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# Design, development and characterization of MEMS silicon diaphragm force sensor

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ABSTRACT

The aim of the paper is to describe the design, development and experimental characterization of a MEMS silicon diaphragm based force sensor. In the presented design, a unique combination of a thin single crystal silicon diaphragm has been used as a mechanical sensing element. The force sensor is based on the principle of conversion of applied force to an electrical quantity (e.g. voltage) consists of four piezoresistors in a Wheatstone-bridge configuration. The sensor has been modeled with the help of modern CAD tools and, after several iterations, the diaphragm size and thickness have been optimized to obtain a high sensitivity against an applied load in the designed range. The finite element analysis (FEA) has been carried out for computational investigations to have an approximate evaluation in regard of mechanical design and features. The important parameters like stress, strain and deflection are found to be within permissible limits. The fabricated sensor has been characterized by its metrological capabilities. The relative error due to repeatability is found to be < 1% in the working range of the sensor. The sensitivity has been found to be in order of 0.35–0.40 mV/V/N for 10 N–50 N force range.

## 1. Introduction

For many decades various type of force sensors have been used for force measurement in different industrial applications such as steel, cement, defense, space, railways, aviation, shipping, heavy industries and serve as force standards for disseminating the unbroken chain of measurement traceability from the National Metrology Institute (NMI) to the various manufacturing of industrial products (production hub). Various different force transducer analogous force proving rings or elliptical shaped bow dynamometer, standardizing box, tuning fork type, Hall effect and strain gauge type have been used over the years based on different principles and have different grades of uncertainty. In the Indian scenario about 60–70% analogous ring shaped force transducers are more commonly used despite their many inherited demerits such as non linearity, required temperature correction, limited use for specific points only, inability to interpolate, or, cannot be used for automation purposes. All these demerits are overcome by a strain gauge force transducer which employs strain gauges arranged in the form of Wheatstone bridge and their output is recorded through suitable digital indicators. Some Commercially available force transducers of make GTM-Germany, Interface Inc.-USA, HBM-Germany among others, are available in the market. Machining of these complex elements along with their strain gauging are a very difficult task, which is a critical barrier to the development of such force transducers at laboratory level [1–4]. There is practical constraint found with the analogous and the strain gauged force transducers in the Newton and sub-Newton lower force range.

A new class of force sensors based on Micro-electro mechanical systems (MEMS) has also come up during last one and half decades as new generation devices which have high sensitivity, are small in size and cost effective. With the evolution of this kind of technology; one can combine several techniques in the fabrication of a force sensing chip which is able to measure a wide range of forces. These force sensors utilize the mechanical properties of single crystal silicon as the load or force sensing element and the piezoresistive properties of monocrystalline or that of polycrystalline Si for the transduction of the stress generated during the sensing of the force. The biggest advantage of this kind of force sensors is that the Gauge Factor of the Si piezoresistors is as high as 200, leading to high sensitivity [5–10].

The present paper discusses the design, development and characterization of a circular shaped MEMS diaphragm load sensor. The force sensor has been developed for a capacity of 50 N and analytical as

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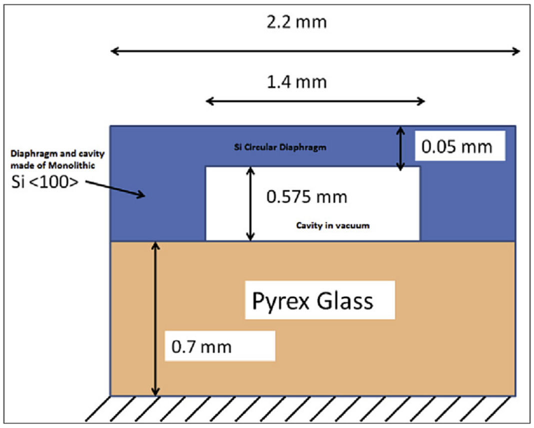



**Fig. 1.** Schematic cross-section of the force sensing element.

well as simulation studies have been done for measurement of stress, strain and deflection. The deflection values are computed by theoretical and computational methods at different loading conditions and there is a good agreement between the two approaches. The computational stress and stress values are found to be within permissible limits. The sensitivity and repeatability of the force sensor are measured according to the standard guidelines. The procedures and results are discussed.

## 2. Computational investigations (simulation)

The force sensor has been modeled in 3D with the help of software tool SolidWorks™. A detailed 3D model has been generated (Fig. 1) in order to have a rigorous evaluation of force sensor for its structural behavior under action of the force applied. The applied loads are in the range of 10–50 N and the load acted at the centre of the sensor diaphragm with compressive nature. Suitable boundary conditions were applied and 3D finite element analysis has been carried out using the software tool Ansys Multiphysics™. Deflection, stress, strain and deformation have been evaluated for a realistic evaluation of the sensing element (Figs. 2–4). Stress is found to be within permissible limits. For FEM, yield strength and modulus of elasticity have been taken for Si as 7000 MPa and 190 GPa respectively. Poisson ratio is considered to be 0.23.

### 2.1. Deflection theory

In the design process we consider various assumptions like small deflection, uniform diaphragm thickness and perfectly elastic behavior of the material used. According to the small deflection theory, deflection w(r) is the function of radial distance *r* in a circular plate [11,12]. The deflection at point of circular plate would be written as

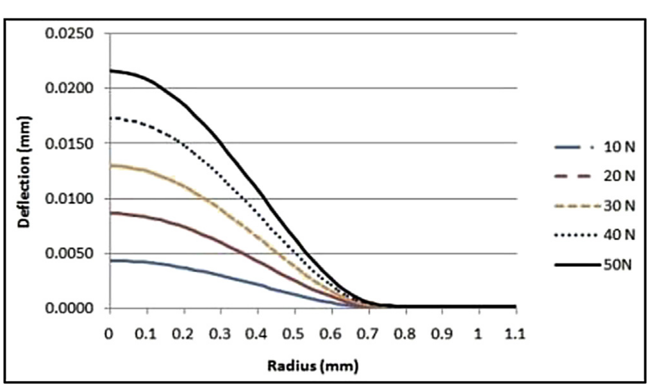
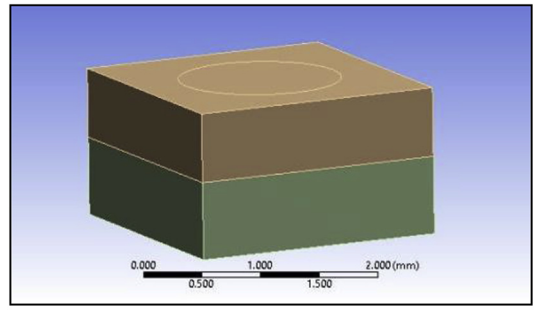
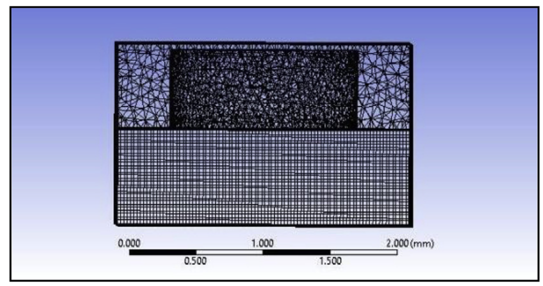



**Fig. 2.** Diaphragm deflection at different loads.




(a)




(b)

**Fig. 3.** (a) CAD model of the sensor (b) Meshing.

$$w(r) = \frac{Fa^4}{64AD}\left\{1 - \left(\frac{r}{a}\right)^2\right\}^2 \tag{1}$$

Where "r" and "a" is the radial coordinate and diaphragm radius respectively. F is the applied load and A is the area of the plate over which the load is applied. Due to applied load, maximum deflection $w_0$ in the plate is observed at the centre of the plate, and hence the deflection equation becomes

$$w_0 = \frac{Fa^4}{64AD} \tag{2}$$

D is the flexural rigidity, which is a measurement of stiffness and is defined by

$$D = \frac{Eh^3}{12(1-\mu^2)} \tag{3}$$

Where E, h and $\mu$ are the modulus of elasticity, thickness of plate and Poisson's ratio, respectively. The deflection is the most important parameter in diaphragm based sensor design [13]. At different loading conditions, simulated deflections obtained are shown in Fig. 2. The maximum deflection is at the centre of the diaphragm, but it tends to decrease along the radius and is almost negligible at periphery of the sensor. Due to the similar deflection trend we have only considered the one side deflection from the centre of the diaphragm.

### 2.2. Simulation studies on a force sensor

The most appropriate geometry of the sensor was worked out by modeling software SolidWorks™. After several iterations on diaphragm thickness; the most optimized dimension was selected (Fig. 1). Silicon is used as the mechanical sensing element because of its higher yield strength which is more than three times that of stainless steel, additionally, Silicon in the form of circular wafers is extremely flat for coatings and additional thin film layers for either being integral structural parts, or performing precise electromechanical functions. Silicon shows virtually no mechanical hysteresis. It is, thus, an ideal candidate for use as sensors and actuators. The model was simulated with different loading condition from 10 N to 50 N. The obtained results by Ansys are found satisfactory. In the first stage Fig. 3 (a) with the help CAD modeling software, sensor model was created. Then in next stage