Microelectronics Reliability 55 (2015) 771–782

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/microrel

Multiphysics modeling approach for micro electro–thermo–mechanical actuator: Failure mechanisms coupled analysis

Jinling Wang [a,b], Shengkui Zeng [a,c], Vadim V. Silberschmidt [b], Jianbin Guo [a,c,*]

[a] School of Reliability and Systems Engineering, Beihang University, Beijing 100191, China
[b] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire LE11 3TU, UK
[c] Science and Technology on Reliability and Environmental Engineering Laboratory, Beijing 100191, China

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 29 January 2015
Accepted 3 February 2015
Available online 13 March 2015

Keywords:
μETMA
Multiphysics modeling
FMMEA
Coupled failure mechanisms

ABSTRACT

The lifetime of micro electro–thermo–mechanical actuators with complex electro–thermo–mechanical coupling mechanisms can be decreased significantly due to unexpected failure events. Even more serious is the fact that various failures are tightly coupled due to micro-size and multi-physics effects. Interrelation between performance and potential failures should be established to predict reliability of actuators and improve their design. Thus, a multiphysics modeling approach is proposed to evaluate such interactive effects of failure mechanisms on actuators, where potential failures are pre-analyzed via FMMEA (Failure Modes, Mechanisms, and Effects Analysis) tool for guiding the electro–thermo–mechanical-reliability modeling process. Peak values of temperature, thermal stresses/strains and tip deflection are estimated as indicators for various failure modes and factors (e.g. residual stresses, thermal fatigue, electrical overstress, plastic deformation and parameter variations). Compared with analytical solutions and experimental data, the obtained simulation results were found suitable for coupled performance and reliability analysis of micro actuators and assessment of their design.

1. Introduction

A micro electro–thermo–mechanical actuator (μETMA) is one of key components in MEMS devices that are known for its advantages, such as low operation voltage, simple fabrication process and CMOS compatibility. Accordingly it has many applications, for instance in optical scanners, optical switches, micro-relays, etc. [1]. Based on different thermal expansions of two narrow "hot" arms and a wider "cold" arm, mechanical deflection of the actuator tip happens. Design of such a device is complicated by the fact that several physical phenomena are strongly coupled in the micro scale. Hence, designer's experience and intuition must be supplemented with multiphysics fields-coupled analysis.

Several research studies were conducted in the area of multiphysics design and analysis of μETMA. Colin illustrated a manufacture process and testing structure for better design in literature [2]. Zhu also employed an experimental approach to demonstrate the device performance and optimize its design [3]. Wilson tried to introduce new materials into micro sensors and actuators [4]. Additionally, more researchers were interested in modeling method to obtain practical information before fabrication. Huang [5], Jiang [6,7] and Yan [8] and others explained an analytical model to provide an insight into operation of actuators, and to predict their performance with new designs. Those studies have concentrated on performance-improving design and manufacture of μETMA, ignoring their reliability/failure matters. However, various unexpected failures under complicated thermo–electro–mechanical coupling mechanism and micro-size effects would greatly decrease its lifetime. Thus, failure mechanisms-incorporated assessment becomes an issue of critical importance for improvement of such devices used in critical applications and acceleration of their industrial uptake.

In recent years increasing attempts were undertaken to study failure behaviors of micro actuators by two ways. The first was the statistical approach based on experimental measurements of many devices. Standardized testing of actuators was partially covered in the Society of Automotive Engineers and Military via SAE J1221, SAE J575G and Military standard 750 [9]. Besides, at Sandia National Laboratories a special testing vehicle was

* Corresponding author at: Science and Technology on Reliability and Environmental Engineering Laboratory, Beijing 100191, China. Tel.: +86 01082313839; fax: +86 01082317663.

E-mail address: guojianbin@buaa.edu.cn (J. Guo).

http://dx.doi.org/10.1016/j.microrel.2015.02.012
0026-2714/

developed which was capable of providing failure test [10]. In order to assess the reliability under desired environmental and operational conditions, comprehensive humidity and temperature reliability tests were also implemented in [11]. And literatures [1,12,13] explained some typical failure mechanisms (such as friction, wear and fatigue), and their testing methods. Such experimental approaches resulted in some common disadvantages, including increased cost, required time and effort. So quite a few researchers tended to the second one based on modeling approach which could provide deeper study from the point of physical mechanism with better efficiency and less expense. Muratet [14] and Matmat [15] built a "virtual prototype" using VHDL-AMS language, aiming at estimating reliability of micro actuators based on failure data. Melle introduced a reliability modeling method to describe the dielectric charging kinetic [16]. In [17–21] typical structure failure phenomena, such as creep, fatigue and delamination of micro actuators, was analyzed based on Finite Element Method (FEM). However, physical modeling method regarding failure matters was still in its infancy stage. As well known, failure behaviors in μETMAs are more complicated because of their tiny scale, layered inhomogeneity and coupling of fields from different physical origins. A systematic failure analysis about μETMA has yet to be done, studying their failure mechanisms, modes, potential causes and effects. And understanding the coupled influence of various failure mechanisms on performance of actuators is also necessary for reliable product design.

To overcome these limitations, a failure mechanisms-coupled multiphysics modeling approach is proposed to study μETMA's performance, reliability and links between them. To obtain systematic failure information, FMMEA (Failure Modes, Mechanisms, and Effects Analysis) tool is employed, taking its advantages of discovering possible failure modes and design weakness from fabrication to operation. It concludes that residual stresses, creep/yielding/plastic deformation of nickel layer, electrical overstress, thermal fatigue, parameter variations, etc. play a significant role on reliability of micro actuators. Then the ways to incorporate these failure behaviors into functional model of μETMA are studied in the platform of COMSOL and MATLAB. Failure mechanisms-coupled analysis is finally implemented to provide recommendations for better device design before its practical fabrication.

2. Working principle of μETMA

Compared with electrostatic actuation, electro–thermal one offers high forces and large deflections, leading to lower contact resistances, reduced risk of stiction and better open-contact isolation. In combination with the use of a clamping mechanism to reduce the power consumption, these devices are well suited for stationary application. In this research a MEMSCAP DC switch (shown in Fig. 1(a)) is studied for failure mechanisms coupled analysis.

It is bi-stable and consumes no power in either ON or OFF position [22]. The switch is fabricated in the "open" position, and in order to close the switch, an appropriate switching sequence, i.e. heating sequence of the two actuators is performed (shown in Fig. 1(b)).

In an individual actuator, the key part is the U-shaped structure ("heatuator") containing two thin "hot" beams and a wide "cold" beam (shown in Fig. 1(c)). The "cold" beam, which is used to carry the electrical signal, is electrically isolated from "hot" beams, actuating the switch. Different thermal expansions are used to achieve motion along the wafer surface. Its working principle can be described in the following way: $U \rightarrow I \rightarrow Q \rightarrow \Delta T \rightarrow S \rightarrow \sigma \rightarrow D$. When voltage U is applied to the terminal anchor, current I flows through the two "hot" beams. Joule heat Q in the two beams leads to thermal stress S, expansion σ and ultimately mechanical deflection D. Detailed electro–thermo–mechanical analysis is given below.

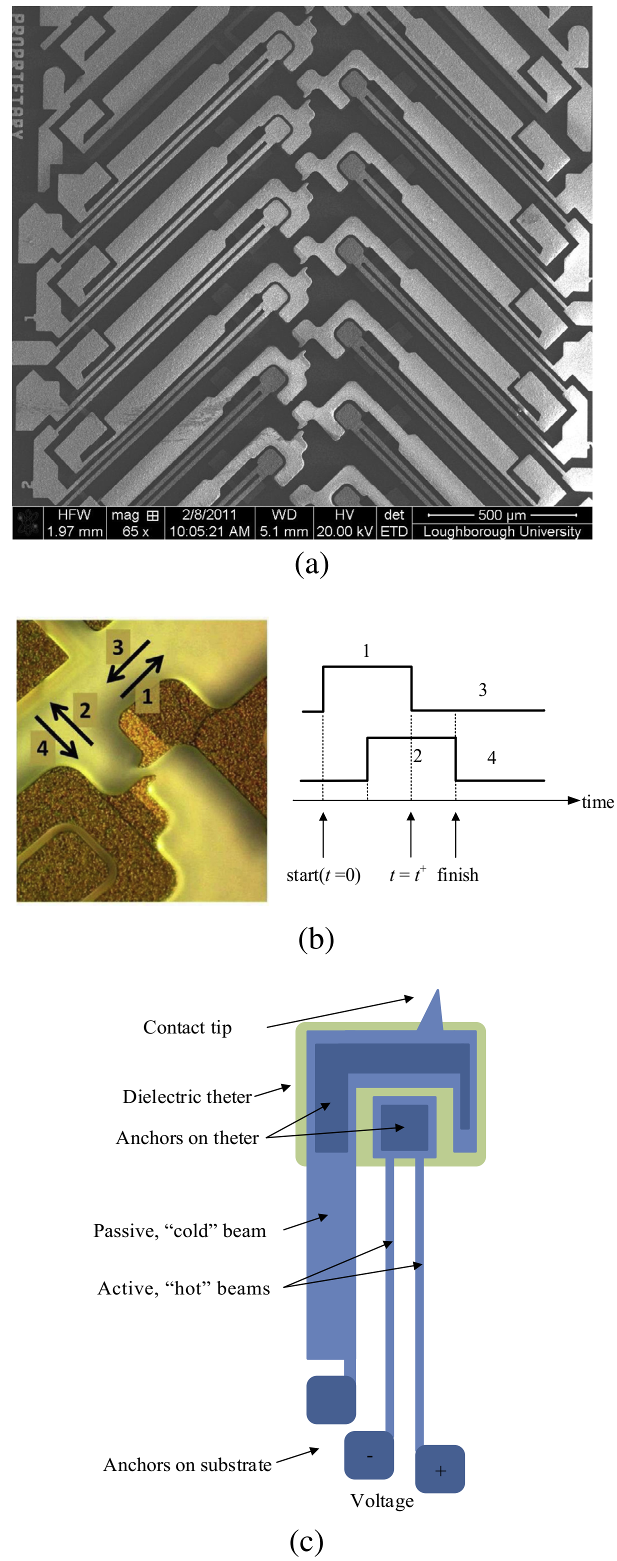

Fig. 1. μETMA: (a) Assembly in MEMS devices; (b) Latching sequence of the actuator; (c) It includes a passive beam carrying the electrical information ("cold" beam), two active beams for actuation ("hot" beams), a dielectric theter between the passive and active beam, a contact tip and some anchors [20].