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Review Article

A Review on Key Issues and Challenges in Devices Level MEMS Testing

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The present review provides information relevant to issues and challenges in MEMS testing techniques that are implemented to analyze the microelectromechanical systems (MEMS) behavior for specific application and operating conditions. MEMS devices are more complex and extremely diverse due to the immersion of multidomains. Their failure modes are distinctive under different circumstances. Therefore, testing of these systems at device level as well as at mass production level, that is, parallel testing, is becoming very challenging as compared to the IC test, because MEMS respond to electrical, physical, chemical, and optical stimuli. Currently, test systems developed for MEMS devices have to be customized due to their nondeterministic behavior and complexity. The accurate measurement of test systems for MEMS is difficult to quantify in the production phase. The complexity of the device to be tested required maturity in the test technique which increases the cost of test development; this practice is directly imposed on the device cost. This factor causes a delay in time-to-market.

1. Introduction

Since the mid-1970, MEMS (microelectromechanical systems) have emerged as an innovative technology by creating new opportunities in physical [1], chemical [2], and biological [3] sensors and actuator applications. Although MEMS technology emerges from IC fabrication techniques, test methods [4] of both technologies significantly differ from each other. This is because MEMS devices respond to both electrical and nonelectrical (physical, chemical, biological, and optical) stimuli.

MEMS devices are tested at different stages during manufacturing processes. This testing is essential to verify the performance metrics of the device, parametrically and functionally. After wafer level fabrication, MEMS are tested by measuring all AC and DC parameters at wafer level [5, 6] using an ATE (Automatic Test Equipment) [7]. This test phase sorts out the wafer for good and bad die by exploiting design for testability circuitries within chip, for instance, self-test mechanisms and scan chains, similarly to common integrated circuits. This is followed by dicing and wire bonding to test the electrical performance; at last, good devices are packaged. In the final stage, these packaged devices are retested parametrically to confirm their overall functionalities. Functional testing and calibration are essential for every MEMS sensor before proper utilization. Therefore, some intrinsic constants or values that belong to the device performance are captured during calibration as reported in [8–10]. Functionality of the device is measured by applying known physical and electrical stimuli and comparing output responses of the device. If the measured output values are different from the estimated one, the device is considered as failed; otherwise, it is accepted as a good device. Comprehensive details of infrastructures about Automatic Test Stations and methods for MEMS testing are reported in [11, 12]. As an example, the fabrication and testing steps in detail for mass production of MEMS pressure sensor are presented in Figure 1.

In MEMS manufacturing process, testing has an important role in verifying performance and reliability of the device; however, this testing process consumes a huge cost

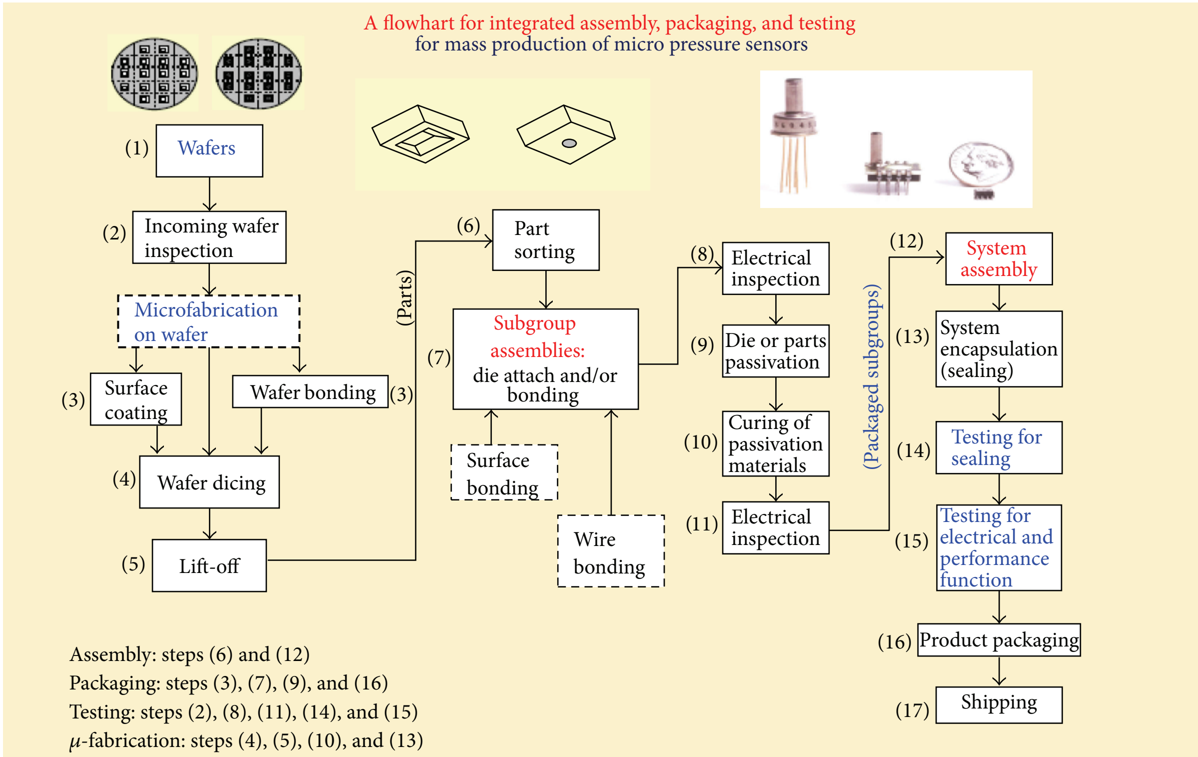

FIGURE 1: Steps for mass production of MEMS pressure sensor [13].

[14]. A plethora of work is reported on the cost of MEMS testing process. Masi and Cortese [15, 16] reported that 25–35% cost is consumed in overall testing process. According to Texas Instruments [17], in case of testing digital micromirror device, the cost of final test (packaged device testing) is 14% whereas the cost of wafer level test is 8%. MEPTEC (Microelectronics Packaging and Test Engineering Council) [18, 19] reported that the cost of MEMS testing is 20–45% of the total device manufacturing cost. On the other hand, in MEMS test standard report of MIG (MEMS Industry Group) [20], testing cost at manufacturing level can accede up to 50% due to device complexity and maturity. Henttonen [21] reported more than 60% testing cost of the device; the reason of this huge cost is that testing systems are mostly associated with automotive sensor testing which can be costly to be adopted as testing systems for ordinary consumer MEMS devices listed in [22].

Therefore, it is of utmost importance to find a suitable alternate to reduce the huge cost of test. A work has been reported on the reduction of testing cost. One way of cost reduction technique is to increase the test throughput by testing multiple DUTs (device under test) in parallel [23, 24]. Substantial research efforts have been practiced to reduce test time and cost by examining various aspects of test [25]. These techniques of parallel testing have been widely used in VLSI test areas [26]. However, these testing techniques are not fully applicable to MEMS because MEMS devices operate under working principle of different domains (electrostatic, electromagnetic, electrothermal, piezoelectric, etc.).

The scope of this review is to highlight the issues of MEMS testing at device and batch levels. The current batch level technique is the parallel testing in which electrical and nonelectrical test stimuli are used for the response of multiple DUTs. Enhancing the parallelism of test system has been tried to reduce the cost. However, these parallel test techniques have issues and limitations that are discussed in the following section. Section 2 differentiates the ICs and MEMS test techniques while Section 3 highlights the failure mechanism and defects in different categories of MEMS devices. Section 4 presents customized testing techniques and also describes the destructive and nondestructive test techniques. Section 5 discusses the issues at device level testing while Section 6 reports on issues in parallel testing techniques in detail. Finally, some conclusions are extracted at the end.

2. Difference between ICs and MEMS Testing

MEMS have to face many testing challenges [27] due to their multiphysics behavior. Similar to analog electronic systems, the mechanical components of MEMS have nonlinear nature. Therefore, analog and mixed signal tests [28] including verification and calibration are essential for MEMS. The test problem for MEMS is exacerbated due to their inherent diverse properties. For example, the output of a MEMS based device is electrical in nature; however, these signals come from mechanical actuations under different domains. Thus, the use of electrical signals for test was found helpful to

Table 1: Comparison between ICs systems and MEMS.

Testing approach	Integrated digital devices	Analog mixed signal devices	Microelectromechanical systems
Fault model	Assertion, gate delay, line delay, redundant, path delay, behavioral, branch, bus, cross-point, stuck-open, stuck-at, stuck-on, bridging, and so forth.	Hierarchical, behavioral, macro model, transistor, physical, catastrophic, and parametric faults and so forth.	Behavioral, shorts and opens in electrothermal and electromagnetic, structural defect level, parametric, functional, fatigue, and reliability model.
Test technique	VHDL, HSPICE, fault dictionary, probabilistic, signature analysis method, LFSR (linear feedback shift register), BIST (built in self-test), and so forth.	Pole-Zero Analysis, artificial neural network, HSPICE, SABER, VHDL-AMS, ATPG, diagnosis of soft faults based on fractional correlation, BIST (built in self-test), and so forth.	Neural network, VHDL-AMS, device-level (FEM) and HDLs and transposition of techniques developed for microelectronics, BIST (built in self-test).

an extent for controllability and observability of mechanical components. Field of MEMS is relatively not as advanced as ICs. MEMS testing and fault modeling [29] are a new area as compared to MEMS manufacturing and designing. Even though MEMS devices have been introduced since 1970, testing MEMS remained a big challenge. Testing MEMS at the early stage can help in production, fabrication, and packaging flow. The testing tools required to diagnose the origins of MEMS failures are essential to upgrade and design.

Causes of failures [30] are as distinctive as the MEMS devices. In ICs manufacturing, significant efforts are being done in testing and handling to appropriately characterize and judge the device performance in comparison with the device specifications. The main differences in testing MEMS and ICs are the environmental circumstances. For several cases, integrated circuits are being analyzed in a variety of environments under different conditions of temperature and moisture. Relatively analogous testing and handling measures [31] are being performed during manufacturing process; however, essentially, the device is operated within different environmental conditions. Any change in the test environment can considerably affect the sensitivity and functionality of the device. The additional complication regarding mechanical motion demands extra heed during testing and handling. Auspiciously, in case of MEMS analysis, there is a plus point of utilizing testing techniques [32] leveraged from IC industries. Although the variety of devices are growing because of different applications, therefore, multidisciplinary knowledge is deemed essential to properly identify the causes of failures. Table 1 briefly summarizes the difference of fault modeling and testing techniques of ICs and MEMS [33].

3. A Comprehensive Study on Failure of MEMS Devices

MEMS devices have features of motion unlike ICs; therefore, special techniques and tools are required for measuring mechanical response on micro- and nanoscale. The device's behavior was analyzed in detail using these tools which helped in providing feedback to improve the design. A number of MEMS devices are used in a range of applications across the world. In the past, it was considered that MEMS devices belonged to ICs family and might have the same failure issues like ICs. Conversely, MEMS devices have different failure mechanism due to complex mechanical geometry and unique material and these have different biasing techniques. The failure mechanisms due to complexity of these devices are categorized in the following four groups.

Group 1 includes stationary MEMS devices without moving parts, such as chemical sensor, microphones, and DNA sequencers. The major source of failure in this group is the particle contamination. The contaminated particles, which are small in size and inherently nonelectrical, adversely affect the device performance. The particle contaminations are insulator in nature and these are unable to bridge the device structure electrically and contaminants become difficult to detect as short circuits.

Group 2 contains MEMS devices that have moving structure without rubbing surfaces, such as comb drives accelerometers and gyroscopes, whose components like hinges and microcantilever yoke regions suffered from fatigue failure. The fatigue (structural failure) is studied in this group; electrostatically actuated comb fingers with a perforated proof mass and a microcantilever with a notch are the main constituents of this group. The increase in stress levels at the notch initializes cracks on the surface of the microcantilever that reduces device life and eventually causes the failure of the device by fracture.

Group 3 consists of MEMS devices that have moving structure with impact surfaces, such as relays, thermal actuators, and valves. These devices are easily influenced by debris created on the surfaces, fracture constituents, cracks [34], and so forth. Fracture generated due to impact forces on the opposite structure causes failure in the device.

Group 4 surrounds MEMS devices that have moving parts, rubbing, and impacting surfaces, for instance, micromirror, optical shutter, and geared devices. Friction is created due to rough surfaces of moving components that create wear in material or debris initiating several failures, such as (1) stiction of rubbing or contacting surfaces, (2) wear created by particles that can change the motion tolerance, and (3) particle contamination.

3.1. Reliability Test of MEMS Devices for Failure Analysis. The functionality of MEMS devices depends upon its material of structure, design, and actuating parts. Therefore, electronic industry also prefers the reliability test of MEMS based products. Reliability test of MEMS devices is a major challenge in manufacturing at mass production level. In this test, failure analysis of DUT is performed under certain conditions of device application for a specific time period. The origins of MEMS reliability failures highly depend upon product and application environment. Reliability test also requires a cost-effective technique for characteristic failure analysis in order to understand the mechanical and electrical properties of DUT.

It is perceptible that all kinds of MEMS devices have failure mechanisms due to particle contamination and stiction, and so forth. It is, therefore, more important to understand the origins of failure before finding the remedies of the specific failure. MEMS sensors and actuators have different and distinctive failure mechanisms by their classifications and nature. In ICs, testing only electrical parameters is done to find the fault, while in MEMS testing both the electrical and mechanical parameters is to be done to deal with the failure. MEMS causes of failures during reliability test are summarized in Table 2.

3.2. Failures of MEMS Devices. MEMS structures consist of flexible or rigid membranes or beams such as cantilever and bridges, and some contain perforation on its surface. These devices also contain insulated or conductive flat layers, gears, cavities, and hinges integrated with an electronic readout circuit. On the other hand, more than one device is being integrated in a single chip. Single axis moving MEMS structures have been upgraded to multiaxis movements. MEMS are getting more multifaceted design features to fit for more applications. The failure analysis helps to understand the basic reasons of faulty behavior of device during testing process from wafer level to the final device packaging. Failure mechanism due to defective interconnects and low compatibility results in poor performance of the device. Table 3 indicates the foremost mechanical failures of MEMS devices. Generally, MEMS failures are not only related to only mechanical parts of the device; however, electrical failures cannot be ignored. These are originated due to contact failure, electromigration, and dielectric degradation. Table 4 shows common electrical failures of MEMS devices.

MEMS devices due to multiphysics behavior are the hardest to test. Recently, the devices are being tested on the base of functional specifications. Variations in manufacturing process of device may alter its specs, which is the disadvantageous scenario in MEMS testing, as a number of errors can be induced due to process fluctuations. Moreover, the specifications of the device are multifarious and its measurements at several testing stages may increase the test time. Therefore, quite different test techniques are required to measure the performance parameters of various devices, which forces the manufacturer to procure different test equipment for different products. Fast transient test methodologies are required to check the DUT specifications. In multistructured complex devices, specifications are disturbed mostly due to drifts in the fabrication process and defects. For the devices that were designed near the specification limits, the violations in the specifications occurred due to normal process variations. Drifts in processes were identified at initial stage in the production phase by the process monitoring systems. Defects become the reasons of catastrophic failures that were detected by tests of parametric and functional failure analysis.

4. Development of Different Testing Techniques for MEMS Devices

The development of cost-effective testing techniques is the major challenge for MEMS. A number of techniques and methodology have been reported in literature. Table 5 shows the list of destructive and nondestructive testing techniques that are being implemented for MEMS measurements electrically and mechanically [72]. Jeffrey et al. [73] reported an online monitoring technique which is based on bias superposition for MEMS integrated sensors. They injected the test stimuli into biased conductance sensor and analyzed the structural integrity of the device and interface on the base of signal injection and signal extraction. Islam [74] reported optical techniques to test MEMS structures at wafer level. They utilized microscopic interferometry and computer microvision to perform MEMS measurements for analyzing static and dynamic properties. Biswas et al. [75] developed statistical based ε-SVM model for testing MEMS accelerometer to eliminate redundancy. Their work disclosed that, with the help of specification based tests, the redundancy in test can be statistically identified with minor error. When hot and cold tests are performed for the accelerometer, they observed the defect escape of 0.2% and yield loss of 0.1. Dumas et al. [76] developed online testing technique for sensors using superposition of the test stimuli on the specifications. They utilized the signal processing technique to reduce the fluctuations of test output by encoding the test stimulus through pseudorandom sequence. They also studied the overall test time and level of perturbation rejection.

The dynamic Electrostatic Force Microscopy is used in [77] to characterize the beam resonators. The resonator was actuated by placing probe cantilever above the beam. Then, modulated signal was applied to the probe cantilever. The resonance frequency response of the test beams was analyzed by studying coupled electrostatic interaction between the conductive beams. Izadian and Famouri [78] developed fault diagnostic system for MEMS using multiple model adaptive estimation technique. They used Kalman filters to model and diagnose the fault in MEMS in real time application. Lateral comb MEMS resonators are fabricated to validate the fault diagnosis unit in multiple model adaptive estimation technique. They also developed another fault diagnosis technique [79] for MEMS resonator by combining least square forgetting-factor method and multiple model adaptive estimation method. This technique identified the parameters of slowly time-varying systems. Another work developed by Izadian [80] is the self-tuning-based parameter estimation technique for fault diagnosis of MEMS. He used this technique to recognize the parameters of system and generation of residual signals. Repchankova [81] developed an antistiction and self-recovery mechanism in order to recover the functioning of RF-MEMS switches in case of malfunctioning due to stiction. An effective heat-based mechanism was designed in order to release the stuck component. Reppa [82] developed a fault detection and diagnosis (FDD) technique

Table 2: Summary of failures, their causes, and procurement for various MEMS devices.

Group	Causes of failures	Reliability test
Group 1		
Chemical sensor nozzles microfluidic DNA sequencers	Dielectric breakdown	The reliability test of flagellar microfluidic motors was performed in environmental conditions. Probabilistic mathematical model was used to analyze the rotational behavior. The decay time of 55 h was predicted for the bacterial motor [35].
Group 1 or Group 2		
Accelerometers	Fracture, fatigue, mechanical wear, charging, and change in friction	(1) Accelerated life time of devices was tested experimentally for 1000 hours at about 145°C to 200°C [36]. (2) Tytron 250 was used to test fatigue. The experiment showed fatigue life between 7.78×10^4 and 1.48×10^7 cycles when the stresses increased from 2.05 to 2.83 GPa [37]. (3) Sandia National Laboratories developed the SHiMMeR (Sandia High Volume Measurement of Micro Machine Reliability) that can simultaneously control and test up to 256 MEMS parts [38]. (4) Fatigue and creep were observed by using X-rays diffraction. Wear was analyzed through DLC coating (Diamond Like Carbon), stiction was observed by using MIL-STD-883F (Military Test Standard Device) and SAM (Scanning Acoustic Microscope) was used for contamination [39].
Group 2		
Pressure Sensors	Vibrations, shock Fatigue, fracture, and change in friction	The fatigue was detected in the fabricated sensors operating below the stress level; it is observed that fatigue can occur at equal stress and fracture levels [40].
Gyroscopes	Vibrations, shock, and charging	(1) The reliability assessment of a three-axis gyroscope was performed under several shock loading conditions [41]. (2) The temperature degradation and variations in signal to noise ratio were also reported [42].
Group 3		
Thermal actuators	Vibration, shock, and mechanical wear	(1) Weibull statistics was used to analyze the fracture tests on the beam by applying different loads. (2) Experimental technique was proposed for micro switches to observe malfunctioning due to charging and creep [43, 44]. (3) The effects of pull-in voltages were observed during bending and torsional modes of beams. Mechanical wear and fatigue tests were performed to predict the life time [45].
Micro relays	Fatigue, fracture, mechanical wear, shock, vibrations, and charging	Effects of stiction and welding failure were performed at 10^9 on/off switching cycles [46, 47].
Group 4		
Electrostatic actuators	Charge in friction, fatigue, fracture, mechanical wear, shock, and vibrations	Stochastic method was used to analyze the pull-in and pull-out voltages for prediction of device life time [48, 49].
Mirror devices	Optical degradation, fatigue, fracture, mechanical wear, shock, and vibrations	Texas Instruments (TI) developed the optical inspection tool for DMD devices that examines each pixel of the DMD array [50].
Gear devices	Charge in friction, fatigue, fracture, mechanical wear, shock, and vibrations	Sliding surfaces were analyzed through simulations to prevent adhesion and wear [51].

for MEMS. Parametric faults can be captured, isolated, and identified with the help of this technique. This technique depends on estimation of parameters arrayed in a set membership identification framework. Zheng et al. [83] developed a characterization technique of computer microvision for microresonator. The method of video imaging is used for this technique to measure the in-plane motion of MEMS device. The blur image synthesis technique is used to obtain the magnitude of displacement.

5. Issues in Device Level Testing

MEMS devices are categorized in six different classes. The classification is based on their operating mechanism and applications are discussed in this section.

MEMS sensors [84, 85] are designed and fabricated for sensing multiple environmental changes. The sensors are capable of sensing behavior of fluids, force, inertia, gas, and so forth. Testing this category of devices has many challenges

Table 3: MEMS mechanical failures.

			Mechanical fracture		
Failure	Shock	Overload	Fatigue	Corrosion	
Causes	Mechanical interference disorder, excessive loading, and drops	Excessive stress	Structural damage due to cyclic loading	Oxidation, chemical reaction	
			Stiction		
Failure	Capillary forces	Vander Waals forces	Residual stress	Chemical bonding	Electrostatic charging
Causes	Monolayer of moisture or lubricants on the surfaces prompting capillary force	Interaction of atoms or molecules at the surface of close contact	Bending and deformation of structure during the release process	Chemical bond between contact surfaces	Potential difference at two closed surfaces
			Wear		
Failure	Surface fatigue	Corrosion	Abrasion	Adhesion	
Causes	Cyclic loading instead of smooth surfaces	Chemical interaction between two surfaces	Material loss due to sliding of different surfaces	Pull-in interaction between two surfaces during sliding due to surface forces	
			Creep and fatigue		
Failure	Thermal stress	Intrinsic stress	Applied stress		
Causes	Overheating	Residual stress	Applied stress		

Table 4: MEMS electrical failures.

		Electric short and open circuit		
Failure	Oxidation	Electromigration	ESD, high electric field	Dielectric material degradation
Causes	Environmental	Mismatch load	Excessive load	Capacitive discharges
		Contamination		
Failure	Usage environment	Intrinsic (crystal growth)	Manufacturing-induced	
Causes	Low and high temperature and humidity	Environmental	Rough handling in industry	

due to complex sensing functionality and a variety of designs. The test mechanism developed for theses sensors also has issues of fault detection as reported in [86–88], because each device required individual test bench to analyze the sensing environment. As these tools and testing techniques have been leveraged from the IC technology, therefore, these were helpful in resolving various fault mechanisms to an extent. The major dilemma was to discover the faulty origins in multiple devices that were put together on single test bench for mass production. Recently existing tools [89] have limitations to test specific MEMS devices electrically and mechanically. The emerging challenge is to analyze and identify unique source of failure during assessment of multiple die on single test stage.

In the development of a test bench for gas sensors, the main obstacle was the chamber designing for chemical environment for the device sensibility. Mechanical sensors [90, 91] that are designed to sense physical changes like motion and pressure are relatively easy to test or characterize, while chemical sensors have issues of selectivity in case of sensing targeted gases. Carbon monoxide CO and H_2 sensors are operated in a variety of challenging environments of industries. Fast response is the critical requirement for theses sensors; therefore, readout mechanism of testing system faces high level of noise signals because detecting device signal at ppm (part per million) level to find the selectivity of these gases is very cumbersome effort. [92] reported the sensitivity issues in ethanol sensors during the device analysis; without readout circuitry interface on chip, these sensors become difficult to characterize.

The packaged devices that have specific environment, any change in the environment, or defective packaging may cause incorrect outcomes and induce additional faulty behavior during testing. In MEMS analysis reported in [93],

Table 5: Destructive and nondestructive techniques for MEMS testing.

Technique	Observation	Mode
Optical microscopy	Stains, debris, fracture, and abnormal displacements [52].	Nondestructive
Scanning laser microscopy	Extended depth-of-focus, abnormal vertical displacements [53].	Nondestructive
Scanning Electron Microscopy (SEM)	Imaging defects at high magnification [54].	Nondestructive
Focused Ion Beam (FIB)	To image structures, to cross-section elements of concern, and to cut elements free for subsequent examination [55].	Destructive
Laser-Doppler Vibrometer	To measure out of plane motion [56].	Nondestructive
Computed tomography (CT)	Visualizing 3D internal structures [57].	Nondestructive
Interferometry	To detect the tilt or deflection of a sample [58].	Nondestructive
Transmission electron microscopy (TEM)	To observe thin films deposited on MEMS [59].	Nondestructive
Energy dispersive X-ray spectroscopy (EDS)	To analyze chemical composition of surface coating [60].	Nondestructive
Wavelength dispersive X-ray spectroscopy (WDS)	To analyze chemical composition of surface coating [61].	Nondestructive
Atomic force microscopy (AFM)	Topographic images and surface traces [62].	Nondestructive
Auger electron spectroscopy (AES)	To perform qualitative and semiquantitative compositional analysis of surface of materials [63].	Nondestructive
Secondary ion mass spectroscopy (SIMS)	Compositional analysis of the sample with sensitivities in ppm to ppb, removing material from the device [64].	Destructive
Thermally induced voltage alteration (TIVA)	To identify electrical failure mode [65].	Nondestructive
Resistive contrast imaging (RCI)	To identify electrical failure mode [66].	Nondestructive
Infrared Microscopy	To construct thermal images based on the infrared radiance emitted from the structures [67].	Nondestructive
Light emission	To observe MEMS optical devices [68].	Nondestructive
Acoustic emission	To observe running device within package [69].	Nondestructive
Laser cutting	To impart elements of device such as gears and links [70].	Destructive
Lift-off technique	Accumulation of wear debris at the surfaces [71].	Nondestructive

lid removing changed the device environment and caused change in functionality. It was observed that device had to face the malfunctioning due to contaminant particles, environmental change, and other potential defects.

MEMS actuators [94, 95] generate power using any electrical or physical stimulus. These mechanical components generate power and motion for other MEMS components. A variety of devices, for example, BioMEMS, RF MEMS, microfluidic, or optical MEMS, need some forms of actuations to interact with another microstructure, in moving a fluid or a micromirror. MEMS actuators are stimulated under different electrical domains. Electrothermal actuators exploit heat producing due to power dissipation in the device. The increase in temperature causes expansion in the structure; then, necessary displacement is induced for motion. In electrostatic actuators [96], electric field is involved to attract other parts of device to generate motion. Prevailing fault modes of stiction [97] and particle contamination were observed in both thermal and electrostatic actuators. Actuators can contain rubbing surfaces which may result in formation of wear or debris. The major concerns for testing of MEMS actuators must be nondestructive regarding fault analysis of stiction films and coatings, and functional testing of multiple devices in parallel. Every type of actuator may have distinctive failure mechanisms and tribulations for fault analysis.

Thermal actuators face the typical fault mechanisms of thermal degradation [112, 113]. The side effects of electrothermal cycles in these devices are under observations. Faults under stress [114] were analyzed by introducing permanent deformation in the mechanical structure. Structural defect is produced out of plane nonlinear motion of thermal actuator and due to increase in temperature; actuator was welded to the substrate. Analyzing thermal behavior of dynamic structures is a difficult task. Techniques involved in generating thermal actuations were destructive; they slowed down the motion of actuator. The significance of understanding heating effect of a thermal actuator and occurrence of localized heat can support thermal behavior modeling and reduce the fault mechanisms.

Table 6: Common testing issues in different category of MEMS devices.

Category	Source of failure	Testing issues	Observations
RF MEMS Switches, resonators, lab-on-chip, capacitor, varactor, sensors, and filters.	Stiction failure, surface contaminations, and accumulation of charges in the dielectric part.	A short occurred when two parts of the device stick to one another. Major issue was because leftover charge in the dielectric causes increase in voltage required for the device actuation and signal transmission. Other issues of catastrophic failure occurred due to constant increase in voltage that causes the dielectric breakdown. Crack initiated due to high stress in the structure. Breakage of structure due to impact with the substrate.	A challenge in RF MEMS testing was to analyze stiction failure nondestructively. Tracing the genuine adhesion point without removal of any part or component was challenging. Hillocks and high roughness of contact area created gap between contact surfaces. Issues about contact area, geometry and the asperity in contact area were highlighted to understand RF MEMS [98–101].
Optical MEMS Sensor, resonator, optical buffers, mirrors and filters	High surface roughness, stiction, and accumulation of charges.	Roughness of micromirror surface, stiction due to the accumulation of charges that caused stuck in actuation. Tracing faults of shorts and stiction beneath the mirror surface. Cracks initiated during detachment of the micromirror while doing failure analysis under the mirror surface. Structure breakage during handling.	Surface roughness of single mirror was determined feasibly and it takes time for analysis of various mirror locations. The surface roughness analysis of arrays of mirrors was not reasonable using current AFM techniques. Parallel test technique provided satisfactory results in determining surface roughness of entire array or collection of mirrors [102–104].
Microfluidics Lab-on-chip, flow sensors, micro channel, and micro needles.	Fluid contamination, leakage, no compatibility with MEMS, short-circuit defect, and catastrophic and parametric faults due to structural defects.	Device was flushed of fluid before analysis; this effort negotiated the failure mechanism and induce erroneous outcomes. The common issues are fluid contamination, deprocessing, leak detection and compatibility with MEMS. The fluid flowing under electrostatic domain was stuck due to opposite charged molecules causes channel blockage. Channel with the rough walls caused a turbulent flow of fluid sample.	During typical analysis using SEM, the device was flushed of fluid before analysis. High quality resolution was required for microfluidic systems during an analysis of pressure or flow sensor exclusive of flushing the device. Therefore in verification of device functionality, purpose of using test fluid was helpful in tracing the movement of the fluid during operation. The approach of using diagnostic fluid also proved helpful to trace the breakage, leakage or cracks in the device [105–108].
BioMEMS Lab-on-chip, biosensors.	Fluid contamination, leakage, blockage of channel, cracks, and material compatibility.	Analogous tribulations with the existence of additional biological materials was experienced during testing. In the analysis of DNA purification, the surface area of channel was limited. Sample clogging occurs in the channel during testing [109–111].	Challenges of functional testing were device deprocessing and biocompatibility.

Electrostatic actuators typically have single cantilever, bridge, or two sets of comb fingers; the actuator is derived due to the change in polarity of the electric fields at the opposite fingers. Releasing of multistructure MEMS devices [115] is also a challenging job; occurrence of structural defects in comb fingers was found as one of the origins of failure. Rapid identification of failure mechanism of microstructures is essential. Table 6 briefly describes the failure analysis reported for different categories of MEMS devices.

6. Issues in Parallel Testing

In the previous research work, a lot of discussions [16, 88, 116–121] have been made to cope with the challenges and issues in

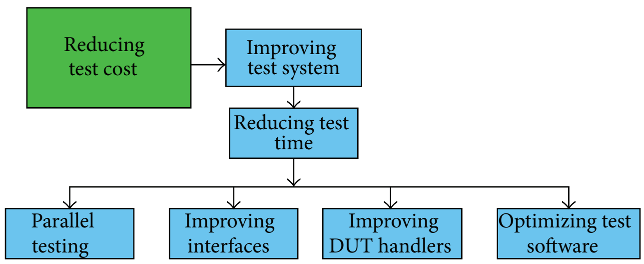

Figure 2: Efforts of reducing MEMS testing cost.

MEMS testing and its requirement. MEMS final testing has limited visibility in the literature from industries that have successfully manufactured MEMS devices such as humidity sensors, pressure sensors, and magnetic field sensor. This type of trend shows an indication of custom nature of test for MEMS. According to MIG's (MEMS Industry Group) METRIC (MEMS Technology Roadmap and Industry Congress) [20, 122], there are no agreed testing standards and this is the major limitation for the industries growth and innovation. The flow chart in Figure 2 shows the efforts of developing and improving the MEMS test systems to reduce the cost of testing.

A very few test systems are commercially available [123] and are limited to test specific commercial devices, that is, accelerometers, gyroscope, pressure sensors, microphones, combo sensor, proximity sensor, and magnetic sensor. This section discusses the limitation and issues of test systems reported in literature. An attempt was made by Maudie et al. [124] to improve ATE (Automated Test Equipment) for testing accelerometers in parallel. Variations in electrical parameters occurred from device to device in case of producing MEMS devices in bulk. ATE was unable to perform proper calibration of these devices due to lack of modularity and flexibility. ATE was improved by changing electrical and nonelectrical interfaces of DUT (device under test). Moreover, these efforts and test system were limited to accelerometers only.

Various approaches to test MEMS optical devices and flow sensors were reported by Kerkhoff [10]. Packaging of flow sensor altered the device specifications due to change in environment. The test system had to face issues in handling mechanism of nonelectric input for flow sensor. That increased the testing time; therefore, test handlers required improvement to reduce test time and to enhance parallelism. This test system was limited to the specific devices. Chen reported an effort of improving traditional test system in [125]. The technique was able to test only 16 devices (motion sensors) in parallel. They used the QSPI (quad serial port interface) to enhance the parallelism. However, test system had to face the high noise effects in case of enhancing parallelism. [126] presented a test methodology for microfluidics biochips using linear programming model. They investigated the problems in detection catastrophic faults in these devices. They tried to minimize the test time through linear programming model.

A case study based on accelerometers testing was introduced by Ciganda et al. [127]. In conventional tester, interfaces of DUTs were connected through wires, which were being stretched and twisted due to mechanical movement of test stage. Some DUTs suffered through the lack of signal communication during testing process, resulting in raising the test time and reducing the parallelism. Then, an enhanced architecture was proposed which was able to implement calibration and testing process by hardware, serial interface module (SIM), reducing the amount of tester internal wires. In [128], Ciganda Brasca et al. also used the FPGA technique in conventional testing machine of MEMS devices. Lengthy communication distance and wires between tester and DUT interface were the limiting issues in ATE, tending to limit the electrical stimulation frequency, which ultimately slowed down the test process. High testing parallelism was achieved to overcome such limitations using FPGA module. This technique was used on commercial gyroscopes and accelerometers.

Several MEMS test systems introduced by [129] have the ability to test multiple MEMS applications like accelerometer, gyroscope, pressure sensor, magnetic sensor, and microphone. These systems are capable of testing the devices in parallel. Schaeffel et al. in [130] introduced the design of interferometry test station for parallel testing of optical MEMS. They tested up to 100 DUTs simultaneously through this inspection technique, as optical test systems had the ability to test devices serially, which consumed a lot of testing time and costs. Another technique was reported by Oesterle et al. [131] for a massive parallel test of MEMS microphones. A reconstruction method was adopted by utilizing techniques of tomographic imaging. The specific parameters of all parallel connected DUTs are superimposed through one signal and the DUT response was read out with the reference of single measurement of device.

Testing of single MEMS device is also a challenging task; it is drastically escalated in cost in case of simultaneous testing of multiple devices. The cost of test station for high volume production can accede to millions of dollars. The main tools for these test systems are common including physical, electrical, and temperature stimulus. The modular fixtures perform different measurements (acceleration, pressure, etc.). These modular testers are basic requirement for the industries. Figure 3 shows a general schematic of MEMS tester. Most of efforts are being emphasized on modification of conventional test systems. Issues in parallel testing are summarized as follows:

(i) There is lack of signal communication when a number of DUTs are increased to an extent.

(ii) Noise level is increased with the increase in test sockets.

(iii) One type of devices is tested at one time.

(iv) DUT handler has to modify if device is different.

(v) There is limitation of test coverage.

(vi) Test algorithms are different for dissimilar devices.

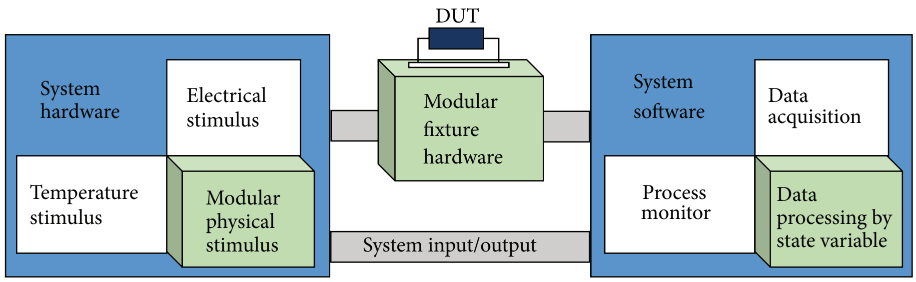

FIGURE 3: Generic MEMS testing system [37].

(vii) Different test programs have to be designed for electrical and mechanical domains.

(viii) Test redundancy is required in case of simultaneous fault detection of multiple DUTs.

The test systems reported in this section utilize both electrical and nonelectrical stimuli for final testing and calibration. But the nonelectrical stimuli such as humidity, pressure, and motion are intrinsically slower than electrical signals and, as a result, they take long test time and they also affected the cost. Ongoing changes in MEMS market are the warnings for future testing issues and challenges. A lack of test standards [122] has a negative indirect effect on the business of MEMS. There is still need of cost-effective parallel test methodology. Testing imposes large direct costs on the product as test equipment is expensive and test programs are limited to test specific devices.

7. Conclusion

MEMS devices are enormously dissimilar in their application and function. Various limited tools and techniques leveraged from the IC technology are being utilized in MEMS testing; however, there is need of developing new test tools for the diagnosis of different faults. Several classes of devices discussed in this literature have common issues related to MEMS testing. MEMS can only be penetrated as an emerging technology until the cost of testing is reduced substantially and valued added technique is applied at the early stage of the market. MEMS testing is fetching difficult challenges, for the reason that conventional electrical testing is unable to comprehend the mechanical behavior of a MEMS device. In addition, mechanical behavior requires different technique to test it (e.g., flow, movement, and pressure). Therefore, integration of multifunction in devices increases the testing problems as a function of the device complexity. Techniques of MEMS testing are different in development processes, that is, design, prototype, and production. The Design for Test (DFT) is becoming a paramount as MEMS designers are facing the pressure of more cost and time-to-market. In the design phase, it is essential to know the requirements of device testing and it should be cost-effective and reliable as a predictor of device performance.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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