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Design optimization of RF-MEMS switch considering thermally induced residual stress and process uncertainties

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ABSTRACT

This paper presents the Design of Experiments (DOE) based parametric design optimization of the Symmetric Toggle RF-MEMS Switch (STS) for minimizing the actuation voltage considering the fabrication process uncertainties and thermally induced residual stress. Initially, three-dimensional (3D) non-linear Finite Element Method (FEM) models are developed and the formation of residual stress during the plasma etching step of the microfabrication process is explained using the Bauschinger effect. The pull-in voltage values and the switch profiles obtained after the thermal loading–unloading cycle in the FEM models are compared with the experimental values and optical profile measurements which showed a close agreement. A DOE based Dual Response Surface Methodology (DRSM) is implemented to identify the significant design parameters affecting the STS switch pull-in voltage in the presence of thermally induced residual stress. Two separate response surface empirical models are developed; one for the mean pull-in voltage and other for variation in the pull-in voltage due to microfabrication process tolerances. The developed response surface models are optimized simultaneously using the desirability function approach. The optimal levels of the design parameters that result in minimum pull-in voltage with increased insensitivity to process uncertainties are obtained using the direct search algorithm.

1. Introduction

MEMS reliability is of primary concern for the designers with its increasing applications in several industrial segments in the form of pressure sensors, inertial sensors, micromirror arrays, inkjet printerheads and RF MEMS switches. Each of these devices has its own failure mode. For example, membrane stress in pressure sensors, fatigue and creep phenomenon in inertial sensors, impact wear in micromirror arrays, high temperature material interaction in thermal inkjet printerheads and high actuation induced charge induction in RF MEMS switches [1]. The MEMS reliability is generally considered at system, component and material levels. The tolerances related to MEMS fabrication process and material properties uncertainty, directly influence the reliability of the constituent components and hence the overall MEMS device [2–5].

The switching mechanism in the electrostatically actuated RF MEMS switch is achieved by using the pull-in effect. One of the major RF-MEMS switch reliability issues is the charge injection in the dielectric layer due to high actuation voltages [6]. Rangra et al. [7] have presented a new switch design based on the push–pull mechanism, named as "Symmetric Toggle RF-MEMS Switch (STS)", to achieve low actuation voltages and good electrical performance. Farinelli et al. [8] implemented the STS switch design to achieve high tuning range MEMS varactor. Dey et al. [9] used STS switch design as a building block of a true-time-delay phase shifter and presented a detailed structural analysis considering the effect of van der Waals and Casimir effects along with the electrostatic and restoring torque. The STS switch designs presented in [7–9] were fabricated using the gold electrodeposition process. The final fabricated devices showed an undesired deflection due to the presence of the residual stress which resulted in the high actuation voltages and deterioration of the electrical performance. The thin film gold is an excellent choice for the RF-MEMS due to its high conductivity and chemical inertness. But the high temperature fluctuations, extreme pressure, physical and chemical reactions and different resist layer etching methods used during microfabrication process affect the mechanical properties of gold and are considered to be the sources of the induced residual stress in microstructures [9–12].

Traditionally, an optimized geometrical MEMS configuration is achieved by developing analytical design models, FEM modeling, genetic algorithms, artificial neural networks and topology optimization [13–18]. For the robust design optimization, Shalaby et al. have proposed strength Pareto evolutionary algorithm for RF MEMS cantilever switches [19]. The genetic algorithms have been used for the robust design of MEMS accelerometer in [20]. The Monte Carlo simulations combined with the genetic algorithms have been implemented for the

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electrostatically actuated microbeam resonators [21]. Maute et al. [22] have used topology optimization for MEMS considering the stochastic loading and material properties. To improve the thermal reliability of the MEMS based quartz resonator, a design optimization is carried out using the FEM modeling in [23]. These optimization methods have proved to be efficient to a certain extent, but their inconvenience for the complex multiphysics MEMS devices and high computational costs raises the need for the alternative optimization methodologies. Moreover, the uncertainty in the fabrication process along with the device operating environmental conditions can result in a large deviation of a designed device output response from its expected value. Thus, it becomes vital to consider the microfabrication process uncertainties during the design optimization phase.

The DOE based robust design optimization has been widely used in different fields [24]. This approach explores the design space of a device in an efficient manner, resulting in minimization of high computational costs for the device performance analysis and optimization of the devices with complex geometries. The Taguchi method based inner/outer arrays and dual response surface methods are the two major DOE based robust design optimization methods. The goal of these methods is to identify and optimize the design parameters affecting the output response and simultaneously minimize the variations, induced due to uncontrollable factors. The limitation of the Taguchi method based optimization to be restricted only to the design points where the results were actually obtained makes the dual response surface method a preferable choice for the MEMS robust design optimization. The DRSM develops two separate empirical models, one for the mean value of the output response and another for the standard deviation due to the variations [25]. The two separate models help the designers to get a better understanding of the device behavior and optimize the design parameters for a desired output response with increased insensitivity to the uncontrollable variations.

The DOE based designs were originally developed for planning the physical experiments with the concept of blocking, replication and randomization to account the random error due to experimental variations. However, these designs have been effectively implemented for simulation experiments. Sacks et al. [26] have pointed out that since the deterministic computer experiments lack random error, the response surface model adequacy is determined only by the systematic bias. Simpson et al. [27] have argued that the trade-off for deterministic computer experiments becomes one of appropriateness vs. practicality and suggested to use some of the design parameters in the simulation as noise for replication and have the approximation of the random error. The high fabrication costs and long device development cycle makes implementation of the physical design of experiments impractical. However, with the development of the commercial MEMS simulation software that is capable of analyzing MEMS devices from the mask layout level to the final multiphysics level along with high performance computing, makes simulation based design of experiments approach a good choice for the robust MEMS design optimization. The main goal of this paper is to present a combined FEM modeling and DOE based dual response surface optimization methodology for the parametric design optimization of symmetric toggle RF MEMS switch considering the thermally induced residual stress and fabrication process uncertainties.

2. Symmetric toggle switch working principle

Fig. 1 shows the schematic and the working principle of the STS switch. The pull-in and pull-out electrodes, shortened by polysilicon lines, control the switching mechanism. The central bridge comes in contact with the bottom oxide layer when the pull-in electrodes are biased to an actuation voltage higher than the pull-in threshold. This sets the switch in off-state. When the bias voltage is applied to the pull-out electrodes the central bridge moves to a height double to zero bias height and the switch is in on-state.

3. Microfabrication process and FEM modeling of residual stress

3.1. Microfabrication process

The RF-MEMS switch specimens tested for the analysis of the residual stress are fabricated using RF Switch Surface (RFS) Micromachining process developed at the ITC-IRST research center (Trento, Italy) [28, 29]. This process allows obtaining the suspended microstructures through the gold electroplating process. A summary of the RFS microfabrication process steps is presented in [4]. During the RFS microfabrication process, following three main mechanisms result is the formation of the residual stress in suspended microstructures;

1. A chromium–gold PVD (10 nm Cr and then 150 nm Au) adhesion layer is deposited on the sacrificial photoresist layer. This layer, called the seed layer, is used to enhance the adhesion of the gold layer to the substrate. However, a diffusion of the chromium through the grain boundaries of the polycrystalline films occurs due to the reduced thermal stability of the gold. This leads to the formation of the Cr_2O_3 which results in the induced residual stress. The developed residual stress varies along the microstructure thickness due to irregular diffusion of the chromium.
2. A stress gradient is developed in the microstructures due to the difference in the coefficient of the thermal expansion (CTE) between the gold thin film and the photoresist. The CTE values for the gold and photoresist are 14.7 μm/m/°C and 68.6 μm/m/°C respectively [30]. A tensile residual stress develops at the interface between the gold and photoresist because the sacrificial layer expands at a faster rate than the gold layer. The induced residual stress and stress gradient create a bending moment and the gold microbeams deform immediately after the release.
3. The microstructure release in the RFS process is obtained by removing the sacrificial layer through plasma oxygen ($O+$) etching at 200 °C. The oxygen plasma etching process allows avoiding the problem of sticking which is a typical problem of the RF-MEMS devices. However, during plasma etching process, fast temperature variations occur and contribute to the formation of residual stress. High release process temperature of 200 °C causes the gold to reach the yield point, especially in the highly stressed regions like anchors and narrow parts.

In this study the last step of the RFS microfabrication process i.e. release of the STS switch specimens through plasma oxygen ($O+$) etching at 200 °C is modeled and its effect on the residual stress formation is analyzed.

3.2. FEM modeling of residual stress

The heating of the STS switch specimens to 200 °C during plasma etching step and the subsequent cooling to room temperature can be hypothesized as the material would be first loaded up to a plastic state and then unloaded and reloaded in tension. The development of the plastic deformation and the resultant formation of the residual stress in the STS switch can be explained with the Bauschinger effect during the thermal loading and unloading cycles. The stress–strain behavior of the metals for the elastic range is bounded by the yield stress limit σ_y. When the level of the stress is above the yield stress, the metal yields and exhibits an irreversible amount of deformations. After reaching the yield point the metals generally show the hardening behavior which is categorized as the isotropic hardening and kinematic hardening. A uniform expansion of the yield surface occurs during isotropic hardening while in the kinematic hardening the yield surface is shifted due to the reverse loading as shown in Fig. 2. The kinematic hardening is considered to be a good approximation of the Bauschinger effect, i.e. after metal is deformed plastically in one direction, under tensile or compressive stress, the yield stress in the opposite direction is generally lower [31]. The new yield point in the stress–strain curve during cooling of