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Development of the basic acoustic elements models on the base of the VHDL – AMS language for computer-aided design at the schemotechnical level

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Abstract. In this paper the basic acoustic elements models are developed on the base of the VHDL-AMS language. Constructed models are based on the thin plates theory and are intended to be used in computer-aided design at the schematic level of basic acoustic MEMS elements. The results of the models for basic acoustic elements of piezoelectric and electrostatic types investigation are also presented.

Key words: microelectromechanical systems (MEMS), VHDL-AMS model, basic acoustic element, schematic design level.

1. INTRODUCTION

Development and implementation of the microelectromechanical systems (MEMS) [Esteve, 1997] is a new branch in the global microelectronics field, which has great potential and is rapidly developing. The main advantages of such microsystems are their small sizes, low price, group manufacturing technology [Esteve, 1997, Szermer, 2009] and others. The microelectromechanical systems are used in various fields of science and engineering, which enables improving the output parameters of the designed device. Today we have a large-scale use of the MEMS technologies in acoustic systems [Allan, 2003, Arensman, 2006, Keller, 2006, Horowitz, 2006, Johansson, 2006], which are used to solve specific [Keller, 2006] and domestic problems [White Paper-Confidential, 2003, Johansson, 2006]. Nowadays we are witnessing the widespread introduction of MEMS in cell communication [White Paper-Confidential, 2003], which provides reducing of the device weight and used board space, reducing materials costs, improved battery performance, and also provides higher quality level, increases device functionality, provides high values of acoustic output parameters, improves the display settings, security, gives a new principle of data management, improves performance of the global positioning system and others. In practice, in most cases, in the process of acoustic microphones performance, an electrostatic, piezoelectric, piezoresistive and other principles are used, the constructions of such integrated acoustic microphones are given in [Rombach, 2002, Neumann, 2001, Yu X.Rajamani, 2006, Pilch, 2011].

Since the microelectromechanical systems include components from different scientific and engineering areas and relate to the interdisciplinary field [Esteve, 1997, Szermer, 2009], there are significant difficulties in their modeling and design. In most cases, for MEMS design the block-hierarchical approach [Napieralski, 2012] is used, which provides design automation on the system [Teslyuk, 2007] schematic [Beznosyk, 2008] and the component [Maflin, 2012] levels. At the schemotechnical level of the MEMS design the VHDL-AMS language [Peter J. Ashenden, 2011] is used, which allows to take into account the different nature signals which are inherent to MEMS. All these facts form the topicality of the work devoted to creation of the mathematical models of basic acoustic elements for the automation of the MEMS development process at the schemotechnical level.

2. THE BASIC MODEL OF PIEZOELECTRIC MICROPHONE WITH THE USE OF VHDL-AMS LANGUAGE DEVELOPMENT

Piezoelectric microphones constructions typically include a thin plate with a hard pinch on its edges. Piezoresistences are located in the largest pressure concentration area, which arise in the process of integrated basic acoustic MEMS element performance.

The principle of this integral element functioning implies that the acoustic wave influences the thin plate. Which, in its turn, bends and generates tension in the piezoresistences area, resistance change leads to changes in electrical network voltage.

In some literature [Keller, 2006, Horowitz, 2006, Neumann, 2001, Yu X. Rajamani, 2006, Steffora, 2007, Yu H.et al, 2008, Allan, 2003, Beus, 2005] devices of such types and technologies of their design have been analyzed and the peculiarities of their constructions studied. However, according to the performed analysis not enough attention has been paid to the development of the mathematical models, specifically, for multilevel computer aided design of basic acoustic MEMS microdevices.

In the developed model the displacements distribution in the thin circular plate can be described by the following differential equation [25] on the condition of hard pinched boundaries

$$\frac{\partial^4 w(r)}{\partial r} + \frac{2}{r}\frac{\partial^3 w(r)}{\partial r^3} + \frac{1}{r^2}\frac{\partial^2 w(r)}{\partial r^2} = \frac{P}{D}, \quad D = \frac{Eh^3}{12\left(1-\nu^2\right)}, \tag{1}$$

where *w(r)* – plates deflection; *r* - the radius current value; *E* - Young's modulus of the plate material; *v* - Poisson's ratio of the material elastic element; *P* - the intensity of the distributed on the plate surface load.

To determine the tension in the thin circular plate the following equations should be used:

$$\sigma_r(r,\varphi) = \frac{Eh}{2\left(1-\nu^2\right)}\left(\frac{\partial^2 w(r)}{\partial r^2} + \frac{\nu}{r}\frac{\partial w(r)}{\partial r}\right),$$
$$\sigma_\varphi(r,\varphi) = \frac{Eh}{2\left(1-\nu^2\right)}\left(\nu\frac{\partial^2 w(r)}{\partial r^2} + \frac{1}{r}\frac{\partial w(r)}{\partial r}\right). \tag{2}$$

While determining *w(r)* we will use the thin plates theory and assume that the plate`s maximum displacements are twice smaller than its thickness h, which is rigidly incarcerated at the edges. By entering such limitations we can apply the analytical solution of the problem (1) for displacement determination:

$$w(r) = \frac{3}{16}P\frac{1-\nu^2}{E}\frac{(R-r)^2(R+r)^2}{h^3}, \quad w(r) \le \frac{h}{2}, \tag{3}$$

where *R* - the radius of the small plates.

Since the diameter of the plate is much larger than the thickness of the circular plate, we assume that *w(r)* equals the maximum displacement. Then the following equation can be used for the displacement determination

$$w_{max} = \frac{3}{16}P\frac{(1-\nu^2)}{E}\frac{R^4}{h^3}. \tag{4}$$

As the maximum tensions concentrate when $r = R$, the equation for the tensions determination will look in the following way:

$$\sigma_l(R) = \frac{3}{4}P\frac{R^2}{h^2}(1+\nu), \quad \sigma_t(R) = \frac{3}{4}P\frac{R^2}{h^2}\nu. \tag{5}$$

For determining changes in piezoresistor resistance with regard to the silicon type and its orientation following formula the [26 - 30] is used:

$$\frac{\Delta R}{R} = \pi_l\sigma_l + \pi_t\sigma_t, \quad \pi_l = \frac{1}{2}(\pi_{11}+\pi_{12}+\pi_{44}),$$
$$\pi_t = \frac{1}{2}(\pi_{11}+\pi_{12}-\pi_{44}), \tag{6}$$

where σ_l, σ_t - tensions which arise under the pressure influence on the thin plate in parallel (longitudinal) and perpendicular (transverse) directions to the piezoresistors current direction; π_{11}, π_{12}, π_{44} - constants (Table 1.)

Table 1. Values of π_{11}, π_{12}, π_{44} parameters for silicon

Material	ρ (Ohm*cm)	π_{11} $\left[10^{-11}\,\mathrm{Pa}^{-1}\right]$	π_{12} $\left[10^{-11}\,\mathrm{Pa}^{-1}\right]$	π_{44} $\left[10^{-11}\,\mathrm{Pa}^{-1}\right]$
n – Si type	11,7	-102,2	53,4	-13,6
p – Si type	7,8	6,6	-1,12	138,1
p – polySi type	0,005	$\Delta R/R = \pi\sigma$, $\pi = 12 * 10^{-11}\,\mathrm{Pa}^{-1}$		

To increase the sensitivity of piezoresistive MEMS acoustic element, the resistors are connected into the bridging scheme [Bouwstra, 1991], an example is shown in Fig.1.

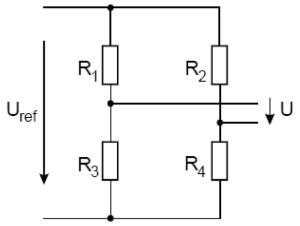

Fig 1. Microsensor piezoresistors bridge connecting scheme

These equations (1 - 6) allow building VHDL-AMS piezoresistive microphone models [Maflin Shaby, 2012] taking into account the structural and technological parameters, their fragments are shown in Fig. 2. – Fig. 4.

```
use  Disciplines.electrical_system.all;
use  Disciplines.mechanical_system.all;
entity      Acustic_2 is
generic ( v : real := 0.22; E : real := 160.0e9; R :
real := 0.001;h : real := 0.6e-6; Rez : real := 1.0;
     pi : real := 12.0e-11;Vo : real := 3.0 );
port (  terminal Pin : mechanical;
terminal Vout : electrical );
end entity Acustic_2;
architecture archAcustic_2 of Acustic_2 is
quantity G : real := 0.0;
quantity P across Pin to GROUND;
quantity U across Vout to GROUND;
begin
G==3*P*R*R*(1+v)/(4*h*h);
U==Vo*Rez*pi*G;
end architecture archAcustic_2;
```

Fig.2. pezoresistive microphone VHDL-AMS model (p – polySi type)

The VHDL-AMS model shown in Figure 2 includes: applied libraries (03 – 04 lines), description of global variables (06 - 13), model ports description (14 - 15), the equation determining the maximum tension in microphone piezoresistors area (27), the equation determining the initial voltage value (28).

Figure 3 shows the fragment of the VHDL-AMS piezorezistive microphone model with the ability to account temperature influence on the output voltage (32 line).

To consider the piezoresistor impurity concentration influence the VHDL-AMS model has been developed, it is shown in Fig. 4.

```
18 architecture archAcustic_3 of Acustic_3 is
23  quantity G : real := 0.0;
24  quantity P across Pin to GROUND;
25  quantity U across Vout to GROUND;
30  begin
31  G==3*P*R*R*(1+v)/(4*h*h);

32  U==Vo*Rez*pi*G(0.481+ 0.519*exp(-(T-300.0)/ 149.0));
33  end architecture archAcustic_3;
```

Fig.3. Fragment of the piezoresistive microphone VHDL-AMS model considering temperature influence (p – polySi type)

```
18 architecture archAcustic_4 of Acustic_4 is
23  quantity G : real := 0.0;
24 quantity P across Pin to GROUND;
25 quantity U across Vout to GROUND;
30  begin
31 G==3*P*R*R*(1+v)/(4*h*h);
32 U==0.481+ 0.519*exp(-(T- 300.0)/ 149.0));
33 IF C>=1.0e18 USE
34  U==(1.0e19*U-1.0e18*(U-(U-0.2)/4)+C*(U-0.2)/4.0)/( 1.0e19-1.0e18);
35 ELSIF C>=1.0e19 USE
36  U==(1.0e20**(U-(U-0.2)/4.0)-1.0e19*0.2+C*(0.2-(U-(U-0.2)/4.0))/( 1.0e20-1.0e19);
37 ELSIF C>=1.0e20 USE
38 U==0.2;
39 END USE
40 U==Vo*Rez*pi*G*U;
41  end architecture archAcustic_4
```

Fig.4. Fragment of the piezoresistive microphone VHDL-AMS model considering temperature and alloy concentration influence (polysilicon)

3. MATHEMATICAL MODEL OF THE CAPACITIVE MICROPHONE BASIC CONSTRUCTION

In the basic constructio of a capacitive microphone a thin round plate is used. Accordingly, we can take advantage from number of known equations for estimating microphone capacitance changes and for other outgoing parameters. Thus, for determining the microphone capacitance without tension the known formula [Пат. на корисну модель №73621, 2012] can be applied:

$$C_O = \varepsilon_O \, \varepsilon \frac{A}{d}, \tag{7}$$

where ε - dielectric permeability of the material between the capacitor plates; ε_O - vacuum dielectric permeability; A - area of the membrane (πR^2 - in the case of circular plates); d - initial distance between the plates.

In case of load application to the membrane the last will shift in w distance, then the formula for capacity determination (7) should be changed to

$$C_1 = \varepsilon_O \, \varepsilon \, \frac{A}{d - \Delta d}. \tag{8}$$

During the w displacement determination we will use the theory of thin plates [33] and assume that the maximum displacement of the plate, which is rigidly clamped at its edges, is twice less than its thickness h. After introducing these restrictions, we can use the analytic equation for displacement determination (3).

In cases, where the circular plate diameter is much bigger than its thickness, it can be assumed that w equals the maximum displacement determined from the equation (3).

Thus, in the finite case, the capacitance change is determined by the following equation $\Delta C = C_1 - C_0$, and to determine current changes we will use the next equation

$$i = \frac{\partial Q}{\partial t}, \; Q = CU, \tag{9}$$

where U - the applied voltage: t- time; Q - accumulated capacitor charge.

During the VHDL-AMS capacitive microphone model (Fig.5) development for mechanical and electrical characteristics description are used (3, 4) and (7, 8, 9) equations, respectively.

In particular, lines 03 - 04 contain information about the included libraries, which are used in VHDL-AMS capacitive microphone model. Lines 05 - 15 contain data on the model global parameters, their types, and values. The 16 line describes the model ports and their types. The Pin Port is the input of the mechanical type, and the Iout port is the output of the electric type. Lines 22 - 27 contain constants and variables description and their types and, if it necessary, their values. The 28 line contains the begin command, after which is a mathematical description of the element (lines 29 - 36, formulas 3, 4, 7 - 9).

4. RESULTS OF THE DEVELOPED VHDL-AMS MODELS INVESTIGATION

Results of the developed VHDL-AMS models investigation are shown in Figure 6 - 9. For determining the intensity of the sound wave in dB following equation is used:

$$I = 20\log\left(\frac{P}{P_0}\right), \tag{10}$$

where P - the sound wave pressure in Pa; P_0 - threshold ($2*10^{-5}\,Pa$).

The obtained results allow asserting that the output voltage is within the boundaries of microvolts, and during the microphone control scheme development the circuitry with high tension sensitivity should be used. This problem can be partly solved with the help of ideas introduces in [Пат. на корисну модель №78173, 2012, Пат. на корисну модель №73621, 2012].

```
use  Disciplines.electrical_system.all;
use  Disciplines.mechanical_system.all;
entity        DAVACH_ACUSTUKA_5 is
generic ( eps : real := 8.85419e-12; eps1 : real := 1.0006; Rplate : real := 1000.0e-6; Hplate : real := 3.0e-6; d : real := 10.0e-6; Vin : real := 10.0; ModulUnga : real := 160.0e+9; Pi : real := 3.14; ATM : real := 1.01325e5; ModulPyassona : real := 0.22 );
port (terminal Pin: mechanical; terminal Iout: electrical);
end entity DAVACH_ACUSTUKA_5;
architecture archDAVACH_ACUSTUKA_5 of DAVACH_ACUSTUKA_5 is
    quantity x : real;  quantity AREA : real;
    quantity C : real; quantity Q : real;
    quantity R4 : real;            quantity R5 : real;
    quantity I across Iout to GROUND;
    quantity P across Pin to GROUND;
    quantity C0 : real := 0.0;
begin
    AREA == Rplate*Rplate;
R4 == Rplate/Hplate;
R5 == 3.0*R4*R4*R4*Rplate/(16.0*ModulUnga);
x == P*R5*(1.0-ModulPyassona);
C0 == eps*eps1*Pi*AREA/(d);
C == eps*eps1*Pi*AREA/(d-x);
Q == C*Vin;
Q'dot == I;
end architecture archDAVACH_ACUSTUKA_5;
```

Fig.5. Example of the VHDL-AMS electrostatic microphone model with an elastic circular element

The built VHDL-AMS capacitive microphone model allows determining capacitance change and displacement of a thin plate as the result of applied pressure. Example of the pressure change form is shown in Fig.9. Corresponding changes of the thin plate displacement and integral microphone current and capacity are shown in Fig.10 - Fig.12.

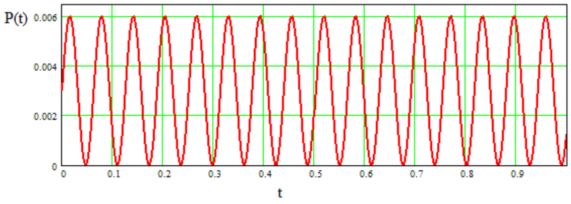

Fig.6. Depiction of the income signal change

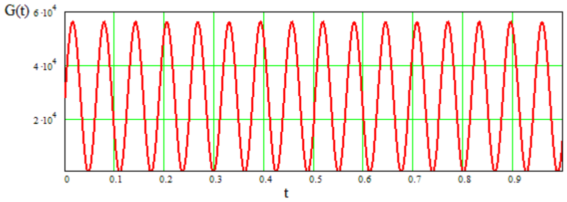

Fig.7. Dependency of the tension changes in the piezoresistence location area

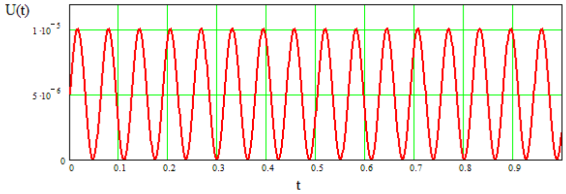

Fig.8. Example of the outcome tension change during intensity of the sound wave changes from 0 to 50 Db

The modeling results allows arguing that, as the capacitance changes for this class devices are within tenths PF (picofarad), and the current are within tens and hundreds of nA, so the implementation of the capacitive microphone outgoing signal processing requires application of the high sensitivity scheme [Пат. 88405 Україна, 2009, МПК (2009) G01P 15/125, 2008].

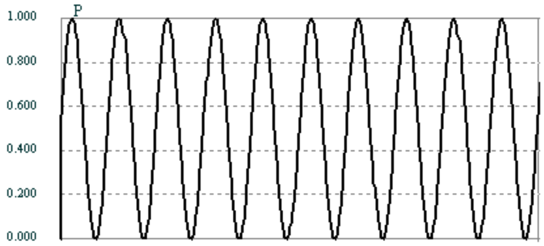

Fig.9. Example of the pressure change

CONCLUSIONS

The VHDL-AMS models of the basic capacitive and piezoresistive microphones with the elastic circular element, which allows defining output parameters at the schemotechnical elements design level with regard to MEMS design and engineering parameters, were developed.

The developed models will allow increasing the efficiency of the MEMS acoustic elements computer-aided design at the schemotechnical level. They will also enable investigating the microphone mechanical, structural and technological input parameters influence on the electrical output parameters.

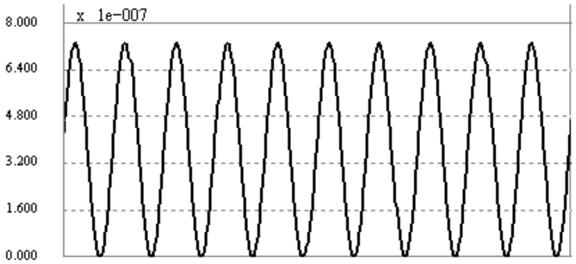

Fig.10. Dependency of the X displacement change from the applied P pressure

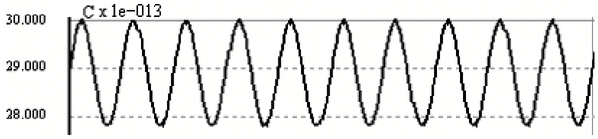

Fig.11. Change of the C capacity as a result of the applied P pressure

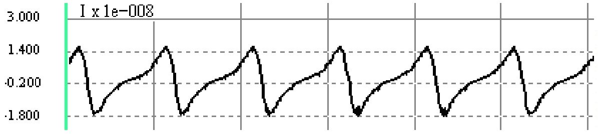

Fig.12. Change of I current as a result of the applied P pressure

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