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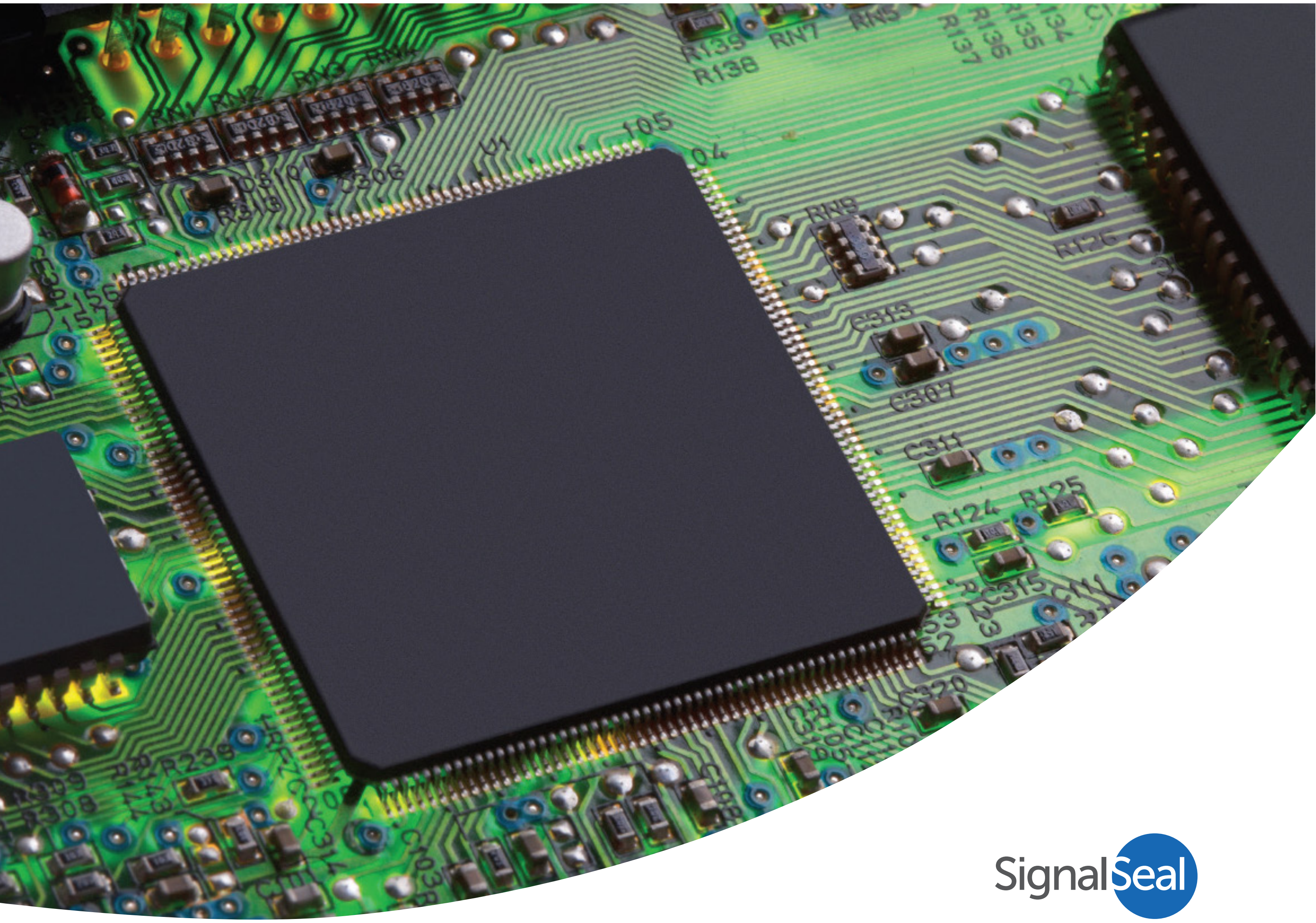

SignalSeal

Conformal Coating Evolves for RF Circuits

TECHNICAL BRIEF

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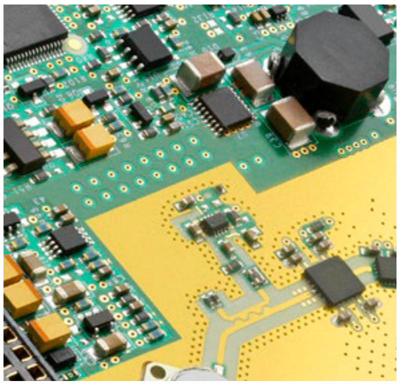
Complex and multi-domain systems-on-chip (SoC), systems-in-package (SiP), and printed circuit boards (PCBs) are now the norm for many consumer and automotive applications. The benefits of these compact and feature-rich systems are increasingly attractive for extreme applications, such as military, aerospace, naval, and industrial. Most militaries have been making modernization efforts in order to keep ahead of growing competition abroad from peer and near-peer threats. A key enabler of reliable and capable electronic systems in these applications is environmental protection. However, there are very few choices for protecting electronics that allow for minimal impact on RF (Radio Frequency) and high-speed digital performance, common and efficient mass assembly processes, and military-grade ruggedness. Though there are polymer conformal coating materials that fulfill some of these requirements, legacy materials usually fall short on some of the electrical, mechanical, or process criteria. Now, however, there is a new polymer conformal coating material and process, SignalSeal, that exhibits desirable properties meeting and exceeding the most rigorous electronic protection standards.

INTRODUCTION



There has been a burgeoning interest in the development of microwave and millimeter-wave wireless communication and sensing technology for a wide range of medical, military, aerospace, naval, and industrial applications. Part of the impetus for this trend is the greater accessibility of microwave and millimeter-wave hardware, enabled by the advancements toward more compact and integrated RF and high-speed digital circuitry. The results of the progress in this area have been multi-functional, programmable, or otherwise more capable integrated circuits (ICs) and printed circuit boards (PCBs) with complex multi-domain (power, analog, RF, and digital) circuits with increasingly compact layouts. Though attractive from a size, weight, power, and cost (SWaP-C) perspective, the complexity, density, and sensitivity of these modern sensing and communication systems yields a variety of challenges when deploying these circuits in extreme environments or for critical applications. One method of protecting these ICs/PCBs is the use of an insulating passivation layer or conformal coating applied near the last stages of production. Passivation and conformal coating can provide enhanced environmental and mechanical protection, but often comes with sacrificing high frequency performance. Furthermore, many coating technologies aren't suited to the rigors of the most extreme applications, manufacturing processes, or rework/repair.

This technical brief aims to educate readers on the challenges associated with selecting passivation and conformal coating materials for microwave and millimeter-wave applications. Moreover, this brief will illuminate how passivation and conformal coating materials technology has evolved over the past several years to culminate in a new polymer conformal coating material, SignalSeal by Paratronix, which solves many of the RF, mechanical, environmental, and process challenges associated with protecting ICs and PCBs deployed in extreme applications.

Legacy Circuit Board - Environmental Protection and Passivation RF Challenges

ICs and PCBs have been treated with a variety of coatings for decades and for virtually every electronics application. It is a common practice to environmentally protect ICs and PCBs during processing and once they are installed in a housing or assembly. Hence, the majority of passivation and conformal coating materials are designed for legacy applications, and are not necessarily suited to modern high frequency circuits or high-speed digital circuits where the surface traces carry signals well into the microwave and millimeter-wave frequencies.

Microstrip and coplanar waveguide surface traces (or other surface structures with field lines that extend beyond the surface of the substrate and conductors, such as microstrip filters) are generally designed with the expectation that the dielectric on the outer surface of the waveguide is air, which has a relative permittivity of ~1 and very low loss tangent. However, when conformal coatings are placed on the surface of a microstip and coplanar waveguide, the impact of the coating on high frequency performance depends on many factors.

One of these factors is the thickness of the coating material and its respective dielectric constant and loss tangent. The thickness of a conformal coating is directly related to the high frequency performance of these structures, and that thinner conformal coatings may minimize the high frequency impact of environmental protection coatings—something that is difficult to achieve with legacy solutions without compromising environmental protection.

Other drawbacks of traditional insulating coatings are generally associated with their electrical performance, as their dielectric properties don't tend to scale well with frequency. The main factors to consider for dielectric materials used in high frequency applications is dielectric constant and dissipation factor, though dielectric strength, resistivity, and thermal properties are also critical in many applications.

Dielectric Constant

The dielectric constant, or relative permittivity, is a frequency dependent measure of how well a material behaves as a dielectric compared to vacuum [1]. A low dielectric constant is desirable for most electronics insulating materials and substrates, as a low relative permittivity means that a material allows for lower parasitic capacitances developed between conductive traces and features. For instance, some materials used as PCB environmental protection, such as epoxy or silicone, exhibit a relative permittivity over 4 *(See Table 1)*, which is over 50% greater than leading materials. This means that the parasitic capacitances developed across the poorer performing dielectrics would be larger than if a material with 50% lower dielectric constant were used.

Table 1: Electric Properties of Conformal Coating/Passivation Materials

Property	Dielectric Strength V/mil	Volume Resistivity ohm•cm, 23°C, 50% RH	Dielectric Constant 60 Hz, 1 KHz, 1 MHz	Dissipation Factor 60 Hz, 1 KHz, 1 MHz
Method	ASTM D149	ASTM D257	ASTM D150	ASTM D150
SignalSeal	7,200	4.0×10^{15}	NA, NA, 2.62*	NA, NA, 0.001*
Parylene N [3]	7,000	1.4×10^{17}	2.65, 2.65, 2.65	0.0002, 0.0002, 0.0006
Parylene C [3]	5,600	8.8×10^{16}	3.15, 3.10, 2.95	0.020, 0.019, 0.013
Acrylic [1,2]	3,500	1.0×10^{15}	NA, NA, 2.7-3.2	0.04-0.06, NA, 0.02-0.03
Epoxy [1,2]	2,200	1.0×10^{16}	3.3-4.6, NA, 3.1-4.2	0.008-0.011, NA, 0.004-0.006
Polyurethane [1,2]	3,500	1.0×10^{13}	4.1, NA, 3.8-4.4	0.038-0.039, NA, 0.068-0.074
Silicone [1,2]	2,000	1.0×10^{15}	3.1-4.2, NA, 3.1-4.0	0.011-0.02, NA, 0.003-0.006

**Preliminary testing performed with a MDC Mercury Probe at 1MHz with device limitations on measuring lower values of dissipation factor*

This is especially important for high frequency applications, as the impact of parasitic capacitances scale with frequencies, essentially acting as filters or otherwise degrading the transmission line characteristics of coplanar waveguide and microstrip transmission lines. As planar transmission lines and structures on ICs and PCBs already leave little performance budget for factors such as impedance, phase, and insertion loss, adding passivation layers or conformal coating that further degrades the RF performance is far from ideal.

Dissipation Factor

The other case to consider is the dissipation factor, or loss tangent. The dissipation factor is also frequency dependent, and is a measure of the loss of electrical potential energy dissipated in a dielectric. Specifically, the dissipation factor is the ratio of equivalent series resistance (ESR) and the capacitive reactance of the dielectric at a given frequency. It is desirable to have as low a dissipation factor as possible for high frequency circuits in order to yield the best electrical characteristics for coated circuits.

In the case of planar transmission lines and surface features of a PCB, a material with a high dissipation factor would directly result in loss of energy within the dielectric, which is usually converted to heat. In the case of high frequency and high power applications, a material with a high dissipation factor could lead to undesirable increases in insertion loss and localized heating in areas that typically aren't a focus of thermal management design. Though any additional insertion loss is undesirable, heating in an insulating material could also cause deteriorating effects, especially if the circuit is already in a high heat environment, including delaminating, material degradation, and otherwise derating of the electrical performance or environmental protection of the material.

For instance, some materials have dissipation factors on the order of 10^{-2}, such as acrylic and polyurethane, and are not suited to high frequency or high power applications as they lead to a high degree of loss compared to materials with a dissipation factor orders of magnitude lower. As the dissipation factor is also a function of frequency, it is important to keep in mind that some materials may have a dissipation factor that is very different at higher frequencies than at lower frequencies, and the relationship may not be predictable without full frequency testing.

Thermal Properties

The thermal performance of coatings for RF circuits cannot be ignored for most applications. In some cases where the temperature is tightly controlled, there is little humidity, negligible debris, and good thermal management is available, such in some laboratory or clean room conditions, then the thermal performance of a coating may not be as critical. However, using coatings with poor thermal properties may add to costs and complications during rework, and limit the applications for which the IC/PCB may be used.

Some of the main thermal performance considerations for coatings are if the electrical or environmental performance of the coating changes with temperature. Nevertheless, some insulating materials also exhibit substantial changes in chemical and mechanical properties at temperatures well below their melting point. For instance, some passivation/conformal coating materials may delaminate, change phase, permanently change dimensionally, discolor, oxidize, or otherwise degrade at temperatures between 100°C and 200°C, which are common in IC processing and PCB rework conditions, not to mention military and aerospace operating conditions.

Though the coefficient of thermal expansion (CTE) mismatch between a coating and PCB board or die will likely not lead to substantial mechanical strain for the die or PCB, it could lead to a loss of adhesion between the coating and board/die. With a high enough CTE, a coating material may delaminate or otherwise deform and lose conformality. The results of this may have a substantial impact on the electrical performance of high frequency surface traces as even minor non-conformity leads to impedance changes in high frequency transmission lines.

Other thermal performance considerations include how thermally conductive an insulator may be. In certain applications, a coating or passivation layer may need to be applied before a heatsink is installed and the heat sink area may not be masked off. In these cases, a material with a lower bulk thermal conductivity and greater thickness will add to the thermal resistance of the stack and need to be accounted for during the thermal management design. Also, materials with lower bulk thermal conductivity and greater thickness also reach higher temperatures if layered over or near RF devices or structures carrying high frequency or power signals.

Environmental Protection

The primary goal of a passivation layer or conformal coating is to protect the underlying circuitry from environmental factors and mechanical damage without impacting the performance of the circuits beyond an acceptable threshold. Therefore, a coating's environmental performance dictates its applicability. In the case of military, aerospace, and naval applications, this means that a coating is required to protect an IC/PCB under extreme conditions, typically between -55°C to +125°C operating conditions while being exposed to harsh chemical environments and wear.

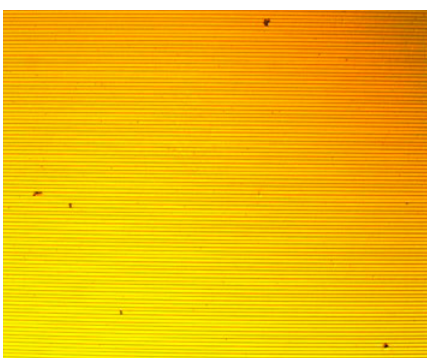
These factors commonly include salt fog and high humidity testing. Common standards for environmental ruggedness include IPC-CC-830, MIL-I-46058C, JESD22-A101C, and MIL-STD-883 Method 1009.8. Most notable among them are temperature humidity bias tests. Under accelerated testing, the amount of time a coating maintains protection and performance can be an indicating factor that that coating may perform well under regular stress conditions for a much longer time, typically a factor of hundreds to thousands. For example, a 1000 hours of continuous 85°C at 85% relative humidity (RH) exposure can predict up to 25 years of operation. [6]

It is extremely important for high frequency applications that the behavior of a coating remains consistent over the lifetime of the circuit, or a derated coating may lead to early failure or derating of the circuit. For critical applications, microwave and millimeter-wave communication and sensing circuits are typically built of high power transmitters and extremely sensitive receivers. This means that any loss in transmitter, receiver, interconnect, or antenna performance directly contributes to a loss of range, resolution, throughput, or reliability.

Polymer Conformal Coatings at RF Frequencies

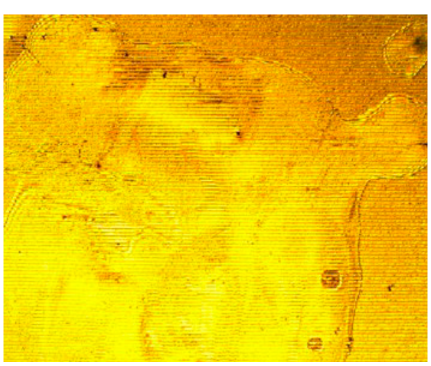
In order to provide environmental protection for RF ICs/PCBs using materials with better electrical performance, researchers have been investigating polymer conformal coatings for both PCB and IC applications [4,5,7,8,9]. Of the most promising have been polymerized variants of para-xylylene, known as parylene. By replacing hydrogen atoms on the phenyl ring or aliphatic bridge with other function groups, variants of parylene can be made using chemical vapor deposition (CVD) as a polymerization process. Parylene materials have been used in industry since 1965, when a viable commercial process was developed that yielded chemically resistant films that were also free from pinholes.

Initial use cases included using parylene as a conformal coating for medical applications, and in more recent years, there has been interest in using parylene variants for high frequency electronics conformal coating and IC passivation. In some applications, parylene variants outperform many legacy coating technologies, such as acrylic, epoxy, polyurethane, and silicone from an electrical perspective *(See Table 1)*. Two commercially available parylene variants, Parylene N and C, both exhibit dielectric strength, volume resistivity, dielectric constant, and dissipation factor performance that lead these parylenes to be viable for some high frequency applications. Moreover, being deposited using CVD methods, means that a parylene polymer coating can be applied much more conformally, thinner, with greater penetration of fine geometries, can be done at room temperature.



Above: *A sample of SignalSeal at 2.3 micron thickness after1000 hours of 85%RH/85°C testing.*

Below: *a sample of Parylene C at a thickness of 5 microns after 1000 hours of 85%RH/85°C testing*



However, both Parylene N and C exhibit behavior that is undesirable in a conformal coating used for high frequency circuits in extreme applications. There are also other commercially available parylene variants, but these variants are not as widely available and have not undergone as much study as to their use in microwave or millimeter-wave applications.

Firstly, Parylene C demonstrates both dielectric constant and dissipation factor behavior that is far higher than is typically desired for upper microwave and millimeter-wave applications. Hence, Parylene N is generally the more researched material for millimeter-wave and terahertz applications.

As with all parylenes, achieving the necessary levels of environmental protection to conform to common standards requires thicknesses of parylene typically beyond what is used in many of the studies (tens of micrometers). Typical application thickness of Parylene N for environmental protection is established in standards (IPC J-STD-001, IPC-A-610, MIL-I-46058, NASA-STD 8739.1) to be at least 10 micrometers for adequate environmental protection, though some of the standards present a minimum requirement of 13 micrometers. These minimum thickness, though substantially thinner than acrylic, urethane, epoxy, or silicone, leave no room to reduce the coating thickness to better meet RF or signal integrity requirements.

Moreover, parylenes tend to suffer rapid aging in oxygenated atmosphere at temperatures beyond room temperature, but well below maximum temperature ranges for electronics used in military and aerospace applications. For instance, Arrhenius extrapolations of test data indicate that Parylene N and C could survive continuous exposure to air for 10 years at 60°C and 80°C, respectively [3]. Beyond those temperatures, Parylene N and C experience dramatically shortened lifespans. This can be demonstrated by common 85/85 testing, as the sample of Parylene C coating an array of 5 micron spaced interdigital electrodes extensively delaminated from the surface of the PCB after 1000 hours of 85/85 testing. Other sources have also tested Parylene C at 120°C/100% RH, for which the material failed after 2 hours of testing. Given that Parylene N exhibits lower environmental resilience than Parylene C, the results for Parylene N would likely be shorter.

New Polymer Conformal Coating Operates to Millimeter-wave Frequencies

Though Parylene N appears promising for some microwave and millimeter-wave applications, it is not suited to harsh environments. This factor mitigates the use of Parylene N in many military, aerospace, and naval applications, for which there is a growing need for environmentally protected circuit boards with advanced electronics. Fortunately, a new polymer conformal coating process and material has been developed, and is showing signs of significant advantages over parylene for high frequency applications in extreme environments.

SignalSeal is a proprietary polymer originally developed as an electrically-insulating, biostable coating for microelectrode neuroprosthetic devices [11]. It has since been indicated that SignalSeal is a very promising conformal coating technology that may address many of the challenges of protecting electronics without some of the key drawbacks of legacy conformal coating technologies.

SignalSeal Environmental Properties

Like parylene, SignaSeal is deposited using CVD in a room temperature, dry environment, which allows for uniform and conformal coverage of complex geometries. To achieve excellent environmental protection, SignalSeal only needs to be applied at 1 micron thickness, and has demonstrated to withstand 85/85 testing for 1000 hours, without any apparent damage, delamination, or degradation *(See Table 2)*. The coating can even be left on high power devices that are typically connected to heatsinks, preventing corrosion of heatsink materials and environmental ingress to the device.

Table 2: SignalSeal Environmental Testing

Salt Fog
48 hr I MIL-STD-810G **PASS**
500 hr I ASTM B117 **PASS**

Temperature Cycling
-75°C to + 125°C, 50x I MIL-I-46058C **PASS**
-70°C to + 225°C, 10x I MIL-STD-810G **PASS**

Humidity
85C/85%RH (unbiased) I JESD22-A101C **PASS**
-70°C to + 225°C, 10x I MIL-STD-810G **PASS**

SignalSeal also provides excellent protection in extremely corrosive environments; for example, a coated printed circuit board exposed to 500 hours of Salt Fog (ASTM B117) showed no signs of corrosion or loss in functionality at the end of the test. Even after extensive environmental exposure, SignalSeal still demonstrated excellent protection of the underlying PCB substrate with an adequately low thermal resistance and ultra-thin layering. Moreover, SignalSeal is stable to 225°C and can be treated to be stable to 250°C, and has been tested to withstand contact with high temperature devices reaching 250°C during operation.

To further demonstrate that SignalSeal can survive even the most hostile environments, temperature shock testing as extreme as -70°C to + 225°C has been performed (MIL-STD-810G). The coating remained well adhered after undergoing extreme temperature swings (5B, tested according to ASTM D3359 Method B), and showed no evidence of bubbling, cracking, peeling, discoloration, or corrosion.

SignalSeal RF Performance

SignalSeal performs well as a conformal coating for PCB environmental protection, and early testing shows signs that SignalSeal is also an excellent conformal coating technology for high frequency and high speed applications. Early data has shown that SignalSeal has a dielectric constant around 2.62 (at 1 MHz), which is comparable to Parylene N, and a dissipation factor less than 0.001 (at 1 MHz, but likely limited by the testing apparatus). Furthermore during several demonstrations, SignalSeal has shown minimal RF impact at least to 100 GHz. For instance, in a side-by-side comparison of an uncoated microstrip and a microstrip coated with 2.5 microns of SignalSeal (over twice what is needed), the insertion loss difference between the two parts was minimal. Even in full S-parameter tests of a MMIC amplifier board coated with SignalSeal that had undergone 8 days of 85/85 testing show negligible RF performance impact to 20 GHz.

In a study of the high frequency impact of SignalSeal, Rogers Corp. was contracted to perform a battery of tests on 50 ohm microstrip transmission lines on 0.0047" thick Rogers RO4350B ™. Broadband testing to 50 GHz was performed on several samples of coated and uncoated samples and the insertion loss over length was analyzed and plotted. The graph shows a direct comparison of a SignalSeal coated and uncoated microstrip sample, which demonstrates negligible insertion loss impact across the full bandwidth of the test. Results are predicted to inherently improve when a minimal coating thickness of 1 micron is applied.

SignalSeal RF Performance

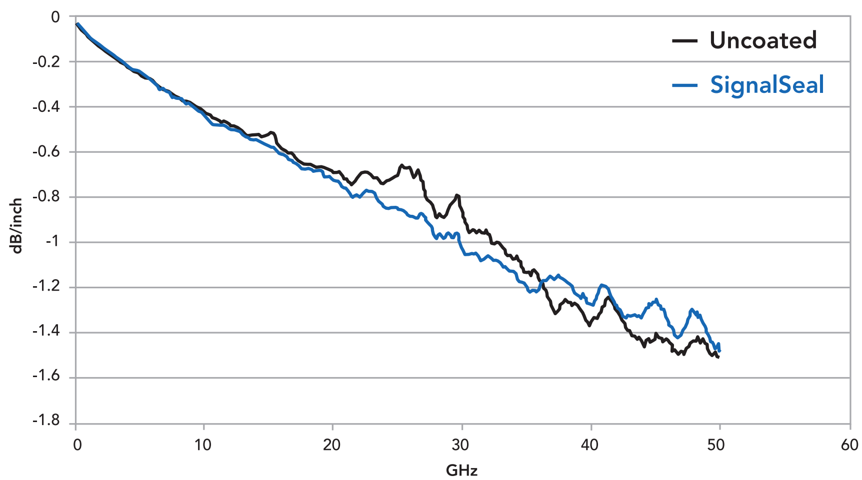


Table 3: SignalSeal Comparison to Legacy Solutions

Coating Type	Dielectric Constant (@ 1MHz)	Dissipation Factor (@ 1MHz)	Typical Thickness (micrometers)	Continuous Use Temperature (°C)	RF and High Speed Digital Performance	Environmental Protection	Reworkability
SignalSeal	2.62	<0.001	1	225	★★★★	★★★★	★★★★
Parylene N	2.65 [3]	0.0006 [3]	12.5-51*	60 [3]	★★★★	★★	★★
Parylene C	2.95 [3]	0.013 [3]	12.5-51*	80 [3]	★★	★★★★	★★
Acrylic	2.7-3.2 [1],[2]	0.02-0.03 [1],[2]	25-127*	82 [1]	★	★★	★★
Epoxy	3.1-4.2 [1],[2]	0.004-0.006	25-127*	177 [1]	★	★★★★	★
Polyurethane	3.8-4.4 [1],[2]	0.068-0.074 [1],[2]	25-127*	121 [1]	★	★★	★★
Silicone	3.1-4.0 [1],[2]	0.003-0.006 [1],[2]	51-203*	260 [1]	★	★★★	★★★

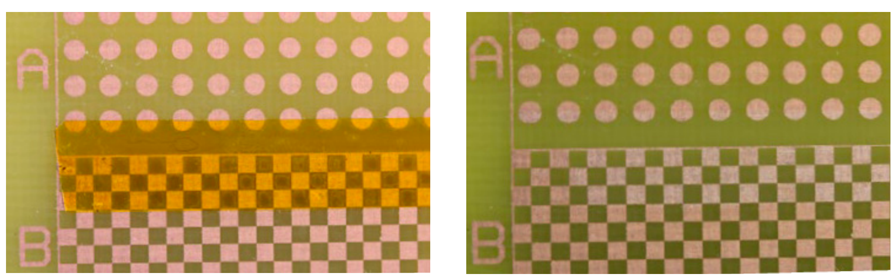
**According to MIL-I-46058, IPC-CC-830, and NASA-STD 8739.1 standards*

SignalSeal Physical & Chemical Properties

Adhesion & Water Absorption. SignalSeal is a well-adhered polymer that provides molecular-level coverage of the surface without the use of adhesion promoters. Due to this feature, there is no room for water absorption or condensation on the surface of the substrate, and SignalSeal is stable in the presence of water molecules. High polymer adhesion inhibits the formation of conductive aqueous films that would otherwise lead to device failure as a product of electrochemical corrosion.

Reworkability. SignalSeal is also easy to mask and rework. Because the coating is more adhesive to the substrate than it is cohesive with itself, demasking does not result in any peelback or delamination, or require scoring. Additionally, when rework of the PCB is needed, the toughness and cohesiveness of parylene can make it difficult to perform any localized repairs, or remove individual components. Parylene coating will often need to be stripped via aggressive mechanical methods (including scraping and micro blasting) that pose a risk of damage to the part, resulting in additional expenses and longer processing times. With SignalSeal, rework is simple: components can be easily replaced by standard methods without having to remove the coating first, and a new application of SignalSeal is all that is required to completely protect the circuit board.

Even under mechanical stress, SignalSeal's strong mechanical adherence (achieved without adding an adhesion promoter, unlike Parylene) prevents delamination even under high strain and instead only exhibits minor deformation. In a test comparing Parylene C and SignalSeal, a 3 mN to 500 mN progressive load was applied via a scribe dragged over hundreds of micrometers. The Parylene C coating initially delaminated at 27 mN and exhibited continuous delamination after only a few more mille-newtons of pressure. SignalSeal on the other hand continued to protect the substrate even after 500 mN of pressure and did not delaminate.



SignalSeal is effective with an ultra-thin application (<2 μm) and provides greater adherence, resulting in clean demasking.

Scalability & Compliance

Just like legacy conformal coating solutions, SignalSeal complies with the strict industry standards required for defense and aerospace applications. In addition to meeting the requirements of the legacy MIL-I-46058 standard, the recent inclusion of Ultra-Thin coatings in the Revision C of IPC-CC-830 (Qualification and Performance of Electrical Insulating Compound for Printed Wiring Assemblies) has allowed SignalSeal to be qualified to the updated standard. The coating passed the full panel of IPC-CC-830C testing, including dielectric withstanding voltage, moisture resistance, and thermal shock requirements *(see Table 4)*.

SignalSeal ultra-thin coating technology system has been successfully commercialized and scaled for the deposition of new RF-compatible conformal coatings to help meet the fast-paced, and high volume demands of the industry. To achieve the necessary thickness and complete coverage, the proprietary process requires less than 5 hours of deposition, which enables low chamber maintenance costs and fast turnaround times.

Table 4: MIL and IPC Conformal Coating Specifications for SignalSeal

Test	Method	Passed
Dielectric Withstanding Voltage	MIL-I-46058C, Am. 7, 4.8.7 IPC-CC-830C	✓
Moisture Resistance	MIL-I-46058C, Am. 7, 4.8.10 IPC-CC-830C	✓
Thermal Shock	MIL-I-46058C, Am. 7, 4.8.9 IPC-CC-830C	✓
Insulation Resistance	MIL-I-46058C, Am. 7, 4.8.6	✓
Flexibility	MIL-I-46058C, Am. 7, 4.8.11	✓
Flammability	UL94-HB	✓
Temperature Humidity Aging/Hydrolytic Stability	IPC-TM-650, method 2.6.11.1	✓
Fungus Resistance	IPC-CC-830C	✓
Salt-Fog Test	MIL-STD-810G	✓

CONCLUSION

Given the enhanced mechanical and environmental performance of SignalSeal over parylenes, SignalSeal is a prominent new candidate for high-reliability applications with high frequency or high speed digital boards in need of environmental protection.

NEXT STEPS

SignalSeal can help you protect your high-frequency electronics

Contact us to find out how:

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RESOURCES

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