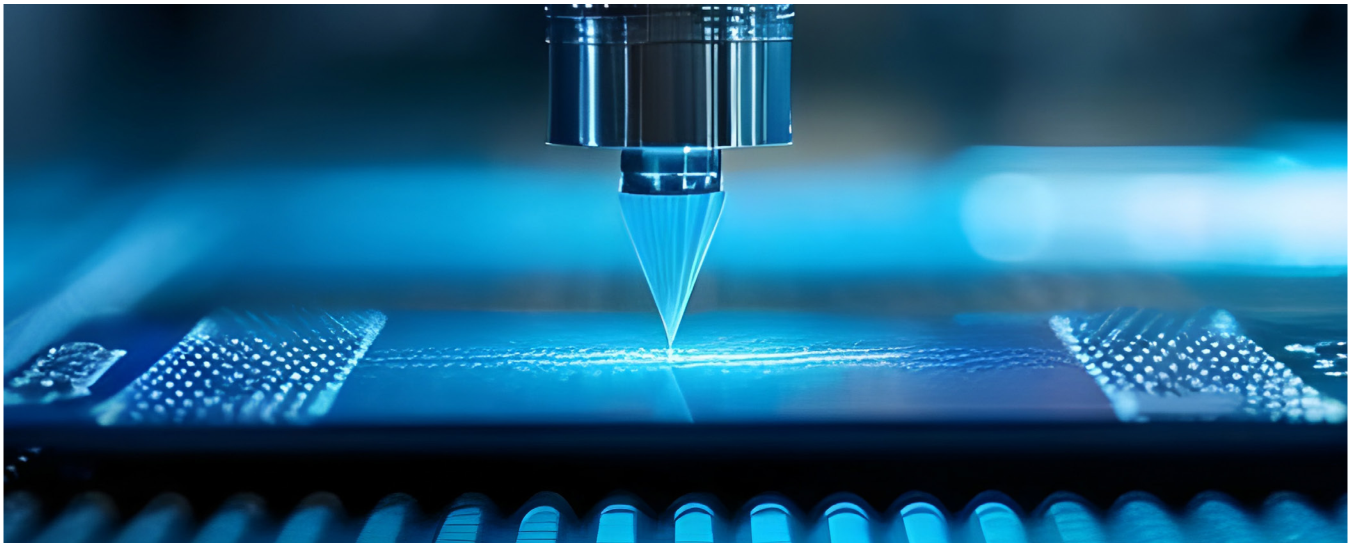

High Sensitivity Accelerometers to Monitor Traffic and Railroad Vibration for Semiconductor Manufacturing Facilities

Written By

Edward Lin, Prowave Engineering, Taiwan
Carmine Salzano, PCB Piezotronics Inc., Depew, USA

High Sensitivity Accelerometers to Monitor Traffic and Railroad Vibration for Semiconductor Manufacturing Facilities

Written by:

Edward Lin, Prowave Engineering, Taiwan, edward@prowavegroup.com

Carmine Salzano, PCB Piezotronics Inc., Depew, USA, csalzano@pcb.com

Abstract

Amplified piezoelectric accelerometers, better known as IEPE (or by the PCB Piezotronics, Inc. brand name, ICP®) are widely used in industry, civil, and military applications. In this paper, we will focus on a particular type of accelerometer and pressure sensor with high sensitivity, used for precisely measuring very small levels of vibration or pressure. These sensors find various applications in vibration control of machinery used for semiconductors and microchip production, as well as in many civil applications. The measurement system described in this paper was intended for vibration control to ensure good microchip quality, but also made it possible to measure an earthquake event that occurred in another country far from Taiwan, where the monitoring took place. In fact, technicians involved were informed of the earthquake in real-time, even before the international media.

Keywords: High sensitivity piezoelectric accelerometers, rail and road monitoring, semiconductor manufacturing, earthquake.

1 Introduction

This paper introduces the technology of piezoelectric and IEPE accelerometers, and then continues with a discussion of high sensitivity versions. It covers the most common applications regarding vibration monitoring for infrastructure, and references a related case study published separately. The paper addresses the vibration issues in microchip production machinery, where even micro vibrations during semiconductor production can affect quality. Finally, the paper presents a case study of railroad vibration monitoring in Taiwan, and concludes with a paragraph on early earthquake detection as a real-time consequence of the vibration monitoring.

2 Piezoelectric Accelerometers

The most widely used sensor for measuring response in a structural dynamic test is undoubtedly the accelerometer. Accelerometer technologies used in dynamic tests can be divided into piezoelectric or MEMS types. Piezoelectric accelerometers were originally limited to a charge output that required external amplification, until the development of amplified piezoelectric accelerometers, better known as IEPE or by PCB Piezotronics, Inc. brand name, ICP®. MEMS are mainly of two types: piezoresistive, used for tests at high acceleration values such as impacts and shocks; and capacitive, which can also be used in dynamic measurements characterized by limited acceleration values. The main benefit of MEMS capacitive compared to IEPE lies in their ability to measure from 0 Hz, which is not essential for dynamic tests, making the IEPE accelerometer the most popular sensor for the structural response in modal analysis and OMA.

An IEPE accelerometer is a sensor that generates an electrical output proportional to applied acceleration [1]. IEPE accelerometers are designed to measure vibration and shock for a wide variety of applications. They are simple to use and accurate over a wide frequency range, which makes them the recommended choice for many testing situations.

An accelerometer structure can be characterized as a single degree of freedom system that is governed by Newton's Law of Motion, **F=MA.** Various mechanical designs perform the transduction required for IEPE accelerometers. The designs consist of sensing crystals that are attached to a seismic mass. A preload ring or stud applies a force to the sensing element assembly to make a rigid structure and ensure linear behavior. Under acceleration, the seismic mass causes stress on the sensing crystals, which results in a proportional electrical output. The output is collected on electrodes and transmitted by wires connected to the microelectronic circuitry in IEPE accelerometers. The schematic of the IEPE accelerometer is shown in Figure 1 below.

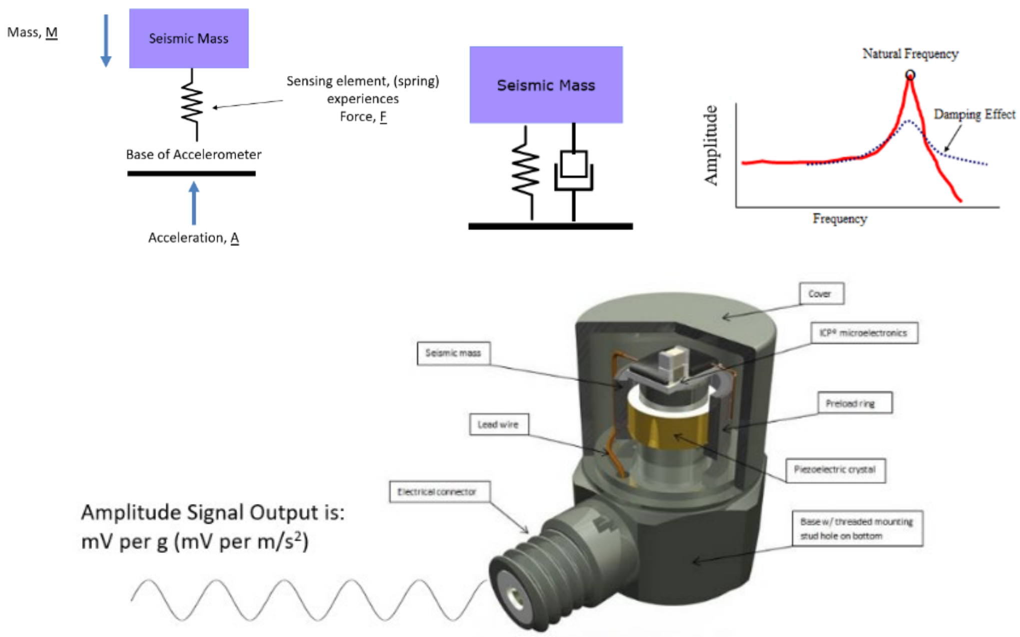

Figure 1: Operating principle and schematic of an IEPE accelerometer.

There are many types of IEPE accelerometers to accommodate different application requirements. Desirable specifications for structural testing include: lightweight, high sensitivity, low frequency response, good phase characteristics, low base strain sensitivity, simple cabling requirements, single axis or triaxial, TEDS transducer electronic data sheet (for easy setup of large tests), miniature, cubic (for easy alignment), adhesive mounting, low cost (as tests can require tens to hundreds of channels), frequency range (5%) from close to 0Hz to ~3kHz, sensitivity from 100mV/g to 1V/g. An example of a modal or operational modal test accelerometer with highest sensitivity can be found in Figure 3 below.

3 High Sensitivity Accelerometers

Figure 2: High sensitivity ICP® accelerometers in use - low frequency and seismic.

High sensitivity IEPE accelerometers are specifically designed to enable the detection of ultra-low-level, low-frequency vibrations associated with very large structures, foundations, and earth tremors. These sensors typically possess exceptional measurement resolution as the result of their larger size, providing a relatively larger output signal and a lower noise floor. They are hermetically sealed in a titanium or stainless steel housing. Models that include a 2-pin, military-style connector provide the added benefit of being electrically case isolated for superior RF and EMI protection.

Vibration monitoring of buildings, monuments, and critical infrastructure is a key in smart cities to identify stress levels on structures, ensure occupant protection during full-capacity or environmental events, and greatly reduce the amount of time required to assess for damage. Studies have shown that crowds of people in a stadium grandstand or a theater balcony impart tremendous forces and harmonic motion to the structure when the crowd acts in a synchronous manner. Earth tremors, foot traffic, and vehicles can cause a structure to sway, shift, crumble, or collapse. Permanently installed high-sensitivity accelerometers provide real-time data used for trending, analyzing, and alerts. When structural motion approaches established safety thresholds, alerts and emergency response plans can be initiated.

Decaying infrastructures, particularly bridges, have received heightened attention in recent years. Among the several techniques for determining the health and longevity of civil structures, vibration measurements are used for continuous monitoring, modal analysis, and structural integrity investigation. High sensitivity accelerometers generate signals in response to a variety of stimuli such as traffic, wind, and programmatic impulse. Analyzing these signals provides insight for determining the condition and safety of the structure, leading to recommendations for remedial construction or further monitoring.

Accelerometer Highlights:

- Resolution down to 1 µg rms broadband
- Extended low frequency measurement capability
- Hermetically sealed

Applications:

- Semiconductor manufacturing
- Smart infrastructure: monitoring foundation stability, floor vibrations, and security systems
- Earthquake detection/sway fatigue analysis
- Structural testing of bridges and foundations

- Geological formation studies

Selecting the correct high sensitivity piezoelectric accelerometers for infrastructure structural health monitoring (SHM) is crucial. Four unique features of high sensitivity designs that are not found together in more general-purpose IEPE accelerometer configurations include: sensitivity, sensing range, frequency range, and low spectral noise.

4 High Sensitivity Accelerometers for Infrastructure Monitoring

The trend of using numerical simulations when designing buildings is growing with the availability of increasingly higher capacity computers and performance-based design philosophy requiring accurate forecasts of structural movements under seismic stress. In geotechnical engineering, simulations often provide the only rational approach where consolidated calculation procedures do not exist. The reliability of these forecasts depends on correct problem modeling, advanced knowledge of subsoil characteristics, and most importantly, valid calculation models proven through comparisons with well-documented case studies of full-scale construction projects.

The need to measure the dynamic responses of structures has driven the scientific community to design and create different types of monitoring plans. As an example, within this field of study, a seismic monitoring system has been installed for the construction of the "Casa dello Studente" (Student House) near the Campobasso campus of the University of Molise (Italy) [3]. The system consists of a retaining wall of reinforced concrete piles and instrumentation of four inclinometer casings and eight customized accelerometer systems installed inside two piles. This installation is one of the few examples of seismic monitoring on actual full-scale geotechnical works, providing an interesting case study through which to calibrate simplified and complete calculation methodologies.

5 Machinery and Vibration Monitoring for Semiconductor Manufacturing

Semiconductor manufacturing processes are extremely complex and rapidly evolving. As consumer demand for smaller sizes and more advanced capabilities continues to grow, it becomes more challenging to avoid manufacturing errors at the nanometer scale. Increased throughput demands require faster-moving manufacturing and inspection machinery, making semiconductors susceptible to higher vibrations during production. These vibrations can corrupt the patterns deposited on the semiconductors, leading to circuit failures in the finished parts.

The patterns on a chip layer are measured in the tens of nanometers, and because the vibrations that can cause manufacturing errors are miniscule (in the millionths of g's), accelerometers typically used for process monitoring simply can't measure the tiny deflections that can jeopardize semiconductor quality. Fortunately, high sensitivity accelerometers, more commonly used to measure seismic, low-frequency vibrations, can measure deflections at the nanometer scale. The cited white paper [4] explains how those accelerometers work, and demonstrates their ability to measure at scales necessary for semiconductor manufacturing and inspection.

Customization of the accelerometer may be required to meet specific application needs. Requirements may include:

- Low outgassing to prevent tiny particles from affecting the quality of semiconductor production, with tests carried out in accordance with any stringent requirements

- Special connectors and cables
- Hermeticity, already present in PCB seismic accelerometers as they are laser welded

Piezoelectric accelerometers are uniquely qualified to meet the rigorous requirements for vibration monitoring during semiconductor manufacturing. Due to their low noise and high sensitivity, they are able to measure low amplitude events, such as nearby civil events and even seismic events.

6 Railroad and Traffic Monitoring for Semiconductor Manufacturing

In 2002, Prowave (PCB Piezotronics Inc. exclusive distributor in Taiwan) partnered with Rockwell Automation and obtained the BOTHSR contract to build a system to monitor vibration, noise, and related environmental parameters along the high-speed rail line in Taiwan. The aim was to monitor the vibrations produced by sources (mainly road and rail traffic) reaching the semiconductor manufacturer's facilities in order to protect the quality of chip production.

There are four monitoring stations in Shulin (New Taipei City), Hsinchu, Shanhua (Tainan), and Qiaotou (Kaohsiung). The sensor types used in this project include:

- Accelerometers to monitor vibrations when high-speed trains pass by. Sensors are mounted not only on the ground, but also underground. All ground-mounted sensors are PCB 393B31, and TOKYO SOKUSHIN sensors are used underground.
- Pressure sensors: PCB 106B50 to measure pressure changes in tunnels when trains pass through.
- Acoustic sensors: Outdoor-type microphones to measure ambient noise.
- Weather sensors to measure temperature, humidity, atmospheric pressure, wind speed/direction, and rainfall.
- Optical sensors to detect and calculate train speed and direction.

All data is measured simultaneously and continuously, without interruption.

Figure 3: PCB ICP® high sensitivity accelerometer Model 393B31

Figure 4: PCB ICP® high sensitivity pressure sensor Model 106B50

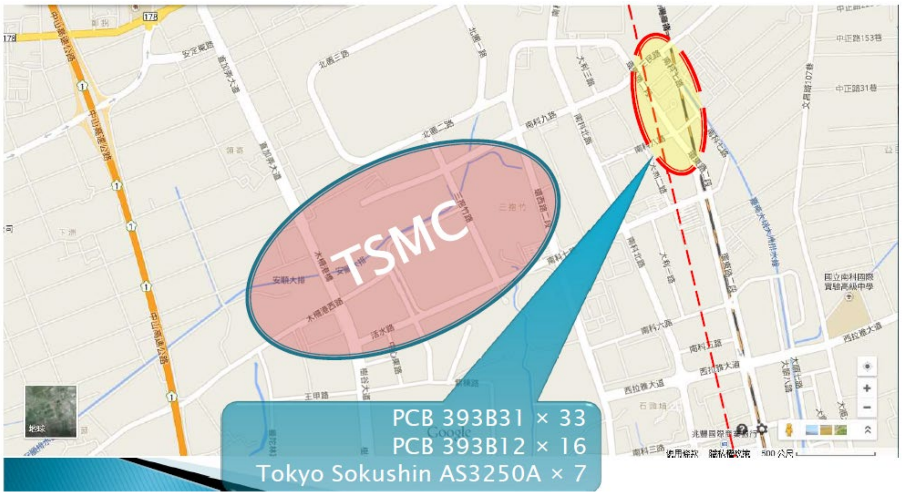

Figure 5: PCB ICP® sensor locations in map highlighting the semiconductor manufacturing site.

Figure 6: PCB ICP® accelerometers mounted in box and green box locations.

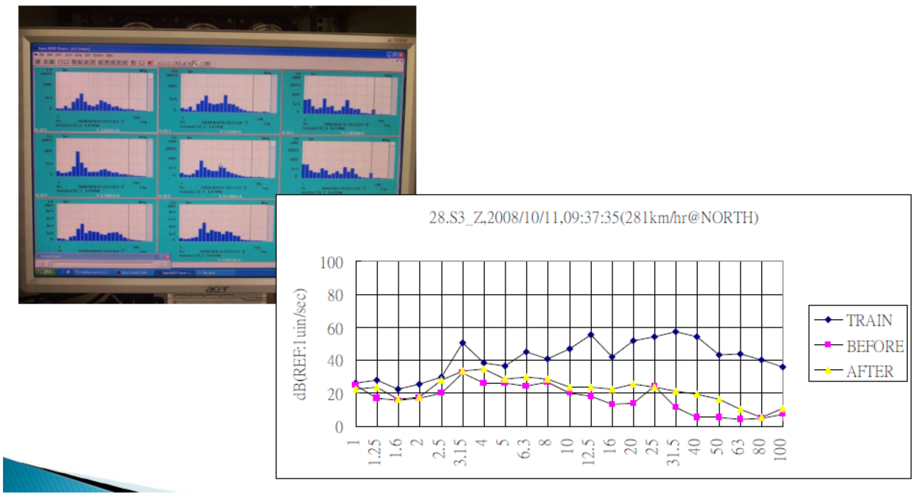

Figure 7: Typical acceleration data from PCB 393B31 accelerometer, Z axis

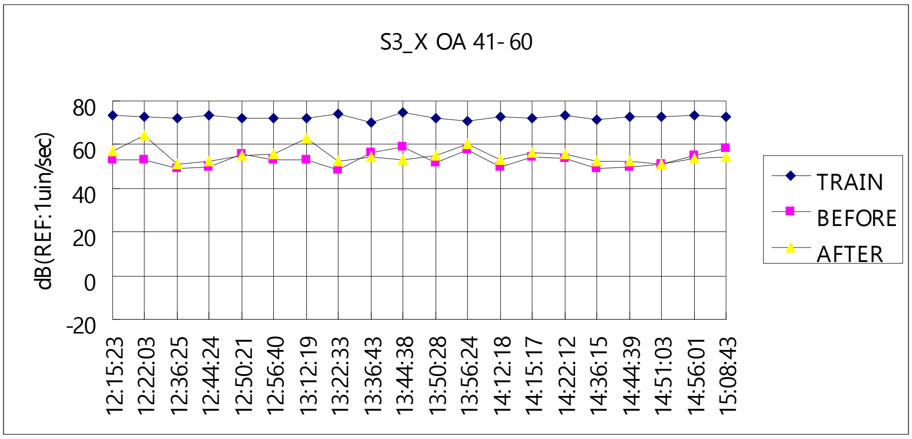

Figure 8: Typical acceleration data from PCB 393B31 accelerometer, X Axis

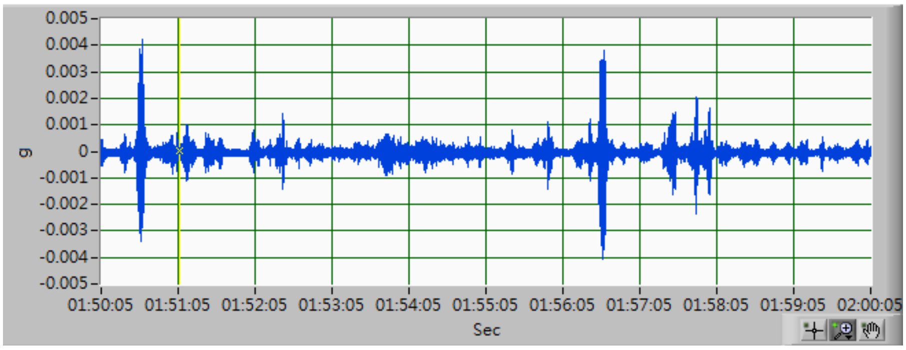

Figure 9: Typical acceleration time history data from PCB 393B31 accelerometer, X axis

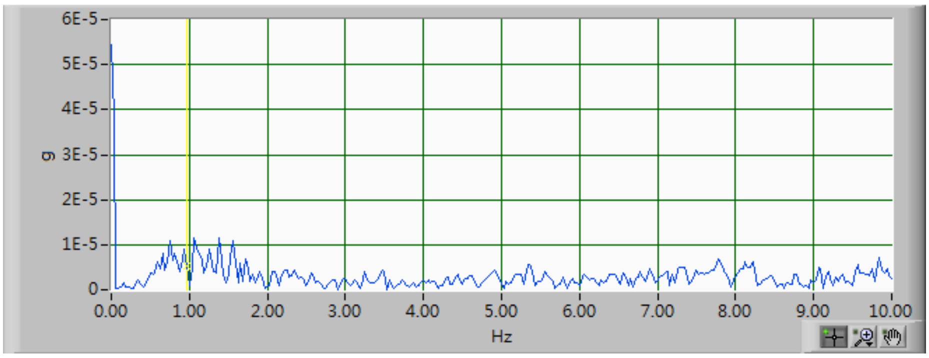

Figure 10: Typical acceleration FFT data from PCB 393B31 accelerometer, X axis

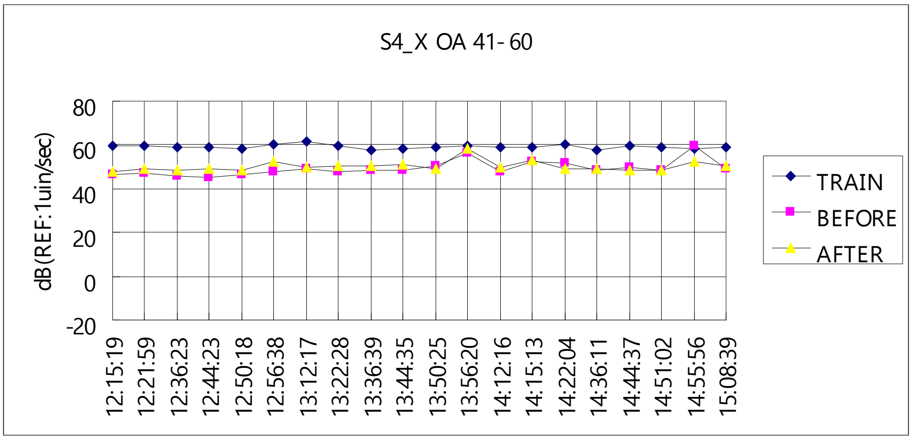

Figure 11: Typical velocity data, integrated from PCB 393B31 acceleration data, X axis

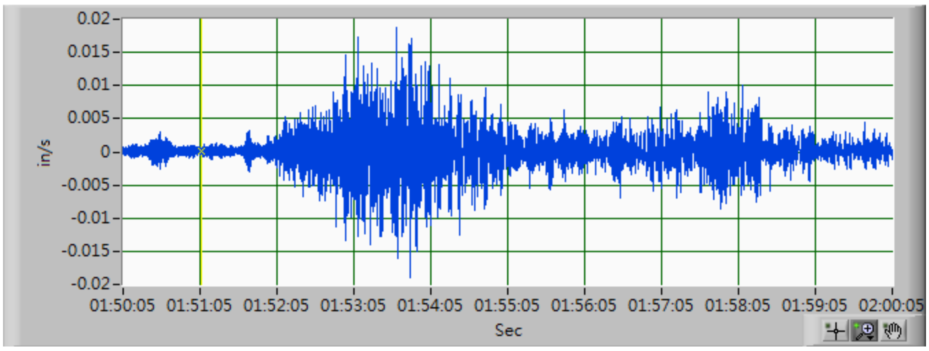

Figure 12: Typical velocity time history data, integrated from PCB 393B31 acceleration data, X axis

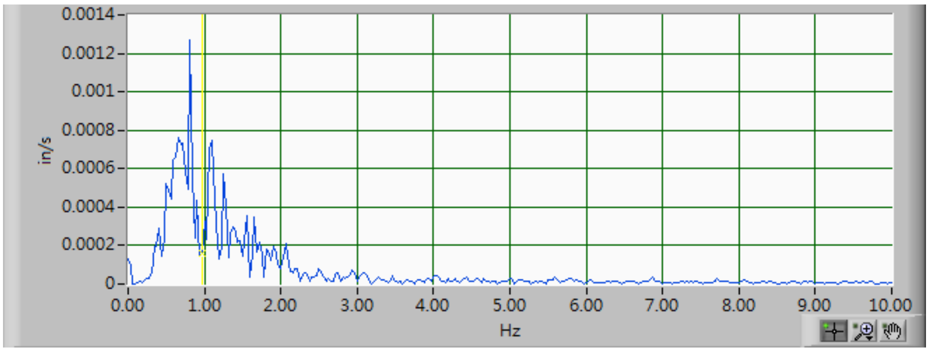

Figure 13: Typical velocity FFT data, integrated from PCB 393B31 acceleration data, X axis

Figures 8-13 above highlight the capabilities of the monitoring station and the PCB accelerometers. Even though the civil infrastructure is >100 meters from the monitoring stations, the system can clearly identify when trains are transiting nearby. The elevated vibration levels that occur as trains are in transit nearby is visible in both the acceleration and velocity data. This level of information allows end users the ability to monitor, predict, and protect their semiconductor processes that will be exposed to nearby environmental and civil factors.

7 Earthquake Detection

While the goal of the measurement and monitoring system was to provide insight into timing and amplitudes of nearby environmental and civil events, this system has also proved adept at monitoring and detection of seismic events in the region.

Due to the system's uninterrupted measurement characteristics, when a major earthquake occurred in Japan in 2011, the seismic wave signals transmitted to Taiwan were completely recorded.

The 2011 Tohoku earthquake occurred at 14:46 local time in Japan. At the Shanhua monitoring station, according to the optical sensors, the passing time of a high-speed train was 13:50:28 and 13:56:24 Taiwan time. Around 13:52 Taiwan time, a set of earthquake waveforms was recorded.

According to calculations, the distance from Sendai to Shanhua is about 2800 km (S wave speed is 4 km/sec; transmission time is about 6 minutes; P wave is 7 km/sec, about 10 minutes). It can be determined that this signal is the seismic wave transmitted by the Japanese earthquake.

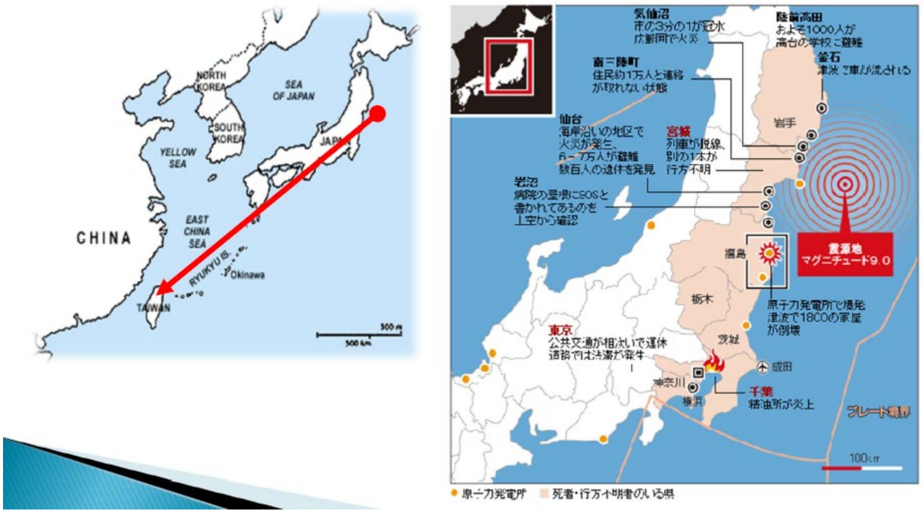

Figure 14- Map showing the relative locations of the earthquake and measurement stations

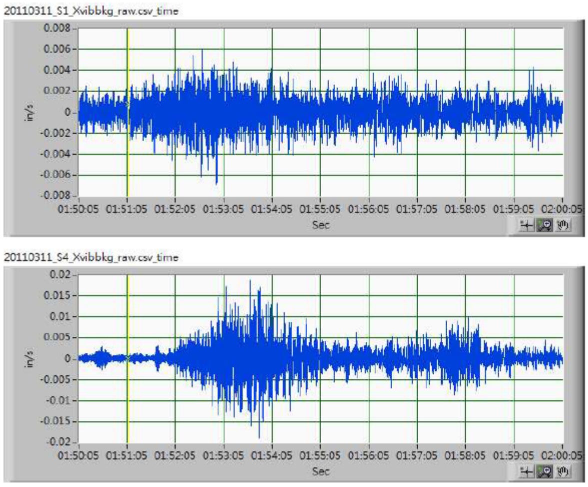

Figure 15- Time history plot from the earthquake

8 Conclusions

Piezoelectric sensors, particularly high-sensitivity IEPE accelerometers, have become essential in monitoring vibrations during the various stages of semiconductor manufacturing. Their ability to detect even the smallest vibrations, whether from nearby civil infrastructure, environmental factors, or seismic activity, is critical for maintaining product quality. Their characteristic low noise levels, high sensitivity, and rugged construction make them highly effective in capturing reliable data across a wide frequency range.

When integrated into comprehensive monitoring systems, such as the one along Taiwan's high-speed rail line, piezoelectric sensors allow semiconductor manufacturers to proactively manage and mitigate external vibrations that could compromise production. This proactive approach towards safeguarding product quality allows manufacturers to optimize manufacturing processes, reduce downtime, and prevent costly production errors.

Beyond their primary application in semiconductor manufacturing, piezoelectric sensors have demonstrated versatility in broader monitoring contexts, as shown by their unexpected ability to detect seismic activity during the 2011 Tohoku earthquake. The successful implementation of these sensors in real-world systems underscores their potential to significantly improve operational efficiency and safety in modern industrial and environmental applications.

Acknowledgments

The high-speed rail project is being completed by Prowave Engineering, Rockwell Automation and BOTHSR (Bureau of Taiwan High Speed Rail) under contract numbers 90F-43CD-FP-047 and 92F-43CDGA-039. Also special thanks to Andy Taggart at PCB Piezotronics for reviewing this paper.

References

[1] PCB Piezotronics Inc., Technical data from www.pcb.com

[2] *Selecting the Correct High Sensitivity Piezoelectric Accelerometers for Infrastructure Monitoring (SHM)* https://www.pcb.com/contentstore/mktgcontent/whitepapers/WPL_87_Infrastructure.pdf

[3] Giovanni Fabbrocino, Carmine Laorenza, Carlo Rainieri, Filippo Santucci, Carmine Salzano, and Luca Deseri. *Seismic Monitoring of a Retaining Wall in Reinforced Concrete Piles.* https://www.pcb.com/contentstore/MktgContent/WhitePapers/WPL_89_SeismicMonitoring.pdf

[4] Dr. S.A. Hambric, Hambric Acoustics, LLC . *High Sensitivity Accelerometers for Monitoring Semiconductor Manufacturing.* https://www.pcb.com/contentstore/MktgContent/whitepapers/WPL_92_Semiconductor_Manufacturing.pdf

PCB PIEZOTRONICS
AN AMPHENOL COMPANY

3425 Walden Avenue, Depew, NY 14043 USA

pcb.com | info@pcb.com | 800 828 8840 | +1 716 684 0001

WPL_99_0924