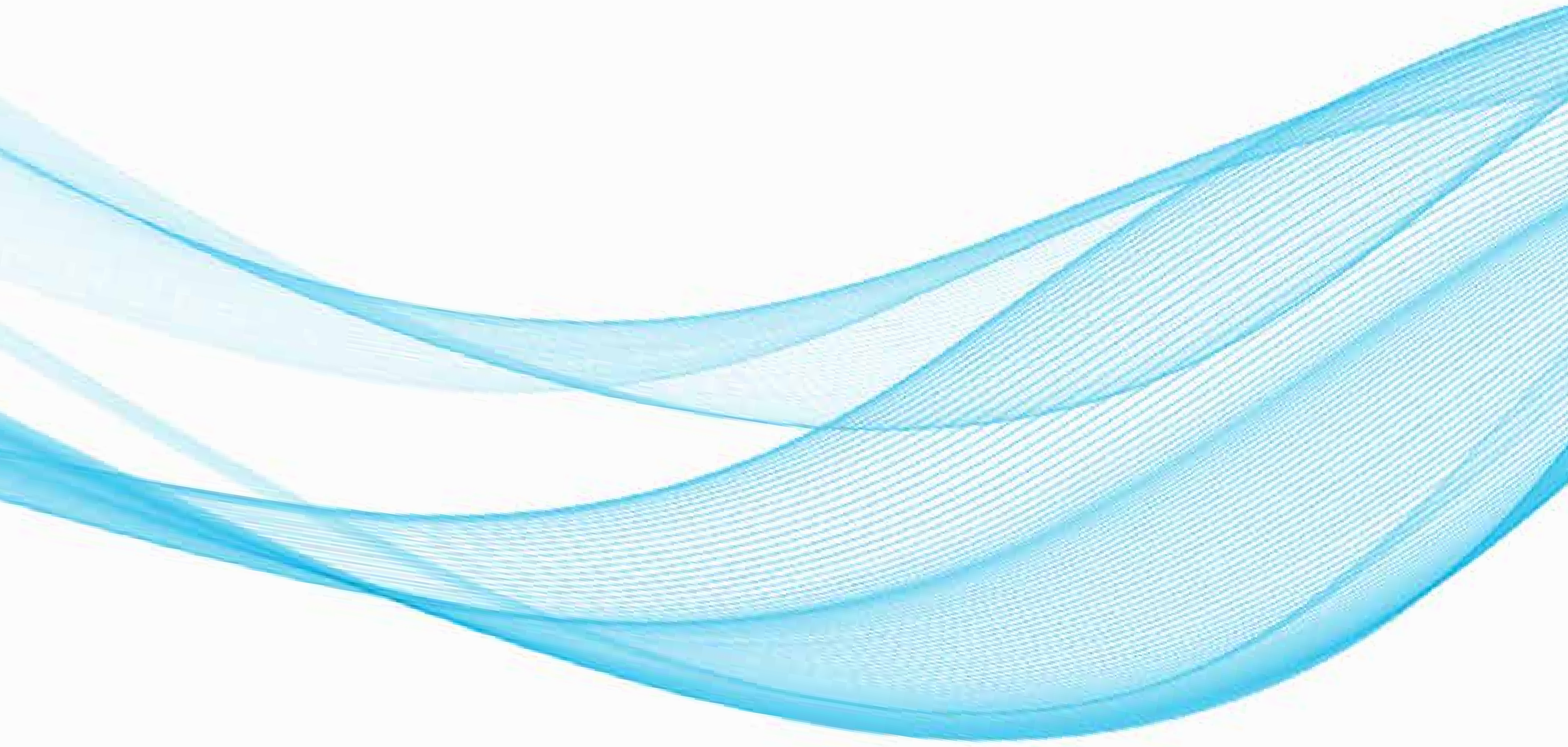
WHITE PAPER

Introductory Guide
To Protective Coatings:
Methodologies

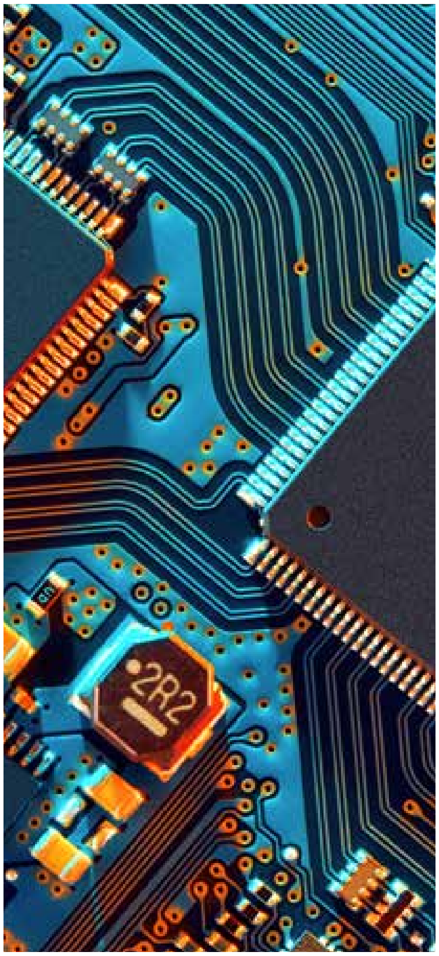


Contents

Abstract

Designing an electronic product that is appropriately protected against environmental hazards and meets thermal, electrical, and mechanical requirements can be a daunting challenge. Several methods may be employed to meet the desired outcome, including mechanical seals, thick-film conformal coating, thin-film conformal coating, and nanocoatings. Choosing the appropriate protection will have a pronounced effect on the end product and total cost of ownership and entails careful consideration of the pros and cons of each method.

Choosing the appropriate protection will have a pronounced effect on the end product and total cost of ownership and entails careful consideration of the pros and cons of each method.



Introduction

By 2030, 125 billion globally connected devices will be used to increase productivity, improve safety, and enhance security in a world that depends on them. These products exponentially expand opportunities for improved reliability, durability, higher utilization, and new functionality and capabilities that cut across traditional product boundaries. Electronics are fulfilling new, critical roles across industries and market segments, including automotive, industrial, consumer electronics, IoT, and medical devices, guiding autonomous vehicles, managing critical energy infrastructures, powering personal electronics, and monitoring healthcare treatments.

As these functions are deployed, connected devices are exposed to a wide range of environments, including water, sweat, humidity, corrosive chemicals, and wide temperature fluctuations. They must reliably operate to avoid catastrophic failures. The challenges involved in safeguarding electronics from the most demanding environments must not only consider what protection is required, but how to incorporate that protection into the design, functionality, and manufacturing process of the device.

Electronics are fulfilling new, critical roles across industries and market segments, including automotive, industrial, consumer electronics, IoT, and medical devices.

Overview of Electronic Protection Choices

In an intrinsically networked world, device designers and manufacturers need to deliver electronic devices that can reliably run in harsher, more complex environments than ever before. Because environmental threats, including liquids, chemicals, and gases, are so varied and ubiquitous, it is critical for device experience and survivability to adopt a protective methodology, such as mechanical seals, thick-film conformal coatings, and thin-film coating solutions, including nanocoatings.

However, engineering devices for use across environments is both an art and a science. This *Introductory Guide to Protective Coatings* provides a high-level overview of the information needed to make informed decisions about device protection. Specifically, this guide discusses various protection applications and variables to consider while employing these methods.

This Introductory Guide to Protective Coatings provides a high-level overview of the information needed to make informed decisions about device protection.

Mechanical Seals

Mechanical seals such as gaskets and O-rings have historically been popular as a protective method, based on the principle of keeping contaminants out of a device. The seal design is critical and has a significant effect on functionality, aesthetics, and overall performance of the device. Although every application is different, there are several factors to consider for achieving a functioning seal, including material selection, size, and weight, sealing environment, gap opening, and attachment.

Material selection is perhaps the most critical step in providing protection. Considerations include resistance to chemical and environmental hazards, as well as physical and mechanical properties. Several common sealing materials include:

Common Sealing Materials

Material	Advantages	Disadvantages
Silicone	Wide temperature range	Chemical resistance
	Low-stress relaxation	Abrasion resistance
	UV/Ozone Resistance	Tear strength
	Low outgassing	Higher cost
Polyurethane	Low-stress relaxation	Acid/base resistance
	Low outgassing	H2O absorption
EPDM	UV/Ozone Resistance	Outgassing
	Abrasion resistance	Petroleum resistance
	Tear strength	Acid resistance
	Low-temperature range	
	Base resistance	
Vinyl Nitride	Petroleum resistance	Outgassing
	Chemical resistance	
PVC	UV resistance	Narrow temperature range
	Solvent/chemical resistance	Outgassing

Seals typically need to be attached mechanically or with adhesive. For mechanical attachment, the attachment itself cannot interfere with the compression of the seal. For adhesive attachment, careful attention must go into the thickness of the adhesive itself, along with the compatibility of the adhesive material. Devices using seals may need to have a method for venting off materials that get trapped inside. Trapped liquids, if not vented, can cause corrosion to the device leading to failure.

Material selection is perhaps the most critical step in providing protection. Considerations include resistance to chemical and environmental hazards, as well as physical and mechanical properties.

Thick-Film Conformal Coating Technology

Conformal coatings prevent damage from environmental contaminants such as dust, liquids, moisture, and corrosive vapors by conforming to the topography of an electronic component, PCBA, or device. These polymeric films are typically applied at 25-250 micrometers thickness, providing electrical insulation that prevents contact between conductive features on electronics and physical contaminants.

Although conformal coatings are not typically hermetic and therefore do not seal electronics from moisture and corrosive vapors, they act as barriers to the diffusion of these elements. While each conformal coating material has distinct characteristics, all thick-film conformal coatings, when successfully applied, can help prevent corrosion. Common materials include acrylics, epoxies, polyurethanes, and silicones.

If the proper material is not selected, coated products may not operate as expected or meet application requirements. Thus, the designer should carefully consider the characteristics of each material. For example, dielectric and thermal properties should be evaluated, as well as coating properties like transparency or translucency. Meanwhile, mechanical abrasion may occur during shipping, storage, or handling and can compromise the protection provided, allowing an area of ingress. If contact with chemical agents is possible, a coating with strong chemical resistance is essential, and excellent corrosion resistance is a critical element for applications that entail moisture exposure.

Cure time (a period spent for the coating to reach the optimum mechanical and electrical properties) can extend from several minutes or hours to days, so lower cure time is ideal if high throughput is necessary, and to minimize the Work In Progress (WIP) state. A coating that is easy to rework may also be a key consideration. Finally, the cost should be considered.

The various properties and characteristics of thick-film conformal coating materials, as compared to Parylene thin-film conformal coating, are summarized in the chart on page 10.

For adhesive attachment, careful attention must go into the thickness of the adhesive itself, along with the compatibility of the adhesive material.

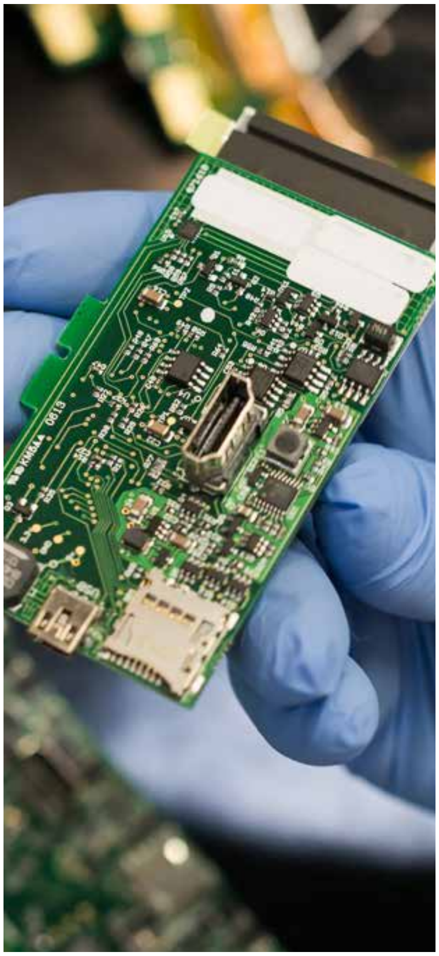
Thin-Film Conformal Coating Technology

Thin-film conformal coatings, while similar in intent to thick-film alternatives, bring the added dimension of being thinner, lighter, and less bulky, and in most cases providing a greater level of protection through alternate material options and achieving greater conformality. Thin-film materials can also be stacked to create tailored protective solutions.

The process of depositing thin-film materials also allows for greater uniformity and precision in laying down protection, usually measured in the 300-nm to 25-micron range, with some methods allowing for single layers atomic deposition. Notable chemical deposition techniques include chemical vapor deposition (CVD), plasma-enhanced CVD (PE-CVD), and atomic layer deposition (ALD). Additionally, dip coating and dispensed technologies are occasionally utilized to apply liquid-phase coatings and engineered materials that can achieve sub 25-micron thicknesses by virtue of carrier solvents or molecular physics.

Parylene Conformal Thin-Film Coating

Parylene is a polymeric material used to produce thin-film conformal coating protection with a distinctive deposition method, namely chemical vapor deposition polymerization (CVDP), or CVD for short.

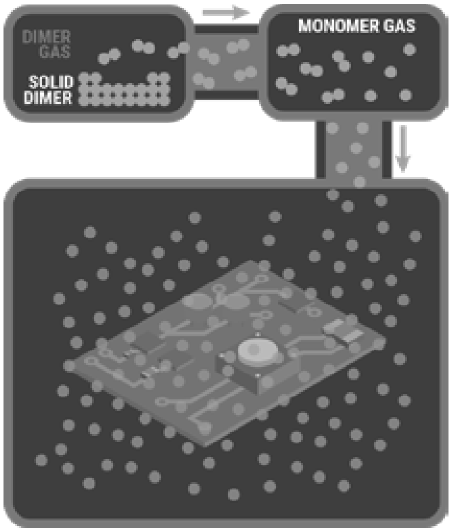


The process of depositing thin-film materials allows for greater uniformity and precision in laying down protection, usually measured in the 300-nm to 25-micron range.

CVD is a process that heats a precursor material in a pyrolizer, which is attached to a vacuum chamber. The material is altered into a gas state and subsequently deposited onto a substrate, forming a polymer film. Deposition occurs at a very thin layer (~2 to 25 microns).

CVD Process

CVD is a process that heats a precursor material in a pyrolizer, which is attached to a vacuum chamber. The material is altered into a gas state and subsequently deposited onto a substrate, forming a polymer film.

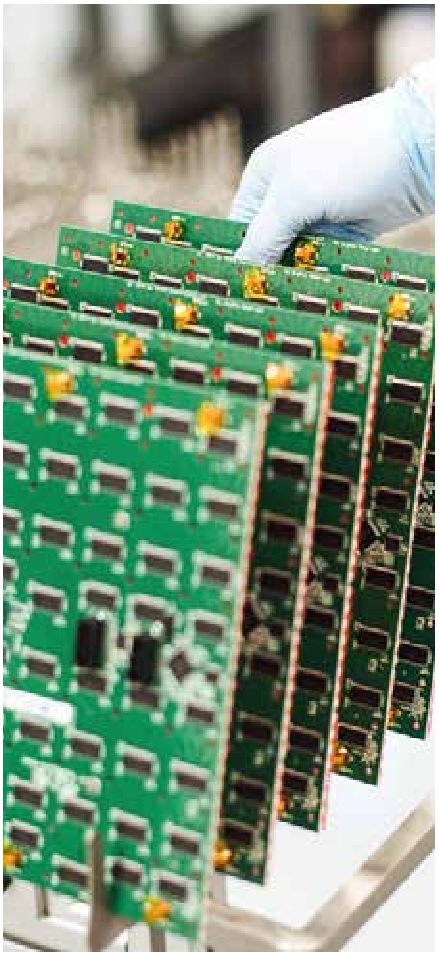


Parylene can achieve high levels of submersion protection that excels based on IPC and IEC standards and can exceed IPX8 requirements. Notably, the coatings provide high barrier protection against liquids, corrosive chemicals, and gases while providing low permeability to moisture.

Additionally, it is optically transparent, and there are no initiators or catalysts in the polymerization process, so the coating is free from trace ionic impurities. Parylene is also REACH, RoHS, PFOA/PFOS-free, and CA Prop 65 compliant. Other properties include high tensile strength, a low dielectric constant with good high-frequency properties, good dielectric strength, and high bulk and surface resistance.

Parylene is only deposited via the CVD process, with cycle times varying based on the desired thickness. The cost is very competitive with more traditional conformal coatings, depending on the requirements for masking and demasking. This step defines the area where coatings are not required or preferred, including connectors, test points, grounding pads, and select circuitry.

The mask/demask process can be manual or automated. Automated masking considers traditional dispensing of masked materials and the various methods available for automated material removal, including plasma ashing and laser ablation. Plasma ashing uses various materials (e.g., oxygen, argon) in a process that bombards the surface with ions that remove select protective coating material. The process



occurs under vacuum with the tolerance varying depending on the equipment deployed. Laser ablation, on the other hand, irradiates material with a laser beam, essentially vaporizing it. In this process, the material is heated by laser energy and evaporates or sublimates, converting it to plasma, swept away with an inert gas. Both methods reduce the need for masking and demasking, decreasing labor and material costs by as much as forty percent (40%).

As a general rule of thumb, laser ablation is typically applied to two-dimensional surfaces, while plasma ashing is commonly associated with removing material from three-dimensional surfaces (e.g., connectors, shield cans).

Parylene C provides the best barrier compared to other Parylene types. At the same time, Parylene N is halogen-free and has high barrier protection against corrosive chemicals and gases while providing low permeability to moisture. It also has a higher dielectric strength than Parylene C. Parylene VT-4 offers higher resistance to heat than Parylenes C and N, while Parylene AF-4 provides the highest temperature and UV resistance of all the Parylenes but at a considerably higher cost. The tables below illustrate the traditional thick-film material performance vs. Parylene and the detailed advantages of the respective Parylene alternatives.

Parylene is only deposited via the CVD process, with cycle times varying based on the desired thickness. The cost is very competitive with more traditional conformal coatings, depending on the requirements for masking and demasking.

Thick-Film versus Thin-Film

		Parylene N	Parylene C	Acrylic	Epoxy	Silicone	Urethane	Ideal Output
Dielectric Strength DC (V/mil)		7000	5600	1200	900-1000	1100-2000	1400-3000	High
Sheet Resistivity (Ω .cm) @ 23°C 50%RH		1.4x10^{17}	6-8x10^{16}	10^{13-14}	10^{12-17}	10^{15-16}	10^{11-15}	High
Dielectric Constant	**60Hz**	2.65	3.15	3.0-4.0	3.5-5.0	2.7-3.1	5.3-7.8	Low
	1KHz	2.65	3.1	2.5-5	3.5-4.5	2.6-2.7	5.4-7.6	
	1MHz	2.65	2.95	3.0-4.0	3.3-4.0	2.6-2.7	4.2-5.2	
Dielectric Loss (tan δ)	**60Hz**	0.0002	0.02	0.2-0.4	0.002-0.01	0.001-0.007	0.015-0.05	Low
	1KHz	0.0002	0.019	0.02-0.04	0.002-0.02	0.001-0.005	0.04-0.06	
	1MHz	0.0006	0.013	0.035-0.056	0.03-0.05	0.001-0.002	0.05-0.07	
	1GHz	-	< 0.007	-	-	-	-	
Young's modulus (Mpa)		2400	3200	480	2400	720	80-800	High
Tensile Strength (Mpa)		45	70	32-77	28-91	5.6-7	1.13-70	High
Elongation to Break (%)		20-250	200	3-85	3-6	100	100-1000	Application Specific
Water Absorption after 24h (%)		< 0.1	< 0.1	0.3	0.8-0.15	0.12 (7 days)	0.02-4.50	Low
Hardness		R85	R80	H-2H	M80-110	40-45 (Shore)	10A-25D (Shore)	Application Specific
Melting Point (°C)		420	290	85 - 105	Curing	Curing	-170 or Curing	High, Application Specific
Operative Temperature in Air (°C)		-200~100	-200~100	-59~137	-	-64~199	-45~110	Application Specific
Coefficient of Linear Expansion @ 25°C (10^{-5}/°C)		6.9	3.5	0.5-15	4.5-6.5	25-30	10-20	Low
Thermal Conductivity (Cal/cm s °C)		3	2	3-6	4-5	3.5-7.5	5	High
Specific Heat @ 20°C (Cal/g°C)		0.2	0.17	-	0.25	-	0.42	N/A
Water Vapor Transmission Rate @ 37°C 90%RH (g mi/100in^{2}d)		1.5	0.21	27.8	6.6	220	20.2	Low
UV Stability		≤ 100 hrs	≤ 100 hrs	-	-	-	-	Application Specific
Index of Refraction		1.661	1.639	-	1.55-1.61	1.43	1.50-1.60	Low
Density (g/cm3)		1.10	1.289	-	1.11-1.40	1.05-1.23	1.10-2.5	High
Taber Wear Index		9	29	-	42	-	60	Low
Impact Resistance (kg-cm)		>85	>85	-	35	-	23	High

1. *Handbook of Plastics, Elastomers, and Composites, 4th Edition, McGraw Hill, Inc. New York, 2002.* Chapter 6.
2. Acrylic, expoxy, urethane and silicone data is nominal, chemistries can vary and other different ranges of protection.

Advantages of Various Parylene Types

Attributes	Parylene C	Parylene N	Parylene F (VT-4)	Parylene F (AF-4)
High levels of submersion protection – IPX8+, depending also on device design.	✓	✓	✓	✓
Uniform, pinhole free coating.	✓	✓	✓	✓
Excellent conformality, can completely penetrate spaces as narrow as 0.01mm.	✓	✓	✓	✓
High barrier protection against corrosive chemicals and gases while providing low permeability to moisture. Best barrier when compared to the other Parylene types.	✓	✓	✓	✓
Optically transparent and can be used to coat optical elements.	✓	✓	✓	✓
Biostable, biocompatible, environmentally friendly – no VOCs, no solvents.	✓	✓	✓	✓
No initiators or catalysts in polymerization process, coating is pure and free from trace ionic impurities.	✓	✓	✓	✓
REACH, RoHS, PFOA/PFOS-free and CA Prop 65 compliant.	✓	✓	✓	✓
Room temperature formation makes the coatings effectively stress-free.	✓	✓	✓	✓
Low dielectric constant with good high frequency properties, good dielectric strength and high bulk and surface resistance.	✓	✓	✓	✓
High tensile strength.	✓	✓	✓	✓
No cure time.	✓	✓	✓	✓
Vibration resistant.	✓	✓	✓	✓
No pooling of coating in low areas.	✓	✓	✓	✓
Halogen free.		✓		
Free from bromine and chlorine halogens; contains fluorine.			✓	✓
Higher resistance to heat than Parylene C and N.			✓	✓
Highest temperature and UV resistant Parylene.				✓

Nanocoatings

Nanocoatings are functionalized films that protect from humidity, salt spray, liquid immersion, corrosive gases, and temperature fluctuations at nanometer thicknesses. In units of measurement, the prefix “nano” represents a one-billionth part of a physical unit (1 nm = 10^{-9} m, for example). For reference, a sheet of paper is approximately 100,000 nanometers thick.

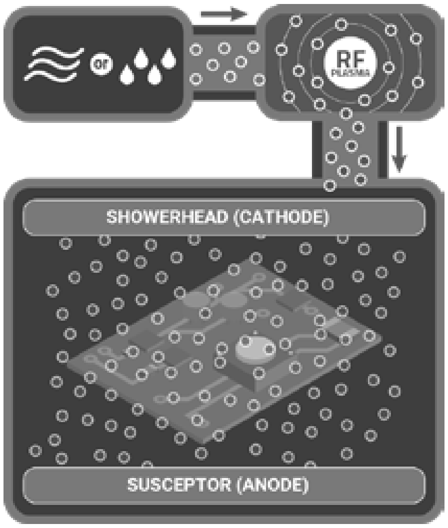
Plasma-Enhanced Nanocoatings

Plasma-enhanced nanocoatings are a type of nanocoating used for device protection. When polymeric materials are formed under the influence of plasma conditions, the coatings are referred to as plasma-polymerized, and the coating application process is known as plasma-enhanced chemical vapor deposition (PE-CVD). Like CVD, plasma-applied coatings are typically deposited in a vacuum chamber. However, with the PE-CVD process, precursors are activated through high energy electrons in the plasma—the plasma polymers deposit a uniform layer across the exposed surface. The PE-CVD process can be used for the deposition of a range of materials, including hydrocarbons, fluoropolymers, silicones, and even oxides and metallics, producing single or multilayer films that can be functionalized on the surface for desirable properties such as hydrophobicity and oleophobicity. It is possible to optimize the PE-CVD process for high throughput, using in-chamber shadow masks in place of traditional masking and demasking steps.

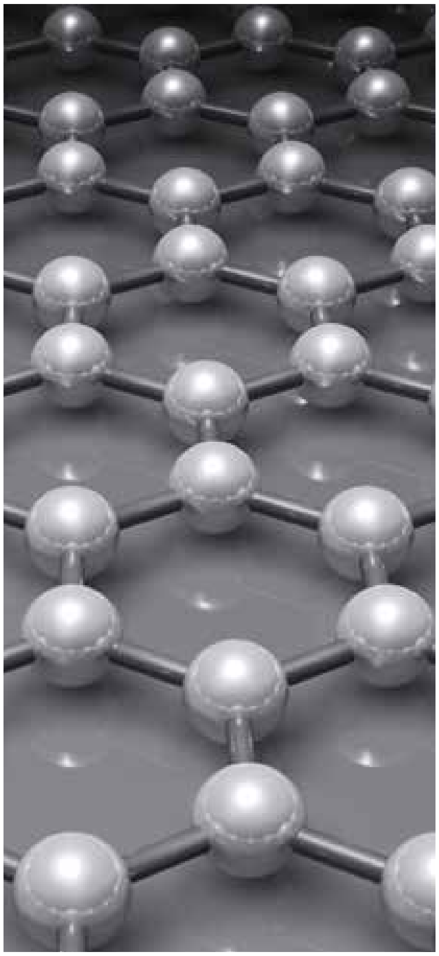
Like CVD, plasma-applied coatings are typically deposited in a vacuum chamber. However, with the PE-CVD process, precursors are activated through high energy electrons in the plasma—the plasma polymers deposit a uniform layer across the exposed surface.

PE-CVD Process

With the PE-CVD process, precursors are activated through high energy electrons in the plasma—the plasma polymers deposit a uniform layer across the exposed surface.



Plasma-enhanced nanocoatings form good bonds with components, PCBAs, and other substrates, eliminating defects such as coating delamination. Property-wise, nanocoatings are typically water-



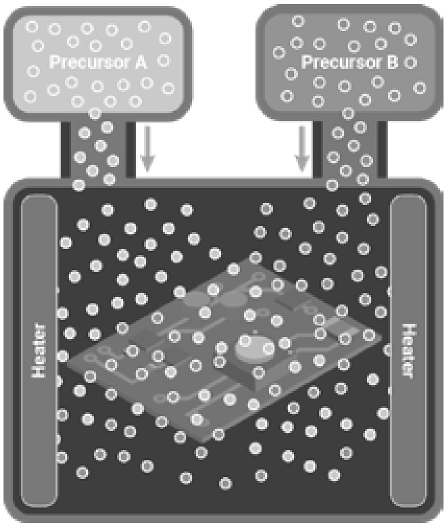
repellent and corrosion-resistant, depositing in a transparent layer. The coatings are acid and liquid-resistant to many agents, with a low water vapor transmission rate (WVTR), and are reworkable.

Atomic Layer Deposition (ALD)

Atomic layer deposition (ALD) is a thin-film deposition method that the majority of the time utilize two chemicals called precursors or reactants in a gas phase process that react with a substrate in a self-limiting, sequential manner, with each chemical interacting with the substrate one step at a time. This technique can deposit very thin conformal films with precise control over the composition and thickness of the films from the atomic level to uniform, conformal coatings over complex substrates. The ALD process is typically performed at higher temperatures on semiconductor and related substrates, but processes and tools have been developed that work at lower temperatures for more temperature-sensitive products, such as PCBAs. ALD can be used to deposit a wide range of materials, including metals, metal nitrides, metal oxides, and hybrid metal-organic structures that offer a wide range of desirable properties, such as moisture and oxygen barriers, as well as oxidative resistance for end use environments that include high temperatures and/or direct UV exposure.

ALD Process

Atomic layer deposition (ALD) is a thin-film deposition method that the majority of the time utilize two chemicals called precursors or reactants in a gas phase process that react with a substrate in a self-limiting, sequential manner, with each chemical interacting with the substrate one step at a time.



ALD can be used to deposit a wide range of materials, including metals, metal nitrides, metal oxides, and hybrid metal-organic structures that offer a wide range of desirable properties.

ALD films feature some of the lowest water vapor transmission rates (WVTR), which are orders of magnitude lower than the organic polymer films of acrylates, epoxies, silicones, and urethanes, and even Parylenes. Most ALD thin metal oxide films are transparent in the ultraviolet (UV), visible, and near-infrared (NIR) and resistant to prolonged outside exposure in oxidative and corrosive environments with high relative humidity and salt fog/spray protection. Many ALD coatings also have high mechanical and dielectric strength and good abrasion resistance. However, some constraints must be considered with the ALD method, namely lower coefficients of thermal expansion (CTE) can lead to cracking over significant thermal cycling and would likely recommended to be combined with a supplemental polymer coating to minimize the effects of CTE mismatches, as well as potentially higher coating material costs for the special chemical precursors that are required.

CVD vs. PE-CVD vs. ALD

The prior sections reference the various processes employed to deposit thin-film alternatives—specifically, CVD, PE-CVD, and ALD. The following provides a quick summary of the associated advantages and disadvantages.

Application Process Comparison

Process	CVD	PE-CVD	ALD
IPC Class	**XY (Xylylene)**	**UT (Ultra Thin)**	**UT (Ultra Thin)**
General Materials	***Parylene-Type Polymers***	***Plasma-Deposited Polymers***	***Ceramic Thin Films***
Advantages	• Delivers coatings that are completely conformal. • Process substrates in large batches. • Coating application is complete at the end of deposition. No curing required.	• Shorter deposition times than CVD. • Minimal to no masking and demasking required. • Coating application is complete at the end of deposition. No curing required.	• Delivers coatings that are completely conformal. • No masking required. • Coating application is complete at the end of deposition. No curing required.
Disadvantages	• Masking and demasking may be required. • Longer deposition times than PE-CVD and traditional conformal coating deposition processes. • Process is not inline with device manufacturing line.	• Conformality varies based on PE-CVD process. • Nanocoatings have material optimization challenges. • Process is not inline with device manufacturing line.	• Substrates are processed in smaller batches. • May need combination with a polymer layer to mitigate any coefficient of thermal expansion (CTE) challenges for certain applications. • Process is not inline with device manufacturing line.

Conclusion

Exploring options for device protection can be exhaustive, but it is an essential step towards achieving product reliability and resiliency. Material selection and their associated processes play a pivotal part in the nature of protection afforded and the associated benefits each alternative provides. With the proliferation of devices, miniaturization of electronics, tighter tolerances, and weight and bulk considerations, thin-film solutions are quickly displacing legacy approaches to protection. In the end, the benefits are clear, namely:

- **Minimize costs** associated with unnecessary repairs, warranty claims, service calls, and unplanned downtime.
- **Mitigate risk** associated with mission-critical device failure, preventing safety-related events, and avoiding unnecessary liabilities.
- **Drive revenue** by increasing product value through better reliability and durability.

Material selection and their associated processes play a pivotal part in the nature of protection afforded and the associated benefits each alternative provides.

About HZO

HZO is a global leader in delivering world-class thin-film conformal coatings and protective nanocoatings that safeguard electronics from the most demanding corrosive and liquid environments. The company brings together people, processes, capital equipment, and material science, leveraging an extensive patent portfolio to create unique solutions to meet specific customer requirements. HZO works with some of the largest companies across industries, including consumer electronics, IoT, industrial, medical device, and automotive, delivering a more reliable water-resistant and waterproof product that reduces costly returns, improves customer satisfaction, and drives overall brand value.

Questions? HZO.COM/CONTACT-US or 1-877-757-4HZO (4496)

HZO
PROTECTION FROM THE INSIDE OUT®