Evaluation Trial of MEMS Devices by LSI Process Diagnostics

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1. Introduction

Recently, the demand for MEMS has expanded rapidly. Many of the manufacturing technologies used for semiconductor integrated circuits (ex. Photolithography) is used for manufacturing MEMS devices. However, the MEMS device has a peculiar mechanical architecture and failure mode making the application of the analytical method for conventional semiconductor devices to MEMS difficult. The establishment of a reliability evaluation technology has not kept pace with the MEMS technology. The establishment of an effective technique for evaluating the reliability of the MEMS device needs to be developed immediately.

We have developed a quality evaluation technique "Large Scale Integrated (LSI) Process Diagnostics" with Japan Aerospace Exploration Agency (JAXA). Using this technique, the wafer process quality of the semiconductor device used in systems such as a car, space, Airlines, and electric power products that needed a high level of reliability was evaluated. By use of the “LSI Process Diagnostics” criteria devices that failed to pass could be improved.

"LSI Process Diagnostics system" is a technique to investigate the existence or non-existence of a problem inside the device which is believed to be of good quality and the looseness of the device structure to predict a potential failure. The concept of the conforming article is based on the Destructive Physical Analysis (DPA) of the MIL standards (US military standards) and can be considered as an analysis method with a proven track record. The device is evaluated by using the inspection and the diagnostic criteria of each LSI manufacturing process (isolation formation, gate formation, and wiring formation, etc.). Moreover, a data base of various process data such as sizes, the structures, materials, and shape are constructed in "LSI Process Diagnostics system". The strengths and the weaknesses if each device maker and each design rule can be extracted from the diagnostic data accumulated in the data base. The diagnostic data has been effectively used to improve the reliability of the devices.

The goal of our project was to construct a process diagnostic system of the MEMS device based on this "LSI Process Diagnostics system" then perform a structural evaluation of the devices based upon the data. The diagnostic system was important because a peculiar problem to the analysis of the MEMS device had been found.

2. Analysis method

MEMS devices are built with various structures. It is necessary to use a method for analyzing each structure that corresponds to the particulars of that structure. We report here the evaluation result of a MEMS chip for a game machine as a representative case of our new technique.

The MEMS structure is greatly different from that of conventional LSI devices. Therefore, a first pass inspection using the "LSI Process Diagnostics" was executed. An item required for MEMS was identified and added to the "LSI Process Diagnostics". As a result the "LSI Process Diagnostics" process was restructured. Table 2.1 shows the inspection item of the MEMS device.

Table 2.1: Inspection item of MEMS device

No.	Inspection item	Observation equipment	Inspection object	Detected defect factor
▨ 1	Assembly process inspection	OM,X-ray, SAT,IR	State of package Assembly abnormality Silicon cap State of chip side Internal structure	Existence of discoloration Crack, Void Abnormal sealing Delamination Abnormal internal structure Dust etc.
▨ 2	Structure part inspection	OM, SEM	Silicon sealing inner wall Metallisation Structure part of sensor (surface and back)	Existence of discoloration Crack, Void, and dust Abnormal shape Structural damage etc.
▨ 3	Cross-section SEM inspection	SEM	Silicon sealing inner wall Metallisation Contact Structure part of sensor	Void ,Dust Shape factor (film thickness, structure L/S, contact diameter and others) Structural damage Coverages, etc.
4	Plane SEM inspection	SEM	Silicon sealing inner wall Structure part of sensor	Vioid and Dust Shape factor (structure, L/S, another) Structural damage Mask defect Crystal defect, etc.
▨ 5	Cross-section TEM inspection	TEM	Structure part of sensor Composition	Void, Dust Crystalline (crystal defect) Structural factor (film uniformity), etc.
6	Plane TEM inspection	TEM	Structure part of sensor Composition	Dust, crystalline (crystal defect) Structural factor (film uniformity), etc.

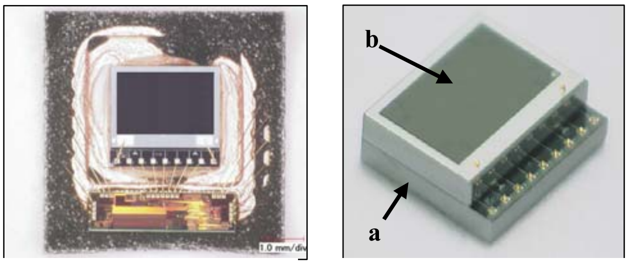
▨ Inspection item (common with LSI process diagnosis)

OM : Optical Microscope X-ray : X-ray inspection system
IR : Infrared rays microscope SAT : Scanning Acoustic Tomograph
SEM : Scanning Electron Microscope
TEM : Transmission Electron Microscope

2.1 Method of analysis for assembly process

The outside of the package is inspected first. "Wound on the surface of the package", "Fin", and "State of the outer leads", are some of the possible observations. Next, an X-ray system is used to "Observe the internal structure", "Voids in the mold resin", and "State of the inner lead." Afterwards, the mold resin is removed. After mold resin removal, internal "Wire bonding", "Inner lead", and "State of the chip" can be inspected. This inspection flow was applied to the MEMS device effectively.

The information that is necessary for the inspection of "wafer process" is acquired along with each inspection item of "assembly process". When the inspection of "assembly process" ends, the MEMS sensor is covered with the Si cap. Figure 2.1 shows an internal structure of the MEMS device after the molding resin is removed.



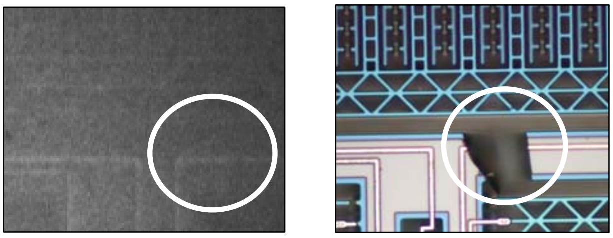
Device whole image after the removal of molding resin

Chip whole image
(a: Sensor part, b: Si cap)

Figure 2.1: Internal structure of MEMS device

After the inspection of "assembly process", it is necessary to remove the Si cap to inspect the sensor structure. At first, "Mechanical grinding" and "Flaked off at the cap sealing part" were tried as a removal method of the Si cap. However, the sensor was easily broken by the removal process. A removal technique that doesn't damage the MEMS structure is necessary. In this analysis, at first, the Si cap was mechanically ground. After the cap had been made flimsy by grinding, the residual material was flaked off with adhesive tape. As a result, an excellent removal with little damage was possible. However, the cap cannot be removed with no damage by this method.

An inspection prior to Si cap removal with an infrared microscope was developed. The presence of an abnormality of Si cap internal structure could be observed with this inspection technique. As a result, the cause of damage by deprocessing vs. processing could be determined. Figure 2.2 shows a chip internal structure before and after the Si cap removal. Damage is not observed before the Si cap is removed. However, after the cap is removed, damage is observed. Therefore, the damage was generated by the Si cap removal.



Before removing the cap (IR) After removing the cap (OM)

Figure 2.2:
Chip internal structure before and after Si cap removal

Si dust can fall to the sensor even with good deprocessing techniques. Therefore, the ability to distinguish between dust generated by deprocessing from that generated during manufacture must be developed. Si dust cannot be observed with the infrared microscope. When dust is detected internally, it is necessary to observe shape and the thickness of dust in detail to judge its origin.

The inspection flow of the device during assembly for the MEMS device was constructed based on the result of preparatory investigations. Figure 2.3 shows the inspection flow.

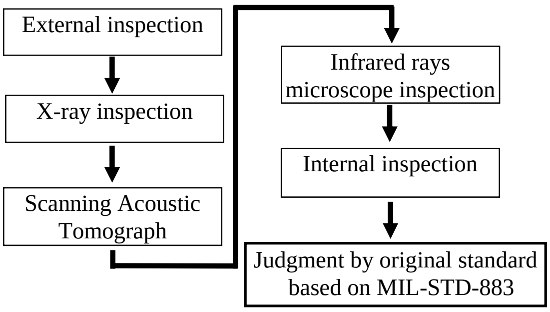


Figure 2.3: Inspection flow of assembly process

2.2 Method of analysis for wafer process

At the first of inspection of "wafer process", we inspect the sensor structure. The observation of the LSI component of the device can be performed from the silicon surface. However, because the sensor part is formed in the midair for the MEMS component of the device, inspection from the silicon side is insufficient. Observation from the backside is necessary to observe the sensor. Next, the Shape of the device cross-section and the state of the films between layers is determined by cross-sectional SEM analysis. We take care for the sensor not to be broken when the sample is made. Inspection of the clearance of the Si cap and the sensor is necessary as well as the state of the Si cap seal in the cross-section SEM analysis. The sample must be made without removing the cap. To make the sample the entire chip is encased in a resin. Next, the cave part where the sensor is formed must be exposed by grinding. To prevent breakage of the sensor when the cave first appears during grinding, grinding is stopped. Afterwards, resin is used to fill in the cave.

If grinding reaches the sensor the sensor breaks if not properly supported. Monitoring the grinding progress is important to prevent breakage of the sensor. Because the structure is complex, a bubble might remain in the resin around the sensor. Therefore, vacuum degassing is indispensable. During vacuum degassing, there is a possibility that the sensor is broken by the bubble. The viscosity of the resin must be monitored to prevent breakage. In initial investigations, the vacuum degassing processing of the resin was done under the normal temperature conditions. As a result, the transformation of an internal structure by the bubble was observed as shown in Fig. 2.4.

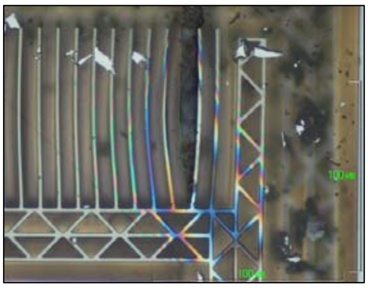


Figure 2.4:
Structure transformed by remaining bubble (OM image)

This phenomenon can be reduced by the use of a low viscosity resin and/or reducing the viscosity by raising the temperature of the resin. The sectional inspection in the structure of the MEMS machine becomes possible by proper use of the fill material.

MEMS has a moving part unlike LSI devices. The belief exists that stress concentrates on the support part (spring part) of the MEMS. Therefore, fatigue fracture of the support is frequently discussed. Inspection of the crystalline structure of the support of the moving part of the MEMS is important. To highlight the crystal defect a seco-etch is applied to the support material. The presence of a crystalline defect in the support can be determined by SEM inspection. Next, the detailed shape of the device structure, crystal defect in the sensor structure, and composition of each component is determined by cross-sectional TEM. Finally, the support is inspected in detail by plane TEM. Figure 2.5 shows the inspection flow in the wafer manufacturing process of the MEMS device based on the result of initial investigations. The MEMS device was analyzed as shown in this flow.

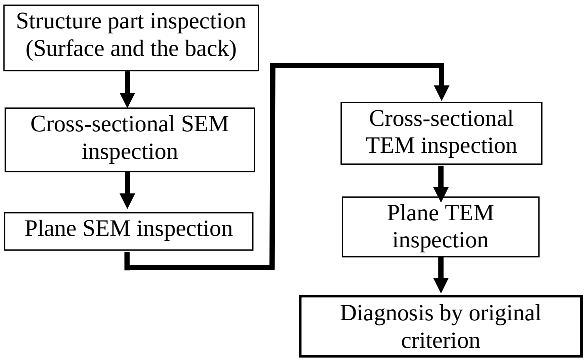


Figure 2.5: Inspection flow of wafer process

3. Analytical result

3.1 Result of assembly process inspection

The assembly process of the MEMS device was checked based on the inspection flow shown in Fig. 2.3.

The assembly process of the MEMS device was inspected with the inspection procedure of an LSI device. An abnormality was not observed as a result of inspection according to an original criterion based on MIL-STD-883. Table 3.1 shows the summary of the inspection result of assembly process. "LSI process diagnostics" for the process of the assembly was effective in locating potential failure.

Table 3.1: Result of assembly process inspection

Inspection item	Inspection point	Pass/Fail
External inspection	Shape of package each part	○
	Shape of outer leads	○
	Others	○
X-ray inspection	Package internal assembly structure	○
	Inner lead	○
	Others	○
Scanning Acoustic Tomograph	Presence of delamination	○
	Others	○
Internal inspection	State of wire bonding	○
	Inner lead	○
	State of chip	○
	Others	○
Infrared rays microscope inspection	Chip internal structure	○
	Others	○

3.2 Result of wafer process inspection

The wafer process of the MEMS device was inspected based on the inspection flow shown in Fig. 2.5.

The Si cap was able to be removed by the technique described in paragraph 2.1. The sensor surface was inspected. Inspection confirmed that the sample used electrostatic capacitance to detect acceleration. Figure 3.1 is a bird's-eye view SEM image of the device and a chart explaining the operation of the sensor.

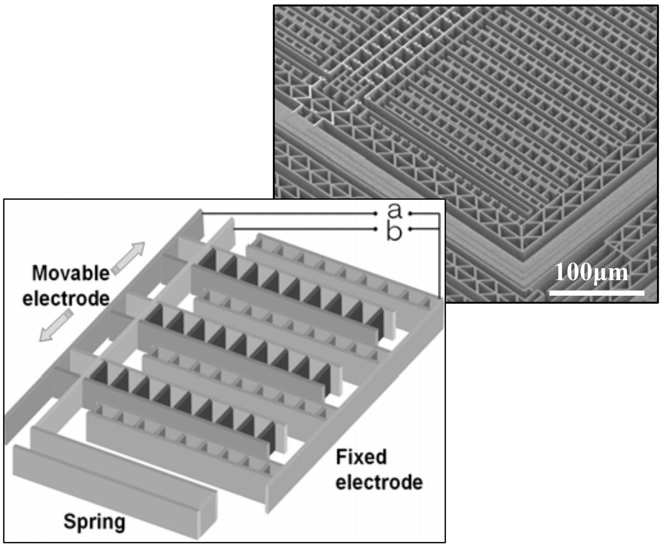


Figure 3.1: bird's-eye view SEM image and the operation explanation chart of the sensor

Next, the back of the sensor was inspected. Figure 3.2 shows bird's-eye view SEM image of the back of the sensor.

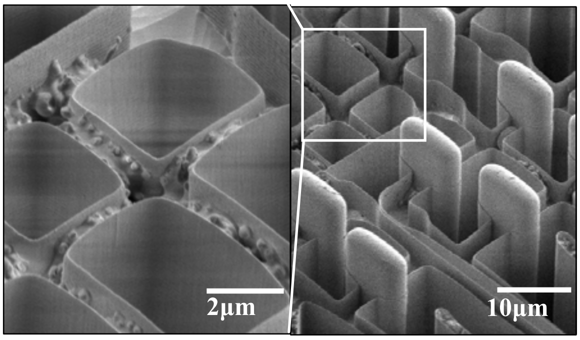


Figure 3.2:
bird's-eye view SEM image on the back of the sensor

A shape that had dented the back side of the sensor was observed. When the sensor is etched, this shape is formed during etching the back by surplus gas. Moreover, the residue of the etching was on the side in the part. The residue is flimsily. There is a possibility that the MEMS doesn't function normally if this residue drops out and touches the sensor. The structure is easy to understand by cross-sectional inspection described later.

Next, cross-sectional SEM inspection was preformed. The sample in cross-sectional SEM was able to be made by the method of paragraph 2.2. Figure 3.3 shows a cross-sectional SEM image of the MEMS structure.

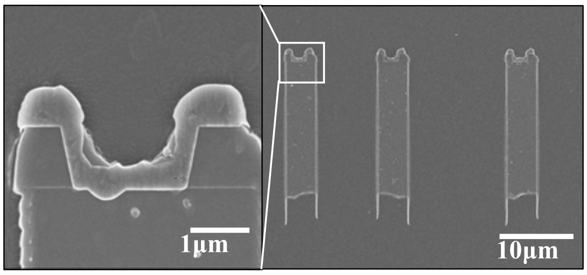


Figure 3.3:
cross-sectional SEM image of the MEMS structure

Wave-like shape that originated in deep etching was observed on the side of the sensor. The residue was observed under the structure side.

The coverage of the metal wiring contact formed on the sensor was good. An alloy spike was observed with two or more contact joints. The alloy spike is generated as the Si substrate reacts to heat-treatment of the metal wiring. In LSI devices, it is necessary to note a leakage current is generated when the alloy spike exceeds the diffused region. However, it seems to be inconsequential because a diffusion zone is not formed in the sensor of this MEMS device. Thus, even if it is a defect in the process of an LSI device, the same defect is not necessarily judged a problem for MEMS. It is necessary to construct a defect judgment criterion of the MEMS device carefully because there might be other such cases.

Next, to observe the structure in more detail, cross-section TEM analysis was performed. Figure 3.4 shows a cross-sectional TEM image of the MEMS structure.

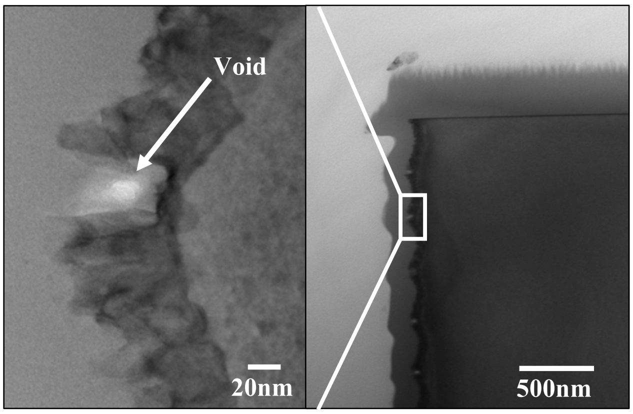


Figure 3.4:
cross-sectional TEM image of the MEMS structure

As a result of cross-sectional TEM inspection, the sensor was formed by monocrystalline Si. Moreover, it was confirmed by elementary analysis that the film on the sensor side was an oxide. Moreover, an amorphous layer and minute void were observed in an interfacial part of monocrystalline Si and the oxide film. This amorphous layer is thought to be a damage layer formed by the etching. Note that there is a possibility the void may become the starting point of cleavage breaking with when a big stress is applied.

Moreover, the thin film under the structure side that had been observed by cross-sectional SEM inspection was a residue of the oxide film that had been formed on the side. The residue that had been broken from the root as shown in Fig. 3.5 was observed. This damage might have been generated by stress when the sample was made. However, if device with such residue is dropped, the MEMS might start to fail. Therefore, it is necessary to care when handling devices.

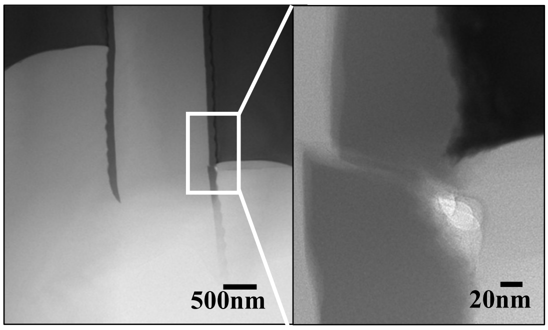
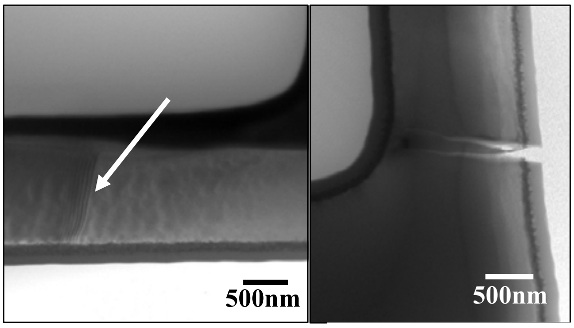


Figure 3.5: Cross-sectional TEM image of filmy residue

Next, plane TEM observation was performed. Figure 3.6 shows plane TEM image in the sensor support. The left figure is an image in the vicinity of the root of the spring that supports the moving part. The stacking fault crosses the inside of the sensor structure (arrow part in the figure). To break the spring intentionally, stress was added to another part. The right picture of Fig. 3.6 shows the destruction of the part. The breaking part broke at the cleavage as shown in this figure. From this situation, it is presumed that the possibility of a stacking fault (shown in the left of Fig. 3.6) causing a cleavage break is high.

This stacking fault might have been generated by the stress when the sample was made. The crystal defect made by scratch damage might occur in the sample while making the TEM sample. In this case, random dislocation along the scratch line as shown in Fig. 3.7 is seen. Such a scratch often steps over the adjoining structure. Therefore, such a defect can be presumed to have originated during the making of the sample.



The stacking fault inside of the sensor structure

Breaking part intentionally broken

Figure 3.6: Plane TEM image in structure support part

However, there is a possibility that the crystal defect occurs because of the stress of the Si cap removal. Therefore, it is difficult to specify the process (wafer process or de-cap process) when the defect was generated. Moreover, a lot of huge oxygen defects were observed by plane TEM. Figure 3.8 shows the oxygen defect observed in the sensor structure. The oxygen defect of such a size is not usually seen in the observation of LSI devices. The influence of the oxygen defect on the quality of MEMS is uncertain. However, there is a possibility that strength of the support decreases when such an oxygen defect is in the support part of the sensor. Therefore, it is a point that should be noted in constructing the defect judgment criteria of the MEMS device.

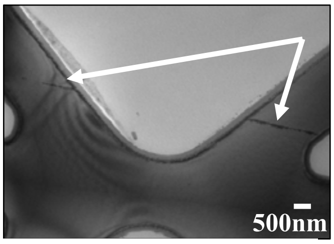


Figure 3.7:
Plane TEM image of scratch

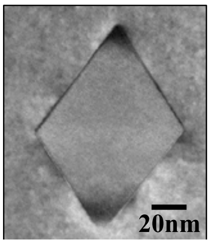


Figure 3.8:
Oxygen defect (TEM image)

A structural defect that might occur for each manufacturing process of MEMS has been extracted based on the above-mentioned inspection result. The evaluation item of the wafer process for MEMS was developed from these defect items. The evaluation item of the wafer process is shown in Table 3.2 and the list of the inspection result of the wafer process is shown in Table 3.3 respectively. It is thought that the quality rating in the wafer process of the acceleration sensor analyzed this time is possible by the evaluation of the item shown in Table 3.2.

Table 3.2: Evaluation item of wafer process

Process name	Defect item
Electrodes and wiring formation	Abnormality of wiring film thickness
	Structural abnormalities and etching defects
	Aluminum crystallization grain radius abnormalities
	Line breaks at stepped wiring segments (wire disconnection)
	Hillock
	Voids and scratches
	Interfusion of foreign materials and contamination
	Coverage of connecting sections
	Mismatched alignments (mask alignments)
	Interlayer connection sections (aspect ratios)
	Interlayer connection sections (opening ratios)
	Interlayer connection section defects
	Silicon nodule of contact section
	Alloy spikes
Sensor structure formation	Abnormality of size (L/S/H)
	Structural abnormalities and etching defects
	Interfusion of foreign materials
	Crystal defect
	Damage, breaking
	Abnormality of the back shape
	Abnormality of side shape
	Abnormality of passivation film shape
	Cracks, chips, fractures and peelings of passivation film
	Boyd of passivation film
	Defect of passivation film formation
	Interfusion of foreign materials to passivation film
Silicon sealing process	Abnormality of sealing
	Boyd in encapsulant, Interfusion of foreign materials
	Infiltration of encapsulant to sensor area
	Abnormality of space (between sensor – sealing layers)
	Cracks, chips, fractures

Table 3.3: Inspection result of wafer process

Inspection item	Analytical result	Remarks
Structure part inspection	△	Shape abnormality on the back of sensor
Cross-section SEM inspection	△	○Alloy spike △Shape abnormality on the back of sensor
Plane SEM inspection	○	―――
Cross-section TEM inspection	△	○Void on the side of the sensor ○Oxygen defect △Amorphous layer structured on the side of the sensor △Shape abnormality on the back of sensor (damage)
Plane TEM inspection	△	△Amorphous layer structured on the side of the sensor △Crystal defect in the sensor part

○ ; Abnormality none or Slight defect
△ ; Caution needed
× ; Serious abnormality

4. Conclusions

A process diagnostics technique for MEMS devices has been newly developed. An acceleration sensor was evaluated as one example of how to use the new diagnostic technique. As a result, the process of the assembly was able to be evaluated as well as an LSI device. Moreover, the evaluation of the wafer process indicated changes were required for MEMS devices vs. conventional LSI diagnosis. The assembly inspection process was shown to be possible by that given in Fig. 2.3. A method for evaluating the wafer process was possible for MEMS. Moreover, it was confirmed that "A peculiar inspection point to MEMS", "Sample making technology" and "Judgment criteria of the defect" were necessary.

In this result, diagnostic criteria of LSI devices were able to be applied to the wiring formation process of the MEMS manufacturing processes. However, it was necessary to construct the diagnostic criteria anew for other processes. A concrete correlation of the constructed diagnostic criteria and the reliability of the MEMS device are uncertain at the present stage. Therefore, it is necessary to investigate the correlation in the next step. Moreover, it is necessary to construct the diagnostic criteria for each process of each particular MEMS.

Therefore, it is necessary to do preliminary studies of each MEMS device. It is necessary to restructure the inspection menu corresponding to the structure based on the inspection results.