Joule Heating Simulation of Poly-Silicon Thermal Micro-Actuators

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ABSTRACT

Previous studies of surface micro-machined polycrystalline silicon MEMS thermal micro-actuators have shown that these simple devices can provide deflections on the order of 10 micrometers at CMOS compatible drive voltages. These thermo-mechanical devices operate by differential thermal expansion caused by ohmic heating in higher resistance regions of the double beam device. Because of thermal conductivity and temperature dependent resistivity in polycrystalline silicon, the temperature profile along the "pusher" section of the beam is not uniform, and motion simulation can be complex. Using a new Joule-heating finite element simulation module, reasonable agreement between simulation and near-IR microscopy on MEMS thermal actuators has been established. This work demonstrates the need to develop optimized design criteria in this class of devices to mitigate the thermal conduction and temperature variation effects in the pusher beam, which degrade displacement performance.

Keywords: MEMS, thermal actuators, Joule heating, thermal conductivity, finite element analysis

Introduction

Comtois et al.[1] have presented poly-silicon double beam thermal horizontal in-plane actuators that demonstrate large deflections(>10μm) and operate at CMOS compatible drive voltages with current levels below 5mA. This actuator concept has been applied to a wide variety of applications, including scanning and rotating micro-mirrors, Fresnel lenses, movable gratings, linear micro-motors, and self-assembly systems.[2, 3, 4] A representative diagram of this beam design, used both in the experimental and simulation studies in this paper, is indicated in Fig. 1. This structure has two parallel beams, coupled at the free end, with one beam significantly more electrically and thermally conductive than the second beam. As the more resistive beam (with a smaller cross section) heats up relative to the attached less resistive beam (with a larger cross section), the effect of differential thermal expansion causes the narrower beam to push on the wider beam where they are attached at the free end. The experimentally optimized design in Fig. 1 has been used in other studies with limited theoretical evaluations.[5, 6] Functional modeling of these devices is complex because the extent of localized ohmic heating depends on the temperature distribution in the expanding elements. This temperature distribution depends on a number of criteria, primarily on the absolute thermal conductivity of the heated elements, and to a lesser extent, the temperature dependence of the resistance of the doped poly-crystalline silicon elements that heat up. Simulation studies in this work utilize a new MemCad 4.0 MEMS simulation module available from MicroCosm, Inc.[7] This "MemECad" Joule heating module, in conjunction with other parts of this commercial finite element design and simulation package, computes the thermal and electrical potential field distributions resulting from an applied voltage or current through a resistive material. The localized Joule heating effects are coupled to the MemCad finite element mechanical simulation package to determine overall displacement and stresses related to thermal expansion.

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Devices

The devices used for the experimental observations were originally fabricated at the MCNC/MUMPS processing facility as part of an array of test structures for related work.[8] Test chips as received from MCNC were released, mounted and bonded in an open package. As indicated in Fig. 1, the length of the 2.5μm wide, 2.0 μm thick, narrow "pusher" beam is 235μm. The nominal resistivity of the polycrystalline silicon is $10\pm5\ \Omega$/sq., resulting in a room temperature device resistivity of $1300\pm650\Omega$-cm. Because of this resistance variability, device current is likely to be a more pertinent independent variable in terms of calibrating thermal actuator functions than applied voltage.

These devices were individually connected to a stable variable voltage DC power supply, and the current was monitored with a digital milliamp meter. Beam deflection was observed through a microscope coupled to a PULNIX TM 840 TV camera, which has significant relative sensitivity below λ=1.0μm wavelength. Pictures were captured in a bit map format. Typical captured images of an operational device are given in Fig. 2. Deflections can be measured using a vernier structure at the coupled free end of the beam. Images were taken both in bright optical field illumination, and in dim optical illumination, in order to highlight the IR luminosity of the hot part of the narrow beam. The IR luminosity observed with the PULNIX camera is not seen for low applied voltages, and increases in intensity with voltage. For example, no IR luminosity is seen for the device of Fig. 2 below 8 volts applied to the two-anchored beam-ends. Fig. 3 shows typical behavior of an actuator indicated in Fig. 1 for both current and displacement. Precision displacement measurements are limited by the use of vernier indicators and by stiction of the dimple spacers in contact with the substrate surface.

The dimples prevent contact of the double beam structure with the substrate, nominally 2μm below the beam.

The wide, cold arm of the coupled beam structure has a flexure section 40μm long with a 2.0x2.0 μm^2 cross section that serves as a hinge. Without this flexure element, little thermally activated deformation would be seen at the free end of the coupled beam structure. Because the cross section of this flexure region is 20 pct. smaller than that of the "hot" arm, there could be a concern that Joule heating in the flexure will mitigate the deformation at the free end of the "hot" arm. The IR observation indicates that both the large thermal conductivity and the small voltage drop in the short flexure is sufficient to prevent the appearance of IR luminosity in this part of the structure. This observation has also been confirmed by the simulation studies.

Experimental Results

The current and displacement dependence on applied voltage for a typical actuator is indicated in Fig. 3. The displacement measurements are based on observation of the vernier at the free end of the beam, and are also subject to stiction of the dimple spacers on the substrate. A displacement of over 12 μm is achieved at less than 5mA, in agreement with prior observations.[10] The current dependence with voltage is sub-ohmic, most likely because the resistance of the poly-silicon increases with temperature. No IR luminosity is observed for this device below 8 volts applied to the beam ends, but above this value, IR luminosity is quite apparent, even with moderate white light optical illumination, as seen in Fig. 4. The sharp focus position of the microscope for bright optical illumination and sharply defined IR radiance are not coincident, most likely, because of the wave length dependence of the optics The range of IR luminosity never extends more than 50 μm on the 235 μm long pusher beam, and never appears on the 40 μm flexure. Because of thermal heat flow effects, one might presume that the IR luminescence should be localized about the center of the "pusher" arm or beam, but the actual position varies from device to device, even on the same chip. One possibility is that local variations of the effective doping in the "pusher" beam could shift the "hot spot." Another source for this phenomena could be local etch variations in the cross section of the "pusher" beam.

The temperature at the center of the IR radiance is estimated to be in the range of 850-1000 ^{o}K, while the edge of the IR luminosity is estimated as 800 ^{o}K from blackbody spectral exitance considerations.[9] Clearly, the temperature distribution due to ohmic heating along the narrow beam is far from uniform, and the highest temperature region—corresponding to the elements of largest thermal expansion—extend no more than 30% of the length of this beam.

MemCad Simulations

MemCad is an integrated set of MEMS simulation tools enabling the design, specification, modeling, and engineering of accurate and performance predictive devices and systems with a wide variety of functional properties and applications. The complete suite of MemCad modules, used in this work, resides on an HP workstation at the AFRL Information Technology Division at Griffith AFB, Rome, NY, and is accessed remotely at Hanscom AFB. The recent availability of an integrated Joule heating module provided an opportunity to compare experimental observations of local heating and thermal conductivity for thermal actuators to the new simulation code, without the need to assume or infer a temperature profile on the narrow "pusher" beam.

Recently, Allen et al.[10] have modeled a very similar ohmic heating structure using the IntelliCad simulation program,[11] finding very good correlation to prototype experimental devices. Because the code used by Allen et al. did not have a Joule heating module at the time of their work, a temperature profile of the narrow arm or beam had to be devised. In the current work, using MemCad's MemETherm module, no adjustable fiting parameters are used, other than specification of poly-silicon properties. Because of the variability in apparent poly-Si resistivity, device current is, generally, a more pertinent independent variable than applied voltage.

Simulation Results

Simulated results using MemCad are indicated in Fig. 5. Because MemCad does not incorporate a model for material plastic flow or melting, calculations in the range of temperatures above 1500 ^{o}K are not meaningful. As clearly evidenced in the graph, the simulated displacement and reaction force at the anchors increases in a nominally linear manner with temperature. These calculations also demonstrate that only the middle sections of the pusher beam gets "hot," and that the free end of the double beam structure gets no hotter than 400 ^{o}K. The center of the pusher beam can reach 1500^{o}K with only 3.5 volts applied to the fixed ends of the beams, as indicated in Fig. 5. The simulated calculation also indicates that virtually all the voltage drop is across the pusher bream, and only 10 pct. across the flexure. Since, in addition, both ends of the flexure are constrained to be close to room temperature, no IR "hot spot" can develop in this part of the structure.

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