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Atomic Layer Deposition for OLED and MicroLED Display Technologies

Summary

Display technologies have evolved rapidly over the decades, from 19" cathode ray tubes to <1um- pitched microLEDs. Consumers demand thinner screens, higher pixel densities, flexible/curved screens and near-eye viewing distances. Organic Light Emitting Diode (OLED) displays have found success as a high performing, low-cost technology in the market with a compound annual growth rate (CAGR) of 13.6% reaching $72.8 billion in 2026.[1] MicroLEDs are a slightly newer, competitive and higher-performing technology with a CAGR of 89.3% reaching $18.8 billion by 2026.[2]

Despite the expected growth in OLED and microLED technologies, they both suffer from technical drawbacks. OLEDs suffer from short lifetimes due to moisture/oxygen infiltration and MicroLEDs struggle with scaling production due to the decreased pitch size leading to poor sidewall passivation and low pixel efficiencies. Atomic layer deposition (ALD) can improve both OLED and microLED technologies by depositing defect-free films to provide a hermetic encapsulation, and sidewall passivation to improve lifetimes.

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ALD Improves Display Performance and Lifetimes

The benefits of ALD layers:

- Pristine conformality in high-aspect ratio structures
- Hermetic sealing encapsulation layers with minimal thickness
- Ultra-low particle generation
- Low stress films
- Improved lifetime of OLEDs
- Increased quantum efficiencies for microLEDs

ALD for OLED Technology

OLEDs exhibit an attractive price-to-performance ratio but are susceptible to moisture and oxygeningress through the organic layers within the pixel. Due to this sensitivity, OLEDs have the most stringent water vapor and oxygen transmission rate requirements of all optoelectronics technologies at 10^{-6} g/m^2/day and 10^{-3} cm^3/m^2/day, respectively.[3] Once moisture has penetrated the encapsulation surface, dark spots or “dead pixels” will appear due to the hydrolyzation of electrodes or electron injection layers.[4]

To protect OLED active components, encapsulation processes have been developed that reduce water and oxygen exposure. The most common encapsulation process uses a series of alternating layers consisting of organic epoxy resins and deposited inorganic films. Organic films have good step coverage but poor protection against humidity, where inorganic films deposited via CVD have poor step coverage but good barrier protection against humidity.[5] Though these films work together to improve humidity protection, several layers up to 25um thick must be deposited due tothe pinhole-prone nature of the deposited inorganic film. This is called the “Labyrinth effect” as humidity must travel through several imperfect layers to reach the thin film transistor (TFT) substrate. This is particularly inefficient in monolithic OLED devices built on wafers which do not require flexible films for optimal encapsulation.

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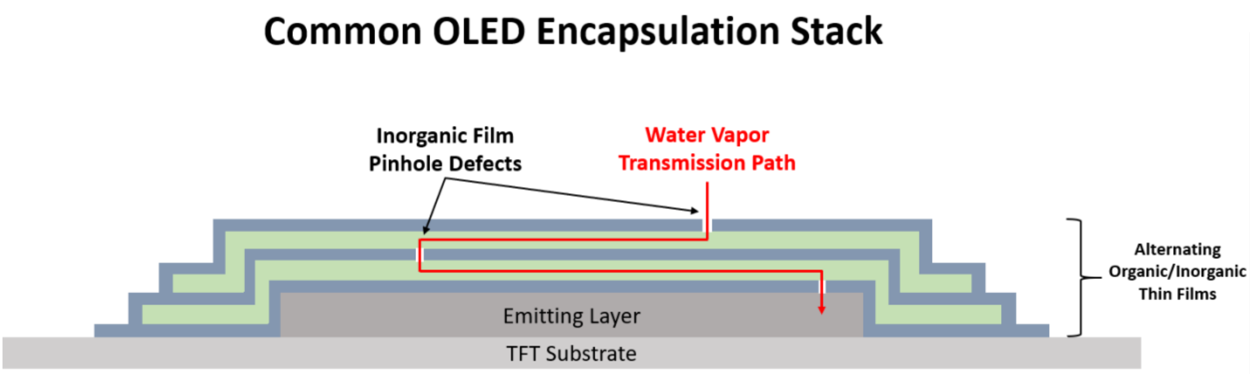
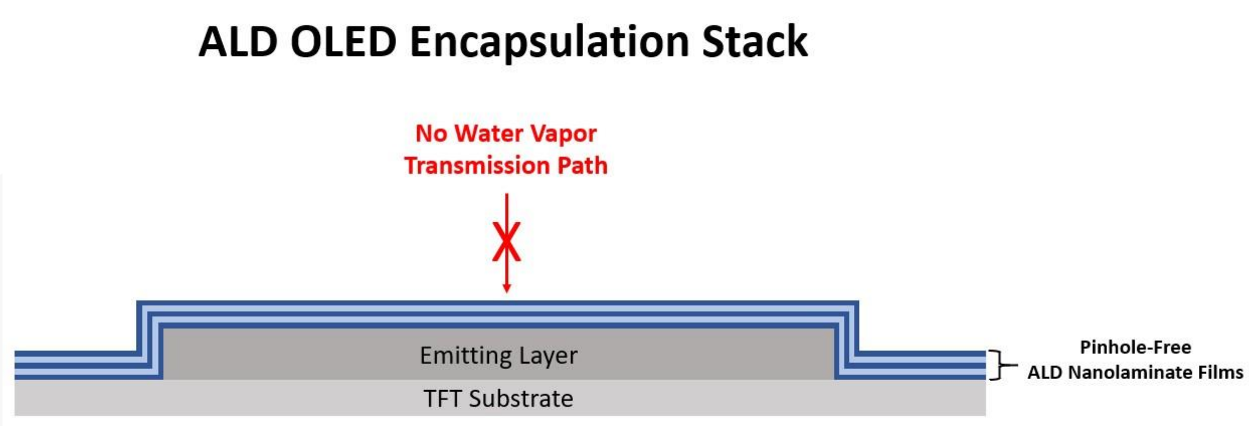


Alternatively, ALD maintains both excellent step coverage and barrier protection against humidity eliminating the need for the organic film layer.[6] Previous research using calcium corrosion tests have shown ALD alumina films have an effective water vapor transmission rate (WVTR) on the order10^{-6} g/m^2/day at room temperature which is sufficient for demanding applications such as OLEDs.[7] While these ALD films have been deposited with thicknesses up to 50 nm, the critical thickness has been shown to be down to 5 nm.[8,9] In a recent study, Riedl et al. demonstrated an ALD Al_2O_3/ZrO_2 nanolaminate barrier structure on OLEDs where a lifetime in excess of 20,000 hours was achieved.[10]



In contrast to the conventional encapsulation process, ALD nanolaminates do not require multiple processing steps to deposit the individual encapsulation layers. Encapsulation films can be deposited sequentially without the need for the substrate to leave the deposition tool which dramatically decreases processing time. ALD-Cap, a Forge Nano ALD nanolaminate encapsulation technology, has been shown to outperform other encapsulation materials while depositing a defect-free 50nm film in 4 minutes.[11]

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Measurement	ALD-Cap®	Urethane	Parylene C
Hardness (GPa)	8-10	<<0.13	0.13
Young's Modulus (GPa)	130-180	1.5	2.8-3.2
Elongation to Failure (%)	100-300	250	200
Density (g/cm^3)	3-5	0.9-1.2	1.29
Dielectric Constant	6-9	3.5	3.15
Dielectric strength (MV/cm)	>8	1.4	2.2-2.8
Oxygen Permeability, atm(cm^3/m^2/day)	$<1x10^{-7}$	80	2.83
Water Vapor Permeability, 38^oC(g/m^2/day)	$<4x10^{-10}$	0.7	0.083
Maximum Temperature (^oC)	>1500	130	290
Linear Coefficient of Expansion($10^{-6}/^oC$)	6	100-200	35
Heat Dissipation (W/cm^2 C, at 0.2um)	2550	<0.16	0.33
Typical Thickness (um)	0.05-0.2	25-75	25

Comparison of ALD-Cap, a Forge Nano ALD nanolaminate, versus urethane and parylene Cencapsulation coatings.[11]

OLEDs require a high-performance encapsulation film to be protected from oxygen and water vapor transmission. Current encapsulation methods are inadequate to create long OLED lifetimes. ALD provides defect-free films at lower cost, faster processing times, and higher protection than legacy encapsulation processes to enhance OLED performance and lifetime.[10] Forge Nano's patented ALD- Cap technology outperforms PECVD on film quality, density, speed, and cost for OLED encapsulation processes.[11]

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ALD for MicroLED Technology

MicroLEDs, an emerging display technology, offer many improvements over existing OLED displays. In a review of display technologies from 2021, researchers found microLEDs offer higher contrast ratios, higher pixel density, faster response times, longer lifetimes and greater environmental stability in extreme environments. However, microLEDs suffer from lower quantum efficiencies and high fabrication costs compared to OLEDs.[12]

Measurement	MicroLED	OLED	LCD
Mechanism	Self-emissive	Self-emissive	Backlighting and color filter
Luminance	Max. >4000 nits (full color)	Max. <5 × 10^3 nits (full color)	Max. 7 × 10^3 nits (full color)
Contrast ratio	>1,000,000:1	>10,000:1	5000:1
Pixels per Inch(PPI)	Max. 30,000 PPI	Max. 1,433 PPI	Max. 806 PPI
Pixel size	Min. submicron	Min. 18 µm	Min. 32 µm
Compactness	High	Medium	Low
Lifetime (LT90%)	>100,000	10,000	30,000–60,000
Operation temperature	−100 °C–120 °C	−50 °C–70 °C	−20 °C–80 °C
View angle	Max. 180°	Max. 89°	Max. 89°
Environmental stability	High	Low	Medium
Response time	Nanoseconds	Microseconds	Milliseconds
Enhanced function	High	Medium	Medium
Power consumption	Low	Medium	Medium
External Quantum Efficiency (EQE)	10%–30% (~80% in theory)	10%–40%	5%–12%
Cost	High	Low	Low

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The miniaturization of pixel size and pitch has created manufacturing challenges for the development of microLEDs, both with the fabrication of the pixel and sidewall passivation.[13] The decreased pixel size has also impacted quality of the pixel which has decreased the external quantum efficiency (EQE) of the device. MicroLED pitch size, or the distance between pixels, is less than 1/100th the size of OLED pixels which impacts the ability to passivate the sidewalls of the pixel at ultra-high aspect ratios and decreases overall efficiency.

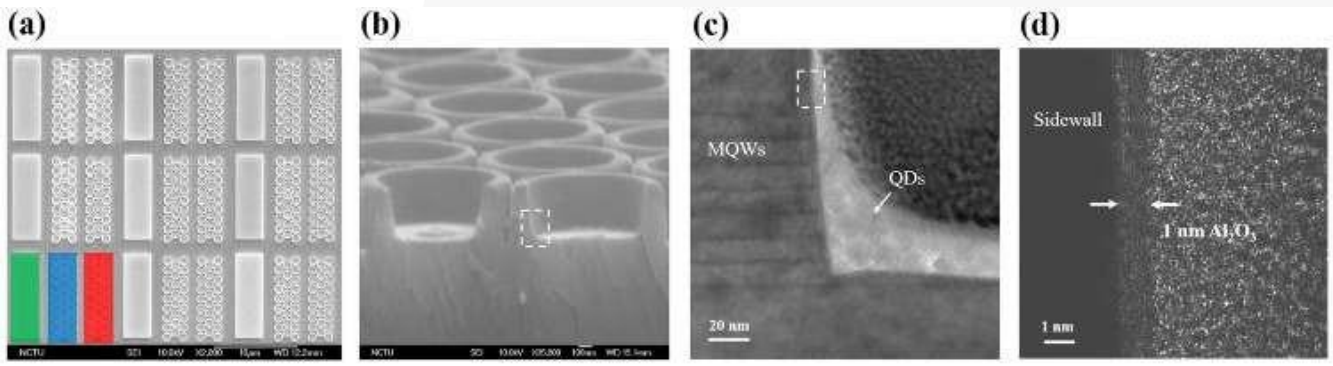

Fig. 4. (a) SEM image of RGB pixel array (top view), (b) SEM image of NR-μLED with 30° tilt angle, (c) TEM image of the contact area between MQWs and QDs, (d) TEM image of 1 nm Al_2O_3 deposited on the sidewall of NR-μLED through ALD.

Image source: Huang Chen, Sung-Wen, et al. "Full-Color Monolithic Hybrid Quantum Dot Nanoring Micro Light-Emitting Diodes with Improved Efficiency Using Atomic Layer Deposition and Nonradiative Resonant Energy Transfer." Photonics Research, vol. 7, no. 4, 2019, p. 416., doi:10.1364/prj.7.000416.

Deposition on the pixel sidewalls is an effective process to passivate the dangling bond and defects caused by the dry etching process to create the pixel trench. ALD enables passivation at ultra-high aspect ratios and outperforms PECVD passivation for EQE improvements in the same film according to a recent study with red microLED devices.[14] Several other studies have shown ALD is the preferred passivation technique due to its excellent uniformity, high-quality film density, angstrom level thickness control and perfect surface coverage.[15] In a 2018 study, ALD passivated sidewalls in a III-V microLED device exhibited 10% higher efficiency and conformal step coverage compared to PECVD deposited films.[16]

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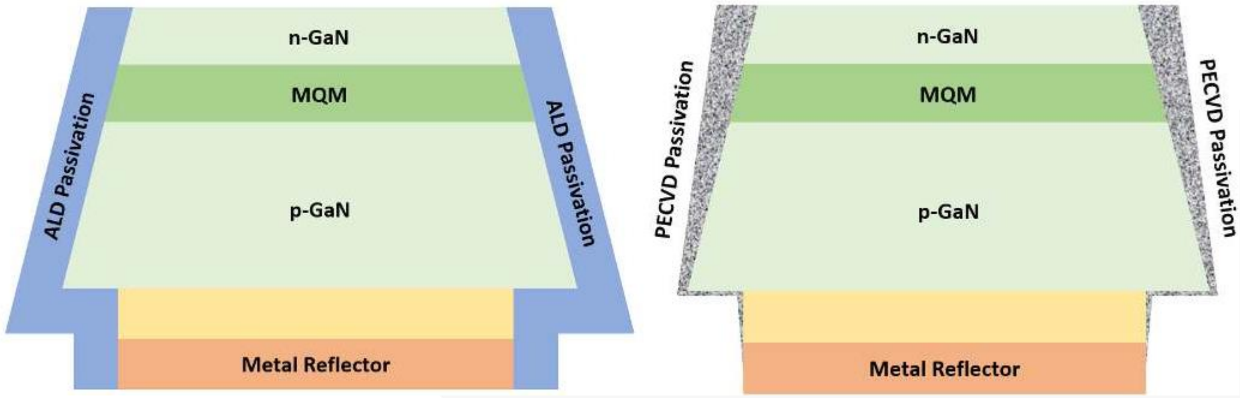

PECVD has been sufficient and cost-effective for display fabrication in the past, however, it struggles with film quality and conformal step coverage over high aspect ratios structures that are needed for microLED fabrication and passivation. Forge Nano's patented SMFD-ALD technology outperforms PECVD on film quality, density, speed, cost, and enables next-generation microLED fabrication.[11]

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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