Research Development of MEMS Reliability

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***Abstract*—With the wide application of MEMS in aerospace and other industries as well as the continuous improvement of its importance, more and more attentions have been paid to MEMS reliability. This paper expounded the understanding of MEMS reliability, and then summarized the present research status of MEMS common failure modes and mechanisms, MEMS reliability design and analysis technology, MEMS reliability testing technology and MEMS reliability evaluation technology. Finally, the development trends of MEMS reliability technology were discussed.**

Keywords-MEMS; failure modes; reliability design and analysis; reliability testing; reliability evaluation

I. INTRODUCTION

MEMS (Micro Electro Mechanical System) refers to micro device or system which can be produced by micro mechanical processing technology in quantities. It integrates micro sensor, micro mechanism, micro actuator, signal processing and control circuit, interface, and communication system and so on [1]. Because of the advantages of small size and high precision, it has been widely used in aerospace and other fields in recent years. Industrial developed countries attach great importance to the development of MEMS technology. They take MEMS as a new economic growth point in the 21st century and spend a lot of manpower and financial resources to promote the development of MEMS. The research of MEMS technology in China started in 1989. With the attention and support of the government, many universities and research institutes have now established MEMS related laboratories, and have obtained certain achievements [2].

Reliability is the product's ability to complete its required function within prescribed time in prescribed conditions. MEMS reliability is the prerequisite for its wide application and long-term use. MEMS products in use or MEMS devices being researched play an important role in the whole application system. Once their reliability problems occurred, the losses would be enormous. Therefore, MEMS reliability, as the key link of MEMS design, simulation, manufacturing and quality control, is getting more and more attention of the researchers. In order to provide reference for further research on MEMS reliability technology, this paper researched massive data of MEMS reliability at home and abroad, then expounded the understanding of MEMS reliability, and summarized the present research status of MEMS common failure modes and mechanisms, MEMS reliability designing and analysis technology, MEMS reliability testing technology and MEMS reliability evaluation technology. Finally, the development trends of MEMS reliability technology were discussed.

II. UNDERSTANDING OF MEMS RELIABILITY

MEMS technology is widely related to mechanical science, modern optics, microelectronics, magnetic, gas dynamics, fluid mechanics, thermodynamics, acoustics, automatic control, bionics, materials science, surface physics and chemistry, and other disciplines [3]. Its reliability is not a simple combination of electrical reliability, material reliability and mechanical reliability. MEMS reliability involves the knowledge of material mechanics, fracture mechanics, probability and statistics, physics, thermodynamic stress model and other disciplines [4] and its associated schematic diagram is shown in Fig 1.

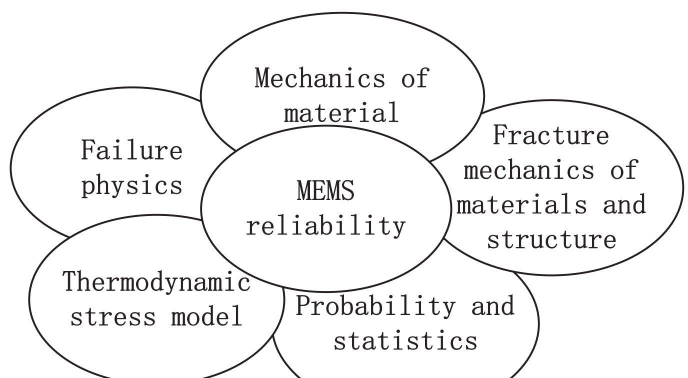

Figure 1. Associated schematic diagram of MEMS reliability

III. MEMS FAILURE MODES AND MECHANISMS

Compared with traditional machinery, MEMS has prodigious differences in material, mechanism designing, friction characteristics, processing methods, testing and positioning, drive mode and so on, leading to many special reliability problems related to structure's miniaturization [5]. Meanwhile, more failure modes are caused due to its more complicated manufacturing process, shape and integration [6]. Up to now, the known common MEMS failure modes are adhesion, wear, delamination, fatigue, corrosion, fracture, creep, and the dielectric damage. The failure mechanisms involve static friction, wear, fracture, creep, crystal defects and dielectric degradation, as shown in table 1.

TABLE I. MEMS FAILURE MODES AND FAILURE MECHANISMS [4,7,8]

Failure mode	Failure mechanism
Adhesion	The adjacent micro mechanical structures keep in touch due to the capillary force and electrostatic force
Wear	Relative motion of tangent surface causes the lack of material in solid surface
Delamination	Insufficient of material strength, mismatching of thermal expansion coefficient, or the drift of environmental stress makes interlayer adhesion bond rupture
Fatigue	Mechanical structure's reciprocating motion makes the tangent part's stress concentration, and then cause the material fatigue
Corrosion	The silicon surface oxidation layer be corrosion cracked due to static and cyclic stress
Fracture	Mechanical prestress is too large, or environmental stress makes the structure's inner stress exceed the fracture strength
Creep	Slow movement of atomic under Mechanical stress
Dielectric damage	The generation of parasitic charge changes the excitation voltage and devices' mechanical properties

IV. MEMS RELIABILITY DESIGN AND ANALYSIS TECHNOLOGY

The main research work of MEMS reliability design and analysis technology focused on the analysis method of MEMS failure mechanisms in theory.

Zaghloul U et al. [9] analyzed the critical failure mechanism (dielectric charging and static friction) of the MEMS related knowledge. They described the nanometer characterizing technique of the failure mechanism, and put forward a new characterizing method which could be used to establish the connection between MEMS devices and MIM (metal-insulator-metal) capacitor. This method can accurately explain MEMS failure mechanism related to dielectric charging and static friction, as well as provide guidance for encapsulation of electrostatic MEMS devices.

Langfelder G [10] proposed a fatigue and fracture testing method for chip. By using this method, the MEMS capacitance sensor's experiment was carried out. The experimental results showed that the elastic stiffness of MEMS device material decreases gradually during the fatigue life. Its compressive stress plays an important role during the whole life. Large compressive stress will reduce the fatigue resistance of the materials.

Zhang G et al. [11] summarized the fatigue properties characterization's testing methods of metal film used in MEMS. They proposed the testing and analysis methods of metal film with different thickness, and revealed that film's fatigue fracture behavior is different from the fatigue fracture behavior of bulk materials, which is controlled by the length of the metal film. Meanwhile, because the ratio of surface to volume of thin film is large, and the damage related to diffusion is widely spread in materials of small size, the interface constitute a serious threat to the reliability of the thin film.

Walraven J et al. [12] analyzed the root cause of failure during MEMS device packaging, capping and sealing. After performing failure analysis on several MEMS components at device and package level, experience has shown that there is little consideration during designing period for testing and failure analysis. It has been shown that over 80% of the cost associated manufacturing MEMS devices are related to packaging. It is not surprising that some of the more difficult failure mechanisms to assess occur during packaging or post package testing. A major problem observed in package level failure analysis on MEMS technology is the difficulty accessing the die. By implementing a design for testing and failure analysis approach, transparent lids can be used instead of metal or ceramic ones to allow rudimentary inspection of the device after test. This would provide very important feedback from testing and would decrease the time needed to determine the root cause of failure.

Melle S et al. [13] analyzed the dielectric charging failure mechanism caused by leakage current of RF MEMS capacitance, and then detected two parameters of the failure mechanism: drive voltage conversion rate and electric stress parameter (based on tangent quality between bridge and dielectric) drive by reliability. Finally, a quality factor was proposed which quantifies the reliability of the capacitive RF-MEMS.

Tambe and Bhushan [14] studied the friction and adhesion of SC-Si with native oxide layer and two polymers. The dependency of each polymer on sliding velocity, relative humidity, and rest time was analyzed. The results indicate that both polymers are highly hydrophobic. Furthermore, the adhesive force is not dependent to relative humidity and rest time (while this is not the case for silicon), and the coefficients of friction for both of them are lower than silicon. The authors concluded that both polymers can be successfully used in micro -devices including MEMS in diverse environmental conditions.

Gao Yang [15] researched the MEMS reliability analysis method based on failure physics by using RF MEMS as a sample. The main steps including: A) Studying the MEMS devices' behaviors with 3D multi-physics finite element models; B) Studying the MEMS devices' failure mechanism with its behavior model and the experimental technology of the failure physical model; C) establishing a common MEMS devices' failure prediction model by introducing an optimal value.

From the research status of MEMS reliability design and analysis technology, it can be concluded that many design and analysis methods for MEMS reliability have been proposed, but their generality is not strong enough.

V. MEMS Reliability Testing Technology

The main research work of MEMS reliability testing technology focused on developing MEMS reliability testing equipment and testing methods.

Many experiments related to MEMS reliability have been carried out abroad, as well as many testing equipments developed by researcher in the past. The most typical representative abroad is a set of MEMS reliability testing system developed by Sandia national laboratory of United States, which named ShiMMeR (Sandia High volume Measurement of Micromachine Reliability), as shown in Fig 2. 256 MEMS devices can be tested in the same time, while each of them is connected to the cable. Through the cable signals, the device can be activated. With high-performance optical microscope and video camera observing and recording the state of MEMS devices, the failure causes, location and time were detected [16].

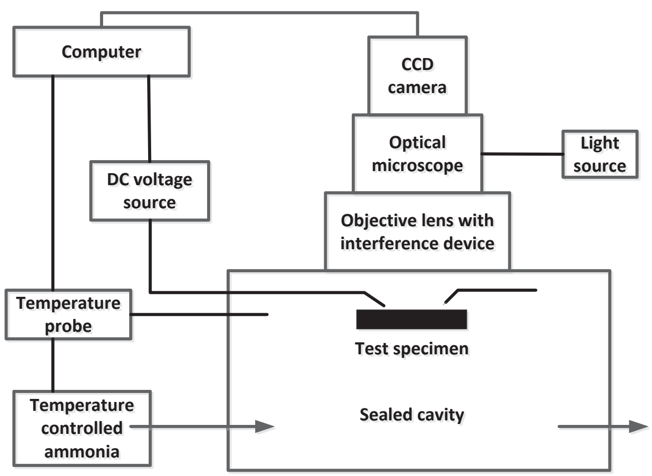

Figure 2. Schematic diagram of ShiMMeR

Aiming at investigating the failure modes, especially the failure modes under different environment (temperature, humidity, shock, vibration and storage) of micro engine system, Sandia laboratory has carried out a lot of experiments by using ShiMMeR. The reliability prediction model of surface wear for micro engine was proposed. This model formula considered the strength, adhesive wear, critical volume, radius of pins, force, resonance frequency and quality factor. The result deduced by this model is very close to actual result obtained by experiment.

Accelerated life testing techniques should be developed to economically evaluate the reliability of MEMS in a short time. Srikar et al. [17] analyzed the mechanical responses and formulated failure criteria for a large class of shock-loaded MEMS. Shocks were modeled as pulses of acceleration applied to the substrate over a finite time range, and MEMS were modeled as micro-structures attached to elastic substrates. Their study shows that for many MEMS structures and shock loads with durations in the range of 50 to 5000 ms, the responses of substrates are like rigid bodies and are expected to be immune against stress-wave-induced damages. Tanner et al. [18] studied the impacts of temperature and humidity on aging process of a vapor-deposited SAM-coated electrostatically actuated MEMS devices with contacting surfaces. Degradation of surface coating was observed when it was stressed at temperature of 300 °C and humidity of 500 and 2,000 ppmv, respectively. The result shows that both temperature and humidity account for failures and can accelerate the degradation process.

Mechanical properties test of thin films as a component of many MEMS devices is also important in analyzing the reliability and the performance of such devices. Youssef et al. [19] proposed a detailed experimental procedure in order to improve the reliability of mechanical characterization of thin films by bulging test as a nondestructive testing technique. The proposed methodology is useful for characterization of geometry and thickness of any type of membrane. Tanner et al. [20] analyzed the absolute maximum rating for shock tested on a commercial off the shelf (COTS) MEMS accelerometer and compared it to the published absolute maximum rating for acceleration. The first failure was observed at 8000G showing a margin of error of two. Based on the failure distribution, it turns out that an in-plane, off-axis acceleration is more damaging than the acceleration in the shock sensing direction.

Tang Jieying et al. [21] conducted the impact testing for MEMS cantilever beams by using Machet hammer. The testing results agree well with fracture failure's reliability model established by stress-strength interference theory.

Hu Xiaotang et al. [22] conducted a series of vibration and impact experiments by using the standard vibration and impact testing system as experimental platform. From the failure situation of micro cantilever beam under a particular vibration and impact load, the micro structure's vibrating and shocking resistance was analyzed.

Shi Yunbo et al. [23] built a Hopkinson bar impact testing system. By using this system, the impact testing of piezoresistive MEMS accelerometer in beam-island structure was carried out. The failure mode of high range MEMS accelerometer was obtained, including microstructure's crack, fracture, and breaking off of bond pad.

From the research status of MEMS reliability testing technology, it can be concluded that MEMS reliability testing technology has reached a high level, with many testing equipment for MEMS reliability been developed, as well as many testing methods been proposed. The problem is that most testing experiments for MEMS reliability are confined to one single physical condition while the MEMS products are usually used in multi-physical coupled fields.

VI. MEMS Reliability Evaluation Technology

The main research work of MEMS reliability evaluation technology focused on the evaluation of MEMS devices' service life and reliability.

Since wear is a phenomenon associated with rubbing or impacting surfaces that can be a concern in MEMS devices with sliding elements. DiBenedetto [24] proposed that the volume of a material fractured by adhesive wear determined by the relationship

$$V_{AW} = \frac{k_{AW} F x}{3\sigma_y} \tag{1}$$

where σ_y is the yield strength of the material, k_{AW} is the material dependent wear constant, x is the sliding distance, and F is the load on the material. Experiments showed that the sliding velocity of a micro-cantilever can affect the adhesion forces between two contacting surfaces, and in turn affect the adhesive wear [25, 26]. Abrasive wear occurs when a hard, rough surface slides on top of a surface and strips away material from the softer surface. Corrosive wear occurs only when two surfaces chemically interact with one another and the sliding process strips away one of the reaction products. In air, the most dominant corrosive medium is oxygen. This type of wear could cause failure in chemically active MEMS devices, especially micro fluidic and biological MEMS. Corrosive wear depends upon the chemical reactions involved, but it can be modeled as [21]:

$$h_{CW} = \frac{k_{CW} x}{3} \tag{2}$$

where h_{CW} is the depth of wear, k_{CW} is the corrosive wear constant (on the order of 10^{-4} to 10^{-5}), and x is the sliding distance.

McMahon M [27] put forward the accelerated life testing method to evaluate the reliability of MEMS. This method uses mechanical devices to drive the MEMS thin film to evaluate its service life. In their study, a smooth surface measurement system was used to make MEMS thin film rotate with a stylus. The experiment stopped until the thin film failed (judging from the details provided by manufacturing).The experiments were repeatedly carried out under different forces, thus making the standard life testing technology can give life prediction under normal conditions.

Van Spengen et al. [28] present a model that can be used to investigate the sensitivity of MEMS to stiction. It quantitatively predicts the surface interaction energy of surfaces in contact. Included in the model is the roughness of the contacting surfaces and the environmental conditions (humidity and temperature). This is done by describing the surface interaction energy as a function of the distance between the surfaces. This distance is not a unique number, but rather a distribution of distances. It is shown that, if we know this distribution, we can calculate the surface interaction energy. The model is suitable for the prediction of forces due to capillary condensation and molecular interactions.

Matmat M et al. [29] researched the dielectric charging effect on reliability of the capacitive RF - MEMS switch. They proposed an evaluation model to evaluate the failure time of RF-MEMS switch. The model considered the components' driving deviation, working cycle and the degradation temperature.

Tanner D [30] proposed a new method to evaluate the reliability of MEMS. The method is based on the model simulation and material science. Unlike the traditional reliability evaluation method (using a large number of sample data), this method relies on the following five jobs: a) designing, modeling and manufacturing; B) testing structure and equipment; C) confirming failure mode and failure mechanism; D) building reliability prediction model (accelerated aging); E) developing appraisal method.

Van Driel et al. [31] researched the reliability prediction method of siliceous encapsulating which is used in the top of MEMS devices to prevent it from external load. They put forward a combined parameters' finite element model and testing methods to illustrate the reliability of four covering, and confirmed some covering problems (cavity deformation, fracture, moisture permeability).

System-level reliability is concerned when dealing either with more than one failure mode or with the issue of porting them on to the next complexity level to make a statement on board level. From the system design point of view, errors are classified as follows: transient (faults), permanent (defects), or intermittent [32]. Soboyejo et al. [33] proposed a system-level reliability evaluation methodology for MEMS devices. Their proposed procedure is capable to implement theoretical reliability models as functions of material performance parameters. Their proposed model can be used to establish performance standards on the design and function of the MEMS. Moreover, it can be applied to assess the reliability of MEMS devices using available data.

By using the method that MIS (Metal Insulator Semiconductor) structural experiment determines the dielectric charge, Zhan Linxian et al. [34] in Xiamen University found a simplified method to evaluate the dielectric material whether meets the reliability of RF MEMS switch. In this method, MIS device was manufactured with dielectric material, and then its loading experiment was carried out, finally, the C_V curve was measured. As long as the flat band voltage measured does not exceed the critical flat band voltage, there will not appear adhesion phenomenon.

The research team led by Professor Shang Deguang [35] introduced the MMT-11N micro mechanical fatigue testing machine and its affiliated system from Japan. By using the testing system, the fatigue characteristic for MEMS plating copper film was analyzed, and the S-N curve of MEMS plating copper film, as well as its cyclic stress strain curves and strain life curve was obtained. By using the local stress strain method, the fatigue life of notched MEMS plating copper film was evaluated, and the evaluation results agree well with the experimental results.

From the research status of MEMS reliability evaluation technology, it can be concluded that MEMS reliability evaluation technology has also reached a high level, with many reliability model been developed and validated. The problem is that most of the reliability models are confined to a single

MEMS device while MEMS products are often in a system level.

VII. SUMMARIZATION AND PROSPECTS

From the research status at home and abroad, it can be concluded that both the research and application technology of MEMS reliability have reached a high level, but there are still three aspects should be further strengthened:

(1) The generality of MEMS reliability design and analysis method is not strong enough now and it's remained to be strengthened.

(2) The current research of MEMS reliability testing technology mostly considers only one single physical condition for MEMS devices. In the future, the research of multi-physics coupled conditions' influence on MEMS reliability will be strengthened. Meanwhile, there is no commercial MEMS reliability testing equipment in the market now. The research on the commercial testing equipment which can be used for reliability testing of most common MEMS devices should be strengthened.

(3) The current MEMS reliability evaluation technology is mostly confined to a single MEMS device. In the future, the research of reliability evaluation technology for MEMS in systemlevel should be strengthened.

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