrodes and the formation of silicon-gold eutectics. The press-on contacts are pressed together in this step and give electrical contact between the wafers, thus connecting the upper electrodes (Fig. 4b). A halo around the contacts indicates not bonded area due to separation.

To reduce the thickness of the actuator, the handle layer of the SOI wafer is wet-etched in a potassium hydroxide (KOH) solution. The buried oxide layer is a defined etch stop and is subsequently etched in fluoric acid. Only the uniformly 20 µm thick silicon device layer for the actuator structure remains. To release the actuator, thick photo-resist is used to mask the silicon layer for etching in a deep reactive-ion etcher (DRIE). The dry etching results in device features with nearly vertical sidewalls. The photo-resist is finally stripped in oxygen plasma to prevent fluid getting in the electrode gap which would later be hard or even impossible to remove.

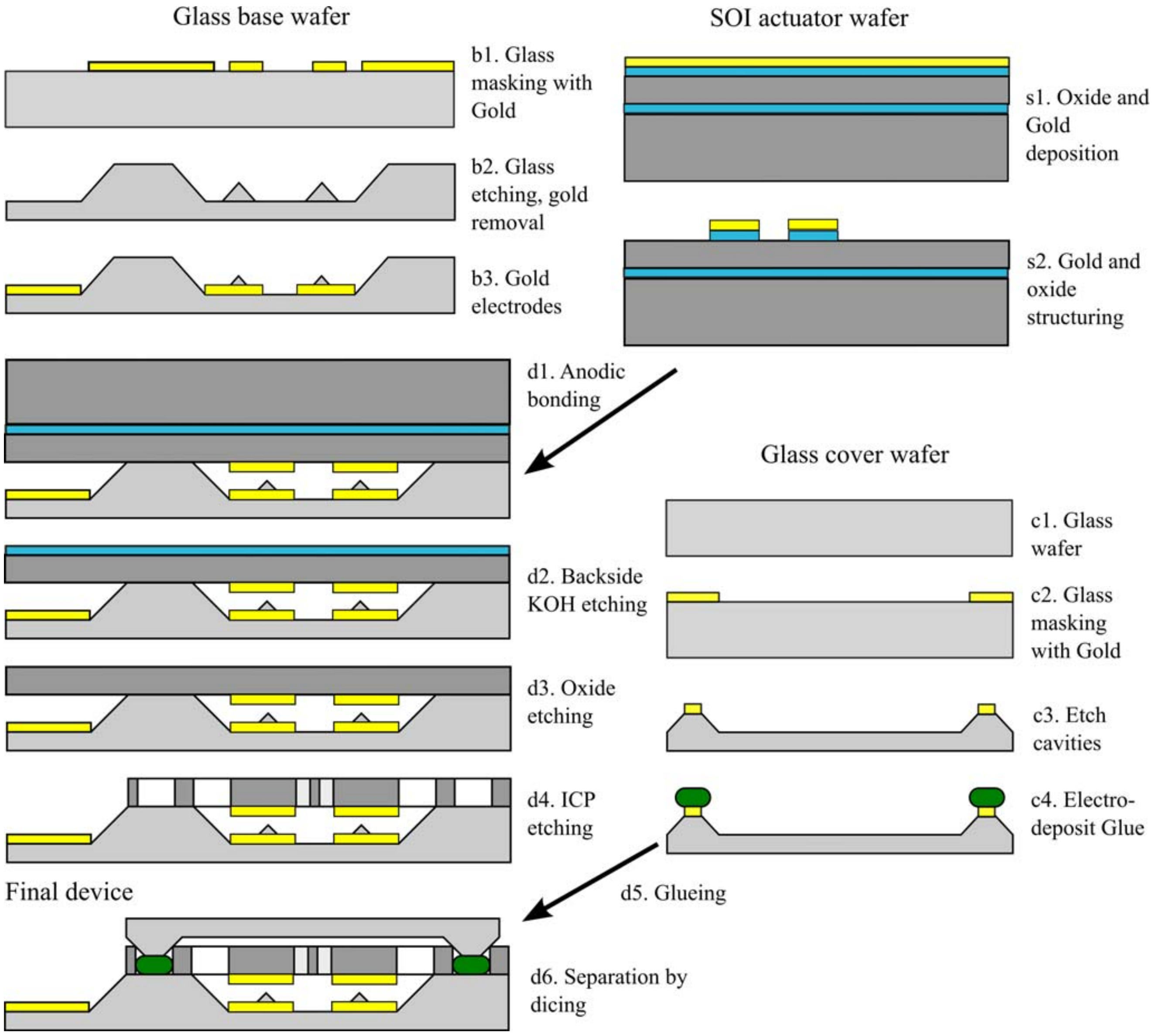
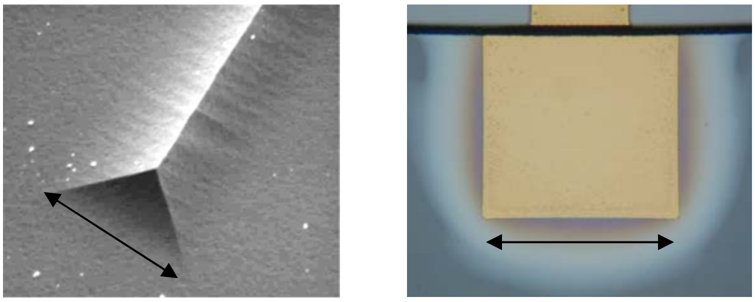


Fig. 3. Fabrication process steps of the micromechanical actuator.



(a) (b)

Fig. 4. (a) Wet-etched bumper to prevent stiction (arrow 20 µm); (b) Press-on contact created by anodic bonding (arrow 250 µm).

For environmental protection and handling purposes, the device is finally sealed with a cover piece made of glass which has glue electro-deposited on it, to define the adhesion lines. For depositing the glue, gold is sputtered on the wafer and structured to form rectangles around the edges of the devices. The layer is masked in a way that electrical contact between all areas remains. Further on the wafer is drowned in the resist bath, electrical voltage is turned on, and the resist deposits on the gold lines. Finally, the wafer is dried, baked and diced on adhesive tape. The covers are then aligned to the rest of the wafer stack. Another bake step glues the covers tightly to the actuators and the tape can be removed.

The whole process is optimized for batch processing. After combining the three wafers, they are diced by breaking along semi-sawn lines, to prevent fluid coming in the devices, which would cause stiction. The finished device is shown in Fig. 5.

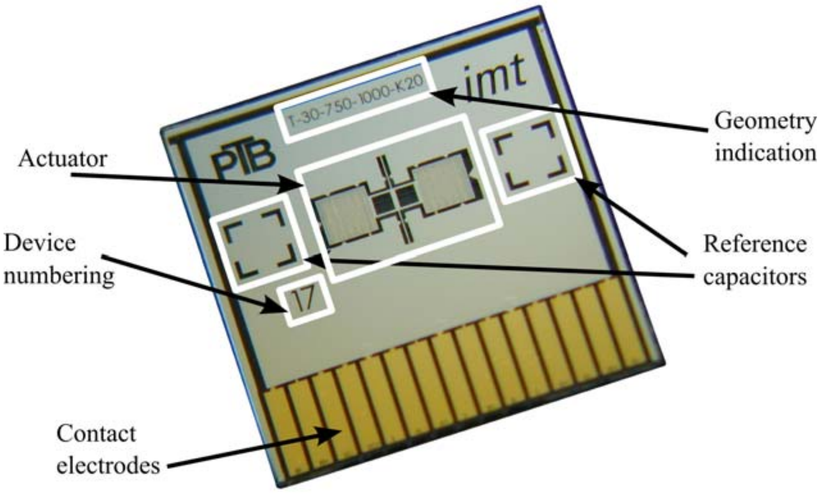


Fig. 5. Picture of the finished sensor (8 mm x 8 mm). The actuator is visible in the center, contact area at the bottom and reference capacitors to the left and right.

To validate the assembly step, small reference capacitors and short circuit elements are provided at the sides of the structure. To connect the device, it is wire-bonded to a matching PCB substrate. Alternatively, for fast and easy testing, a commercially available flat flexible cable socket with 0.5 mm connector pitch can be used (Fig. 6). The disadvantage is that only approximately 10 inserts can be done until the contact electrodes are scraped off. To improve on this a zero force socket could be used. Another possibility would be thicker, or even galvanically reinforced, electrodes. For long term usage wire bonding has proven to be the superior technology.

4. Test and Results

The setup for the characterization of the sensors consists of an arbitrary waveform generator (DC to 20 MHz) for excitation and an *Analog Devices* capacitance measurement integrated circuit AD7747 with a theoretical resolution of up to 24-bit or 6 aF [6] at a maximum capacitance change of 8 pF. The sensor directly outputs the digital capacitance value over a two-wire interface. An *Atmel* microcontroller is used to convert the signal to a standard RS232 interface.

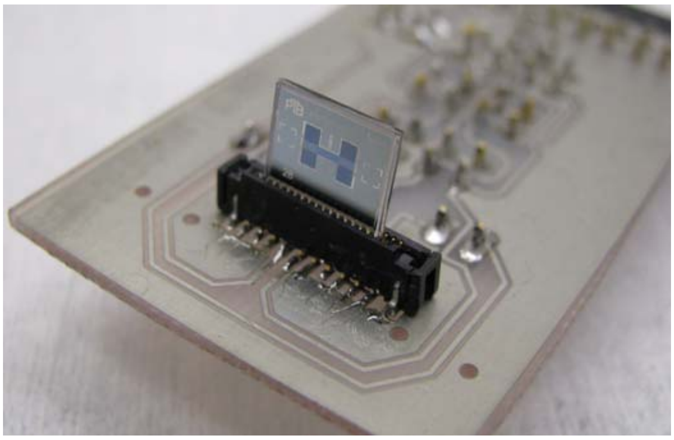


Fig. 6. Picture of the sensor fitted into a flat flexible cable socket on a PCB with supporting electronics.

Practical resolution and repeatability of the setup including parasitic effects, but without averaging, is about 500 aF. The fabricated sensors are mounted in the flex-cable socket with a direct and short connection to the measurement IC, eliminating parasitic effects as much as possible. The whole system is placed in a temperature controlled and electrically isolated chamber set to 25°C. The sensor platform has also been mechanically decoupled to reduce the influence of vibrations.

The waveform generator is connected to one pair of electrodes C_A and the capacitance-meter to the other electrode pair C_B. In this configuration capacitance over voltage curves at different frequencies are recorded. To exclude any kind of hysteretic behavior or memory effects, after each measurement the generator output is switched off and the zero voltage capacitance is recalibrated.

The capacitance over voltage curve for different frequencies is plotted in Fig. 7. For the frequency range up to 100 kHz it shows a good agreement with the DC curve. For frequencies higher than that, high-frequency effects probably cut-off the voltage on the capacitance. By varying the frequency at fixed amplitude of the wave (Fig. 8) the good performance of the device between 100 Hz and 100 kHz can be confirmed.

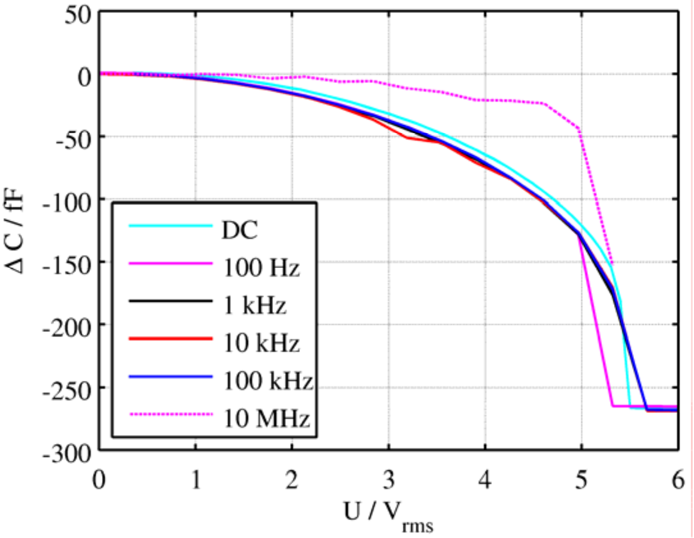


Fig. 7. Capacitance change over RMS voltage at frequencies from DC to 10 MHz.

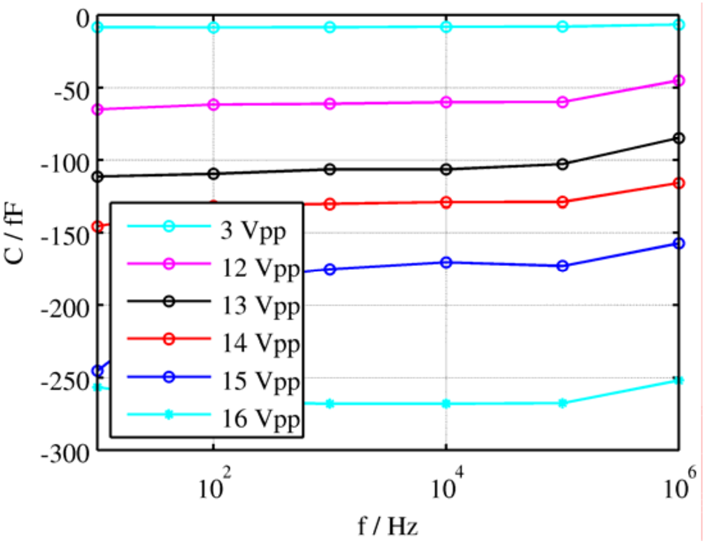


Fig. 8. Capacitance over frequency at different peak-to-peak voltages from 3 V to 16 V.

This may be especially surprising, as the resonance frequency is at about 10 kHz. But measurements and simulations show, that the squeeze-film damping at resonance already gives an attenuation of 30 dB. The high-aspect ratio of the actuator plate to the gap distance leads to very slow step responses.

5. Conclusion and Outlook

The described fabrication process was tested in several production runs and the batch assembly process has proven to be sophisticated. For the completed devices steady-state results for DC and RF excitation have been obtained. For the high frequency domain, results show homogeneous behavior from 100 Hz up to 1 MHz. Further research will focus on examining a broader range of sensors, extending the usable frequency range up to 100 MHz and achieving pull-in voltages of 1 V or lower to obtain sensors with higher sensitivity in the low amplitude range. For higher frequencies a different approach based on surface micromachining seems more promising, due to the hard to control parasitic effects in silicon, like built-in voltage, loss and leakage [7].

Acknowledgments

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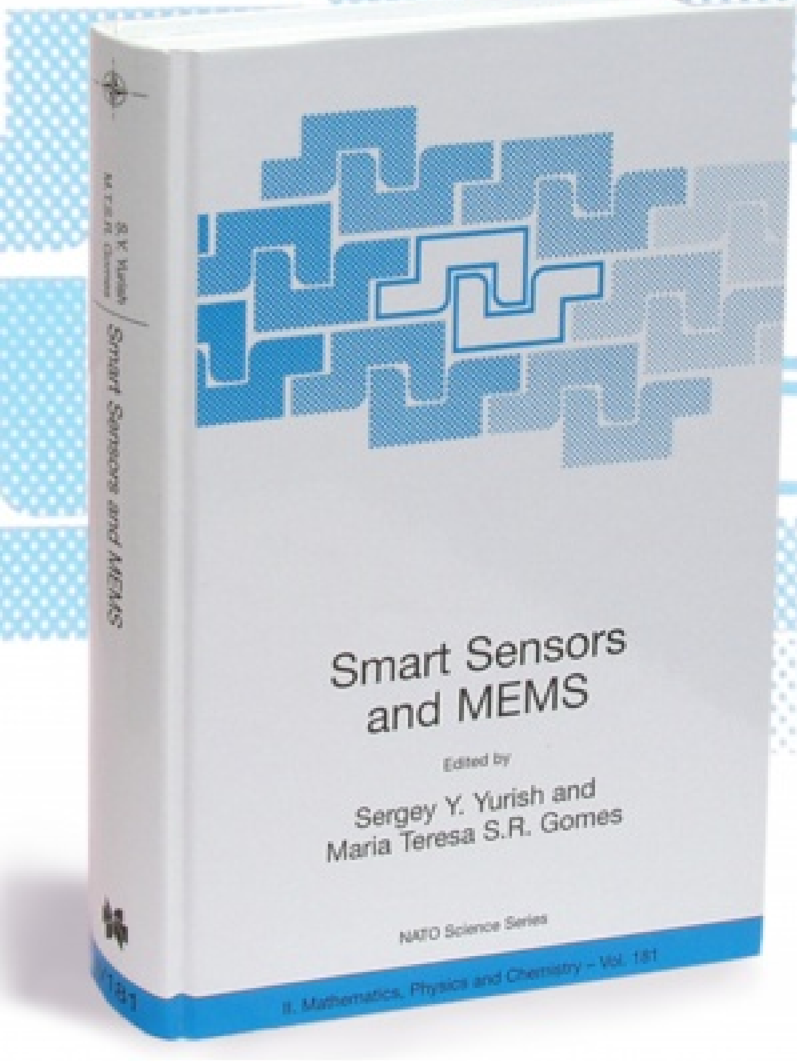

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