MEMS Multimorph Capacitive Temperature Sensors in COMSOL Multiphysics®

Level 3 Semiconductor, Physics and Devices

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Abstract

This report describes how the C–T characteristics of MEMS multimorph capacitive temperature sensors vary with geometry, material choice and prestress conditions. The unmodified sensor had a sensitivity 1.3403 fF K^{-1} at room temperature, with an operating range up to 46.2 °C. The range was increased to 310 °C and linearised up to 80 °C, at the expense of reduced sensitivity. The sensors were modelled using FEM and physics simulation software—COMSOL Multiphysics®—so the key design parameters, physics modelling choices and mesh analysis are also included.

Nomenclature

DOF	Degrees of freedom	
CMOS	Complementary metal oxide semiconductor	
FEM	Finite element modelling	
MEMS	Micro-electromechanical systems	
RTD	Resistance temperature detector	
α	Thermal expansion coefficient	K^{-1}
ϵ	Permittivity	F m^{-1}
h	Support height	µm
l	Cantilever length	µm
t	Time	s
w	Width	µm
C	Capacitance	fF
S	Sensitivity	fF K^{-1}
S_e	Electrical sensitivity	fF µm^{-1}
S_m	Mechanical sensitivity	µm K^{-1}
T	Temperature	°C
T_0	Temperature at zero displacement	°C
T_{max}	Maximum operating temperature	°C

1 Introduction

In an increasingly data centric world, the number of sensors found in consumer electronics, industrial health monitoring, the automotive industry and other sectors is expected to exceed one trillion in the next 20 years [1].

Temperature sensors make up an sizeable portion of this industry: the demand for smaller, more efficient and more accurate sensors is rising. There are a many existing temperature sensors available across the different sectors.

Multimorph capacitive sensors are an alternative sensor investigated by Scott in his 2012 paper [2].

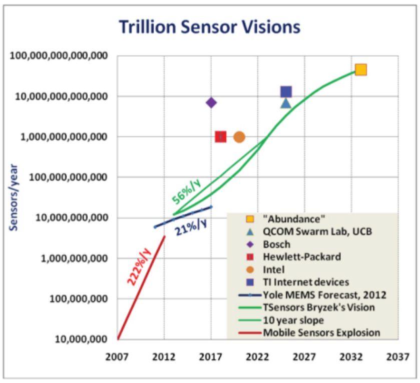

Figure 1: J. Bryzek's trillion sensor vision [1].

Unlike resistive temperature sensors, capacitive sensors do not consume power at constant temperature. Low power consumption combined with small MEMS package size means there is opportunity for these sensors to dominate in portable devices moving forward.

2 Background

A multimorph is a cantilever composed of layers with increasing expansion coefficients. When current travels in opposite directions through two piezoelectric multimorphs layers, the layers are subjected to different stresses and the cantilever deflects. This is an actuator.

Temperature responsive multimorphs are composed of layers with increasing thermal expansion coefficients. When the multimorph cantilever is heated, it's temperature increases, the layers expand by differing amounts and the cantilever deflects. This deflection can be sensed through changing capacitance. The sensitivity of these devices is thus composed of two parts: the mechanical and electrical sensitivity, such that

$$S = S_m S_e \tag{1}$$

2.1 Construction

An effective temperature sensitive multimorph has layers with increasing *thermal* expansion coefficients. Table 1 show the thermal expansion coefficients for a range of CMOS compatible materials—the majority of those used in MEMS manufacture.

Table 1: Thermal expansion coefficients of some CMOS compatible materials [3].

CMOS compatible material		α [K^{-1}]
Metals		
Aluminium	Al	23.1×10^{-6}
Gold	Au	14.2×10^{-6}
Titanium	Ti	8.6×10^{-6}
Semiconductors		
Silicon	Si	2.6×10^{-6}
Insulators		
Silicon Nitrate	Si_3N_4	2.3×10^{-6}
Silicon Oxide	SiO_2	0.5×10^{-6}

A practical implementation of a multimorph capcitive temperature sensor should have at least two layers: a conductive metal terminal layer over one or more insulating oxides. The cantilever must be mounted on a ground conductive substrate so the potential may be measured at both sides of the varying air gap.

3 Modelling

The model used and varied in the following experiments was based on the Au–Si_3N_4–SiO_2 sensor proposed by Scott [2], with a conductive silicon base.

3.1 Geometry

In FEM computation there is a trade-off between computation time and accuracy, where computation time and normally accuracy increase with the number of degrees of freedom. However, techniques can be applied to reduce degrees of freedom without affecting accuracy. Figure 2 illustrates the sensor geometry modelled and the lines where the two symmetry planes intersect external faces.

Rather than mesh the entire geometry, only one of the four symmetric quadrants was modelled, with symmetric boundary conditions applied to those

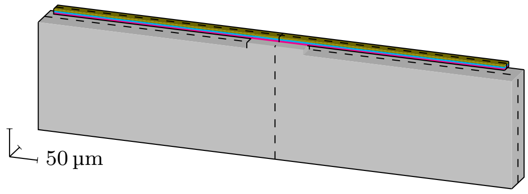

Figure 2: Symmetry lines of the multimorph capacitive temperature sensor—marked with dashed lines.

intersecting the symmetry planes. The total capacitance of the four parallel quadrants was then found by multiplying all evaluated readings by four

$$C_{||} = \sum_{i}^{4} C_i = 4C \tag{2}$$

Figure 3 details the dimensions and geometric parameters of the COMSOL model.

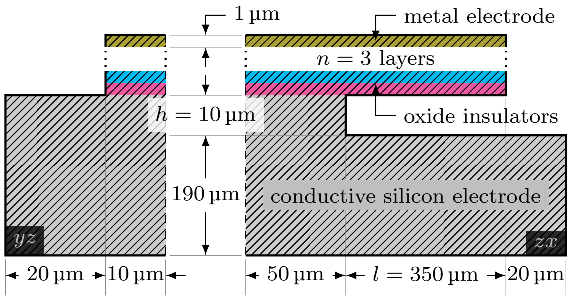

Figure 3: Cross-section of the multimorph temperature sensor—not to scale.

The sensor model had a margin of 20 µm around the cantilever so the electric field lines at the edge of the multimorph could be accounted for. This did lead to inverted mesh errors at large displacements so was set to zero for some studies.

3.2 Mesh

The blocky nature of the model called for a mapped swept mesh with the greatest mesh density in the cantilever and air gap. The custom mesh for the sensor quadrant is shown in Figure 4, with the two symmetric boundaries facing the camera.

Geometric distributions were defined along the length of the cantilever and down into the substrate. In the cantilever, the displacement was greatest at the ends, so a finer mesh was chosen for this region.

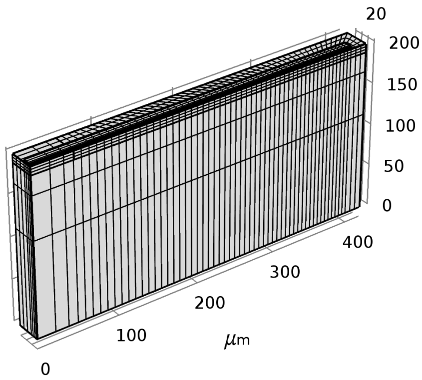

Figure 4: Mapped-swept mesh for sensor model.

On the other hand, the conductive base experienced little deflection and had a high relative permittivity so degrees of freedom were saved in this region. COMSOL reported an average mesh quality of 0.88.

The mesh size was driven by the vertical distribution of elements in the 10 µm air gap. A short mesh study was conducted to determine the relative error and find a suitable tradeoff between accuracy and computation time. The resulting model comprised 102081 degrees of freedom.

3.3 Studies

The studies carried out were as follows: first, a study into C–T characteristic of a multimorph capacitive temperature sensor; then, how the C–T characteristic varied with parameters h and l; the effect of metal choice and thermal expansion coefficient was investigated; the cantilever was pre-stressed to increase the temperature range; and finally, a time-dependent study was used to model the step response of the sensor.

The COMSOL *electromechanics* module was used for the majority of the studies. The air gap was defined an electrical material with a mesh which was allowed to move in the vertical direction. All other domains were modelled as linear elastic materials so their displacement could be modelled. Thermal expansion was added to the cantilever but not the substrate to reduce complexity.

For the pre-stress study, a compressive initial vertical stress was added to the cantilever domains. The margin around the edges of the cantilever was removed to mitigate the inverted mesh errors caused by the resulting large displacements. The modified model and mesh are shown in Figure 5.

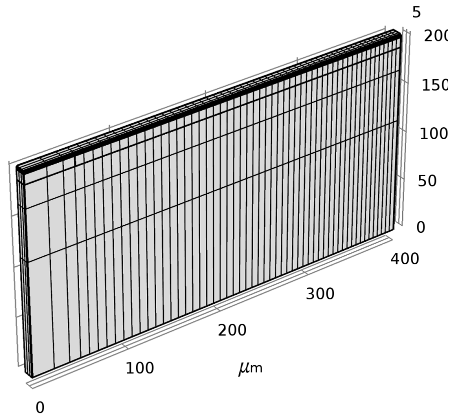

Figure 5: Mapped-swept mesh without air gap margin for pre-stress study.

To model the step response, a different set of physics was required. The air gap was removed and all domains were defined as solids in the *heat transfer in solids* module. An air box was added as a fluid so a step in temperature could be applied. *Thermal expansion* and *thermal coupling* multiphysics was used to couple the heat transfer module to the *structures* module, which simulated the deflection of the linear elastic bodies in the model in response. To get the solution to converge, the step function was smoothed to a 0.1 s transition from 20 °C to 21 °C.

4 Results and Discussion

4.1 Step response

The step response of the reference temperature sensor was shown in Figure 6. The graph revealed the thermal time constant for the sensor was 43.5 ms. This was the time for the sensor to complete $1/e = 63\%$ of the transition from it's initial to final value and was a measure of the speed of the sensor.

4.2 Stationary study

The F-value of a regression model gives the variance of the error in the full model vs a reduced model

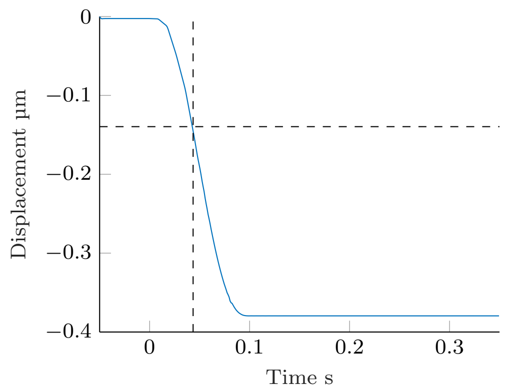

Figure 6: Step response for the Au–Si_3N_4–SiO_2 sensor.

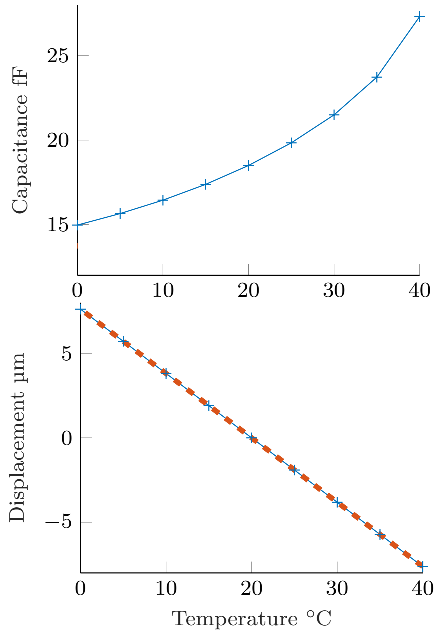

Figure 7: Capacitance and vertical deflection plotted against temperature for the Au–Si_3N_4–SiO_2 sensor.

divided by the variance in the original model.For a given significance level, an F-test can be used to determine whether the regression model is a significantly better predictor than the reduced model.

To assess the linearity of different characteristics, a linear and quadratic regression model were fitted to data between each pair of points. An F-test yielded a p-value for each model. This was used to find the largest region which was not significantly better explained by the quadratic model than the linear model at the 5% level of significance.

The gradient of the regression model in the linear region was used to determine the sensitivity for those sensors which exhibited a linear response. Outside of the linear region the sensitivity gradient was only valid for small signal approximations.

Figure 7 contained the characteristic for the base Au–Si_3N_4–SiO_2 temperature sensor with a support height $h = 10\,\mu\text{m}$ and a cantilever length $l = 350\,\mu\text{m}$.

The capacitance of the original sensor was not linear at the 5% siginificance level, but at room temperature the sensitivity was $1.3403\,\text{fF}\,\text{K}^{-1}$

On the other hand, the displacement characteristic was significantly linear: the line of best fit suggested the mechanical sensitivity of the multimorph was $-0.3810\,\mu\text{m}\,\text{K}^{-1}$. Extrapolating the line of best fit suggests the sensor was only capable of reaching 46.2 °C before saturating, when the vertical displacement closed the air gap, potentially damaging a physical sensor.

In general, the maximum temperature T_{max} was described as follows:

$$T_{max} = T_0 + \frac{h}{S_m} \tag{3}$$

4.3 Dimension study

The sensing range was extended by varying two dimensions.

For a range of support heights, Figure 8 showed the mechanical sensitivity was unchanged. Increasing the support height allowed the cantilever to deflect more before saturating, increasing temperature range. However, positioning the terminal further from ground allowed electric flux to leak from the system and lose electrical sensitivity.

In another study, the cantilever length was reduced. Figure 9 revealed increasing l, decreased the magnitude of the gradient S_m. (3), explains why the sensing range was extended.

However, the effects of l and h on electrical sensitivity were not ignored. For a parallel plate capacitor

$$C = \frac{\epsilon l w}{h} \tag{4}$$

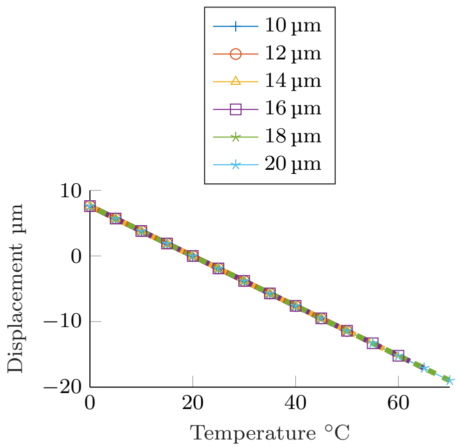

Figure 8: Effect of support height h on end deflection for the Au–Si_3N_4–SiO_2 sensor. Gradient S_m

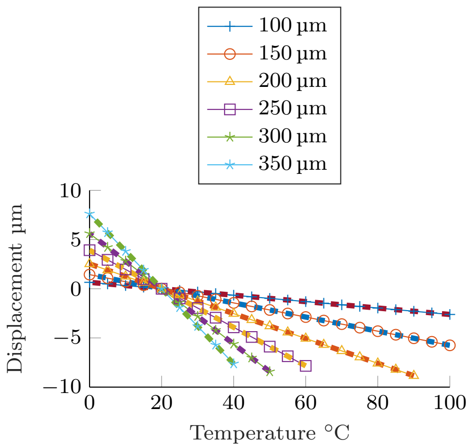

Figure 9: Effect of cantilever length l on end deflection for the Au–Si_3N_4–SiO_2 sensor. Gradient S_m

This relationship was be distorted at large deflections, but the result implications were the same: capacitance bias and hence electrical sensitivity increased with cantilever length; capacitance bias and electrical sensitivity decreased with support height.

4.4 Material study

An alternative approach to increase mechanical sensitivity without affecting electrical sensitivity was to choose a materials with different coefficients of thermal expansion. The displacement characteristics of Al and Ti were compared in Figure 10. The high expansion coefficient of Al determined the high sensitivity of the Al sensor; conversely the Ti sensor was less sensitive than the reference sensor which used Au.

However, unlike varying geometry, the electrical characteristic of each material chosen was the same. All the data points in Figure 11 belonged to the same characteristic. Subsequently there exists two independent parameters which can be varied to produce a desired small signal sensitivity.

$$S(\alpha, T) = S_m(\alpha) S_e(T) \tag{5}$$

4.5 Pre-stress study

None of the previous studies identified a method to improve the linearity of the C–T characteristic.

An auxillary sweep located the pre-stress which caused a 100 µm displacement. This occurred at −0.87 GPa—compressive load. Figure 12 showed the displacement field.

Figure 13 showed the characteristic at this pre-stress, which is linear at the 5% significance level up to 80 °C. The maximum temperature was extended to

5 Conclusion

The multimorph capacitive temperature sensor detailed in this report can be characterised using the following: the thermal time constant was 43.5 ms, the C–T characteristic is non-linear at the 5% level, but does have a mechanically linear response. The mechanical sensitivity is $-0.3810\,\mu\text{m}\,\text{K}^{-1}$ and the small-signal sensitivity is $1.3403\,\text{fF}\,\text{K}^{-1}$ at room temperature. Finally the maximum temperature is 46.2 °C.

There is an inherent trade-off between temperature range and mechanical sensitivity. Support height, cantilever length and material properties can be varied to select an appropriate small-signal sensitivity. However, electrical sensitivity can be always be increased by adding more cantilevers.

Linearity and temperature range are best improved by pre-stressing the multimorph cantilever. The 100 µm deflected sensor achieved a linear response up to 80 °C and was operable at 310 °C. How-

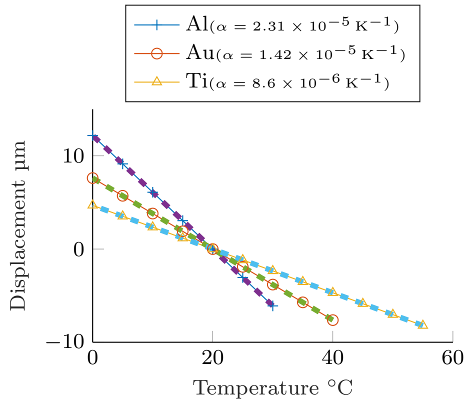

Figure 10: Effect of α on mechanical sensitivity for a metal–Si_3N_4–SiO_2 sensor. Gradient S_m

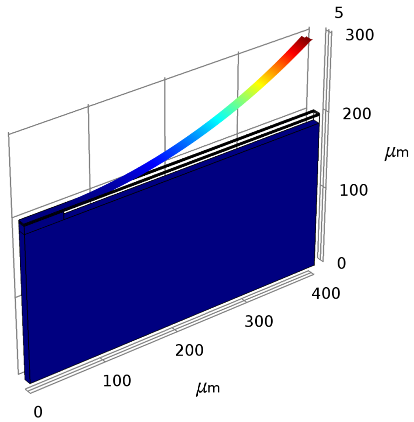

Figure 12: Au–Si_3N_4–SiO_2 sensor displaced to 100 µm by a −0.87 GPa pre-stress.

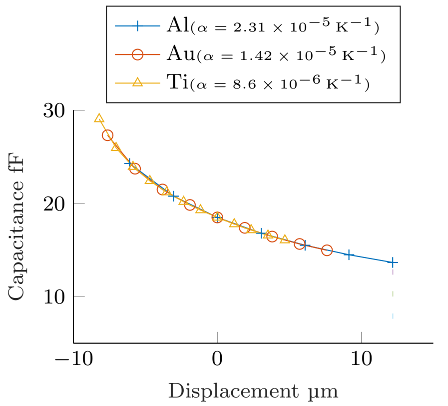

Figure 11: Effect of α on electrical sensitivity for a metal–Si_3N_4–SiO_2 sensor. Gradient S_e

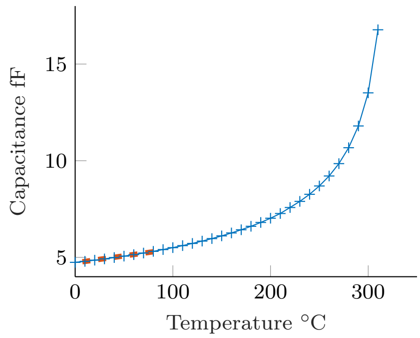

Figure 13: Capacitance against temperature for the Au–Si_3N_4– SiO_2 sensor pre-stressed to 100 µm.

ever, this sensor had a much lower sensitivity at 0.0657 fF K^{-1}.

References

[1] J. Bryzek, “Emergence of trillion sensors movement”, TSensors summit, 2014, [Online]. Available: `http://sites.ieee.org/scv-mems/files/2013/09/Emergence-of-Trillion-Sensors-Movement.pdf`.

[2] S Scott, M Scuderi, and D Peroulis, “A 600 °C wireless multimorph-based capacitive MEMS temperature sensor for component health monitoring”, in *Micro Electro Mechanical Systems (MEMS), 2012 IEEE 25th International Conference on*, IEEE, 2012, pp. 496–499.

[3] COMSOL Multiphysics, “Material library”, version 5.3, 2017.