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PIEZOELECTRIC FEM ANALYSIS OF SURFACE ACOUSTIC WAVE SENSOR

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Abstract. The paper is focused on modeling and simulation of surface acoustic wave devices using finite element method, especially by code ANSYS. SAW sensor is made of piezoelectric GaN layer, in which the Rayleigh waves are generated, and of SiC substrate. Full 3D model of SAW sensor is investigated, where mechanical material model of GaN is considered to be transversally isotropic. Two different analyses are performed: modal and full transient. Modal analysis is performed to determine the speed of the Rayleigh waves in piezoelectric material and also in order to determine the interdigital transducer eigenfrequency, which is used in next transient analysis as electric frequency of excitation. The second analysis is the transient analysis, where the goal is to compare voltage on input and output interdigital transducer as well as wave propagation delay.

1 INTRODUCTION

Surface acoustic wave (SAW) device typically generate mechanical waves, which propagate on surface of piezoelectric layer. The waves are also called Rayleigh waves [1]. The velocity of waves depends on density and elasticity material properties and are very sensitive on change of surface layer mechanical parameters (e.g. density). This sensitivity is the reason why SAW devices are so popular as sensor devices [2].

The SAW can be generated in piezoelectric material using interdigital transducer (IDT)[3]. It is basically comb-like structure with fingers connected to electric terminals (see Figure 1). These electrodes can be fabricated by lithographic process, metal deposition and lift-off technique. The width and spacing of fingers affect the center eigenfrequency of IDT. The number of interdigital transducers affects the length of impulse characteristics and filter bandwidth [3,4]. The length of IDT fingers affects primarily the input admittance of IDT and defines the width of wave-beam, what is important when considering the diffraction effects [4]. The basic IDT concepts use uniform transducer with equal finger lengths. By weighting the length of IDT fingers we can adjust SAW filter passband characteristics.

2 MEMS PIEZOELECTRIC SAW SENSOR

SAW sensor investigated in this article is based on GaN piezoelectric layer, that is placed on SiC substrate. IDT are formed from Nickel and Gold and the sensitive layer is from Palladium. In this section, geometry and material properties of SAW sensor are presented.

2.1 Geometry of SAW sensor

Figure 1 shows SAW sensor with location of individual layers as well as IDT and sensitve layer. The thickness of real SiC substrate is far higher that is the thickness of piezoelectric layer, but in our FEM model, we set the thickness of SiC h_{SiC}=5μm and the thickness of GaN piezoelectric layer is h_{GaN}=2μm. The thickness of sensitive layer is 0.1μm.

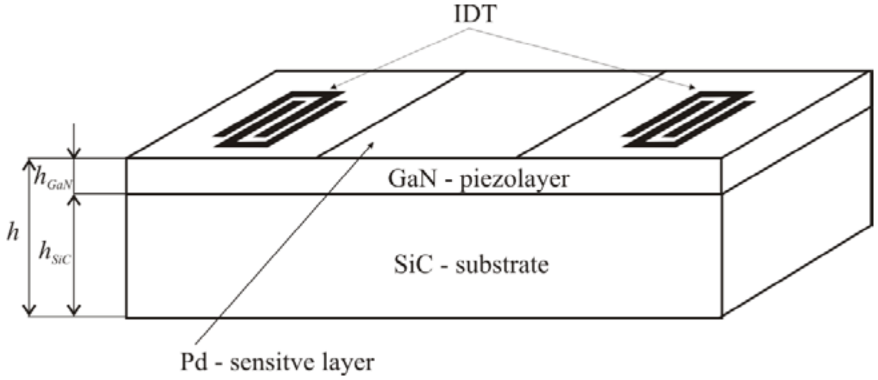

Figure 1: Geometry of SAW sensor

The position and shape of IDT are shown in Figure 2. The distance between each pair of IDT is half of wave length λ and the number of IDT pairs is 7. Distance between input IDT and output IDT is 20μm and the length of sensitive layer is 18 μm. In our simulation, we used following wave length: λ=4μm.

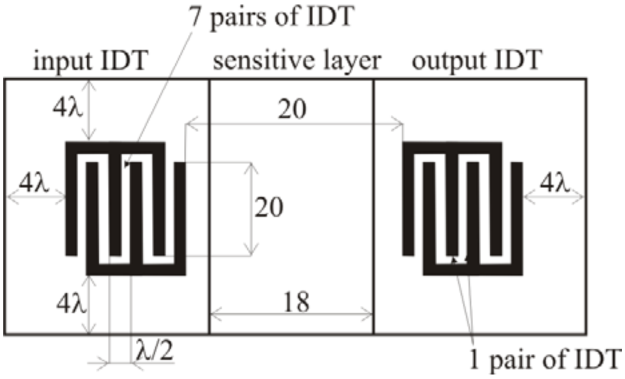

Figure 2: Main dimensions of SAW IDT and sensitive layer positions in [μm]

2.2 Material of SAW sensor

Material properties, which have to be considered in piezoelectric modal or transient analysis of SAW sensor, belong to three categories: mechanical, electrical and piezoelectrical. Mechanical properties have to be defined for all parts of SAW sensor: IDT - Nickel and Gold, chemical sensitive layer - Palladium Pd, piezoelectric layer - GaN and substrate SiC. All mechanical material properties are considered as isotropic except GaN material, which is considered transversally isotropic. Electrical and piezoelectrical properties have to be defined only for GaN layer.

Mechanical properties of individual material are:

- Nickel: E=200 GPa, μ=0.31, ρ=8600 kg/m^3
- Gold: E=78 GPa, μ=0.44, ρ=19300 kg/m^3
- Palladium: E=121 GPa, μ=0.39, ρ=12023 kg/m^3
- SiC: E=130 GPa, μ=0.27, ρ=2329 kg/m^3
- GaN: ρ=8600kg/m^3, material properties of GaN are transversally isotropic and elasticity matrix can be written in form

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ & c_{11} & c_{13} & 0 & 0 & 0 \\ & & c_{33} & 0 & 0 & 0 \\ & s & & c_{44} & 0 & 0 \\ & & y & & c_{44} & 0 \\ & & & m & & c_{66} \end{bmatrix} \tag{1}$$

where parameters c are shown in Table 1.

Table 1: Example of the construction of one table

Elasticity Constants c [GPa]	c_{11}	c_{12}	c_{13}	c_{33}	c_{44}	c_{66}
	390	145	103	405	105	123

Electric and piezoelectric properties of GaN are included in constitutive law of piezoelectric properties and has form:

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

where E is the vector of electric intensity, D is the vector of electric displacement, e^{ε}_p is the permitivity matrix on condition constant strain ε, C^E is the elasticity matrix on condition constant electric intensity E and e is the matrix of piezoelectric properties. For polarization in z direction (number 3 in numerical labeling), elasticity matrix C^E has form (1), permitivity matrix e^{ε}_p has form:

$$e_p^{\varepsilon} = \begin{bmatrix} e_{p11} & 0 & 0 \\ 0 & e_{p11} & 0 \\ 0 & 0 & e_{p11} \end{bmatrix} \tag{3}$$

and matrix of piezoelectric properties e has form:

$$e = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & e_{15} \\ 0 & 0 & 0 & 0 & e_{15} & 0 \\ e_{13} & e_{13} & e_{33} & 0 & 0 & 0 \end{bmatrix}^T \tag{4}$$

Relative permitivity of GaN has value e_{p11}=8.9 and piezoelectric constants are: e_{13}=-0.51 pC/μm^2, e_{p11}=0.375 pC/μm^2 and e_{p11}=0.67 pC/μm^2.

3 MODELING AND SIMULATION OF SAW SENSOR

FEM analysis of MEMS SAW piezoelectric sensor contains two different analysis type - modal analysis and transient analysis. Modal analysis is used to determined the eigenfrequency of SAW sensor, that can be used in subsequent transient analysis. All analyses are performed in code ANSYS [5].

3.1 Modal analysis of SAW sensor

Because the geometry of SAW sensor under IDT is periodic, we can model only small part of SAW device with length equal to wave length λ. Only 2D model is considered - see Figure 3 left.

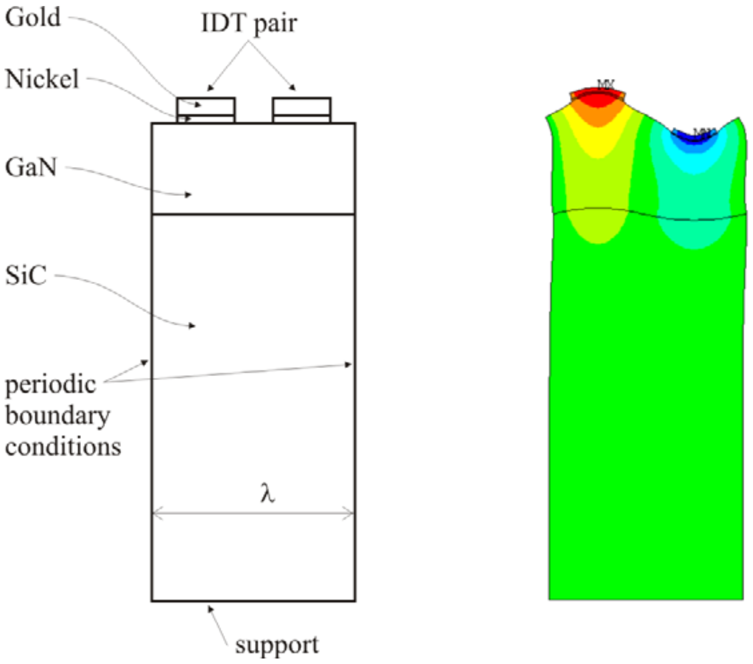

Figure 3: Geometry of 2D model (left) and mode shape (right)

Boundary conditions have to enable periodic deformation of model. These conditions are satisfied by coupling of individual degree of freedom on left and right side of the model. Bottom of the model is fixed and the top is free. To perform modal analysis, piezoelectric element PLANE223 of code ANSYS is used. Block Lanczos method is used to compute eigenfrequencies and eigenmodes of the system. Obtained eigenmode of Rayleigh wave is shown in Figure 3 (right) and corresponding eigenfrequency is 1.29 GHz. This frequency is used in subsequent transient analysis as frequency of electric excitation.

3.2 Transient analysis of SAW sensor

SAW sensor for transient piezoelectric FEM analysis was modeled as 3D system - real geometry shown in Figure 1 was considered. In this 3D model, piezoelectric element SOLID226 and structural element SOLID186 were used. Model contains 236036 elements. Detail of the mesh is shown in Figure 4.

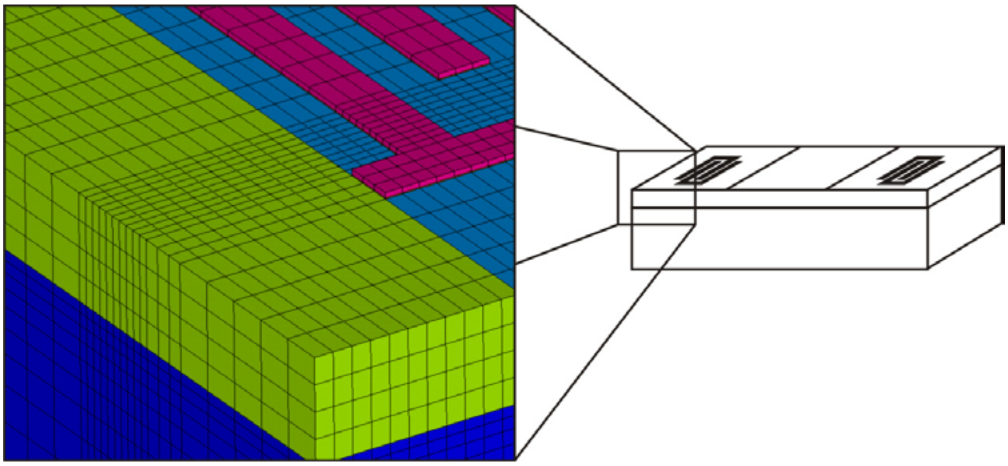

Figure 4: Detail of mesh of 3D model

Loading of the SAW sensor is harmonic electric voltage on input IDT with amplitude 1 V and with frequency equal to the eigenfrequency computed in modal analysis f=1.29 GHz - see Figure 7 (left side) - red curve. SAW sensor is fixed at the bottom of substrate. The goal of the simulation is to investigate wave propagation on the surface of SAW sensor as well as induced voltage on output IDT. Also the influence of density change of sensitive layer on the wave shift is investigated. Total time of simulation is 1.5x10^{-8} s.

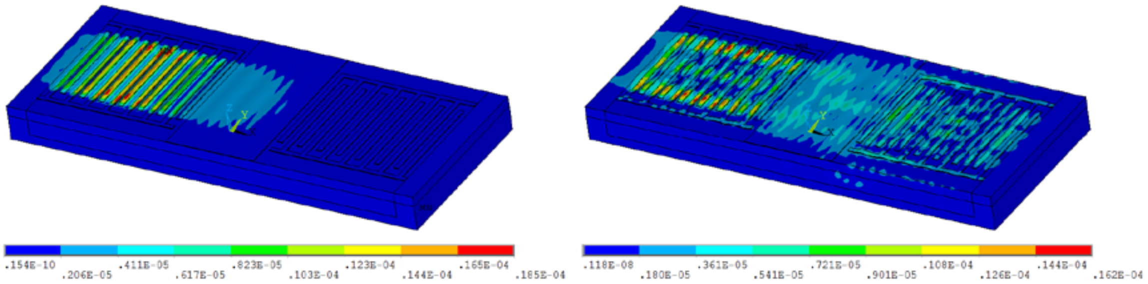

Figure 5: Total deformation (3D view) of system at the beginnig (left) and end of simulation (right) in [μm]

The first simulation is performed with original density of sensitive layer. Figure 5 shows total deformation of system at the beginning of simulation - left side and also at the end of simulation (time 1.5×10^{-8} s) - right side. As we can see from both deformations, dominant direction of wave propagation is from input IDT to the output IDT. This direction is better viewed in Figure 6, where only 2D front view on SAW sensor is shown. As we can see from Figure 6, wave propagates to the substrate only in limited range and the dominant direction is from input IDT (left side) to output IDT (right side).

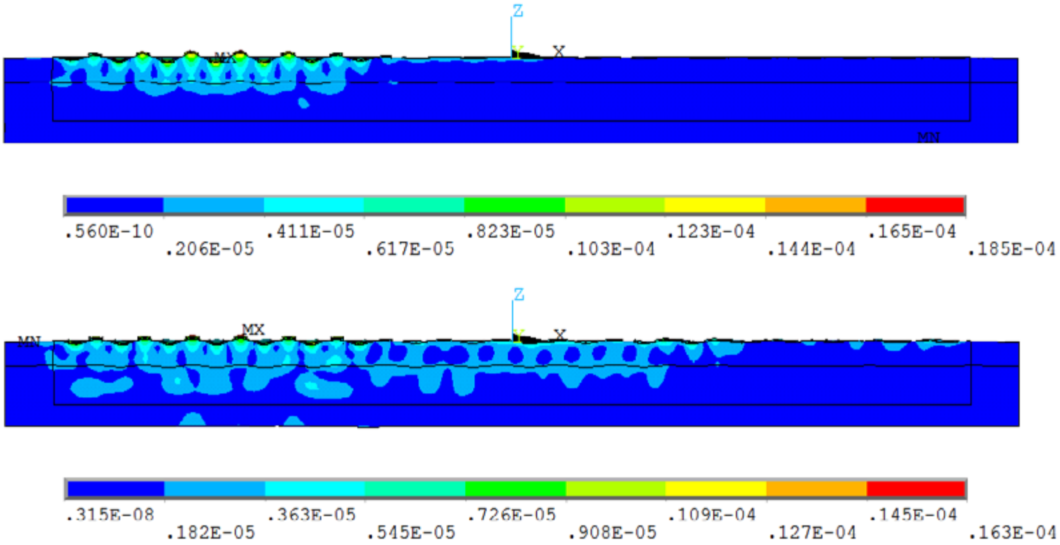

Figure 6: : Total deformation (2D view)| of system at the beginnig of simulation (top) and at the end of simulation (bottom) in [μm]

Input and output electrical signal on IDT is shown in Figure 7 - right side. As we can see from this figure, wave needs approximately 3 ns to propagates form input to the output IDT.

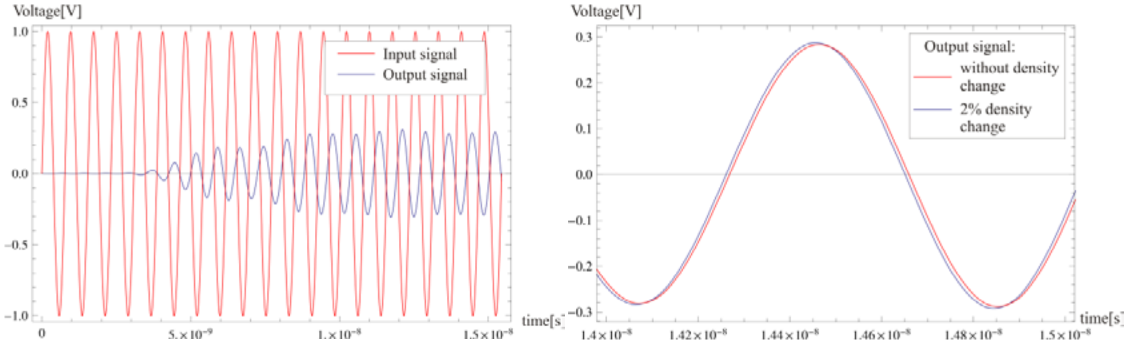

Figure 7: Input and output electrical signal on IDT - left and shift of wave caused by density change - right

Next analysis was performed with change of sensitive layer density. The change of density is set to 2% of original density of Palladium and this density change represents the process of chemical absorption in sensitive layer. The shift of wave is shown in Figure 7 - right side.

4 CONCLUSION

The paper deals with modeling and simulation of surface acoustic waves sensor using finite element method - FEM code ANSYS is used. Two analyses were performed - modal and transient. In modal analysis only 2D model is used to determined eigenfrequency of the system. The frequency determined by modal analysis is used as input in transient piezoelectric analysis as frequency of excitation, where 3D model was used. In transient analysis with harmonic loading wave propagation and the influence of sensitive layer density change is investigated.

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REFERENCES

[1] Mayers, M.A. *Dynamic behavior of materials.* John Wiley & Sons. Ltd, Chichester, U. K., (1994).

[2] Fraden, J. *Handbook of modern sensors.* Springer, New York, (2003).

[3] Datta, S. *Surface Acoustic Wave Devices*. Prentice-Hall, (1986).

[4] Campbell, C.K. *Surface Acousitc Wave Devices of Mobile and Wireless Communications*. Academic Presss, (1998).

[5] ANSYS - Theory manual, Version 14 (2013).