Device Modeling and Optimization of MEMS based Capacitive Pressure Sensor

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***Abstract* – Capacitive pressure sensors are widely used in various applications due to their advantages over other types of sensors, such as low power consumption, high resistance to temperature changes, and improved stability. This paper presents a performance analysis of a capacitive pressure sensor operating on the electro-mechanical interface. The analysis includes diaphragm deflection, sensitivity, linearity, capacitance versus pressure, and thermal considerations. Simulation results illustrate diaphragm displacement and capacitance under uniform external pressure (25kPa) and compare them with linearized analytical capacitance values. Additionally, the impact of packaging stress on the MEMS design process is discussed, along with a sensitivity comparison of capacitive pressure sensors with and without packaging stress.**

Keywords* – *Capacitive pressure sensor, COMSOL Multiphysics, Diaphragm displacement, Packaging stress, Sensitivity.

I. INTRODUCTION

In today's technological landscape, the continuous monitoring of various devices is paramount, driving the widespread adoption of Micro-Electro-Mechanical Systems (MEMS)-based pressure sensors. These sensors play integral roles across diverse industries, including automotive, aerospace, biomedical, telecommunications, security systems, and more. Capacitive pressure sensors offer distinct benefits, characterized by their thin membrane structure, compact size, ability to measure both static and dynamic changes, high resolution, cost-effectiveness, simple manufacturing processes, and suitability for high-frequency applications. At the heart of capacitive sensors lie capacitors, comprised of two conducting parallel plates separated by an insulating dielectric material, serve as fundamental components in the electronic realm. The study delves into modelling diaphragm displacement, capacitance, sensitivity, and linearity across varying applied pressures of the MEMS capacitive pressure sensor featuring a square diaphragm, employing COMSOL Multiphysics. Additionally, emphasis is placed on the effects of thermal considerations on capacitance resulting from packaging stress. Thus, gaining an understanding of the permissible packaging stress is imperative prior to device fabrication

II. SENSOR STRUCTURE

The capacitive pressure sensor comprises two parallel plates functioning as the electrodes of capacitors, separated by an air gap. Several parameters, including material type, size, shape, and structure, significantly influence the device's optimization to achieve desired specifications. The geometric model used for the capacitive pressure sensor is illustrated in Figure 1. In this model, single-crystal germanium is utilized, possessing specific material properties such as a Young's Modulus (E) of 130 GPa Poisson's ratio (μ) of 0.28 and a density (ρ) of 5323[kg/m^3]. The square diaphragm's dimensions measure 500 μm x 500 μm. Germanium is selected due to its advantageous characteristics, including a high melting point and minimal mechanical hysteresis and expansion (5.8 ppm/°C). These properties make it well-suited for the creation of the square diaphragm through anisotropic etching of germanium in bulk.

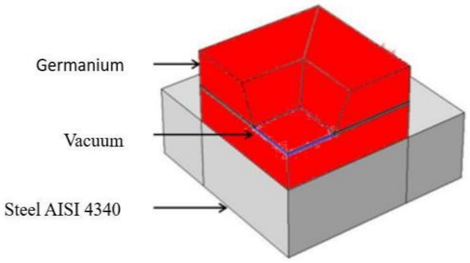

Fig. 1. Structure of the capacitive pressure sensor

III. DESIGN STUDY

COMSOL Multiphysics offers a comprehensive integrated environment through its Model Builder, providing users with a complete overview of the model and access to all functionalities. For this study, we utilize the Structural Mechanics with an Electromechanics interface, a built-in physics module that enables stationary study analysis. The capacitive pressure sensor is subjected to a uniform external pressure of 25 kPa, with an operating temperature set at 20°C and a die bonding temperature of 70°C. Taking advantage of the geometry's symmetry, symmetric boundary conditions are applied to the device. Boundary loads are imposed to simulate the pressure exerted on the surface of the diaphragm. The membrane is permitted to move solely in the z-direction to accurately capture capacitance changes.

TABLE I. SIMULATION PARAMETERS

Parameters	Value	Expression	Description
P_o	20000 Pa	20 KPa	Pressure
T_o	293.15 K	20 °C	Operating Temp.
T_{ref}	343.15 K	70 °C	Die bonding temp.
Ge	5323	130 GPa	Young Modulus
Steel AISI4340	7850	205	Young Modulus

IV. RESULTS AND DISCUSSIONS

Simulation results, both with and without packaging stresses, demonstrate the displacement of the diaphragm and the corresponding changes in device capacitance when external pressure is applied. In the simulation, a uniform pressure of 25 kPa is applied to the sensing electrode. Fig.2 shows the maximum and average displacement of the membrane as a function of the applied Pressure.

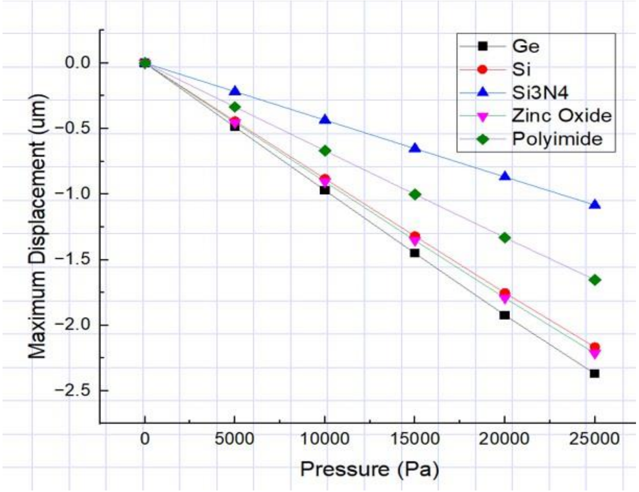

Fig. 2 Displacement of membrane with and without packaging stress.

The deformation of the membrane resulting from applied pressure induces a variation in capacitance. Figure 3 demonstrates a non-linear increase in device capacitance with applied pressure.

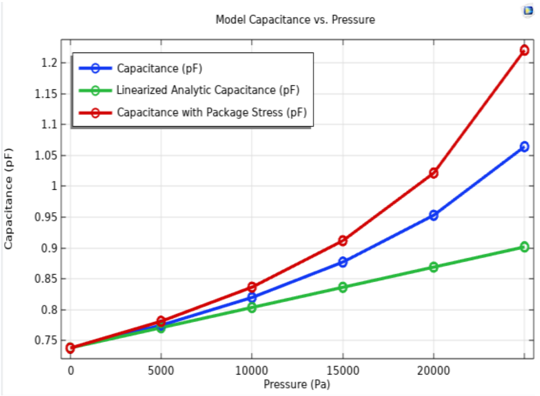

Fig. 3 Impact of Capacitance vs. Pressure

In subsequent analysis, the model is expanded to incorporate thermal expansion effects, to assess the impact of packaging stress on the device's performance. Considering the thermal coefficient of expansion for Ge to be 6.1e-6 1/K, the effects of thermal expansion are observed across the entire structure, providing insights into its influence on the sensor's behavior and performance. The results presented encompass scenarios both with and without packaging stress. The maximum displacement is concentrated at the diaphragm's center. Consequently, this non-uniform displacement generates differential potentials between the capacitor plates.

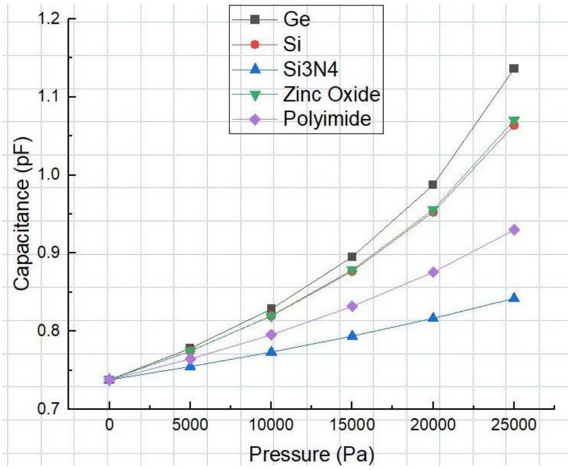

Fig. 4. Effect of series resistance on device performance

The terminal charge consistently increases regardless of pressure due to factors like charge accumulation, pressure-independent charging mechanisms, efficient design, or feedback mechanisms.

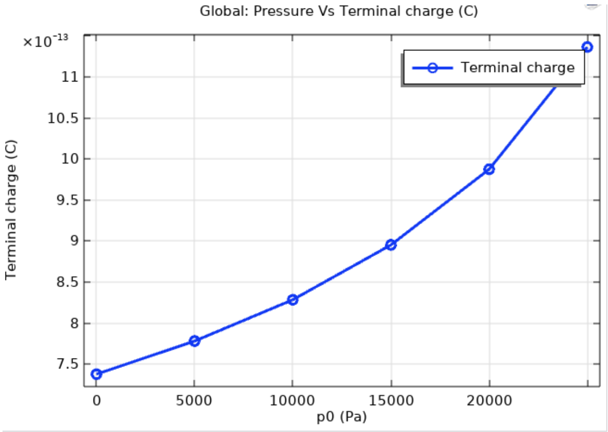

Fig. 5. Pressure vs Terminal Charge

CONCLUSION

This study deals with the design and analysis of MEMS based capacitive pressure sensor focusing on the analysis of diaphragm displacement, capacitive behavior, and sensitivity. The study reveals that the maximum deflection occurs at the center of the diaphragm and that sensitivity correlates with the change in capacitance—the higher the change, the greater the sensitivity of the device. It is found that the sensitivity of the device increases by 1.5 times when compared to devices without packaging stress. However, it's crucial to note that thermal stress renders the device temperature-dependent, underscoring the importance of considering packaging in the MEMS design process

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