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A NEW THICK-FILM TILT SENSOR BASED ON THE HEAT TRANSFER PRINCIPLE

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Abstract – Among the various sensor technologies, thick-film technology (TFT) on ceramic substrates offers several appreciable capabilities, e.g., flexibility in choice of material and design, high shock resistance, ease of integration into electronic circuits and packaging. In this application a thick-film tilt sensor has been developed based on heat transfer by natural convection. The device measures internal changes in heat transfer caused by the inclination using the force of gravity as an input. The device is functionally equivalent to traditional proof-mass accelerometer. The proof mass in the new thick-film sensor is a gas. The gaseous proof-mass provides great advantages over the use of the traditional solid proof mass. Preliminary tests on the first prototypes show an accuracy of about 2% full scale output, repeatability of about 0.2° and thermal stability less than 0.2%/° C over a ± 50° range.

Keywords: thick-film technology, tilt sensors, heat transfer priciple.

1. INTRODUCTION

Thick-film technology (TFT) was introduced about thirty years ago as a means of producing *hybrid* circuits. Such circuits comprise semiconductor devices, monolithic ICs and other discrete devices in addition to the thick-films themselves. A key factor distinguishing a thick-film circuit is the method of film deposition, namely screen-printing, which is possibly one of the oldest forms of graphic art reproduction. Thick-film hybrid circuits are generally regarded as being compact, robust and relatively inexpensive and have found application in areas such as televisions, calculators, telephones, automotive electronics and missile guidance systems to name but a few. Thick-film sensors are a relatively new application of the technology, with a majority of the published working appearing in the past decade [1],[2],[3],[4]. It should be noted however, that the technology is also widely used for the fabrication of chemical and gas sensors and many commercial devices exist. The integrability of the technology also allows combination with other enabling technologies, such as silicon, to provide powerful and economically viable solid-state sensors. This paper describes a thick-film tilt sensor utilizing all of the above aspects.

2. THE OPERATING PRINCIPLE AND THE FRABRICATION METHOD IN THICK-FILM TECHNOLOGY

The principle of operation of the TFT devices is based on heat transfer by natural convection.

The devices measure internal changes in heat transfer caused by the inclination using the force of gravity as an input. The devices are functionally equivalent to traditional proof-mass accelerometers.

The proof mass in the new thick-film sensor is a gas. The gaseous proof-mass provides great advantages over the use of the traditional solid proof mass. The device does not display striction and particle contamination problems associated with competitive devices and provides a high shock survival leading to significantly lower failure rates and lower loss due to handling during assembly. The arrangement necessary for measuring the inclination effects on heat transfer is described next.

A double structure heat source, centred in the ceramic substrate is suspended across a cavity. Equally spaced temperature sensors are located equidistantly on all two sides of the heat source. Under zero inclination, a temperature gradient is symmetrical about the heat source, so that the temperature is the same at all two temperature sensors, causing them to output the same voltage (reference Figure 1 (A)). Inclination in the sensing direction will disturb the temperature profile, due to free convection heat transfer, causing it to be asymmetrical (reference Figure 1 (B)). The temperature, and hence voltage output of the two temperature sensors will then be different. The differential voltage at the temperature sensor outputs is directly proportional to the inclination.

The TFT tilt sensor is most sensitive to changes in position, or tilt, when the sensitive axis is perpendicular to the force of gravity, or parallel to the Earth's surface. Similarly, when the sensitive axis is parallel to the force of gravity (perpendicular to the Earth's surface), it is least sensitive to changes in tilt.

The fabrication method involves the standard thick-film procedures on 96% alumina substrate. The planar resistor adopted for the heating processes is based on a Pt/Au ink. In order to achieve adequate electrical characteristics, a firing process has been adopted at a peak temperature of about

950°C. The temperature sensor is based on an nickel conductor (with a nominal resistance of about 200Ω).

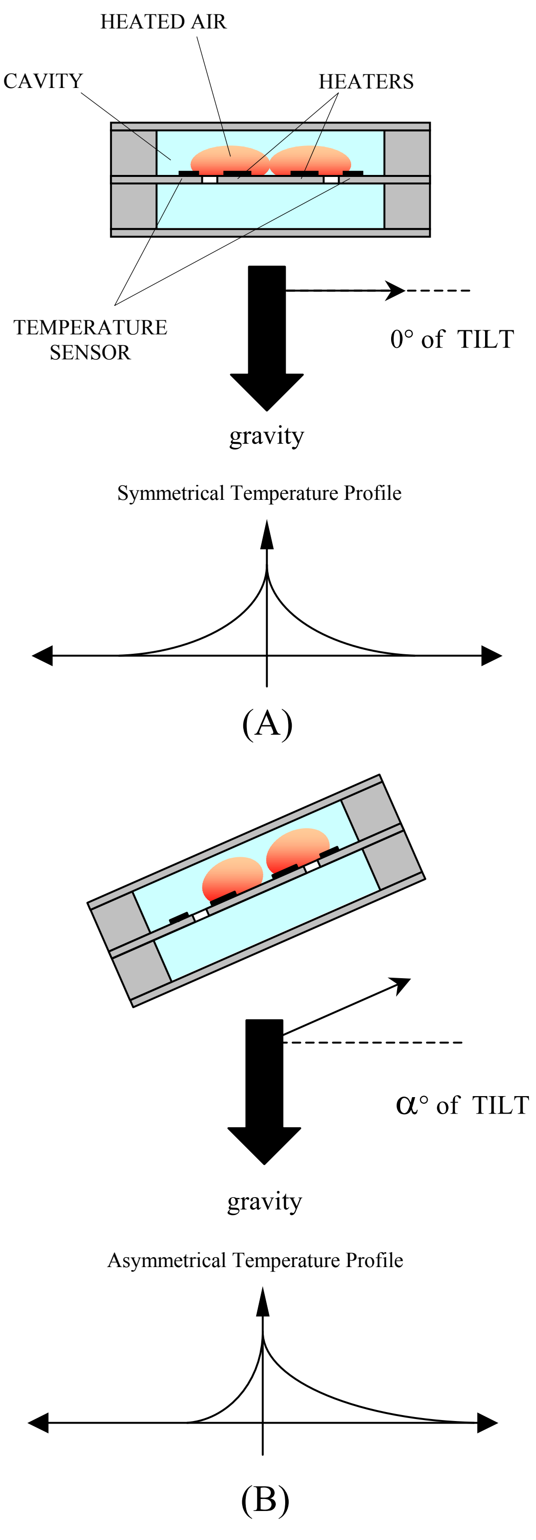

Figure 1 - Vertical cross-section showing the sensing sequence (a) 0° TILT angle (b) α° TILT angle

The nickel film (20 μm thick) has a high positive temperature coefficient of resistance (≅ 5000 ppm/°C) and it is suitable candidate for commercial temperature-sensing applications. The nickel conductor is termined onto a conductive film based on Pt/Au ink. The aim is to give a solderable connection.In figure 2 a schematic drawing of the sensor prototype is presented. The central heater is suspended on a cavity by means of a bridge structure. The temperature sensors are located equidistantly on two sides of the heat source.

Figure 3 shows a photograph of the TFT prototype of the inclinometer sensor. In Figure 3 (A) the central heater and the RTD deterctors are clearly distinguishable. In Figure 3 (B) the sensor is presented with the complite housing.

3. INCLINATION MEASUREMENT FROM A HORIZONTAL POSITION

Figure 4 shows a graphic example of an accelerometer inclination from a horizontal initial position. To measure inclination a calculation is necessary because the inclinometer output simply represents the acceleration of gravity acting on the sensing axis. The relationship between accelerometer outputs and gravity is given by (reference Figure 4):

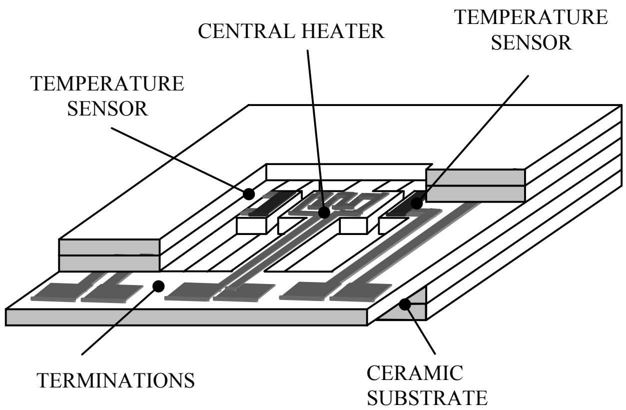

Figure 2 - Schematic drawing of the tilt sensor in thick-film technology

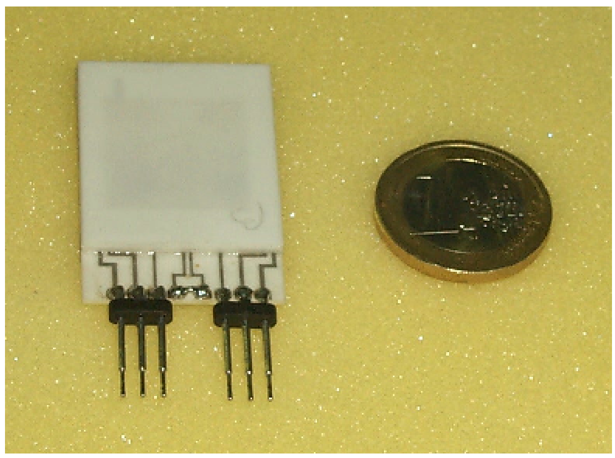

Figure 3 (A) – Photograph of the tilt sensor prototype in thick-film technology

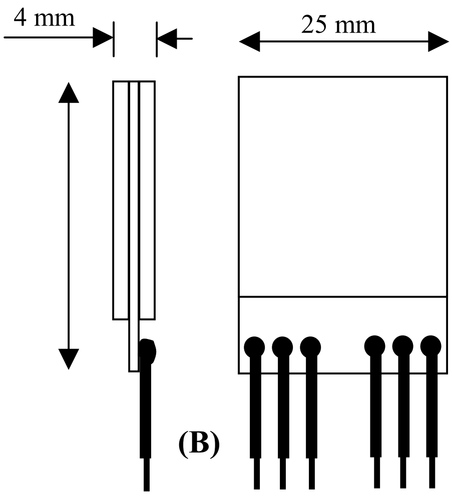

Figure 3 (B) – Geometrical dimensionsof the tilt sensor prototype in thick-film technology

Sout = g · sin (α) [1]

Where Sout represents the inclinometer output, *g* is the acceleration due to gravity, and *α* is the inclination angle. To calculate the inclination angle it is necessary to know the inverse of the sine function:

α = sin-1 (Sout/g) [2]

Figure 5 shows the graph of this sine function relation. Note that for inclination angles greater than 60°arc, very little change appears at the inclinometer output. This sine function characteristic is why an accurate measurement of inclination is not possible for angles approaching 90°arc from a horizontal position.

Another interesting observation from Figure 5 is that for small inclination angles the sine function is very close to a linear function:

α = k ·Ax [3]

In some applications a linear function approximation may meet the accuracy requirements. Table 1 shows the errors in accuracy resulting from using the linear approximation for different inclination ranges. To calculate *k* for each inclination range a linear curve fit was performed.

With the linear function approximation the inclinometer sensitivity is converted into an inclination sensitivity by dividing by *k*. For example, if the inclinometer sensitivity is 1000mV/g and the inclination range is ± 50°, the inclination sensitivity would be:

(1000mV/g) / (61.35°arc/g) = 16.3 mV/°arc

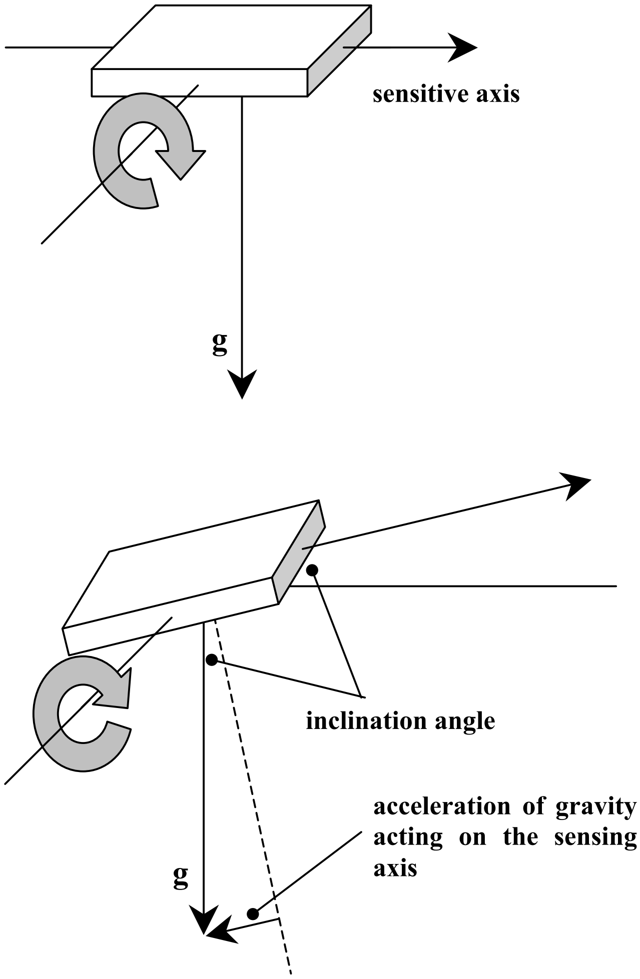

Figure 4 - Graphic example of an inclination from a horizontal initial position

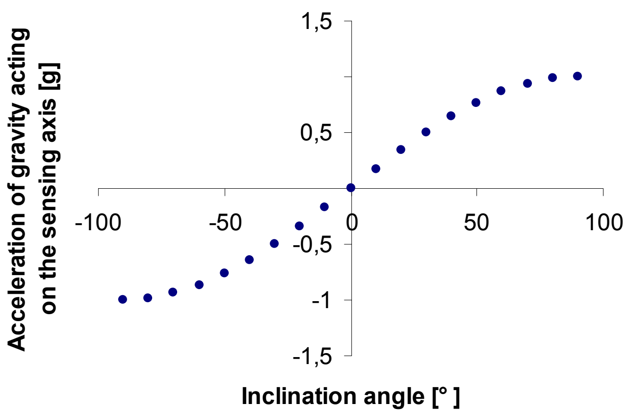

Figure 5 – Gravity component vs. Inclination angle

Table 1: Inclination angle errors

Inclination range [°]	*K [°/g]*	*Maximum Error [°]*
±10	*57.50*	*±.02*
±20	*58.16*	*±.16*
±30	*59.04*	*±.48*
±40	*60.47*	*±1.13*
±50	*61.35*	*±2.24*

4. PRELIMINARY EXPERIMENTAL RESULTS

Preliminary tests on the first prototypes show a sensitivity of about 8 mV/° from + 50° to 0. Figure 6 illustrates, in the case of a constant room temperature, the inclinometer output at different inclination angles. Figure 5 illustrates, the percentage deviation of the experimental data from the regression line.

A maximum error of about 3° can be found in the case of ± 50° full scale output. Differently, a lower nonlinearity errors near 0.3° can be obtained adopting a 20° maximum range. The repeatability has been evaluated and a value less than 0.2 ° has been observed. Thermal tests from 0° C to 50°C show a zero shift of about 0.2 %/°C.

The supply current is less than 20 mA while the settling time is 1500 ms at 20°C.

Note that the voltage output change for a small inclination angle is relatively small (9mV for 1°arc), so careful consideration to noise must be applied in the TFT inclinometer design. A noise filter that limits the bandwidth to 1Hz will display a noise level in the order of 0.1mVrms. With such an accelerometer the inclination output noise would be less than 0.1°arc rms.

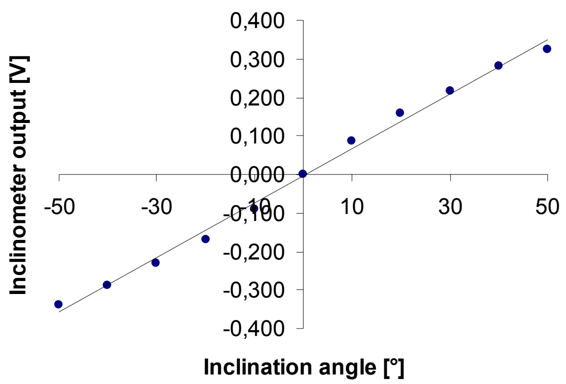

Figure 6 – Inclinometer output vs. Inclination angle

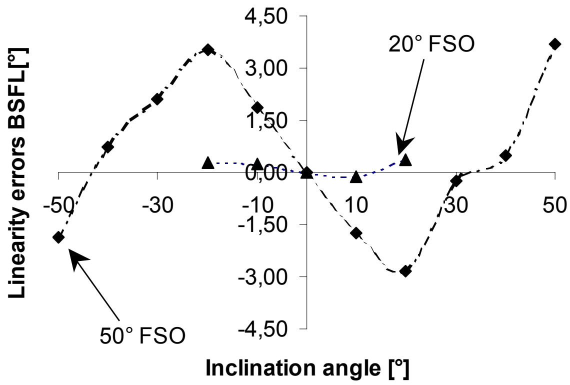

Figure 7 – Linearity errors

5. CONCLUSIONS

Using thick-film technology on a ceramic substrate, a new tilt senor based on the heat transfer principle has been developed. The sensor is fabricated from ceramic materials and thick-film technology that results in an accuracy of about 2% full scale output, repeatability of about 0.2° and thermal stability less than 0.2%/° C over a ±50° range. The TFT tilt sensor is capable of resolving less 0.1°.Finally, the sensor is inexpensive enough to be, in the near future, competitive with other types of commercial tilt transducer.

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