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Verilog-A Modeling and Analyzing of Piezoresistors Connected into Wheatstone bridge and used in MEMS Device Processing

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ABSTRACT - *Microelectromechanical system design presents a unique engineering challenge. In addition to the both mechanical and electrical design knowledges, a MEMS engineer must have computer aided design (CAD) tools to design devices. Hand analysis of the investigated mechanical structure is the first step in the design process. In the traditional MEMS design flow, the engineer will proceed with a finite element or boundary element simulation using software such as MEMS Xplorer, Coventor's ANALYZER, ANSYS, or FEMLAB. Hand calculated design is verified and refined using these packages until the structure meets the engineer's specifications. A macromodel of the structure then is created. During the device designing is made an analysis in order to test functionality of the circuit and to avoid any kind of design errors before sending to the factory for manufacturing.*

KEYWORDS - *Macromodel MEMS, MUMPs process, Verilog-A, Wheatstone bridge*

I. INTRODUCTION

The macromodel of a created structure reproduce the behavior of the structure based on external stimuli. A macromodel is useful when a simple and accurate model of the system is desired. Macromodels can be created to be used in system level simulators or in circuit simulators. If they are used in an electrical circuit simulator, an electrical equivalent of the macromodel can be generated to model the mechanical behavior. This macromodel can then be used with electrical devices to simulate the system behavior.

Although both structural and electronic halves of the MEMS design can be completed separately, it is often necessary to simulate the system as a whole in order to verify the functionality of the signal paths from mechanical structures to electrical circuits. A valid design flow for a macromodel of the mechanical system is created by extracting the behavior from a finite element or boundary element simulation, and then using the macromodel in a circuit level or system level simulator. However, if the mechanical design needs to be changed, the finite element or boundary element model must be recreated and the macromodel must be re-extracted.

II. MEMS PROCESSING

Several options exist for fabricating MEMS devices. MEMS processes can be split into two types: bulk and thin-film micromachining [1].The silicon substrate in bulk micromachining is used to create mechanical structures. Typical thicknesses of these devices are in hundreds of microns.

Thin-film micromachining uses the deposited layers on the top of the silicon wafer (polysilicon, oxide, and metal) [2]. The typical thicknesses are below ten microns. The MUMPS process and post foundry CMOS micromachining processes are typically used for thin-film micromachined MEMS devices.

III. MEMS LIBRARY

Every MEMS device can be designed using standard library elements in the CAD software like Cadence. However, for some MEMS devices specific library elements are needed. These library elements are created using describing languages, like Verilog-A [3]. The MEMS model library consists of atomic element: anchors, beams, piezoresistors, membranes, electrostatic gaps, and plates. The models are written in Verilog-A. The Verilog-A allows the MEMS designer to simulate both the mechanical and electrical responses of the system through the circuit simulator.

The MEMS model library is treated by Cadence as a standard design-kit. The absolute path of model library must be added to the ”Library Path Editor” within Cadence in order to make the libraries visible and usable within Cadence together with the other preexisting libraries and design-kits.

The MEMS models deal with mixed domain magnitudes (electrical and mechanical). Proper definitions for the electrical and mechanical magnitudes are declared within the libraries.

For each of them two parameters are used by the Spectre simulator to define convergence and non-convergence cases for all magnitudes. All the magnitudes with their physical meaning, name within Cadence, unit and parameter(s) value(s) are reported in the Table 1.

Table 1: Summary of all electrical and mechanical magnitude definitions within the Verilog-A.

Name within Cadence	Physical meaning	Unit	abstol	blowup
disp	Mechanical linear displacement	Meter (m)	1.0e-9	--
frc	Mechanical linear force	Newton (N)	1.0e-9	--
vel	Mechanical linear velocity	Meter/Second (m/s)	1.0e-3	1.0e+12
acc	Mechanical linear acceleration	Meter/Second^2 (m/s^2)	1.0e-3	1.0e+12
ang	Mechanical rotation	Radiant (rad)	1.0e-3	--
trq	Mechanical torque	Newton*Meter (N*m)	1.0e-3	--
avel	Mechanical angular velocity	Radiant/Second (rad/s)	1.0e-3	1.0e+12
aacc	Mechanical angular acceleration	Radiant/Second^2 (rad/s^2)	1.0e-3	1.0e+12
V	Voltage	Volts (V)	1.0e-6	1.0e+12
I	Current	Ampere (I)	1.0e-6	1.0e+12

All definitions implemented in the Table 1 are included in the file ”discipline.h” and no specific settings are required to properly link such a file.

IV. DESIGNING

By the components within the model library can be composed objects that can be simulated by adding instances within a “Cadence Composer Schematic” window as it is usually done with standard libraries. Components are then connected together by wires.

Each component has Verilog-A description. It is possible to define a custom configuration of the components depending on the type of simulation that must be performed. Every time a change is performed the component code must be re-compiled in order to allow Spectre to generate the proper netlist for the simulation. To do this, the main code file must be opened and saved within Cadence. Each component is defined in a subdirectory within the library.

The electrical part of MEMS device contains four piezoresistors connected into the so called Wheatstone bridge. The circuit of the Wheatstone bridge is placed at the core of cantilever beam. The Verilog-A code for defining the cantilever beam and resistors is:

```
// VerilogA for MEMS, H_Res_Pos, veriloga

`include "constants.h"
`include "discipline.h"

module H_Res_Pos (in, out);
   inout in, out;
   electrical in, out;
   kinematic z, velocity;

   // Dimensions
   parameter real g_0=2e-6 from (0:inf); // nominal gap height [m]
   parameter real l=300e-6 from (0:inf); // beam length [m]
   parameter real t=0.5e-6 from (0:inf); // beam thickness [m]
   parameter real t_d=0.2e-6 from [0:inf); // dielectric thickness [m]
   parameter real w=80e-6 from (0:inf); // beam width [m]
   parameter real W=100e-6 from (0:inf); // electrode width [m]
   // Material parameters: beam (gold)
   parameter real nu=0.44 from [0:inf); // Poisson ratio []
   parameter real rho=19.2e3 from (0:inf); // mass density [kg/m^3]
   parameter real sigma=100e6 from [0:inf); // residual stres [Pa]
   parameter real E=78e9 from (0:inf); // Young's modulus [Pa]
   // Material parameters: dielectric (silicon nitride)
   parameter real epsilon_r=7.6 from [1:inf); // dielectric constant []
   // Material parameters: gas (air):
   parameter real lambda = 1.5e-7 from [0:inf); // mean-free path [m]
   parameter real mu = 1.845e-5 from (0:inf); // viscosity coefficient [kg/(m.s)]
   // van der Waals and nuclear force coefficients
   parameter real c_1=10e-80 from [0:inf); // van der Waals force coefficient [N.m]
   parameter real c_2=10e-75 from [0:inf); // nuclear force coefficient [N.m^8]

   real A, b, C, C_d, C_u, F_c, F_e, F_s, f_m_0, IIP3, k_1, k_3, m, Q_e, Q_m, t_s_max, t_s_min, V_H,
V_P, V_S;
   analog begin

      @ ( initial_step ) begin
         A=W*w;
         $strobe("\n%M: A (electrode area [m^2]) = %E",A);
         m=0.4*rho*l*t*w;
         $strobe("%M: m (effective beam mass [kg]) = %E",m);
         k_1=32*E*w*pow(t/l,3)*27/49+8*sigma*(1-nu)*w*t/l*3/5;
         $strobe("%M: k_1 (spring constant [N/m]) = %E",k_1);
         k_3=pow(`M_PI,4)*E*w*t/(8*pow(l,3));
         $strobe("%M: k_3 (stretching constant [N/m^3]) = %E",k_3);
         V_H=sqrt(2*k_1*g_0*pow(t_d/epsilon_r,2)/(`P_EPS0*epsilon_r*A));
         $strobe("%M: V_H (pull-in voltage [V]) = %E",V_H);
         V_P=sqrt(8*k_1*pow(g_0+t_d/epsilon_r,3)/(27*A*`P_EPS0));
         $strobe("%M: V_P (pull-in voltage [V]) = %E",V_P);
         f_m_0=sqrt(k_1/m)/(2*`M_PI);
         $strobe("%M: f_m_0 (mechanical resonant frequency [Hz]) = %E",f_m_0);
         Q_m=sqrt(E*rho)*pow(t,2)*pow(g_0,3)/(mu*pow(w*l/2,2));
         $strobe("%M: Q_m (mechanical quality factor []) = %E",Q_m);
         V_S=V_P;
         t_s_max=27*pow(V_P,2)/(4*2*`M_PI*f_m_0*Q_m*pow(V_S,2));
         $strobe("%M: t_s_max (maximum switching time [s], V_S = V_P) = %E",t_s_max);
         t_s_min=3.67*V_P/(V_S*sqrt(k_1/m));
```

```
            $strobe("%M: t_s_min (minimum switching time [s], V_S = V_P) = %E",t_s_min);
            C_u=`P_EPS0*A/(g_0+t_d/epsilon_r);
            $strobe("%M: C_u (up-state capacitance [F]) = %E",C_u);
            C_d=`P_EPS0*A/(t_d/epsilon_r);
            $strobe("%M: C_d (down-state capacitance [F]) = %E",C_d);
            IIP3=10*log(2*k_1*pow(g_0,2)/(`M_PI*10e9*pow(C_u*50,2)))+30;
            $strobe("%M: IIP3 (third order intercept [dBm], C=C_u, delta_f < f_m_0, f=10 GHz,
Z=50 Ohm) = %E",IIP3);
        end

        // b: damping coefficient [N.s/m] (displacement-compensated squeeze-film damping)
        Q_e=Q_m*pow(1.1-pow(g_0*tanh(Pos(z)/g_0)/g_0,2),1.5)*(1+9.9638*pow(lambda/(g_0-
g_0*tanh(Pos(z)/g_0)),1.159));
        $strobe("\n%M: Q_e (displacement-compensated mechanical quality factor []) = %E",Q_e);
        b=k_1/(2*`M_PI*f_m_0*Q_e);
        $strobe("%M: b (damping coefficient [N.s/m]) = %E",b);

    // Forces
        F_c=c_1*A/pow(g_0-g_0*tanh(Pos(z)/g_0)+1e-9,3)-c_2*A/pow(g_0-g_0*tanh(Pos(z)/g_0)+1e-
9,10);
        $strobe("%M: F_c (attractive van der Waals and repulsive nuclear forces [N]) = %E",F_c);
    F_e=`P_EPS0*A*pow(V(out,in),2)/2/pow(g_0+t_d/epsilon_r-Pos(z),2);
    //F_e=`P_EPS0*A*pow(V(out,in),2)/2/pow(g_0+t_d/epsilon_r-g_0*tanh(Pos(z)/g_0),2); // Envelope
simulation
        $strobe("%M: F_e (electrostatic force [N]) = %E",F_e);
    F_s=k_1*Pos(z)+k_3*pow(Pos(z),3);
    //F_s=k_1*g_0*tanh(Pos(z)/g_0)+k_3*pow(g_0*tanh(Pos(z)/g_0),3); // Envelope simulation
        $strobe("%M: F_s (spring force [N]) = %E",F_s);

        // Nonlinear time-varying state-space description
        Pos(velocity):ddt(Pos(z))==Pos(velocity);
        Pos(z):ddt(Pos(velocity))==1/m*(-b*Pos(velocity)-
F_s+F_e+F_c+white_noise(4*`P_K*$temperature*b, "BROWNIAN_NOISE"));

        if (Pos(z)<g_0)
            C=`P_EPS0*A/(g_0+t_d/epsilon_r-Pos(z));
        else
            C=C_d;

        I(out,in)<+ddt(C*V(out,in));

  end

endmodule
```

In some MEMS devices Wheatstone bridge circuit is used to measure an unknown electrical resistance by balancing the two legs of a bridge circuit (Fig.1.). The value of piezoresistors in each leg changes depending on applied strain on the cantilever beam. The cantilever beam has horizontal displacement, therefore in the two legs there is tensile and compressive stress.

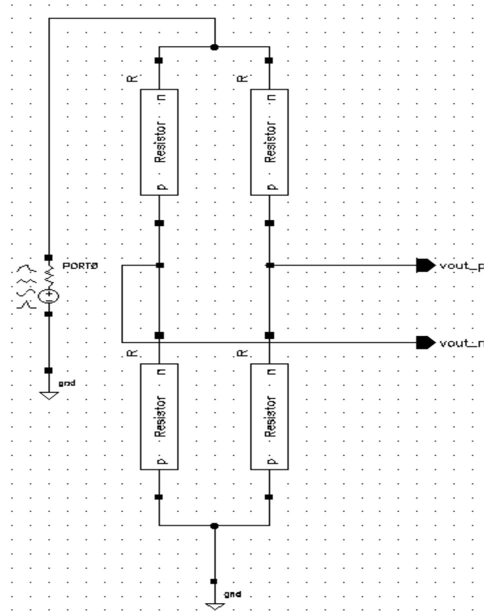

Figure.1. Wheatstone bridge circuit

The typical value of each piezoresistor is 1,5kΩ. Voltage with value of 1V flows through the circuit.

During the device designing is made an analysis in order to test functionality of the circuit and to avoid any kind of design errors before sending to the factory for manufacturing. Fig.2. shows the analysis results.

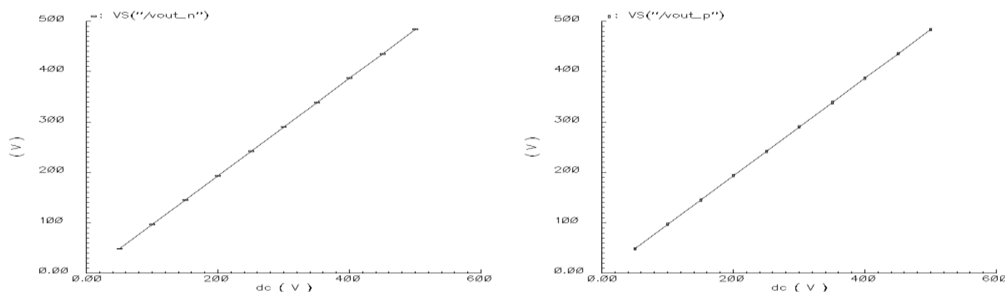

Figure.2. Circuit output characteristics

In the Fig. 2 it can be seen that both circuit outputs have equal linear characteristics. The output voltage increases with the increase of mass applied. The output response increases linearly. These characteristics are good enough, i.e., the output signals are strong enough and can be used without any amplification.

During analysis some cantilever beam physical parameters are also calculated. The values of the calculated physical parameters are:

```
********************************************
DC Analysis `dc': PORT0:dc = (50 V -> 500 V)
********************************************
Important parameter values:
    reltol = 100e-06
    abstol(I) = 1 pA
    abstol(V) = 1 uV
    abstol(F) = 1 uN
    abstol(Pos) = 1 um
    temp = 27 C
```

```
   tnom = 27 C
   tempeffects = all
   gmin = 1 pS
Trying `homotopy = gmin'.

I16: A (electrode area [m^2]) = 8.000000e-09
I16: m (effective beam mass [kg]) = 9.216000e-11
I16: k_1 (spring constant [N/m]) = 3.634939e+01
I16: k_3 (stretching constant [N/m^3]) = 1.407020e+12
I16: V_H (pull-in voltage [V]) = 4.324828e-01
I16: V_P (pull-in voltage [V]) = 3.556747e+01
I16: f_m_0 (mechanical resonant frequency [Hz]) = 9.995337e+04
I16: Q_m (mechanical quality factor []) = 2.913192e-02
I16: t_s_max (maximum switching time [s], V_S = V_P) = 3.689414e-04
I16: t_s_min (minimum switching time [s], V_S = V_P) = 5.843711e-06
I16: C_u (up-state capacitance [F]) = 3.495679e-14
I16: C_d (down-state capacitance [F]) = 2.691673e-12
I16: IIP3 (third order intercept [dBm], C=C_u, delta_f < f_m_0, f=10 GHz, Z=50
     Ohm) = 6.481434e+01

I16: Q_e (displacement-compensated mechanical quality factor []) =
     4.020853e-02
I16: b (damping coefficient [N.s/m]) = 1.439467e-03
I16: F_c (attractive van der Waals and repulsive nuclear forces [N]) =
     -7.277934e-14
I16: F_e (electrostatic force [N]) = 1.810297e-04
I16: F_s (spring force [N]) = 1.810297e-04
```

The list of all possible features of the beam is contained in the file ”beam.rgd”.

The features of changeable parameters are accessible through the ”Edit Object Properties” window. The material properties as well as several constants can be modified to adapt the beam model to the technology specifications. Verilog-A implementation has a header file defining which other files containing the technology and constants definitions must be included. This file is called ”quantities.tf”. By this file connection with “constants.tf” is made.

Both ”constants.tf” and ”air.tf” files define some constants as well as the air characteristic values (e.g. viscosity and permittivity), respectively (Fig. 3).

```
//////////////////////////////////////////GOLD VALUES//////////////////////////////////////////
rho= 0.005; // Structural layer sheet resistance ohm/square.
E=98.5e9; // Youngs modulus (Pascal).
dens=19300.0; // density (kg/m^3).
Poi_nu=0.42; // Poisson's ratio.
thox=100.0e-9; // Oxide thickness above bottom plate.
erox=5.7; // Oxide dielectric constant
rough_air_spacer=0; // Extra air gap due to the oxide roughness.
K_touch=10.0G; // Fictitious elastic parameter when collision occurs.
min_dist = 10.0e-6; // Minimum distance between two hole on plate surface.
Stat_damp = 9.0e-2; // Static damping coefficient.
Dyna_damp = 2.0e-2; // Dynamic damping coefficient.
//////////////////////////////////////////////////////////////////////////////////////////////////
```

Figure. 3. Constants values

The designer's process follows the algorithm shown on Fig.4.

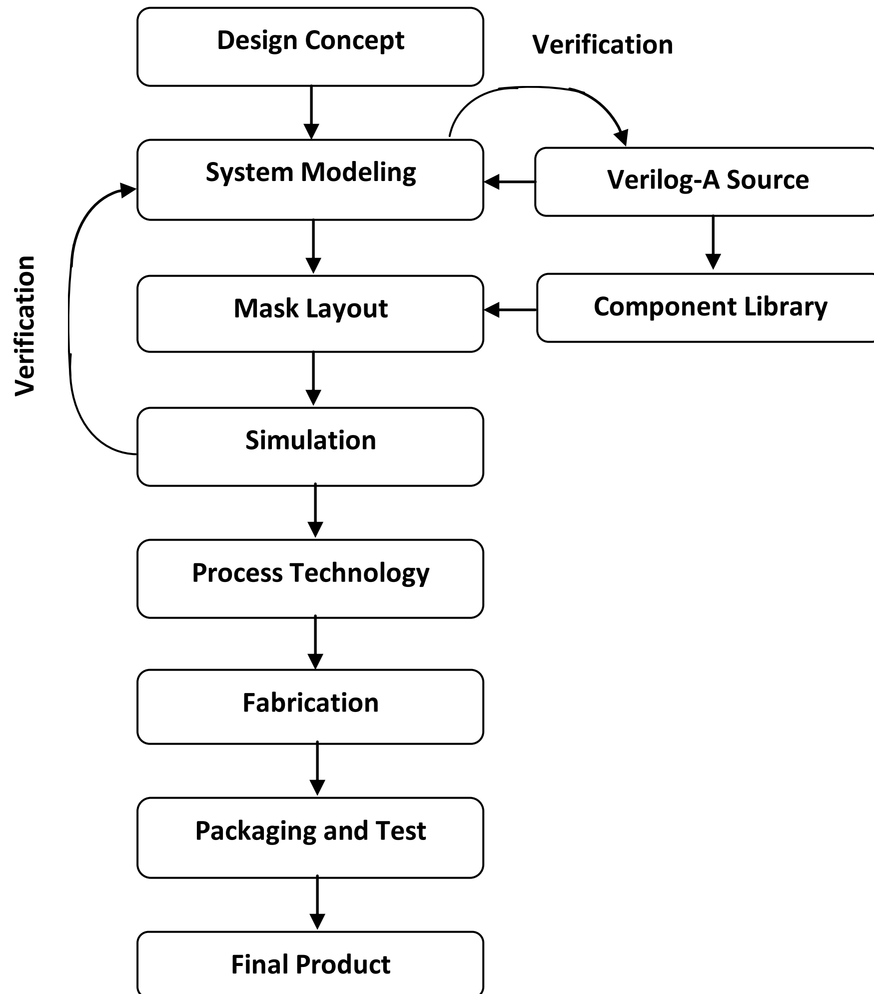

Figure. 4. Designer's process

MEMS CAD software is used to design and test MEMS devices before their fabrication. All stages from design to packaging have mutual relationship with the device modeling (Fig.5.).

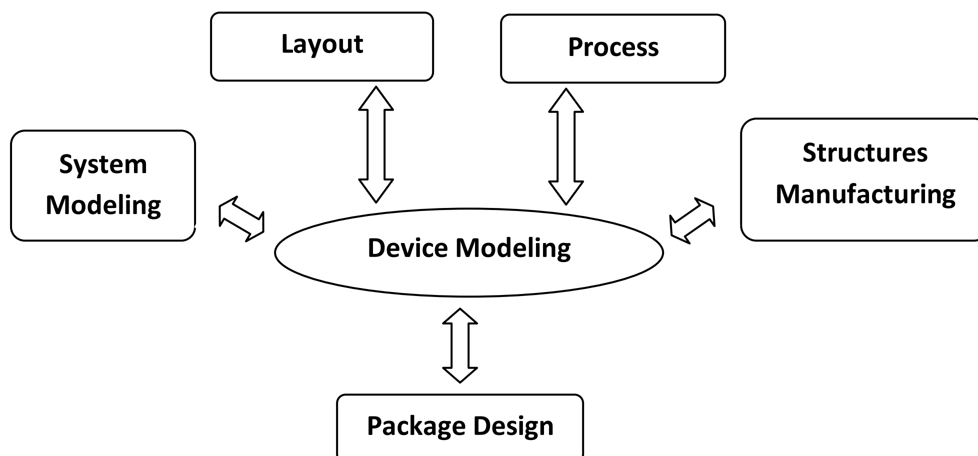

Figure.5. Stages of design and test

V. CONCLUSION

MEMS devices can be fabricated by bulk and thin-film micromachining. Standard and specific library elements are used in the device design. The specific library elements are created by Verilog-A describing language. The Verilog-A allows the MEMS designers to simulate both mechanical and electrical responses of the system. In order to use simulation tools, electrical and mechanical parameters are described within source code of each library element. Most often in MEMS devices are used piezoresistors which are connected into bridge. The two legs of the bridge are balanced and in that way an unknown electrical resistance is measured. The piezoresistors are used in MEMS which use cantilever beam. Analysis shows that output signals are strong enough and can be used without any amplification.

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