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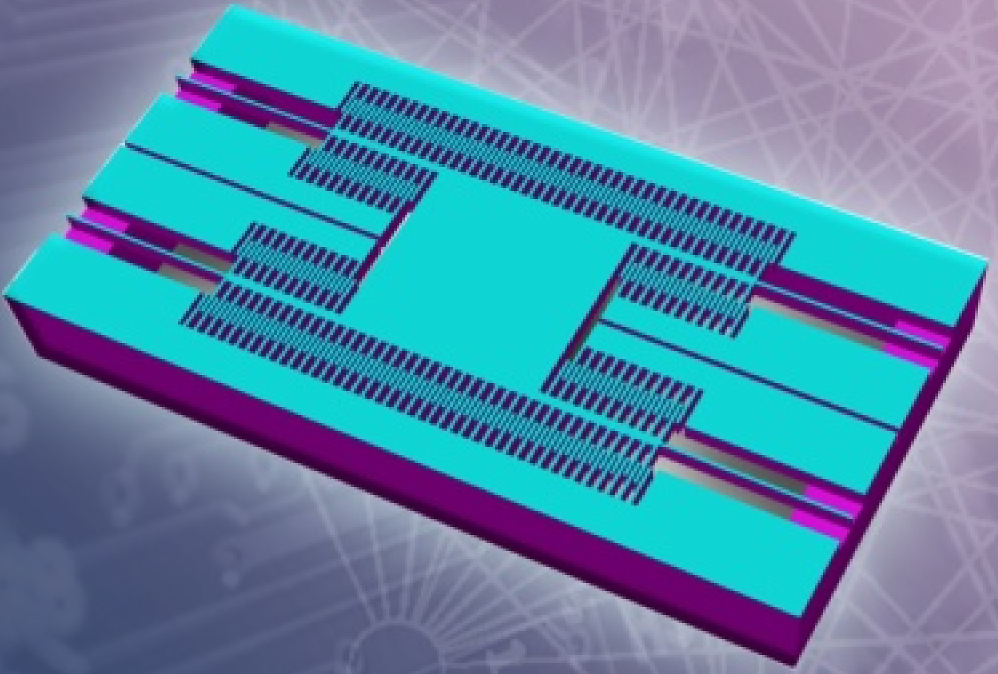

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Design, Simulation and Fabrication of a Mass Sensitive CMOS-MEMS Resonator

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Abstract: The design, simulation and fabrication of a mass-sensitive CMOS-MEMS resonator are presented in this paper. The principle of detection of the gaseous species is based on the change in resonant frequency of the microresonator as a result of the absorption/adsorption of an analyte molecule onto the surface of the active material deposited on the microresonator resulting into a change of the mass of the microresonator device. CoventorWare simulation software is used to design and simulate the micromachined resonator gas sensing platform/membrane. From simulation, the resonant frequency of the resonator is found to be 6.45 kHz and 23 kHz for mode 1 and mode 2 (in y and z direction), respectively. The frequency decreases with increasing mass added on top of the CMOS-MEMS resonator membrane and the mass sensitivity of the resonator determined to be 0.18 Hz/pg. *Copyright © 2012 IFSA.*

Keywords: Natural frequency, CMOS-MEMS, Resonator, CoventorWare and Deep Reactive Ion Etching (DRIR).

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1. Introduction

Micromachining is a process of shaping silicon or other material to realize 3-D mechanical structures (moving or static) in miniature form. Micromachining has become a dominant and fundamental technology in the fabrication of microsensors, micro- actuators and microstructures. The micromachining techniques are categorized into bulk micromachining and surface micromachining processes [1]. Bulk micromachining is a process used to produce MEMS. It defines structures on silicon substrate by selectively etching inside the substrate. Membranes, cavities, bridges and cantilevers are fabricated using etching of silicon. There are two basic categories of etching processes [2], wet etching where the material is dissolved when immersed in a chemical solution (removed of unmasked layer is done by selective liquid etchants) and dry etching where the material is sputtered or dissolved using reactive ions or a vapor phase etchant (the plasma is used in the form of low pressure gaseous discharges to remove unmasked layer). There are two different types of wet etching; isotropic and anisotropic wet etch. Isotropic wet etch etches in all directions at the same rate (non-directional etchants are used to remove exposed areas of a substrate) while anisotropic etch etches the substrate faster in one direction than another [3]. Anisotropic wet etching of silicon is the most common micromachining technique. Surface micromachining uses layers deposited on the surface of a substrate as the structural materials, rather than using the substrate itself. As the structures are built on top of the substrate and not inside it, the substrate's properties are not as important as in bulk micromachining, and the expensive silicon wafers can be replaced by cheaper substrates, such as glass or plastic. Comb drives capacitive actuators often used linear actuators that utilize electrostatic forces that act between two interdigitated fingers structures. They are normally placed in the same plate parallel to the substrate where one comb is fixed and the other set is suspended and free to move in one or more axes. By applying difference voltage between the fixed comb and movable comb, the movable comb will move. There are many applications in Micro Electro Mechanical Systems (MEMS) structures using comb drive actuators as resonators [4-7]. Comb-drives can be used either for electrostatic actuation or capacitive sensors [8]. There are three driving schemes for alternating electrostatic actuator as follows [9]:

a) Alternating voltage driving;
b) Driving by an alternating voltage with a dc bias;
c) Push-pull driving.

Push-pull driving is often considered as the best solution because the forces can be applied in both directions.

In 2005, Ioana Voiculescu, et al presented the design, fabrication, and testing of a resonant cantilever beam in complementary metal–oxide semiconductor (CMOS) technology for the detection of chemical weapons [10]. The design of the cantilever beam includes interdigitated fingers for electrostatic actuation and a piezoresistive Wheatstone bridge design to read out the deflection signal. The beam structures fabricated and designed with a range dimensions to explore the effect of device shape on resonant frequency, and mass sensitivity. Six different designs were included in a single chip. Short, wide, and thick cantilever beams are preferred for higher resonant frequencies, and large surface structures which maximize the area for polymer coating and subsequent gas sorption. The dimensions of the fabricated cantilever were varied from 130 to 300 μm in length and varied from 60 to 150 μm in width. The whole device is fabricated using a 0.6 μm, three-metal, double-poly CMOS process, combined with subsequent micromachining steps. A custom polymer layer is applied to the surface of the microcantilever beam to enhance its sorptivity to a chemical nerve agent. Exposing the sensor with the nerve agent stimulant dimethylmethylphosphonate (DMMP) demonstrates gas detection at a concentration of 20 ppb or 0.1 mg/m^3. In 2009, Xinxin Li, et al from Chinese Academy of Sciences studied the integrated MEMS/NEMS resonant cantilevers for ultrasensitive biological detection [11]. The dimension of the cantilever used is $300 \times 100 \times 3$ μm^3. The calculated effective mass is 52.5 pg. The frequency for the fundamental resonance mode is designed as 45.9 kHz. The sensitivity is calculated as 0.43 Hz/pg. Margarita Narducci et al developed a resonant cantilever sensor based mass detection [12]. The cantilever resonance was driven by a piezoactuator and the frequency sense of by four piezoresistors in a Wheatstone bridge. Two cantilevers with different dimensions were fabricated. Dimensions of the first cantilever are 400 μm, 300 μm and 15 μm, while for the second cantilever the dimension are 200 μm, 150 μm and 15 μm, length, width and thickness, respectively. The first is operated at 100 kHz with a quality factor of 830 and the second is operated at 400 kHz with a quality factor of 900. From an experiment the mass sensitivity is found to be around 1.3 Hz/pg. In order to become competitive with existing commercial sensing technologies, microresonator sensors must provide good sensitivity, smaller sizes, low cost, rugged, and reliable. The most important areas identified for future research is the development of more selective coatings that give rise to large changes in surface mass. The objective of this paper to design, simulate and fabricate a Mass-Sensitive CMOS-MEMS Resonator. The proposed structure exhibits better sensitivity compared to previously discussed devices.

2. CMOS-MEMS Resonator Design

CoventorWare is an integrated suite of design and simulation software that has the accuracy, capacity, and speed to address real-world MEMS designs. The suite is filled with MEMS-specific features for accurately and efficiently simulating all types of MEMS, including inertial sensors (accelerometers and gyros), microphones, pressure sensors, resonators, and actuators. The included field solvers provide comprehensive coverage of MEMS-specific multi-physics, such as electrostatics, electromechanics, piezoelectric, piezoresistive, and damping effects [13]. It acts as a design environment that reduces design risk, manufacturing time and lowers development costs. The major components of CoventorWare simulator are the material properties database, process editor, architect, designer and Analyzer. CoventorWare supports both system level and physical design approaches. The system level approach involves the use of behavioural model libraries with a high-speed system simulator. The system level MEMS design can be used to generate a 2-D layout and involves building a 3-D model, generating a mesh, and simulating using Finite Element Method (FEM) or Boundary Element Meshes (BEM) solvers. The CMOS-MEMS resonator design CoventorWare environment and is based on CMOS technology and bulk micromachining processes. For structure release, a post-CMOS processing steps are included in the process recipe. The post-CMOS steps involve a Deep Reactive Ion Etching (DRIE) process which etches deep cavities in substrates from back side and front side of the silicon wafer leaving a 40 μm silicon substrate under CMOS layer and from the front side to release the structure.

The resonator was designed in the architect; the Architect tool uses the information in the Material Properties Database (MPD) and process files in its simulation of a top-down design. With the architect, instead of using a layout drawing tool to create a 2-D model, a high-level design techniques is utilized can be created a system model of a device that can be simulated. Also designs faster and a complex designs simulated. After the device is completely designed in architect the layout is extracted and viewed in designer to get the 2-D layout editor. This layout is the combined with a process description to create 3-D model, then meshed and is the ready to be simulated using the analyzer's Finite Element Method (FEM) and boundary element method (BEM) solvers.

Fig. 1 shows the schematic of the CMOS-MEMS resonator generated using architect in the software. It consists of global variables that define all the component parameters, beams with different width, rigid plate as the membrane supported by four bridges (beams), and straight comb with stator, mechanical bus connector, straight comb capacitance connectors, fixed knots, grounds, and the voltage sources. Interdigitated combs are used for driving the structure. A sinusoidal voltage is applied to oscillate the device in mode 1 (y) direction. Partial of the interdigitated combs are also used as sensing capacitors.

Fig. 2 shows the 2-D Layout of the CMOS-MEMS resonator. The dimensions of the structure is 1700 μm × 800 μm with the membrane area of dimension 400 μm × 400 μm supported by four bridges (beams). These beams consist of two different widths of 7 μm for beam without fingers and 19 μm for beam with fingers. The fingers are used for actuation and sensing. The length and width for actuation and sensing fingers are 80 µm and 7 µm, respectively. The 2-D layout information is used to create 3-D model for meshing and FEM analysis. Fig. 3 shows the 3D model of the resonator generated in the designer part of the CoventorWare simulation software.

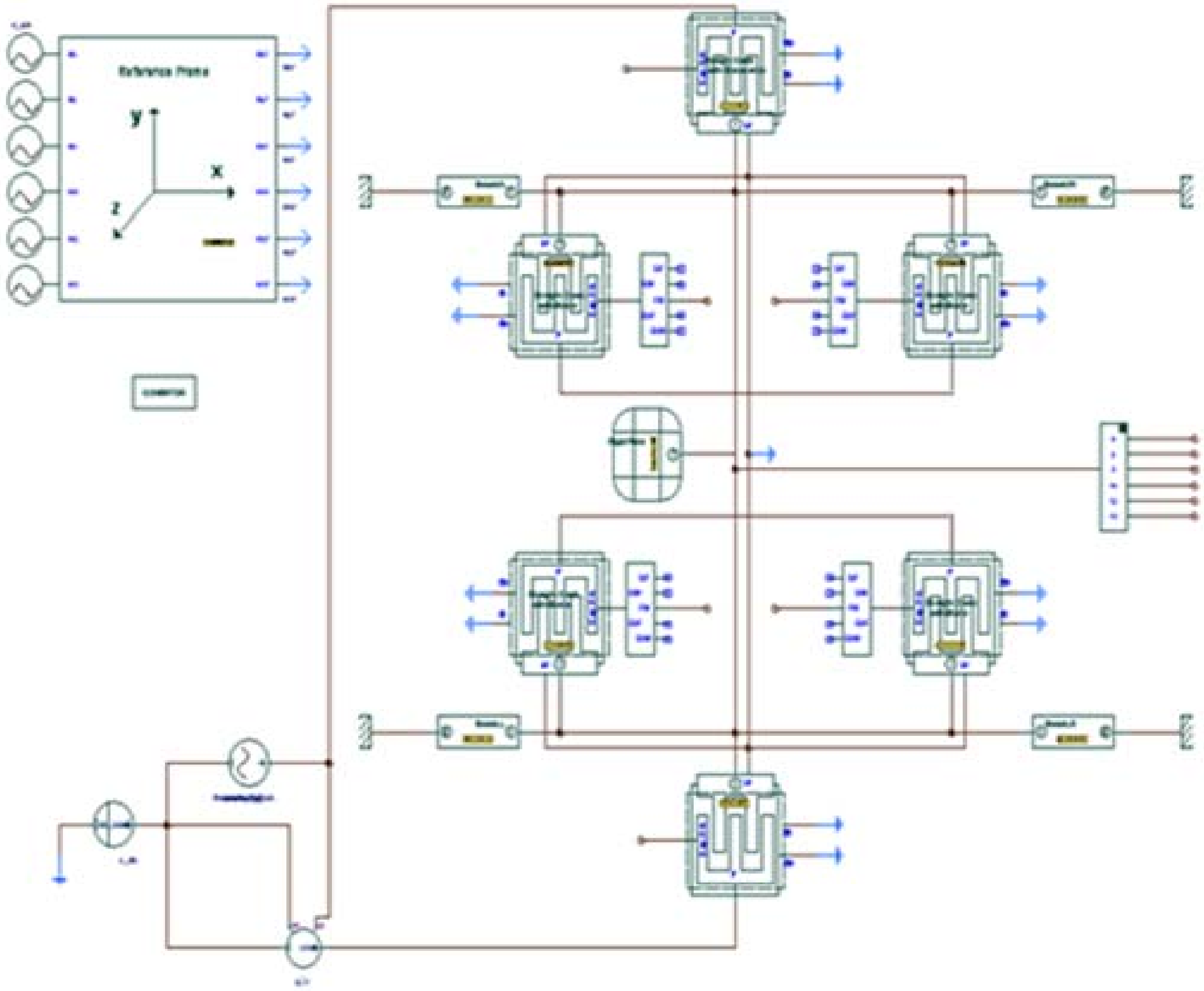


Fig. 1. Schematic of the CMOS-MEMS resonator.

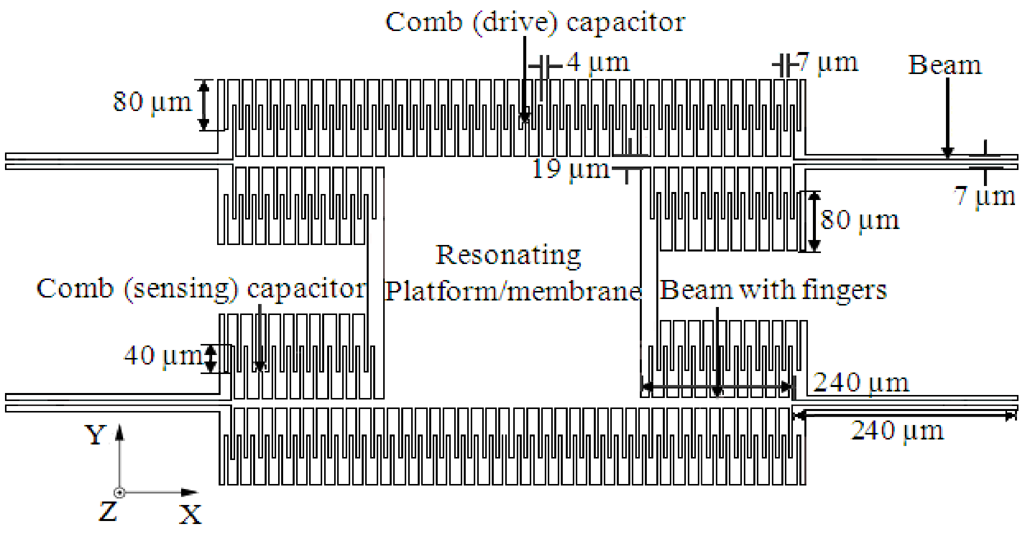


Fig. 2. 2-D Layout of Device Schematics.

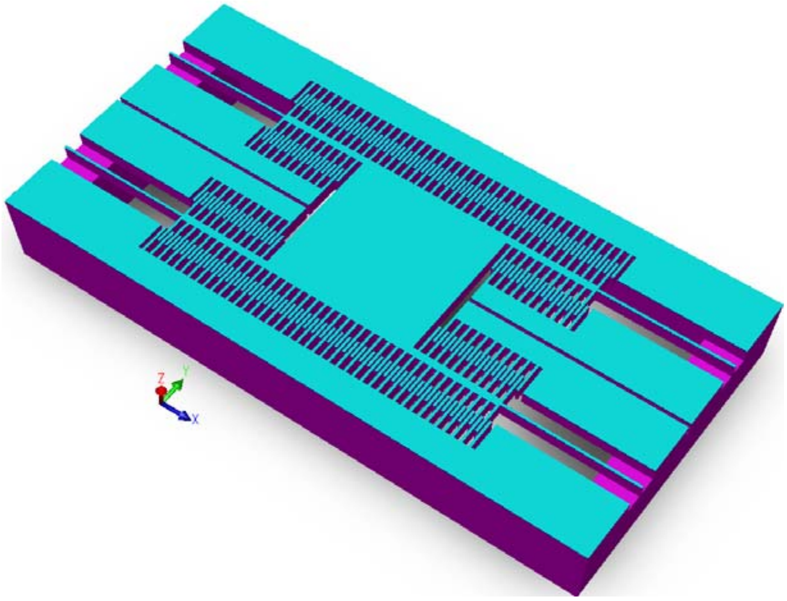


Fig. 3. 3D structure of CMOS-MEMS resonator.

3. Device Fabrication

The layout of mass-sensitive gas sensor based on CMOS-MEMS resonator is fabricated using 0.35 µm CMOS process and post-CMOS micromachining process. The CMOS process consists of two polysilicon layers, three metal layers, two vias and several dielectric layers. All metal layers are made of aluminium and the dielectric layers are silicon dioxide while vias are used for the connection from metal 1 to metal 3 layers where required. Metal 1 on the membrane is used as heating and temperature sensing elements while metal 2 and metal 3 are used as heat distributor layers to improve the uniformity of the temperature distribution on the sensing membrane, actuation and sensing capacitor. After the CMOS process and dicing, a post-CMOS micromachining process is carried out which includes 4 steps as shown in Fig. 4 (a, b, c and d). Fig 4 (a) shows the as received die and, Fig. 4 (b) shows a DRIE anisotropic etching from the back side used to etch the silicon and produce proof mass with thickness up to 40 µm followed by (c) Reactive Ion Etching (RIE) with C_4F_8 and O_2 used to etch the silicon oxide and, finally, (d) shows DRIE with SF_6 and O_2 from the front used to etch through the structures' 40 µm Silicon substrate and release the microstructure.

4. Results and Discussion

From CoventorWare simulation, the resonant frequency of the CMOS-MEMS resonator is found to be 6.45 kHz and 23 kHz in mode 1 (y) and mode 2 (z) direction as shown in Fig. 5. It is important to have accurate results for y resonant frequency. The mode 1 (y) mode resonant frequency should be far as possible from y mode resonant frequency to avoid mode coupling which can affect device performance and structural stability.

Fig. 6 shows the variation of beam length selected to investigate the resonant frequencies in the mode 1 (y) direction. From the plot, it shows that the frequency increases from 6445.7 Hz to 11900 Hz with decreases in the length of the beam from 600 µm to 400 µm.

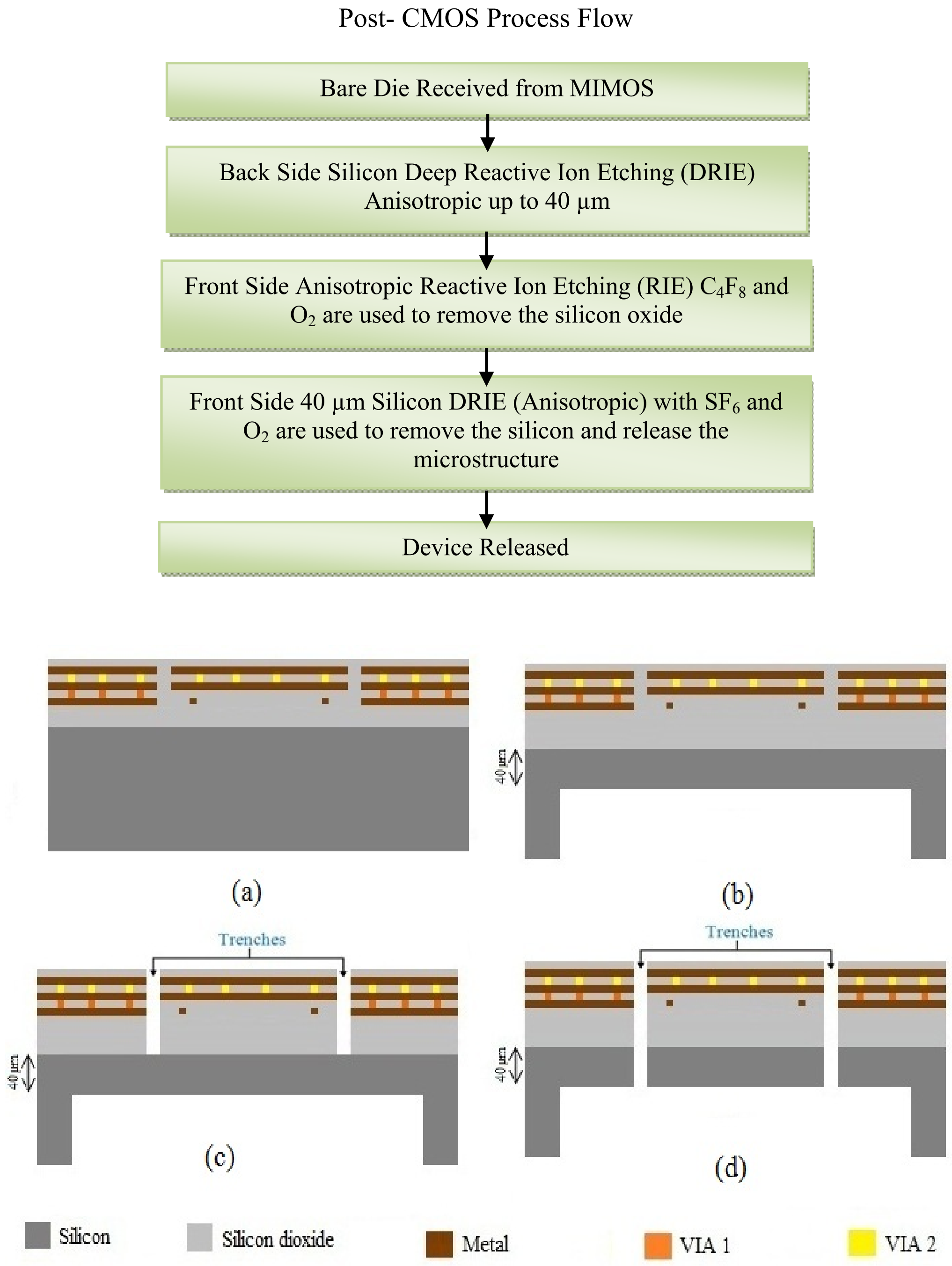


Fig. 4. Post-CMOS process of the CMOS-MEMS resonator.

The sensitivity is a very important factor to determine in the design of the CMOS MEMS resonator. There is it is important to investigate the sensitivity by varying the thickness of the add mass on the top of the CMOS-MEMS resonator. Fig. 7 shows the variation of thickness of the add plate to investigate the resonant frequencies in the mode 1 (y) direction. The frequency increases from 6417.3 Hz to 6451.3 Hz with decreased thickness of the added mass from 500 nm to 100 nm. Variation in thickness of the plate means changing in added mass. Frequency change as a function of added mass on the CMOS-MEMS resonator is shown in Table 1. Fig. 8 shows the frequency change as a function of added mass. From Fig. 9, it shows that the sensitivity is determined to be 0.18 Hz/pg with a negative slope which indicated that the frequency decreases with increasing mass.

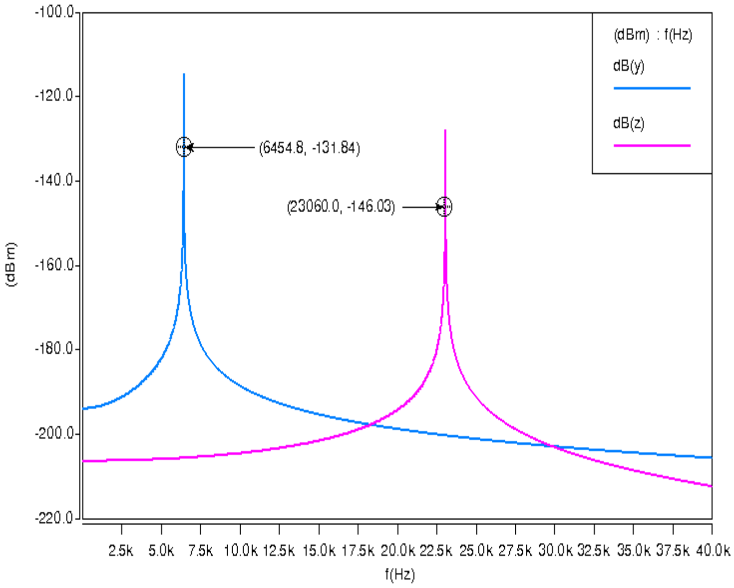


Fig. 5. Resonance frequencies for mode 1 (y) and mode 2 (z) directions.

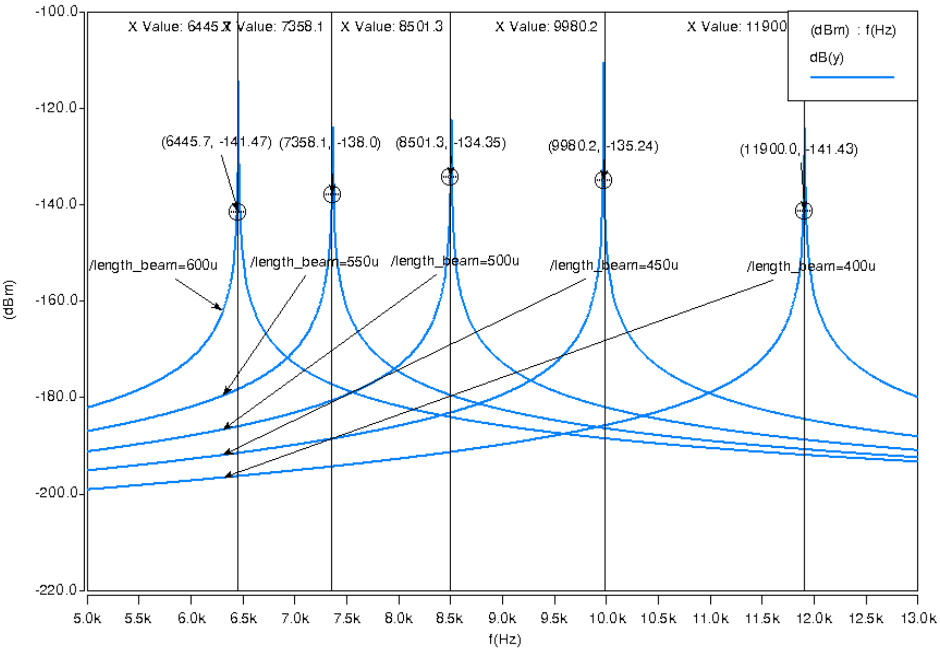


Fig. 6. Resonance frequencies vs. beam lengths.

Table 1. Frequency change as a function of added mass.

Add Mass (pg)	Frequency (Hz)	*Δf (Hz)*
0	6454.8	0
42.37	6451.3	3.5
84.74	6443	11.8
127.1	6434.3	20.5
169.95	6425.7	29.1
211.8	6417.3	37.5

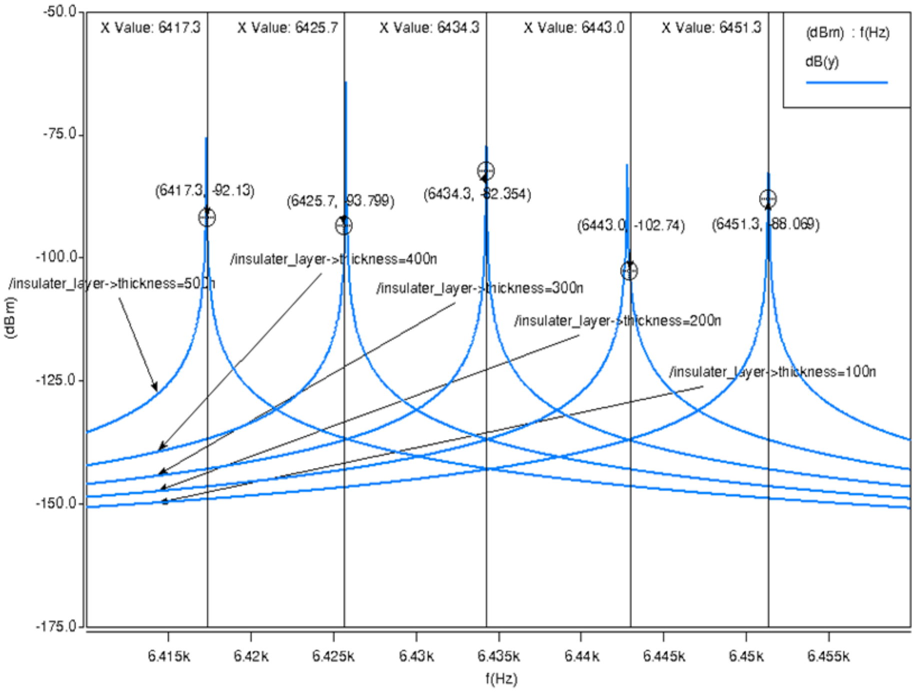


Fig. 7. Resonance frequencies vs. thickness of the add plate.

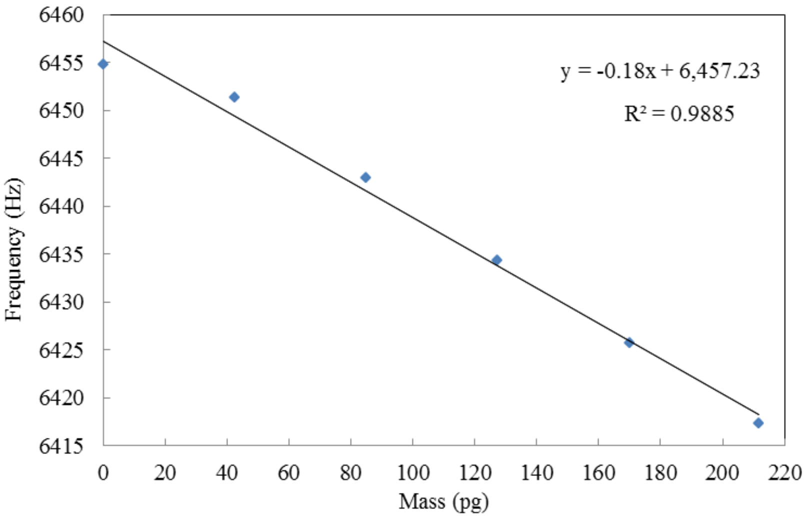


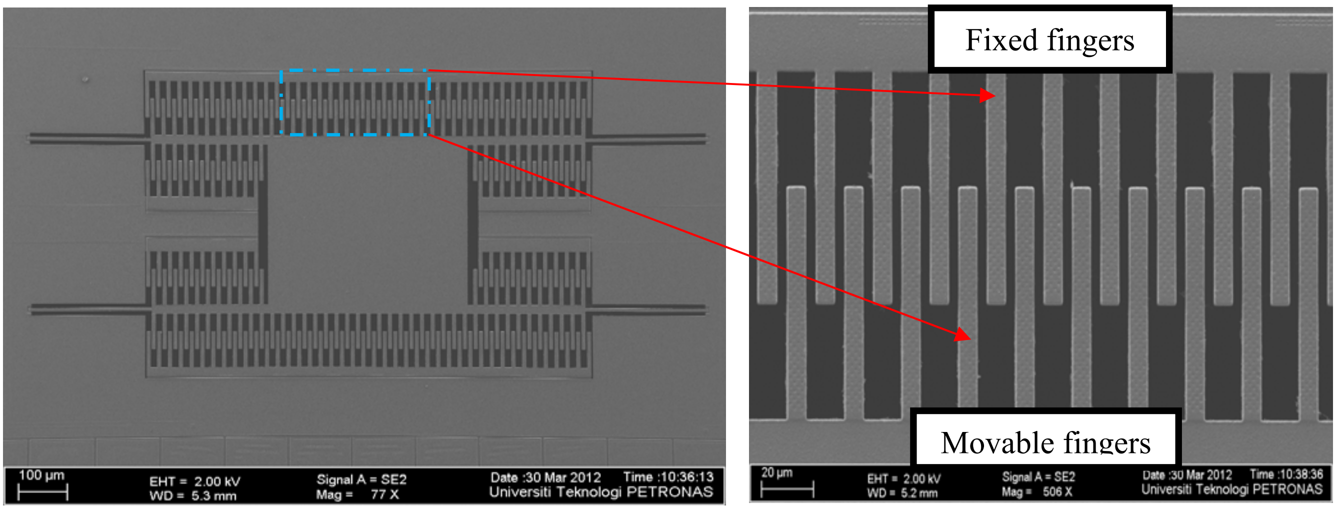
Fig. 8. Frequency change vs. added mass on the CMOS-MEMS resonator.

The optimized fabricated CMOS-MEMS resonator is shown in Fig. 9 (a) and a magnified view of fixed and movable fingers of CMOS-MEMS resonator is shown in Fig. 9 (b). The device was successfully fabricated and released using a post-CMOS micromachining process.

5. Conclusions

A CMOS-MEMS resonator for gas detection via frequency change due to mass loading has been designed, simulated and fabricated. The resonant frequency is found to be 6.45 kHz and 23 kHz in mode 1 (y) and mode 2 (z) direction, respectively. The variation of beam length and thickness of add mass was investigated. The frequency decreases with increasing mass added on top of the CMOS-

MEMS resonator and the sensitivity is determined to be 0.18 Hz/pg with a negative slope which indicated that the frequency decreases with increasing mass. The device was successfully fabricated in a 0.35 µm CMOS technology and released using a post-CMOS micromachining process.



(a) (b)

Fig. 9. Device fabricated (a), and a magnified view of fixed and movable fingers (b) of CMOS-MEMS resonator.

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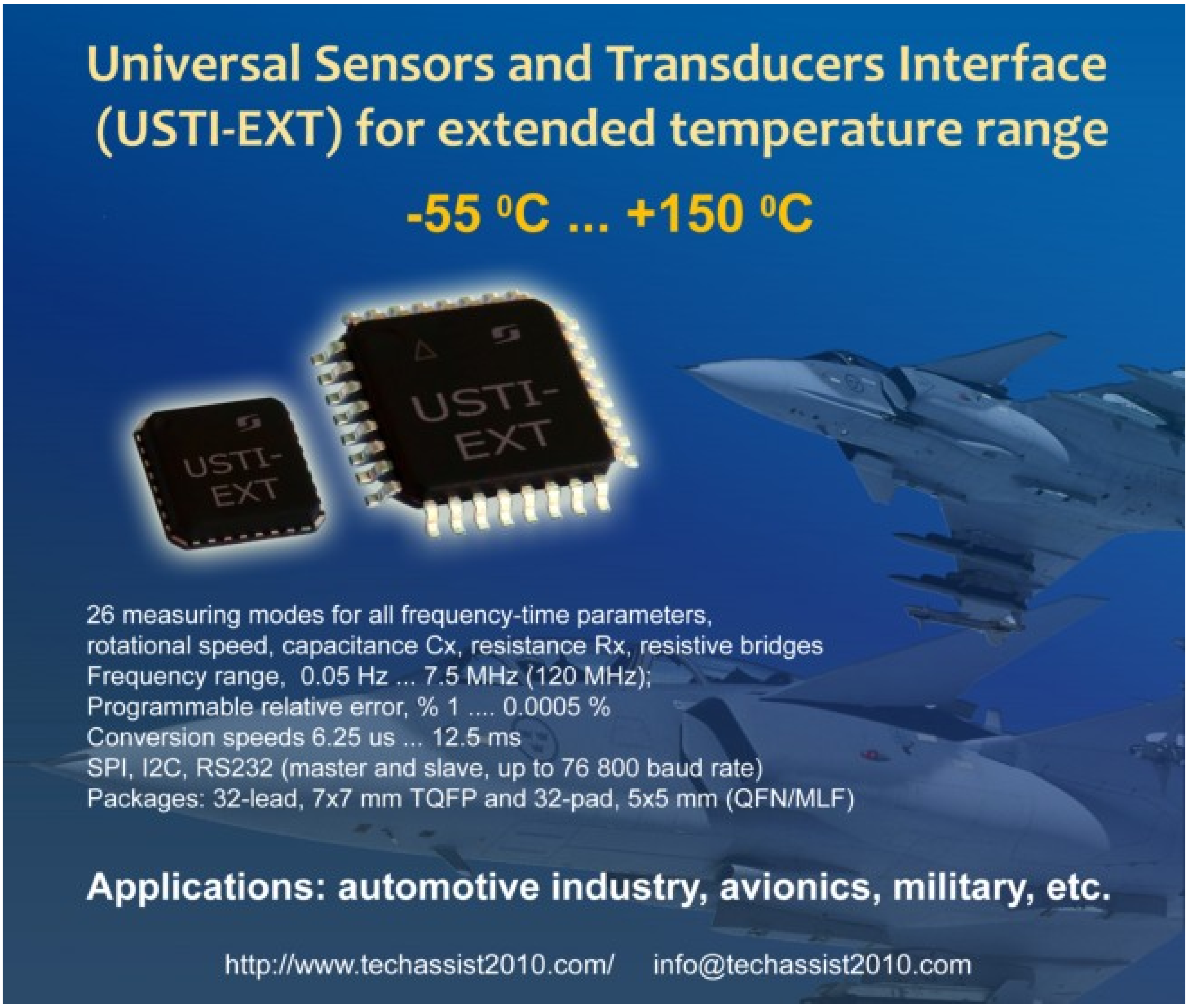

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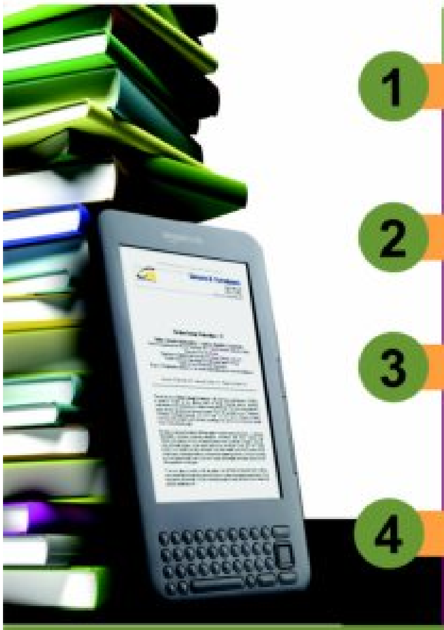

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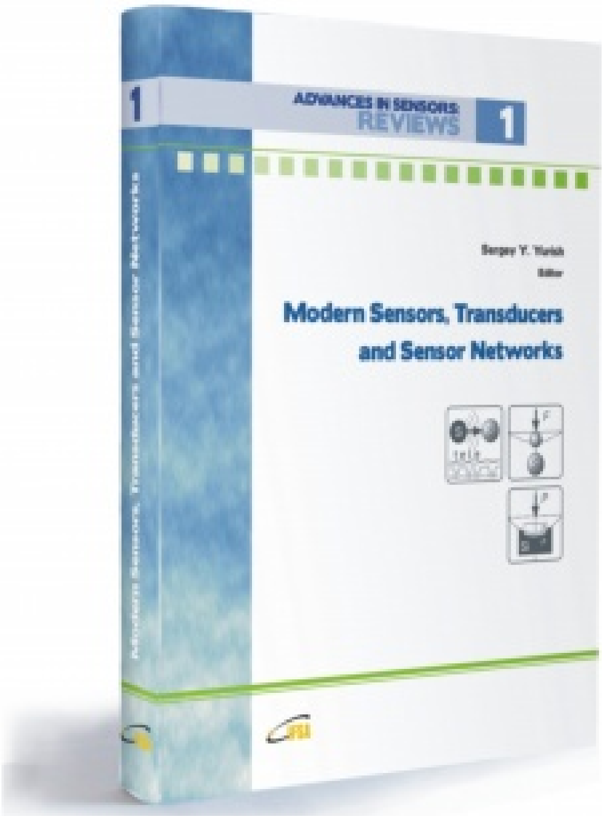

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