Macro Model of Capacitive MEMS Accelerometer in Cadence Environment

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Abstract

Designing of MEMS devices requires modeling step. Many devices combines mechanical and electrical domains. Very often it is desired to use one simulation tool that allows taking into account both domains. Such functionality has CADENCE environment. In this paper we do such simulations using developed macro model of capacitive MEMS accelerometer. The accelerometer is described in Verilog-A language and placed in electrical schematic that consist of read-out circuit. The simulations were performed for the device z-axis CMOS-integrated acceleration sensor that has been developed in UPC Barcelona. The results of simulations were compared to those obtained by measurements of fabricated device.

1. Introduction

During last 15-20 years, capacitive micro-accelerometers have found many applications and become one of the examples of successful implementation in MEMS technology [1]. Different kinds of accelerometers (piezoresistive, piezoelectric, and capacitive) have been developed and the capacitive micro-accelerometers become more attractive than others due to their high sensitivity, low temperature sensitivity and low power dissipation.

Wide range of applications creates a need of designing structures with specific parameters to meet the requirements. Thus, the modeling and simulation is essential for predicting the device performance and its optimization. It allows shortening the time to market and cost of development as this stage can be performed before the fabrication of real device.

One of the most common and reliable method is FEM simulation. However, it has some disadvantages. The main is the necessity of building a three-dimensional model and solving a high number of differential equations related to number of nodes created in model meshing. This method is not very simple and takes relatively long time. The better idea is to use faster analytical modeling, especially for simple structures like accelerometers. In early stage of the development the results will be precise enough to obtain basic information on the device performance. Moreover, analytical modeling allows creating one model of the device that includes all its parts (mechanical, electrical, etc.).

In this paper we present the macro-model of a z-axis CMOS-integrated acceleration sensor. The model combines the mechanical part of accelerometer and its electrical part including the read-out circuit. In order to have a possibility of performing full device simulation, the model was created in CADENCE environment with use of Verilog-A language to describe the mechanical part.

2. Accelerometer Sensor Model

A. Accelerometer description

Figure 1 presents the image of the accelerometer taken with scanning electron microscope. The z-axis (out-of-plane) acceleration sensor is composed of the bottom fixed plate and the top perforated square plate suspended on its corners inside a fixed frame. The diameter, size of holes, suspension geometry as well as the bottom and top layers are subjects of the design process. When the device body accelerates the inertia force acts on the plate and causes its deflection in normal direction. The induced stresses remains within the flexible suspension legs. Therefore, relatively stiff top plate does not deform. Due to distance change between the substrate and the plate, the acceleration can be measured as a change in electrical capacitance.

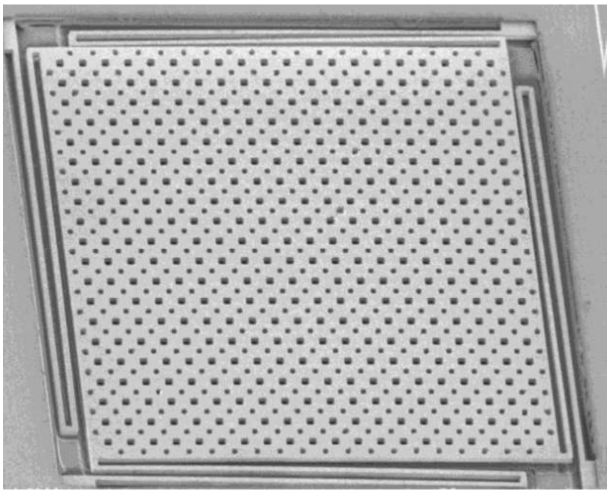

Figure 1: CMOS BEOL-embedded z-axis accelerometer [2]

The acceleration signal is picked up by on-chip integrated readout circuit. This circuit uses modulation-demodulation technique. The real device integrates on-chip only the amplifier to reduce design cycles and complexity. Modulation and demodulation blocks are located outside the chip. In model development all blocks of read-out circuit are taken into account. In order to facilitate the capacitance change measurement, the sensor combines two the same accelerometer structures. The second one is used only as a reference capacitor. It means that this structure does not response to applied

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acceleration causing its capacitance to be constant during the operation. Due to the same technological process and the same dimensions its capacitance is almost the same as for operational structure under no load.

B. Modeling of mechanical and electrical part

According to the results of finite-element simulation [3], the analytical model of the sensor can be built using following assumptions:

- The top plate is assumed to be non-deformable and flat
- The suspension elements are considered as inertialess beams
- The inertia force field is assumed to be uniform and the external acceleration vector is directed normally to the plate surface

Thus, the movement of the sensor can be represented as a simple translation of a rigid flat plate along z axis.

Let z is the top plate displacement towards the fixed plate (Fig. 2). The top plate is assumed to be a rigid square plate of size a and area $A=a^2$. The elasticity of the suspension is modeled as a linear spring. The top plate is being acted upon three forces. F_a is the force associated with the acceleration and F_{el} is electrostatic force produced by voltage V_{in} applied between accelerometer plates. These forces cause movable top plates to change its position. The suspension legs of accelerometer works as a spring and generate the spring force F_{spr} in opposite direction to sum of F_a and F_{el}. The equilibrium state occurs when the sum of all forces will be equal to zero, e.g. in x position (assuming that the pull-in state will not occur [4]).

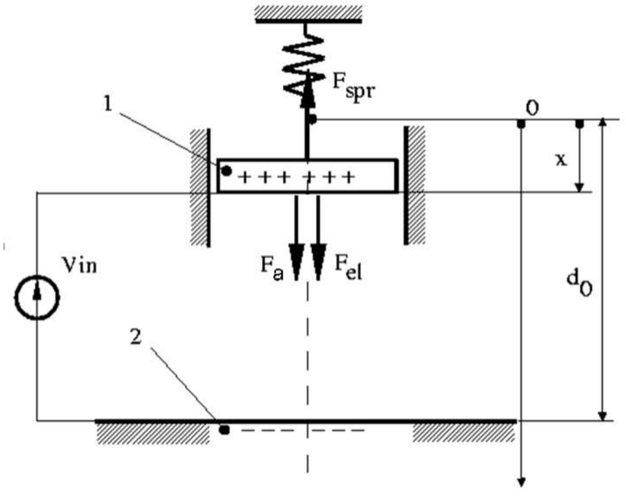

Figure 2: Accelerometer Sensor Model

We derive the equations of motion for the system under consideration by applying the Lagrange-Maxwell equations [5]. The displacement z will be used as the "mechanical" generalized coordinate and the charge will be considered as the "electrical" generalized coordinate. The Lagrange-Maxwell equations for this electromechanical system are:

$$m\ddot{z} + b\dot{z} + kz = \frac{q^2}{2\varepsilon A} + ma_e; \qquad (1)$$
$$\frac{q}{\varepsilon A}(d_0 - z) = V_{in},$$

where z is the plate displacement; q is the electrical charge; V_{in} is the input voltage; m is the top plate mass; b is the damping coefficient; k is the suspension stiffness; ε is the dielectric permittivity of environment; A is the top electrode area; d_0 is the initial gap distance; a_e is the external acceleration.

Differentiating the second equation (1) yields:

$$i = \dot{q} = \frac{d}{dt}\left(\frac{\varepsilon A}{d_0 - z} V_{in}\right) = \frac{d}{dt}\left(C(z) V_{in}\right) \qquad (2)$$

where i is the input electrical current of the device and C is the capacitance between plates. From a modeling standpoint, equation (2) represents a nonlinear capacitor of capacity:

$$C(z) = \frac{\varepsilon A}{d_0 - z} \qquad (3)$$

As one can see in Figure 1, each element of the suspension consists of two cantilever beams, each of length l, connected in series, opposite to each other. Due to symmetry, the angle of rotation of a cross-section at the connection point of two beams is zero. The deflection Δ of no-rotatable cross-section at the free end of the cantilever beam attached to a proof mass under a force P applied to the free end (fixed – guided beam) is [6]:

$$\Delta = \frac{Pl^3}{12EJ} \qquad (4)$$

where E is the Young's modulus of the material, and J is the beam cross-section moment of inertia. Particularly, for the rectangular cross-section of width b and height h, moment of inertia of such beam is equal to:

$$J = \frac{bh^3}{12} \qquad (5)$$

Thus, the equivalent stiffness of four-element suspension that each consists of two cantilevers connected in series is:

$$k = \frac{4P}{2\Delta} = \frac{2Ebh^3}{l^3} \qquad (6)$$

C. Macro-model in Cadence

The macro-model of the accelerometer sensor has been developed in Cadence environment. The accelerometer sensor cell has been realized as a 4-port component (Figure 3).

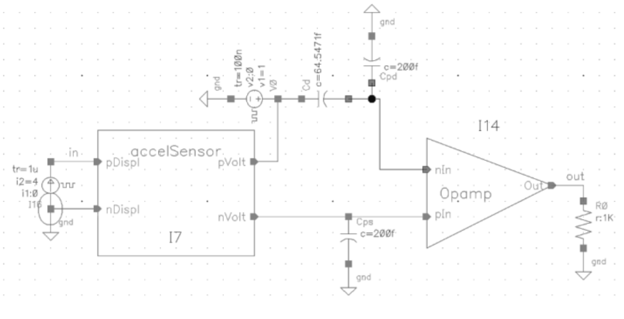

Figure 3: Accelerometer sensor combined with electronic interface

The first couple of external ports (*pDispl*, *nDispl*) correspond to mechanical input. The current of *I16* source is equal to the value of external acceleration in units of G (G=9.81 m·s^2). The voltage between denoted ports is equal to z displacement of the plate. The second couple of external ports (*pVolt*, *nVolt*) correspond to the variable capacitance according to equation (3). This cell has been described in Verilog-A language according to equations (1)- (3):

```
module cell01(pVolt, nVolt, pDispl, nDispl);

inout pVolt, nVolt;
electrical pVolt, nVolt;

input pDispl, nDispl;
electrical pDispl, nDispl;

parameter permittivity = 8.8542e-12;
parameter area = 1.8225e-8;
parameter initialGap = 2.5e-6;

parameter mass = 0.61e-9;
parameter damp = 1.36e-4;
parameter stiffness = 12.06;

parameter inVolt = 1;

electrical capacity;
electrical velocity;

analog
begin
  // Mechanical part
  V(velocity) <+ ddt(V(pDispl,nDispl));
  I(pDispl, nDispl) <+
    ( stiffness/mass * V(pDispl, nDispl)
    + damp/mass * V(velocity)
    + ddt(V(velocity))
    -area * permittivity * inVolt * inVolt / mass
    / (initialGap - V(pDispl, nDispl))
    / (initialGap - V(pDispl, nDispl)) ) / 9.81;

  // Electrical part
  V(capacity) <+ permittivity*area
                    / (initialGap - V(pDispl, nDispl));
  I(pVolt, nVolt) <+ V(capacity)
                    * ddt( V(pVolt, nVolt) );
end

endmodule
```

All parameters used in accelerometer description are visible as parameters of Cadence component. Therefore, the access to them is direct in component properties without need of changing Verilog-A code.

The idea of measurement is to compare the actual capacitance C_s of the accelerometer sensor and its dummy copy of the same size with stiff suspension used as a reference capacitance C_d. The signal processing chain is realized at component level. It starts from V_0 voltage source that combines 1 MHz carrier and test signal that electrostatically actuate the accelerometer. The high frequency signal does not affect the top plate position because its frequency is much higher than accelerometer resonant frequency. Thus, this voltage is not included in Verilog description. The test signal corresponds to V_{in} voltage. The sensor and dummy capacitors (C_s, C_d) form voltage dividers with parasitic capacitors (C_{ps}, C_{pd}) associated with their top electrodes (about 200 fF) and input capacitance of the sensing amplifier (65 fF). Then, if top plate changes its capacitance, the voltage on sensor and dummy capacitors will not be the same. The difference of these voltages will be linearly dependent on applied acceleration.

3. Results and discussion

We analyze CMOS BEOL-embedded z-axis accelerometer fabricated in Universitat Politècnica de Catalunya (Barcelona, Spain) presented in Fig. 4.

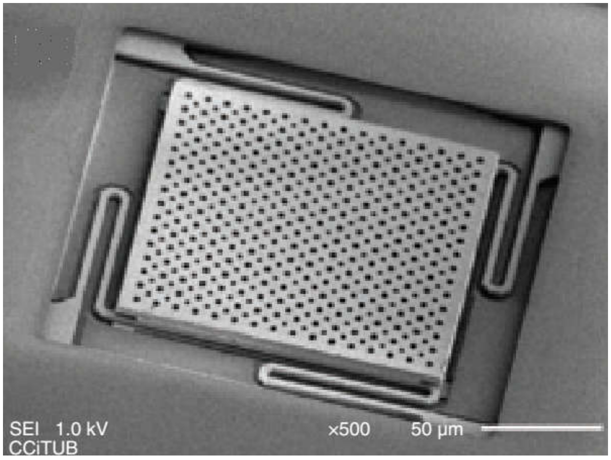

Figure 4: Image of analyzed accelerometer taken by scanning electron microscope [7]

The structure contains a top square plate with dimensions of 135×135 µm^2. The initial gap distance is d_0=2.5 µm. Therefore, the initial capacitance is:

$$C_0 = \frac{8.8542\cdot10^{-12}\cdot\left(135\cdot10^{-6}\right)^2}{2.5\cdot10^{-6}} = 64.55\,fF \qquad (7)$$

This is also the capacitance of dummy copy of the accelerometer (C_d). The accelerometer plate is made of aluminum (E=69·10^9 Pa) suspended by cantilevers of dimensions l=65 µm, b=3 µm, h=2 µm. The resulting spring constant is then:

$$k = \frac{2\cdot69\cdot10^{9}\cdot3\cdot10^{-6}\cdot\left(2\cdot10^{-6}\right)^3}{(65\cdot10^{-6})^3} = 12.06\,N\cdot m^{-1} \qquad (8)$$

For the plate of mass m=0.61 µg the resonant frequency of the plate can be obtained:

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{12.06}{0.61\cdot10^{-9}}} = 22.3\,kHz \qquad (9)$$

The calculated values demonstrate good accordance with results of experimental measurement of fabricated device. The difference can be seen in resonant frequency (mechanical resonance found at 20 kHz by measurement [7]). It has to be emphasized that the model of suspension assumes one cantilever with double length. In real device two legs are placed next to each other laterally connected on its endings. The model does not take into consideration such geometry of supporting legs leading to some erroneous results in deformation. In real the stiffness will be lower and according to equation (9), the resonant frequency will be lower.

The first simulation concerns the accelerometer response to test signal of voltage equal to 12 V with no external acceleration. The results are presented in *Figure 5*. The response of the accelerometer is visible on node *in* that gives the value of plate displacement. The displacement is equal to 465 nm. The pull-in state does not occur (the gap distance is 2.5 µm). The capacitance change leads to voltage difference on amplifier inputs. The amplification is set to k_{amp}=200. The output signal is visible on node *out* and repeats the frequency of V_0 (amplitude of 1 V) and has the amplitude of about -8 V. The peak-to-peak value corresponds to the value of sensor capacitance and can be calculated as follows:

$$V_{out} = k_{amp}\left(\frac{C_d}{C_d+C_{ds}} - \frac{C_{z=2.05\mu m}}{C_{z=2.05\mu m}+C_{ps}}\right)V_0 = -7.94\,V \quad (10)$$

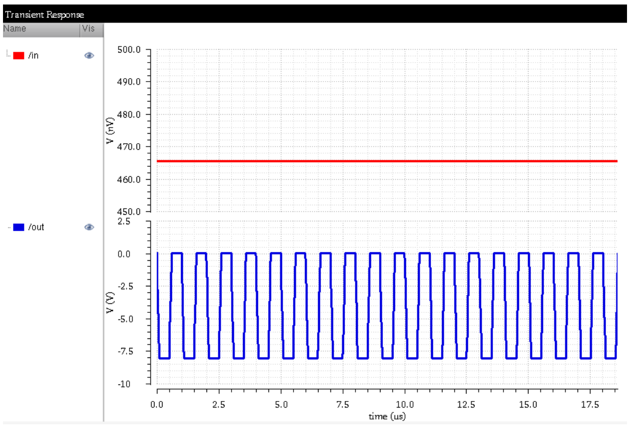

Figure 5: Simulation results for electrostatic load

The second simulation concerns the accelerometer response to external acceleration. The input signal (current source *I16*) that corresponds to the external acceleration changes in pulse manner from 0 to 1 G with period of 100 µs. The transient response of the system created in Cadence environment is presented in *Figure 6*.

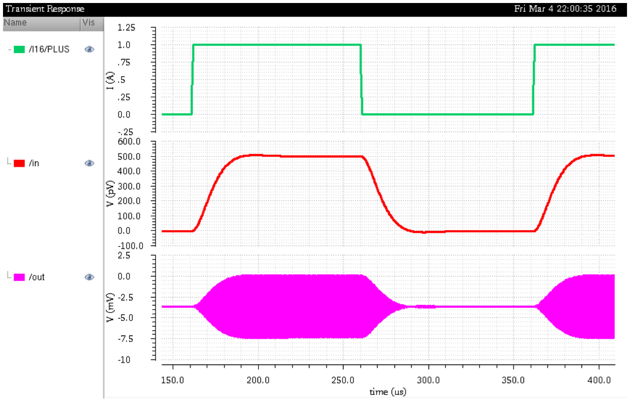

Figure 6: Simulation results for acceleration load

The accelerometer response is visible on node *in*. The plate displacement varies from 0 to 500 pm depending on acceleration. The plate oscillate with frequency of about 13 kHz. It has to be emphasized that the damping coefficient *c* has not been verified with experiment and the value of 1.36e-4 has been calculated from [8] for atmospheric pressure. The damping ratio that defines the system response is calculated using the following formula:

$$\xi = \frac{c}{2\sqrt{mk}} = 0.79 \quad (11)$$

Therefore, the system is underdamped and the moving plate oscillates with frequency smaller than natural frequency. Because the damping ratio is close to 1, the overshoot value is very small and equal to 8 nm. One can calculate the sensor sensitivity as a change of capacitance per 1 G:

$$\frac{\Delta C}{1G} = C_{z=0.5\mu m} - C_0 = 12.9aF/1G \quad (12)$$

that correspond to the measured value [7]. It has to be mentioned that the capacitance change is not linear with acceleration (only plate deflection is linear). Therefore, this sensitivity will vary with acceleration.

The output signal fixed at voltage node *out* (amplifier output) also repeats the input signal and gives the sensor capacitance value converted into measurable voltage signal. It is the plate deflection signal modulated by carrier V_0 frequency and gained by output amplifier. In our case the peak-to-peak value is equal to -7.32 mV. At final step this signal has to be demodulated to cancel the carrier frequency. We have used the simplest model of amplifier just to visualize the output signal. In designing the real device, one should use built-in amplifiers or create a new one that is made of real electronic components. Then, we can simulate the device performance including real parameters of the electronic circuitry.

4. Conclusions

The CADENCE provides powerful tools for simulating such MEMS system that consists of mechanical and electronic elements. The mechanical behavior can be described in Verilog-A language as a black box with electrical inputs and outputs using simple analytical models of microstructures. Then both domains are used in only one simulation providing the results directly from electronic circuitry. Furthermore, the schematic of the device can be also used in designing of the device layout. It has to be mentioned that this kind of simulation cannot be used as a final one as the analytical modeling in not accurate as FEM simulation. Nevertheless, this method is much simpler and faster. The results of simulation of developed accelerometer model showed the correlation with the real device. Thus, in prototyping and optimization phase this method will be very efficient.

Acknowledgments

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