Fault Simulation of Surface-micromachined MEMS Accelerometer

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Abstract

Surface-micromachined MEMS accelerometers have been used in many applications, such as automobile airbag deployment systems and aerospace inertial navigation. Due to the movable parts involved and their diversity in device structure and working principles, MEMS devices are vulnerable to much more defect sources compared to their VLSI counterparts. Typical defect sources for MEMS devices include point stiction, etch variation, broken-beam, etc. Such defects may greatly lower the fabrication yield and degrade the device reliability. It is important to understand the MEMS failure mechanisms and see how various defects will affect the device behavior. In this paper, point stiction defect in a surface-micromachined MEMS comb accelerometer is investigated. ANSYS simulation is used to see how the influence of the point stiction defect on device behavior depends on the locations of the defect. ANSYS model for the defect-free device is developed and simulated. After that, point-stiction defects are injected to simulate the faulty device behavior. Simulation results demonstrate that depending on the location of the defects, the influence on the device behavior may be trivial, parametric or fatal. The fault simulation of MEMS accelerometer is helpful in finding an effective testing strategy for MEMS devices. It may also offer some hints on how to further improve the yield and reliability of MEMS.

I. Introduction

As a newly emerged interdisciplinary technology, MEMS (Microelectromechanical Systems) have achieved tremendous progress in the past decades. Due to its small size, low cost, low energy consumption and high resolution, MEMS devices have been used in many fields such as automobile, light display, optical and RF communications, biomedical devices. For MEMS commercialization, the yield is an important issue. Furthermore, with more and more MEMS devices utilized in safety-critical applications (e.g. aerospace, biomedicine), MEMS reliability is also becoming a serious concern. Both yield and reliability of MEMS devices are related to the failure source of MEMS. In order to improve the yield and reliability of MEMS, it is imperative to study the MEMS failure mechanisms and how they will affect the behavior of MEMS devices.

Unlike the VLSI circuits, most MEMS devices have movable parts. Further, due to the multiple energy domains involved, and the diversity in MEMS structures and their working principles, MEMS devices are vulnerable to many more defect sources compared to its VLSI counterpart. A failure source is any abnormality in the fabrication process that causes a defect, where a defect is any physical (structural or material) change from the intended design. A defect causes misbehavior if one or more performance specifications of the defective device fall outside of the specified acceptable range. MEMS devices are vulnerable to many failure sources. Some popular MEMS failure sources include stiction, etch variance, mechanical fracture, material fatigue, wear, delamination, residual stress, shock, vibration, humidity, particle contamination, electrostatic discharge, etc. In this paper, we select the point stiction as a failure source and performed ANSYS simulation to see how the point stiction defects in different locations will affect the device behavior and function. The simulation results show that depending on the location of the point stiction defects, the effects may be parametric, catastrophic, or no influence. The MEMS failure analysis offers helpful information to improve the yield and reliability with the existence of the point stiction defects.

II. ANSYS Failure Analysis for Point Stiction Defects

Most MEMS devices contain some movable parts and their functions rely on the activation of the movable parts. However, due to some physical defects, the movable parts may be blocked and cannot move. In this way, the whole device may fail and a catastrophic failure is resulted. For example, a typical MEMS comb accelerometer device contains around 40-80 comb finger groups. Each movable comb finger constitutes differential capacitances with its left and right fixed comb fingers. Due to the input acceleration, the movable parts experience inertial force and deflect for a certain small displacement. In this way, the differential capacitance gaps are changed. As a result, the differential capacitance is also changed. By measuring the differential capacitance change, the input acceleration is known. However, due to the defects introduced during the device fabrication or in-field usage, a particle contamination may fall into the capacitance gap between movable and fixed fingers. In this way, the movement of the movable finger is blocked and the whole device may be faulty. Such a failure mechanism is quite popular in MEMS and must be thoroughly studied. Stiction is the failure mode that describes the situation when surface adhesion forces are larger than the mechanical restoring force of a suspended micromechanical element. Surface adhesion forces include capillary forces electrostatic attraction and van der Waal forces. Stiction is a serious problem in surface micro machine devices that occur immediately after removing the die from the aqueous solution used to etch the sacrificial layer a liquid meniscus formed on the hydrophilic surfaces inside the suspension gap pools the micro structure towards the substrate, causing the two surfaces to come into contact and stick. Stiction can also occur after deployment in the field if water condenses inside the gap.

In addition to the large-scale stiction defects in surface-micromachining, there is another type of local point stiction defect. If the movable part of MEMS device is stuck to the substrate in some small local points, we call it as point stiction defect. There are many possible reasons which may result in point stiction defects, such as particle contamination, or a small metal spot in photolithography mask, or incomplete local etching, etc. Point stiction defect is different from the stiction problem in surface-micromachining in which a large area of movable parts are permanently stuck to the substrate due to surface forces. In this paper, the point stiction defect is simulated for the failure analysis of a surface-micromachinined MEMS comb accelerometer to see who the location of the point stiction defect affects the behavior of the device. The reason we select MEMS comb accelerometer device as an example is because MEMS comb accelerometer is the world's first commercial MEMS product and it has been widely used in the airbag deployment in automobile industry. ANSYS FEM software is used for the fault simulation. Initially, the ANSYS model of a fault-free comb accelerometer device is designed and simulated. The maximum displacement of movable fingers is derived through ANSYS coupled-field simulation. After that, point stiction defects are injected into different locations of the accelerometer (on different locations of the beams and comb fingers) and the corresponding maximum displacement of the device in response to given same input acceleration is extracted by ANSYS simulations. The collected data is used to plot the curves for maximum displacement versus the location of the point stiction defects. The simulation results show that the actual influence of a point stiction defect does depend on the location of the stiction.

The surface-micromachined MEMS comb accelerometer device design is shown in Figure 1. The movable mass is connected to four anchors on silicon substrate through four flexible beams. On the both sides of the movable mass, there are many movable comb fingers extruding from it. At the left and right side of each movable finger, there are left and right fixed fingers. Together they constitute the differential capacitance. The comb finger groups are divided into driving finger groups (for electrostatic self-test) and sensing finger groups (for acceleration sensing). As an example, three point stiction defects are shown in different locations along the flexible beam. In order to tell the different locations, the end of the beam connecting to the mass is defined as 0% location, and the end of the beam connected to the mass is defined as 100%. For the movable fingers, the end connected to the mass is defined as 0% location, and the free-standing end is defined as 100% location.

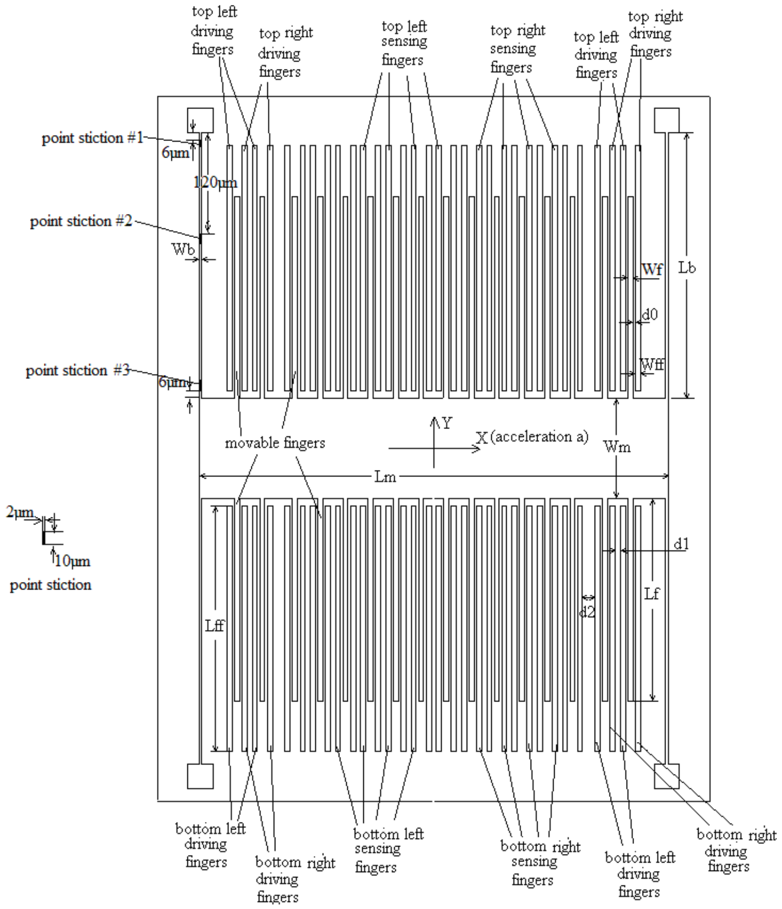

Figure 1. Poly-Si surface-micromachined comb accelerometer

The design parameters for the MEMS comb accelerometer is shown in Table 1.

Table 1. Design parameters for the comb accelerometer device

Device thickness	t = 2µm
Beam width	W_b = 5µm
Beam length	L_b = 220µm
Mass width	W_m = 96 µm
Mass length	L_m = 372µm
Movable finger width	W_f = 4µm
Movable finger length	L_f= 150µm
Fixed finger width	W_{ff} = 4µm
Fixed finger length	L_{ff} = 200µm
Total number of driving fingers	N_d = 8
Total number of sensing fingers	N_s = 24
Capacitance gap between moving and driving finger	2µm
Gap d1 between two driving or Sensing finger groups	4µm
Gap d2 between driving and sensing finger groups	6µm

The MEMS comb accelerometer device model for the fault-free device is shown in Figure 2.

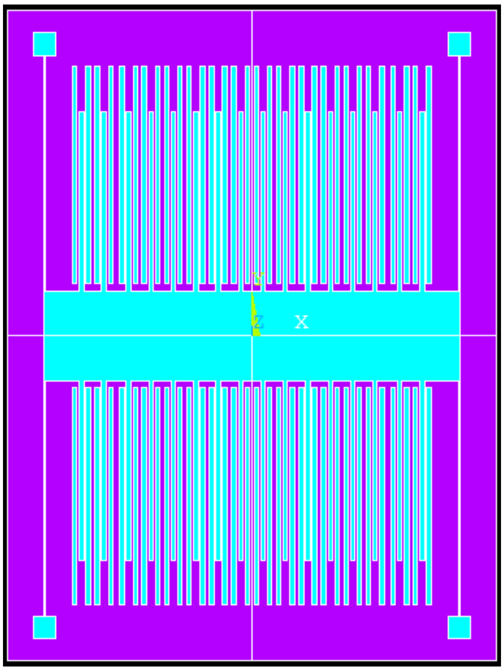

Figure 2. ANSYS model of the MEMS comb accelerometer device

The ANSYS model for the movable part and the four anchors after meshing is shown in Figure 3. Due to the device symmetry, the 2D model is used for ANSYS simulation.

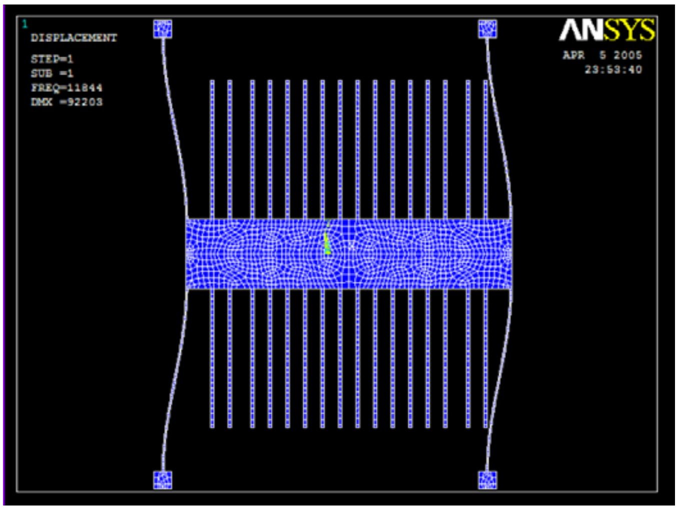

Figure 3. ANSYS model of the MEMS comb accelerometer

III. Results and Discussion

3.1. Point stiction on beam

When point stiction is on the beam, we vary the location of point stiction defect along the beam. The location on the beam connecting to the sensing mass is defined as 0% location, and the location on the beam connecting to the anchor is defined as 100% location. With the point stiction location varying from 0% to 100% locations, ANSYS simulation is used to extract the maximum displacement of the accelerometer. The results are shown in Figure 4. As we see from Figure 4, when the point stiction defect moves along the beam from 0% location (connected to the mass) to 100% (connected to the anchor), the maximum displacement of the device is approaching the fault-free device value (5.8×10^{-2}μm). That is, the influence of the point stiction defects depends on its location along the beam. When the point stiction is closer to the anchor, the influence will become smaller. Assume the device demonstrating a deviation of ±20% of maximum displacement of good device can be treated as "good" devices. In this case, it is $5.8\times10^{-2}\mu m\times(1\pm20\%)=(4.64\sim6.96)\times10^{-2}\mu m$. From the simulation result, we can see that when the point stiction defect location is below 60% along the beam, the point stiction defect will cause a failure to the device.

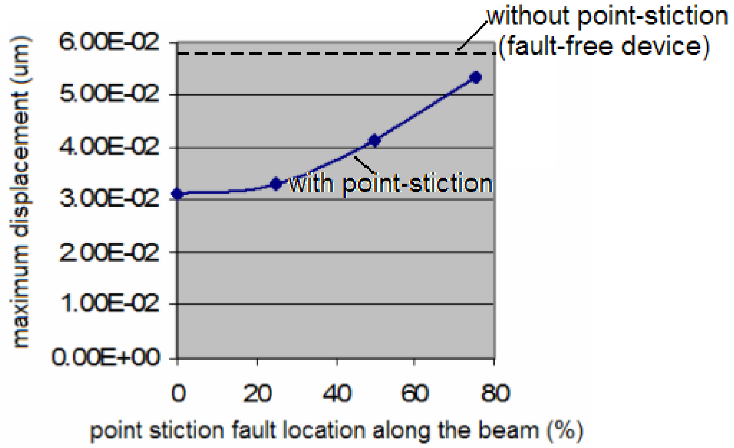

Figure 4. Maximum displacement vs. point stiction fault location along the beam (0%: the end connecting to the mass, 100%: the end connecting to the anchor)

3.2 Point stiction on 8th movable finger from left

When point stiction is on the movable finger, we vary the location of point stiction defect along the movable finger. We first select the movable finger in left side, i.e., the 8th movable finger from left as an example. The location on the movable finger connecting to the sensing mass is defined as 0% location, and the location on the free end of movable finger is defined as 100% location. With the point stiction location varying from 0% to 100% locations, ANSYS simulation is used to extract the maximum displacement of the accelerometer. The results are shown in Figure 5. As we see from Figure 5, when the point stiction defect moves along the beam from 0% location (connected to the mass) to 100% (free end), the maximum displacement of the device is approaching the fault-free device value ($5.8\times10^{-2}\mu m$). That is, the influence of the point stiction defects depends on its location along the beam. When the point stiction is closer to the anchor, the influence will become smaller.

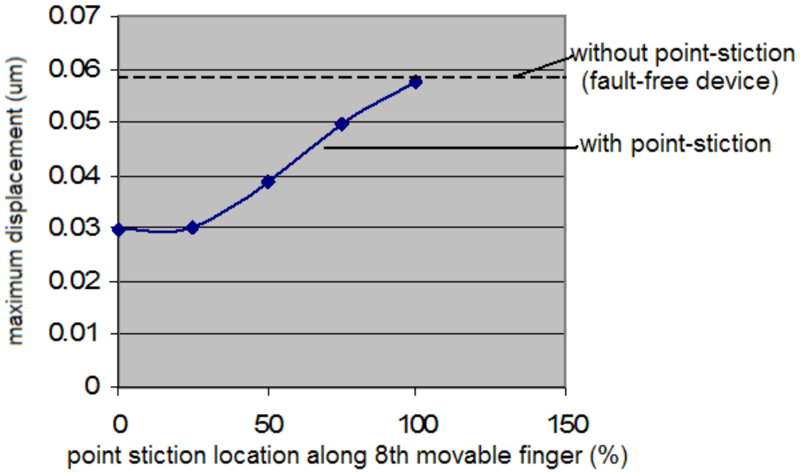

Figure 5. Maximum displacement vs. point stiction fault location along the 8th movable finger from left (0%: the end connecting to the mass, 100%: the end connecting to the anchor)

3.3 Point stiction on 12th movable finger from left

In this case, we select the movable finger in the middle, i.e., the 12th movable finger from left as an example. The location on the movable finger connecting to the sensing mass is defined as 0%

location, and the location on the free end of movable finger is defined as 100% location. With the point stiction location varying from 0% to 100% locations, ANSYS simulation is used to extract the maximum displacement of the accelerometer. The results are shown in Figure 6. As we see from Figure 6, when the point stiction defect moves along the beam from 0% location (connected to the mass) to 100% (free end), the maximum displacement of the device is approaching the fault-free device value ($5.8\times10^{-2}\mu m$). That is, the influence of the point stiction defects depends on its location along the beam. When the point stiction is closer to the anchor, the influence will become smaller. Furthermore, when the point stiction is close to the movable mass (0~50%), significant degradation on maximum displacement is observed compared to the previous two cases. This indicates that once a point stiction defect is around the middle of the device, its overall influence to device behavior is more significant.

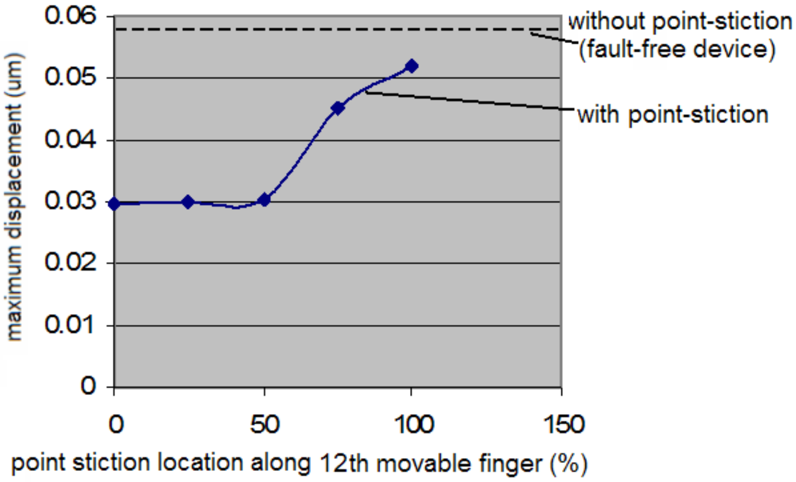

Figure 6. Maximum displacement vs. point stiction fault location along the 12th movable finger from left (0%: the end connecting to the mass, 100%: the end connecting to the anchor)

Based on above simulation, we see that the influence of a point stiction defect depends on the relative location of the defect. If it is in the important functional area, such as beam or comb fingers or movable mass, it may cause parametric or catastrophic effects on the device. However, if the point stiction is in some unimportant area (e.g. empty field area or anchors), it may not cause any harm to the device. This information is helpful for us to develop MEMS yield and reliability models, and guide us how to modify the defect clustering effects to improve the yield.

IV. Conclusions and Future Work

In this paper, the relationship between the location of point stiction defects and their influence on device behavior is investigated. ANSYS simulation is used to see how the various defects will affect the device behavior. Simulation results demonstrate that depending on the location and extent of the defects, the influence on the device behavior may be trivial, parametric or fatal. When the point stiction defect is closer to the center of the device, its influence on device behavior will become more and more serious. The fault simulation of MEMS accelerometer is helpful in finding an effective testing strategy for MEMS devices. It is also helpful in guiding us how to further improve the yield and reliability of MEMS. In this paper, only single point stiction defect is considered. That is, each time only a single point stiction defect is introduced. However, in reality, it is highly possible that multiple point stiction defects may occur at the same time. In those cases, the multiple point stiction defects may correlate with each other, resulting enhancement or cancellation of the faulty effects. In the future, we may further look into this issue and see how the device behavior will be changed due to multiple point stiction defects.

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