High Temperature Operation of Gimbal-less Two Axis Micromirrors

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Abstract – We demonstrate seamless operation of gimbal-less two axis micromirror devices at high temperatures up to 200°C by characterizing the temperature stability of the mirror tilt angle and first resonant mode. The ability to provide a repeatable, high temperature vector or raster scanning micromirror opens up opportunities for ruggedized products in extreme environments. This capability is also relevant in high incident optical power applications, where energy is absorbed at the mirror. A first order thermal model is presented that allows the temperature rise of mirrors under high optical power operation to be estimated.

INTRODUCTION

Two axis micromirror devices can provide point-to-point, vector, and raster optical beam steering capability for various applications including projection displays, optical data storage, ranging, and bio-medical imaging. The capability of device operation at high temperatures is of particular interest when developing for extreme environment applications; when developing micromirrors for high optical power applications, and finally for robustness in product reliability tests. The two axis micromirror devices in this work are gimbal-less, monolithic single-crystal silicon actuators that may include an integrated mirror, or a mirror that is fabricated separately and subsequently bonded [1],[2]. The actuators are based on electrostatic attractive forces in vertical combdrives that are mechanically coupled to the mirror by bi-axial linkages. Micromirror devices with integrated and bonded mirrors are shown in Figs. 1a and 1b, respectively.

OPERATION AT ELEVATED TEMPERATURES

In order to study the performance of the devices at elevated temperature, a resistively heated stage was constructed that would accept packaged micromirror devices. A schematic of the experimental setup is shown in Fig. 1c. The devices were mounted in commercially available 24 pin dual in line packages using a thermal epoxy. In order to monitor the operating temperature of the die, a K-type thermocouple was mounted on the package as close to the die as possible. The thermocouple was mounted with thermal epoxy, and was typically within 1 mm from the edge of the micromirror die. This allowed the temperature of the device to be monitored and controlled.

Static voltage to angle transfer function as well as a small-signal frequency response of each device was recorded at various temperatures. In each case, the system was allowed to stabilize at a temperature set point for longer than 10 minutes, before performing the measurements using a position-sensitive detector (PSD) and a programmed data-acquisition system.

Static tilt angle for 69V and 81V of actuator voltage for both the x and y axis at temperatures from 25 ^{o}C to 200^{o}C is shown in Figure 2a. The tilt angle increases slightly with increasing device temperature. For the data sets shown in Fig. 2a, starting from the top of the plot, linear regression lines show slopes from of 1.2, 0.9, 0.9, and 0.6 milli-degree of mechanical tilt/^{o}C. From frequency response measurements we extracted the frequency of the first resonant mode, which is of interest for both point to point and resonant scanning. In point to point mode the device can be precisely controlled at frequencies that approach this first resonant mode. In other words the useable bandwidth is defined by the first resonant frequency. In resonant scanning, the device oscillates at or near this first resonant mode frequency, so its stability is highly relevant. Figure 2b shows the temperature dependence of the frequency of the first resonant mode for temperatures from 25^{o}C to 200^{o}C. The dependence of this frequency on temperature, based on linear regression of the data, is -73 mHz/^{o}C for the x axis and -44 mHz/^{o}C for the y axis.

Overall, the performance of the devices was highly stable at all tested temperatures, and the upper limit was only defined by our experimental setup. This result is attributed to the monolithic single-crystal silicon construction of the devices and the electrostatic nature of actuation, which both have very low sensitivity to elevated temperatures.

THERMAL MODELING

The above tests apply directly to applications in a high temperature ambient environment. On the other hand, even at room-temperature, the temperature of a device can also increase in applications where the mirror is illuminated with high optical power. In these conditions, the temperature of the mirror and actuator structure will not be uniform. The magnitude of the temperature rise of the mirror is predominately a function of the reflectivity of the mirror, the mirror size, the actuator geometry, and the ambient environment. In order to study the temperature rise of micromirror devices, we conducted numerical studies which showed that when operated in ambient pressure environments, thermal conduction through the gas was typically the dominant mode of heat transfer from the mirrors. This finding is in line with similar work on micromirror heating [3]. This was despite the high thermal conductivity of silicon beams in the actuator, as the relatively large area of the mirror as well as the large area of the actuator itself (including combfingers) contributes to the dominance of gas-conduction.

A representative result for a square mirror on a two axis actuator is shown in Fig. 3a. Based on these numerical studies, a simple analytical model for the temperature rise of the mirrors was developed that considers only two paths of heat conduction operating in parallel: (1) a conduction path through the ambient gas from the mirror to the die and (2) a solid conduction path through the mirror and the silicon actuator to the die. The estimated temperature rise of the mirror for 1 Watt of incident optical illumination is shown in the Fig. 3b. The temperature rise is shown for mirror reflectivities of 90% (characteristic of Aluminum for visible wavelengths) and of 99% (characteristic of thin film multilayer reflective coatings). The data in the table illustrates how gas conduction from a larger mirror to the die and higher reflectivity coatings can significantly reduce temperature rise in this type of micromirror device.

CONCLUSIONS

The static tilt angle and first resonant mode of monolithic, gimbal-less micromirror devices tested in this work show only a slight sensitivity to elevated ambient temperature. For applications where the temperature rise is due to high power optical illumination, any performance degradation can be mitigated by geometric design of the device and the use of highly reflective mirror coatings.

[1] V. Milanović, *et al*, "Gimbal-less Monolithic Silicon Actuators For Tip-Tilt-Piston Micromirror Applications," *IEEE J. of Select Topics in Quantum Electronics*, vol. 10, no. 3, Jun. 2004.

[2] V. Milanović, K. Castelino, "Sub-100 µs Settling Time for Gimbal-less Two-Axis Scanners", Optical MEMS 2004, Takamatsu, Japan, Aug. 2004.

[3] J. Zhang, Y. C. Lee, A. Tuantranont, and V. M. Bright, "Thermal Analysis of Micromirrors for High-Energy Applications", *IEEE Trans. On Advanced Packaging*. Vol. 26, no. 3, Aug. 2003.

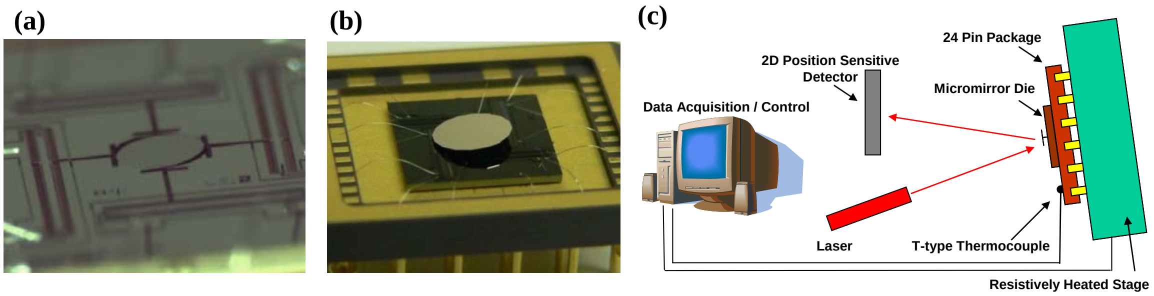


Figure 1. (a) A gimbal-less two axis silicon micromirror device with an integrated 800µm mirror. (b) A similar device with a bonded mirror (3600 µm diameter.) (c) A schematic diagram showing the experimental setup for testing micromirror devices at elevated temperatures. A resistively heated stage was computer controlled using a thermocouple that was attached to a 24 pin package near the device die. Mirror motion was detected using a low power laser and a position sensitive detector.

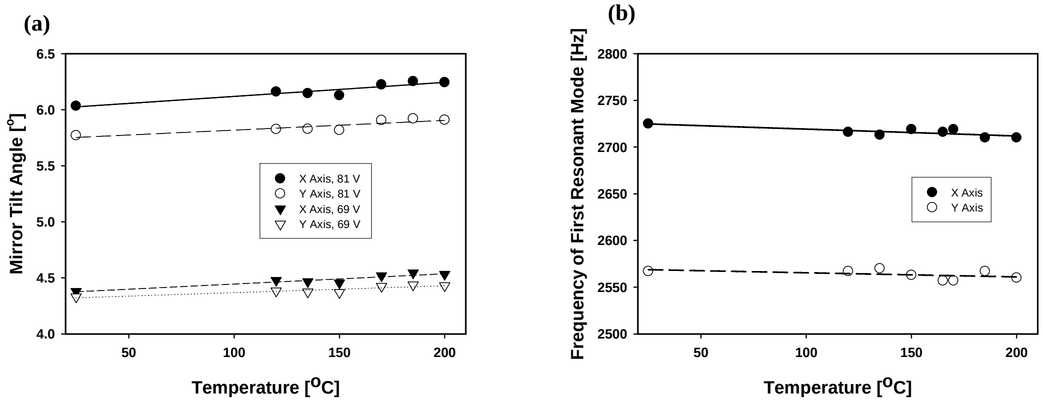
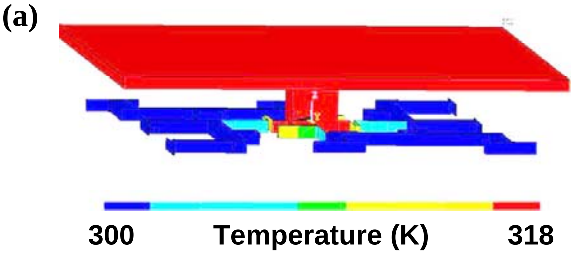


Figure 2. (a) Mirror tilt angles at two select voltages are shown as a function of the device temperature. Both x and y axis were tested and perform similarly. The tilt angle shows a slight increase as a function of temperature. (b) The frequency of the first resonant mode for both x and y axis is shown as a function of device temperature. The resonant mode frequency shows a slight decrease with increasing temperature.



(b)

Mirror Temperature Rise (K)

	D=1mm	D=2mm	D=3mm
Reflectivity=90%	198	59	27
Reflectivity=99%	20	6	3

Figure 3. (a) A representative false-color image of numerical simulations performed in order to study the dominant paths of heat conduction in gimbal-less micromirrors. (b) Summarized results from a simple thermal model that considers heat flow from the mirror through the ambient air as well as heat flow through the silicon structure of the device. Temperature rise of the mirror is shown for two values of mirror reflectivity and for three mirror diameters. All simulations assume 1 Watt of optical power incident on the mirror and uniformly distributed over each mirror's surface.