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Design and On-Line Test of Nano Electro-Mechanical Switch

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Abstract

In this paper, Nano Electro-Mechanical Switch (NEMS) was designed and simulated by using MATLAB simulation, then was tested by the on-line test through bias super-position. This switch has 4.5 nm thickness, offers low power dissipation, and permits nonstop observing of all essential jobs. On the other hand, some challenges are facing this Nano system. One of them is very difficult to resonators collective products with the same characteristics. The fabrication process was also complex and much hardness occurred during repetitive operations, which failure and stiction caused problems. In this work, a comparison between the response of a fault-free system and the system with some failures has been carried out. The test results showed a decrease in pull-in voltage with increasing overlap area as a result of wear failure mechanism in Nano Switch (NS). Creep in (NS) affected the value of the young modules and this increased the output voltage, also the crack in the beam of (NS) increased the effective mass and decreased output signal.

Introduction

There are many kinds of test techniques, have been used for integrated sensors such as Software-Based Self-test (SBST), System-On-Chip (SOC) testing, Built-in self-test (BIST), on-line test through bias superposition, electro-thermal stimulus test, etc. These tests are employed to detect errors and faults that appear during the system operation and affect the response of the device. Also, they indicate that the system in failure mode, which decreases the effectiveness of the mechanism.

All previous checks can be also separated into (On-line and Off-line) tests [1]. System-On-Chip (SOC) test and Built-in self- test (BIST) can be done when the device is offline, immediate the test cannot be operated under normal condition and have dangers in its output waveform if the medium is uncontrolled and perturbed. Heating the structure through the dispersing element is the way used to test the cantilever structure of the electro-thermal stimulus. These kinds of tests are called off-line because they cannot be performed during the work of the sensors [1, 2].

SBST and Wavelet-Analysis of Measurements (WAM) are online tests but with difficult and complex steps. In this paper, the NEM switch was monitored on-line by utilizing the bias superposition method to test it this technique was named on-line test through bias superposition. In this technique, the check signal (second signal) was added to the measurement input signal (carrier or first signal) by using an adder so the characteristics of the first signal must be selected differently from the characteristics of the second signal.

Furthermore, the second signal needs to exist chosen exclusive the bandwidth of the switch [3]. This manner is a low-cost way, simple, and is utilized to escape troubles in switch results, ensuring that the test result depends totally on the result of the first input rather than the exterior things induced by [1, 2]. Several researches are utilized this test method to check different types of Micro Electro Mechanical Systems (MEMSs) where on-line monitoring bias superposition method for

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integrated micro capacitive accelerometer (2.6mm2.6mm) accelerometer area with 10 thick of accelerometer mass) was presented [4].

When the device operates without any fault then it is called the first case and if a defect was adopted, it is called the second case, however, the effect of disturbances caused by the environment in this work was not taken into consideration. Therefore, the system proposed by [5] in which the on-line test method through bias superposition is used with a micro accelerometer that has an area equal (2.6 mm×2.6 mm) and with 100 thick accelerometer mass. In this paper, disturbance due to the surrounding environment is considered when the thick of the Nano accelerometer mass is 3.3nm.

Principles of Bias Superposition

Figure 1 illustrates the general structure for the bias superposition technique where the test stimulus is placed inside the configuration of the Nanoelectromechanical switch to check if it works normally and gives us accurate outcomes or not because of a certain kind of failure mechanism. The bias superposition technique is a simple and low-cost method because it does not require modifications to the design of the device to generate the stimulus.
Typically, a square wave signal with half of the period is ON (duty cycle is 50%) and is utilized as a second signal. This second signal (test signal) is modulated with an input signal (duty cycle is 70%). It can be recognized that the output of test signal is non-ideal and need filtration; therefore, suitable filters are required to extract the acceptable output information [5]. Then to know this sensor is worked without any defect and is offered the correct outcome or not due to a certain kind of defect. We make a comparison between the two test signals and if the output signal of two cases is similar in phase, amplitude, and frequency, this means Nano switch (NS) has no-fault and operates with no defect otherwise the device operates with fault.

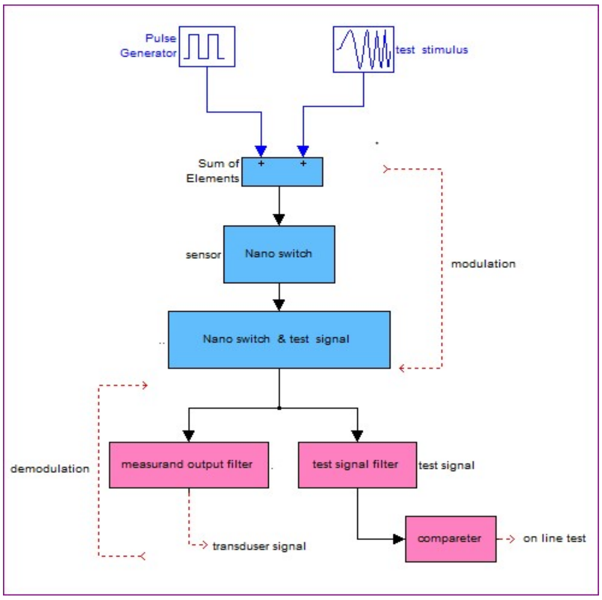

Figure 1 Test of (NS) including Bias Superposition

Nano Electromechanical switch

Overview

In this paper, the NEM switch was taken as a case study. This switch consists of two parallel plates (movable and fixed) with three-terminals; drain, source, and gate, and an actuation gap (go) that separates these two parallel plates of the electrostatic switch [6, 7]. Figure 2 illustrates the generic three-terminal electrostatic switch.

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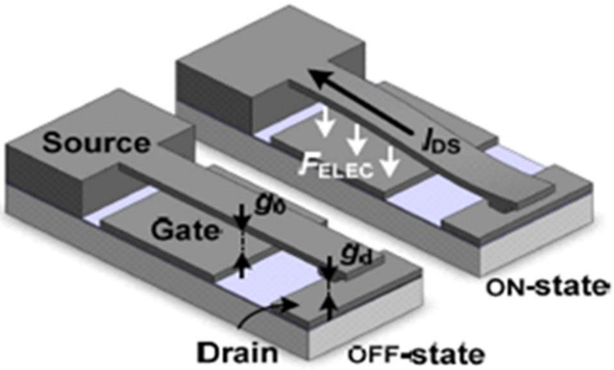

Figure 2 basic Planar of three-terminal Electrostatic Switch [7]

Principle of Operation

The principle of electro-mechanical devices operation is the electrostatic attractive force produced due to voltage applied across the plates and this will accelerate the movable electrode toward the fixed electrode. The area of the two electrodes and the actuation gap, which splits electrodes, are factors on which the weakness of the electrostatic attractive force depends [3, 8]. Another force impact on the electromechanical device is spring force produced because the moveable part is suspended by a spring, so it has an elastic constant.

In general, electro-mechanical switches have ON and OFF states. The current, from source to drain is limited and near to zero leakage current due to the air gap between drain and source. Therefore, the current does not move from one electrode to another, and the device in the OFF state. During the OFF state, Vgs (voltage between gate and source) is smaller than the release voltage (the voltage that is needed in order to pull-out the device) [9]. If electrostatic force overcomes spring force this leads to providing a conductive path for current to flow and the device becomes in an ON state.

Mathematical Model of Nano Electromechanical Switch

A second-order spring-mass-damper system equation has been utilized to define the mechanical model of the Nanoelectromechanical switch, at what time we applied voltage between the first electrode (drain) and the second electrode (source). Translate of a mobile part in nano switch is overseen with the aid of equation (1).

Nonlinear 2nd order differential structure can be expressed by utilizing three factors, namely: the inertial proof mass m, nonlinear viscous damping b, and spring constant k, [10-14].

$$F_{ele}(X) + F_{vdw}(X) = m_{eff}\ddot{X} + \frac{\sqrt{Km_{eff}}}{Q}\dot{X} + KX \quad (1)$$

Where: F_{ele}: Electrostatic force, F_{vdw}: Van der Waals' force, m_{eff}: is the effective mass,

X: displacement of a gate in Nano switch, Q: quality factor [10^3-10^4], K is spring constant

Simulink Model of NEMS

The system shown in Figure 3 was modeled in MATLAB / Simulink, input square wave signal (70% duty cycle) with 10 HZ frequency of input signal. This signal is multiplied by 9.81 gains to give us an equivalent acceleration by utilizing equation (2).

$$a = \left(\frac{V^2}{2}\right)\frac{\partial c}{\partial x} \quad (2)$$

Where: v is the input voltage, x is the displacement of the gate and c denotes capacitance and can be calculated by equation (3).

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$$\mathbf{c} = \frac{\varepsilon_o \varepsilon_r\ A}{x} \qquad \mathbf{(3)}$$

As displayed in Fig 3, the square first signal (input) before amplification could be gotten.

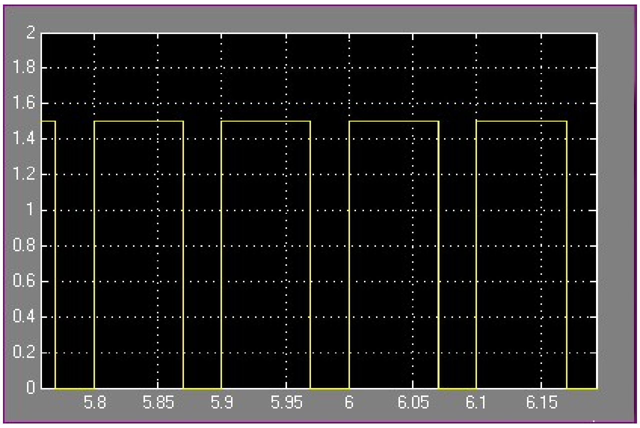

Figure 3 Waveform of First Signal (Input Signal)

Nano switch test process provides an on-line test by using a bias superposition method, this process is active when the second signal is put in the construction of NEMS to test it, if it works without any fault and results in the right outputs or not due to some kind of fault. Then the output is filtered by a Butterworth structure of a second-order high pass filter with a cutoff frequency equal to 100 Hz was designed to remove unwanted signals and get input signal as shown in Figure 4.

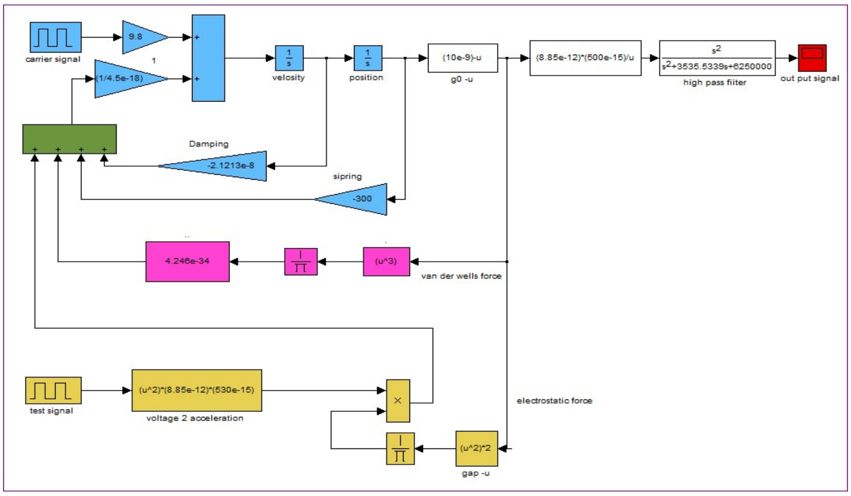

Figure 4 the Simulink Model of Nano Electromechanical Switch

Nano Electromechanical Switch (NEMS) Simulation Test Results

The output characteristics of the above model (NEMS) are presented in Figure 5 (without any defect), are tested by employing an on-line test through the bias superposition method. The influence of wear, fracture, creep, and crack is considered in this test. Where a square wave is entered to this model, a 1.5 V peak amplitude, for 70% of the cycle, will activate the ON state and a 0 V, for 30% of the cycle, will activate the OFF state. The output wave of this model can be seen with two levels, the high level is $2.55*10^{-22}$ V denoting the ON state, while the low level is roughly equal to zero denoting to OFF state. This outcome can be offered when the Nano switch normally works (without failure mechanism).

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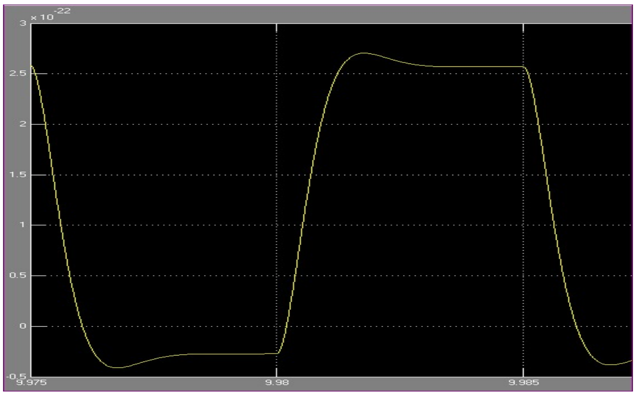

Figure 5 Output of Nano Switch without any defect

To test Nano switch whether it works in failure mode or not, a comparison must be carried out between the output signal of Nano switch (under testing) and the output signal when the switch runs normally. If the two signals have the same frequency, identical in phase, and equal in amplitude, this signalizes that the switch operates without any fault while any difference in these three properties is attributed to some defects or failures in the Nano switch.

Creep in Nano Electromechanical Switch

The creep in the switch variation spring factor k affects the value of the young modules $\boldsymbol{E}$. This will alternate the response of Nanoelectromechanical switch, when the spring factor increases from 10 Nm^{-1} to 500 Nm^{-1}, this leads to an increase in the level of output voltage from $1.14*10^{-23}$ V to $2.5*10^{-22}$V as seen in **Error! Reference source not found.**.

Wear in Nano Electromechanical Switch

The corrosive in Nanoelectromechanical switch, because of the environmental impacts, will result in wear in the switch and impact on the system parameters (effective mass and damping factor), then will decrease pull-in voltage accordingly to increase in overlapped area between gate and electrode body as shown in **Error! Reference source not found.**.

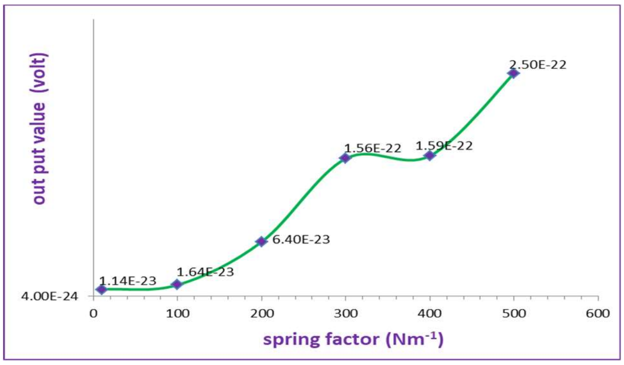

Figure 6 increasing in the output of Nano switch due to an increase in the value of spring Factor

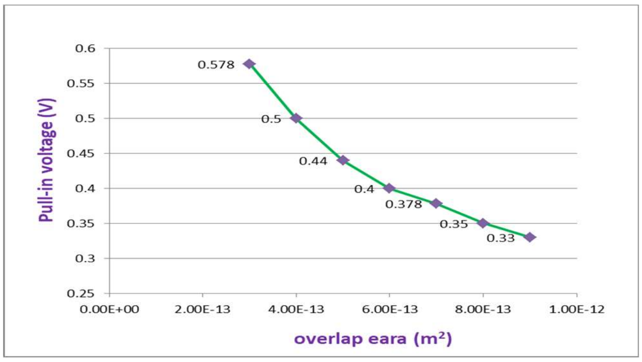

Figure 7 Inverse proportionality between pull-in voltage and overlap area

Cracks in Nano Electromechanical Switch

The crack in the beam of Nano switch affects resonance frequency and stiffness and leads to an increase in the effective mass also variates in the response of Nano switch. Figure 8 shows a reduction in the response of the Nano switch from $5*10^{-16}$ V to $3.89*10^{-17}$ V when the effective mass increased from $6.5*10^{-18}$ to $6.9*10^{-18}$ g this change in response denoted that the Nano switch works in failure mode due to the crack in its beam.

Figure 9 explains that the resonant frequency is changed due to increasing the effective mass, where decreasing the resonant frequency leads to increasing the time that is required to change the state of Nano switch from ON to OFF and this will decrease the speed of Nano switch.

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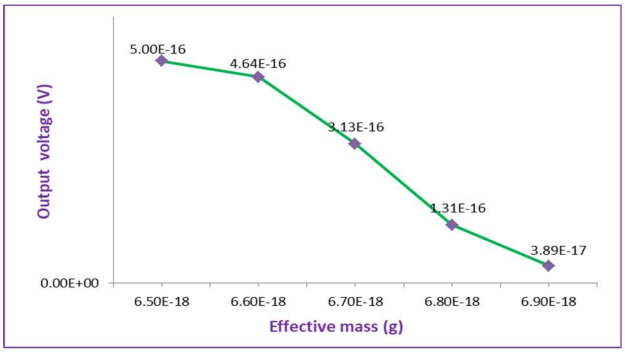

Figure 8 decreasing output signal because of increasing effective mass

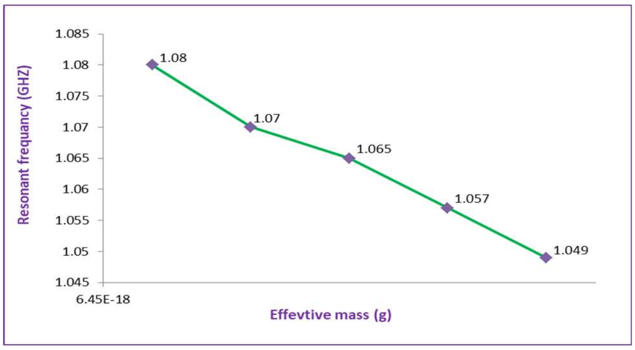

Figure 9 Resonant Frequency is decreased when the effective mass is increased from 6.5*10-18 g to 6.9*10-18 g

Conclusion

The nanoelectromechanical switch had been modeled in MATLAB/ Simulink and then had been tested by utilizing an on-line test through a bias superposition technique. Here, there is no need for any modifications to the switch to apply this test technique. Only the test signal was injected in the bias structure of the sensor to achieve the correct test operation. Low cost and on-line test capability were presented. Therefore, this test technique had been used. Downsizing of the switch in the Nano scale was led to increasing the random collision of air molecules, ultra-small mass and Van der Waals had been great affected in this design. The test results showed Wear and Crack in the beam of Nano switch (NS) was increased the effective mass and was decreased output signal. While Creep in Nano switch (NS) was led to increasing output signal.

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