Microelectronics Journal 71 (2018) 47–60

Contents lists available at ScienceDirect

Microelectronics Journal

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

Multiphysics design optimization of RF-MEMS switch using response surface methodology

Sadia Younis [a], Muhammad Mubasher Saleem [b,*], Muhammad Zubair [c], Syed Muhammad Tahir Zaidi [a]

[a] Department of Electrical Engineering, National University of Sciences and Technology, Islamabad, Pakistan
[b] Department of Mechatronics Engineering, National University of Sciences and Technology, Islamabad, Pakistan
[c] Department of Electrical Engineering, Information Technology University of the Punjab, Ferozpur Road, 54000 Lahore, Pakistan

A R T I C L E I N F O

Index terms:
RF-MEMS
Multi-response
Finite element method
Design of experiments (DOE)
Response surface methodology
Desirability function
Residual stress

A B S T R A C T

This paper presents the multi-objective geometric design exploration and optimization of an electrostatic Symmetric Toggle RF-MEMS switch (STS), considering both the electromechanical and RF characteristics simultaneously. The output responses considered for the STS switch optimization are pull-in voltage, switching time, insertion loss in the on-state and isolation in the off-state. Metamodels for the output responses, with respect to geometric design parameters, are developed using Design of Experiments (DOE) based Response Surface Methodology (RSM) and Finite Element Method (FEM) simulations. A single optimization objective function, considering all the four output responses and microfabrication process constraints, is defined and optimized for the design factors using combined desirability function and heuristic search algorithm approach. The predicted values of the output responses are verified through both the electromechanical and electromagnetic FEM simulations. The effect of residual stress, developed in the RF-MEMS switch during the sacrificial layer removal step of the microfabrication process, on both the electromechanical and RF characteristics of the final optimized switch geometry is analyzed using coupled structural-thermal-electric FEM simulations. The proposed DOE and RSM based design optimization technique can be implemented for the design space exploration and optimization of complex MEMS devices which involve coupled multiphysics interactions.

1. Introduction

In recent years, a rapid growth in the field of wireless communication has led to the evolution of RF-MEMS devices. These devices, fabricated at a microscale using micromachining technology, have enabled to achieve both power and bandwidth efficient wireless appliances. The RF-MEMS switches have been frequently used in wireless RF communication systems because of their low power consumption, small size, low loss, low intermodulation distortion and high linearity as compared to the traditional GaAs FET and p-i-n diode switches [1]. In an RF-MEMS switch the switching between the on and off states is obtained using the vertical deflection of suspended movable micro-plate. This deflection in the moving micro-plate is generally achieved using electrostatic [2–4], electrothermal [5–7] and electromagnetic [8,9] actuation mechanisms. Among these actuation mechanisms, the electrostatic actuation offers the benefits of less power consumption, simple microfabrication, and compatibility with a standard integrated circuit (IC) process and most importantly easy integration with the transmission lines [10].

One of the main drawbacks of the electrostatic RF-MEMS switches is their high actuation voltage to change the state from on to off state and corresponding high switching time. The switching mechanism in capacitive RF MEMS switches is based on the pull-in phenomenon, which is a sudden snap down of the switch top movable plate to the bottom fixed electrode. The pull-in phenomenon occurs when the electrostatic force exceeds the mechanical restoring force. Several designs, based on the electrostatic actuation, have been presented in literature to achieve low pull-in voltages and switching times. The low value of pull-in voltage and switching time is generally achieved by selecting the proper materials for low stiffness [11], increasing the overlap area and decreasing the gap between the suspended plate and fixed electrode [12], using a combination of both static and dynamic actuation [13,14], modifying the conventional electrostatic switch

* Corresponding author.
E-mail addresses: sadia.younis83@ee.ceme.edu.pk (S. Younis), mubasher.saleem@ceme.nust.edu.pk (M.M. Saleem), muhammad.zubair@itu.edu.pk (M. Zubair), tahirzaidi@ceme.nust.edu.pk (S.M. Tahir Zaidi).

https://doi.org/10.1016/j.mejo.2017.11.012
Received 11 August 2017; Received in revised form 16 October 2017; Accepted 21 November 2017

geometry [15,16] and using torsion actuators instead of parallel plate actuators [17].

In addition to the electromechanical response of a capacitive RF-MEMS switch, one of the most important design parameters is its RF characteristics, including low insertion loss and high isolation in on and off state, respectively. Recently, a few electrostatically actuated RF-MEMS switches have been presented in literature to achieve better RF performance. Dai et al. [18] presented a microwave switch fabricated using the 0.35 μm complementary metal oxide semiconductor (CMOS) process. The test results showed an insertion loss of −2 dB and isolation of −15 dB at 50 GHz. A capacitive switch with a return loss of −35 dB and insertion loss of −0.4 dB for a frequency band of 5–20 GHz has been presented in Ref. [19]. Aghaei and Sani et al. [20], proposed a comb structure to achieve insertion loss of 0.33 dB and isolation greater than 13.4 dB at 50 GHz. A float metal approach has been implemented to achieve peak isolation of 47.75 dB and insertion loss better than 0.10 dB for a frequency range up to 25 GHz in Ref. [21]. Yang et al. [22] presented an electrostatic RF-MEMS switch to minimize the effect of residual stress and achieved an insertion loss of 1 dB and isolation of 12 dB at 20 GHz. An insertion loss of 0.8 dB and isolation of 19 dB at 36 GHz is demonstrated for electrostatic RF-MEMS switch in Ref. [23]. Recently, Shekhar et al. [24] developed a capacitive switch with an insertion loss of less than 0.25 dB and 0.7 dB at 20 GHz and 40 GHz respectively, with an isolation of 30 dB.

The optimization of a MEMS device, for a particular output response, is generally carried out by developing complex mathematical device models, FEM simulations, topology optimization, genetic algorithms and artificial neural networks [25–30]. These optimization techniques are mostly implemented considering a single output response of a respective MEMS device. The traditional design optimization of MEMS devices, available in recent literature, mostly relies on the independent single-physics design optimizations of the device corresponding to each physics involved; and a logical combination of independently optimized designs provides an optimal design, as shown in Fig. 1. However, the traditional optimization techniques may not be an efficient approach for MEMS devices with complex geometries and involving coupled multiphysic interactions like structural-thermal-electric in electrothermal micromirros, electromagnetic-structural-fluid in RF-MEMS, thermal-structural and electric-structural in MEMS inertial sensors. The DOE based optimization technique has been implemented in different fields by planning the physical experiments [31]. The DOE technique is based on the concept of blocking, replication and randomness in the output response due to variations in the experimental conditions. However, the application of DOE based optimization for the deterministic computer simulations has also been successfully explored [32,33]. The optimization of MEMS devices using physical experiments is impractical due to the high microfabrication cost involved and specialized testing equipment requirements. With the development in the commercial MEMS simulation tools and high performance computing, the simulation based DOE optimization technique may be a good alternative for MEMS devices at the design level of the device development cycle.

In this work, we present a multiphysics co-simulation approach, as shown in Fig. 2, which takes into account all combinations of design factors to evaluate the multiphysics device performance. We employ DOE and RSM based optimization technique to find out which set of design factors, out of design space, influences the STS RF-MEMS switch performance and are significant design factors. These significant design factors are further explored for their effect on the output response of the switch by developing RSM based metamodels. Finally the simultaneous optimization of output responses related to two different physics is carried out using combined desirability function and heuristic search algorithm. The proposed design exploration and optimization technique overcomes the shortcomings of traditional optimization approaches and provides the easy way to implement an accurate solution for the optimization of RF-MEMS switches.

2. Working principle of the symmetrical toggle RF-MEMS switch

Rangra et al. [34], initially presented a STS RF-MEMS switch, working on the push-pull mechanism, to obtain low pull-in voltage and improved RF characteristics. Fig. 3 shows the schematic of a STS switch in which the central bridge is designed in a capacitive shunt configuration and switch is implemented over a standard 50 Ω coplanar wave guide (CPW) configuration. The switching phenomenon is controlled by the pull-in and pull-out electrodes of the torsion microactuators, shortened together by the polysilicon lines. When the actuation voltage to the pull-in electrodes is higher than the pull-in threshold voltage, the central suspended bridge comes in contact with the bottom dielectric layer on the RF transmission line and switch is in off-state. The switch is designed using the design rules of the RF Switch Surface (RFS) microfabrication process [35]. This process is developed to fabricate suspended microstructures using an electroplating process with a gold layer thickness of 1.8 μm and 4.8 μm. A detailed description of the switch microfabrication steps is presented in Ref. [36].

3. FEM based electromechanical and electromagnetic modeling

The pull-in voltage and switching time analysis of the STS switch, for different geometric design parameters used in DOE based optimization, is carried out using FEM based coupled multiphysics simulations in ANSYS. The switch geometry is modeled using 2D Shell 63 elements with the mechanical properties of thin gold film of RFS microfabrication process i.e. Young's modulus of 98.5 GPa, Poisson ratio of 0.42 and density of 19.32×10^{-15} kg/μm^3. The coupling between the electrical and structural domains for an electrostatic analysis is achieved using transducer elements (TRANS 126). These transducer elements provide a reduced-order FEM modeling of the coupled electrostatic-structural interaction. The transducer elements simulate the contact between the top suspended plate of the torsion microactuator with the bottom polysilicon layer as the pull-in occurs.

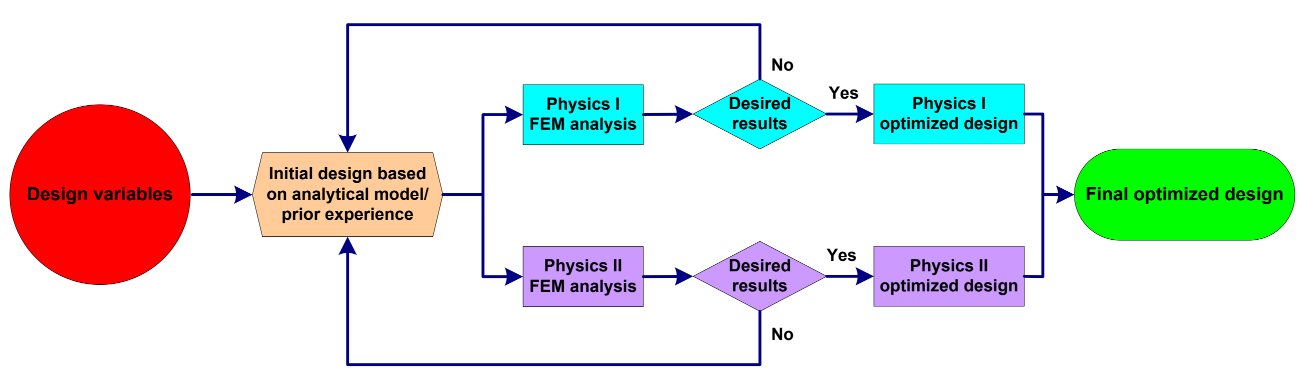

Fig. 1. Traditional design optimization approach for MEMS devices.