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Multiphysics Modeling and Optimization of A Polymeric Thermal Micro-actuator with An Embedded Skeleton

***G. K. Lau [1], J. F. L. Goosen, F. van Keulen [2]**

Department of Precision and Microsystems Engineering, Faculty of 3ME,
Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherlands
[1] gihkeong@gmail.com; [2] a.vankeuelen@tudelft.nl

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ABSTRACT

This paper presents modeling and optimization of a new class of polymeric thermal micro-actuator with a meander-shaped silicon skeleton (see Fig. 1). In the actuator design [1], the skeleton is embedded in a polymer block to improve heat transfer and reinforce the latter. In addition, the skeleton restrains thermal expansion of polymer laterally along the skeleton's sidewall but direct the thermal expansion in the transverse direction. Therefore, the polymer micro-actuator with the embedded skeleton features improved thermal response and high actuation stress, without compromising the actuation strain. In the present paper, the main focus is on the development of approximate models and their application in design optimization.

However, modeling of the present actuator is very involved. This is because the actuator has an intricate and complex geometry and it consists of multiple materials, namely an aluminum heater, a silicon skeleton and a SU-8 epoxy expander. Although it is designed for mechanical actuation, the actuator shows complex multiphysics behavior and responses to multiple stimuli (namely, electrical, mechanical and thermal). Therefore, a simple analytical modeling is very much needed to help design and optimize the actuator.

Approximate analytical modeling for the actuator is made possible based on geometrical simplification and property averaging. Heat transfer and generation happen along the same path of the highly conductive silicon skeleton and the aluminium heater. This enables electro-thermal modeling using a 1-D straightened heat path (see Fig. 2). On the other hand, thermoelastic behavior of the actuator can be approximated using the constrained thermal expansion of a rigidly bonded polymeric layer. These two relative simple models capture the actuator behavior at steady state, and are in good agreement with results of finite element simulations.

These presented models enable us to identify the most important design parameters that affect the actuator performance. These design parameters are volume fraction of the polymer expander and length of the meandered aluminium heater and silicon skeleton. Design optimization based on the models suggests that a design with 70% SU-8 can optimize the actuation work density. The optimized work density is 20.5% higher than that for a reference design with 50% SU-8 [2]. In addition, the optimized

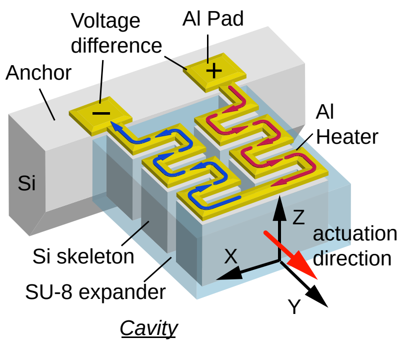

Figure 1: Illustration of a polymeric actuator with an embedded silicon skeleton (in a meandered shape).

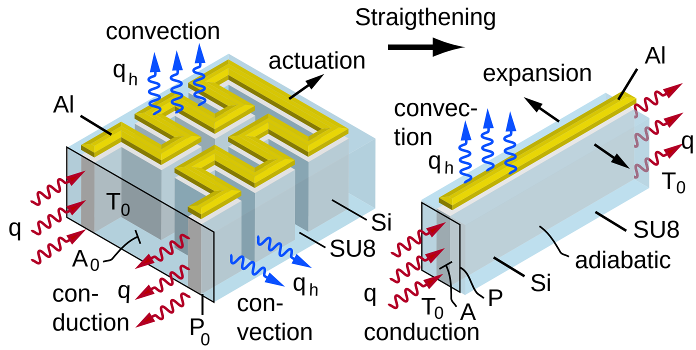

Figure 2: Model simplification by straightening the meandering heat conduction path.

Table 1: Performance of actuators with various volume fractions of polymer

Geometry and Performance	Symbols	Units	100% SU-8	50-50% SU-8/Si	*70-30% SU-8/Si
Volume fraction	ϕ	1	1	0.5	0.7
Actuator length	L_0	μm	480	480	480
Actuator width	$W = 2w$	μm	60	60	60
Actuator height	H	μm	50	50	50
Silicon thickness	t_s	μm	–	3	3
Polymer thickness	t_p	μm	480	3	7
Heater length	L	mm	(6.84)	10.46	6.84
Apparent CTE	α_c	10^{-6}/K	150.7	123.9	158.4
Apparent Young's moduli	E_c	GPa	3.2	9.80	7.1
Apparent stress	σ_c	MPa/K	0.48	1.25	1.18
Apparent work density	$\sigma_c \alpha_c / 2$	J/m^3/K^2	36.3	77.8	93.8
Time constant	τ_1	ms	(229.5)	120.9	97.7

design also exhibits roughly a 20% shorter thermal characteristic time constant because the heater length, which depends on the volume fraction, is shortened. The optimized performance is summarized in Table 1

In conclusion, effective approximate models have been developed and they enable inexpensive design optimization. As a result, a new actuator layout is proposed, which is significantly more effective than our prototype.

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