International Journal of Reliability, Risk and Safety:
Theory and Application / Vol. 1, No. 1, 2018
www.IJRRS.com

Probabilistic Physics of Failure (PPOF) Reliability Analysis of RF-MEMS Switches under Uncertainty

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Abstract

MEMS reliability analysis is a challenging area of research which comprises various physics of failure and diverse failure mechanisms. Reliability issues are critical in both design and fabrication phases of MEMS devices as their commercialization is still delayed by these problems. In this research, a hybrid methodology is developed for the reliability evaluation of MEMS devices. Its first step is the identification of dominant failure modes by FMEA, evaluation of failure mechanisms and an updated lifetime estimation by Bayesian method. The reliability of MEMS devices is studied using probabilistic physics of failure (PPoF) by determining the dominant failure mechanism. Accordingly, a deterministic model is selected for the analysis of the life and reliability of the dominant failure mechanisms. To convert the deterministic model to a probabilistic model, the uncertainty sources affecting the dielectric lifetime are determined. This model is simulated by utilization of Monte Carlo method. In the final stage, the results of life estimation are updated using the Bayesian method.

Considering the wide applications and advantages of RF MEMS capacitive switches, they have been selected for a case study. A framework is developed for the reliability evaluation of these switches failures due to stiction mechanism. The results contain FMEA table, lifetime estimation in different voltages, number of duty cycles and at the end, updated results of life estimation using Bayesian method.

Keywords: Bayesian updating; Dielectric charging; Probabilistic model; Reliability evaluation; RF MEMS capacitive switches; Uncertainty

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Nomenclature and Units

RF	Radio Frequency
MEMS	Micro-Electro-Mechanical Systems
MIM	Metal-Insulator-Metal
SRAV	Shift Rate of the Actuation Voltage
CDF	Cumulative Density Function
Vpi	Pull In Voltage
Vpo	Pull Out Voltage
V	Voltage
MC	Monte Carlo
MCMC	Markov Chain Monte Carlo
RPN	Risk Priority Number
FMEA	Failure Modes and Effects Analysis

1. Introduction

The prevention of failures and process of understanding why and how failures occur involves realization of the physics of failure. This requires studying physics of failure in general and failure mechanisms in particular. Studying the physics of failure is very important for reliability analysis. It has been done for many studies and for a broad range of mechanical and electrical failure reasons such as fatigue [1-6] and corrosion [7]. In this study, MEMS (Micro-Electro-Mechanical Systems) is selected for a case study and its physics of failure is investigated. MEMS technology has wide applications in areas of inertial navigation, RF/Microwave communications, optical communications, energy resources, biomedical engineering, environmental protection and so on. Today's, extensive use of MEMS devices and the increasing customer demand for highly reliable products, make MEMS reliability a more challenging task.

In recent years, RF MEMS (Radio Frequency Micro-Electro-Mechanical Systems) devices have been growing and gaining potential performance in commercial and defense communication systems in a

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broad range of frequency. Capacitive RF MEMS switches are frequently used devices in MEMS systems. These switches are quite attractive since they combine excellent RF performances and low power consumption of mechanical switches with the small size and low weight of semiconductor devices. RF MEMS capacitive switches show a great potential for use in wireless applications and are designed to operate in a wide range of frequencies from 0.1 to 100GHz [7]. RF switches designed with this technology have been demonstrated to havelow loss, low power consumption, low distortion, and higher off-state isolation as compared to p-i-n diodes or field effect transistors. However, before such switches can be used in commercial or spatial applications, they must demonstrate the ability to switch reliably over millions of cycles [8-9] or, as in the case of a redundancy switch, to maintain their electrical, mechanical and RF performances for a very long time. The appearance of MEMS switches in the market has been hindered by reliability issues [10].

1.1 A review on Previous Studies

Current publications on MEMS reliability involved almost every aspect of microsystems including structures, electrical components, materials, electronics, packaging and so on. Due to the importance of failures caused by dielectric charging in RF switch MEMS, the majority of research is centered around this device. Goldsmith et al. [12] modeled electrical load trapping in the presence of high electrical field by Poole-Frenkel conduction mechanism. They developed an exponential relation between lifetime, and applied voltage and estimated device lifetime in low voltages, accordingly. Van Spengen et al. [13] presented a theoretical model for zero release voltage as failure criteria. It was shown that the frequency of applied wave is not the sole factor in switch lifetime and it depends on the total time of switch. Melle et al. [14-15] introduced the Shift Rate of the Actuation Voltage (SRAV) parameter. The intensity of electrical tension was calculated and verified by comparison of experimental data with modeling results of the Poole-Frenkel conduction mechanism. Herfst et al. [16] presented an experimental model (square-root of time) demonstrating that the dielectric charging is governed by charge trapping in current induced metastable defects, also it is responsible for changes in the conductivity of silicon nitride MIM capacitors. Mardivirin et al. [17] proved the dependence of charging mechanism on the biasing signal by applying unipolar and bipolar waveforms with different duty cycles and modeled charging using a simple Curie-Von Schweidler equation. They showed that the duty cycle of the bias signal strongly accelerates switch failure and using bipolar signals improves the lifetime of these switches by several orders of magnitude. In the past years, reliability questions and technology acceptance were the main concerns limiting RF MEMS technology penetration into the expansive cellular market. Mechanical aspects such as creep and fatigue can derate the normal operating life as found inAu alloys [18], with the added inconvenience of self-heating produced by RF power [19]. However, none of these problems stood out as severely as dielectric charging that not only can cause drift in the switch performance, but also can shorten the switch lifetime [20]. Wispry’s tunable capacitor design minimizes the mechanical effects and mitigates the dielectric charging, so that the product can exceed the lifetime to enable its usage in the handheld cellular market (>2.5 BCycles at 65 °C). However, future applications will demand much higher lifetimes for the number of tuning events, and therefore, an extended lifetime will be needed. Yaqiu et al. [21] reviewed significant failure mechanisms of MEMS products and proposed a new correlative model for MEMS reliability evaluation. They developed a reliability model by considering both the effects of degradation mechanism on catastrophic failure process and the inverse situation. Based on the nature of different failure mechanisms, dependent factors of the correlations were discussed toward derivation of their mathematical models. Tavassolian et al. [22] studied the effect of dielectric material stoichiometry and substrate temperature on the charging performance and reliability of capacitive MEMS switches. Matabosch et al. [23] presented a novel failure investigation methodology dedicated to RF-MEMS capacitive switches based on a 250 nm BiCMOS BEOL technology. The research has dealt with the detection of failure mechanisms which have been identified by measuring the associated membrane height lowering, or even its stiction with the underneath RF line. Lamhamdi et al. [24] evaluated the effect of stress voltage and temperature on the dielectric charging and discharging processes of silicon nitride thin films used in RF-MEMS capacitive switches. The investigation has been performed on PECVD-SiNx dielectric materials deposited under different deposition conditions. In the previous paper, [25] failure mechanisms for MEMS devices were evaluated for determining the most common failures. For this propose, a deterministic model was selected for the analysis of the life and reliability of the dominant failure mechanisms.

An overview of the research undertaken in this field determines that most of these studies have identified all potential failure modes in the devices. The majority of researchers have presented deterministic models to estimate the lifetime.

In the present study, failure modes and effect analysis (FMEA) is used for systematic evaluation of the failure modes and their mechanisms and also identification of the dominant failure mode. After determination of the dominant failure mode, the designated failure lifetime of MEMS devices is estimated by a deterministic model. By detecting the uncertainty sources affecting dielectric lifetime, the deterministic model is converted to a probabilistic model. This model is simulated by utilization of Monte Carlo method by simple sampling from the uncertainty distribution of the parameters. The result of life estimation is then updated using the Bayesian method, in order to take into account the experimental data and also to have a better estimation of the parameters in the model.

The paper is organized as follows: Section 2 describes the method structure and its steps. Section 3 introduces the case study and demonstrates the modeling, results of FMEA and updated results, and the final section presents some concluding remarks.

2. Methodology Structure

In this research, a hybrid methodology is developed for evaluation of reliability in MEMS devices which includes six main stages. The methodology begins with identification of dominant failure modes by FMEA and culminates in the determination of updated lifetime by Bayesian method. The flowchart for the proposed method is shown in Fig. 1 with its main steps explained below.

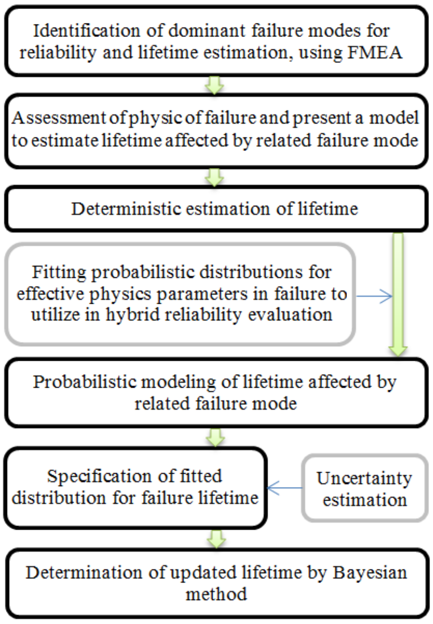


Fig. 1. Flowchart of hybrid methodology for evaluation of reliability in MEMS devices

A reliability evaluation of a device will be valid and attributable if all possible failures are identified and causes of failures as well as their impact on the device are specified. In this case, the most common failure in a specified device will be obtained and reliability research is carried out in this direction.

Failure Modes and Effects Analysis is a semi-qualitative risk assessment method which makes possible the use of linguistic expressions. It aims to identify potential failure modes, investigates their effect on the system, specifies the causes, prioritizes them, and allocates corrective actions to the crucial ones. In order to rank failure modes, each possible failure mode is valued by three parameters of severity (S), occurrence likelihood (O), and detection difficulty (D) to obtain a risk priority number (RPN=S×O×D[26]).

Monte Carlo Simulation method is an artificial sampling method which may be used for solving complicated problems in analytic formulation and for simulating purely statistical problems [27]. MC method procedure is composed of sampling from the CDF of each x_i parameter Fig. 2. In this research, MC is involved in the conversion of a deterministic model to a probabilistic one.

Simple random sampling is designed to take into account the dependency among the variables if the trend analysis shows that it is significantly available. This process is repeated for sufficient sample sizes to estimate availability values. F typical sampling for k elements in n iterations for estimating the availability function is given by [28]:

$$\begin{cases} x_1^1, x_2^1, \dots, x_k^1 = F(x_i^1) \\ x_1^2, x_2^2, \dots, x_k^2 = F(x_i^2) \\ \vdots \\ x_1^n, x_2^n, \dots, x_k^n = F(x_i^n) \end{cases} \tag{1}$$

Wherex_k^n is the n-th iteration of *k*-th parameter and F(x) is the cumulative distribution function.

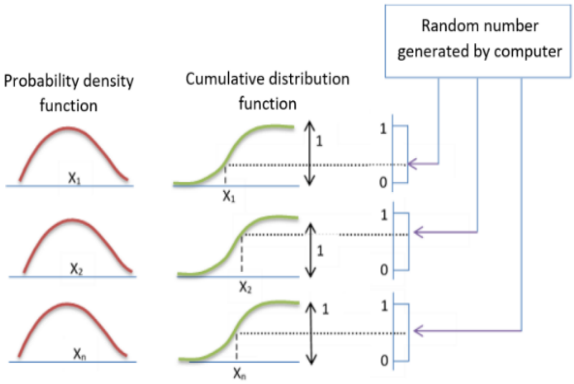


Fig. 2. A schematic of Monte Carlo sampling process [28]

Bayesian analysis uses a likelihood function, reflecting the information about the parameters in the data, and the prior distribution, which quantifies what is known about the parameters before observing the data. The prior distribution and likelihood are combined to form the posterior distribution. This posterior distribution demonstrates the uncertainty about the parameters and their functions. Bayesian theory corrects the prior distribution and generates secondary production by the following equation [29].

$$\pi_1(\theta|x) = \frac{f(x|\theta)\pi_0(\theta)}{\int f(x|\theta)\pi_0(\theta)d\theta} = \frac{f(x|\theta)\pi_0(\theta)}{f(x)} \tag{2}$$

where:

$\pi_1(\theta|x)$:posterior distribution
$\pi_0(\theta)$: prior distribution
$f(x|\theta)$: likelihood or Aleatory model
$f(x)$: marginal distribution

Because of failures modes' effects on the system, their control is essential. In this research, the failure surveying is done by FMEA, the dominant failure mode is recognized and modeling the wear-out life time is identified deterministically and probabilistically, respectively. The next target is the system's life time estimation. The obtained results of simulation are approached to the real life time results by including the random behavior of materials. The life time probabilistic distribution is obtained by considering the probabilistic distribution for effective parameters and utilization of Monte Carlo simulation method. Additionally, there are several parameters and factors which affect the failure physics that ignoring them influences the real result. These unknown results are included in model by updating the simulation results by empirical data. This process is done by Bayesian approach.

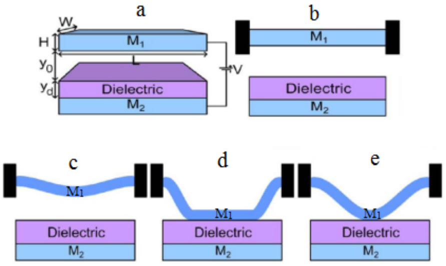


Fig. 3. A capacitive fixed-fixed beam RF MEMS switch [30]

3. Case Study

Capacitive RF MEMS switch is a frequently utilized device; however, its commercialization is currently hindered by reliability problems; so, this switch has been selected and analyzed as a case study for its reliability evaluation.

A schematic representation of an RF MEMS capacitive (fixed beam) switch is shown in Fig. 3. As the figure shows, the switch consists of two fixed and mobile electrodes, which are separated by a dielectric layer and an air gap [30].

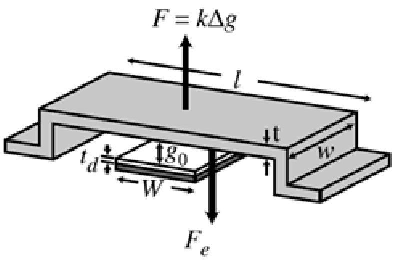


Fig. 4. RF MEMS switch schematic: (a) Switch situation before applying voltage, (b) Before pull in, (c) After pull in, (d) Before pull out [31].

Fig. 4 illustrates a functional cycle of a RF MEMS switch. Before applying any voltage (in off state), the fixed electrode is in up condition. As a voltage is applied, M1 is deviated due to the electrostatic force (FE) which pulls the mobile electrode (M1) downward until it is in equilibrium with the restoring mechanical spring force (F) (Fig. 4-c). In this position, the air gap is reduced up to one third. Higher than a certain voltage, called the pull-in voltage, Vpi, the balance between FE and F spring becomes unstable and the switch is in "On" position, which is marked by a sudden increase in the capacitance. Since the distance between the two electrodes is relatively small in this position, the electrostatic force is larger than the restoring force in the "On" state (Fig. 4-d), so that when the voltage is decreased again, the distance between dielectric and M1 decreases, too. At pull-out voltage Vpo (Fig. 4-e), a lower voltage than Vpi, the pull-out phenomenon occurs and a "On- Off" cycle is completed. In other words, the "On" state happens between pull in and pull out stages. At the end of this cycle, the voltage decreases to 0. As the electrostatic force is proportional to the voltage squared, this pull-in and pull-out behavior is present for both positive and negative voltages. For this duty cycle, the capacitive hysteresis diagram is shown in the Fig. 5 (C-V diagram).

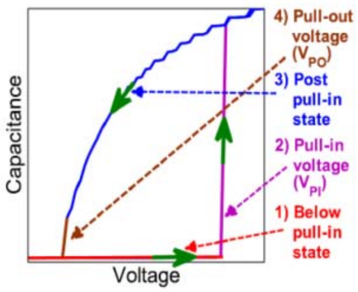


Fig. 5. Diagram of capacitance-voltage hysteresis in capacitive RF MEMS switch by unipolar driving voltage [32]

3.1. FMEA for RF MEMS Switch

In accordance with FMEA, there are various failure modes which can influence the reliability of RF MEMS switches, listed briefly in Table 1.

According to Table 1, there are several failure modes that affect the RF MEMS reliability. However, results of the literature review [11] and the data from ref. [33-35] show that the sticking caused by dielectric charging is by far the main failure mode in RF MEMS capacitive switches due to the presence of a high electric field across the dielectric, and the existence of point defects in these materials.

Table 1. Failure modes for FR MEMS switch

Row	Failure Mode
1	Sticking caused by dielectric charging
2	Micro welding of mobile electrode and dielectric
3	Elastic deformation of upper dielectric
4	Plastic deformation of upper dielectric
5	Short Circuit
6	Sticking caused by Capillary Forces
7	Fusing
8	Mobile electrode fatigue and breakdown
9	Dielectric breakdown
10	Corrosion
11	Corrosion between dielectric and mobile electrode
12	Wear and deformation of electrode
13	Self-actuation tools
14	Self-actuation caused by Lorenz Forces
15	Bumps, holes, cracks caused by Whisker's
16	Cracks and Micro-cracks caused by electrode's fatigue
17	Holes in the metal crystal and cracks, metal thickness variation, and short circuit caused by electro-migration
18	Sticking caused by Van der Waals Forces

3.2. RF MEMS switch modeling and physics of failure

Since silicon nitride (Si_3N_4) is one of the most widely used dielectric in RF MEMS [36], this dielectric has also been used for simulation in this project.

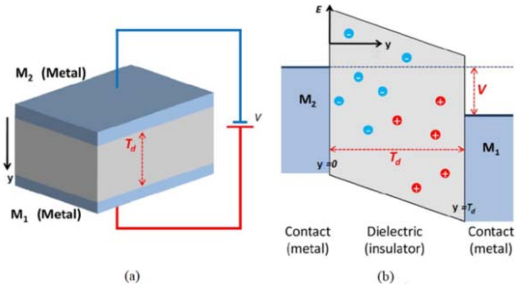
So far, various models are provided to evaluate dielectric charging in MIM systems. In most of the previous studies, Frenkel-Poole (FP) conduction mechanism [37] has been used for dielectric charging in RF MEMS capacitor switches and this mechanism is applicable for dielectrics with more than a micrometer thickness. Direct tunneling is another way for evolution of trapped charges within the dielectric with a thickness of less than 5 nanometers. Since the thickness of the dielectric used in a RF MEMS switch capacitor is between 100-500 nm, in this project, the combination of Frenkel-Poole (FP) and direct tunneling is found as a suitable model for this category of dielectrics.

Some assumptions are used for problem's simplification such as:

- One dimensional electric field
- Neglecting the electron penetration
- Monotonic condition for holes distribution
- Effective mass considered as an empirical parameter.

3.3. Description of the problem

The band diagram for MIM systems is shown in Fig. 6. This diagram shows the electron's energy in the various distance of dielectric. In this diagram, the vertical and horizontal axes show the electron's energy and the distance from metal-dielectric common area, respectively. The positive and negative signs show the holes and trapped electrons.



(a) (b)

Fig. 6. (a) A schematic of an MIM system with voltage V, (b) The band diagram of an MIM system [37]

Fig 7. shows the electron flux in an MIM system by the augmented method of direction tunneling and induction mechanism of Frenkel-Poole. In this figure, FT and FB (barrier height) represent the minimum required energy for the release of electric charge from trap and the difference between metal Fermi level and dielectrics conduction band, respectively.

According to the diagram, electron flux into the dielectric takes place through 3 ways, i. transmission of electron from metal surface into the existence traps in the dielectric (Jin), ii. transmission to the electrode surface, and at the end, iii. escape of the electrons from traps into the conduction energy band due to Frankl-Pool radiation process.

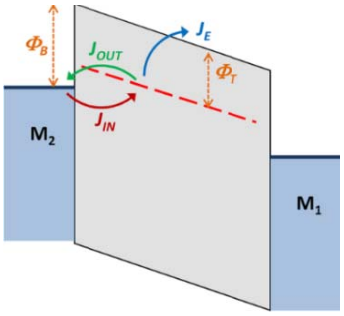


Fig. 7. Electron flux in energy band diagram [37]

3.4Calculation of current transmission and electron leakage

In this case study, the compact model is used for leakage and electron transfer current [37]. In this model, the energy band is divided to areas of R1, R2, R3 by trap depth, barrier height, and electric field as shown in Fig. 8.

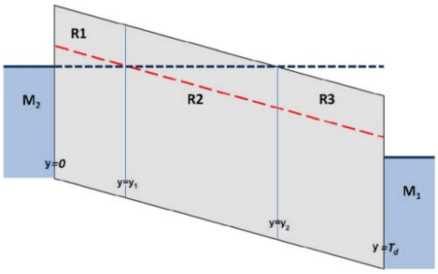


Fig. 8. Energy band in compact model [37]

Current transmission and electron leakage in a period of time is calculated by specifications of the dielectric and the following equations.

In compact model, y_1 and y_2 are calculated as below:

$$y_1 = \frac{\emptyset_B - \emptyset_T}{qE} \tag{3}$$

$$y_2 = \frac{\emptyset_B}{qE} \tag{4}$$

where, q and E represent the elementary electronic charge and electric field, respectively.

The J_{IN}, J_{OUT}, and J_E are calculated by equations 5, 6, and 7 [37] as:

$$J_{IN}(y,t) = A_{IN}(y)[N_T - n_T(y,t)] \tag{5}$$

$$J_{OUT}(y,t) = A_{OUT}(y) n_T(y,t) \tag{6}$$

$$J_E(y,\mathrm{t}) = A_E(y)\eta_T(y,t) \tag{7}$$

N_T and $n_T(y, t)$ represent the traps density and trapped electron density in the distance y and time t, respectively. The coefficients A_{IN}, A_{OUT}, and A_E are calculated by the following equations as:

$$A_{IN-R1}(y) = \alpha_{IN}\,\Delta y \exp(-\eta y + \xi y - \emptyset) \tag{8}$$

$$A_{OUT-R1}(y) = \alpha_{IN}\Delta y \exp(-\eta y) \tag{9}$$

$$A_{IN-R2}(y) = \alpha_{IN}\Delta y \exp(-\eta y) \tag{10}$$

$$A_{OUT-R2}(y) = \alpha_{IN}\,\Delta y \exp(-\eta y - \xi y + \emptyset) \tag{11}$$

$$A_E(y) = q\gamma\Delta y \exp(-\chi) \tag{12}$$

$$\begin{cases} \alpha_{IN} = \frac{2\pi^3 m^* q\sigma(k_n T)^2}{3h^3}, \eta = \frac{2\sqrt{2m^*\emptyset_n}}{h}, \ \ \xi = \frac{qE}{k_B T^2} \\ \emptyset = \frac{\emptyset_N - \emptyset_T}{k_B T}, \ \ \chi = \frac{\emptyset_T - \beta\sqrt{E}}{k_B T}, \ \ \beta = \sqrt{\frac{q^3}{\pi\varepsilon_0\varepsilon_\infty}} \end{cases} \tag{13}$$

where, m•, σ, γ, kB, T, h, η, ε0, $\varepsilon_\infty$are the electron's effective mass, trapping lateral segment, attempt frequency, Boltzmann's constant, environment temperature, Planck's constant, reduced Planck's constant, permittivity of free space, and optical dielectric constant, respectively.

3.5 RF MEMS switches Motion Modeling

Considering the function cycle of a MEMS system, the mobile electrode is regarded as a fixed beam. In the time period between the first voltage and accruing the pulling, the spring force of beam and electrostatic force are equivalent. Considering beam as two dimensional and utilizing Euler-Bernoulli equation, beam flexural deformation is calculated as equation (14) [38].

$$\rho WH \frac{\partial^2 y(x,t)}{\partial t^2} + b(y)\frac{\partial y(x,t)}{\partial t} + \frac{EI}{1-\upsilon^2}\frac{\partial^4 y(x,t)}{\partial x^4} = F_{electronic} = \frac{W\varepsilon_0\varepsilon_r^2 V^2}{2(y_d + \varepsilon_r y(x,t))^2} \tag{14}$$

ρ, W, x, y, t, b(y), E, υ, I,ε_0, v, ε_r, $y_d$are beam density, width, length direction, deflection in x, time, squeeze film gas damping coefficient, Young's modulus, Poisson coefficient, second moment of area, permittivity of free space, voltage, dielectric constant, and dielectric thickness, respectively.

Generally, the beam flexural equation can be calculated for every voltage using equations (14) by considering the geometry of RF MEMS switch, electrode and dielectric materials, and boundary conditions for fixed beam as below:

$$\begin{cases} y(0,t) = y(L,t) = \ y_0 \\ \frac{\partial y}{\partial x}(0,t) = \frac{\partial y}{\partial x}(L,t) = 0 \end{cases} \tag{15}$$

L is the beam length and y_0 is the air distance between the upper and the dielectric electrodes.

In a capacitive RF MEMS switch, in pull in and pull out modes, the upper electrode can be in contact with the dielectric and can be modeled as an MIM system. So, when the switch is turned on, dielectric charging will occur. According to [30, 36-37], already given, with the passage of time, the only parameter affecting the current transport and electron emission from dielectric will be the trapped electrons density (n_T(y, t)). The following equation is used to calculate the change rate of this parameter:

$$q\Delta y\frac{dn_T(y,t)}{dt} = J_{IN}(y,t) - J_{OUT}(y,t) - J_E(y,t) \qquad (16)$$

where J_{IN}, J_{OUT}, $J_E$are current flux for electron injection from the metal contact (M2) into the traps by tunneling, electron leakage from the traps into M2, and electron emission from the traps into dielectric conduction band, respectively.

By the increase of contact time between dielectric and the above electrode, the trapped electrons density will raise, causing more dielectric charging. Equation (17) represents the amount of voltage alteration by utilization of $n_T(y, t)$ at a random t.

$$\Delta V(t) = \frac{q}{\varepsilon_0\varepsilon_r}\int_{-yd}^{0} y n_T(y,t)dy \qquad (17)$$

The produced voltage difference is the cause for the electrostatic force increase acting on M1, and will change it according to the following equation:

$$F_{electrostatic} = \frac{W\varepsilon_0\varepsilon_r^2(V+\Delta V(t))^2}{2(y_d+\varepsilon_r y)^2} \qquad (18)$$

The increased electrostatic force acting on the electrode reduces pull in voltage (VPI) and pull out voltage (VPO). Pull out phenomenon will not occur, even without applying any voltage, if pull out voltage decreases to zero. In this situation, the electrode will not be separate from the dielectric and sticking occurs. Therefore, the failure will occur when the pull out voltage declines to zero. According to equation (4), if the potential difference caused by dielectric charging reaches the pull out voltage of RF MEMS capacitive switches in the static state, time interval is considered as the dielectric lifetime.

The below empirical equation [32] is used for pull out voltage calculation of RF MEMS as a fixed beam in the static switch.

$$V_{PO} = 26.74\sqrt{\frac{K_0 z_0^2}{C_{ON}}\left(\frac{y_d}{\varepsilon_r z_0}\right)^{0.1467}} \qquad (19)$$

$$K_0 = \frac{EH^3}{6(1-\upsilon^2)L^3},\quad C_{ON} = \frac{\varepsilon_0\varepsilon_r L}{y_d},\quad z_0 = y_0 + \frac{y_d}{\varepsilon_r} \qquad (20)$$

3.6 Deterministic lifetime estimation of RF MEMS switch

In order to estimate the lifetime of RF MEMS capacitive switches, firstly, lifetime of dielectric charging was calculated by its simulation in the MATLAB software [39].Then, the number of duty cycles of switch was assessed. For a silicon nitride dielectric with 250 nm thickness at 300 K, the estimated lifetime is shown in Fig. 9 for different voltages.

With the increase in the electric field, the energy of free electrons will raise in the metal-dielectric interface. Thus, the trapped electron density will reach to the limiting value more quickly. Accordingly, the use of RF MEMS capacitive switches in high voltage seriously jeopardies its reliability. The following equation is used to estimate the number of duty cycles of RF MEMS capacitive switches [31].

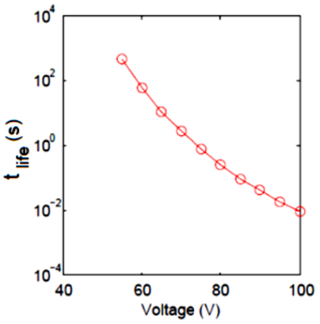


Fig. 9. The curve of lifetime estimation in different voltages for RF MEMS switch

$$N_{life} = \frac{t_{life}}{d_cT - t_{PI}} \qquad (21)$$

where,

N_{life}: duty cycle of switch before failure,

t_{life}: dielectric lifetime,

d_cT: pure functional time per cycle, and

t_{PI} : the time between start of applying pull in voltage.

Fig. 10 illustrates the number of duty cycles of RF MEMS capacitive switches for different d_cT over a range of voltage.

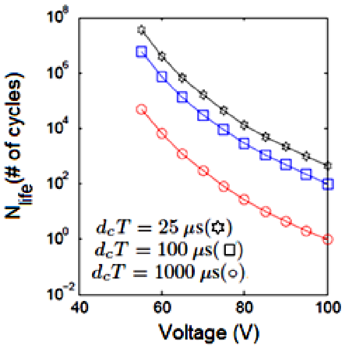


Fig.10. The number of duty cycles of RF MEMS capacitive switch

According to Fig. 9 and Fig. 10, at low frequencies and high voltages, the lifetime of the dielectric and, as a result, the lifetime of RF MEMS capacitive switches declined significantly. The deterministic model is converted to a probabilistic model by utilizing Monte Carlo method. In this research, due to the lifetime evaluation of capacitive RF MEMS switch in terms of its dielectric failure, Monte Carlo random variables included parameters affecting dielectric (Silicon Nitride) charging. Table 2 shows these parameters and relevant distributions.

These distributions have been selected according to the experimental data, expert judgment, and the results obtained from the statistical goodness of fit testing.

Table 2. The probabilistic distributions considered for variables in Monte Carlo simulation

Probabilistic variables	Distribution
Barrier height: ϕ_B (eV)	Uniform (1.2, 2.2)
Trap depth: ϕ_T (eV)	Uniform (0.7, 2.2)
Optical dielectric constant: ε_∞	Uniform (3, 7)
Electron effective mass: $^*m$	Uniform (0.1, 0.6)
Attempt frequency: γ (s^{-1})	Lognormal (1.5169, 29.188)
Capture cross section: σ (m^2)	Lognormal (1.506, -46.819)

3.7 Bayesian Updating Analysis and Uncertainty Results

Many unknown factors are related to dielectric charging and the presented model is no exception. Therefore, to account for these factors, improving outcomes and adapting it to the actual performance, the predicted lifetime results are updated using Win BUGS software [40]. Fig. 11 compares the prior and posterior distributions of failure lifetime at 60 V.

Potential uncertainties in lifetime modeling of dielectric charging are parameter uncertainty and model uncertainty which have been considered in the modeling and calculations. By comparing the prior and posterior distributions of lifetime in Fig. 11, it is clear that the initial distribution has a wide failure range, which is a challenge for decision making. However, by applying the MCMC method, the range of secondary distribution is shrank for less variability, and the uncertainty amount has increased. According to the updated distribution, the failure probability of the dielectric at 60 V and in the first seven seconds is more than all other times. So, it is concluded that the initial distribution has a high uncertainty, while applying the MCMC method significantly reduced the uncertainty of the secondary distribution.

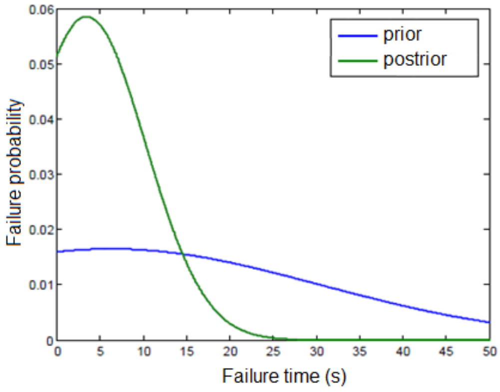


Fig. 11. Comparison of prior and posterior distribution of failure lifetime in seconds

4. Conclusions

In this research, a framework is developed for hybrid evaluation of reliability for MEMS devices. Capacitive RF MEMS switches are frequently utilized devices in MEMS systems. However, their commercialization is currently hindered by reliability problems. This device is selected here for reliability evaluation as case study. The results of studying the physics of failure and FMEA show the potential failure modes and prove that the sticking caused by dielectric charging is the main failure mode in RF MEMS capacitive switches. This is due to the presence of a high electric field across the dielectric and existence of point defects in these materials. By detecting the uncertainty sources affecting dielectric lifetime, the deterministic model is converted to a probabilistic model. This model is simulated by utilization of Monte Carlo method by simple sampling from the probabilistic distribution of the parameters. Modeling results show that dielectric charging has stochastic behavior. Finally, the results of lifetime estimation are then updated using the Bayesian method and utilization of MCMC method significantly reduces the uncertainty of the secondary distribution.

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