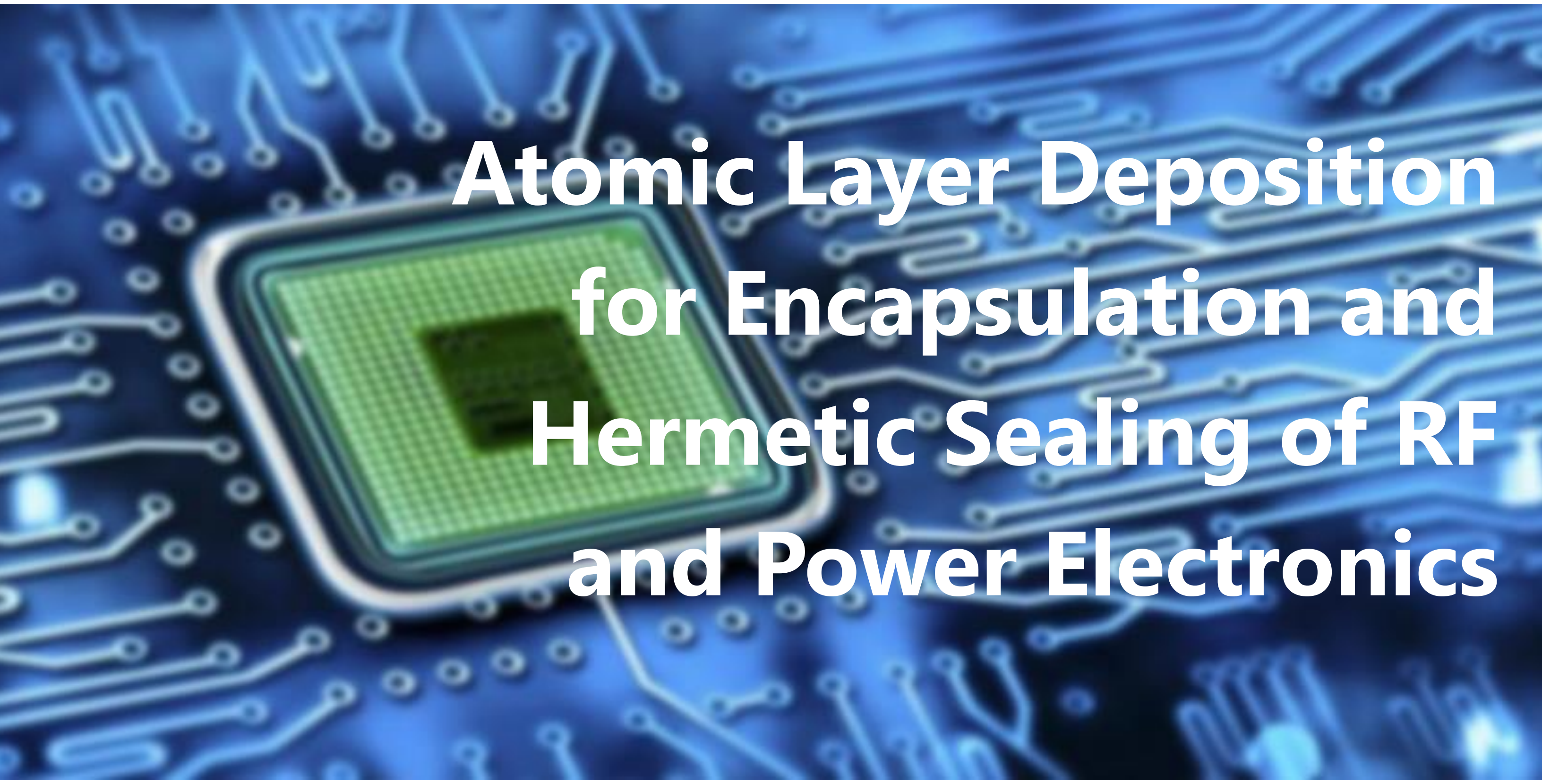

Atomic Layer Deposition for Encapsulation and Hermetic Sealing of RF and Power Electronics

Introduction

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 longer lifetimes, higher performance and lower cost without adding considerable mass gain and high temperature processing associated with conventional hermetic coatings.

About Forge Nano

Global leaders in surface engineering and precision nano-coating technology, using Atomic Layer Deposition. Forge Nano’s proprietary technology and manufacturing processes make angstrom-thick coatings fast, affordable and commercially viable for a wide range of materials, applications and industries.

For more information visit: **www.stinstruments.com**

ALD improves RF an 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 pressure >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 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. This encapsulation layers have 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 SiNx thin films for environmental 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 increase the average power output fourfold by enhancing the conductivity and prevention oxidation at the semiconductor surface. *[6]*

Plasma enhanced chemical vapor deposition (PECVD) has historically been used for encapsulation deposition, however, the use of plasma damages delicate semiconductor surface states with energetic 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°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 b ALD using commercial precursors commonly used for PECVD/CVD processes.[2]

Compared to other deposition techniques ALD provides a hermetic seal which provides greater device protection. Sputtering, physical vapor deposition (PVD), and CVD provide imperfect coatings where pinhole defects are common. These pinholes 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 ohmic contacts, 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° and 85% relative humidity, the PECVD coated FETs had a 99% failure rate compared to 2.7% for ALD coated FETs, predicting reliable ALD performance under worst-case conditions for MMICs.[8]

GaAs Process	Coatings	Bias	Failures
0,50 µm Optical FETs	SiN	11V	99%
0,50 µm Optical FETs	ALD-Cap	11V	2,7%
0,50 µm 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 stress condition. The ALD FETs had a much lower failure rate than the original SiN FETs.[8]

ALD Encapsulation at the package lever

Due to application challenges in extreme environments, RF and power electronics require robust hermetic sealing to maintain reliability over conventional integrated circuits. Electronics demanding this extra layer of protection frequently use plastic 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 plastic packaging 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 then traditional 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 chiplets showed 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 no protected with hermetic seals. Tin whiskers, thin electrically conducting structures that form on PCB assemblies, 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 thin whiskers, dramatically extending the lifetime of the product.

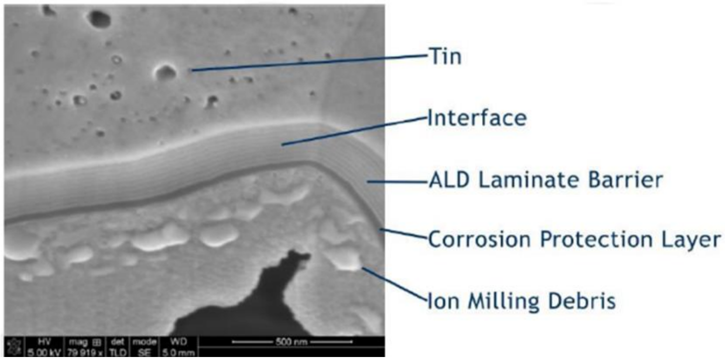

Figure 1: FIB-cut SEM image showing SiO_2/HfO_2 ALD laminated layers on a circuit card assembly with a 250nm thickness.[11]

References

[1] "Power Electronics Market Size, Latest trend; competitive statistics 2027." Allied market research June 2020, www.alliedmarketresearch.com/power-electronics-market

[2] "Section 16.3." III-V integrated circuit fabrication technology, by Shiban Kishan Tiku and Dhrubes Biswas, Pan Stanford publishing, 2016.

[3] A. Leuther, M. ohlrogge, L. Czornomaz, T.Merkle, F. Bernhardt and A. Tessman, "A 250 GHz millimeter wave amplifier MMIC based on 30nm metamorphic InGaAs MOSFET technology," 2017 12th European Microwave integrated circuits conference (EuMIC), Nuremberg, 2017, pp. 130-133, doi: 10.23919/EuMIC.2017.8230677.

[4] Ferdinandus J.H. van Assche, Sandeep Unnikrishnan, Jasper J Michels, Antonius M.B. van Mol, Peter van de Weijer, Mauritius C.M. van de Sanden, Mariadriana Creatore, on the intrinsic moisture permeation rate of remote microwave plasma-deposited silicon nitride layers, thin solid films, volume 558, 2014, pages 54-61, ISSN 0040-6090.

[5] A. Persano, F, Quaranta, A. Taurino, P.A. Siciliano and J. Iannacci, "thin film encapsulation for RF MEMS in 5G and modern telecommunication systems," Sensors (Basel, Switzerland), vol. 20, no. 7, p., Apr. 2020.

[6] C. Headly et al., "Improved performance of GaAs-based terahertz emitters via surface passivation and silicon nitride encapsulation," in IEEE journal of selected topics in quantum electronics, vol. 17, no. 1, pp. 17-21, Jan-Feb. 2011, doi: 10.1109/JSTQE.2010.2047006.

[7] Kääriäinen Tommi, et al. Atomic Layer Deposition: principle, characteristics, and Nanotechnology applications. Wiley-Scrivener, 2013.

[8] "Atomic Layer Deposition (ALD) environmental coatings for GaAs MMICs. " Sundewtech.com, Raytheon / Sundew Tech, 2013, https://sundewtech.com/wp-content/uploads/2020/10/CS-Mantech_2013_02R-Environmental-Protection-through-ALD.pdf

[9] Yota, Jiro, et al. "Characterization of Atomic Layer Deposition HfO_2, Al_2O_3, and Plama-Enhanced Chemical Vapor Deposition Si_3N_4 as metal-insulator-metal capacitor dielectric for GaAs HBT technology." AVS, American Vacuum Society, 1 Nov 2012, avs.scitation.org/doi/abs/10.1116/1.4769207.

[10] "PEM-INST-001"instructions for Plastic Encapsulated Microcircuit (PEM) selection, screening, and qualification. "NASA technical reports Server (NTRS), NASA, 2003, ntrs.nasa.gov/citations/20040082092

[11] "MMIC coatings and encapsulation for non-hermetic, low cost, Transmit/Receive modules with the reliability of hermetic packaging." https://www.sbir.gov/sbirsearch/detail/319997

[12] Jeong, Joonsoo, et al. "Conformal hermetic sealing of wireless microelectronic implantable chiplets by multilayered Atomic Layer Deposition (ALD)." Advance functional materials, 2018, p. 1806440., doi:10.1002/adfm.201806440.

[13] E.Chason, N. Jadhav, et al. "Atomic Layer Deposition (ALD) to mitigate tin whisker growth and corrosion issues on printed circuit board assemblies." Journal of electronic materials, Springer US, 1 Jan 1970, link.Springer.com/article/10.1007/s11664-019-07534-7

[14] "Sundew Technologies – ALD Cap Exceptional Barrier Performance."

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The Forge Nano Theia system is the only R&D tool for ALD that delivers ultra-fast deposition, compatible with large-scale production. THEIA delivers ultra-fast deposition with Forge Nano's patented SMFD-ALD™, in a low cost system for R&D budgets. Sub-second ALD cycle times allow efficient and rapid exploration of applications requiring thick films. Covering challenging patterned substrates such as advanced-generation DRAM device wafers, membranes, sensors, electron multipliers, etc. with aspect ratios up to 1,000..

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