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MEMS: Physical Properties

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This month's Feature Article covers some important physical properties of MEMS devices. Properties at the microscale can be quite different than at the macroscale, so we will highlight some of the important differences in Table 1.

Volume	$V \sim L^3$
Mass	$M \sim L^3$
Surface	$SA \sim L^2$
Strength	$S \sim L^2$
Force	$F \sim L^2$
Acceleration	$A \sim 1/L$
Frequency	$f \sim 1/L$
Power	$P \sim L^2$
Power density	$P \sim 1/L$

* *Assumes constant mass density*

Voltage	$V \sim$ constant
E Field	$E \sim 1/L$
Resistance	$R \sim 1/L$
Capacitance	$C \sim L$
Current	$I \sim L$
Magnetic wire	$B \sim$ constant
Heat capacity	$C_v \sim L^3$
Heat flow	$dT/dt \sim 1/L^2$
Turbulence	$Re \sim L$

* *Assumes constant voltage*

Table 1. How physical properties scale with length.

First, let's review some important properties of fundamental materials and highlight their behavior according to scale or size. As shown in Table 1, volume scales as a function of the cube of the length of the element. Mass and heat capacity also scale with the cube of the

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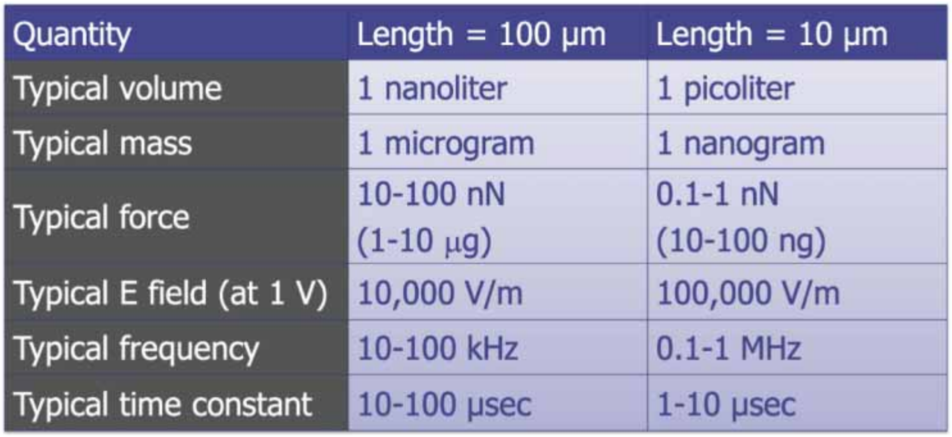
length of the element. Some properties scale with the square of the length of the element, like surface, strength, force, and power. Other properties, like capacitance, current and turbulence, scale in a manner that is directly proportional to length. Still other properties vary as one over the length, like acceleration, frequency, power density, electrical field, and resistance. Finally, heat flow scales as one over the square of the length.



Quantity	Length = 100 µm	Length = 10 µm
Typical volume	1 nanoliter	1 picoliter
Typical mass	1 microgram	1 nanogram
Typical force	10-100 nN (1-10 µg)	0.1-1 nN (10-100 ng)
Typical E field (at 1 V)	10,000 V/m	100,000 V/m
Typical frequency	10-100 kHz	0.1-1 MHz
Typical time constant	10-100 µsec	1-10 µsec

Table 2. Properties of MEMS devices at 100mm and 10mm.

To gain a sense for the scale of MEMS devices, we show two columns in Table 2: one where the length is 100µm, and the other where the length is 10µm. The typical volume of the structure, mass, forces, electric fields, frequencies and time constants are given at these two lengths.

One property that changes significantly as length scales down is surface tension. Surface tension, or P, is equal to γ (or force per unit distance) divided by distance d. The surface tension force for a 100µm opening is approximately 5.7 µN, but the typical force for a 100µm device is only 10 nN, so the surface tension is over 500 times greater than the force the object exerts. Therefore, surface tension predominates at the microscale. We see this in everyday life, as insects and other small objects make use of this property as shown in Figure 1.

Figure 1. Examples of surface tension.

Another important property at the microscale is fluid flow, which can be described using the Reynolds Number:

$$Re = \frac{\rho u L}{\mu}$$

Where:

ρ is the density of the fluid
u is the flow speed
L is the linear dimension
μ is the dynamic viscosity of the fluid

The Reynolds number is the ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities. This number scales as the length scales. A typical Reynolds number for a 100µm device is approximately 0.1. However, the onset of turbulence does not occur until the Reynolds number is approximately 2000. This means that the characteristic flows in micro-channels are smooth. We show an example from nature in Figure 2 on the left, and an example from a microfluidics device in Figure 2 on the right.

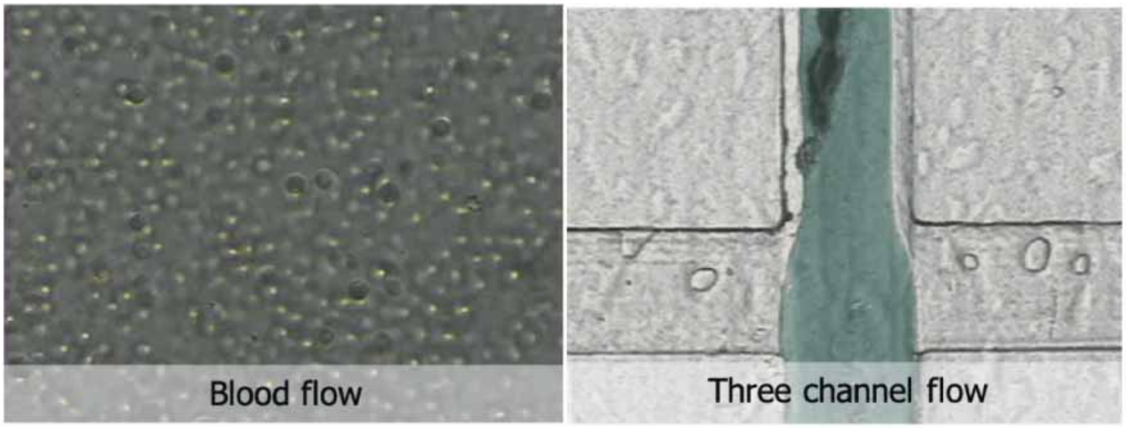


Figure 2. Example of blood flow (left) and example of microfluidic flow (right).

Yet another important property at the microscale is heat transfer. The surface area to volume ratio is large at small scales. However, heat capacity depends on mass. Therefore, the heat transfer rate is very fast at small scales. For example, the temperature of a small filament in a 75 watt light bulb is ~2500°C. The ramp up time of the filament temperature is ~20 msec, and the ramp down time is ~60 msec. Therefore, heat flows through small devices quickly, which means it is hard to maintain a temperature gradient.

Another important concept at the microscale is the surface area to volume ratio. As we have mentioned previously, the surface area to volume is large at small scales. This means that mass flow saturates quickly in small volumes, and equilibrium can be reached very quickly. Therefore, micro-scale systems must utilize physical barriers (such as is shown in Figure 3 with plant cell walls) to maintain concentration gradients.

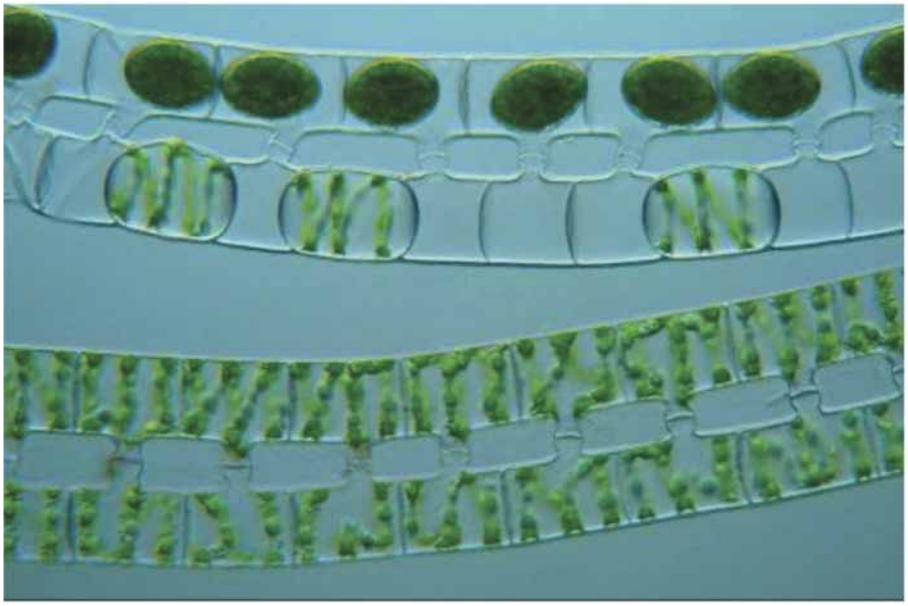


Figure 3. Examples of plant cells.

Microscale structures also lose continuity. At sizes below approximately 50μm, the granularity of nature becomes relevant. Many bulk-scale physical laws are no longer accurate. Be aware that metals and materials are not continuous materials. They have microscopic grain structure. For example, the typical grain size of a metal is approximately 10μm. This affects the physical, thermal and electrical properties. Figure 4 shows an example of the microscopic grain structure of stainless steel.

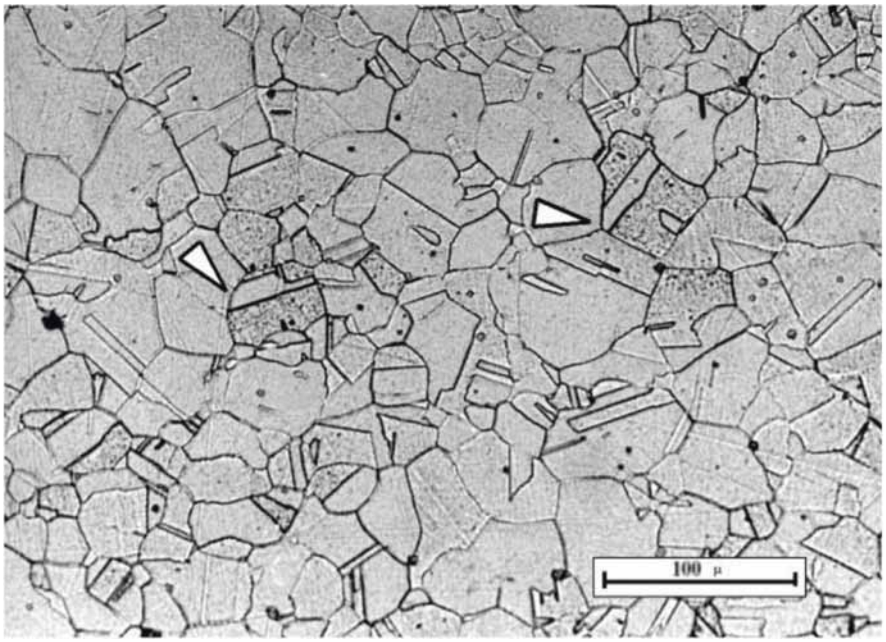


Figure 4. Grain structure in stainless steel.

As we scale down even further, atomic granularity plays a role. At sizes below approximately 100nm, the bulk properties of a material are essentially meaningless. Instead, we require an atomic level understanding of molecular forces. Figure 5 shows a hypothetical molecular motor.

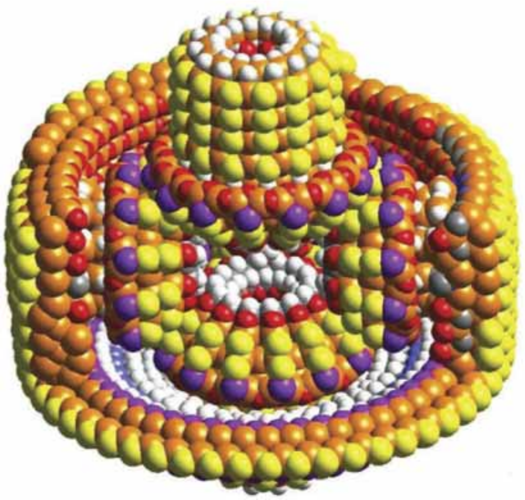


Figure 5. Drawing of hypothetical molecular motor.

Yet another issue at the microscale is noise. At sizes below approximately 50μm, thermal induced fluctuations are noticeable. We cannot think of heat as a continuous “fluid”. Heat is instead a statistical sum of molecular vibrations, so at the microscale, vibrations and Brownian motion add statistical fluctuation and noise, rather than averaging out like they do at the macroscale. Therefore, thermal fluctuations depend on size and temperature. For example, milk particles exhibit Brownian motion, or random vibrations, at a microscopic view, as shown in Figure 6.

Figure 6. An image of 2% milk particles showing Brownian motion, or random vibrations.

Residual forces, another microscale issue, include local electrostatic charging, hydrogen bonding, dipole interactions, and Van der Waals forces. These play an important role. The small scales allow very close interaction and a large surface interface (as in Van der Waals). Figure 7 shows an image of micromachined gecko hairs, made from plastic dry tape and sticky fabric, which takes advantage of this phenomenon. Low humidity is favorable for electrostatic charging, while the wet or humid state mediates hydrogen bonding.

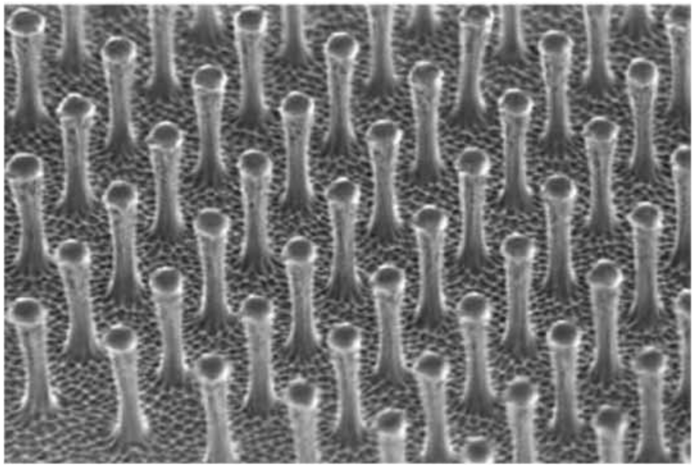


Figure 7. Micro-machined gecko hairs (0.2mm x 0.2mm) made from plastic dry tape and sticky fabric.

Finally, at the microscale, time constants become quite short. For a MEMS structure, the typical time constant is 10 to 100µs. In comparison, a hummingbird heart beat occurs every 50msec, a honeybee wing beat occurs every 4msec, and even a vibrating drop of water oscillates every 120µs.

In conclusion, things are much different at the microscale than they are at the macroscale. We discussed how different properties scale with length, or size of the structure. A number of properties play an important role at the microscale, including surface tension, fluid flow, and heat transfer. Other issues include surface to volume interactions, loss of continuity, atomic granularity, noise, residual forces, and time scales.

Technical Tidbit

Manufacturing Constraints

In this month’s Technical Tidbit, we will briefly discuss the subject of manufacturing constraints.

Manufacturing a product in a timely manner in quantities required by the customer is a challenging activity. This process is only as good as the weakest link in the process. Conceptually, we can think about this chain as a supply chain. We have simplified it into five links to illustrate the concept. Here we have chains associated with marketing, planning, manufacturing, shipping, and the customer. If one of these links breaks down, the entire chain is disrupted. For the purpose of our discussion, we will primarily focus on the manufacturing portion of the diagram, since that is the scope of our discussion in this Technical Tidbit.

We can measure productivity in terms of throughput and operation expenses. Net profit is equal to throughput, or revenue, minus operation expenses, excluding fixed costs. Return on investment, or ROI, is equal to net profit divided by investments, or fixed costs. So productivity then is defined as throughput, or revenue, divided by operation expenses.

$$Net\ Profit = \underset{\text{(Revenue)}}{Throughput} - \underset{\text{(Excluding Fixed Costs)}}{Operation\ Expenses}$$

$$Return\ on\ Investment = \frac{Net\ Profit}{\underset{\text{(Fixed Costs)}}{Investments}}$$

$$Productivity = \frac{\overset{\text{(Revenue)}}{Throughput}}{Operation\ Expenses}$$

We need to delve into some jargon for a minute to better understand how a company might manage their supply chain. A company’s supply chain goodness or effectiveness is only as good as the data it gathers from the system, so it needs accurate data. A company’s customer commitments are dependent on good supply availability information, and the supply availability is determined by systemic capacity data, residual supply, cycle times, and yields. Typically, the manufacturing group within a company is responsible for most aspects of the semiconductor production system. This includes cycle time and yield, capacity consumption, the amount of capacity and timing of placing new equipment in service, or the removal of old equipment, the product business group's level of support commitment, the number of chips per wafer, the Work In Progress, or WIP, movement, meeting the committed starts and outs, and downstream factories that are dependent on the output of upstream factories. This data is used by a Supply Chain Planning system to plan a company's factories and pass information to the Supply Chain Availability System. This system uses this information to determine the best possible customer commitments for their orders.

What types of internal constraints might occur? Constraints can occur in three main areas: equipment, people, and strategy. The first area is equipment. The way equipment is currently used limits the ability of the system to produce more salable goods and services. The second is people. Lack of skilled people limits the supply chain, or mental models held by people can cause behavior that becomes a constraint. The third is strategy. This is a written or unwritten approach in a business that prevents it from making more product. Now let's contrast this with a breakdown. Organizations have many problems with equipment, people, and so forth. For example, a processing tool can fail and require maintenance to fix the problem, so this limits the ability to process product. Once the piece of equipment is brought back online, production returns to normal. Some people think of these problems as constraints, but they are considered to be breakdowns, and breakdowns are simply breakdowns, and not constraints in the true sense. A constraint is an item that prevents the organization from obtaining a higher level of throughput of its products or services. This is typically revenue through sales.

Managing constraints is very important. Constraints are also called bottlenecks because they have the smallest flow capacity, relative to the need, in a process. The higher the capacity utilization, the more pronounced the bottleneck in the process. A company needs to analyze suspected bottlenecks because they don't necessarily manifest themselves where there is a backup in production. The constraint will regulate the total output capacity and line speed for the process, and will determine the strategic flexibility to capitalize on market swings.

Ask the Experts

Q: How can we differentiate between moisture-induced delamination of dielectric layers and other causes of delamination?

A: Differentiating can be quite difficult. Packages exhibiting moisture-induced delamination would typically show signs of swelling or weight gain compared to a non-moisture-laden package. Usually, engineers would request history on the component to understand whether the component had been exposed to moisture or not.

Spotlight: Failure and Yield Analysis

OVERVIEW

Failure and Yield Analysis is an increasingly difficult and complex process. Today, engineers are required to locate defects on complex integrated circuits. In many ways, this is akin to locating a needle in a haystack, where the needles get smaller and the haystack gets bigger every year. Engineers are required to understand a variety of disciplines in order to effectively perform failure analysis. This requires knowledge of subjects like: design, testing, technology, processing, materials science, chemistry, and even optics! Failed devices and low yields can lead to customer returns and idle manufacturing lines that can cost a company millions of dollars a day. Your industry needs competent analysts to help solve these problems. ***Advanced Failure and Yield Analysis*** is a four-day course that offers detailed instruction on a variety of effective tools, as well as the overall process flow for locating and characterizing the defect responsible for the failure. This course is designed for every manager, engineer, and technician working in the semiconductor field, using semiconductor components or supplying tools to the industry.

By focusing on a ***Do It Right the First Time*** approach to the analysis, participants will learn the appropriate methodology to successfully locate defects, characterize them, and determine the root cause of failure.

Participants learn to develop the skills to determine what tools and techniques should be applied, and when they should be applied. This skill-building series is divided into three segments:

1. **The Process of Failure and Yield Analysis.**Participants learn to recognize correct philosophical principles that lead to a successful analysis. This includes concepts like destructive vs. non-destructive techniques, fast techniques vs. brute force techniques, and correct verification.
2. **The Tools and Techniques.** Participants learn the strengths and weaknesses of a variety of tools used for analysis, including electrical testing techniques, package analysis tools, light emission, electron beam tools, optical beam tools, decapping and sample preparation, and surface science tools.
3. **Case Histories.** Participants identify how to use their knowledge through the case histories. They learn to identify key pieces of information that allow them to determine the possible cause of failure and how to proceed.

COURSE OBJECTIVES

1. The seminar will provide participants with an in-depth understanding of the tools, techniques and processes used in failure and yield analysis.
2. Participants will be able to determine how to proceed with a submitted request for analysis, ensuring that the analysis is done with the greatest probability of success.
3. The seminar will identify the advantages and disadvantages of a wide variety of tools and techniques that are used for failure and yield analysis.
4. The seminar offers a wide variety of video demonstrations of analysis techniques, so the analyst can get an understanding of the types of results they might expect to see with their equipment.
5. Participants will be able to identify basic technology features on semiconductor devices.
6. Participants will be able to identify a variety of different failure mechanisms and how they manifest themselves.
7. Participants will be able to identify appropriate tools to purchase when starting or expanding a laboratory.

INSTRUCTIONAL STRATEGY

By using a combination of instruction by lecture, video, and question/answer sessions, participants will learn practical approaches to the failure analysis process. From the very first moments of the seminar until the last sentence of the training, the driving instructional factor is **application**. We use instructors who are internationally recognized experts in their fields that have years of experience (both current and relevant) in this field. The handbook offers hundreds of pages of additional reference material the participants can use back at their daily activities.

THE SEMITRACKS ANALYSIS INSTRUCTIONAL VIDEOS™

One unique feature of this workshop is the video segments used to help train the students. Failure and Yield Analysis is a visual discipline. The ability to identify nuances and subtleties in images is critical to locating and understanding the defect. Many tools output video images that must be interpreted by analysts. No other course of this type uses this medium to help train the participants. These videos allow the analysts to directly compare material they learn in this course with real analysis work they do in their daily activities.

COURSE OUTLINE

1. Introduction
2. Failure Analysis Principles/Procedures
    a. Philosophy of Failure Analysis
    b. Flowcharts
3. Gathering Information
4. Package Level Testing
    a. Optical Microscopy
    b. Acoustic Microscopy
    c. X-Ray Radiography
    d. Hermetic Seal Testing
    e. Residual Gas Analysis
5. Electrical Testing
    a. Basics of Circuit Operation
    b. Curve Tracer/Parameter Analyzer Operation
    c. Quiescent Power Supply Current
    d. Parametric Tests (Input Leakage, Output voltage levels, Output current levels, etc.)
    e. Timing Tests (Propagation Delay, Rise/Fall Times, etc.)
    f. Automatic Test Equipment
    g. Basics of Digital Circuit Troubleshooting
    h. Basics of Analog Circuit Troubleshooting

6. Decapsulation/Backside Sample Preparation
    a. Mechanical Delidding Techniques
    b. Chemical Delidding Techniques
    c. Backside Sample Preparation Techniques
7. Die Inspection
    a. Optical Microscopy
    b. Scanning Electron Microscopy
8. Photon Emission Microscopy
    a. Mechanisms for Photon Emission
    b. Instrumentation
    c. Frontside
    d. Backside
    e. Interpretation
9. Electron Beam Tools
    a. Voltage Contrast
        i. Passive Voltage Contrast
        ii. Static Voltage Contrast
        iii. Capacitive Coupled Voltage Contrast
        iv. Introduction to Electron Beam Probing
    b. Electron Beam Induced Current
    c. Resistive Contrast Imaging
    d. Charge-Induced Voltage Alteration
10. Optical Beam Tools
    a. Optical Beam Induced Current
    b. Light-Induced Voltage Alteration
    c. Thermally-Induced Voltage Alteration
    d. Seebeck Effect Imaging
    e. Electro-optical Probing
11. Thermal Detection Techniques
    a. Infrared Thermal Imaging
    b. Liquid Crystal Hot Spot Detection
    c. Fluorescent Microthermal Imaging

12. Chemical Unlayering
    a. Wet Chemical Etching
    b. Reactive Ion Etching
    c. Parallel Polishing
13. Analytical Techniques
    a. TEM
    b. SIMS
    c. Auger
    d. ESCA/XPS
14. Focused Ion Beam Technology
    a. Physics of Operation
    b. Instrumentation
    c. Examples
    d. Gas-Assisted Etching
    e. Insulator Deposition
    f. Electrical Circuit Effects
15. Case Histories

You may want to stress some aspects more than others or conduct a simple one-day overview course. Many of our clients seek ongoing just-in-time training that builds in-depth, advanced levels of reliability expertise. We'll work with you to determine the best course of action and create a statement of work that emulates the very best practices of semiconductor reliability analysis.

Our instructors are active in the field and they practice the disciplines daily. Please give us a call (505) 858-0454 or drop us an e-mail (info@semitracks.com).

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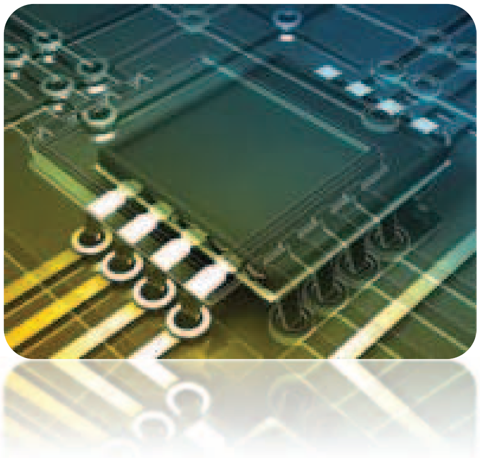

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Upcoming Webinars

(Click on each item for details)

Failure and Yield Analysis

4 sessions of 4 hours each
US: November 29 – December 2, 2021
(Mon – Thur), 11:00 A.M. – 3:00 P.M. EST;
8:00 A.M. – 12:00 NOON PST

Advanced CMOS/FinFET Fabrication

4 sessions of 2 hours each
US: December 6 – 9, 2021
(Mon – Thur), 11:00 A.M. – 1:00 P.M. EST;
8:00 A.M. – 10:00 A.M. PST

Wafer Fab Processing

4 sessions of 4 hours each
February 28 – March 3, 2022
(Mon – Thur), 11:00 A.M. – 3:00 P.M. EST;
8:00 A.M. – 12:00 noon PST

Semiconductor Reliability / Product Qualification

4 sessions of 4 hours each
US: March 7 – 10, 2022 (Mon – Thur),
11:00 A.M. – 3:00 P.M. EST;
8:00 A.M. – 12:00 noon PST