PIEZOELECTRIC ANALYSIS OF MEMS PRESSURE SENSOR

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1. Introduction

Micro-Electro-Mechanical Systems (MEMS) can quite replace bulky actuators and sensors with microscale devices. Pressure sensor presented in this article is based on C-HEMT structure defined on AlGaN/GaN heterostructure. It is well known that the III-V nitrides (especially gallium nitride, GaN) propose tremendous potential for microelectronic device application due to their high mechanical and physical stability and high thermal stability [1]. Also their excellent piezoelectric properties can be used in pressure and strain sensor applications. Compared with other commonly used piezoelectric materials, they have some important advantages such as direct compatibility with high electron mobility transistors (HEMTs), high biocompatibility, possibility to be operated at high temperatures and harsh environments. Piezoelectric response of AlGaN/GaN devices integrated on membrane structures also have been reported [2]. The process technology and piezoelectric performance analysis of C-HEMT devices were presented as well [3].

The goal of the presented paper is to performed finite element piezoelectric analysis of membrane, which is initially stressed due to lattice mismatch and thermal expansion coefficient (TEC) mismatch. The influence of electrode location is also investigated. Two different analysis of pressure sensor are presented - modal and static, where 2D and also 3D FEM models are used.

2. Design of pressure sensor

Fig. 1 shows two different designs of presented MEMS piezoelectric pressure sensor. In both designs the working layers AlGaN/GaN are placed on Si substrate and between substrate and GaN layer there is AlN layer used as a nucleation layer that helps reduce the intrinsic stress of the structure. This AlN layer is not included in our FEM models because it is very thin.

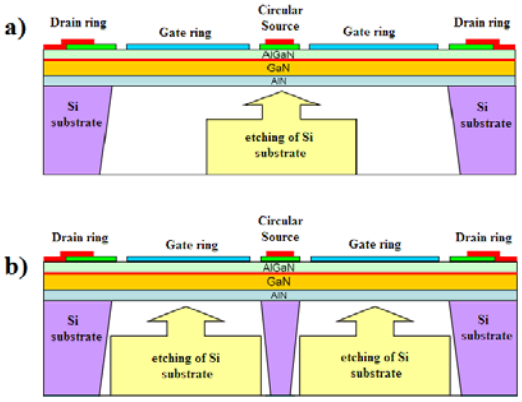

Fig. 1: *Design of pressure sensor, a) circular design, b) ring design*

In this paper, only ring design is investigated - see Fig. 2. Geometry parameters of ring design are: outer radius: R_2=240μm, inner radius: R_1=60μm, location of top electrode is defined by parameters R_{E1} and R_{E2}, thickness of AlGaN layer: h_{AlGaN}=28nm, thickness of GaN layer: h_{GaN}=1.9μm.

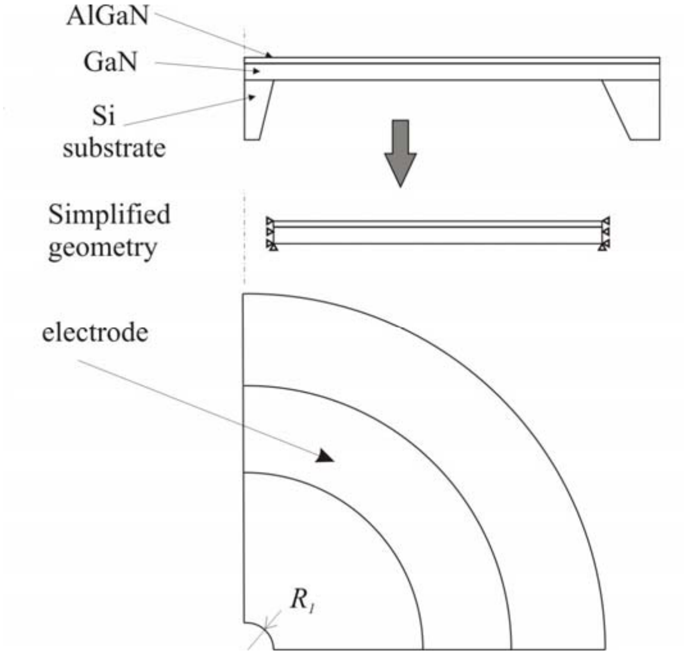

Fig. 2: *Simplified ring geometry of pressure sensor*

Constitutive law for mechanical behaviour (only GaN layer) can be written in matrix form as

$$\sigma = C\varepsilon \tag{1}$$

where σ is stress vector, ε is strain vector and C is elasticity matrix. Constitutive law for piezoelectric behaviour (only AlGaN layer) can be written in matrix form as

$$\begin{aligned} \sigma &= C^E\varepsilon - eE \\ D &= e\varepsilon + e_p^\varepsilon E \end{aligned} \tag{2}$$

where E is vector of electric intensity, D is vector of electric displacement, $e^\varepsilon{}_p$ is permittivity matrix on condition constant strain ε, C^E is elasticity matrix on condition constant electric intensity E and e is matrix of piezoelectric properties. Matrices C, $e^\varepsilon{}_p$ and e for transversally isotropic material with polarization in z direction have following forms

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ & c_{11} & c_{13} & 0 & 0 & 0 \\ & & c_{33} & 0 & 0 & 0 \\ & s & & c_{44} & 0 & 0 \\ & & y & & c_{44} & 0 \\ & & & m & & c_{66} \end{bmatrix} \quad e_p^\varepsilon = \begin{bmatrix} e_{p11} & 0 & 0 \\ 0 & e_{p11} & 0 \\ 0 & 0 & e_{p11} \end{bmatrix} \quad e = \begin{bmatrix} 0 & 0 & e_{13} \\ 0 & 0 & e_{13} \\ 0 & 0 & e_{33} \\ 0 & 0 & 0 \\ 0 & e_{15} & 0 \\ e_{15} & 0 & 0 \end{bmatrix} \tag{3}$$

Considered material parameters for AlGaN and GaN are shown in Tab. 1.

Tab. 1. *Material properties of AlGaN and GaN.*

material	mechanical prop. [GPa]						perm. [-]	piezoelectric prop. [pC/μm^2]		
	c_{11}	c_{12}	c_{13}	c_{33}	c_{44}	c_{66}	e_{p11}	e_{13}	e_{33}	e_{15}
AlGaN	395	146	104	386	110	125	8.9	-0.51	0.375	0.67
GaN	390	145	103	405	105	123	-	-	-	-

Residual stress, which is present in AlGaN/GaN layers, is caused by two different physical phenomena, namely lattice mismatch and TEC mismatch. As measurement showed, stress in AlGaN/GaN layers has value 300MPa. The influence of residual stress on pressure sensor is shown on modal analysis. Next step is to determined optimal size of electrode, i.e. where the electric charge induced from piezoelectric effect on deformed membrane is the largest. All simulations are performed by FEM code ANSYS [4].

3. Modal analysis of pressure sensor

The results of modal analysis are strongly influenced by residual stress in ALGaN/GaN layers. Shape mode for stressed or stress free layers are the same, but natural frequencies are different. Three different modal analyses were performed: without residual stress, with residual stress 150 and 300MPa, respectively. In modal analysis, performed in code ANSYS, coupled field element SOLID226 (AlGaN) and structural element SOLID186 (GaN) were used. Obtained natural frequencies are shown in Tab. 2. First two mode shapes are shown in Fig. 3.

Tab. 2. *Caption of the table.*

	Natural frequencies [MHz]			
	1.st	2.nd	3.rd	4.th
stress free	0.466	0.542	0.845	1.288
residual stress 150MPa	0.684	0.808	1.172	1.623
residual stress 300MPa	0.843	1.002	1.424	1.896

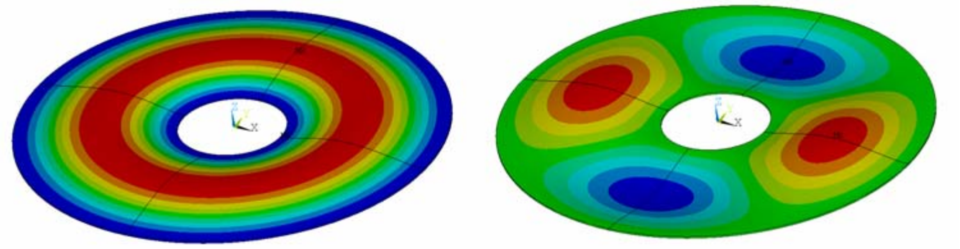

Fig. 3: *First two mode shapes of the pressure sensor*

4. Static analysis of pressure sensor

Piezoelectric static analysis of pressure sensor was performed by FEM code ANSYS [4] in order to determine optimal size of electrode. Because nonlinear analysis had to be used, the computational time is very sensitive to the number of nodes of FEM model. This was the reason why 2D analysis was chosen in the analysis, where the location of electrode was changed. In 2D analysis, coupled field element PLANE223 (AlGaN) and structural element PLANE183 (GaN) were used. Boundary conditions were set according Fig. 2, the tensile residual stress 300MPa was set as initial stress state of the system. The sensor is loaded by external pressure 10kPa. For verification calculation (2D and 3D FEM model), location of top electrode was chosen as follows: R_{E1}=70μm and R_{E2}=230μm. Obtained transversal deformations are shown in Fig. 4.

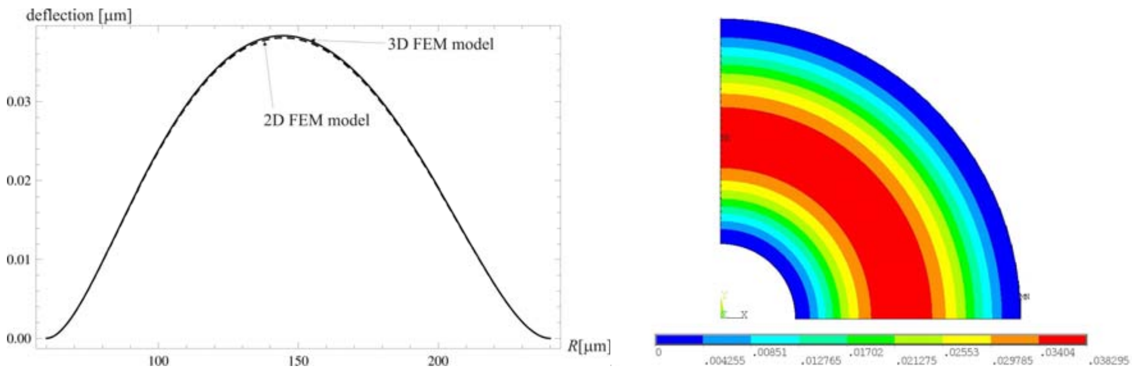

Fig. 4: *Verification of 2D axisymmetric model of ring design - deflection of membrane*

Our next step was to determine the location and size of electrode, where the induced charge is the largest in order to have the best sensor sensitivity. We chose the width of the top electrode 5μm and in sequence we changed the central radius of electrode $R_{E21}=(R_{E2}+R_{E1})/2$. Obtained dependence of induced charge on electrode central radius R_{E21} is shown in Fig. 5.

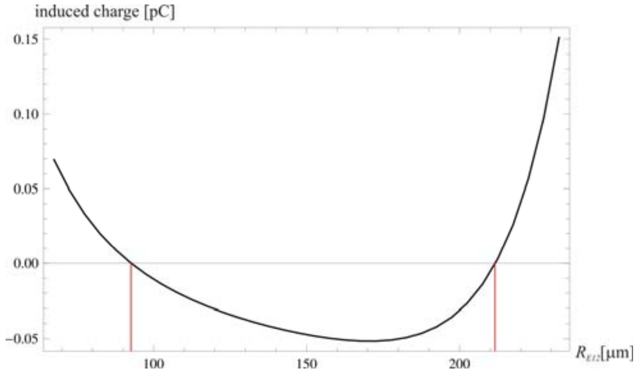

Fig. 5: *Dependence of induced charge on central radius of electrode*

5. Conclusion

The paper deals with piezoelectric MEMS pressure sensor, which is made as membrane AlGaN/GaN C-HEMT structure. The focus was put on FEM piezoelectric simulations, that was performed by code ANSYS. Two different piezoelectric analyses were performed, modal and static. In modal analysis only 3D model was considered, but in static analysis 2D and 3D models were performed in order to verify 2D FEM model loaded by external pressure. In next calculations simpler 2D model was used. Also residual stress was considered. In our next research all these calculations will be compared with measured data.

Acknowledgement

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