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 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

CMOS	Complementary metal oxide semiconductor	
FEM	Finite element modelling	
MEMS	Microelectromechanical systems	
RTD	Resistance temperature detector	
α	Thermal expansion coefficient	[K^{-1}]
C	Capacitance	[F]

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 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 few existing temperature sensors available across different sectors.

- Thermistors: which exhibit a non-linear inverted resistive response across a wide range of temperatures.
- Thermocouples: which generate a non-linear potential difference response to across two dissimilar conductors due to a thermoelectric effect.
- Resistance thermometers (RTDs): which respond with a very linear resistance for some materials: Pt, Cu and Ni.

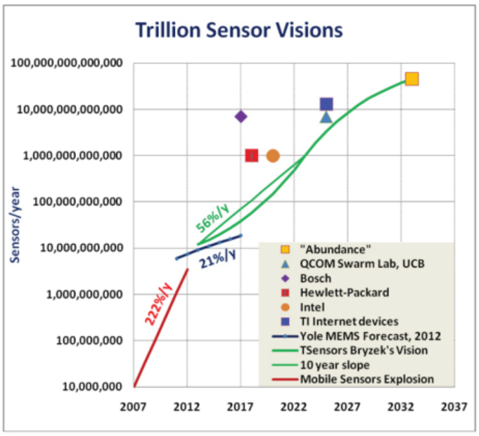

Figure 1: J. Bryzek's trillion sensor vision [1].

- Silicon bandgap sensors: which respond in conductivity at scales suitable for ICs.

Multimorph capacitive sensors are an alternative investigated by Scott in his 2012 paper [2]. 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 of with increasing expansion coefficients. When current travels in opposite directions through two piezo-electric 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.

Figure 2: Cross-section of a temperature sensitive multimorph.

2.1 Construction

An effective temperature sensitive multimorph has layers with increasing thermal expansion coefficients. Scott uses a three layer multimorph with thermally grown SiO_2, vapour deposited Si_3N_4, sputtered Au. 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}

By layering Au ontop of Si_3N_4 ontop of SiO_2 (Au–Si_3N_4–SiO_2), Scott was able to design a multimorph cantilever with increasing temperature expansion coefficients and two boundaries where the internal stresses of each layer interacted. The cantilever to deflected increasingly downwards with temperature.

The Au multimorph layer was an easily accessible electrode. However, two electrodes are required to read the capacitance developed through a flexible dielectric—air and in this case. A conductive Si substrate acted as a fixed electrode on the other side of the air gap, providing mechanical stability during operation and fabrication. The oxide layers insulated the moving Au electrode from the fixed Si substrate.

A practical implementation of a multimorph capcitive temperature sensor at least two layers: a conductive metal contact ontop of one or more insulating oxides. The cantilever must be mounted ontop of a 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].

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 3 illustrates the sensor geometry modelled and the lines where the two symmetry planes intersect external faces.

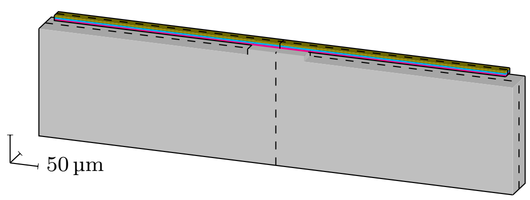

Figure 3: Symmetry lines of the multimorph capacitive temperature sensor—marked with dashed lines.

Rather than mesh the entire geometry, only one of the four symmetric quadrants was modelled, with symmetric boundary conditions applied to those intersecting the symmetry planes. The total capacitance of the four parallel quadrants was then found by multiplying all evaluated readings by four as in (1).

$$C_{||} = \sum_{i}^{4} C_i = 4C \qquad (1)$$

Figure 4 details the dimensions and geometric parameters of the COMSOL model.

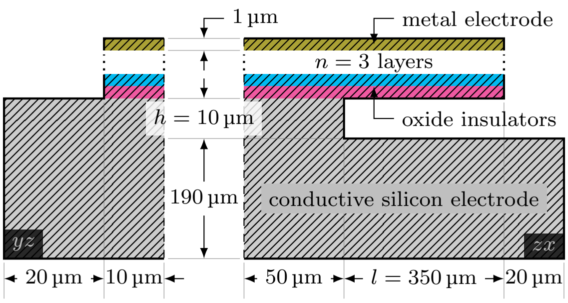

Figure 4: Cross-section of the multimorph temperature sensor—not to scale.

The model was designed with a thick wafer to provide significant stability. In reality silicon wafers range from 200 mm to 300 mm. Here the substrate was 200 µm thick prior to removing material for the air gap. An air gap was left in the model so the electric potential could be meshed and simulated.

The sensor was modelled with a margin of 20 µm to determine the

3.2 Mesh

The cuboid nature of the model called for a mapped swept mesh with the greatest mesh density in cantilever and air gap.

3.3 Material

3.4 Physics

4 Results

4.1 Material study

5 Analysis

6 Conclusion

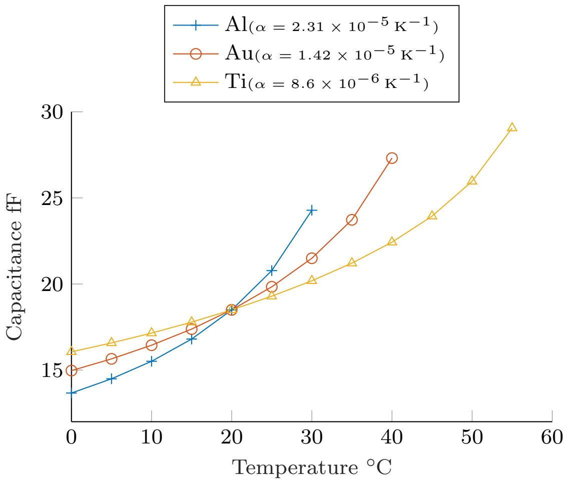

Figure 5:

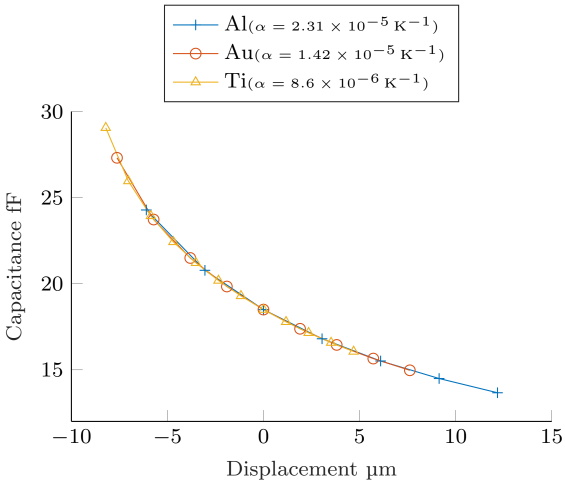

Figure 6: