White Paper

Using piezoelectric sensors to measure dynamic force in semiconductor applications

Abstract
New 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. Industry is exploiting the power advantages of lower-node technology and advanced packaging (AP) to accommodate increased functionality on a single small form factor – 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. Process 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 in order 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 Manufacturer can achieve higher and more accurate machine performance. Manufacturing and packaging companies in the semiconductor industry thus benefit from higher process visibility, enhanced performance, lower quality costs, and traceability of process data.

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Acknowledgments
The author would like to thank Matthias Giese, Bernd Rueeck, Felix Meier, Stefan Affeltranger and Stefan Schäfer, all of Kistler Instrumente AG, for their support and inspiration.

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 a 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 and 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 the applications listed 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.

Failure type:	• Non-visible damage • Die cracking
Caused by:	• Tool wear • Warpage • Material change and behavior • 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

Table 1: Implications of process force deviations

2. Piezoelectric force measurement

2.1 The piezoelectric effect

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

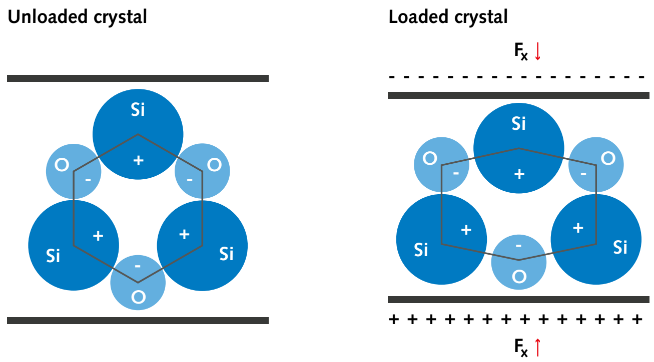

Figure 1: Principle of the longitudinal PE effect

The charge displacement in picocoulombs is linearly proportional to the applied force in newtons, as shown in Figure 2, and the high linearity allows measurement in different orders of magnitude (0 … 10 N, 0 … 100 N, 0 … 100 kN). The sensitivity is the ratio between the force 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.

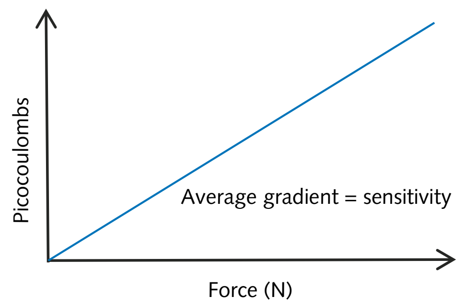

Figure 2: Force versus charge in (pC)

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 (in relation to the force) or diagonally (as a shear effect). PE force sensors are designed for ranges from 0 ... 1200 kN and, because of their rigidity, they have a high natural frequency. This not only makes them highly responsive to rapid force changes but also gives them a wide usable measuring range.

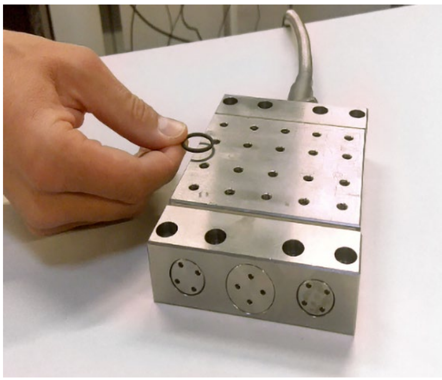

Figure 3: Force O-ring testing

The experiment shown in Figure 3 was performed with an O-ring placed on a piezoelectric sensor with a measuring range of up to 10 kN. 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.

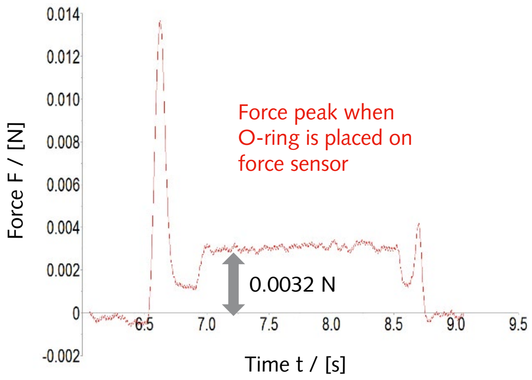

Figure 4: The sensor detects the force impact from the O-ring

2.2 Comparison of force measurement methods

Most force sensors are based on an elastic or spring element. Strain gauge sensors, for example, are metallic-electric measuring elements that measure forces in static and dynamic processes. Their operation is based on the physical effect whereby the electrical resistance of a wire changes in proportion to the strain exerted on the wire when it is stretched or compressed. High sensitivity requires deformation. Table 2 compares the main features of the piezoelectric and strain gauge technologies in relation to the requirements for semiconductor processes.

Motor current is the basis for another commonly used method of 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 The piezoelectric measuring chain

Figure 5 shows an industrial measuring chain. The PE sensor measures the force; a charge amplifier converts it and provides the programmable 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

Main features	Piezoelectric	Strain gauge
Highly dynamic measurements	✓	✓ Limited by stiffness of carrier material
Measurement of small force fluctuations	✓	✓ Severely limited due to fixed measuring range
Sensor compactness	✓	✓ Technology requires more space
Static measurements	✓ Possible over period	✓
Temperature influences	✓ Higher temperature resistance	✓ Easier to compensate temperature changes
Precision – linearity – hysteresis	✓	✓ Limited by properties of carrier material
Lifespan	✓	✓ Creep effects reduce lifespan

Table 2: Comparison of force measurement features

With the help of process monitoring hardware and software, users can also check and evaluate the quality of a production step on the basis of a curve (force/time or displacement). They can apply evaluation objects (EOs) in order to adapt the curve evaluation to the individual monitoring task. With this approach, every production step can be checked to determine whether the part is good or bad.

2.3.1 Selecting the piezoelectric sensor

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 used 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 in order to find the best sensor to match their application.

When 1-component force sensors are installed, they must always be mechanically preloaded in order to achieve high rigidity – which, in turn, ensures a wide frequency range. Preloading is between 20% and 70% of the usable measuring range.

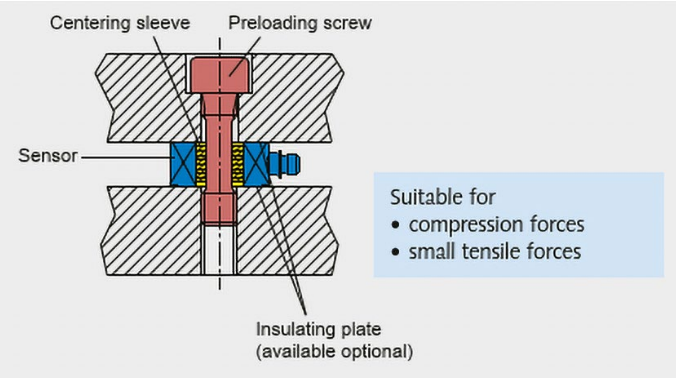

Figure 6: Installation with preloading screw

Preloaded sensors such as the press force variant shown in Figure 8c allow easy installation and do not require recalibration. Figure 7 shows an example where a vacuum can be routed through the sensor by using customized preloading elements together with a load washer sensor.

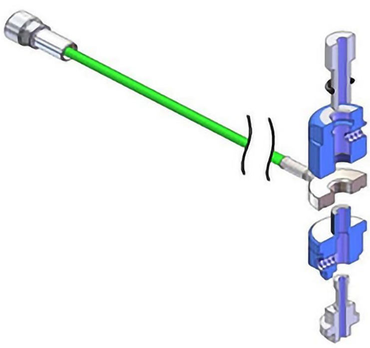

Figure 7: Customer-specific sensor

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 natural frequency can be used to measure highly dynamic forces.

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

Figure 8: Sensors used in semiconductor applications

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 the 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 N, where 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 offers an advantage here: the charge can be discharged with <Reset> before every <Operate> measurement cycle, so the zero point can be redetermined. This basically excludes errors due to drift or external influences caused by changes over 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 3, these factors can be assigned to three categories: Measuring chain, Application, and Post-process, or real-time calculation.

1. Measuring chain	• Sensitivity • Hysteresis • Linearity • Resolution • Repeatability • Cable insulation • Drift • Reset/Operate jump • Amplifier noise • Signal transmission delay • Temperature
2. Application	• Temperature • Humidity • EMC • Machine vibration • Cable (length, bending and movement) • Force shunt • Force transmission • Same producibility • 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 3: Factors influencing measurement results

Table 3 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 <+/-0.05 pC/s occurs regardless of the measured force. This means that the duration of the measurement must be taken into account and, if necessary, consideration should be given to compensation. The same is true of 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 4 will help users to select the right measuring chain; this table also offers advice on integrating force measurement into semiconductor process applications.

• 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 their influence
• Provide good cable insulation and routing
• Define optimal Reset/Operate measurement cycles
• Compensate the Reset/Operate jump with the 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 absolute measurement accuracy

Table 4: Good measurement practices

2.4.5 Inline measurement

Inline measurement means that a force sensor is mounted in the mechanical structure of the semiconductor equipment; together with the charge amplifier and process evaluation unit, these goals can then be achieved:
- 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

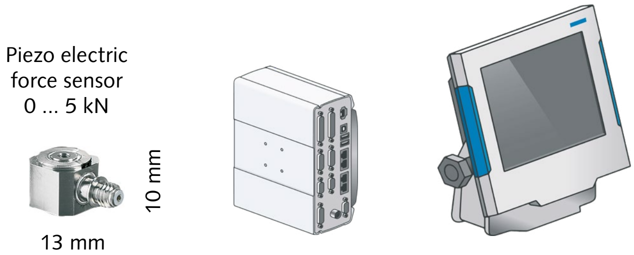

Figure 9: Measurement chain with evaluation system

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

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. In order to measure warpage, a minimum of three force sensors must be installed in a mechanical structure so that the parallelism of the machine tools can be measured.

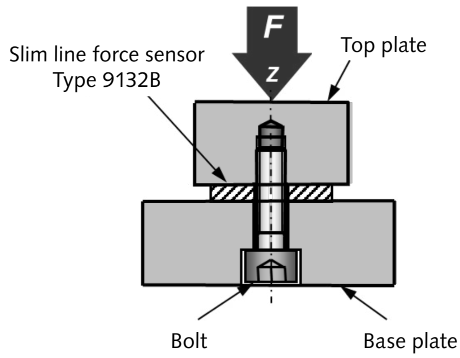

Figure 10: Sensor integrated into a mechanical structure

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 semiconductor manufacturing processes. Table 5 lists various semiconductor applications together with the features, benefits and added values obtained by using piezoelectric force measurement technology for them.

	Manufacturing process step	Force measurement integration		
		Features	**Benefits**	**Added values**
Front end	• Polishing • Grinding • CMP • Dicing • Lamination • Delamination • Handling	• Improve down force precision and control, e.g. with wafer polishing heads • Monitor forces applied during lamination and pick-and-place • Trace force during critical production processes	• Verify flatness and force limitations • Identify wear on machine 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 reduced 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 parts • Reduce die defects	
Testing	• 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	

Table 5: Semiconductor manufacturing processes where force measurements are required

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

- Highly dynamic measurements
- High resolution and repeatability – even for low forces
- Stiffness – no wear – long lifespan
- 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 the 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.

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