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ENABLING NEXT GENERATION
ELECTRONIC MEDICAL DEVICES WITH

Atomic Layer Deposition

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ALD brings outstanding benefits in medical technology

Prolonged implant lifetime, miniaturization of electronic implants, enhanced patient safety, brain-machine-interfaces, reduced healthcare costs, and fewer corrective surgeries/infections make up just a few of the opportunities being developed by leading MedTech companies today. Nanotechnology offers a solution for these opportunities through ALD - Atomic Layer Deposition.

ALD is an advanced deposition technique belonging to the family of chemical vapor deposition (CVD) techniques. Since mid-2000's, ALD has been a gold standard coating method in various electronics industries and is now entering a lot of uses in the medical field.

An ALD coating is deposited as a vapor encapsulating the object one atom layer at a time. ALD creates a completely conformal and pinhole-free coating on the surface of an object, covering each atom of the object with the desired material, leaving the coated device undetectable by the body. In addition, the coating is only tens to some hundreds of nanometers thick, making it is virtually dimensionless. As such, ALD coatings provide an outstanding opportunity to the MedTech field.

> *"Compared to traditional coating methods ALD has many advantages.*

What makes ALD so special?

ALD is extremely versatile due to its basic principle of depositing one atomic layer at a time. Such an extreme level of precision affords ALD coatings several advantages over other existing coating methods.

Extreme uniformity

Molecule vapor forms uniform surfaces when repeated

Extreme conformality

As a gaseous form, vapor spreads over a given surface

Completely pinhole-free surfaces

Molecule vapor forms an intact layer over the targeted surface

Atomic level thickness control

ALD coating is formed a monolayer at a time and can be repeated as needed

Low defect densities

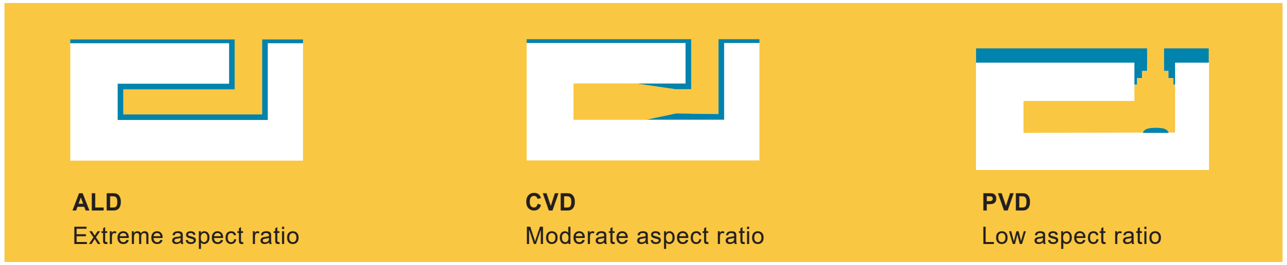
Atomic layer control allows precise control over the coating process

Biocompatible coatings

ALD is compatible with many elements and can be customized for biocompatibility

Low deposition temperatures

ALD process temperatures make ALD-coated devices better suited for e.g. biomedical use



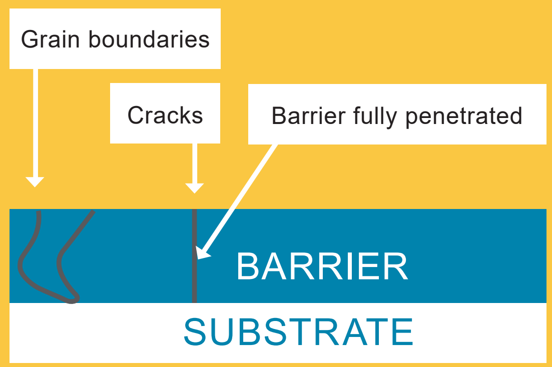
Compared to traditional coating methods, CVD and PVD, aspect ratio is one of ALD's advantages.

	ALD	CVD	PVD
Growth mode	Step-wise, layer by layer	Continuous	Continuous
Conformality	Independent of Transport. 100% uniform coverage.	Transport dependent reasonable step coverage. Prone to pinch-offs.	Transport dependent - Line of sight deposition
Thickness control based on	Number of cycles	Time based	Time based
Film properties	Pin hole free, some means for stress control	Defects, Varied stress	Defects, Varied stress
Temperature	Moderate temperatures (typically 80°C to 350°C)	Moderate to high temperatures (typically 100°C to 1000°C)	Room temperature typically

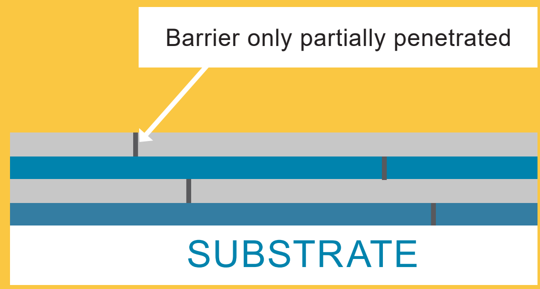
Additional advantages of ALD include applying coatings at moderately low temperatures compared to many other coating methods. The lower deposition temperature provides significant improvements in the coating's - and consequently the coated device's - performance. At the lower end of ALD coating temperatures, the films available allow the coating to be deposited on highly sensitive surfaces such as those on electronic implants.

Outstanding material performance with lamination

Single layer ALD films provide excellent performance, but diffusion paths can still exist due to the presence of grain boundary cracks. The solution for this is nanolamination. Multilayers reduce both crack and grain boundary formation, reducing the number of active diffusion paths. Due to a nanolaminate structure, no single diffusion path should penetrate the whole barrier resulting in higher barrier performance, more uniform and reliable devices, and a better yield.



Defects penetrate entire single layer barrier



For nanolaminate barrier, defects penetrate only part of the barrier

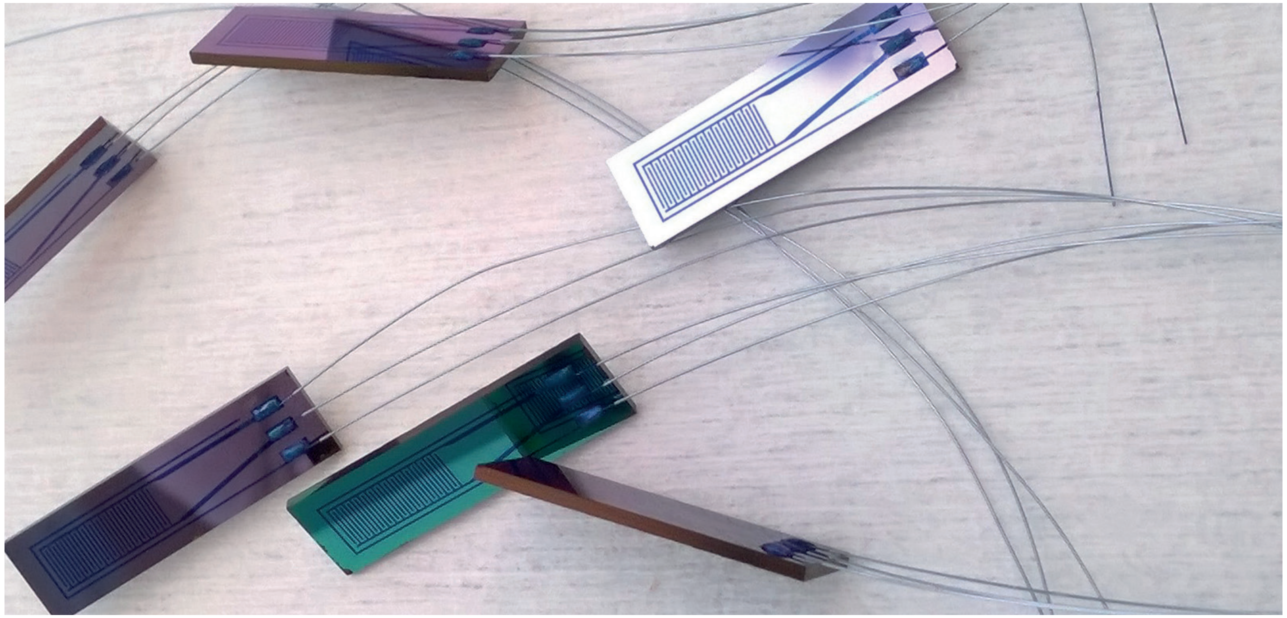
> *"Multilayers reduce both crack and grain boundary formation, reducing the number of active diffusion paths.*

Impenetrable barriers for electronic devices

Implantable medical devices must withstand the corrosive environment inside the human body for prolonged periods of time. Hermetic sealing of the device to protect it from the outside environment, and to protect the body from the device, is a key step to prolong the lifetime of medical devices.

> *"The human body is a very hostile environment for foreign objects.*

Non-toxic and dimensionless



To make a robust protective seal for the medical device, the film properties must fulfill many criteria. In addition to functioning as a diffusion barrier against ions and molecules present in body fluids, the film material needs to be non-toxic and biocompatible. In addition, the adhesion of the film with the device surface needs to be strong enough that delamination does not occur. With ALD coating, it is possible to insulate and minimize the size of electronic implants - such as spinal and cranial implants - with a perfect coating that fits seamlessly around the device, free of bulky metal casings.

Several metal oxides and nitrides have proven ideal for various medical applications. ALD is bioinert, biocompatible, and proven to possess adequate stability and physical properties. The materials used in ALD coatings have been extensively tested for cytotoxicity, antimicrobial activity, skin irritation or sensitivity, hemocompatibility, bacterial endotoxins, bioburden and sterilization residuals.

Long lifetime of ALD coated biomedical electronics

> *ALD has been proven to increase electronic device lifetime in several studies.*

ALD is an instrumental technology in providing comprehensive protection solutions for advanced electronic implants from sub-chip to implantable device level. A number of studies have been conducted on ALD and its suitability for medical technology with excellent results. ALD has been long known to be essential in fabricating sub-layers within microelectronic chips. It provides vital passivation and protection on chip level and can also protect the entire printed circuit board (PCB) assembly without need for traditional, bulky enclosures. ALD has been proven to increase PCB lifetime in several studies.

In research conducted in collaboration with Brown University* sub-millimeter-sized microelectronic chiplets for wireless body implants were coated by ultrathin and electromagnetically transparent ALD coatings. The coatings were HfO_2 single layer and HfO_2/SiO_2 multistack (100nm).

The hermeticity of the devices were characterized with aging tests by immersion in saline at T = 87 °C, while continued functionality was monitored via evaluation of backscattered RF signals (near 1 GHz) to ascertain possible degradation and electronic failure. The results implied **an equivalent lifetime of about 11 years and 15 years at body environment at 37 °C** for HfO_2 and SiO_2/HfO_2, respectively.

* Conformal Hermetic Sealing of Wireless Microelectronic Implantable Chiplets by Multilayered Atomic Layer Deposition (ALD) https://doi.org/10.1002/adfm.201806440

Superior barrier and bending performance

There has been a need for enhanced coating methods also in medical technology as future product iterations need materials that are lighter, more reliable and enable stretching of a device. The use of thin film encapsulation solutions has been recognised as a viable solution.

Thin film solutions rely on vacuum-based thin film deposition techniques like ALD. To add flexibility, ALD can be combined with more elastic molecular layer deposition films (MLD). Nanolamination of dense inorganic layers deposited with ALD to maintain excellent barrier performance, and MLD layers to offer enhanced flexibility, is the perfect solution.

> *There is immense potential with ALD/MLD films in the manufacturing of for example medical wearables and medical packaging.*

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