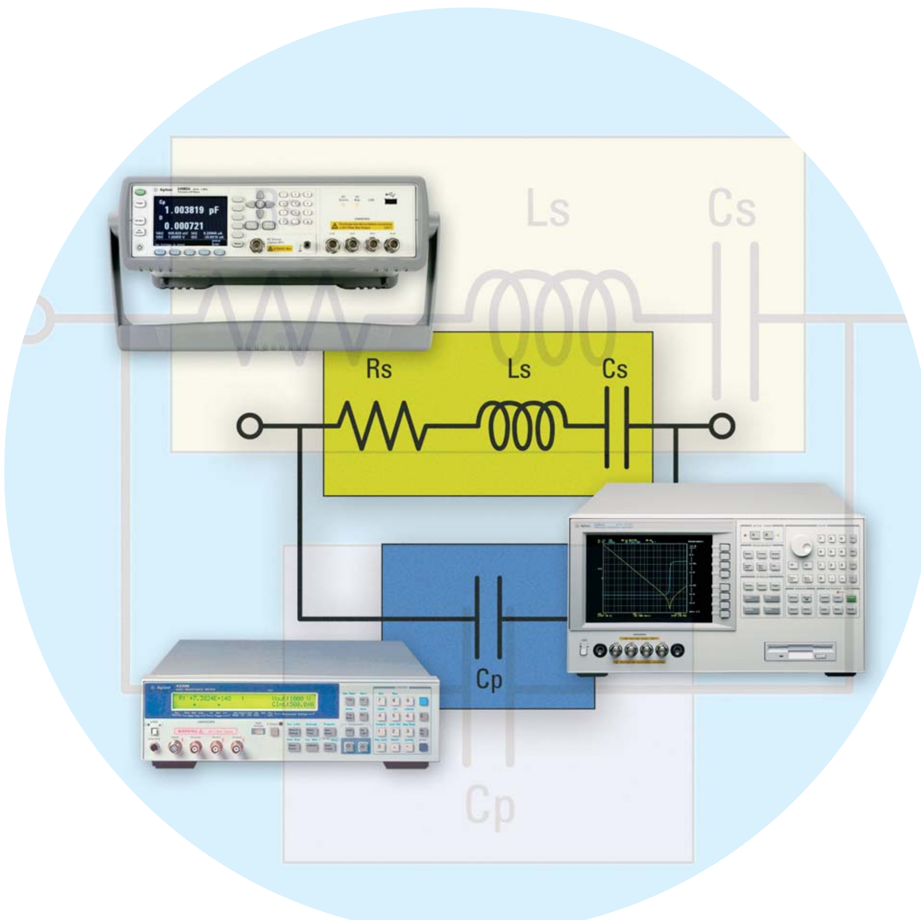
MEMS On-wafer Evaluation in Mass Production

Testing At the Earliest Stage is the Key to Lowering Costs

Application Note



Agilent Technologies

Recently, various devices using MEMS technology such as pressure sensors, accelerometers, and RF MEMS have been commercialized. Additionally, new devices such as silicon microphones have been evolving rapidly. The MEMS market started with the automotive industry and has been expanding to consumer products such as cellular phones.

This MEMS market expansion also applies pressure on manufacturers to lower their costs per unit. However, few opportunities exist, mainly due to:

- Low yields due to the precision process
- Slow throughput due to applying the physical stimulus.

A recent study (see item 1 in the Appendix) attributes 80% of the total production cost to the device packaging process, so defective chip inflow to the packaging process contributes to the cost rise. Therefore, we will discuss how to evaluate MEMS elements at the on-wafer stage in order to lower the total production cost.

Lowering Production Cost in Mass Production

Testing MEMS elements in the earliest stages of the manufacturing process can help contribute to lowering production cost. Key considerations are:

- Prompt product quality improvement by fast process feedback
- Production cost reduction by removing defective chips before package integration.

In particular, testing MEMS at the on-wafer or die level is critical for lowering mass production cost. When testing the MEMS movable part at the wafer or die level, the input and output of the MEMS device needs to be considered.

Input

There are two input methods to drive MEMS devices. One is to apply a physical stimulus such as pressure or acceleration, and the other is to apply an electrical signal. The movable part of sensors is also driven by the bias voltage applied. Applying an electrical signal as the input stimulus is superior in terms of the speed, repeatability, accuracy and usability, while applying physical stimulus is better when duplicating the device's operating behavior.

Output

There are also two different methods to measure the output of MEMS devices. One is a direct displacement measurement with a laser interferometer, and the other is an electrical measurement using test signals. The electrical measurement is applicable for electrostatic capacitance or piezoelectric resistance. Though the direct measurement with a laser interferometer is straight forward, the electrical measurement is superior in terms of repeatability, accuracy and usability.

Both test throughput and yield are critical in the mass production process, as are measurement speed and repeatability of the test instrumentation used. Test equipment usability should also be considered for lowering production cost because the usability affects the ease of maintenance for a test system, which determines the production line up time. Thus, electrical testing to characterize MEMS wafers or dies is preferable to physical stimulus test for lowering production cost (Figure 1).

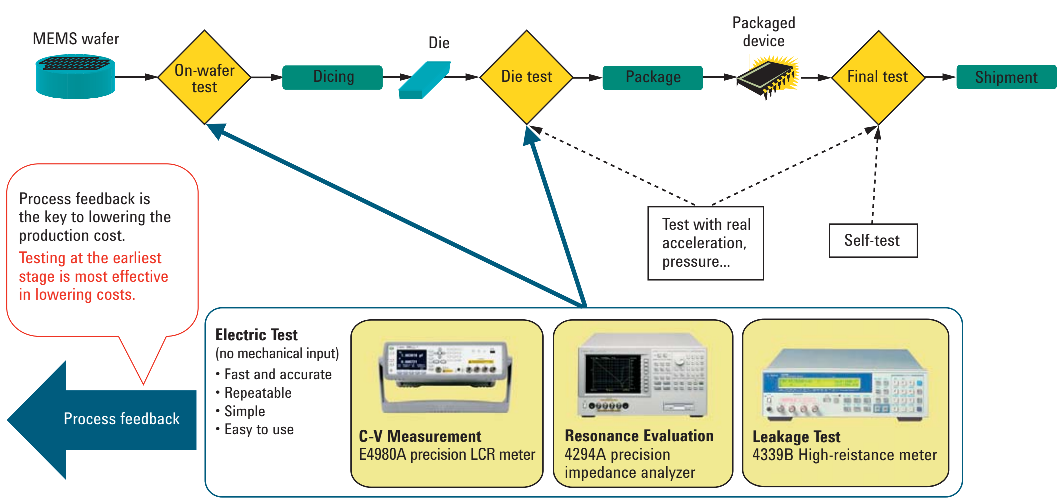


Figure 1. MEMS wafer characterization process

Capacitive Sensor

Common methods for detecting the displacement in MEMS sensors, such as pressure sensors, accelerometers, and silicon microphones, utilize piezoelectric or capacitive techniques. We will examine the electrical test of capacitive sensors as an example.

The capacitive sensor can be modeled as shown in Figure 2. The distance between electrodes is changed by the physical stimulus such as pressure, acceleration, and sound wave. The change in distance can be read electrically as the electrostatic capacitance change.

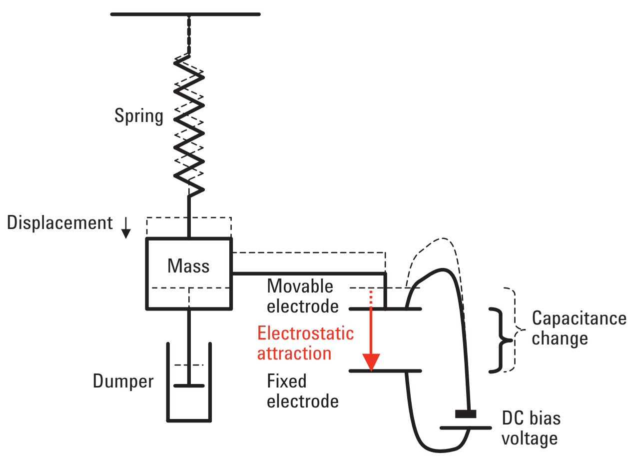


Figure 2. Capacitive sensor diagram

The capacitive sensor has two mechanical characteristics, the static response (static characteristic) and the dynamic response (dynamic performance) against the physical stimulus input. Static response is a fundamental characteristic and is defined as the capacitive sensor displacement when a static physical stimulus is applied. The dynamic performance is explained as the response when a dynamic physical stimulus is input. The dynamic performance is expressed as the frequency response of amplitude and phase, often represented by parameters such as resonance frequency, Q-factor, and 3 dB bandwidth.

Evaluation by Electrical Measurement

As previously mentioned, the physical stimulus input can be replaced with the electrical stimulus input, which we will now examine.

Static performance

The static physical input can be replaced by applying DC voltage bias. Therefore, the static characteristic can be evaluated by measuring the electrostatic capacitance by sweeping the DC bias voltage. This measurement is generally referred to as a Capacitance-Voltage (C-V) measurement. The important specifications and features of the test instrumentation are impedance range, measurement accuracy, frequency range, measurement speed, repeatability, and DC bias voltage range.

The capacitance of the most capacitive sensor is approximately 0.5 to 1 pF at the neutral position. Consequently, the test equipment needs to be capable of measuring electrostatic capacitance accurately in the order of 0.1 pF. The four-terminal pair method is recommended for the most accurate impedance measurement.

Note that an AC test signal is used for the impedance measurement. If the test frequency is set as low as the electrodes of the device, the voltage of the test signal can actuate the electrodes. When the electrodes are moving, electrostatic capacitance cannot be measured correctly. Therefore, the test frequency should be set much higher than the mechanical operating frequency of the device under test. Generally, the operating frequency of the MEMS device is in the low kHz range, so a 1 MHz test frequency is adequate.

As superior impedance measurement repeatability enables narrowing the guard band in the testing process, it also helps to improve yields. Measurement repeatability is important when characterizing small mechanical displacements, as is device processing accuracy. In the case of a capacitive sensor with capacitance of 1 pF, the measurement repeatability should be less than 0.1%, which means that 1 fF or less of the repeatability is recommended.

Caution must be exercised when the DC voltage bias sweep measurement is performed. Capacitive sensors have hysteresis characteristics based on the amount of electrical charge being inducted to the electrodes. This hysteresis is one of the parameters to be evaluated by a C-V measurement.

The Agilent E4980A Precision LCR meter is such an instrument that meets the requirements above. The maximum measurement frequency is 2 MHz, and the repeatability of the measurement is σ < 1 fF, which meets the required performance. The E4980A Option 001 extends the DC voltage bias range up to 40V enabling accurate electrostatic capacitance measurement with DC voltage bias sweep. 40V is suitable for a vast majority of MEMS capacitive sensors.

Dynamic performance

The dynamic physical stimulus can be replaced with the AC voltage applied by the electrical measurement. The characteristic of the movable part as a portion of the electrode can be modeled as shown in Figure 3. The mechanical characteristic of the movable part is reflected to the measured impedance at a lower test frequency than the mechanical operating frequency. Thus, measuring the impedance of the device can illustrate the frequency response of the movable part. The four-terminal pair method with the impedance measurement is recommended to achieve the most accurate measurement.

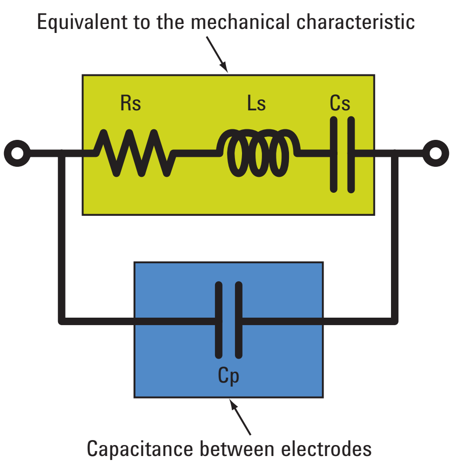


Figure 3. Characteristic of the movable part of the electrode

The movable part being driven by the AC voltage applied has electrostatic attraction between electrodes. Since the electrostatic attraction is proportional to the square of AC voltage applied, it generates a second distortion to the current flowing into the electrodes. Because the impedance analyzer obtains the impedance value by the measured vector value of the fundamental element of voltage over that of the current, the second distortion may cause measurement error. Applying DC bias voltage to the AC test signal is a good way to solve this problem. When the amplitude of the AC voltage is adequately smaller than that of DC bias voltage, the second distortion of the current is negligible so that a valid measurement can be performed. This method allows for a quick and easy evaluation of the frequency response of the device, except when the electrode is at its neutral position.

Impedance versus frequency profile is the fundamental measurement to characterize the dynamic performance of the device and can be obtained with an impedance analyzer. The dynamic performance of the device can be derived from the measurement results which represents the performance at the position of the electrodes driven by a DC bias voltage applied. The dynamic performance at any position can be obtained by varying the DC bias voltage. The level of AC test voltage needs to be set smaller than that of DC bias voltage.

Note that the measured impedance profile has both impedance, representing the dynamic performance and the electrostatic capacitance, representing the electrode displacement. An equivalent circuit model is shown in Figure 3. To determine the dynamic performance of the device itself, electrostatic capacitance can be subtracted. The electrostatic capacitance can be obtained from the measured impedance value at a higher test frequency than the operating frequency of the device. The Agilent 4294A Precision Impedance Analyzer is a suitable test instrument for dynamic performance evaluation. The instrument provides sufficient frequency range up to 110 MHz, excellent 0.08% measurement accuracy, and DC bias voltage function up to 40V. In particular, the 4294A's equivalent circuit analysis function enables quick-and-easy analysis of both dynamic performance and electrostatic capacitance evaluation.

Leakage

Besides characterizing static and dynamic performance of MEMS devices, leakage measurement is also an effective test for quality management. The leakage measurement between the electrodes enables the early detection of device defects.

A pico ammeter such as a semiconductor device analyzer or high-resistance meter is generally used. If parametric testing is required due to monolithic-type MEMS devices containing transistors and MEMS elements in one chip (e.g. at the die level), a semiconductor test system can be used. However, a high-resistance meter can be sufficient for leakage test in terms of cost, simplicity, and quick operation.

The Agilent 4339B High-Resistance Meter is ideal for this application, as it allows resistance measurements up to 1.6×10^7 GΩ and current measurements down to 60 fA.

Setup

Concerning on-wafer measurements, configuring the probe station and probe card with the test instrument also need to be considered. The shape of the probe card depends on the device under test. However, for the precise measurement by four-terminal pair method, the cabling from the device to the probe and also the card design are important.

The impedance measurement requires the ability to compensate for the measurement errors caused by cable extension and the parasitic impedance of the probe card from the measurement data. Compensation has to be performed at the end of the probe, using supplied impedance standard substrates from the probe station vendor.

The above considerations and compensation procedure are the same as that of a FET gate insulator measurement. For more information, refer to 2 and 3 in the Appendix.

Conclusion

As we have discussed, making on-wafer impedance measurements at the earliest stages in the manufacturing process can be very effective for lowering the production cost of MEMS devices. High-performance test instruments with accurate impedance measurement techniques are required to characterize small mechanical displacements. The Agilent E4980A, 4294A and 4339B are well-suited for these types of measurements.

All of the instrumentation enabling production cost reduction are already being used in the production lines of the vast majority of MEMS device manufacturers.

Appendix

1. The MEMS Test Community –
http://www.memunity.org/on-wafer_testing.htm

2. *Application Note: "Agilent Evaluation of MOS Capacitor Oxide C-V Characteristics Using the Agilent 4294A,"* Literature Number 5988-5102EN.

3. *Application note: "Agilent Technologies Impedance Measurement Handbook,"* Literature Number 5950-3000.

4. This application note leverages information obtained by permission from the November 2007 issue of Electronic Parts and Materials magazine, Japan.
http://www.kocho-net.com/magazine/denshi1.php

5. MEMS/NEMS Device Measurement Solution –
http://www.agilent.com/find/mems

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