Piezoelectric Sensors for Measuring Mechanical Stress in Semiconductor Applications

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ABSTRACT

Newer applications such as AI, 5G, IoT, ADAS, AR/VR and others are opening-up multiple growth opportunities for the semiconductor industry. The adoption of these technologies is generating demand for increased performance. The industry is exploiting the power advantages of lower-node technology, wide-bandgap (WBG) materials and advanced packaging (AP) to accommodate increased functionality on a single small form - making production processes even more challenging.

These advances in semiconductor technology and device complexity are stepping up the pressure on monitoring and controlling for semiconductor packaging processes. Processes optimization is a prerequisite for high reliability, which is achieved by selecting appropriate materials and controlling critical process parameters.

Optical and displacement sensors together with electrical testing are currently the most widespread methods used for chip testing and monitoring/control of packaging processes. However, improved methods for process monitoring and failure identification are needed to maintain or improve the quality and yield of a packaging process.

Force, as a physical quantity causing a device failure, may not be accessible to conventional measuring methods, but it plays an equally important part in controlling and monitoring production processes such as bonding, pick-and-place and encapsulation.

Thanks to piezo dynamic force measurement technology, forces can be monitored and controlled with high resolution - even when the forces involved are low. This makes it possible to detect deviations at an early stage; errors can be avoided, and semiconductor equipment manufactures can achieve higher and more accurate machine performance. Manufacturing and packing companies in the semiconductor industry thus benefit from higher process visibility, enhanced performance, lower quality costs and traceability of process data.

Key words: Piezoelectric, Semiconductor Advanced Packaging, Dynamic Force Measurement, AI, 5G, IoT, ADAS, AR/VR, WBG, Chip Test, Wafer- Grinding, Polishing, CMP, Dicing, Wafer Bonding, Thermal Compression Bonding, Sintering, Die Sorting, Sealing, Molding and Sorting - Taping

1. INTRODUCTION

Optical and displacement sensors, together with electrical testing, are currently the most widespread methods used to monitor and control semiconductor production processes and ensure product quality. However, these conventional measuring methods cannot detect mechanical stress, which is a very important parameter for controlling the process and achieving high product quality. The applied process force is critical factor in front-end processes, such as wafer- grinding, polishing, CMP, dicing, delamination, and handling; it is just as important in back-end processes, which include lead frame stamping, die bonding, wire bonding, flip chip, wafer bonding, thermocompression bonding, sintering, die sorting, sealing, molding, as well as sorting, taping and testing with the use of pull strength testers and test handlers. Force process deviations such as mechanical stress can lead to quality issues, in all these applications stated above.

As with any defect, prevention is the best approach. Force measurement allows process visibility, closer monitoring, and tighter process control to avoid mechanical stress caused by tool wear, material behavior changes and malfunctions in semiconductor production processes.

Table 1: Implications process force deviations

Failure Type:
- Non-visible damages
- Die cracking

Caused by:
- Tool wear
- Warpage
- Material Change and behaviour
- Malfunction

Force measurement makes it possible to:
- Evaluate and optimize tool wear
- Understand material behavior and machinability of different material types
- Understand and optimize machine equipment
- Correlate force signals to certain product quality parameters
- Control machines and processes by adaptive loop control based on force signals

2. PIEZOELECTRIC FORCE MEASUREMENT

2.1. Piezoelectric Effect

This technology is based on piezoelectric (PE) materials such as quartz crystals that generate an electrical charge signal in response to mechanical load.

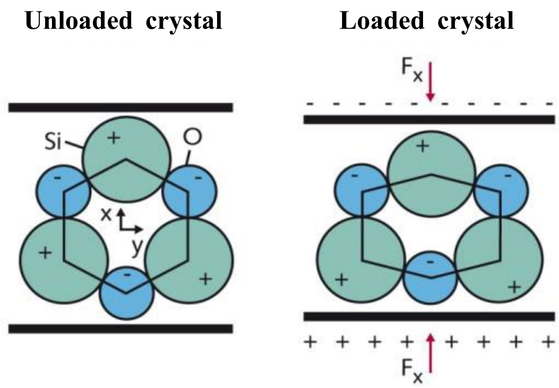

Figure 1: Principal of longitudinal PE effect

The charge displacement in picocoulomb is linearly proportional to the applied force in newtons, as shown in Fig. 2 and the high linearity allows measuring in different orders of magnitude (0…10N, 100N, … 100kN). The sensitivity is the ratio between the force applied and the charge generated (calculated by calibration), it can be converted into an analog signal (such as 0 …10 V) or a digital signal via an industrial charge amplifier. The measuring deflection is very low, thanks to the crystal's high rigidity.

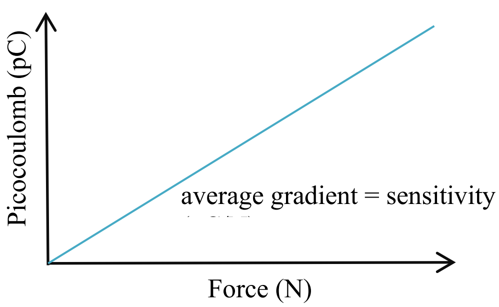

Figure 2: Force versus charge in (pC)

Piezoelectric sensors can be integrated into a machine in various ways. Depending on the direction of the applied force and its position with respect to the polar axes of the crystal, the PE effect occurs longitudinally (in the direction of the force), transversely (with respect to the force) or diagonally, as a shear effect. PE force sensors are designed for ranges from 0 to 1200 kN and, because of their rigidity, they have a very high natural frequency. This not only makes them highly responsive to rapid force changes but also gives them a wide useful measuring range.

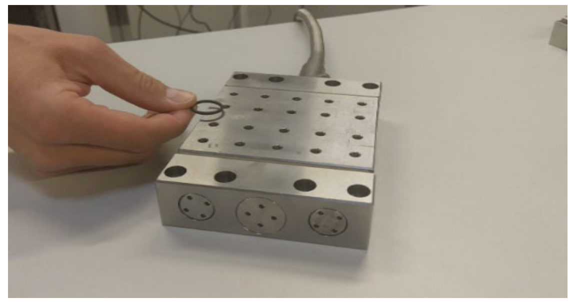

Figure 3: Force O-ring testing

The experiment shown in Figure 3 was preformed with an O-ring placed on a piezoelectric sensor with a measuring range up to 10kN. The measurement result shown in Figure 4 highlights the fact that piezoelectric sensors can detect minor force changes even when the forces involved are very low.

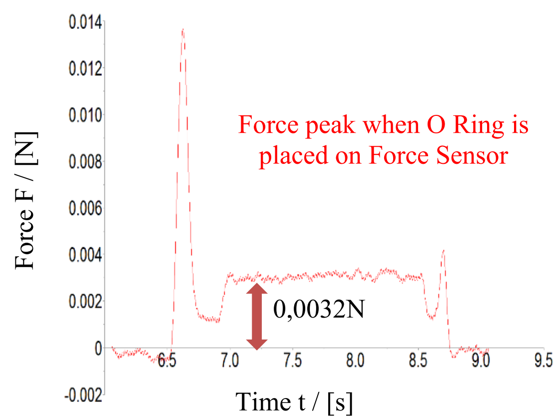

Figure 4: The sensor detects the force impact from the O-ring

2.2. Comparison force measurement methods

Most force sensors are based on an elastic or spring transduction element. Strain gauge sensors, for example, utilize a metallic-electric measuring element that measures forces in static and dynamic processes. Their operation is based on the physical effect of electrical resistance in a wire, which changes in proportional to the strain exerted on the wire when it is stretched or compressed. With this sensing technology, higher sensitivity requires more physical deformation. Table 2 compares the main features of the piezoelectric and strain gauge technologies in relation to the requirements for semiconductor process.

Motor current is the basis for another commonly used method for force measurement. This method of determining the applied force in an actuator (for example) calculates the force value based on the motor's input current. When using motor current to calculate the force, however, relatively large errors and measurement uncertainties can occur, due to power losses and the machine's different operating modes.

Nevertheless, if accuracy requirements are low and the application is suitable, this technology can provide a cost-effective solution.

2.3 Piezo Electric Measuring Chain

Figure 5 shows an industrial measurement chain. The PE sensor measures the force; a charge amplifier converts it and provides the programming logic controller (PLC) or industrial PC with an electrical signal that is equal to the measured force.

Figure 5: PE load washer sensor with charge amplifier and programmable logic controller

With the help of process monitoring hardware and software, as shown in Figure 6, users can also check and evaluate the quality of a production step based on a curve (force/time or displacement). Additionally, they can apply evaluation objects (EO's) to adapt the curve evaluation to an individual monitoring task. With this approach, every production step can be checked to determine, whether the part is good or bad.

Table 2: Comparison of force measurement features

Main features	Piezo Electric	Strain Gauge
Highly dynamic measurements	✓	✓ Limited by stiffness of the carrier material
Small force fluctuations measurement	✓	✓ Strongly limited due to fixed measuring range
Sensor Compactness	✓	✓ Technology requires more space
Static measurements	✓ Possible over period	✓
Temperature influences	✓ Higher temp. resistance	✓ Easier to compensate temperature changes
Precision/ Linearity/ Hysteresis	✓	✓ Limited by properties of the carrier material
Life span	✓	✓ Creep effects reduce life span

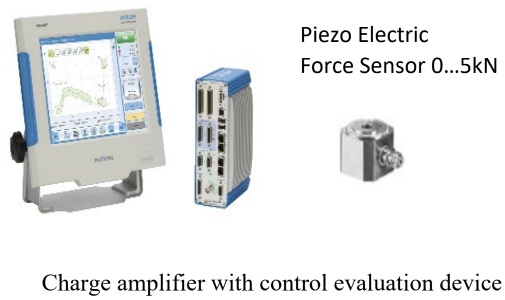

Figure 6: Measuring chain with Press Force

2.3.1. Selecting the piezoelectric sensors

The piezoelectric effect is used to measure one or several force components (x, y, z). The 1-component load washer and the press force sensor are widely utilized in semiconductor applications.

Depending on the specific application requirements and available mounting space, users should consult their piezoelectric sensor supplier regarding product selection, mounting options and customized solutions to find the best sensor to match your application. When 1-component force sensors are installed, they must always be mechanically preloaded to achieve high rigidity – which, in turn, ensures a wide frequency range. Preloading is between 20% and 70% of the useable usable measuring range.

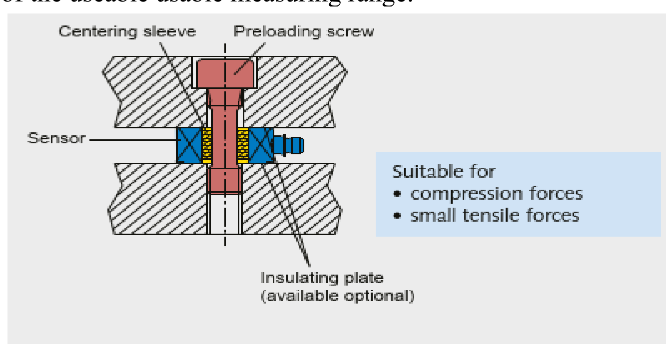

Figure 7: Installation with preloading screw

Table 3: Sensors used in semiconductor applications

a 	**1-component load washer force sensor** • Low overall height – ideal for limited space installations • Lower-cost option for customers with experience of force sensor integration • Installation: preloading required, using a screw or element • Recalibration after installation to ensure accurate measurements
b 	**1-component load washer – preloaded quartz force link sensor** • Easy installation because sensor is already preloaded • Ready to measure because no recalibration is required • Customer-specific versions possible • Dimensions
c 	**1-component quartz force link, press force sensor** • Compact size • Easy installation because force link is already preloaded • Ready to measure because no recalibration is required • Mounting flexibility

Preloaded sensors such as the press force variant shown in Table 3c allow easy installation and do not require recalibration.

Figure 8 shows an example where a vaccuum can be routed through the sensor by using customized preloading elements together with a load washer sensor.

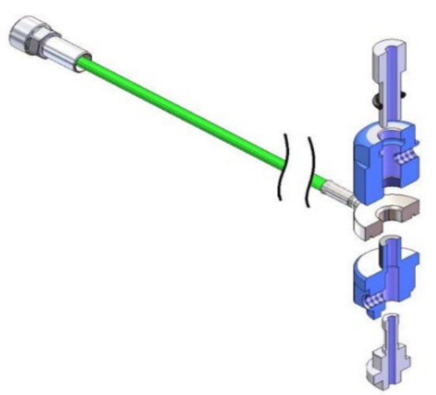

Figure 8: Customer specific Sensor

Piezoelectric sensors are precision instruments whose accuracy can only be exploited and maintained if they are also installed and mounted accurately. The mounting surface must be flat, rigid, and ground, and the force must be distributed uniformly so that the piezoelectric sensor's intrinsic rigidity and high frequency can be used to measure high dynamic forces.

2.3.2. Selecting the charge amplifier

The measuring chain also includes a charge amplifier that converts the charge signal from the sensor into a proportional voltage, current or digital signal. Various criteria determine the choice of a charge amplifier that is suitable for the application.

Key selection criteria are:

- Number of channels
- Measurement range
- Measurement type (static/dynamic)
- Analog or Digital Output Signal
- Frequency range

2.3.3. Selecting cable

Piezoelectric force sensors and charge amplifiers must be connected by a high-insulation cable. Low noise coaxial cables that produce very little triboelectricity during movement may be used for this purpose.

2.4. Measurement considerations

2.4.1. Resolution

Resolution is the ability of the measurement system to detect and faithfully indicate small changes in the characteristic of the measurement result. By their nature, piezoelectric sensors achieve high resolution. The main limitations are electronic converter noise and real-time post-process calculations in the PLC and/or Industrial PC. Even with forces as low as 1 Newton, which measurement is more critical, it is feasible to achieve resolutions of less than 0.01 N in industrial applications.

2.4.2. Repeatability

Repeatability is defined as "serial precision": for example, conformity among several measurements in sequence under largely unchanged conditions. This requirement arises in repetitive manufacturing processes where it is important to determine the accuracy of the repeated measurement between identical production steps. A piezoelectric measuring chain is offers an advantage here: the change can be discharged with <Reset> before every <Operate> measurement cycle, so the zero point can be re-determined. This basically excludes errors due to drift or external influences caused by changes with time (such as temperature). Repeatability of less than 0.1% full-scale output can be assumed for an industrial piezoelectric measuring chain.

2.4.3. Factors influencing measurement results

For many years, piezoelectric force measurement has proven to be an effective measuring method for use in semiconductor production processes. However, even the best measuring chain entails factors that influence the measurement result. As shown in Table 4, these factors can be assigned tom three categories: Measuring chain, Application, and Post-process, or real-time calculation.

Table 4: Factors influencing measurement results

1. **Measurement chain**
   - Sensitivity
   - Hysteresis
   - Linearity
   - Resolution
   - Repeatability
   - Cable Insulation
   - Drift
   - Reset/Operating Jump
   - Amplifier noise
   - Signal transmission delay
   - Temperature

2. **Application**
   - Temperature
   - Humidity
   - EMC
   - Machine vibration
   - Cable (length, bending and movement)
   - Force Shunt
   - Force transmission
   - Produceability
   - Bending moment
   - Amplifier warm-up time
   - Aliasing effect

3. **Post Process**
   - Filter used
   - Rounding error
   - Accuracy of downstream equipment such as analog input card, PLC, industrial PC

Table 4 includes two particularly important factors that should be considered when using piezoelectric measuring chains: drift, and the Reset/Operate jump. It can be assumed that drift of <+/- 0.05pC/sec occurs regardless of the measured force. This means that the time duration of the measurement must be considered and, if necessary, consideration given to signal compensation. The same is true with the Reset/Operate jump of <+/-2 pC, which can be subtracted (by the evaluation system, for example).

2.4.4. Good practices to achieve good measurement results

The good measurement practices in Table 5 will help users to select the right measuring chain; this table also offers advice on integrating force measurement into semiconductor process applications.

Table 5: Good measurement practices

- Contact the measuring equipment supplier for advice on the application
- Follow the measuring equipment supplier's instructions on measuring chain selection, design and installation
- Avoid acceleration during measurement, or define actions to overcome its influence
- Avoid temperature changes during measurement, or define actions to overcome the influence
- Provide good cable insulation and routing
- Define optimal Reset/Operate Measurement Cycles
- Compensate Reset/Operate jump with maXYmos evaluation system or a PLC
- Consider using relative measurement instead of absolute measurement (taking advantage of good piezoelectric repeatability)
- Use partial range calibration
- Consider the aliasing effect
- Ask which sensor is the best choice
- Use the sensor and amplifier test certificate for the measurement uncertainty calculation
- Ask for calibration from an accredited laboratory (such as DAkkS)
- Perform in-situ calibration to increase the absolute measurement accuracy

2.4.5. Inline measurement

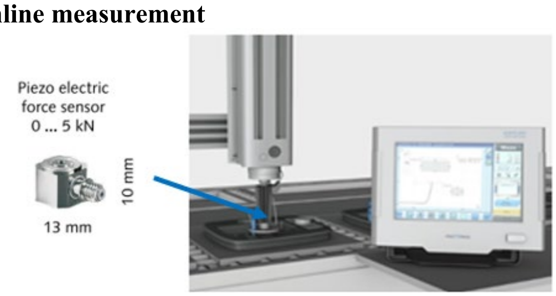

Figure 9: Force measurement w/ evaluation system

Inline measurement means a force sensor is mounted in the mechanical structure (tooling) of the semiconductor equipment; together with the charge amplifier and process evaluation unit these goals can then be achieved (Figure 9):

- Monitoring and control based on force as an important physical variable
- Recording of force and assessment of product acceptability
- Process optimization based on collected assembly process data
- Traceability for each item produced

Integrated inline measurement enables users to measure the force for every production step and/or product, thus allowing automatic inspection of mass-produced products.

2.4.6. Offline Measurement - machine force verification

Offline measurements are performed manually to verify machine axis force values at regular intervals. This method of force testing makes use of calibration kits as shown in Figure 10, where a force sensor is integrated into a mechanical structure. To measure warpage, a minimum of three force sensors must be installed within the mechanical structure, so that the parallelism of the machine tools can be measured.

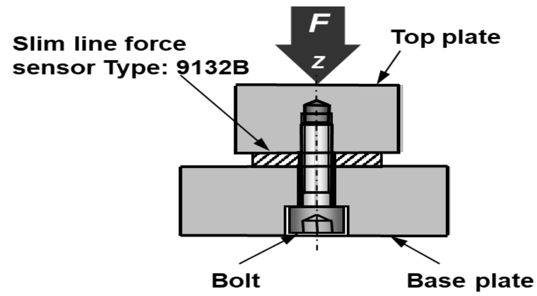

Figure 10: Sensor integrated into a mechanical structure

Table 6: Semiconductor manufacturing processes where force measurements are required

	Manufacturing process step	Force measurement integration		
		Features	**Benefits**	**Added values**
Front End	• Polishing • Grinding • CMP • Dicing • Lamination • De- Lamination • Handling	• Improve down force precision and control (e.g., with wafer polishing heads) • Monitor force applied during lamination and pick-and-place • Trace-force during critical production processes	• Verify flatness and force limitations • Identify wear on machine tool parts, such as pressure plates • Ensure consistent performance during wafer polishing, grinding, cleaning, dicing • Reduce wafer defects	• Increased machine performance (e.g., speed and accuracy) • Increased quality and reduce costs
Back End	• Lead frame stamping • Die bonder • Wire bonder • Flip chip • Wafer bonding • Thermo-compression bonding • Sintering • Die sorting • Sealing • Molding	• Improve bonding precision by full-loop bonder head control with force measurement • Monitor forces applied during bonding and/or pick-and-place processes, and others. • Cavity pressure monitoring • Trace force in critical semiconductor processes	• Keep the critical physical variable of force within allowed tolerances during bonding and pick-and-place • Verify flatness, parallelism • Identify wear on machine tool parts • Reduce die defects	
Test	• Bond pull strength tester • Sorting and Taping • Test Handler (pick-and-place, turret)	• Check bond force • Monitor force during pick-and-place processes	• Identify deviations • Ensure process safety	

3. Applying force measurement in semiconductor processes

Piezoelectric force measurement technology is used in a steadily growing number of applications throughout the semiconductor industry. In the past, this technology was mainly used for machine verification (calibration) and highly accurate wire bonding, wafer grinding and polishing. Today, however, piezoelectric technology is widely utilized to monitor and control the critical physical variable of force in many additional semiconductor manufacturing processes. Table No. 6 lists various semiconductor applications together with features, benefits, and added values obtained by using piezoelectric force measurement technology for them.

4. CONCLUSION

The existing complexities of semiconductor production processes are set to increase even further in the future, creating the need for new methods of improving the quality and yield of wafer, packaging, and test processes.

Dynamic piezoelectric force measurement technology offers many advantages that optimally meet the requirements of semiconductor process applications including:

- High dynamic measurements
- High resolution and repeatability- even for low forces
- Stiffness - no wear - long life span
- Compact sensor size

Force measurements improve the identification of failures by making mechanical stress and process deviations visible.

This approach helps users to:

- Achieve higher quality (and reduce ppm failure rate)
- Increase machine performance (in terms of speed and accuracy)
- Benefit from traceability and Big Data by measuring the critical process variable of force.

5. REFERENCES

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