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Development of thermal actuators with multi-locking positions

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Abstract: To reduce power consumption and operation temperature for micro-thermal actuators, metal-based micro-mechanical locks with multi-locking positions were analyzed and fabricated. The micro-locks consist of two or three U-shaped thermal actuators. The devices were made by a single mask process using electroplated Ni as the active material. Tests showed that the metal based thermal actuators deliver a maximum displacement of ~20μm at a much lower temperature than that of Si-based actuators. However Ni-actuators showed a severe back bending, which increases with increasing applied power. The temperature to initiate the back bending is as low as ~240°C. Back bending increases the distance between the two actuators, and leads to locking function failure. For practical application, Ni-based thermal actuators must be operated below 200°C.

1. Introduction

Compared with other microactuators, microelectromechanical thermal actuators are of great interest owing to their large forces and displacements generated, and hence large work done; therefore they have the potential for widespread applications in microsystems and microelectronics. Compatible voltage to that used in CMOS makes them suitable for integrating with CMOS. However thermal actuators require high operating temperature and suffer high power consumption. For most applications, a constant power is needed to keep the actuator at a fixed position such as optical fibre switches and electrical relays. This leads to a steady rise of the environmental temperature, causing potential damage to the system. This is especially a problem when integrating thermal actuators with CMOS circuits. In order to overcome these shortages, thermal actuators with various latch mechanisms have been developed using the toggle and buckling effect [1, 2, 3]. Once the actuator is in the second stable state, the power can be turned off while keeping the device in required position. In this way, the power consumption is reduced, and most importantly the operation temperature is minimized. Thermal actuators with bi-stable states are believed to be the technology of the future. Here we report the development of thermal actuators with multi-stable states. Metal is used as the active material to reduce the power consumption and potential thermal damage to the environment as metals have a much lower operation temperature owing to their high thermal expansion coefficients. Metal-actuator related issues have been investigated in detail.

2. Design and fabrication of micro-mechanical locks

Two types of micro-mechanical locks with multi-stable locking positions as shown in Figure 1 were designed and analyzed. The mechanical locks utilize the U-shaped lateral thermal actuating mechanism [4]. The first mechanical lock consists of two U-shaped thermal actuators perpendicular to each other as shown Figure 1a. The tip of the lateral thermal actuators have multi-teeth, providing multi-locking positions. A U-shaped thermal actuator consists of one thin hot arm and a wide cold arm [4]. Once a current (or voltage) passes through the device, the thin hot arm heats up more than that of the cold arm due to the difference in resistance, generating a differential change in length, hence produce a deflection downwards as shown for actuator A. When another pulsed current is applied to actuator B, the deflection of the actuator drives the tip into one of the teeth of the actuator A. Removing the current makes actuator A return to its original position, locking the two actuators

together. The power can then be turned-off while keeping actuator B at a fixed position without raising the temperature of the environment.
To provide a more stable locking position, the second mechanical lock has a double-clamping mechanism as shown in Figure 1b. A pulsed current opens the gap of the two parallel thermal actuators, and locks the incoming tip of actuator B into one of the multi-positions. The locks can be released by applying a pulsed current to actuator A or the two parallel actuators; all thermal actuators unlock and return to their original positions. By applying a different power to actuator B for both locks, it is possible to select different locking positions.

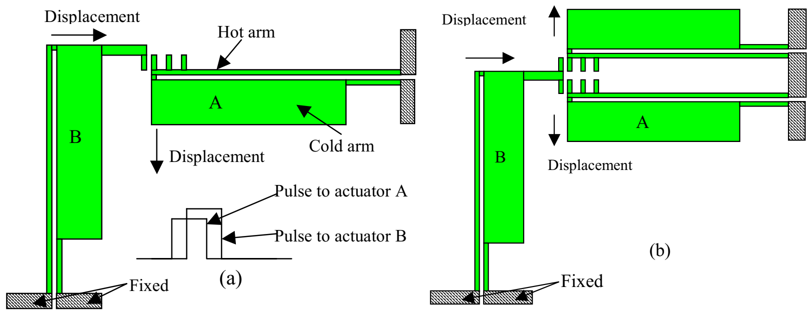


Figure 1. Schematic drawing of a single mechanical lock (a) and double mechanical lock (b).

All the U-shaped actuators used for the mechanical locks have the same dimensions. The length and width of the hot arms were 400/4μm, and those of the cold arm were 360/4μm respectively. The gap between the hot and cold arms is 15μm. The width and the length of teeth bar were 4 and 10μm respectively, with a gap of 8μm. In order to characterize the displacement of the actuators, a single U-shaped actuator with the same dimensions was also designed and fabricated on the same wafer.
Micro-locks were made of an electroplated Ni film using a through-mask-plating technology [5, 6]. The devices were fabricated using a single mask process on a 4” Si wafer and the details of the process can be found in ref.7. The thicknesses of the Ni films for two batches of devices were 3 and 4μm (corresponding to devices D1 and D2 respectively hereafter). The devices were released by etching the Si underneath using an SF_6 reactive ion etch process with a typical etch depth 25 ~ 30μm. The etching time is sufficiently long to remove all residual Si on the back of the device and the device is sufficiently high above the substrate to minimize heat loss through the substrate during operation. Figure 2 shows the SEM pictures of both types of micro-lock. The surfaces of the devices are smooth with typical roughness less than 10nm, and the sidewall is almost vertical.

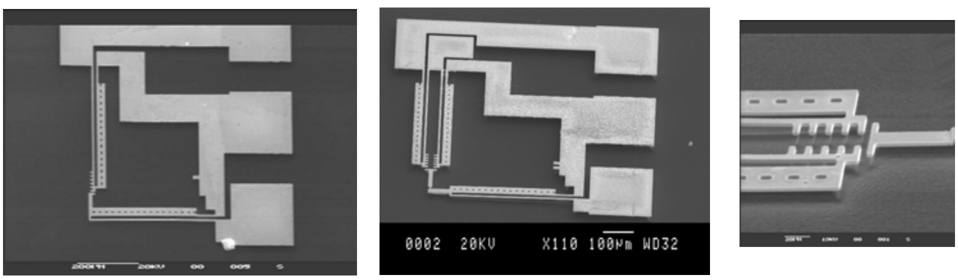


Figure 2. SEM pictures of a single (left), a double (middle) mechanical locks and the detailed teeth.

3. Results and discussion

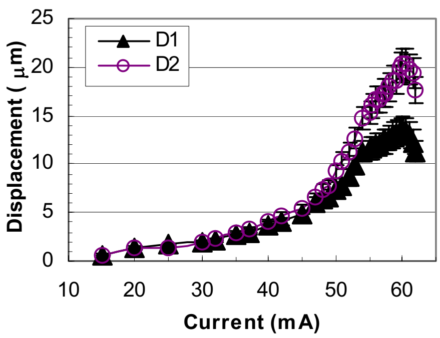
The device performances were characterized as a function of current, power, temperature and frequency. They were measured on a wafer on a probe stage fixed with a camera that takes pictures of the device when a power is applied, and the displacement was analysed using commercial software. A square pulse current was used to heat the devices.

3.1 Displacement vs. power

Since the thermal actuators used in micro-locks have the same dimensions, individual U-shaped actuators were used to investigate the displacement. During initial measurements, it was noticed that after driving the actuators beyond a certain power level, the actuators do not return to their original position due to "back bending" as will be discussed later. The forward displacements thereafter were all measured with a new original point after each measurement. Figure 3 shows the displacements of two actuators with the current and power as variables. The difference between the two actuators is due to the variation in the thickness of the devices. The displacement of the thermal actuator tip increases parabolically with the current applied, and is proportional to the power consumed in the range of <60mW, consistent with theoretical analysis [8]. The maximum displacement of the tip reaches ~20μm at a power of 60mW. Beyond that the displacement decreases with further increase in current and power. The average temperature of the thermal actuator, ΔT_{ave}, can be extracted from the change of resistance by the following equation;

$$\Delta T_{ave} = T - T_0 = (R_D(T) - R_{D0}) / R_{D0}\xi \quad (1)$$

where R_{D0} and $R_D(T)$ are the resistances of the device before and after temperature rises, ξ is the temperature coefficient of resistivity of the Ni film with a value of $3\text{x}10^{-3}$/°C [9]. The displacement is shown as a function of average temperature in Figure 4, and it is almost proportional to the temperature at T<460°C. For a similar displacement, a Si-based thermal actuator typically requires an operation temperature over 1000°C. The low operation temperature is attributed to the large thermal expansion coefficient, α, of the Ni, where α~$15\text{x}10^{-6}$/°C for Ni, and α~$2.5\text{x}10^{-6}$/°C for Si.



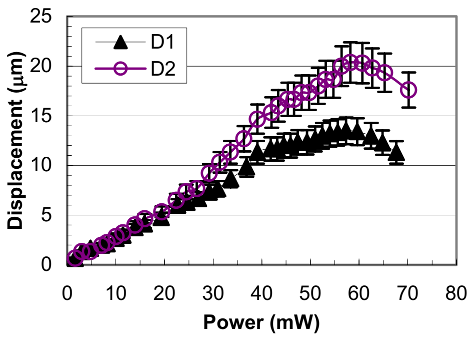


Figure 3. Displacement as a function of current and power applied.

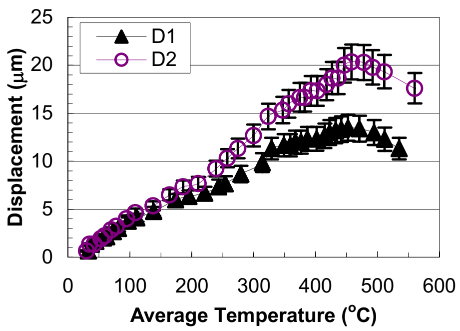
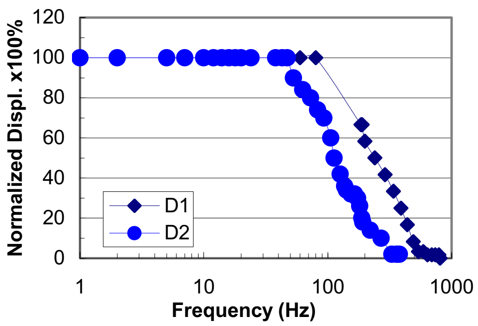


Figure 4. Displacement as a function of average temperature extracted for two thermal actuators.

3.2 Frequency dependence of the displacement

The pulse width of the applied current was found to affect the actuation significantly. The displacement remains constant down to a pulse width of ~1ms, and gradually decreases with further reduction of the pulse width. No displacement was observed at a pulse width less than 10μs. When the pulse width is too short, it is not sufficient to heat up the "hot" arm, and thus is unable to generate a

visible displacement. For the characterisation except the frequency dependence hereafter, a pulse width of 10ms was used. The tip displacement was found to be strongly dependent on the frequency of the current pulse used for measurement. Figure 5 shows the dependence of the normalized displacement as a function of frequency. Up to 50~100 Hz, the displacement remains constant, and then decreases with further increase in frequency, and disappears at 300~700Hz. It is known that the thermal conduction of a U-shaped thermal actuator is dominated by the cooling process with a typical time constant of 1~10ms [10], much longer than the heating process. This is at least one order of magnitude smaller than the mechanical resonant frequency of the actuator. At high frequency, the cooling process of the actuator is suppressed; hence the actuator is no long able to deliver a displacement. This cut-off frequency of the thermal actuator is therefore dominated by the cooling time constant, which is a function of device dimensions and material properties [10]. From eq.(9) in ref.10 based on a simplified model of thermal conduction through the bond pads only, the thermal conduction time constant can be estimated to be ~4.2ms for our devices. This is about one order of magnitude larger than measured, mainly due to simplified model.
The frequency dependence however was found to strongly depend on the voltage (or current) of the pulse. Figure 6 shows the dependence of the normalized displacement on frequency with peak voltage of the pulse as a variable. Displacement of the actuator disappeared at a higher frequency when a pulse with a large peak voltage was used. The cooling process normally has an exponential behaviour with a fixed time constant. Therefore it is faster at the higher temperatures corresponding to application of larger pulse voltages; hence the device has a high cut-off frequency. On reducing the voltage, the actuator has a modest rise in temperature. The cooling takes longer and leads to a low cut-off frequency.



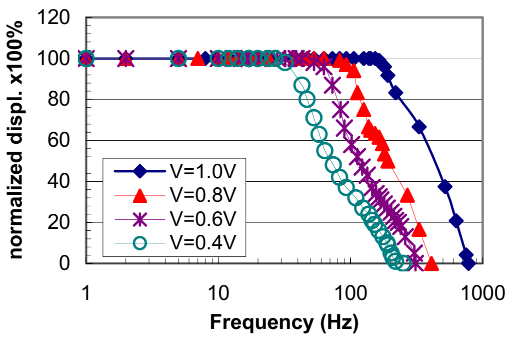


Figure 5. Dependence of normalized displacement on the frequency (left).
Figure 6. Dependence of displacement on the frequency with peak voltage as a variable (right).

3.3 Back bending

Generally speaking, microactuators have a much longer lifetime than those of macro-devices, and switching cycles up to tens billions times were achieved for microcantilever and comb drivers. However thermal actuators have a much shorter lifetime; especially when they are operated at a higher temperature. Reduction in displacement, back bending and burn-off were observed from both lateral and vertical thermal actuators [11, 12]. The degradation of the thermal actuators is believed to be caused by surface oxidation and plastic deformation at high temperature. Once the hot arm of the actuator is heated above a certain temperature, it undergoes a localized material redistribution [11]. A plastic deformation occurs and the hot arm becomes shorter due to the compressive stress generated. After cooling, the actuator returns with an opposite direction displacement; the so-called back bending for U-shaped actuators. Si-based thermal actuators have a much higher operation temperature and brittle-to-ductile transition temperature (~660°C), and hence a higher back bending temperature 650~800°C [12]. Ni has a very high melting temperature, but it is ductile. Also metals oxidize in air at a much lower temperature, therefore a low temperature to initiate the back bending is expected for metals. A back bending temperature of ~200°C was suggested for Ni thermal actuators but with no direct evidence [13]. Since Ni is one of the most important materials for microthermal actuators, we have investigated the back bending behaviour.

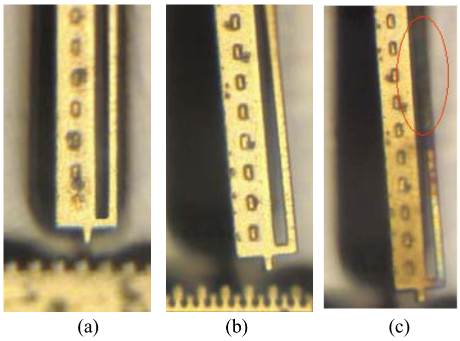


Figure 7 Optical images show the initial tip position (a) and the back bending (b) of a thermal actuator after applying a current pulse of 55mA, and burn-off followed by a high current.

Figure 7 a&b are microphotos of a thermal actuator before and after applying a current of 55 mA. The tip of the actuator significantly displaced from its original position by ~15μm. Further increase in current leads to burn-off in the middle of the hot arm as shown in Figure 7c, but the actuator remains in a back bending position. Figure 8 shows the back bending as a function of power and average temperature for two devices. It is obvious that the back bending occurs at a temperature as low as ~160°C, and reaches a maximum of 15μm (~75% of the forward displacement) at ~460°C. The temperature which initiates the back bending for Ni-actuators is much lower than that for Si-based actuators (~660°C [12]). Similar to the behaviour of the forward displacement of the thermal actuator shown in figure 3, the back bending initially increases with temperature, and then decreases as the temperature further increases to over 460°C. Decrease in back bending is believed to be caused by localized oxidation and vaporization of metal. Eventually there is no sufficient material left to generate the back bending [10, 11]. This is supported by the evidence of burn-off following the back bending, where a thinned beam is normally seen. The decrease in back bending is different from the behaviour of Si-based actuators, where the back bending of Si-based actuators increases first, then remains at a maximum back bending level up to a very large power [12]. The reason may be that the oxidation and plastic deformation of metals accelerates as temperature increases, while Si has a very high melting temperature >1400°C, and no vaporization would occur for the temperature range used here.

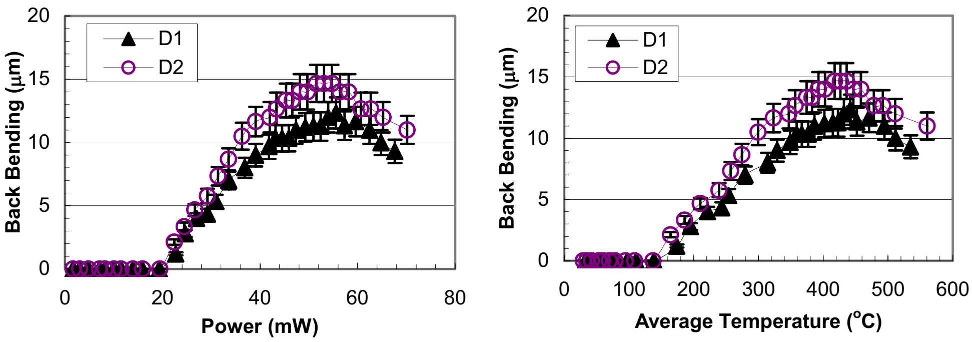


Figure 8 Displacement of back bending as a function of power consumed and temperature for three thermal actuators.

The temperature shown in Figure 8 is the average temperature extracted from the variation of the resistance of the actuator. It is known that the highest temperature is in the middle of the hot arm. A theoretical analysis based on a thermal conduction model showed that the maximum temperature, ΔT_{max}, is 1.5times the average temperature, ΔT_{ave} [7]. An average temperature of 160°C corresponds to a maximum temperature of ~240°C, close to that suggested by Lee et al [13].

3.4 Mechanical lock

Although back bending can be utilized to achieve a larger force from a given actuator [11], back bending shifts the original position for the actuator designed. For the mechanical locks, it increases the distance between the tip of one actuator and the multi-teeth position of another one. The device was initially designed for use in the temperature range of 300~400°C. Severe back bending opens the gap much wider than it was originally designed for. This makes the actuators fail to lock to each other. Increase in power will make the actuator deliver a larger displacement; but it also increases the back bending simultaneously at T_{ave} > 160°C as shown in Figure 8.

Figure 9 shows a photo of a double mechanical lock under a voltage of 0.8 V. Two parallel actuators opened sufficiently wide, and the tip of the vertical actuator almost moved into the first locking position. Although the lock is still unable to deliver a locked state, it clearly showed the functionality of the device. The large distance between the hot and cold arms of the thermal actuators (~15μm) is also partially contributed to the failure of the locking process. The above results clearly show that the operation temperature of a metal thermal actuator should be lower than 200°C. New devices are under development in order to demonstrate this.

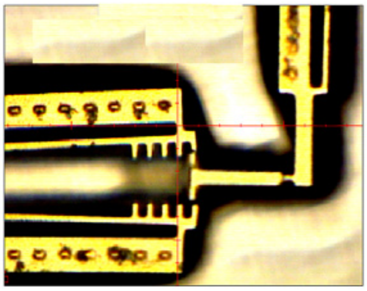


Figure 9. Microphoto of a mechanical lock at a pulse voltage of 0.8V.

4. Summary

Two types of mechanical locks with multi-locking positions were analysed and fabricated. The micro-locks consist of two or three U-shaped electroplated Ni thermal actuators. Electrical tests showed that the Ni-based thermal actuators deliver a larger displacement at a much lower temperature than that of Si-based ones, and a displacement up to 20μm was realized. However Ni-microactuators showed severe back bending, and the initiating temperature for back bending is as low as 240°C, much lower than that of Si-based actuators. Back bending increases with the applied power. For practical application, Ni-based actuators must be operated below 200°C.

References:

[1] Masters N D and Howell L L; 2003 J. Microelectromech. Syst. **12** 273.
[2] Vangbo M; 1998 Sensors and Actuators **A69** 212.
[3] Gomm T, Howell L and Selfridge R H; 2002 J. Micromech. Microeng. **12** 257.
[4] Guckel H, Klein L, Christenson T, Skrobis K, Laudon M and Lovell E G; 1992 Proc. Solid State Sensors & Actuators workshop, pp.73, Hilton Head '92.
[5] Shenoy R V and Datta M; 1996 J. Electrochem. Soc. **143** 544.
[6] Luo J K, D P Chu, Flewitt A, Spearing S M, Fleck N A and Milne W I; 2005 J. Electrochem. Soc. **152** C36.
[7] Luo J K, Flewitt A, Spearing S M, Fleck N A and Milne W I; 2005 J. Micromech. Microeng. **15** 1294.
[8] Luo J K, Flewitt A, Spearing S M, Fleck N A and Milne W I; 2005 J. Micromech. Microeng. **15** 1527.
[9] Luo J K, He J H, Flewitt A, Moore D F, Spearing S M, Fleck N A and Milne W I; 2005 J. Microlith. Microfab. Microsyst. **4** 023012-1.
[10] Enikov E T and Lazarov K; 2003 Sensors & Actuators, **A105** 76.
[11] Comtois J H and Bright V M; 1997 Sensors & Actuators, **A58** 19.
[12] Deladi S, Krijnen G and Elwenspoek M; 2004 J. Micromech. Microeng. **14** S31.
[13] Lee J S, Park S D, Nallani A K, Lee G S and Lee J B; 2005 J. Micromech. Microeng. **15** 322.