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Electric Field Distribution Simulation of Pt/AlN/Sapphire Resonator for Sensor

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Abstract: The sensitivity of resonator sensors was studied through the design of a resonator sensor using a Pt/AlN/Sapphire structure. Sapphire was utilized as the substrate material to increase the sensitivity of the sensor, while the AlN thin film was chosen for its high acoustic velocity, thermal stability, chemical stability, and good piezoelectric coupling. The Finite Element Method (FEM) simulation in COMSOL Multiphysics was used to optimize the design and determine the electrical field distribution within the sensor. The simulation compared the electric field distribution of different substrates, including sapphire and silicon, and found that the electric field distribution was higher on the sapphire substrate. The results showed that the choice of substrate material and thickness can greatly impact the electric field distribution of resonator sensors, with a thinner substrate resulting in a weaker electric field distribution. Ultimately, the study provided sapphire as a potential option for industries and advanced the understanding of electrical field distribution in resonator sensors.

Keywords: Electric Field, Resonator, Sapphire

1. Introduction

A force field that surrounds electric charges is known as an electric field. Vectors that depict the strength and direction of the force at each location in space can be used to illustrate it. The distribution of electric charges in the area affects the location of an electric field. The surrounding charges determine the direction and strength of the field at any time[1]. The language of differential forms, vector fields, and potentials are a few of the numerous ways the electric field can be represented. Differential forms are a mathematical technique that can be used to express the electric field in a fashion that is independent of the choice of coordinates[2].

A resonator is a device that can be used to analyze the distribution of the electric field in a given area. Different types of resonators, such as microwave resonators, optical resonators, and acoustic

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resonators, can be used for this purpose. The microwave resonator, for example, consists of a hollow cavity in which the electric field is measured and studied[3]. The distribution of the field is determined by analyzing the resonance frequency of the cavity. The optical resonator, on the other hand, consists of a cavity with reflective surfaces through which an optical beam is directed. The distribution of the field is determined by analyzing the reflection of the beam. Acoustic resonator works similarly but in the realm of acoustic waves by determining the resonance frequency of the acoustic waves in a cavity[4].

The problem statement in this research is to study the sensitivity of resonator sensor devices in the electronics industry and to determine the efficiency coefficient of electrical field distribution in resonator sensor devices made of Pt/AlN/Sapphire. The resonant sensors are widely used in electrical equipment due to their frequency-based signal output, which is immune to intensity variations and allows easy coupling with digital systems. The researchers aim to design a resonator sensor device with increased sensitivity by adding Pt/AlN/Sapphire to the structure. The AlN/Sapphire structure has strong thermal and chemical stability, making it suitable for use in high-temperature applications. The researchers plan to run simulations to analyze the best combination of Pt/AlN/Sapphire thickness to determine the efficiency of electrical field distribution in the resonator sensor.

Resonant sensor devices are commonly used in the electronics industry to make filters, delay lines, and resonators with frequencies ranging from a few tens of Megahertz to a few Gigahertz. Researchers have explored different forms of resonant sensor devices, including piezoelectric on insulator, which can provide high performance[5]. Resonant sensors are also appealing for sensing applications due to their sensitivity to physical and chemical features of the surroundings. In this research, the authors aim to study the sensitivity of resonators for sensors by designing a resonator sensor using a Pt/AlN/Sapphire structure. The sapphire structure is used to increase sensor sensitivity, while the high-temperature sensor is made of AlN thin film. The AlN material is chosen for its high acoustic velocity, thermal and chemical stability, and good piezoelectric coupling[6].

The electric field distribution of a resonator sensor with platinum, aluminum nitride, and sapphire can be determined using electromagnetic equations and material properties of the components. The electric field distribution is crucial for the proper functioning of the resonator sensor, which has a resonant frequency that is related to the electric field distribution by the capacitance and inductance. To determine the electric field distribution, COMSOL Multiphysics can be used to specify the material properties and set up boundary conditions, and then solve the Maxwell's equations to obtain the electric field distribution. By analysing the electric field distribution, the resonant frequency of the resonator sensor can be determined and optimized for specific applications.

The outcomes of this research on resonator sensors using a Pt/AlN/Sapphire structure will help to advance our understanding of electrical field distribution. This research will enable the use of sensors and substrates as electrical conductivity mediums in the future. The increasing need for improved electrical conductivity in advanced systems such as flight control systems for military aircraft, makes it necessary to explore other fields of electrical conductivity research. This study has introduced Pt/AlN/Sapphire as a promising material to improve the sensitivity of resonator sensors and determine the efficiency of electrical field distribution. This research opens new possibilities for the use of Pt/AlN/Sapphire in industries[7].

The objective of this research is to design a resonator sensor using the properties of the Pt/AlN/Sapphire structure and optimize the design using Finite Element Method (FEM) simulation. The goal is to determine the electrical field distribution within the sensor by using Pt/AlN/Sapphire substrates. The research also aims to compare the electric field distribution strength using different substrates to identify the best substrate material for the resonator sensor and enhance the sensitivity and efficiency of the sensor. The research ultimately aims to provide sapphire as a selection option for industries.

2. Materials and Methods

Resonator sensors are devices that use the mechanical resonant frequency of a material to measure various physical properties such as temperature, pressure, and mass. They are based on the principle that the resonant frequency of a material changes with changes in the physical properties being measured. Platinum, aluminum nitride (AlN) and sapphire are all materials that can be used as resonator sensors. Each of these materials has its own unique properties that make it suitable for certain types of resonator sensors.

2.1 Materials Specifications

For this study, it is important to set the global parameters to achieve the best results. The structure of a resonator using sapphire as a substrate, aluminum nitride as piezoelectric material and platinum as electrode is illustrated in Figure 1. The materials and properties of the components of the resonator sensor are presented in Table 2. Additionally, a comparison of the properties of sapphire and silicon (Si) substrates is shown in Table 2.

Table 1: Parameter of Material in Resonator Sensor [8]

Material	Thickness (μm)
Sapphire substrate	500
Aluminum Nitride	250
Platinum	50
Molybdenum (layer)	180
Silicon Oxide (layer)	180
Silicon substrate	500

Table 2: Properties of Material for Resonator Sensor [8]

Material	Density (kg/m³)	Young's modulus (Pa)	Poisson's ratio	Acoustic velocity (m/s)	Electrical conductivity (S/m)	Thermal conductivity W/(m*K)	Heat capacity J/(kg*K)
Sapphire	3950	5.6×10^{11}	0.27	12000	10^{-17}	27	800
Aluminum nitride	3300	4.1×10^{10}	0.22	11100	10^{-11}	170	600
Platinum	21450	6.5×10^{11}	0.38	5500	10^{7}	71.6	133
Molybdenum	10200	4.0×10^{11}	0.31	6280	10^{6}	138	250
Silicon oxide	2170	6.7×10^{10}	0.17	2170	10^{-14}	1.4	730
Silicon	2330	1.6×10^{11}	0.28	8320	10^{3}	130	700

2.2 Methods

The process of using the Finite Element Method (FEM) in COMSOL Multiphysics to model a resonator sensor involves several steps. The first step is to define the geometry of the sensor, which includes creating a 2D model of the sensor using the geometry tools in COMSOL Multiphysics and including all relevant features such as the resonator element, electrodes, and any other components. Next, the physics of the problem must be defined by selecting the appropriate physics interfaces, such as mechanical, thermal or electromagnetic, and assigning the material properties of the sensor to the different regions of the geometry. Boundary conditions, such as temperature, pressure, or electric potential, must also be applied to the geometry of the sensor. After setting up the model, the problem can be solved using the FEM solver in COMSOL Multiphysics, which will produce a numerical solution to the behaviour of the sensor. The results of the simulation can be analysed using the post-processing tools to analyse the frequency response, the temperature and pressure dependence, and the sensitivity of the resonator sensor. Based on the results obtained, the model can be optimized by changing the parameters of the sensor, such as the dimensions of the resonator element or the material properties, and parameter studies can be performed to explore the effect of different parameters on the sensor's performance.

To test the electric field distribution on different substrates such as sapphire and silicon, the methodology that was followed would involve using a resonator sensor with a fixed thickness. Specifically, the resonator sensor would be simulated on substrates with a thickness of 250 micrometers for both sapphire and silicon substrates as shown in table 3.3. This was done to observe how the electric field behaves on these different substrates at a specific thickness. The simulation results obtained using COMSOL Multiphysics 6.0 were compared to gain insight into how the electric field is affected by the properties of the substrates at this specific thickness. After completing the simulations, a graph of the electrical field distribution of the resonator sensor was obtained. This graph was used to determine the thickness at which the resonator sensor is working most efficiently. By comparing the results obtained at a fixed thickness 250 micrometers on the substrates sapphire and silicon, it was possible to see which substrate yields the highest level of electrical field distribution and thus, the resonator sensor was working most conveniently.

2.3 Equations

The electric field can be determined from the result of COMSOL Multiphysics. It can be calculated from electric potential equation and electric field norm by data that have been collected.

The electric potential (V) can be determined by solving the Poisson equation which is a partial differential equation (PDE) that describes the relationship between the electric potential and the electric field in each region. The Poisson equation can be written as:

$$\nabla^2 V = -\rho/\varepsilon \qquad \textit{Eq.}\,1$$

Where ∇^2 is the Laplacian operator, V is the electric potential, ρ is the charge density, and ε is the permittivity of the medium.

The electric field norm, also known as the electric field intensity, can be determined by solving Maxwell’s equations which are a set of partial differential equations that describe the behaviour of the electric and magnetic fields in each region[9].

$$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t \qquad \textit{Eq.}\,2$$

$$\nabla \cdot \mathbf{E} = \rho/\varepsilon \qquad \textit{Eq.}\,3$$

Where E is the electric field vector, ∇ x is the curl operator, ∂B/∂t is the time derivative of the magnetic field, ∇ . is the divergence operator, ρ is the charge density and ε is the permittivity of the medium.

The first equation describes the relationship between the electric field and the magnetic field, and the second equation relates the electric field to the charge density[10].

In the case of a resonator sensor, the resonant frequency can be related to the electric field distribution by the following equation:

$$\mathbf{f} = \mathbf{1/2\pi} \sqrt{(\frac{\mathbf{C}}{\mathbf{L}})} \quad \boldsymbol{Eq.4}$$

where C is the capacitance and L is the inductance.

To determine the electric field distribution in COMSOL Multiphysics, you would need to specify the material properties of the components (platinum, aluminum nitride, and sapphire), set up the boundary conditions and perform a simulation to solve the Maxwell's equations.

3. Results and Discussion

This section analysed and discussed the models that were created using different materials. The comparison of using sapphire as a substrate and silicon substrate was examined. The simulation results, obtained using COMSOL Multiphysics, were used to analyse the electric field distribution by changing the types of substrates. The results of modelling the resonator sensor were presented in Figure 2 and the electric field distribution simulation was presented in another figure. The comparison of electric field distribution strength was presented in a graph and dataset.

3.1 Results

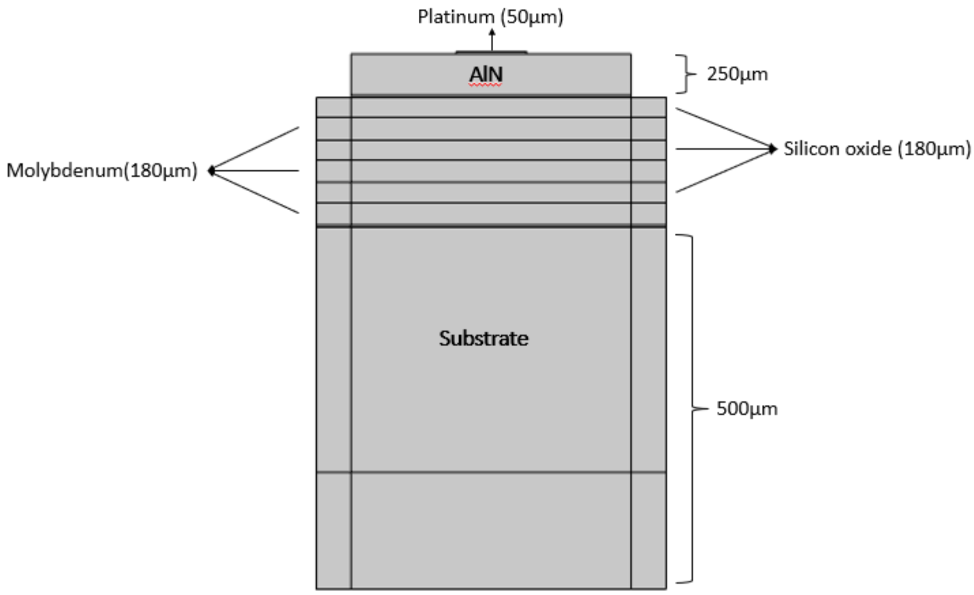

Figure 1: 2D Model of Resonator Sensor for Electric Field Distribution

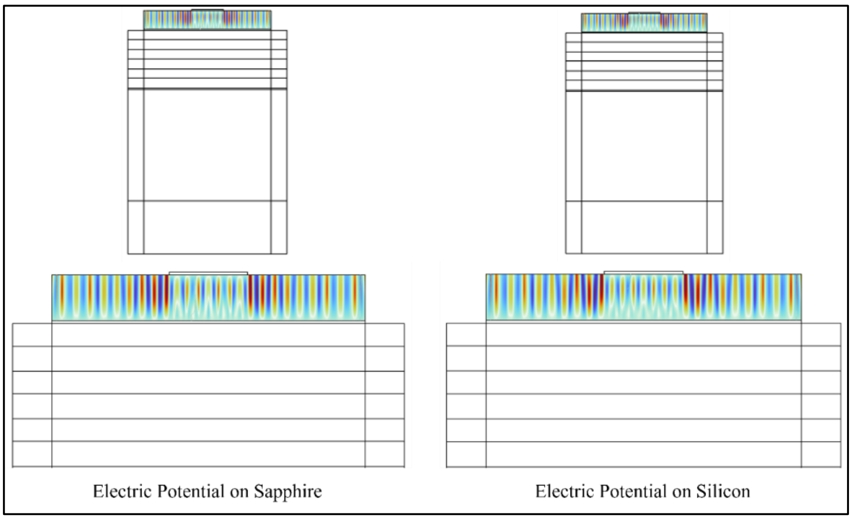

Figure 2: Graphic of Electric Potential on Resonator Sensor COMSOL Simulation using Sapphire and Silicon Substrates

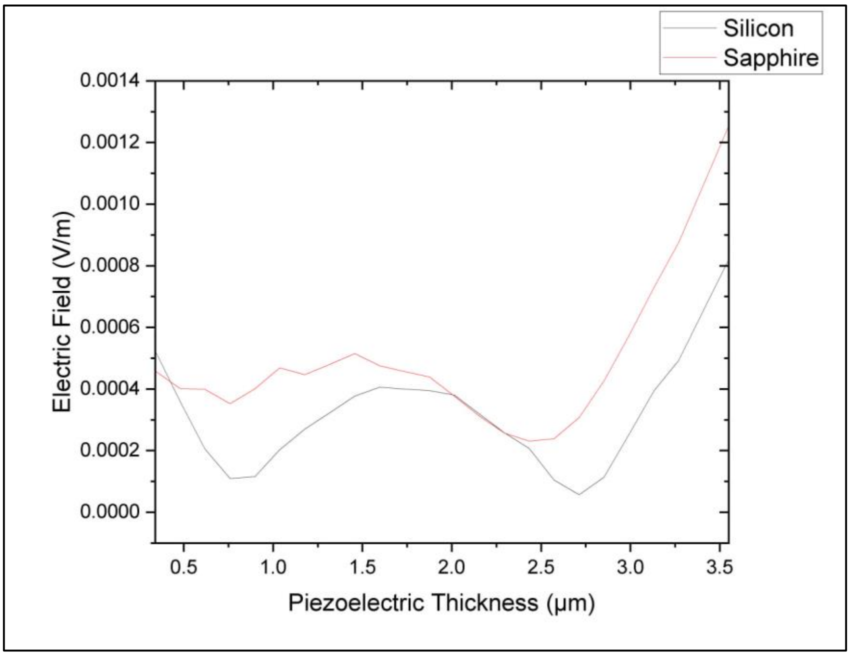

Figure 3: Graph of Electric Field Distribution for Resonator Sensor of Sapphire and Silicon Substrates

Table 3: Results of Electric Field Distribution for Resonator Sensor of Sapphire and Silicon Substrates

Piezoelectric Thickness (μm)	Electric Field, *E* (V/m) Sapphire	Electric Field, *E* (V/m) Silicon
0.5	0.000399	0.000205
1	0.000468	0.000203
1.5	0.000475	0.000405
2.0	0.000377	0.000380
2.5	0.000238	0.000105
3.0	0.000572	0.000251
3.5	0.001254	0.000819

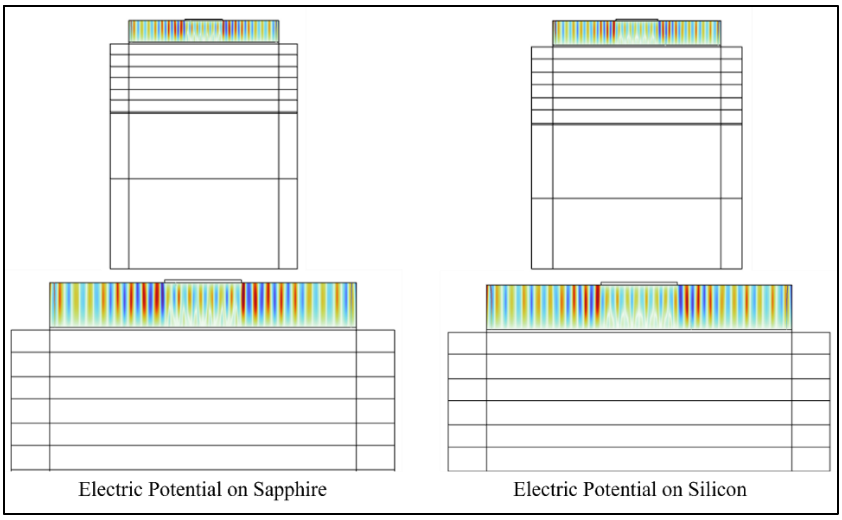

Figure 4: Graphic of Electric Potential on Resonator Sensor COMSOL Simulation using 250 µm Thickness of Sapphire and Silicon Substrates

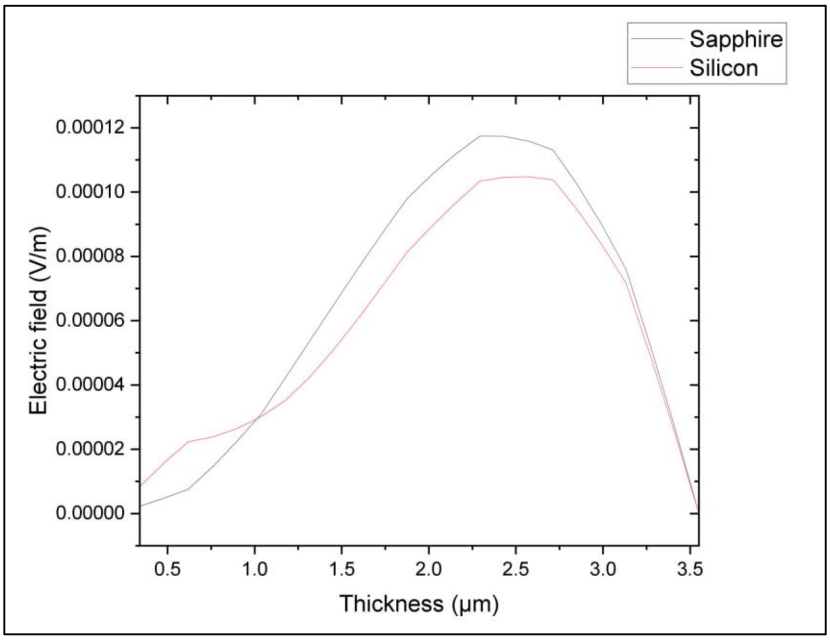

Figure 5: Graph of Electric Field Distribution for Resonator Sensor on 250 µm thickness of Sapphire and Silicon Substrates

Table 4: Results of Electric Field Distribution for Resonator Sensor on 250 µm thickness of Sapphire and Silicon Substrates

Piezoelectric Thickness (µm)	Electric Field, *E* (V/m) Sapphire	Electric Field, *E* (V/m) Silicon
0.5	0.00000476	0.0000157
1	0.0000310	0.0000301
1.5	0.0000651	0.0000511
2.0	0.000105	0.0000892
2.5	0.000116	0.000105
3.0	0.0000900	0.0000838
3.5	0.0000271	0.0000254

3.2 Discussions

The simulation of the resonator sensor was performed to determine the electric field distribution with the use of different substrates. The COMSOL simulation was used to model the electric potential on the resonator sensor using sapphire and silicon substrates. The graphic results as shown in figure 2 showed that the electric potential on the resonator sensor using both sapphire and silicon substrates were similar. However, the electric field distribution results showed that the electric field on the sapphire substrate was higher than that on the silicon substrate. This was further confirmed by the graph in figure 3 of electric field distribution for the resonator sensor of sapphire and silicon substrates at 800 MHz, which clearly illustrates the higher electric field on the sapphire substrate. The results shown in table 3 indicate that the choice of substrate material can have a significant impact on the electric field distribution of the resonator sensor. The sapphire substrate is more suitable for resonator sensor application because of the higher electric field it generates.

The graphic of the Electric Potential on a Resonator Sensor in a COMSOL Simulation using 250 μm thickness of Sapphire and Silicon Substrates shown in figure 4 is compared to 500 μm thickness to visualize the distribution of the electric potential on the sensor and determine the electric field. The contour plot can be used to compare the electric potential on the sapphire and silicon substrates of different thicknesses and observe the difference in the electric field distribution. The results of the Electric Field Distribution for the Resonator Sensor in table 4 would depend on the specific geometry and material properties used in the simulation. However, it is expected that the electric field distribution on a 250 μm thickness substrate would be weaker than on a 500 μm thickness substrate due to a thinner substrate having a lower capacitance and resulting in a lower electric potential. A graph in figure 5 of the Electric Field Distribution for the Resonator Sensor on 250 μm thickness of Sapphire and Silicon Substrates is constructed by plotting the electric field values at different locations on the sensor for both substrates, and it shows that the electric field value of the Sapphire substrate is higher than the Silicon substrate.

4. Conclusion

Based on the results of the COMSOL simulation of the resonator sensor, it was concluded that the choice of substrate material has a significant impact on the electric field distribution of the resonator sensor. The electric potential on the resonator sensor using both sapphire and silicon substrates was found to be similar, however, the electric field distribution results indicated that the electric field on the sapphire substrate was higher than that on the silicon substrate. This was confirmed by the graph of electric field distribution, which clearly showed the higher electric field on the sapphire substrate.

The results of the electric field distribution for the resonator sensor on 250 μm thickness of sapphire and silicon substrates showed that the electric field distribution on the sapphire substrate would be weaker than on the 500 μm thickness of the sapphire substrate, due to a thinner substrate having a lower capacitance and resulting in a lower electric potential. This was also observed for the silicon substrate. The graph of electric field distribution for the resonator sensor on 250 μm thickness of sapphire and silicon substrates showed that the electric field value of the sapphire substrate was higher than that of the silicon substrate.

The key findings of the simulation were that the choice of substrate material has a significant impact on the electric field distribution of the resonator sensor and that the sapphire substrate is more suitable for resonator sensor applications due to the higher electric field it generates. Additionally, the thickness of the substrate also affects the electric field distribution, with thicker substrates having a higher electric potential. The significance of the current work lies in the fact that it provides insight into the impact of substrate material and thickness on the electric field distribution of resonator sensors. This information can be used to optimize the design of resonator sensors for specific applications. However, it should be noted that the results are limited to the specific geometry and material properties used in the simulation and may not apply to other resonator sensor configurations. Further research is needed to validate the results and to explore the impact of other factors on the electric field distribution of resonator sensors.

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