Optimal Design of the Electrothermal V-Beam Microactuator Based on GA for Stress Concentration Analysis

M. S. Suen, J. C. Hsieh, K. C. Liu, David T. W. Lin

Abstract—**The stress concentration of the electrothemal microactuator is an important issue in the MEMS structure resulting from the existence of stress concentration essentially to change the performance and reduce the structural life time of MEMS devices. This paper proposes a method to optimize the fillet radius of the electrothermal V-beam microactuators due to bent beam connected with electrical pad. The genetic algorithm combines with the finite element method to design the optimal fillet radius of bent beam. A novel design of the fillet radius on V-beam actuator can significantly improve the stress concentration. In this study, we use the proposed method to design the beam width and thickness to obtain the relative minimum stress, firstly. Then, the optimal fillet radius can achieve by using the same method at the given beam width and thickness. The results show that the stress concentration can be reduced about 57.7% after optimization.**

Keywords: **Fillet radius, stress concentration, genetic algorithm**

I. Introduction

In recent years, microactuators develop gradually in MEMS. Microactuators with capability of providing dynamic motion or static displacement has had enabled and demonstrated many applications, such as electrothermal microactuator, electrostatic microactuator, electromagnetic microactuator, piezoelectric microactuator and shape memory alloy microactuator. Electrothermal microactuators have been known as their large displacement and high force output. This characteristic is attributed by that static displacement generated from electrothermal actuators is formed by net volume expansion due to the thermal expansion difference distributed over the whole actuator structure. Electrothermal microactuators have been intensively studied for wide applications such as accelerometers, actuators, angular rate sensors, optical switch, wavelength-division multiplexers (WDM), optical attenuators and pick-up head of hard-disk drive, etc. Polycrystalline silicon is one of the most usually used structural materials in microdevices that have been investigated since past years. So concentration stress problem in the microactuators are obviously very important, will influence the device performance. In order to avoid the fracture of the beam in the beam stress, this paper proposes the optimal method used GA (genetic algorithm) to design the fillet shape of the electrothermal V-beam microactuator for decrease the beam stress.

As shown as Fig.1. [1] V-beam microactuator process technology has gradually matured. The poly-silicon microactuator beams are often fabricated on silicon wafer. Poly-silicon has been selected for saving device cost and convenient. When voltage is applied across V-beam structures, the electrical current leads to joule heating in the V-beam structures, the electrothermal microactuator will generate displacement and force to operate microdevices. MEMS technology has emerged to be the promising one for V-beam microactuators due to the advantages of high precision, small size and low cost, large displacement, high force output, action fast, easy to operate, simple fabrication process and so on.

Fig.1 The V-beam electrothermal microactuator [1]

In this paper, a simulation of the beam stress in the V-beam microactuator is used for designing fillet shape by genetic algorithm. The GA is an optimization-searching algorithm, which simulates evolution mechanism on a

M. S. Suen was with the Institute of Mechatronic System Engineering, National University of Tainan, Tainan 701, Taiwan, R.O.C. (phone: 886-0986-711-447; e-mail: yingdo0928@msn.com).
J. C. Hsieh was the Industrial Technology Research Institute, Tainan Taiwan, R.O.C. (e-mail: thermal88@yahoo.com.tw).
K. C. Liu was the Department of Mechanical Engineering, Far East University, Hsin-Shih, Tainan County, Taiwan 744, R.O.C. (e-mail: kcliu@cc.feu.edu.tw)
David T. W. Lin was with the Institute of Mechatronic System Engineering, National University of Tainan, Tainan 701, Taiwan, R.O.C. (e-mail: david@mail.nutn.edu.tw).

ISBN: 978-988-19251-2-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

computer-based platform in conjunction with natural selection and genetic mechanism. This paper proposes the simulation for beam stress concentration which is based upon the finite element method by ANSYS. Afterward, the results can combine optimal numerical method with genetic algorithm to design fillet shape of the actuator, and gain greatest benefits in improving the beam stress concentration of electrothermal microactuator beam. The main objective of the study is to identify the relationship between aspect ratio and fillet radius to improve the stress concentration problem. It is showed the SEM photo of typical fracture position of the microacruator in the Fig.2. [2].

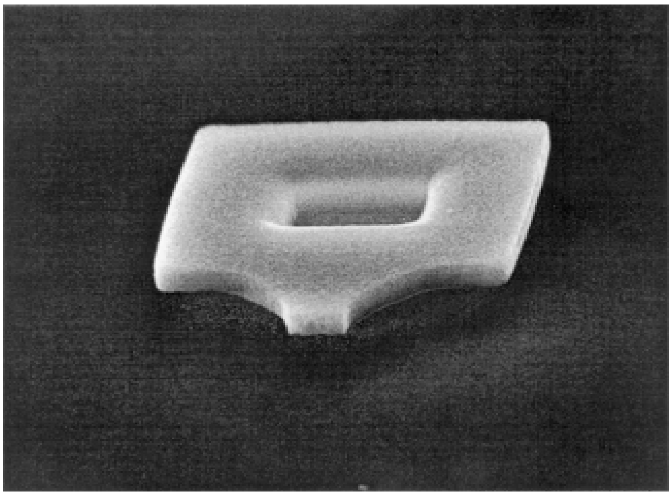

Fig.2 The SEM photo of typical fracture position of the microacruator [2]

Chen et al. [3] combined a new H-beam actuator, movement link structure, reflective micro-mirror, and arched buckle spring to demonstrate a new-compact latched 2×2 optical switch device is first reported. Yang et al. [4] presented a novel 2 × 2 MEMS optical switch using the split crossbar (SCB) design was demonstrated in this work. This SCB design consists of two fixed mirrors and two movable mirrors that are driven by electro-thermal V-beam actuators and the bi-stable mechanisms. Lee et al. [5] proposed the H-beam electrothermal actuator for providing bi-directional static displacement. The design concept and preliminary experimental results of H-beam actuators are presented in this paper. Due to its symmetric structural design, this H-beam actuator can avoid the influence from rotational torques during its bi-directional dynamic and static movement. Sassen et al. [6] presented an improved thermal actuator design, providing high work per unit of chip area. The actuator was developed for high accuracy fibre alignment. Lee et al. [7] verified new optical switch devices based on a bi-stable microelectromechanical structure driven by two sets of one-directional movable electrothermal V-beam actuators. Zhang et al. [8] illustrated a polymer V-shaped electrothermal actuator (ETA) array that is capable of compressing a live biological cell with a desired strain was designed, fabricated and characterized. Hocheng et al. [9] investigated that the influence of various dimensions and stress on the fatigue endurance is studied when an external force is loaded on the microcantileve beam. Based on the experimental results and ANSYS analysis, it shows that the longer specimen reduces the stresses when the displacement, width and thickness are kept the same. Simulation and analysis on the design of the fillet shape and aspect ratio are discussed in this paper.

It includes four sections in this paper. The first section introduces characteristics of electrothermal microactuator on the beam stress, and more investigation that researched for microactuator applications and simulations are stated. In the second section, it is illustrated numerical analysis and modeling in the electrothermal microactuators, and introduces to use genetic algorithm for reducing the stress concentration. Next part, results and discussions of the relationship between aspect ratio and fillet radius are proposed in third section. All contributions and possible applications of this study are concluded in last section. At last, it can be combined optimal numerical method by GA with the proposed simulation to gain greatest benefits in optimizing both aspect ratio and the shape of the fillet to increase the longevity of the V-beam electrothermal microactuators.

II. Numerical Analysis And Modeling

2.1 Thermal Energy Balance

As Fig.3 shown, the present device employs the V-beam thermal actuators for in-plane tracking for this study. The microactuators are actuated by electro-thermally. A temperature gradient develops as electrical current passes through the crank beams with electrical resistance. The energy conservation principle is applied to heat conduction assumed to exist in the body of the actuator and convection on the surface. The steady-state energy equation with a resistive heating source can be presented as [10]

$$\nabla(K\nabla T)+\frac{E^2}{\rho_e}=0 \tag{1}$$

where ∇ is the gradient, T is the temperature, and K, E, and ρ_e are thermal conductivity coefficient, electric field and resistivity, respectively. The boundary condition on the system is [8]

$$K\left(\frac{\partial T}{\partial x}n_x+\frac{\partial T}{\partial y}n_y+\frac{\partial T}{\partial z}n_z\right)=hA(T_w-T_\infty) \tag{2}$$

where n_i, i =x, y, z, is the direction cosine, h is the coefficient of natural convection, A the boundary area, T_w is the temperature on the boundary, and T_∞ the ambient temperature.

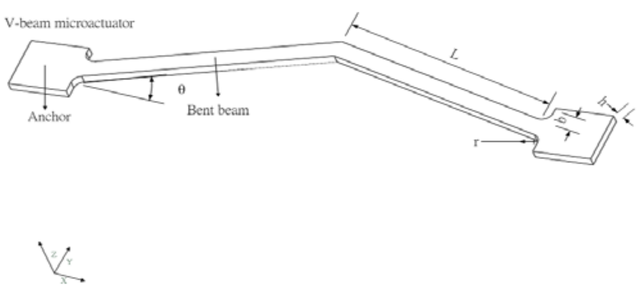

Fig 3 The geometry schematic view of model and parameter of the V-beam microdevice

ISBN: 978-988-19251-2-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

2.2 Thermal Expansion

As electrical current passes through the electrothermal actuator form anchor to anchor, the higher current density in the hot beam because the actuator to heat and expand more than in the lower current density; it will lead lateral arcing motion toward the cold beam side. For this in-plane structural element, the axial deflection, ΔL , due to thermal expansion can be obtained by [10]

$$\Delta L = \alpha L \Delta T \tag{3}$$

where α is the coefficient of thermal expansion of the material, L is is the original length of the element, and ΔT is the temperature difference.

2.3 The elastic curve and the secant formulation

In order to analyze an elastic material of the loaded pinned-pinned case, carried out for thin beam-columns with curvature, *dv/dx,* negligible compared to unity. The resulting elastic curve for the beam and the free body is determined from the governing equation by [11]:

$$EI\frac{\partial^2 y}{\partial x^2} = M = M_A - F_y = F_0 x/2 \tag{4}$$

With the boundary conditions

$$y\Big|_{x=0} = 0;\ \frac{\partial y}{\partial x}\Big|_{x=0} = \frac{\partial y}{\partial x}\Big|_{x=L/2} = \tan\theta_A \tag{5}$$

where *EI* is the flexural rigidity of the actuator, *F* is the reaction force along the x-axis used to model the effects of thermal stress, F_0 is the output force.

2.4 Maximum stress

A buckled beam under compressive loading is subjected to both axial and bending stress. The maximum stress is compressive and located at the midpoint on the lower surface of the beam. To consider the sum of the axial and bending components by [12]:

$$\sigma_{\max} = \sigma_A + \sigma_B = \frac{P}{bh} + \frac{h}{2I}\left|M(x = \frac{L}{2})\right| \tag{6}$$

where I is the beam moment of inertia, P is the pinned beam-column with a compressive load, and b is the actuator of width, and h is the actuator of thickness. The above governing equations along with the boundary conditions are solved by adopting the well-received multi-physics analysis method.

2.5 Finite Element Analysis

The present finite element model of the electrothermal actuator is generated with F.E.M by ANSYS. The Modeling is used 3-D element (SOLID98) to analyze a 3-D thermal-electro couple and structure. The element is defined by ten nodes with up to six degrees of freedom at each node. The joule heat generated by the voltage is considered in the heat balance. The bottom surfaces of the anchors are fixed in all degrees of freedom so as to simulate the practical bonding situation. The ambient temperature is set at $298.15K$ on the boundary surface. The coefficient of natural convection is $50\,Wm^{-2}K^{-1}$. In this study, the thermal radiation is also considered; the radiation of surface emissivity is set 0.7 and Stefan-Boltzman radiation constant is set 5.6704E-8 J/K^4m^2s . The temperature gradient develops in the modeling due to thermal conduction, thermal convection, and thermal radiation. It is assumed that the polysilicon is homogeneous, linear, and isotropic with Young's Modulus, *E*=161 GPa. All of the material properties of the actuator list in Table.1. At last, the maximum stress of the result in the model will employ to optimal method by GA.

Tab.1 Material properties

Parameter	Poly-silicon
Young's modulus (GPa)	161
Density(kgm^{-3})	2320
Poisson's ratio	0.33
Thermal conductivity ($kWm^{-1}K^{-1}$)	34
Thermal expansion coefficient($10^{-6}K^{-1}$)	2.3
Specific heat ($Jkg^{-1}K^{-1}$)	678
Resistivity (Ωm)	0.005

2.6 GA Optimal Method

The genetic algorithm is a numerical optimal technique based on natural selection by mimicking the concept of survival of the fittest. The genetic algorithm is a stochastic search method that borrows the operations and themes from natural evolution. The GA is eligible for searching the global optimal solution. The fitness function for the optimization problem established in Eq. (7) is defined as [13]

$$F(b) = \overline{F} - \prod(b) \tag{7}$$

where $\overline{F}$ is a predefined constant to ensure a positive fitness function. The GA simulated by four elements of the processes in natural genetic system for seeking the improvement of the fitness: populations evolve according to the principles of genetic reproduction to encode the structure of the individual, operators to influence individual (mutation and crossover), a fitness criterion to determine the best of each individuals among the old generation (elitism), and chose better population ranking according to solution fitness (selection). As Fig.4 shown is the flow chart of the genetic algorithm.

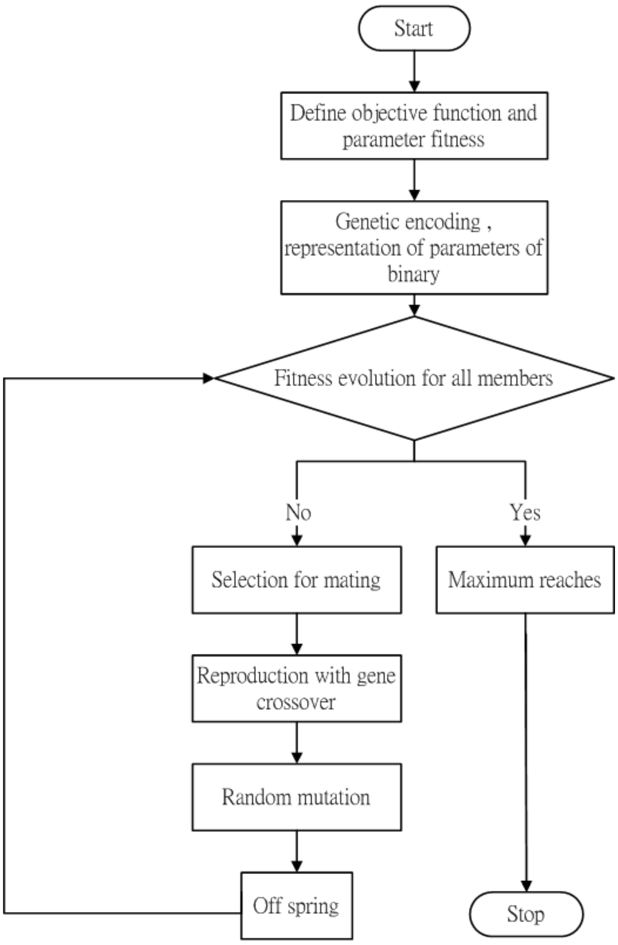

Fig.4 The flow chart of the genetic algorithm

III. Results And Discussions

This paper discusses the effects of geometry and fillet radius of bend beam of electrothermal actuator in stress concentration. The geometric parameters are width of the beam (b) and thickness of the beam (h), separately. It is obvious in the simulation of the electrothermal actuator which has the stress concentration phenomenon within the bent beam. It is a dangerous position in the bent beam due to device broken. The stress concentration problem can be improved and decrease in the bent beam, the device can avoid the fracture of the beam in the beam stress. In order to solve this problem, this paper proposes an optimal method with GA. The minimization of the objective function is accomplished by using GA method. In this case, the range of the width (b) is bounded within 1-30 μm, the range of the thickness is bounded within 1-30 μm, and range of the fillet radius is bounded within 1-15 μm. It is the nature of the genetic algorithm that is by random search, not for the initial specified position. There are 25 generations and 20 populations in the simulation. Crossover rate and mutation probability are taken as 0.5 and 0.001 respectively.

Following Fig.5, the profiles of the objective function with 25 generations. Different range of the initial width and thickness are changed in the model. As in the diagram displaying, the considering 25 generation stopping criterion, a better efficiently obtained. Fig.6 presented a profile of the stress distribution for changing the value of b and h. The variable b and h are dependent on each other. In this part, it is discussed the phenomenon of random variables to try to search the minimum of stress. The maximum stress of initial case is 685MPa and after the optimal process, the better minimum value of the objective function is 290.71(MPa), when b is equal to 3.31747 μm and h is equal to 2.439216 μm. After that, the better case is employed by GA optimal method again to find the fillet radius of the bent beam. The optimal results are showed in the Fig.7. The stress of bent beam is decreased to 289.95MPa. The result is thought as very well due to the stress concentration is reduced about 57.7%. It is worth mentioning that the maximum releases to the four corners of the anchor. Therefore, it also solves the stress concentration problem on bent beam.

The above optimal method proposes efficient a sequence of process steps toward achieving the ideal target. Beside, the phenomenon of stress concentration is improved and reduced the stress of the bent beam to avoid electrothermal actuator broken. This research can solve the stress distribution on the bent beam and design the optimal shape of the electrothermal actuator.

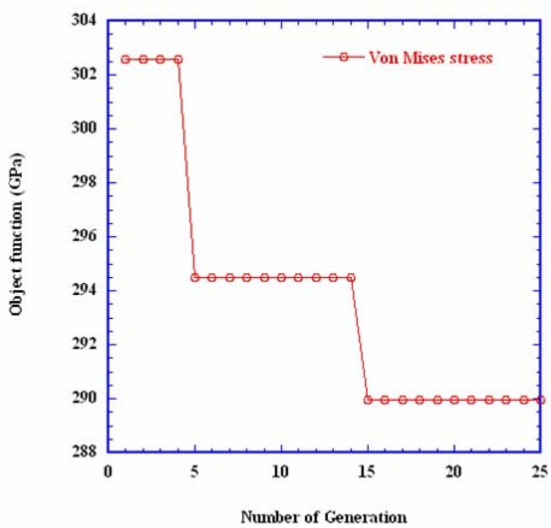

Fig.5 Variation of objective function with 25generations in GA method

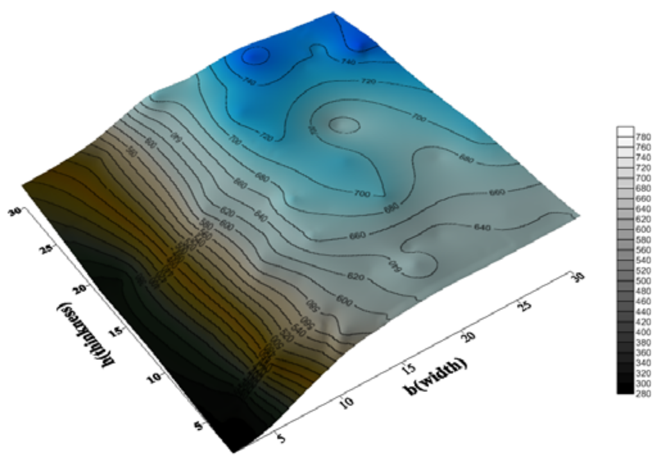

Fig.6 The relationship of effect objective function when b=1-30 and h=1-30

ISBN: 978-988-19251-2-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

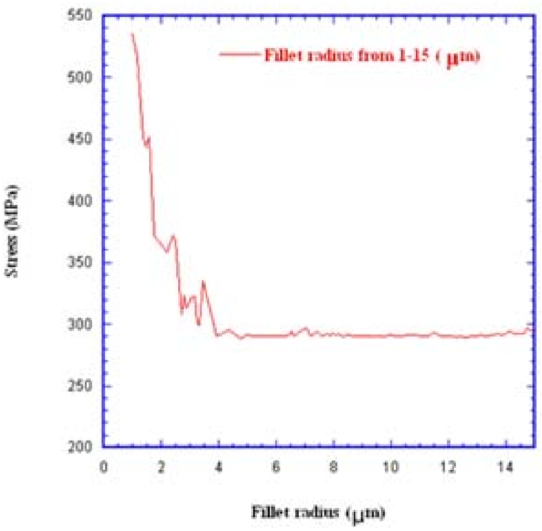

Fig.7 The results of different fillet radius on the bent beam by genetic algorithm

IV. Conclusion

The simulation of the stress on the bent beam is presented successfully in this study. The proposed method is the combination of GA and the finite element package. In order to obtain the better quality of the microactuator, the innovated design is illustrated to improve the stress concentration problem by changing the aspect ratio and the fillet radius. After the optimal process, the optimal result is better than the original case about 57.7%. Moreover, the bent beam stress will release toward the corners of the anchor. The significance of this study shows that the location and size of the bent beam junction are crucial for the design of the bend beam stress. This is not only a promising investigation, but also a better verification for handling a complex problem efficiently in the optimization techniques and the mechanical applications. In addition, it increases the lifetime expectancy of the actuator, and avoids the fracture of the beam due to the lower stress concentration. Finally, the advantage of the present method is an accuracy, stable, reliant, and efficient method to solve the stress concentration problem.

References

[1] J. Roberto and D. Arruda, "Aspects of Fabrication and Characterization of Electro-Thermal Micro-Actuators." *J. of the Braz. Soc. of Mesh Sci. & Eng*. Vol. XXIX, No.1/27, 2007.
[2] S. C. Bromley, L. L. Howell and B. D. Jensen, "Determination of maximum allowable strain for polysilicon micro-devices," *Engineering Failure Analysis*, Vol. 6, pp.27-41, 1999.
[3] W. C. Chen, C. Lee, C. Y. Wu and W. Fang, "A new latched 2×2 optical switch using bi-directional movable electrothermal H-beam actuators," *Sensors and Actuators*, Vol. 123-124, pp.563-569, 2005.
[4] Y. J. Yang, B. T. Liao and W. C. Kuo, "A novel 2 × 2 MEMS optical switch using the split cross-bar design," *J. Micromech. Microeng*, Vol. 17, pp. 875–882, 2007.
[5] C. Lee, "Novel H-beam electrothermal actuators with capability of generating bi-directional static displacement," *Microsyst Technol*, Vol. 12, pp. 717-722, 2006.
[6] W. P. Sassen, V. A. Henneken, M. Tichem and P. M. Sarro, "An improved in-plane thermal folded V-beam actuator for optical fibre alignment," *J. Micromech. Microeng,* Vol. 18, pp. 9pp, 2008.
[7] C. Lee and C. Y. Wu, "Study of electrothermal V-beam actuators and latched mechanism for optical switch," *J. Micromech. Microeng*, Vol. 15, pp. 11–19, 2005.
[8] W. Zhang, M. G. Generlich, J. J. Paly, Y. Sun, G. Jing. A. Voloshin and S. T. Lucic, "A polymer V-shaped electrothermal actuator array for biological applications," *J. Micromech. Microeng*, Vol. 18, pp. 8pp, 2008.
[9] H. Hocheng, J. N. Hung and Y. H. Guu, "Various Fatigue Testing of Polycrystalline Silicon Microcantilever Beam in Bending," *Japanese Journal of Applied Physics.*, Vol. 47, pp. 5256-5261, 2008.
[10] C. Kung and R. S. Chen, "Fatigue analysis of U-shaped flexural electro-thermal micro-actuators." Journal of the Chinese institute of Engineer, Vol. 28, No. 1, pp. 123-130, 2005.
[11] Y. B. Gianchandani and K. Najafi, "Bent-Beam Strain Sensors," *IEEE J.* of *Microelectromechanical Systems* 5(1), pp. 52-58, March 1996.
[12] M. McCarthy, N. Tiliakos, V. Modi and L. G. Fr´echette, "Thermal bucking of eccentric microfabricated nickel beams as temperature regulated nonlinear actuators for flow control," *Sensors and Actuators*,Vol. 134, pp.37-46, 2007.
[13] L. C. Sousa, C. F. Castro, C. António, "Optimal design of V and U beading processes using gentic algorithms, " Journal of Materials Processing Technology, Vol. 172, pp. 35-41, 2006.

ISBN: 978-988-19251-2-1
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)