Abstract — The use of MEMS electrical switches as miniature electrically resettable circuit breakers is described. A prototype based on nickel thermal actuators on silicon has been fabricated and tested, and the performance is compared to analytical models. Trip currents of \( \approx 300 \text{ mA} \) are obtained, with trip times less than 50 ms. Temperature dependence of trip current is shown to be below 0.2%/K. The relation between achievable performance and physical device parameters is discussed.

Key Words: circuit breaker, thermal actuator

I INTRODUCTION

Electrical switches fabricated based on MEMS technologies have been reported by a number of research groups, and while many of these are intended for high frequency applications, switches suitable for DC and low frequencies have also been reported [1,2]. DC switches inevitably require direct physical contact, and a variety of configurations are possible, with specific designs choosing between lateral (in-plane) and vertical movement, and between thermal, electrostatic or other forms of actuation.

An attractive application for MEMS DC switches is in circuit protection, effectively to act as ultra-miniature electro-mechanical circuit breakers. The MEMS approach provides cost, size, function and integration benefits over conventional relay-type circuit breakers. Since the maximum currents are likely to be a few amps at most, applications in electronics (e.g. on-board over-current protection) are the most suitable. Although fuses are often used, increasingly there is a requirement for recoverable protection without component replacement [3]. Therefore the competing technology is not the conventional fuse, but the positive temperature coefficient (PTC) device. The PTC is small, low cost, and recovers its conductive state after the over-current condition ends. However, it has serious drawbacks that a MEMS solution can overcome: slow and variable trip times, high ambient temperature dependence, and lack of controllability of re-setting.

II DEVICE STRUCTURE

The device we have developed is based on latching, laterally moving thermal actuators. The actuators are of the shape bimorph (Guckel) variety. Figure 1 shows a schematic of the device, with the set and trip actuators, contact points, and external terminals indicated. When the actuators are latched together, the load current passes from the source connected at D to the load connected at E, either across the latch contacts or through the cold arms of both actuators via an external connection between C and B. When the load current exceeds the rated value, the trip actuator produces sufficient force to trip the latch, and the contact is broken. Resetting is achieved by applying a reset current between the set actuator terminals A and B.

![Figure 1. Schematic of MEMS circuit breaker.](image-url)
The required trip force depends on the latching force, which can be widely varied by adjusting the stiffness of the set actuator and the displacement needed to set the latch. However, the latching force $F_L$ will determine the contact force, which in turn will set the contact resistance. The optimal $F_L$ will be the minimum that achieves sufficiently low contact resistance, so as to minimize the trip actuator size. Previous studies suggest a few hundred $\mu N$ as suitable contact force values [5]. Neglecting torque at the actuator base, the contact force will be less than $F_L$ by the ratio of the distances of the latch and contacts respectively to the actuator base, so 500 $\mu N$ is chosen as a suitable value for $F_L$. The tripping performance can now be analysed with reference to the geometric parameters indicated in Fig. 3.

![Figure 3. Dimensions and forces for analysis of trip actuator.](image)

The latching force $F_L$ results in a static friction force $\mu_s F_L$ which must be overcome by an equal force $F_c$. This force is in turn provided by a normal force $F_n$ which results from heating of the hot arm. Since the latch trips with minimal deflection of the trip actuators, the actuator stiffness can be neglected, so equating moments we arrive at a required $F_n = \mu_s F_L/g$. This is obtained from the thermal expansion of the hot arm according to:

$$F_n = E \alpha \frac{A}{L_h} \int_0^{L_h} (T(x) - T_A) \, dx$$

(1)

where $E$ and $\alpha$ are the Young’s modulus and thermal expansion coefficient of the actuator material, $A$ is the hot arm cross-sectional area, and $T(x)-T_A$ is the temperature distribution with respect to the ambient.

The hot arm expansion results from Joule heating caused by the load current $I$ passing through the hot arm. If we assume that the cooling is dominated by conduction down the arm to its two ends, and that these remain at ambient temperature, then the one-dimensional thermal equation is easily solved giving a quadratic variation of over-temperature:

$$T(x) - T_A = \frac{I^2 \rho}{2A^2 k} (L_h x - x^2)$$

(2)

where $\rho$ and $k$ are the electrical resistivity and thermal conductance respectively. The integral of the over-temperature given by (2) gives $I^2 \rho L_h^2/(12A^2 k)$, which we can insert in (1) to derive the trip current:

$$\frac{1}{12} \frac{\alpha E}{k} g I^2 R = \mu_s F_L$$

(3)

with $\mu_s$ the coefficient of static friction, the hot arm electrical resistance $R = \rho L_h/A$, and approximating $L_c \approx L_h$. For nickel the combined constant $\alpha E/k \approx 28000$ s/m$^2$ [4]. For $g = 20 \mu m$, $\mu_s = 0.8$ [6], and a target hot arm resistance of 0.1 $\Omega$, we obtain a useful nominal trip current of $I_o = 0.3$ A.

The speed of tripping is an important performance figure. Short of a full dynamic analysis, we can obtain useful analytic approximations as follows. As the temperature distribution approaches equilibrium, the rate of change will drop, as will the rate of increase of the actuation force.

If the equilibrium value of $F_c$ for a given current is denoted by $F_{eo}$, then we can approximate the rate of change of this latch release force by:

$$F_c(t) = F_{eo}(1-e^{-t/\tau})$$

(4)

We then need to estimate the time constant $\tau$. This we can do by approximating the rate of increase of $F_c$ at $t=0$, and equating this to $F_{eo}/\tau$ (the initial slope of (4)).

At the initial stages of heating, the temperature rise will be relatively uniform along the hot arm. Then the integral in (1) is given simply by $(T(x)-T_A)L_h$. Since the conductive cooling is initially negligible, the rise in excess heat per unit volume can be equated to the electrical power according to:

$$\rho_m c_p \frac{dT}{dt} = \frac{I^2 R}{A^2}$$

(5)
where $\rho_m$ and $c_p$ are the mass density and heat capacity respectively. We can then derive $dF_e(t)/dt$ from $dT/dt$, and thus obtain our approximation to $\tau$ as:

$$\tau = \frac{1}{12} \frac{\rho_m c_p}{k} L_h^2$$  \hspace{1cm} (6)

If the required trip force is $F_{eT}$, the trip time can be derived from (4) as $\tau \ln(F_{eo}/(F_{eo}-F_{eT}))$. Since the equilibrium force is proportional to $I^2$, we obtain:

$$t = \tau \ln \left( \frac{I^2}{I_o^2} \right) - I - I_o$$  \hspace{1cm} (7)

Taking values for $\rho_m$, $c_p$ and $k$ of 8900 kg/m$^3$, 0.45 kJ/kg-K and 900 W/m-K respectively, and $L_h = 2$ mm, the time constant $\tau = 18$ ms. For large over-current rations $I/I_o$, (7) reduces to $t = \tau (I/I)^2$.

### IV RESULTS

The devices were successfully fabricated with dimensions as described above. Electrical tests gave contact resistances below 1 Ω in nearly 50% of working devices, and trip currents near the design value at 300 – 400 mA. Fig. 4 shows a prototype device in the set (latched) state.

![Figure 4. Optical micrograph of circuit breaker latch area and contact in closed state.](image)

Trip times were measured as a function of the ratio of applied current $I$ to minimum trip current $I_o$. The results are shown in Fig 5, along with the theoretical prediction of (7). The fit is close for lower currents, but for over-current ratios above 2, the trip time is longer than predicted and appears to level off. One possible cause is the time taken for the mechanism to displace the small distance of the latch mating surfaces (20 µm). However, this time can be shown to be insignificant if inertial factors dominate. The total mass of the actuators is very low ($\approx 0.25$ mg), and the driving force will be a significant fraction of $F_{eo}$, since the dynamic coefficient of friction is significantly less than the static one. Taking the driving force as 100 µN gives a time to release the latch of $\approx 40$ µs. A non-inertial “sticking” effect in the latch may instead be the cause. In any case the measured trip times are orders of magnitude less than for PTCs of similar rating.

The variation of trip current with ambient temperature was also measured, and the results are given in Fig. 6. The slope is about $10 \times$ less than for PTC devices at 0.15 %/K.

![Figure 5. Trip time vs. over-current ratio: experimental values (solid line) and model (dashed line).](image)

![Figure 6. Trip current vs. ambient temperature.](image)
Si substrate. As the temperature rises, the trip actuator elongates with respect to the position of the set actuator (Fig. 1). The displacement needed to latch the two actuators together is therefore reduced. This lowers the holding force, and therefore the current needed to release it.

V CONCLUSIONS

MEMS circuit breakers are described based on thermal bimorph actuators. Trip times are found to be low, and to have a low temperature dependence, compared to PTC devices. A model for trip time is presented which gives good correspondence to measurements for low over-current ratios, but trip times are found to drop less quickly than predicted for high over-currents.

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REFERENCES