MEMS Yield Simulation with Monte Carlo Method

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Abstract. In this paper, Monte Carlo method is used for the simulation of point-stiction defects in MEMS accelerometer devices. The yield of MEMS devices is estimated based on the simulation results. Comparison between simulated yields of BISR/non-BISR MEMS accelerometers demonstrates effective yield increase due to self-repairable design. The simulation results of yield increase versus different initial yields for BISR MEMS accelerometers are in good agreement with theoretical prediction based on previous MEMS yield model. This verifies the correctness of the MEMS yield model.

Keywords: MEMS (Microelectromechanical System), BISR (built-in self-repair), yield, Monte Carlo method, defect simulation.

1 Introduction

In [1], we proposed a built-in self-repair technique for the MEMS comb accelerometer device. The main device of the comb accelerometer consists of *n* identical modules, and *m* modules are introduced as the redundancy. If any of the working module in the main device is found faulty during a built-in self-test (BIST), the control circuit will replace it with a good redundant module. In this way, the faulty device can be self-repaired through redundancy. We also developed the yield model [1] to quantitatively evaluate the yield increase due to redundancy repair. Based on the yield model, the yield increase due to redundancy repair versus initial yield for different *m* and *n* numbers were plotted. MEMS yield is directly related to the behavior of the defects during microfabrication process and in-field application. In order to verify our MEMS yield model, we need to estimate the MEMS yield by defect simulation, and compare the simulation result with theoretical prediction.

Due to the stochastic nature of defect distribution in microfabrication process, Monte Carlo simulation [2] is very suitable for MEMS defect simulation. In [3], Monte Carlo simulation is used for contamination/reliability analysis of Microelectromechanical layout. In [4], Monte Carlo method is used for the yield estimation of digital microfluidcs-based biochips using space redundancy and local reconfiguration. In this paper, we use Monte Carlo method to simulate the point-stiction defects in MEMS accelerometer devices. Based on the Monte Carlo simulation result, we estimate the yields for both BISR (built-in self-repairable) and non-BISR MEMS accelerometers. A comparison between both devices demonstrates an effective yield increase of BISR device compared to non-BISR design. The simulation result of MEMS yield increase versus initial yield is in good agreement with theoretical prediction based on our previous MEMS yield model [1]. This verifies the correctness of our MEMS yield model.

2 Point-stiction Defects and Monte Carlo Simulation

During the fabrication or the in-field usage of MEMS devices, the movable microstructure may be stuck to substrate in one or multiple points. This is different from the stiction problem due to surface forces in surface micromachining techniques, and we denote it as "point-stiction". These local point-stictions can limit or totally block the movement of the movable microstructure, and hence lead to device failure. An example of point-stiction is illustrated in Figure 1. The point-stiction defects can be developed due to various reasons. For example, a pinhole in the sacrificial layer may lead to such point-stiction. A particle on the photolithography mask during the patterning of anchor area may also lead to a point-stiction. Furthermore, a particle may randomly fall into the gap between a movable microstructure and the substrate, and it may block the movable microstructure at that particular point. Even after the device is sealed, particle-resulted point-stiction may still be developed during in-field usage. Thus, point-stiction can be a common defect source for MEMS devices.

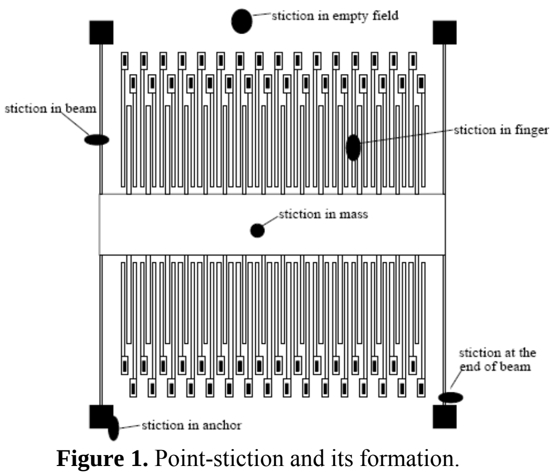

Figure 1. Point-stiction and its formation.

MEMS devices are vulnerable to various defect sources during the fabrication process or in-field usage [5]. The occurrence and the location of these defects are random and cannot be precisely predicted. Such stochastic behavior can be better predicted with statistical simulation methods, such as Monte Carlo simulation [2]. Monte Carlo simulation is a stochastic technique used to approximate the probability of certain outcomes by running multiple trial simulations using random number and probability statistics. In a Monte Carlo simulation, the random selection process is repeated many times to create multiple scenarios. Each time, a value is randomly selected to form one possible solution to the problem. Together, these scenarios give a range of possible solutions with different possibilities. When the simulation is repeated for a large amount of times, the average solution will give an approximate answer to the problem. ANSYS FEM software [6] supports the feature of Monte Carlo simulation in its probabilistic design module.

3 Simulation Strategy

In our research, we use Monte Carlo simulation to simulate the device behavior with point-stiction defects. We made the following assumptions and criteria in our simulation. First, according to Federal Standard 209E [7], the typical particle size in a clean room is 0.1~5μm in diameter. Thus, we set the size of a point-stiction defect in the range of 0.1~6μm. Point-stiction defects (square in shape) with random size in this range will be generated and randomly distributed in the device area (including the surrounding empty area). Second, we assume the point-stiction distribution is totally random without clustering effect. However, if clustering effect is considered, the MEMS device yield will be even higher. Third, we use a similar sensitivity selection criterion as [3] for the simulated devices: devices with sensitivity deviation within ±5% is treated as acceptable "good" devices; sensitivity deviation from ±5%~30% is treated as parametric defects; deviation larger than 30% will be treated as catastrophic defects. Devices with parametric or catastrophic defects will be discarded in our yield analysis.

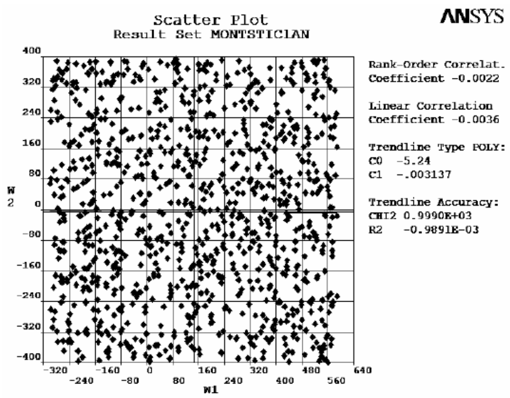

Figure 2. Random defect scattering in Monte Carlo simulation (Case #2: two defects in each of 1000 non-BISR device samples)

In order for fair comparison, we assume equal defect density for both BISR and non-BISR devices in each case of simulation. Since the BISR device has about 1.5 times of area when compared to non-BISR device, it contains 1.5 times of amount of point-stiction defects compared to non-BISR device. We simulated six cases of different defect densities: the number of point-stiction defects in non-BISR device ranges from 1 to 6 separately. Correspondingly, we simulated the BWC (Beam Width

Compensation) [8] BISR device with 1.5, 3, 4.5, 6, 7.5, and 9 point-stiction defects separately for the six cases. In order to simulate the cases of BISR devices with 1.5, 4.5 and 7.5 point-stiction defects, we simulate 3, 9 and 15 point-stiction defects distributing randomly in double device areas. In this way, the area of one device contains 1.5, 4.5 and 7.5 point-stiction defects separately. We simulated 1000 device samples and derived the device displacement sensitivities with such defects. An example of random scattering of 1000 samples (two defects in each device) of point-stictions generated in Monte Carlo simulation case #2 is shown in Figure 2.

4 Simulation Results and Discussion

Yield comparison between the non-BISR and BISR devices is shown in Table 1. As we can see, the yield of the BISR device in the presence of point-stiction defects is apparently much higher than that of the non-BISR device. Take the simulation case #6 as example, where 6 defects occur in the non-BISR device (and correspondingly 9 defects in the BISR device), the yield of the non-BISR device is 45%, while the yield of the BISR device is 97.7%. A yield increase of 52.7% is observed, and this indicates that a significant yield increase can be achieved for moderate initial yield (e.g., 45% in case 6). This coincides with our previous theoretical prediction [1]. A visual comparison between the yields of non-BISR and BISR devices for different number of point-stiction defects is shown in Figure 3. The yield increase due to redundancy repair for six simulation cases is shown in Figure 4. From the bar chart, it is clearly seen that the BISR design leads to positive yield increase when compared with the non-BISR design for all the six simulation cases. It can be observed that the yield decreases only slightly for the BISR design as the defect density increases, while the yield of non-BISR devices decrease rapidly as the defect density increases.

Table 2. Comparison of Monte Carlo simulation results between non-BISR and BISR devices.

Simulation case	#1	#2	#3	#4	#5	#6
No. of defects in non-BISR	1	2	3	4	5	6
No. of defects in BISR	1.5	3	4.5	6	7.5	9
Non-BISR device yield	87.8%	75.7%	65.2%	56.6%	49.4%	45.0%
BISR device yield	100%	100%	99.8%	99.6%	99.0%	97.7%
Net yield increase IY	12.2%	24.3%	34.6%	43.0%	49.6%	52.7%

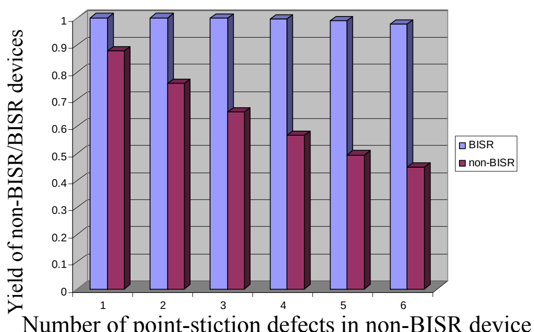

Figure 3. The yield comparison between non-BISR and BISR devices.

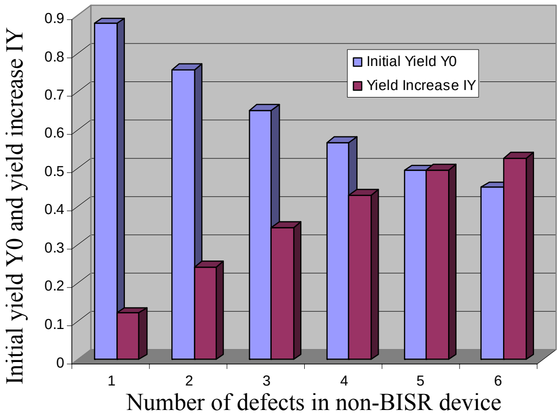

Figure 4. The yield increase due to redundancy repair for six simulation cases.

In the above Monte Carlo simulation, we simulated the cases for large (~1) and moderate (~0.5) initial yields. In order to find out the yield increase for small (~0) initial yield, we further increased the number of defects in non-BISR/BISR devices in our Monte Carlo simulation. Monte Carlo simulation shows that when the defect number is too large (N=60 or above), eventually the BISR device yield will also drop to zero, and the yield increase becomes zero. Because in Monte Carlo simulation the defect distribution is totally random, which means a clustering factor of $k=\infty$. Since it is difficult to simulate the case for $k=\infty$ in computer, we simulate the theoretical analysis of the case when k=2000 (a large number). The comparison between the theoretical prediction (k=2000) and the above Monte Carlo simulation results for yield increase versus initial yield is shown in Figure 5.

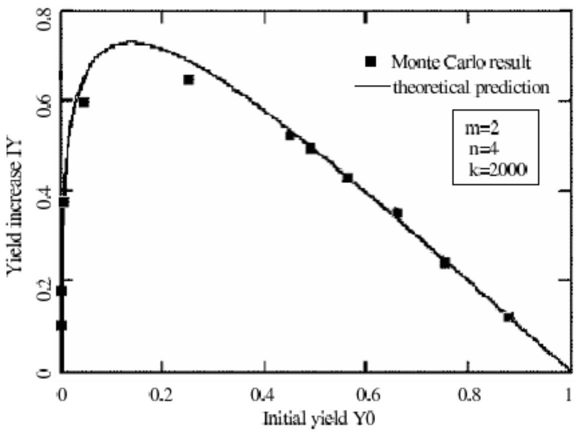

Figure 5. The comparison between theoretical prediction and Monte Carlo simulation result.

From the figure, we can see that the Monte Carlo simulation results coincide with the theoretical prediction very well. There is some slight difference for moderate initial yield. However, considering the above assumption for the clustering factor *k*, this discrepancy is reasonable. In the previous theoretical analysis [1], it has been shown that the yield increase due to redundancy repair is most significant for moderate initial yield. If the initial yield is too large (approaching 1) or too small (approaching 0), the yield increase due to redundancy repair is not significant. Monte Carlo simulation result verifies this prediction. This proves the correctness of our MEMS yield model for redundancy repair.

5 Conclusions and Future Research

In this paper, Monte Carlo method is used to simulate the point-stiction defects of MEMS accelerometers. Based on the simulation results of large batch of devices, we estimate the yields for both BISR and non-BISR MEMS accelerometers. Comparison of simulated yields for BISR and non-BISR MEMS devices demonstrates that an effective yield increase can be achieved due to BISR design. The simulation result of yield increase versus different initial yield is in good agreement with theoretical prediction based on our previous yield model. This verifies the correctness of our yield model.

In this paper point-stiction defects are simulated for MEMS yield estimation. However, in reality, the yield can be affect by various defect sources [8], such as etch variation, broken beam, material fatigue, etc. In the future, we will also simulate MEMS yield due to other various defect sources. In this way, the yield estimation will be more accurate and the result can be closer to the real device behavior.

References

1. X. Xiong, Y. Wu, and W. Jone, "Design and analysis of self-repairable MEMS accelerometer," *Proceedings of the 20th IEEE International Symposium on Defect and Fault Tolerance in VLSI Systems (DFT'05)*, Monterey, CA, USA, pp. 21-29, Oct. 3-5, 2005.
2. C. P. Robert and G. Casella, Monte Carlo Statistical Methods, 2nd edition, June 1, 2005, *Springer*.
3. A. Kolpekwar, T. Jiang, and R. D. S. Blanton, "CARAMEL: Contamination And Reliability Analysis of MicroElectromechanical Layout", *Journal of Microelectromechanical Systems*, Vol. 8, No. 3, pp. 309-318, Sept. 1999.
4. F. Su and K. Chakrabarty, "Yield enhancement of reconfigurable microfluidics-based biochips using interstitial redundancy", *ACM Journal on Emerging Technologies in Computing Systems*, Vol. 2, No. 2, pp. 104-128, April 2006.
5. B. Stark (editor), "MEMS Reliablity Assurance Guidelines for Space Applications", *Jet Propulsion Laboratory Publication 99-1*, Pasadena, USA, Jan. 1999.
6. URL: http://www.ansys.com
7. Federal Standard 209E, 1992, "Airborne Particulate Cleanliness Classes in Cleanrooms and Clean Zones. General Services Administration (GSA)", *GSA Service Center*, Seventh & D Street, SW, Washington DC, USA.
8. X. Xiong, "Built-in self-test and self-repair for capacitive MEMS devices", Ph.D dissertation, University of Cincinnati, 2006.