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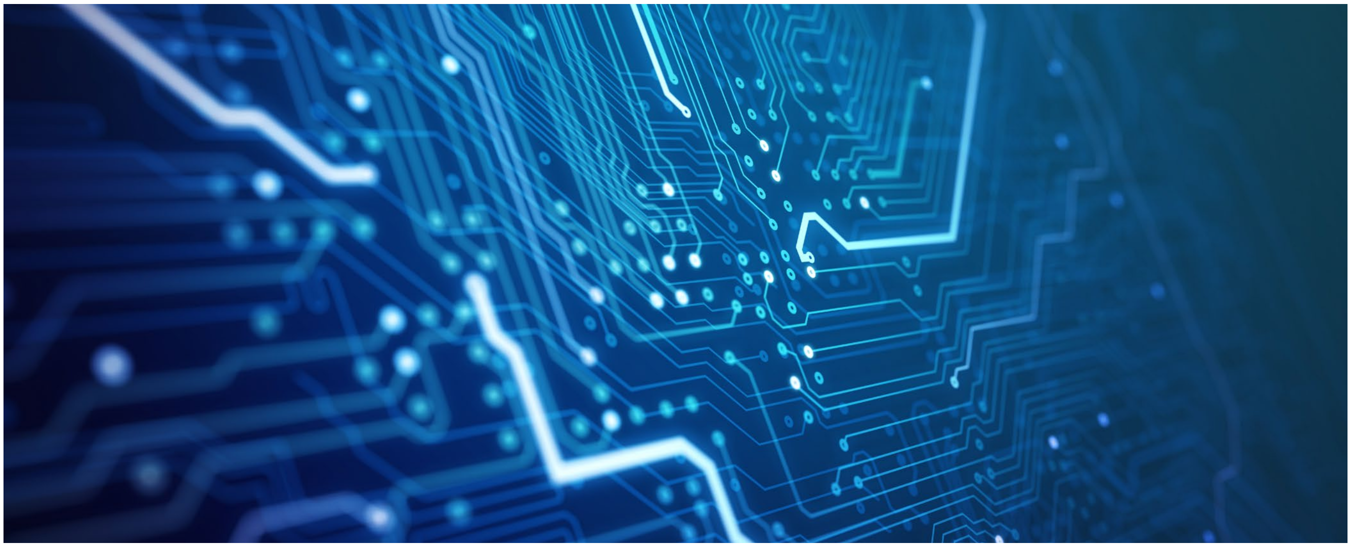


High Sensitivity Accelerometers for Monitoring Semiconductor Manufacturing

Written By
Dr. S.A. Hambric, Hambric Acoustics, LLC

Abstract

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. Additional demands for increased throughput 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 aren't capable of measuring 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. In this white paper, we explain how those accelerometers work, and show some simple specifications to demonstrate their ability to measure at the scales necessary to monitor semiconductor manufacturing and inspection.

Introduction: Typical Semiconductors and Vibration Sensors

At the time of this writing, microchips can have up to 100 stacked layers comprised of trillions of transistors to create an integrated circuit (IC). Each layer can have up to 100 billion contacts, with feature sizes in the order of tens of nanometers. To accommodate strict handling requirements, microchips are made in clean rooms where temperature and air quality are tightly regulated. The chips are passed between different manufacturing and inspection machines with sophisticated robotics, and monitored with artificial intelligence (AI)-based algorithms that continuously interpret process control data.

Despite these precautionary measures, the potential for error persists, as vibrations in manufacturing machinery can easily distort the tiny patterns in the chip layers, leading to shorts and other failures. To combat this, accelerometers are used to take routine vibration measurements for real-time, closed-loop control of health monitoring and process control systems. Accelerometers have been used in process monitoring applications for many decades, are well understood, robust, and reasonably priced. We will discuss how they work and their basic operating parameters in this white paper, along with how these parameters can be tuned to dramatically increase sensitivity and measure displacements at the nanometer scale.

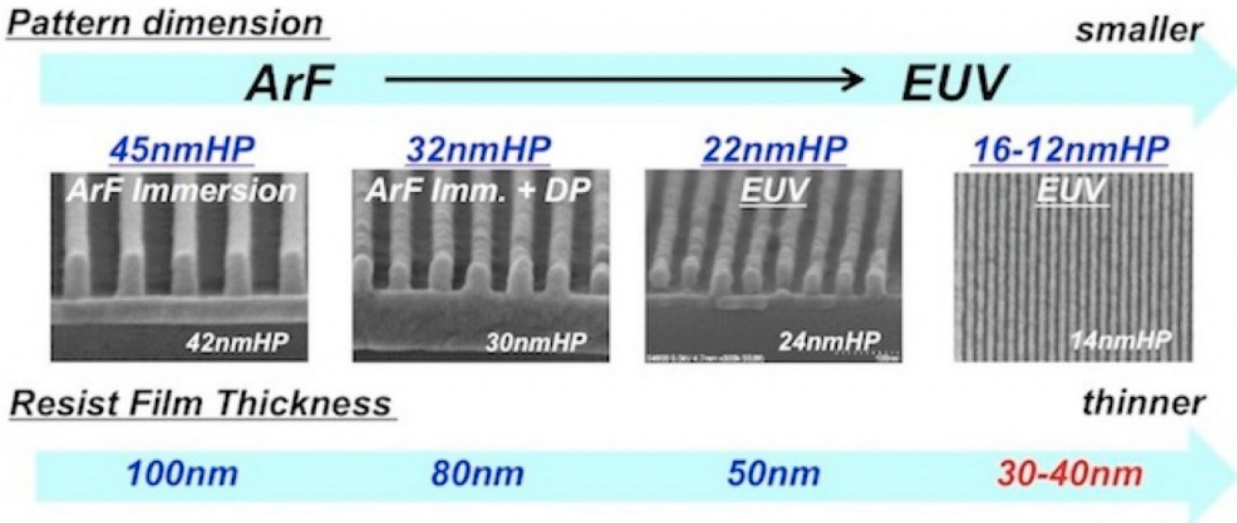


Figure 1. Cross-section of semiconductor chips showing increasingly smaller patterns and reduced resist thickness as design practices evolve. [1]

A Primer on Semiconductor Manufacturing

General Process Steps

Processing methods vary among manufacturers and are constantly improving as the industry evolves. However, general semiconductor manufacturing procedures at the time of this writing include the following steps [2]:

- Prepare the silicon 'wafers' or discs by cutting them from ingots of purified silicone and then polishing them to very fine surface finishes. The wafers are about 7.5 to 30 cm in diameter and 300 – 800 nanometers thick.
- Deposit thin films of metal (conducting), dielectric (insulating), or semiconducting materials on the wafers. This is usually called 'deposition.' The current leading deposition methods are Physical Vapor (PVD), Electrochemical (ECD), and Chemical Vapor (CVD).
- Coat the wafers with light sensitive 'photoresist', or 'resist' for short. Positive resist weakens the material for subsequent deposition and etching; negative resist strengthens the material so it is permanent. Different types of resist include Chemically Amplified Resist (CAR) and Metal Oxide Resist (MOR).
- Project ultraviolet light through a reticle with an embedded chip pattern (sometimes called a 'photomask') to prepare the coating for etching. This is called 'photolithography,' or 'lithography' for short. The most popular methods are Deep Ultraviolet (DUV) for less critical layers with larger features, and Extreme Ultraviolet (EUV) for the most critical layers with the smallest features. It is common to 'pre-distort' the photomask pattern using Optical Proximity Correction (OPC) to account for errors in the lithography process and improve the accuracy of the imprinted pattern.
- Remove the resist that was degraded by the lithography with either 'wet' or 'dry' etching. Wet etching uses chemical baths in a process referred to as 'global removal.' Dry etching is physically based and allows for more control.

- Bombard the wafer with positive and negative ions to tune the electric conducting properties of different parts of the pattern, creating the electronic 'switches' needed in the circuitry.
- Finally, cut or 'dice' the wafer into individual chips with a diamond saw. Tens to thousands of chips are sliced from wafers that are typically 30 cm in diameter. The cut chips are mounted on substrates with metal foils to conduct the signals and topped with a 'heat spreader' for proper cooling when they operate.

The manufacturing steps most likely to be affected by a vibration problem are:

- Deposition
    - Placement errors
    - Thickness uniformity errors
- Lithography (probably the most affected step)
    - Imaging distortions
    - Pattern defects
- Etching
    - Pattern collapse (the features 'keel over' and don't align between layers)
- Cutting and packaging
    - Offsets along the edges can lead to mismatched layers and circuitry failures

Metrology and Inspection

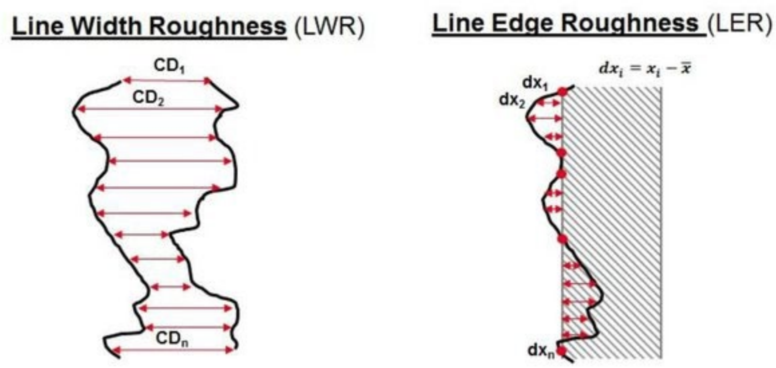
Nearly all microchip manufacturing processes are subject to inspection with metrology, particularly after lithography and etching. Scanning Electron Microscopes (SEMs) and Critical Dimension SEMs (CD-SEMs) can image patterns at the nanometer scale and are routinely used to check components against the desired patterns. Vibration can also compromise the inspection process! If the SEMs are shaking while they measure the components, the resulting images will be distorted.

Critical Errors

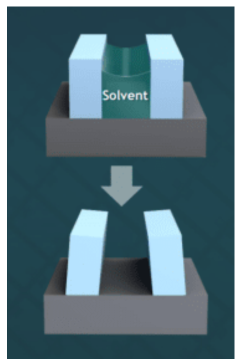
Any errors within or between chip layers can lead to open circuits, short circuits, or other anomalies that can make an expensive microchip unusable (and cost the manufacturer a lot of time and money).

The most critical errors microchip manufacturers face are illustrated in Figure 2, and include:

- Within a layer:
    - Line edge roughness (LER)
    - Line width roughness (LWR)
    - Critical dimension uniformity (CDU), both local and global
    - Pattern collapse (more common with wet etching)
- Between layers:
    - Local edge placement error (EPE), sometimes called 'overlay' error



Pattern Collapse



Local Edge Placement Error

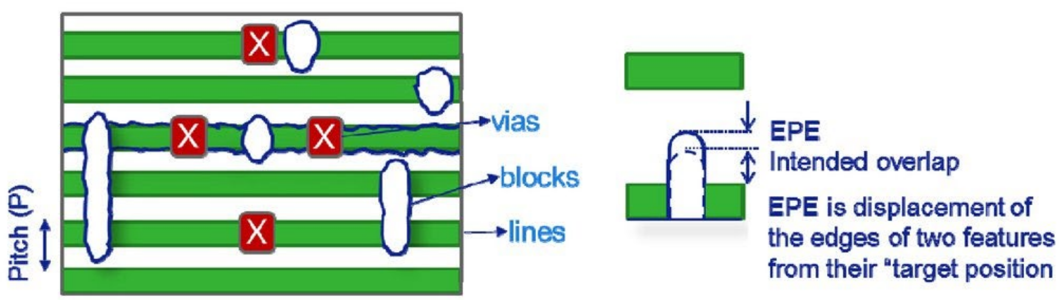


Figure 2. Critical semiconductor errors. [3]

All these potential errors can be induced by unwanted vibration during manufacturing. Let's examine one of the most critical manufacturing steps—lithography—and consider how vibration might distort a chip layer pattern. Figure 3 shows a schematic of a lithography machine. The wafers are loaded onto a stage below the photomask and above the projection lenses. The UV light reflects through a series of mirrors before passing through the photomask. Any vibration of the photomask, the projection lenses, or the wafer stage, can distort the pattern imprinted on the wafer. All of these components can vibrate in-plane, transversely, or even rock about an axis (perhaps the most complex form of vibration and resulting distortion).

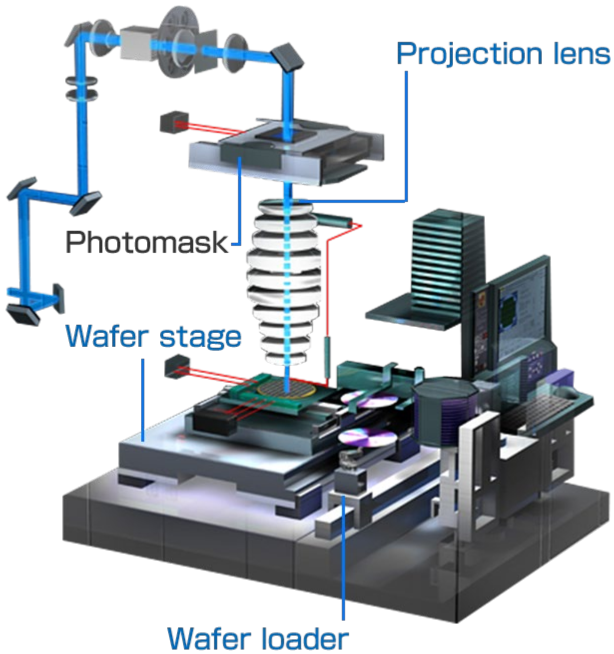


Figure 3. Schematic of a lithography machine. [4]

Vibration Sources

What would cause a machine to vibrate? There are many culprits. First, the machine itself can have components which induce vibration, such as traversing systems (which can include actuators and rolling element bearings) and rotating elements like shafts (which also rest on bearings, often of the rolling element type). The faster traversing systems move, and the faster a shaft rotates, the higher the vibration. If any faults develop in the components (e.g., flats in rolling elements, misalignments, imbalances), the vibrations increase—often significantly. The resulting vibrations are quite unique; a continuously rotating element will generate continuous vibration signals, usually tonal (at specific frequencies), while traversing systems cause intermittent loads and vibration, sometimes called 'transients'. Either can lead to manufacturing errors.

Vibrations can also originate from external sources completely outside the machine. Nearby construction equipment[1], factories, heavy vehicles passing by on nearby roads, other machines in the manufacturing facility, and even heating, ventilation, and air conditioning systems (HVAC) can generate ground-borne vibrations which enter the machines and make them vibrate in kind. It's common to mount sensitive machinery on floating slabs—large reinforced concrete slabs suspended on soft padding. These mounts work well at filtering out mid to high frequency vibrations, but can actually make low frequency vibration worse if it occurs anywhere close to its 'mount frequency' (where the mass of the slab and machinery resonates with the effective spring constant of the padding).

The vibrations are so small and oscillate at such a low frequency that humans can't hear or feel them. Frequencies are often below 20 Hz (the lower limit of the human ear), and vibration levels are

[1] See David Akerson's case study on how vibrations from construction outside a Thermo Fisher Scientific semiconductor manufacturing facility led to distorted images, loss of resolution, and corrupted failure analyses. The facility was forced to limit production to off-hours until an expensive vibration control system was installed. [5]

microscopic. High-sensitivity vibration sensing metrology is needed to measure them accurately and support condition monitoring during microchip manufacturing processes.

Accelerometers

Vibrations are commonly measured using instruments called accelerometers—named as such because their internal sensing mechanisms directly measure the acceleration of the vibration. There are three popular accelerometer types [6]:

- Piezoresistive
    - Piezoresistive sensors have wide frequency responses and can withstand high shock events.
    - But they have a low *sensitivity* to capture the very high amplitude events. This trade-off means they can't measure small vibrations well.
- Variable Capacitive Micro-Electro-Mechanical Systems (MEMS) sensors
    - MEMS sensors are inexpensive and quite popular for use in smart phones and other e-devices. They are best used for displacement measurements as they also capture DC, or zero frequency vibration.
    - But they are generally noisy with only moderately good low amplitude resolution.
- Piezoelectric
    - These are the best instruments for vibration testing, with high sensitivity and fine resolution.
    - They work over wide frequency range, and are customizable for many different applications for different technical requirements as needed.

We'll focus mainly on piezoelectric accelerometers here, along with a high sensitivity MEMS accelerometer.

General Behavior

Accelerometers measure voltage fluctuations, which are directly proportional to the vibration acceleration[2] thanks to the 'piezoelectric effect'. Inside an accelerometer housing is a mass mounted to a piezoelectric crystal. As the mass vibrates, it induces oscillating stresses in the crystal, causing it to generate negative and positive ions on its opposing surfaces. The resulting fluctuating voltage is passed through an amplifier, and into a wire connected to the housing. Plug the wire into any standard data acquisition (DAQ) system and you can measure the fluctuating voltage from an accelerometer mounted to a machine.

The output voltage can fluctuate between maximum limits, typically called the 'range'. For PCB piezoelectric accelerometers, this is usually +/- 5 volts. Each accelerometer is calibrated with known input accelerations to generate its 'sensitivity', or how many g's of acceleration[3] correspond to a volt of output. Commonly expressed in terms of number of volts/g, this is the base parameter of any accelerometer. All the other performance terms we'll discuss are based on sensitivity. Figure 4 shows a

[2] Vibration can be quantified in terms of fluctuating displacements (or deflections), velocities, or accelerations.
[3] It's common to measure acceleration in g's, which is normalized to gravity. G's are non-dimensional so don't depend on whether you prefer to use English or SI units. To convert to dimensional values, just multiply by gravity in your preferred units.

schematic of a normal and high sensitivity accelerometer, with the slope (V/g) of the high sensitivity accelerometer higher than that of the normal sensitivity one.

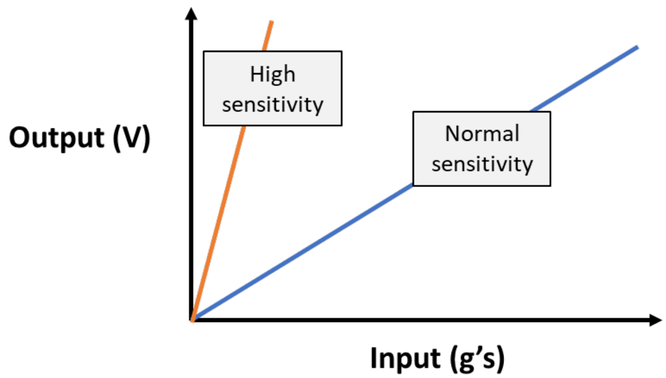


Figure 4. Sensitivity variability of accelerometers.

Key Specifications

Let's examine some other accelerometer performance specifications, such as:

- Resolution (how finely you can measure, or the smallest measurable amount)
- Upper vibration limits (how high a vibration you can measure)
- Frequency range
- Mass

For small-scale vibration measurements we are most interested in the resolution. Before we discuss accelerometer resolution, consider how the audio industry defines it. You may have heard debates between audiophiles about the 'dynamic range' of a digitized audio signal. High-resolution audio (Hi-Res) generally uses a 24-bit resolution, sometimes called 'bit depth'. Figure 5 shows a simple tone at a specific frequency, along with an inset digitization of a small section. While the overall waveform may look continuous, digital measurements subdivide the wave into small segments. The height of those segments is the resolution, or the smallest quantity you can measure. Standard 16-bit resolution (common on many DAQs) can break a full range up into 2^{16} pieces, or 65,536 segments. 24-bit resolution can break it up into 2^{24} pieces, or over 16 million segments!

Accelerometers behave similarly, but have limits associated with their internal electronics. The piezoelectric crystal generating the fluctuating voltages is connected to resistors and amplifiers that have their own resolution limits, which vary with frequency. The resolution must be measured carefully with high bit resolution DAQs in extremely quiet environments over the full frequency range of the sensor. The sensor is connected to the high resolution DAQ, and background noise from the sensor is acquired over a few minutes.

The resolutions are actually integrations of background *frequency spectra* computed from the background noise time histories in 'rms' or root-mean-square levels[4]. These integrations are dominated

[4] RMS levels are commonly used when working with time signals. The time signal is squared and the mean value is taken of the square root of the result. For a sinusoidal signal, rms level is just the peak value divided by the square root of 2.

by very low frequency noise, usually caused by the resistor inside the instruments. The actual frequency-dependent resolutions above a few Hertz can be up to ten times lower than integrated quantities for seismic accelerometers[5]. However, we'll use the integrated numbers for comparisons and to be conservative about how small a vibration you can measure.

Accelerometers also have upper limits on how much vibration they can measure. A vibration that is slightly higher than the limit won't damage the sensor, but the output will be unreliable. A vibration that is *much* higher than the limit can physically damage the internal components. Therefore, all sensors have published overload, or 'shock' limits, which should not be exceeded.

Every sensor also has a frequency range in which measurements are reliable (sometimes called the 'linear range'). Vibrations at frequencies lower or higher than this range can still be measured, but the sensitivity calibrations aren't as accurate. PCB publishes these ranges and their accuracy limits (usually for +/- 5% and +/- 10% variation), along with plots of how closely the vibration at particular frequencies matches a 'flat' or constant sensitivity.

Finally, every sensor has a mass. The highly sensitive accelerometers generally use higher masses to tune the sensitivity upward so they can measure smaller vibrations. In applications where the base structure is quite thin and light, a heavy accelerometer can 'mass-load' the system, and actually reduce the vibration being measured. For most manufacturing machinery, however, this mass loading effect is insignificant.

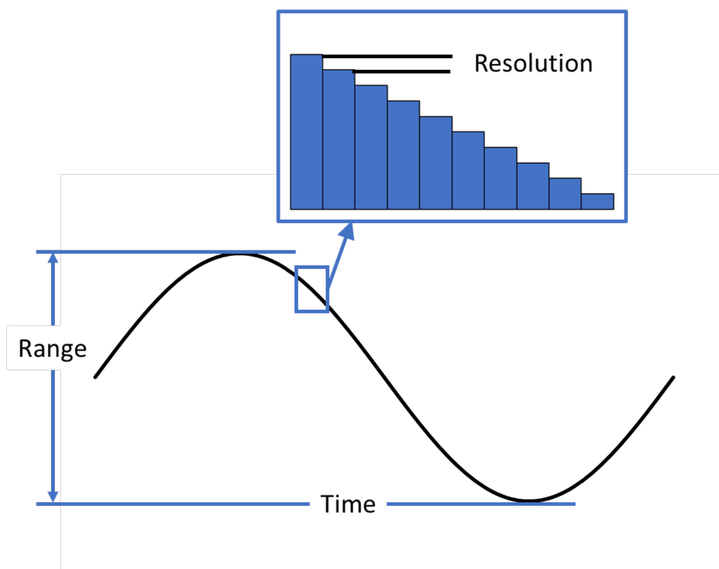


Figure 5. Accelerometer resolution.

[5] See the PCB specification sheets for measured 'spectral noise' levels at specific frequencies, commonly 1 Hz, 10 Hz, and 100 Hz. You'll notice the spectral noise decreases with increasing frequency.

High Sensitivity Accelerometer Options

Let's compare sensitivities, ranges, and resolution of five common PCB accelerometers:

- The 352 series, used for general purpose vibration measurements. We'll look specifically at model 352C03.
- The 333 'modal' series, used for 'experimental modal analysis', where known inputs drive a system into vibration and accelerometers measure the resulting vibration response. We'll consider model 333B30.
- Two models from the 'seismic' 393 group, also known as 'high sensitivity accelerometers':
    - Model 393B04—high sensitivity
    - Model 393B31—highest sensitivity available
- The most sensitive MEMS accelerometer available from PCB—model 3711F112G.

The accelerometer parameters are summarized in Table 1. Notice how:

- Range, resolution, upper frequency limit, and overload limit *decrease* with increased sensitivity.
- Mass generally *increases* with increased sensitivity.
- The MEMS sensors are different, as they:
    - Measure DC (or 0 Hz) values
    - Have very high overload limits (so are generally insensitive to large shock events, like being dropped on a hard floor)

The highest resolution seismic accelerometer can measure vibrations as low as 1 micro-g (a millionth of a g), but maximum vibrations of only 0.5 g. This resolution is smaller than that of 16 bit digital DAQs (which would be 1/65,536, or 15 micro-g's). This means that to measure accelerations that low, you'll need a finer resolution DAQ. Fortunately, these are readily available.

Table 1. Accelerometer parameter summary.

	352C03 (general)	**333B30 (modal)**	**3711F112G (MEMS)**	**393B04 (seismic)**	**393B31 (seismic)**
Sensitivity (V/g)	0.01	0.10	0.675	1	10
Range (+/- g's)	500	50	2	5	0.5
Resolution (micro-g's rms, full frequency range)	500	150	100	30	1
Frequency range (Hz), +/-5%	0.5 – 10,000	0.5 – 3000	0-250	0.06 – 450	0.1 - 200
Overload limit (g's peak)	5,000	5,000	5000	300	40
Mass (grams)	5.8	4	16	50	635

We compare resolution, our most important parameter, in Figure 6. The sensors are depicted in terms of their base sensitivities (V/g), with the general-purpose sensor on the far left and the highest sensitivity sensor on the far right. The MEMS sensor behaves a bit differently than the piezoelectric sensors, and that data point is highlighted separately. The axes are shown on log scales to show the dependence with sensitivity. Clearly, the resolution is inversely proportional to sensitivity. The bounds for the piezoelectric accelerometers range from 5E-6 to 3E-5 / sensitivity. Note that although the MEMS sensor can measure DC, or 0 Hz levels, that capability does not lead to the fine resolution needed for very small-scale vibration measurements.

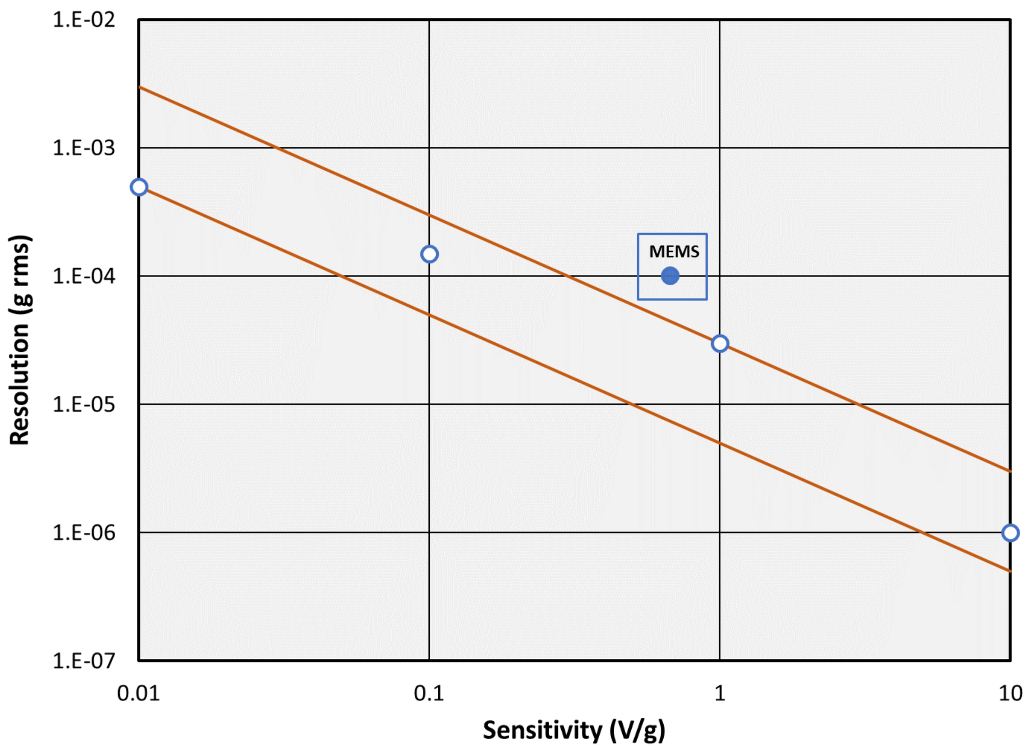


Figure 6. Accelerometer resolution vs. sensitivity (actual in circles and bounds shown in lines).

Nanometer Level Deflection Measurements: How Low Can We Go?

Accelerometers measure vibration acceleration at different frequencies. However, to monitor fluctuating distortions of microchip features in the order of tens of nanometers, we are more interested in displacements[6]. In vibrations, there are specific relationships between displacements (d), velocities (v), and accelerations (a) that depend on frequency:

$$v(\omega) = i\omega d(\omega)$$

$$a(\omega) = i\omega v(\omega) = -\omega^2 d(\omega)$$

[6] Note that we are interested in monitoring *fluctuating* displacements at particular frequencies, not absolute displacement. Since the machines used in semiconductor manufacturing are stationary (they don't move across the factory floor over time), there's no need to measure the actual integrated displacement over long periods of time, which is quite difficult due to neglecting DC and steady velocity terms.

ω is the 'radial frequency', which is the cyclic frequency (also commonly expressed in cycles/second, or Hz) multiplied by 2π. This just calculates how many radians a vibration cycle goes through per second. Working backwards:

$$d(\omega) = -a(\omega)/\omega^2$$

We can divide the accelerometer resolution (smallest amount it can measure) by ω^2 at specific frequencies to estimate how much deflection it can measure. The results are in Figure 7 for frequencies between 1 and 100 Hz. There's a solid black horizontal line at 10 nm resolution. The most sensitive accelerometer (393B31) can measure 10 nm fluctuations or less, at frequencies above about 5 Hz! The MEMS sensor can capture displacements comparable to the modal piezoelectric accelerometers. Remember the actual 'spectral noise' can be up to ten times lower than that above 5 Hz (meaning you get even finer resolution there; once again, check your specification sheets for the noise floors at specific frequencies).

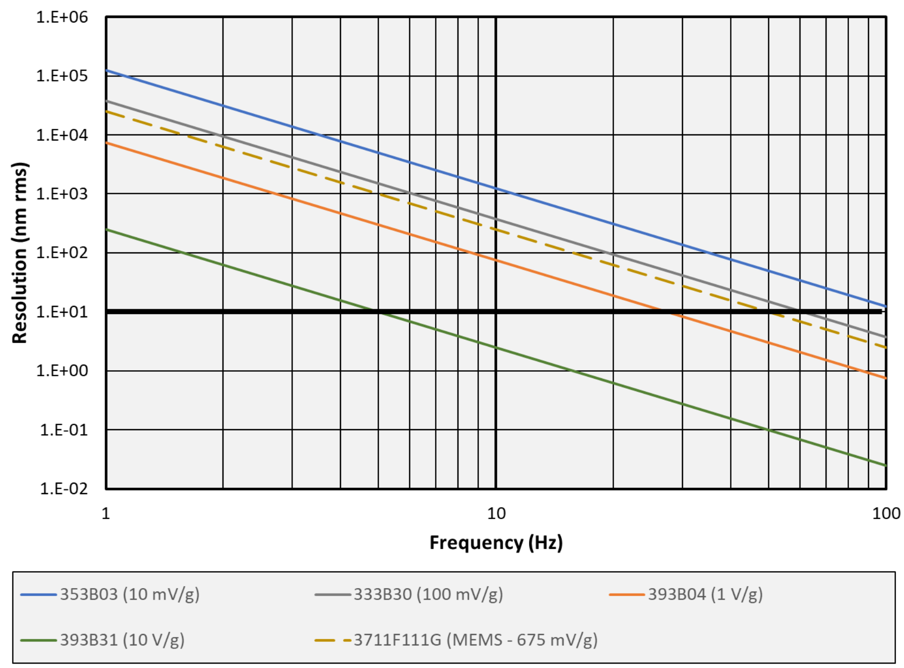


Figure 7. Accelerometer resolution in displacement (nanometers) vs. frequency.

Methods to measure displacement directly include eddy current, optical, and ultrasonic based probes. While they indeed measure deflection directly (it is not integrated from velocity or acceleration), their resolution is limited (generally in the mm to micron range), accuracy depends on the surface reflectivity or magnetism, and calibration is tricky. Any relative movement between a displacement probe and the target surface (e.g., if a mounted probe shifts slightly due to an inadvertent impact) can invalidate a calibration.

Multi-axis Measurements

A final note about accelerometers: sometimes, you need to measure vibration in more than one direction (or axis). Triaxial accelerometers measure in three different directions, and output all three signals via one multi-conductor cable. Triaxial accelerometers are also designed and tested to minimize 'cross-talk', or voltages induced in one direction caused by vibration in another (this is usually less than a few percent).

Triaxial accelerometers offer convenience and easier mounting to measure vibrations in all three axes simultaneously. The primary trade-off is weight; in order to measure multiple axes, the sensors are larger. If multi-axis measurements are not required, end users are encouraged to use single axis sensors to minimize impacts from mass loading.

Conclusions

Semiconductor manufacturing involves extremely complex procedures working with features on the scale of tens of nanometers. Low-frequency vibrations during manufacturing can shake machinery components and chip wafers and lead to critical errors in and between the layers of a microchip. Vibration can also compromise the accuracy of health monitoring systems and imaging checks.

High sensitivity PCB 'seismic' accelerometers can measure fluctuating vibration deflections on the nanometer scale above about 5 Hz. These vibrations can feed easily into a health monitoring system to flag vibrations and alert to critical manufacturing errors.

References

1. Radamson, H. H., He, X., Zhang, Q., Liu, J., Cui, H., Xiang, J., Kong, Z., Xiong, W., Gu, C., Gao, J., Yang, H., Gu, S., Zhao, X., Du, Y., Yu, J., & Wang, W. (2019). "Miniaturization of CMOS." Micromachines, 10(5), 293. https://doi.org/10.3390/mi10050293

2. Timings, Jessica. (2021, October 6). "6 Crucial Steps in Semiconductor Manufacturing." ASML. https://www.asml.com/en/news/stories/2021/semiconductor-manufacturing-process-steps

3. Patel, D., & Ahmad, A. (2023, February 27). Embracing Chaos: The Imperfect Art of Semiconductor Manufacturing and Lithography. https://www.semianalysis.com/p/embracing-chaos-the-imperfect-art

4. Nikon. Semiconductor Lithography Systems | Product Technology. https://www.nikon.com/about/technology/product/semiconductor/index.htm5.

5. Akerson, D. (2021, June 2). "How to Mitigate Environmental Interference During Semiconductor Failure Analysis." https://www.thermofisher.com/blog/semiconductors/environmental-interference-in-semiconductor-failure-analysis/

6. The Modal Shop. Understanding Accelerometers. https://www.modalshop.com/calibration/learn/accelerometers

PCB PIEZOTRONICS
AN AMPHENOL COMPANY

3425 Walden Avenue, Depew, NY 14043 USA

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

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