Reliability Without Hermeticity: Commercial Vapor Deposited Coatings for High-Frequency RF Micro-Electronics

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Abstract: *New ultra-thin coatings have been developed to protect RF electronics from environmental hazards and provide lifetime reliability without expensive hermetic packaging. These technologies save cost, space, and weight while enabling RF electronic designs not compatible with traditional protective approaches.*

Keywords: Environmental Protection; RF Electronics; Electronics Packaging

Introduction

Radio frequency (RF) micro-electronics are used everywhere in today's technology, from the internet of things to military radar systems. Many of these systems, such as military active electronically scanned array (AESA) radar, read and analyze a high volume of RF signals and data using sophisticated analog-to-digital conversation and high-power processors. However, it is challenging for these advanced RF systems to meet size, weight, power and cost requirements (SWaP-C) set by consumer market or defense agency demand. This challenge is due to the need for packaging of the RF components and the associated integrated circuits (ICs) to ensure long term reliability against environmental exposure. Traditionally, this involves hermetically sealing the device in a bulky, heavy expensive metal enclosure to prevent degradation caused by hazards in device operating environments. Standard conformal coatings are unusable due to the significant signal degradation which occurs if applied directly over an RF circuit. There is a critical need for a coating alternative which is compatible with high-frequency RF devices to provide a lower weight and lower volume environmental protection scheme with high reliability and negligible performance impact for RF devices. This approach would allow RF device integration on SWaP-C effective PCBs and eliminate the hermetically packaged chip-and-wire assemblies currently in use.

To address this need, new coatings have been developed that can be applied to both the bare device and completed RF assemblies. These coatings are applied through a dry, room-temperature vapor deposition process that gently encapsulates RF boards and/or components in a thin (<1 micron) film. These coatings have demonstrated negligible impact on RF signal integrity when applied directly to the surface of Monolithic Microwave Integrated Circuits (MMICs) operating in Ku, Ka, and W bands, as validated by independent testing. Another important factor to consider is the coatings' thermal stability, in order for these technologies to be compatible with hot-running semiconductor technologies such as gallium nitride (GaN) components.

Hermetic Packaging for Environmental Protection

For RF and microwave multichip modules and hybrid circuits, the most common method of hermetic packaging uses metallic enclosures with feedthroughs sealed by glass or ceramic. These metal packages are usually custom-made for the particular RF/microwave assembly under construction. The package is then plated with Cu, Ag, or Au and baked to drive out any trapped gas or moisture before final sealing. The package is purged with an inert gas and its lid is sealed via either soldering or laser-welding.

The advantages of hermetic packaging are: 1) It is an established technology with a well-known process flow, 2) If the package is properly manufactured and constructed then it will provide excellent protection against high heat/humidity environments.

However, these packages also incur significant penalties due to increased system weight, larger system volume, and greater cost. In addition, there is the potential of hydrogen poisoning occurring during the life of the package. Many of the alloys and plating used in hermetic packages contain hydrogen in the manufacturing process [1], which outgasses during the enclosure's use life. In the sealed interior of a hermetic package the partial pressure of hydrogen can evolve to be as high as a few percent [2]. It takes as little as 0.5% partial pressure of hydrogen to initiate significant degradation of certain GaAs and InP devices after only a few hundreds of hours of exposure.

Minimizing volume and weight of next generation RF and microwave devices is a driving factor in technology innovation. Effective packaging is a large component in meeting these challenges, which have met a roadblock with conventional hermetic solutions.

Conformal Coatings as an Alternative to Hermetic Packaging

An alternative to conventional hermetic packaging is the use of a polymeric conformal top-coat; such coatings are standard for conventional electronics. However, these coatings encounter significant challenges when trying to use them for protecting RF electronics.

The most common electronics conformal coatings include wet-applied materials such as acrylics, urethanes, epoxies, and silicones. For standard vapor-deposited materials, the most common commercial choice is paraxylyene (AKA parylene). The 'standard' coating thicknesses for wet-applied coatings are typically 25-75 microns for acrylics, urethanes, and epoxies. For silicones, the standard thickness range is 50-200 microns and for parylene it is 12-50 microns.

Conformal coating properties (dielectric constant and thickness) become ever more important as the operating frequency of the underlying RF device increases. For instance, a RF device operating at C band can accommodate a parylene coating with a low impact on signal performance; however, a Ka band device operating at 40 GHz coated with parylene would see such a large performance shift to render the device unusable. This performance impact due to conventional conformal coatings is typically seen starting at X-band (8-12 GHz).

In one paper, Sealguard (silicone gel) and an epoxy were used to encapsulate 'flip-chip' monolithic microwave integrated circuits (MMIC) and the RF impact on performance was tested up to 15 GHz [3]. In this relatively low frequency range, the coatings showed minimal impact. However it should be noted that the active RF portion of the MMIC was not in direct contact with the coating material. In the case of the Sealguard material, the authors had to adopt a quick-cure process in order to prevent the Sealguard material from flowing under the edges of the flip-chip and impacting the MMIC's performance.

For higher frequency RF components, testing of parylene-C coatings on various microwave circuits [4] showed an increasing impact on RF performance above 60 GHz. It should be noted that these coatings were thinner ($\leq$10 microns) than standard.

At higher RF frequencies, hermetic packaging is still seen as the only high-reliability option for environmental protection. In order for conformal coatings to be used in such frequency ranges, they will need to be both thin (on the order of 1 micron or less) and have a lower dielectric constant and loss tangent. This configuration will minimize the coating impact on RF performance.

However, such a configuration will also greatly reduce the effectiveness of standard conformal coating materials. These standard coatings provide environmental protection by minimizing the amount of contaminants (usually moisture) that diffuse to the circuit's surface. As the coating thickness decreases, the rate of moisture diffusion increases. If diffused water molecules can displace the polymer at many surface sites on the circuit, then moisture can condense under the coating and cause failure. As an example of this failure mode, **Figure 1** compares the performance of a well-adhered ultra-thin polymer coating to a standard parylene coating on interdigitated electrodes (IDEs). The parylene coating had a silane adhesion primer applied to the board before coating. The parylene coating failed and showed extensive delamination after 1 week (168 hours) of exposure to an 85°C and 85% relative humidity environment; this failure was due to adsorbed moisture displacing the coating from the surface. In comparison, the well-adhered coating did not show any apparent failure.

Therefore, in order to achieve good environmental protection a thin polymer coating will require excellent adhesion to the surface. With good enough adhesion, any adsorbed water molecules will not be able to displace the coating and result in failure modes such as that observed in **Figure 1**.

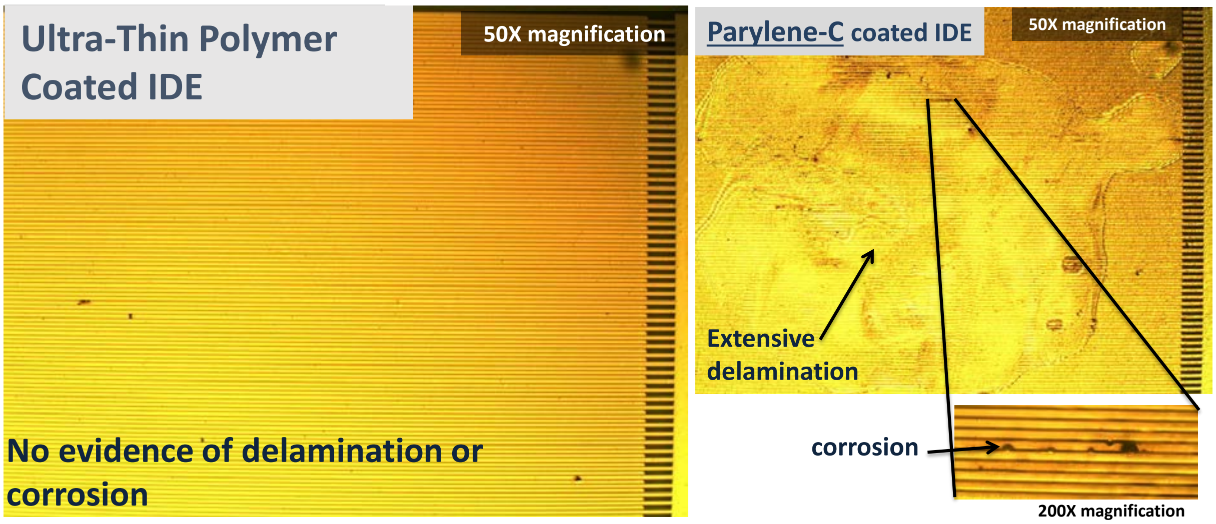

Figure 1. A Highly-Adhered Coating (Left) Provides Better Protection Than Standard Parylene (Right)

These new ultra-thin coatings can also be applied at a number of different points in the circuit manufacturing process (**Figure 2**) providing multiple levels of protection.

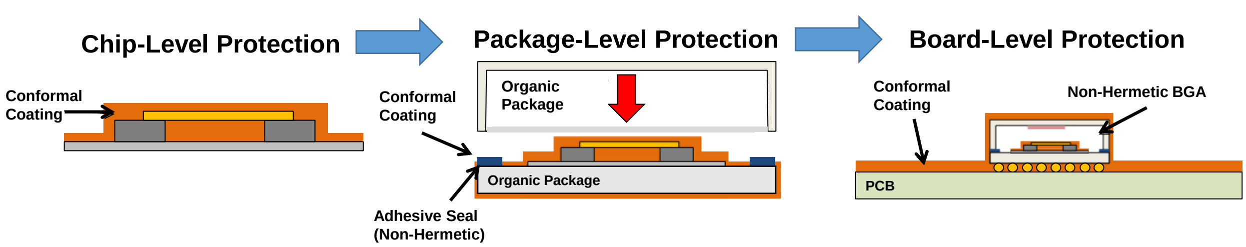

Figure 2. Conformal Coatings Provides Multiple Levels of Environmental Protection for RF Electronics

These new coatings also enable designs which mix RF and signal processing/digital circuits on the same board. In standard hermetic packaging, the signal processing/digital circuitry is segregated into a separate circuit board which is then mated with the RF microwave multichip circuits within their own hermetic package. If the hermetic package can be replaced with an effective polymeric coating, then the design can move to one where both the RF/microwave and signal processing circuitry can be combined into one board, as shown in **Figure 3**.

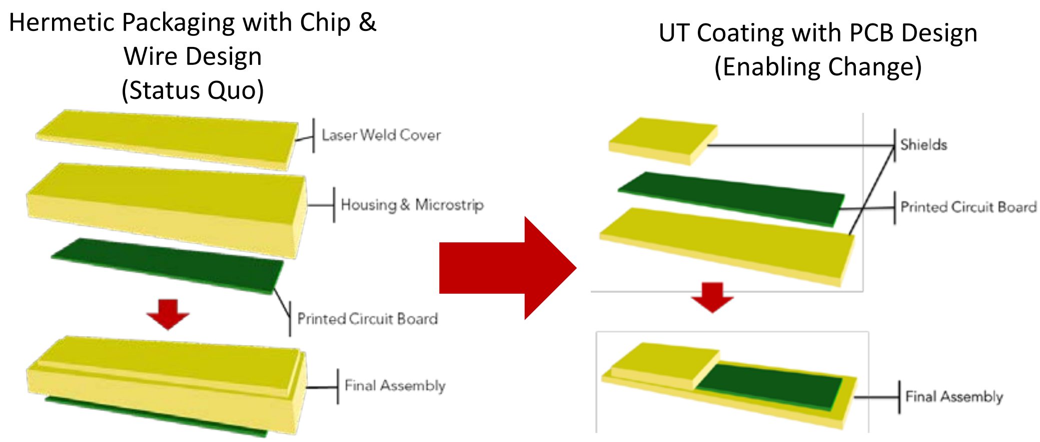

Figure 3. Ultra-Thin Conformal Coatings Enable New Mixed RF/Signal Processing Packaging

Chemical Vapor Deposition (CVD) of Ultra-thin Conformal Coatings

To address the need for advanced circuit board protective coatings, novel and solvent-free vacuum coating technologies have been developed. In Initiated Chemical Vapor Deposition (iCVD), a mixture of gases is introduced into a reactor under a mild vacuum in the vicinity of an energy source such as heat or plasma. The gas decomposes into reactive species that serve as monomer units. These units then migrate to a substrate, on which they combine and grow into a conformal polymer thin film. That is, the monomer units successively add to one another, forming linear or crosslinked polymer chains [5, 6, 7].

In these processes, the substrate being coated can remain near room temperature. The coatings are immediately ready to use after deposition, contain no solvents or surfactants, and require no post-processing (i.e., no high temperature drying or annealing). The deposition process simultaneously adsorbs molecules of monomer units on the surface of the device and crosslinks those monomer units to grow a cohesive polymer film, resulting in molecular-level conformal coverage of the surface. This molecular-level coverage ensures the excellent adhesion to the device that is critical in providing protection from exposure to harsh operating environments. The dense networked structure renders these polymer coatings resistant to dissolution or delamination.

The low operating pressures (75-750 mTorr) of a CVD process allow conformal coating of extremely fine objects with high aspect ratio structures. By exploiting the knowledge of solution chemists, CVD reactants and reactor designs can be chosen such that selective chemical pathways are followed under conditions of low temperature (>100°C) and low energy input (5-200 Watts). CVD coating thicknesses in the 100 nm to 1 µm range are typical. In addition, multiple chemistries may be deposited sequentially in the same chamber without breaking vacuum, allowing for unique combinations of coatings and properties. In the iCVD process, the substrates being coated also remain at low temperature.

RF Performance Before and After Coating

In RF testing, these new coatings show negligible impact on s-parameters, gain, isolation, and return loss from 0 to 20 GHz frequency; this low impact was observed before and after 8 days of environmental exposure at 85°C/85% relative humidity (RH). This low performance impact when applied directly over the RF circuit enables a chip, component, or assembly designer to consider high-reliability environmental protection without the added weight, volume, and expense of hermetic packaging.

GVD's coatings have an extremely low dielectric constant and loss tangent; this, coupled with the coatings' low thickness (microns thick) results in virtually no impact to RF performance. This becomes ever more important as the operating frequency of the board being coated increases, e.g., up to 100 GHz. In comparison with Parylene C, GVD's Exilis-based coating has a dissipation factor over 10 times lower (approximately 0.001).

As proof of the low impact of this coating on RF electronics, **Figure 4** shows the measured insertion loss of a simple 50 Ohm microstrip transmission line before and after depositing GVD's protective coating. The GVD coating shows no measureable increase in insertion loss on these transmission lines up to 50 GHz. There is a small ripple in the insertion loss caused by slight impedance mismatches that change with frequency, but the fundamental performance is unchanged.

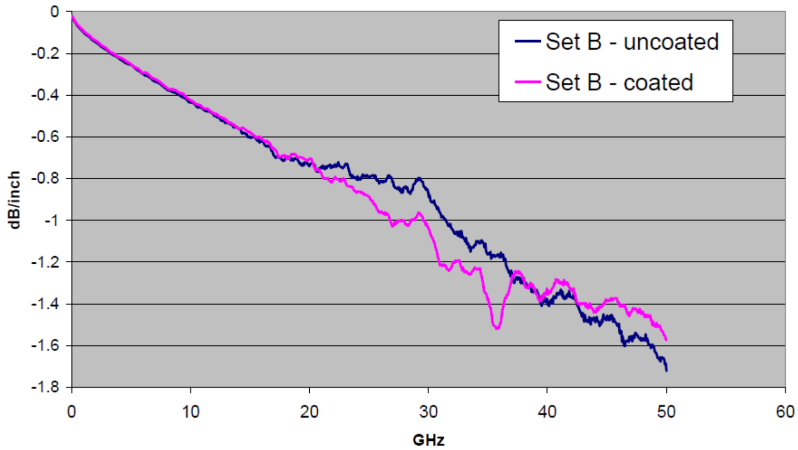

Figure 4. Measured insertion loss on 50-Ohm microstrip transmission lines before and after GVD protective coating. Testing carried out by Rogers Corp.

In addition, the Exilis coating has been directly deposited onto Microwave Monolithic Integrated Circuits (MMICs) with operating frequencies up to 100 GHz (see **Table 1**). The coating has demonstrated little to no impact on the RF performance of these devices after coating. It is expected that with an optimized coating thickness the minimal impact observed will be minimized.

Table 1. Impact of thin conformal coating on high-frequency RF components

Feature	Test Freq. (GHz)	Performance Degradation	Comments
MMIC SPDT Switch	100	0.7 dB	Minor degradation
MMIC LNA	100	1.3 dB	Minor gain degradation
Balanced Ampl. Config.	35	2.9 dB	Moderate gain degradation
MMIC SPDT Switch	37	0.2 dB	Minor degradation
Coupled line band pass filter	35	0.2 dB	Minor degradation in bandwidth and insertion loss
Coupled line band pass filter	17.6	0.5 dB	Minor degradation in bandwidth and insertion loss
Branchline Couplers back to back	35	0.07 dB	No degradation in bandwidth and insertion loss
2-inch 50 Ω microstrip line	40	0.01 dB	No degradation in bandwidth and insertion loss

Environmental Protection Provided by Ultra-thin Conformal Coatings

Some of these thin film materials were originally developed as an electrically-insulating, biostable coating for microelectrode neuroprosthetic devices. One notable feature of this particular coating is its excellent adhesion to a variety of substrates; as described above, this is a critical requirement for protective circuit board coatings. The coatings retain adhesion (exhibits 0% delamination during ASTM 3359 tape test) after exposure to a variety of solvents and after boiling in water.

These new polymer coatings have also demonstrated superior environmental protection of printed circuit board components in harsh environments. They have been demonstrated to ensure the survival of devices for 1,000 hours of accelerated testing per JESD22-A101C, where the device is subjected to 85°C and 85% relative humidity. For maritime applications, the coating has been tested on devices for 500 hours of salt fog exposure per ASTM B117, showing that device still operated and was not corroded after exposure. Additional successful testing has also been carried out as per the MIL-I-46058C and IPC-CC-830 specifications for conformal coatings. It should be noted that for the latter specification a 'Revision C' is in the last stages of approval. This revision will contain corrections allowing the IPC specification to correctly test the new ultra-thin conformal coatings.

GVD circuit board coatings have also demonstrated superior environmental protection of printed circuit board components in harsh environments. A performance comparison of one of the new coatings with a 5 μm thick parylene coating was shown previously in **Figure 1**. For these experiments, interdigitated electrode (IDE) structures were coated with either a thin polymer coating or with parylene. The parylene coating had a silane adhesion primer applied to the board before coating. The IDEs were then exposed for 1 week (168 hours) to an 85°C/85%RH environment under 5 V constant bias. The IDEs with parylene showed obvious delamination and corrosion while the IDEs with the new coating showed no visible delamination or corrosion.

Other Considerations for Conformal Coatings for RWOH

With regard to throughput, any conformal coating process has to take into account both the deposition time as well as masking and de-masking. It is labor intensive to cleanly remove conventional conformal coatings from masked-off regions of coated boards (de-masking), or requires selective application that is highly operator dependent. Decreased manual handling not only reduces cost, but also reduces risk of accidental damage of the device.

Adhesion testing of the new developed CVD coatings have shown that masks can simply be lifted off without any delaminating of the coating, eliminating the laborious scribing steps in de-masking boards coated with traditional environmental protection coatings; for an example of this ease in de-masking, see **Figure 5**.

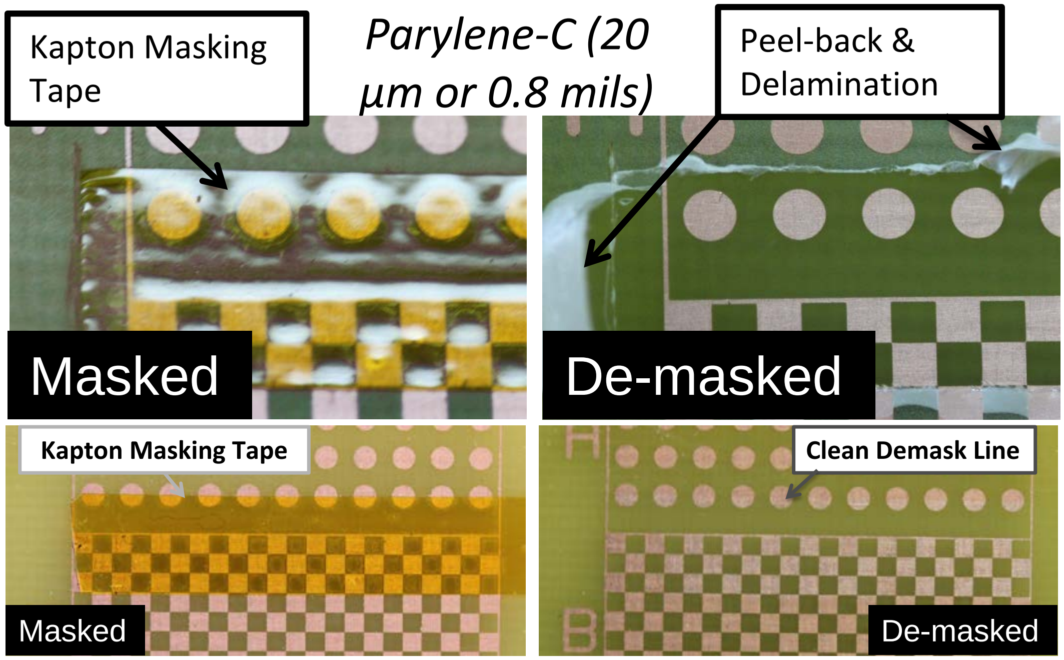

Figure 5. Improved demasking performance of ultra-thin coating (bottom) versus Parylene (top)

If an RF or microwave circuit must undergo rework, hermetic packaging results in further complications. In the case of a laser-welded lid, the package must be milled open. This milling is time consuming and expensive, not to mention it results in conductive foreign debris that can damage sensitive electronics.

Certain 'standard' conformal coatings such as parylene also run into problems during rework. Because parylene is extremely pervasive and relatively tough, it's difficult to remove or rework components onto which parylene has deposited. A pin-connector that has not been sealed completely during the deposition of parylene requires complete replacement, as forcible removal of the coating from the pin risks damaging the connector beyond repair.

For the other standard conformal coatings, these must be manually scribed or stripped using harsh chemicals that risk damaging the device and expose the operator to hazardous materials. Scribing can result in accidental cutting of copper traces on the board, leading to reduced product yield.

In contrast to these problems, the new coatings act as an excellent 'primer' layer for re-coating after rework. This simplifies rework and recoating processes involving these new coatings, especially when compared to more traditional conformal coating materials.

Process Scale-Up

GVD has commercialized and scaled its own ultra-thin coating technology, developing a number of standard coating systems for the deposition of new RF-compatible conformal coatings. GVD's business model is to provide coating services based out of its Cambridge, MA facility for prototyping and low volume production. For full-rate production, GVD will work with customers to either co-locate a facility at the customer's manufacturing site or provide a coating system for in-house use.

Coating tools range from small development-scale systems intended for prototyping and research to large batch coating systems similar to other commercial polymer vapor deposition chambers. These tools are the only commercial systems on the market for producing the types of coatings offered by GVD and can be used by GVD technology licensees.

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