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Displacement sensing of a micro-electro-thermal actuator using a monolithically integrated thermal sensor

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ABSTRACT

The present paper describes a novel concept that employs a thermal-based approach for *in-situ* displacement sensing of electro-thermal actuators. A device encompassing an in-plane electro-thermal actuator and a thermal sensor was monolithically fabricated using the MetalMUMPS process. Analytical models were developed for both the actuator and the thermal sensor. Simulation and experimental results demonstrated good agreement. The experimental results indicated that the sensor achieved high linearity and sensitivity (~4.5 nm/Ω).

1. Introduction

Microelectromechanical systems (MEMS) based electro-thermal actuators comprise an important class of MEMS actuators that have tremendous potential in a wide range of prospective micro-actuation applications. Electro-thermal actuators are mechanically compliant structures that rely on the thermal expansion of its heated components to achieve thermal actuation. A variety of electro-thermal actuators have been explored that each exhibits different functional characteristics [1,2].

Closed loop feedback control of micro-actuators is often desirable for micro-actuation applications that demand high degrees of displacement precision, such as micro-manipulation [3] and nano-positioning [4]. For these purposes, *in-situ* displacement sensors are often necessary to provide a means for on-chip displacement sensing of the micro-actuators. Devices that require *in-situ* displacement sensing of micro-actuators typically employ capacitive, piezoresistive or piezoelectric based micro-sensors [2].

The concept of exploiting thermal conduction as a mechanism for displacement sensing of dynamic articles had received relatively little attention. At the macroscopic scale, size-effects typically render thermal conduction, especially across fluid mediums, an inefficient and unfeasible mechanism for signal transport and transduction in displacement sensing applications. Conversely as size scales tend towards the micro-scale, continuum heat transfer principles dictate that the increasingly smaller heat transfer distances tend to make energy transfer via thermal conduction more effective than at larger size scales. Furthermore, effects of fluid convection are often less significant at the micro-scale due to size-effects [5], making thermal-conduction as a signal transmission mechanism more feasible than at the macroscopic scale. The increased research initiatives at the micro-scale over recent decades naturally lead the way for some of the first conceptual demonstrations of thermal conduction based displacement sensing. In 1986, Williams and Wickramasinghe [6] first demonstrated position feedback control of a thermal-based surface profiler tip using a thermal-based proximity transduction concept. In 1991, Hiratsuka et al. [7] introduced the first thermal-based MEMS accelerometer. Kim et al. [8] followed a similar approach of [6] and characterized the out-of-plane displacement of atomic force microscope tips. Lantz et al. [9] developed a thermal-based displacement sensor for 2D translational nano-positioning stages.

The abovementioned conceptual demonstrations of thermal-based displacement sensing, all commonly involve utilizing the nature of thermal conduction based heat flow between two dynamically interacting surfaces as the principle mean to determine the displacement of the articles of interest. Herein this paper we describe the novel approach of using a similar thermal-based displacement transduction principle, but applied to sense the displacement of MEMS electro-thermal actuators *in-situ* of device operation. In this concept, the heat responsible for actuating electro-thermal actuators and the thermal conduction phenomenon are individually exploited as sensory signals and the signal transmission mechanism, respectively. This facilitates displacement transduction by means of relating heat flow between the actuator and the sensor, to the displacement of the electro-thermal

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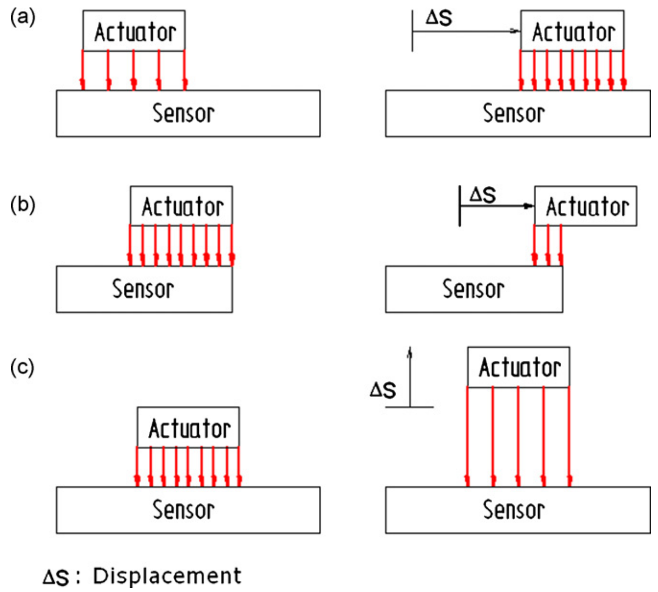

Fig. 1. Concepts for thermal-based displacement sensing of electro-thermal actuators.

actuator based on coupled heat transfer and mechanical models for the actuator-sensor system.

2. General principle

Electro-thermal actuators typically operate in conditions where the main mode of heat transfer for practical considerations is through thermal conduction. Thermal conduction, q^{cond}, is typically modeled by Fourier's law of thermal conduction, which is given by:

$$q^{\text{cond}} = -k'A'\frac{\Delta T'}{\Delta x'} \quad (1)$$

where k' is thermal conductivity, A' is the cross sectional area, and $\Delta T'/\Delta x'$ is the temperature gradient. The effects of fluid convection are typically less significant at the microscopic scale [5].

Fig. 1 demonstrates three general configurations for thermal-based displacement sensing. Arrows towards the sensor in Fig. 1 indicate heat flux, where higher density of arrows indicates greater heat flux towards the sensor. Stray heat flux is ignored in this diagrammatic depiction. Fig. 1a and b depicts motion sensing of the actuator that occurs in the plane parallel to the sensor surface; Fig. 1c illustrates the motion sensing of the actuator that occurs perpendicular to the sensor surface. By relating varying heat flux (Fig. 1a and c) or interface area (Fig. 1b) to the displacement indirectly, displacement sensing of actuators can be realized.

Similar sensing methods shown in Fig. 1b and c for non-actuator dynamic articles have been reported in [9] and [6–8], respectively. This paper reports on the sensing method demonstrated in Fig. 1a and applied in a novel manner specifically for MEMS electro-thermal actuators. Unlike prior works of [7–9] where thermal signal generation served only the purpose for displacement sensing, the heat generated in the electro-thermal actuator herein serves two functional purposes, namely thermal compliant actuation and as thermal signals.

3. Design and fabrication

An in-plane V-shaped electro-thermal actuator was chosen for the purposes of demonstrating this sensing strategy. The sensor is thermally coupled directly underneath the electro-thermal actuator. The sensor was designed to cover the entire substrate area for which the electro-thermal actuator is designed to operate. This is to ensure that the thermal sensor has maximum capture of thermal energy from the electro-thermal actuator during device operation. A schematic of the test device is shown in Fig. 2.

The electro-thermal actuator and thermal sensor device developed in this paper (see Fig. 3) was monolithically fabricated using the MetalMUMPS process [10]. This commercial fabrication process is comprised of several thin film deposition and photolithography steps conducted on the (1 0 0) surface of a lightly phosphorous-doped single crystal silicon (SCS) substrate.

The thermal sensor is fabricated from a 0.7 μm thick highly phosphorous-doped polycrystalline silicon (polysilicon) layer. The polysilicon sensor is selectively enclosed by two 0.35 μm thick silicon nitride (nitride) layers for electrical insulation and structural support. A 27.5 μm air gap spacing is anisotropically wet-etched under the enclosed polysilicon sensor to provide improved thermal insulation of the thermal sensor in an effort to increase the sensitivity of the thermal sensor. The sensor takes the geometry of a meandering polysilicon wire that covers the entire substrate

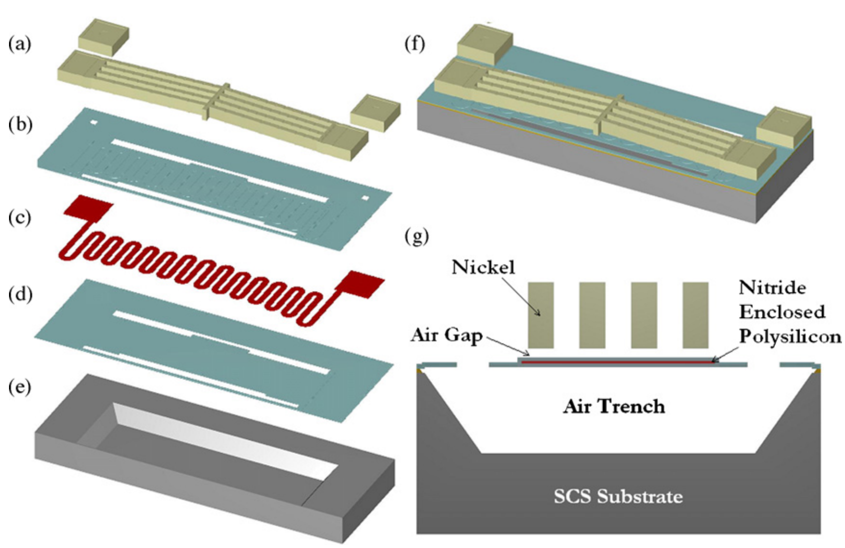

Fig. 2. Schematic of V-shaped electro-thermal actuator fabricated on top of the thermal sensor. (a) Ni V-shaped thermal actuator and probe pads for the sensor, (b) top nitride membrane, (c) polysilicon serpentine thermal sensor, (d) bottom nitride membrane, (e) substrate with a trench, (f) assembly of the sensor and actuator, (g) cross-sectional view of the assembly.