FORGE NANO

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Atomic Layer Deposition for Encapsulation and Hermetic Sealing of RF and Power Electronics

Summary

Radio frequency (RF) and power electronics are vital to an array of industries, from telecom and consumer electronics to transportation and energy distribution. As energy diversification and the prevalence of high-speed electronics continue to grow, RF and power electronics are expected to reach a global market of $36.6 billion by 2027.[1] Extreme environments such as high temperatures, ultra-violet radiation, oxygen, salinity and moisture are all threats that degrade and corrode active components causing early failure. Atomic layer deposition (ALD) has created substantial improvements to the reliability and performance of RF and power electronics. Using ALD as an encapsulation layer at the wafer level or as a final hermetic seal at the chip/module/PCB level has been shown to substantially improve electronic performance and lifetime.[2,3] ALD layers enable longerlifetimes, higher performance and lower cost without adding the considerable mass gain and high temperature processing associated with conventional hermetic coatings.

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ALD Improves RF and Power Electronics

The benefits of ALD layers:

- Hermetic sealing encapsulation layers with minimal thickness
- Pristine conformality in high-aspect ratio structures
- Ultra-low particle generation
- Low stress films
- Improved lifetime of ICs and PCBs
- Increased resistance to harsh environments
- No peeling or flaking of the hermetic seal at pressures >1200 PSI
- Negligible mass gain from coating at 100 nm

There are two major methods of using ALD in RF and power electronics:

1. Overcoat encapsulation layer at the wafer level
2. Hermetic sealing at the package level

ALD at the Wafer Level

One of the most important layers in post-gate processing for RF and power devices is the encapsulation layer to protect the device from environmental degradation. Thin encapsulation layershave found to decrease humidity permeation rates on moisture sensitive devices.[4] In a study from April 2020, RF microelectronic mechanical devices (MEMs) were encapsulated with SiN_x thin films forenvironmental protection on 5G devices and showed successful mechanical protection.[5] Beyond environmental protection, encapsulation layers have also been found to improve RF device performance. One study showed encapsulated GaAs-based terahertz emitters increased the averagepower output fourfold by enhancing the conductivity and prevention oxidation at the semiconductorsurface.[6]

Plasma enhanced chemical vapor deposition (PECVD) has historically been used for encapsulation deposition, however, the use of plasma damages delicate semiconductor surface states withenergetic ions, chemical radicals and UV radiation. Presence of these surface states gives rise to hopping conduction, which lowers the breakdown voltage of the gate. The thermal nature of ALD does not require damaging plasma or high energy ions for deposition and helps maintain delicate surface electronic states and increases reliability of the circuit.[2] ALD provides an electrically-low- leakage film, with no pinholes and a high dielectric constant at deposition temperatures down to 80^{o}C. With these improvements in film quality, ALD has largely started to displace PECVD in post- gate processing as deposition rates have increased.[10] Common ALD chemistries for this application, such as Si_3N_4, Al_2O_3, HfO_2, TiO_2 and ZnO can be deposited by ALD using commercial precursors commonly used for PECVD/CVD processes.[2]

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Compared to other deposition techniques, ALD provides a hermetic seal which provides greater deviceprotection. Sputtering, physical vapor deposition (PVD) and CVD provide imperfect coatings where pinhole defects are common. These pinhole defects provide point locations for corrosion to enter the device leading to early failure.[7] The low-stress and pinhole-free ALD films provide a vital protective barrier over the active device. Active devices will fail if moisture finds a path to the ohmiccontacts, channels of field effect transistors (FETs) or junctions of heterojunction bipolar transistors(HBTs). However, these active devices are well-protected from moisture with ALD films. In one study,SiN ALD encapsulated FETs were compared with PECVD encapsulated FETs under an accelerated stress test, 130°C and 85% relative humidity, the PECVD coated FETs had a 99% failure rate comparedto 2.7% for ALD coated FETs, predicting reliable ALD performance under worst-case conditions for MMICs.[8]

GaAs Process	Coatings	Bias	Failures
0.50 um Optical FETs	SiN	11V	99%
0.50 um Optical FETs	ALD-Cap	11V	2.7%
0.50 um E-Beam FETs	ALD-Cap	7V	0.3%

Table 1: A 96 hour Highly Accelerated Stress Test (HAST) at 130°C and 85% relative humidity was used as a benchmark for the optimization of the ALD layers. The devices are biased at pinchoff during the test which is the maximum stresscondition. The ALD FETs had a much lower failure rate than the original SiN FETs.[8]

ALD Encapsulation at the Package Level

Due to application challenges in extreme environments, RF and power electronics require robust hermetic sealing to maintain reliability over conventional integrated circuits. Electronics demandingthis extra layer of protection frequently use plastic to encapsulate circuits for added protection which creates additional weight and cost to the final product.[7] In certain aerospace applications requiring military standards (MIL-STD), ceramic encapsulation provides more protection than plasticpackaging yet requires higher temperature processing and adds significant weight to the final product.

ALD provides the best of both fabrication methods by using ceramic coatings to create a hermetic seal while maintaining low deposition temperatures (down to 70°C in some cases), lower costs thantraditional plastic hermetic packaging and a negligible mass gain to the final product.[8,11] Using ALD at ~200nm thicknesses has shown more efficient hermetic seals with higher performance and lower temperature processing.[11] In a recent study, 100nm ALD deposited films of SiO_2/HfO_2 onto RF chipletsshowed no degradation after 100 days at 87°C in a saline environment during accelerated aging testing.[12]

At the printed circuit board (PCB) level, environmental factors can introduce failure modes when notprotected with hermetic seals. Tin whiskers, thin electrically conducting structures that form on PCBassemblies, can grow up to 10mm long to create electrical shorts on different board components. Using ALD as thin as 10nm on PCB assemblies saw a significant decrease in tin whiskers, dramaticallyextending the lifetime of the product.[13]

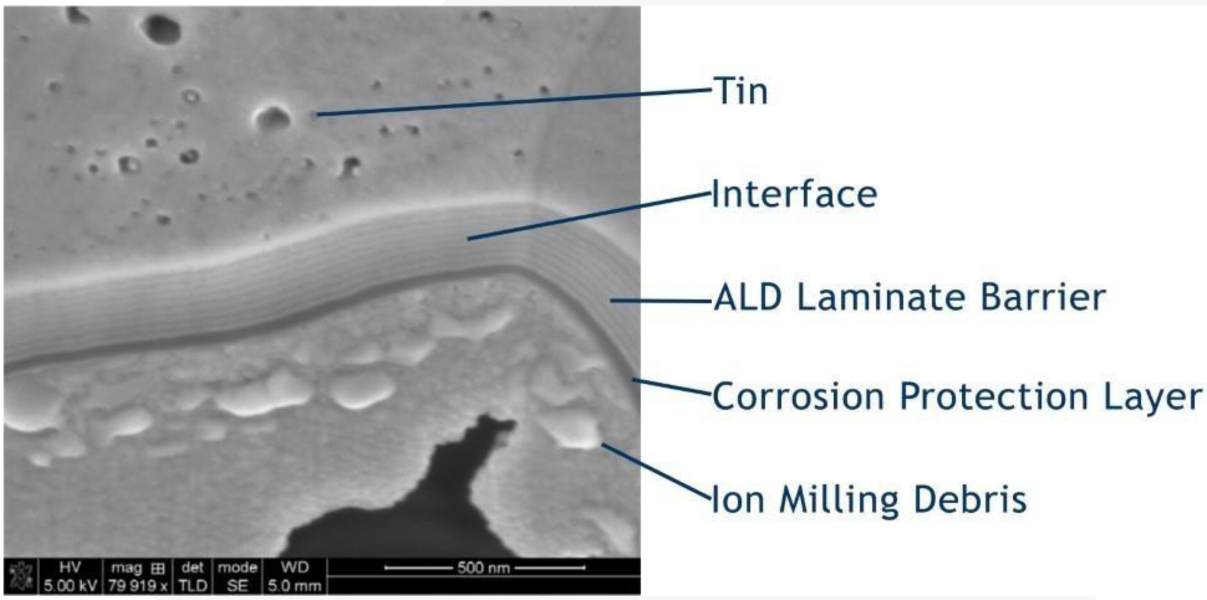

Figure 1: FIB-cut SEM image showing SiO_2/TiO_2 ALD laminated layers on a circuit card assembly with a 250 nm thickness.[11]

For more information on using ALD for RF and power electronic components, please contact Staci Moulton at SMoulton@forgenano.com.

About Forge Nano

Forge Nano is a leading materials science company harnessing the power of Atomic Armor, the company's proprietary ALD nanocoating technology, to accelerate manufacturing innovation, transform product performance and achieve a more sustainable future for a range of industries around the world. Atomic Armor produces superior coatings that can unlock a material's performance at the atomic level and deliver custom solutions from small-scale R&D and laboratory work to large-scale, high-volume production lines. A range of materials can be enhanced through Atomic Armor, including batteries, medical devices, catalysts, propellants and 3D additives. Forge Nano has received major support and signed meaningful partnerships with Volkswagen, LG Technology Ventures, Mitsui Kinzoku, Air Liquide and Sumitomo Corporation of Americas, largely as a result of the company's innovation in the Lithium-ion battery industry and successful track record of improving product performance and safety while reducing cost.

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Forge Nano's Capabilities

- **>20 in-house ALD systems for coating of wafers, powders and objects**
  - Including research, pilot and commercial scale systems capable of processing anywhere from 1.0 g to 30,000 kg powder or extrudates per day
  - Fast deposition times up to 30nm per minute for rapid Al_2O_3 ALD coating solutions
- **The world's most knowledgeable and experienced team for ALD onto a range of materials**
  - PhD scientists, certified Professional Engineers, career scientists
  - 20+ years' experience designing and building powder ALD systems

Working with Forge Nano

Forge Nano assists customers daily with both R&D and commercialization of ALD-enabled materials. For R&D, we offer research services for proofs of concept and also sell our R&D equipment globally. For commercialization, we offer joint development of products, production equipment and IP licensing.

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