

Development of an FET Pressure Sensor Model and use to Predict Sensor Behaviour as a Function of Electrode Geometry

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ABSTRACT

This paper presents the development and solution of a model to describe the behaviour of a surface micromachined FET pressure sensor. Initially an expression is developed to describe the radial deflection of the sensing diaphragm as a function of pressure. This is solved in MATLAB using finite difference methods for a range of applied pressures. The MATLAB code uses the solution for the diaphragm deflection to calculate the capacitance from diaphragm to substrate. The calculated capacitances for each applied pressure are used in the first order MOSFET equations to provide a full solution for FET output current versus applied pressure. The predictions are compared to measured results and the model is then used to predict the sensor behaviour for a different electrode design.

The results suggest that electrode design can be used as a method of modifying the pressure to current transfer function while maintaining a single MEMS manufacturing process optimised for one diaphragm size and cavity height.

Keywords: Pressure, Sensor, FET, Micromachine, finite difference.

1 INTRODUCTION

A pressure sensitive field effect transistor (FET) was manufactured by creating a sealed evacuated cavity between a polysilicon sensing diaphragm (FET gate) and a silicon substrate which contained source and drain regions. The sealed cavity forms part of the FET gate dielectric. A cross section representation is shown in Fig 1.

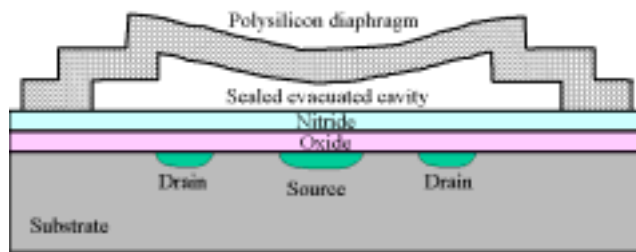


Figure 1. Schematic cross section of FET sensor

Pressure applied to the polysilicon diaphragm causes it to deflect thereby changing the effective dielectric thickness. This dielectric thickness variation changes the FET output current creating a pressure to current transducer, the

manufacturing process and sensor performance are described previously [1], [2]. The work presented here is for a circular 900 nm thick polysilicon diaphragm over a sealed cavity with a cavity gap height of 500 nm.

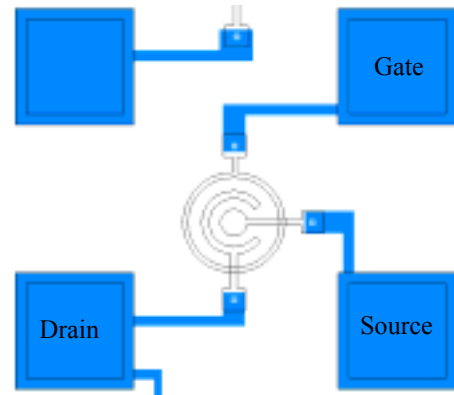


Figure 2. Layout of the circular FET pressure sensor

The polysilicon diaphragm radius is $37.5 \mu\text{m}$ and the source and drain are patterned by an implant mask to create the MOS structure. Fig. 2 shows the actual layout of the source and drain and Fig. 3 is a micrograph of a packaged and bonded sensor.

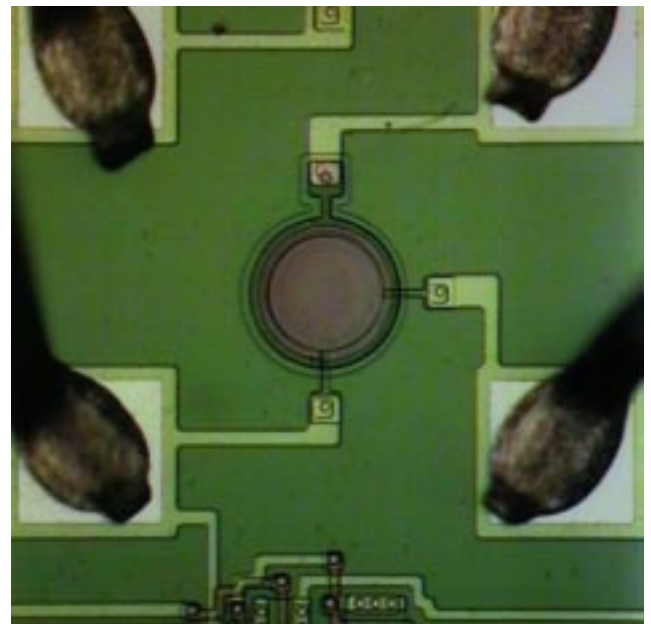


Figure 3. Packaged circular FET pressure sensor

2 MODEL FOR SENSOR BEHAVIOUR

Equations describing the deflection of the diaphragm as a function of applied pressure were developed. A MATLAB script was written to solve these equations and interferometry data from the manufactured sensors allowed extraction of model parameters. A MATLAB script to solve the first order MOS model for the geometries of the FET sensor used here (i.e. gate length, width, dielectric thickness etc.) was written. Measured output from FET sensor structures with no cavity was used to extract the parameters for this MOS model. The solution for the diaphragm deflection as a function of pressure was then used as input to the MOS model to predict FET sensor response as a function of pressure.

2.1 Model for diaphragm deflection

The basic analytical expression describing the deflection of circular diaphragms is known [3] and presented here:

$$\frac{d^3w}{dr^3} + \frac{1}{r} \frac{d^2w}{dr^2} - \frac{1}{r^2} \frac{dw}{dr} = \frac{1}{D} r q dr \quad (1)$$

where w is the deflection at a radial distance r from the center of the diaphragm, q is pressure differential across the diaphragm and D is the flexural rigidity. D is a constant for any diaphragm thickness and is given by:

$$D = \frac{Et^3}{12(1-\nu^2)} \quad (2)$$

where E is the Young's modulus, t the diaphragm thickness and ν is Poisson's ratio for the diaphragm material, polysilicon in this case. If the in-plane stress component N is included in (1) and the equation differentiated with respect to r we have:

$$\frac{d^4w}{dr^4} + \frac{2}{r} \frac{d^3w}{dr^3} + \frac{-N}{D} - \frac{1}{r^2} \frac{d^2w}{dr^2} + \frac{-1}{r} \frac{N}{D} + \frac{1}{r^3} \frac{dw}{dr} = \frac{q}{D} \quad (3)$$

The gate voltage on the polysilicon diaphragm generates an electrostatic pressure P_{ES} between the diaphragm and the substrate given by:

$$P_{ES} = \frac{\epsilon V^2}{2z^2} \quad (4)$$

where V is the voltage between the diaphragm and the substrate, ϵ is the effective permittivity of the combined dielectrics and z is the distance between the diaphragm and the substrate. By rewriting (3) in terms of z rather than w and including the electrostatic term we have:

$$\frac{d^4z}{dr^4} + \frac{2}{r} \frac{d^3z}{dr^3} + \frac{-N}{D} - \frac{1}{r^2} \frac{d^2z}{dr^2} + \frac{-1}{r} \frac{N}{D} + \frac{1}{r^3} \frac{dz}{dr} = -\frac{q}{D} + \frac{\epsilon V^2}{2Dz^2} \quad (5)$$

Setting zero deflection at the plate edge, the slope of the deflection to zero at the plate edge and center and the shearing forces to zero at the center of the plate as four boundary conditions the equation can be solved. Similar to previous work [4], [5] a MATLAB script using finite difference methods was written to solve for the gap height as a function of radius for different applied pressures and voltages. A white light interferometer was used to measure the deflection of a manufactured sensor membrane at atmospheric pressure. The measured data is plotted in Fig. 4, note that the horizontal and vertical axes are different scales.

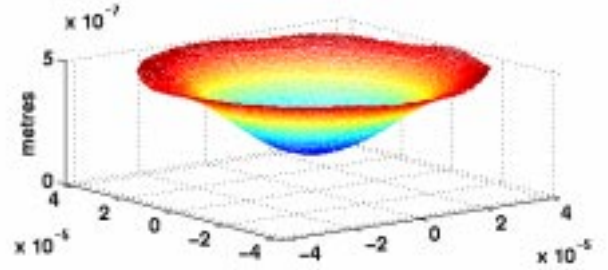


Figure 4. Measured membrane deflection

For the sensors manufactured here, the in-plane stress value N was not known. A value was assigned to fit the maximum predicted deflection in the center of the diaphragm at a differential pressure of one atmosphere with the observed deflection from interferometer measurements above. Having fit the center point the full diaphragm deflection predicted by the model at a pressure of one atmosphere is plotted in Fig. 5. The predicted shape agrees well with the measured data shown in Fig. 4.

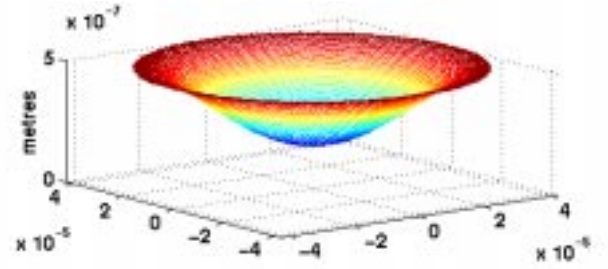


Figure 5. Simulated deflection surface of membrane

2.2 Model for the MOSFET structure

The first order MOS equations expressing threshold voltage and drain current as functions of device geometry and applied bias are well known [6]. The NMOS threshold voltage V_t is given by:

$$V_t = \phi_{gb} - 2\psi_f - \frac{Q_{bo}}{C_{tot}} - \frac{Q_{ss}}{C_{tot}} \quad (6)$$

where ϕ_{gb} is the work function difference between the gate material and the bulk silicon in the channel, ψ_f is the Fermi

level potential difference between the inversion region and the bulk, Q_{ss} is the density of fixed charge at the Si-SiO₂ interface and Q_{bo} is the charge density in the depletion region. C_{tot} is the total capacitance per unit area over the active channel and can be expressed as:

$$C_{tot} = (C_{nit}^{-1} + C_{ox}^{-1} + C_{gap}^{-1})^{-1} \quad (7)$$

where C_{nit} , C_{ox} and C_{gap} are the individual capacitances per unit area of the nitride, oxide and vacuum cavity respectively. The MOS drain current in saturation I_{DSAT} can be expressed as:

$$I_{DSAT} = \frac{\mu C_{tot} W (V_g - V_t)^2}{2L} \quad (8)$$

where μ is the carrier mobility in the MOS channel, W the channel width, L the channel length and V_g the applied gate voltage. The threshold voltage and output characteristics of a sensor structure without a cavity were measured and the above models fitted to the data to extract a value for carrier mobility μ . While they are simple models they predict the performance of FET reasonably well as shown in Fig. 6, note that the subthreshold region is not modelled, I_D is set to zero for $V_g < V_t$.

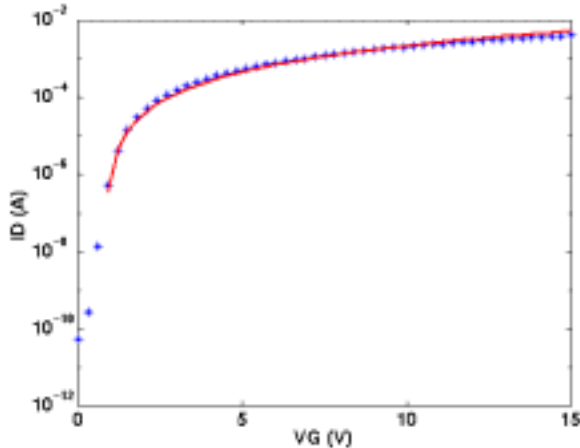


Figure 6. Measured (points) and fitted (line) characteristics for a FET sensor structure with no cavity

A MATLAB script was written to implement this MOS model using the extracted parameters and the appropriate MOS width, length and layer thicknesses.

2.3 Concentric FET Sensor Simulation

Having extracted suitable model parameters for the diaphragm and the MOS structure, a simulation of the complete FET sensor is possible. Initially the diaphragm deflection is calculated for each pressure using (5), this gives a solution for cavity height z as a function of radial position r . The result is used to calculate the capacitance per unit area of the vacuum cavity C_{gap} as a function of radius using the relationship:

$$C_{gap}(r) = \frac{\epsilon_o}{z(r)} \quad (9)$$

where ϵ_o is the permittivity of free space. This is used in (7) to calculate C_{tot} and allows the threshold voltage as a function of radius $V_t(r)$ to be calculated. For the sensor design in Figs. 1, 2 the vacuum cavity height over the channel will be a maximum at the edge of the channel adjacent to the concentric drain. From the equations it is clear that the MOS threshold voltage is therefore also highest at this point and effectively becomes the threshold of the FET sensor. Fig. 7 shows the simulated deflection for applied pressures of 101 kPa and 168 kPa (15 psi and 35 psi) and Fig. 8 compares the simulated FET output current result with the measured characteristic from a manufactured sensor.

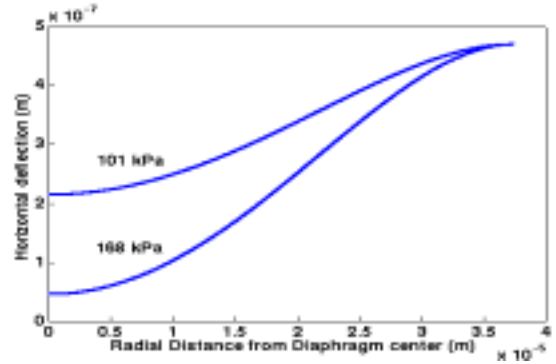


Figure 7. Simulated deflection as a function of radial distance for applied pressures of 101 kPa and 168 kPa

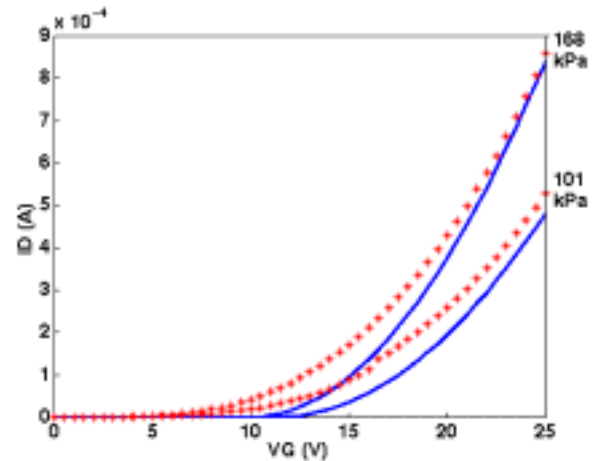


Figure 8. Measured (points) and simulated (solid lines) FET sensor drain current for pressures of 101 kPa and 168 kPa

The increase in saturated drain current for applied pressure is predicted well by the simulation but the subthreshold and linear regions are not well matched. This is expected because the model assumes $I_d = 0$ for $V_g < V_t$ and assumes only saturated behaviour for $V_g > V_t$ (i.e. no subthreshold or linear region models included).

3 EFFECT OF ELECTRODE GEOMETRY

Using the models developed above the effect of different source and drain electrode designs was investigated assuming an identical polysilicon diaphragm, cavity design and electrical bias. The drain current as a function of pressure was simulated for a pressure range from 100 kPa to 440 kPa for the concentric design already described. The result of the simulation at a gate bias of 15 volts is shown as the dashed curve of Fig. 10.

The electrode design underneath the polysilicon diaphragm is defined by an implant mask. This allows the location of the channel with respect to the diaphragm to be varied without changing the manufacturing process for the diaphragm itself. A different sensor layout is shown in Fig. 9, which uses the same diaphragm as previously examined but has a different electrode configuration. In this case the electrode source and drain edges are parallel forming a rectangular channel more typical of standard MOSFET design.

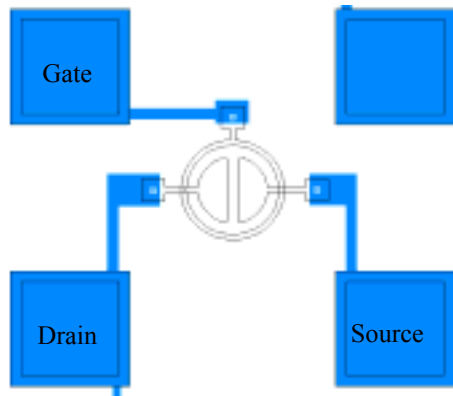


Figure 9. Layout of the parallel electrode design

This parallel electrode structure was simulated using the methods described above. The MOS parameters were changed to reflect the different electrode design but the diaphragm deflection simulation was identical to the concentric case. The predicted response over the 100 kPa to 440 kPa pressure range is plotted as the solid line in Fig. 10. The distinct difference in output between the concentric and parallel electrode designs demonstrates the potential of using electrode design to define the sensor transfer characteristic.

4 CONCLUSIONS

A model describing the behaviour of an FET pressure sensor was developed and implemented as a MATLAB script. The model consists of two parts, the diaphragm deflection and the MOS threshold voltage and drain current calculation. Interferometry was used to measure the diaphragm deflection of manufactured sensors and the diaphragm deflection model was fitted to this data using the in plane stress as the fit parameter. The parameters for the MOS model were extracted from measurements on sensors

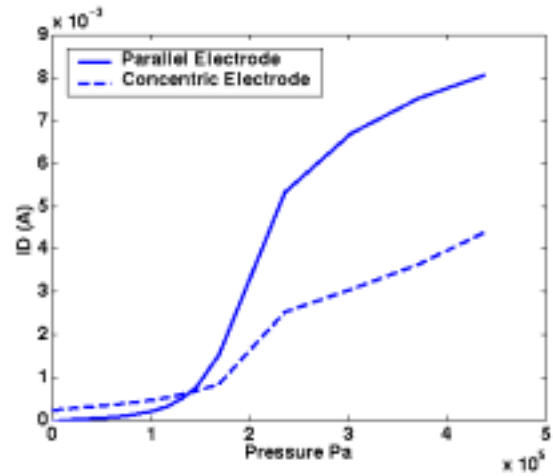


Figure 10. Simulated pressure response for concentric and parallel electrode designs for identical diaphragms and the same electrical bias

without an evacuated cavity. The combined model was capable of predicting the behaviour an FET sensor and was used to demonstrate the effect of electrode design on the sensor transfer characteristics.

It should be noted that a simple assumption was used to account for the membrane touchdown effect [7]. For the case where $w(r)$ is greater than the cavity height, then $z(r)$ in (5) is set equal to zero. This will overestimate the deflection as a function of pressure when the sensor is operating in touchdown mode. This does not significantly affect the comparison of the electrode designs because the same assumption was made in both cases. See references [8], [9] and [10] for approaches to modeling this effect.

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