EDITION 8

LAYERS

ANNIVERSARY EDITION

20 ANNIVERSARY

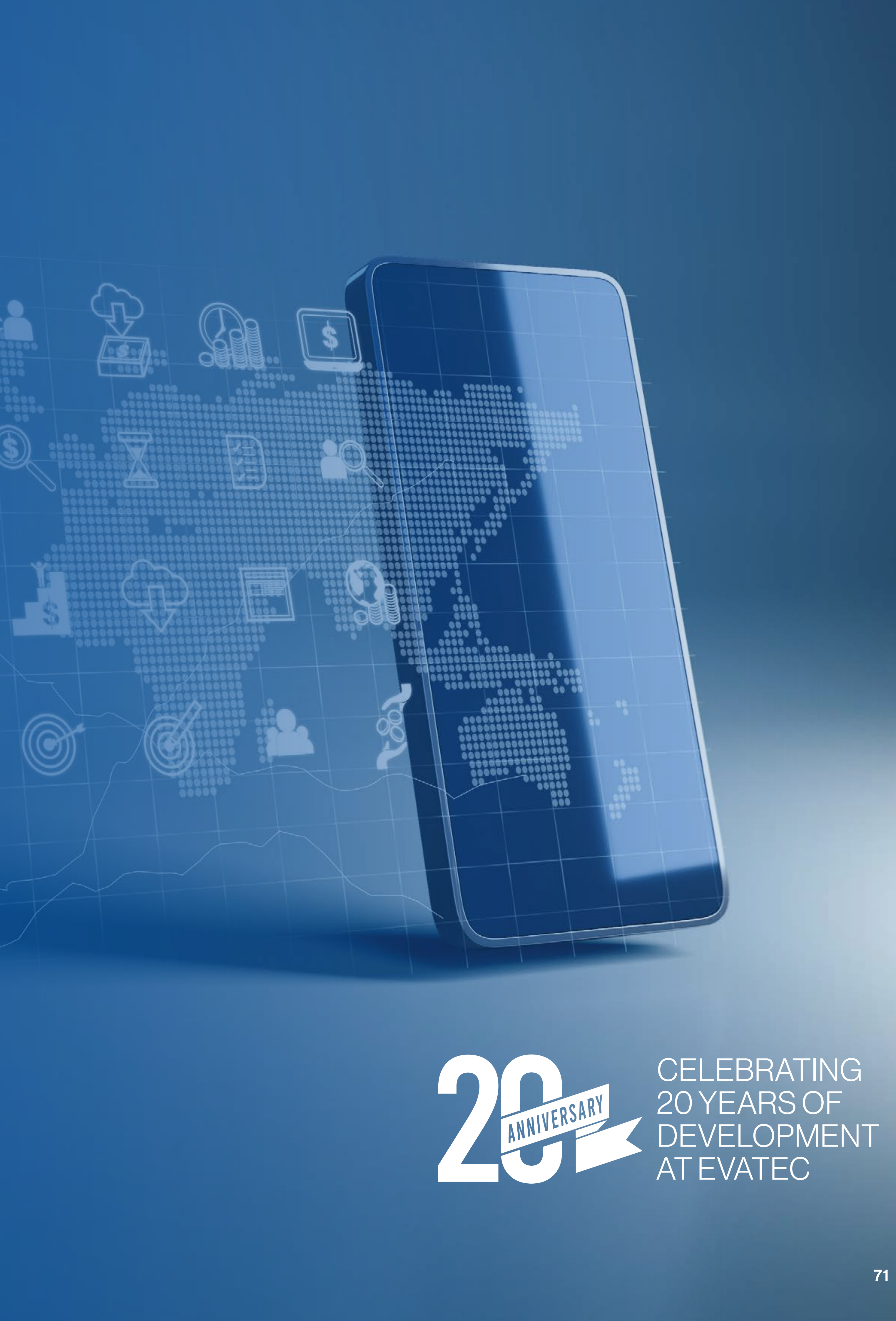
SEMICONDUCTOR & ADVANCED PACKAGING

New thin film solutions – from next-generation glass core IC substrates to Si & WBG Power

COMPOUND & PHOTONICS

From Quantum Computing to Metalenses, Micro LEDs to Solar Cells – Get the latest news

COMPOUND & PHOTONICS NEWS



CELEBRATING
20 YEARS OF
DEVELOPMENT
AT EVATEC

Slowly but surely, Quantum Computing will transform industry and society

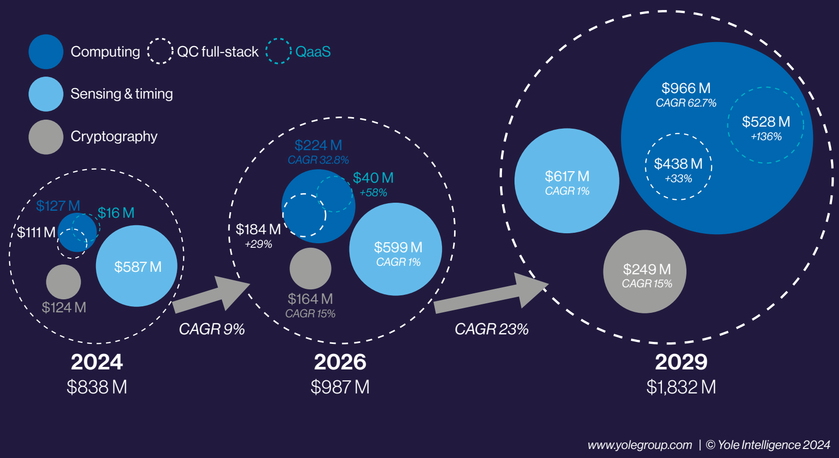
Dr. Eric Mounier of Yole Group talks about both the market potential and supply chain challenges to be overcome to see the successful launch of Quantum Computing Services in the next decade.

In recent years, there has been significant excitement surrounding quantum technologies. Quantum effects can be harnessed for various applications, including ultra-sensitive sensors like gravimeters and atomic clocks, and ultra-secure communication (cryptography). However, the application that garners the most attention and funding, both from private and public sources, is quantum computing. The primary advantage of quantum computers lies in parallelization, enabling simultaneous calculations that offer substantial time and energy savings, along with enhanced computing power.

The potential applications of quantum computing span various sectors, including finance (for anticipating financial risks), healthcare (reducing the time and cost of discovering new drugs, which currently takes 10+ years and billions of dollars), optimizing materials for electric vehicle batteries, and, of course, defense. Consequently, quantum computing has become a strategic priority for countries worldwide, leading to significant investments in research and innovation. Global investments in quantum science and technology currently approach $30 billion, with notable contributions from the USA, China, and Europe (about $5 billion each).

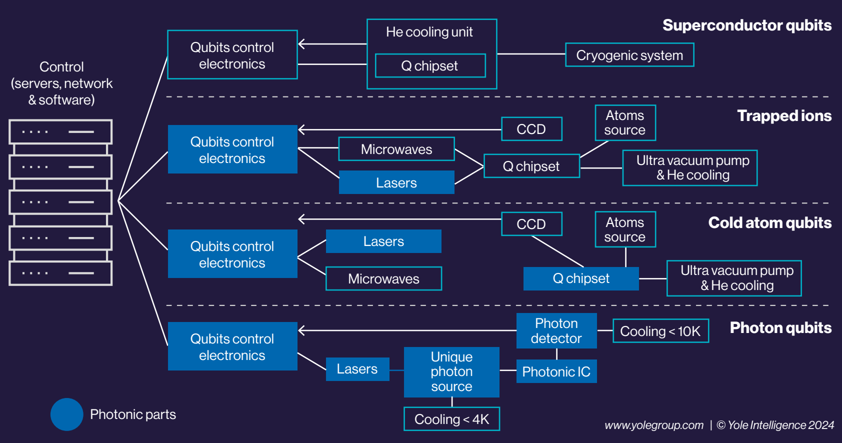
2024-2026-2029 Quantum Technologies Forecast

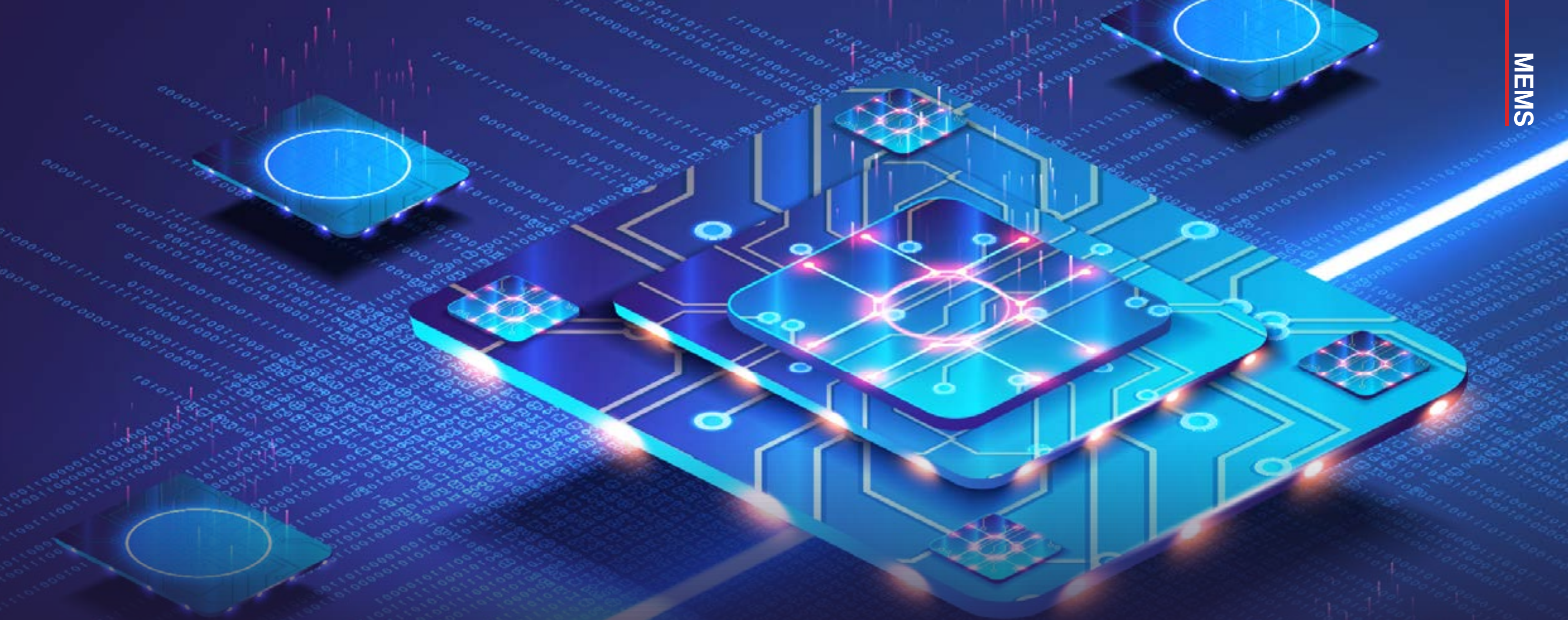
Source: Quantum Technologies report, Yole Intelligence, 2024



The different architectures of Quantum Computers

Source: Quantum Technologies report, Yole Intelligence, 2024





On the supply chain side, the quantum ecosystem is maturing and strengthening through collaborative research projects, the development of patent portfolios, the establishment of startups, and the involvement of semiconductor vendors and equipment makers such as Intel, TSMC, GlobalFoundries, Xfab, and SkyWater. Today, a handful of companies, including D-Wave, IonQ, Rigetti, PsiQuantum, and Xanadu, dominate nearly 70% of global funding in this domain. Each year sees the emergence of numerous quantum startups, primarily in computing, and a complete supply chain is being set up at each level: software, materials, tools, devices, systems, and end-users.

However, the path to achieving quantum supremacy is fraught with challenges. In the quantum world, the equivalent of a bit is a qubit, which can exist in a superposition of both 0 and 1. Qubits are, unfortunately, highly sensitive to errors induced by external factors such as temperature and radiation, necessitating operation in ultra-cold environments. Consequently, quantum computers are highly complex systems with a current price tag of about $15 million. We do not foresee a dramatic cost reduction in the short term.

While practical use cases for quantum computing are still far from being realized, technological developments are progressing well despite the continuous race to achieve the largest number of qubits. We estimate that by 2030, a few dozen quantum computers will be operational worldwide for private use (finance and defense industries are quite eager to have their own quantum computers on-premises for security reasons) and installed at quantum manufacturers' sites that will rent quantum calculation time (QaaS or "Quantum as a Service" business model).

Optimism about the success of quantum technology persists, fueled by significant technological advancements and investments worldwide. Quantum computing hardware is projected to grow from $111 million in 2024 to $438 million in 2029 (26% CAGR). QaaS will increase from $16 million in 2024 to $528 million in 2029 (85% CAGR). Beyond 2030, we forecast the quantum computing market will total $3.74 billion in 2035 (both hardware and service). QaaS (Quantum as a Service) will constitute the major share of this value, with most services running on quantum computers in the cloud. It will grow much faster than quantum computer hardware as we expect to see more use cases being developed for quantum computers before 2030.

About the author

Eric Mounier, Ph.D., is Chief Analyst, Photonics & Sensing at Yole Group.

With more than 30 years' experience within the semiconductor industry, Eric provides daily in-depth insights into emerging semiconductor technologies such as quantum technologies, the Metaverse, terahertz, photonics, and sensing.

Based on relevant methodological expertise and a significant technological background, Eric works closely with all of Yole Group's teams to highlight disruptive technologies and analyze business opportunities through technology & market reports and custom consulting projects.

Eric has spoken at numerous international conferences, presenting Yole Group's vision of emerging semiconductor technologies, markets, and applications. Previously, Eric held R&D and Marketing positions at CEA-Leti (France).

Eric Mounier has a Ph.D. in Semiconductor Engineering and a degree in Optoelectronics from the National Polytechnic Institute of Grenoble (France).

BAW technology – AlScN based RF filters

Helping customers keep the lead in 5G and beyond

Evatec Product Marketing Manager for Wireless applications ***Dr. Oguz Yildirim*** shows how the latest thin film processes for deposition of both piezoelectric layers and electrodes are helping customers keep leading performance in BAW filter technology.

CLUSTERLINE® 200 – The market leader in BAW

Evatec is already well established in delivering thin film production solutions for BAW technology. Previous edition of *LAYERS (LAYERS 6, page 60)* have already reported on the work developing production tools and processes for deposition of high Sc content Piezoelectric films of up to 30%. Today there are more than 150 Evatec modules working in 24/7 production around the world at uptimes higher than 95%. CLUSTERLINE® 200 which can be equipped with up to 6 single process modules and front end cassette or SMIF ports and ARQ 151 cathode technology utilizing 304mm diameter targets is the workhorse to deliver the excellent WiW thickness and stress uniformities demanded by our customers. Now however, our new generation ARQ320 cathode provides even better uniformities and longer lifetimes, improving the cost of ownership (CoO) by one more step.

Bulk acoustic wave (BAW) filters used in RF front end modules enables high speed, large bandwidth data transfer rates in our mobile phones paving the way for 6G, next generation communication (see Figure 1). BAW devices are based on a piezoelectric thin film excited via bottom and top electrodes that are in contact with the piezoelectric layers.

Figure 1: Bulk acoustic wave (BAW) filters.

8 out of 10 mobile devices on the market equipped with BAW RF filters contain Evatec layers

Piezoelectric layers

Taking AlScN performance to the next level by moving to Sc content >30at %

The ongoing move towards transferring larger amounts of data at even higher operating frequencies calls for higher scandium content and thinner films but this must be achieved without compromize on film quality. Average stress and its variance across the wafer must remain under control and film surface quality must be kept free of abnormally oriented grains typically seen at higher Scandium levels. And all this without any compromize on very low levels of edge exclusion on the wafer to maintain manufacturing process yield. Figure 2a shows the gains in piezoelectric coefficient possible by moving to higher scandium content, while Figure 2b shows the variation in electromechanical coupling coefficient as a function of film stress as reported in the literature. This reminds us of the importance of achieving excellent thickness uniformity and narrow stress range across wafers in production.

Typical process performance on 200mm in production is illustrated in Table 1, allowing customers to achieve the highest wafer utilizations with edge exclusion of only 5mm.

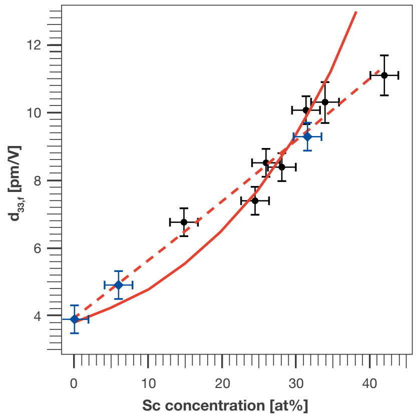


Figure 2a: $d_{33}f$ as a function of the Sc content. Solid red curve represents the value obtained from ab-initio calculation

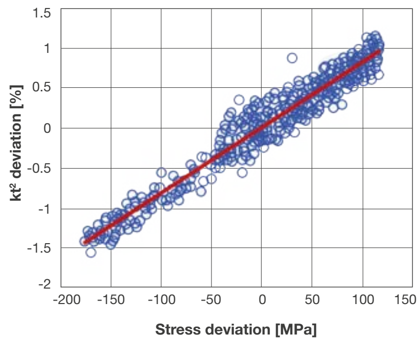


Figure 2b: Coupling coefficient vs stress for $Al_{0.7}Sc_{0.3}N$ film

$Al_{1-x}Sc_xN$ film performance on 200mm

Substrate	Film Parameter
Wafer diameter	200 mm
In film Sc concentration	Up to 39 at.%
Film thickness	500nm
Thickness uniformity (within wafer) 1sigma	<0.5%
Thickness uniformity (wafer to wafer) 1sigma	<0.3%
Refractive index @633nm wavelength	2.07
Average film stress range	-300 to +500 MPa (adjustable)
Film stress range (within wafer)	±75 MPA(@0.5% Uth) ±50 MPa (@ 1.0%Uth)
Stress repeatability (wafer to wafer)	±30 MPa
Rc <002>	< 1.5° (FWHM)

Table 1: Typical process performance

Surface quality of high scandium content films

Figure 3 shows the results by AFM obtained from $Al_{1-x}Sc_xN$ layers where x is varied from 20 at.% to levels higher than 36 at.% in the target material resulting in $Al_{1-x}Sc_xN$ layers with average Sc concentrations up to 39.7 at.%. These were produced on a CLUSTERLINE® 200 using a “manufacturing ready” single target source. These layers have been qualified at a wafer and device level. Based on the results we show the deposition path towards the experimentally achievable limit of Sc doping. However, Sc atoms in the AlN lattice can also lead to defects resulting in abnormally oriented grains (AOGs) or depending on the growth conditions phase segregation. Formation of such defects is the biggest challenge for growing highly uniform, stress neutral $Al_{1-x}Sc_xN$ thin films while can already offer production ready solution for Sc concentrations up to ~40at.%.

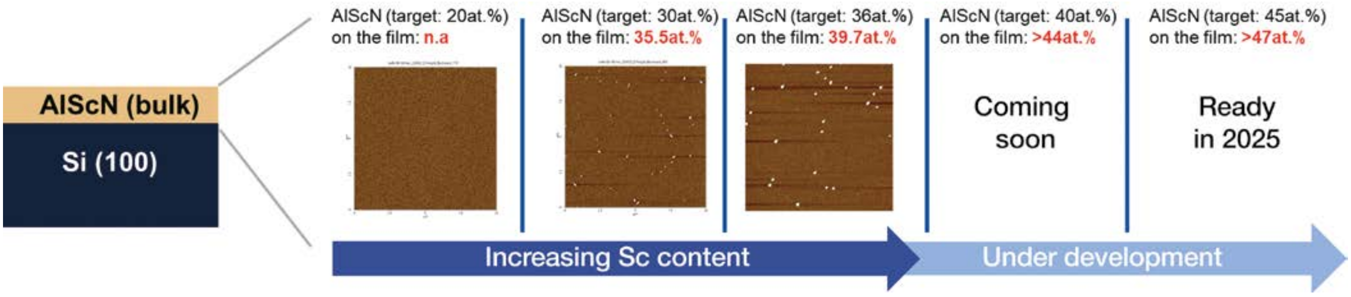


Figure 3: AFM image of $Al_{1-x}Sc_x$ N layers for varying Sc doping levels and 500nm thickness. All these layers were grown during production simulation depositions on 8 inch wafers, and have thickness uniformities <0.5 % (1 sigma), neutral average stress and stress range <150MPa. Sc concentration of the target consistently varies from the measured average Sc concentration in the film.

Electrodes

Delivering the best piezoelectric layers may rightly get lots of attention, but that's not the whole story and we can provide unique solutions for electrode production that provides flexible processes.

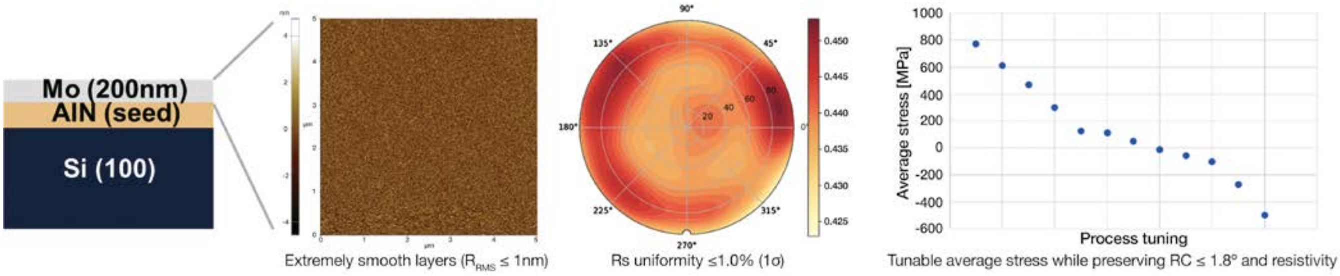


Figure 4: Performance of standard production solution of Evatec Mo layers grown on polycrystalline seed layers. From left to right are; schematic of layers, AFM image, Rs map and average stress data. Average stress is tuned while the other layer properties kept the same.

Current state of the art

Evatec's existing hot Electrostatic Chuck (ESC) technology is already well known as a standard production solution for tuneable electrode deposition processes delivering smooth, highly conductive layers and controlled stress. Our standard production solution gives the flexibility to tune the average stress of the electrode layers while maintaining the basic film performance such as the crystal quality, resistivity and uniformities. Typical results are shown in Figure 4. Further development can be done utilizing our unique sputtering based epitxial seed layer solution prior to electrode deposition. This results in a significant improvement in specific resistivity, roughness and crystal structure without increasing the deposition temperature during the growth of the Mo layer. The results are shown in Figure 5.

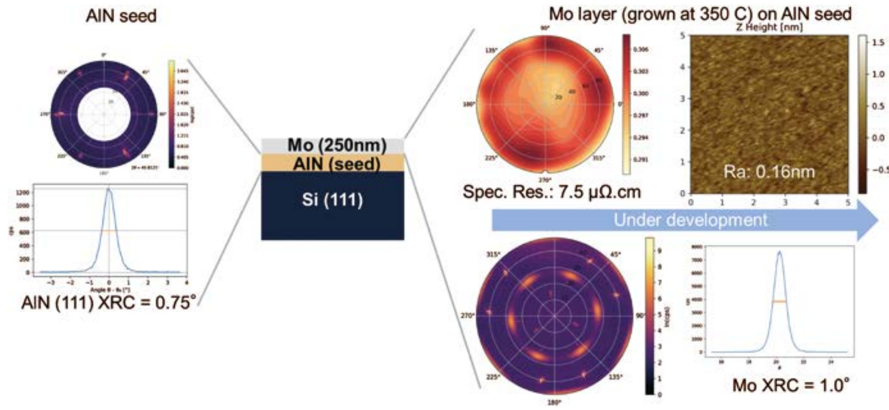


Figure 5: Properties of Epi-AlN seed layer (left) and Mo layer grown on Epi-AlN seed layer (right).

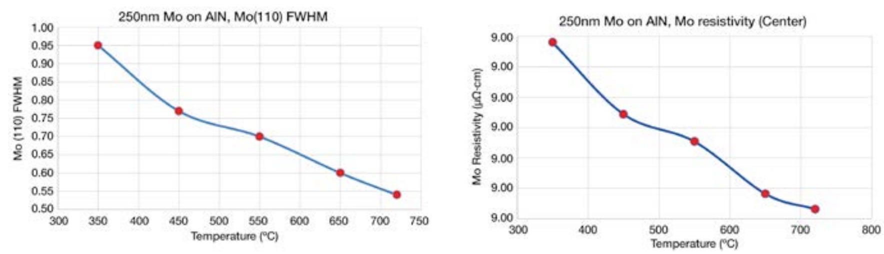


Figure 6: Properties of new generation, very hot Mo layers grown on Epi-AlN seed layers. FWHM of the Mo(110) rocking curve (left), and resistivity (right).

Electrode processes – The future is already here!

Often the electrode materials chosen for BAW applications are so-called high melting point materials comprising of elements such as W, Mo, etc. Further improvement on layers based on these materials thus require production solutions at high temperature. The most recent developments at Evatec are focused on offering customers Very Hot Chuck (VHC) capability at temperatures up to 750ºC and with it, the possibility to achieve significant reductions in resistivity and improvement in the film crystallinity that enhances the device performance dramatically as shown in Figure 6.

Multi BAK – Continuing to push boundaries in evaporation technology

It is only three years since Evatec launched the ground breaking Multi BAK concept. We took our know-how in automated handling and loadlock technology and combined it with up to 4 BAK process chambers in a clustered configuration. This brings even greater levels of process repeatability and enhanced throughput for high volume applications. Evatec Manager Customer Engineering ***Marco Stupan*** tells us about the latest Multi BAK platform capability developments giving customers across typical applications in wireless, power and optoelectronics even greater production choice.

New capabilities in substrate handling

The original platform based on Atmospheric Front End Module (AFEM) with cassette ports was launched in 2021. Since then we have added Standard Mechanical Interface (SMIF) ports as an alternative load port solution. This configuration has enabled handling of thinner wafers and is ideal for those customers looking to integrate the tool within fully automated fabs. The single process module configuration BAK911 with manual wafer loading also remains available. Table 1 compares the substate management capabilities of each configuration in the portfolio.

	BAK 941E – AFEM with Cassette Loadports	BAK 941E – AFEM with SMIF Loadports	BAK 911E – Manual Wafer Loading
Supported wafer sizes	150mm, 200mm	150mm, 200mm	Any type that fits on the calotte
Fully automatic wafer handling	✓	✓	✗
Mixed Operation of different wafer sizes (Bridge tool)	✓	✗	✓ (manual loading)
Substrate Introduction	Open cassette with vertically oriented substrates	SMIF pod or adapter pod for cassette loading	Manual loading of pre-loaded calotte segments or directly substrates
Aligner Type	In cassette batch aligner	Single wafer chuck type aligner	n/a
Warped / bowed wafers	✗	✓ (max ~3mm)	✓
Wafer Thickness	>250µm	> ~120µm	Any
Wafer ID reader	✓	✓	✗

Table 1

Material Management

To maximize throughput of these systems we need to optimize material management, extending the time between process chamber venting for refill of sources. Multi BAK can now be equipped with single or twin electron beam guns with multi pocket crucibles and wire feeders to achieve a maximum amount of process runs before it's needed to vent the chamber for refilling and cleaning.

The Multi BAK – delivering other benefits too!

To maximize throughput of these systems we need to optimize material management, extending the time between process chamber venting for refill of sources. Multi BAK can now be equipped with single or twin electron beam guns with multi pocket crucibles and wire feeders to achieve a maximum amount of process runs before it's needed to vent the chamber for refilling and cleaning.

SAVE ENERGY

"Multi BAK – reducing energy consumption compared with conventional stand alone platforms by up to 60%"

SPOTLIGHT ...Multi BAK

Why Multi BAK?

It is all about automation and throughput!

The driving force at the time of the platform launch in 2021 was to remove manual wafer loading by the operator and to increase the throughput. Evatec's LLTM technology essentially eliminates the pump down time out of the throughput equation.

The AFEM removes all human handling of wafers to load the calottes and provides a high class clean room environment to do so. Table 2 shows how throughput compares between a traditional system and a system equipped with LLTM based on the evaporation process times.

PROCESSING TIME (min)	CLASSIC BAK (Batch/h)	BAK WITH LLTM (Batch/h)	BENEFIT FACTOR
20	0.67	1.76	2.6
40	0.55	1.11	2.0
60	0.46	0.81	1.8
90	0.38	0.58	1.5
120	0.32	0.45	1.4
180	0.24	0.31	1.3
240	0.19	0.24	1.2

Table 2

One concept – Multiple configurations optimized for your process and throughpout

Designed for up to 4 process chambers the Multi BAK delivers:

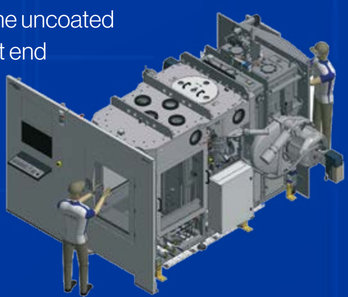
- Front end automation of wafer loading (6 or 8 inch), directly from cassettes to calotte segments in a controlled environment eliminating risk of operator errors and reducing risk of particles, wafer damage or breakage
- Automated substrate journey management to ensure a return of each substrate to the original cassette and slot.
- Wafer ID reading on the fly
- Tracking of each and every wafer to an individual location, segment or process batch

Watch the Multi BAK video

Starter configurations are available too

For single process chamber configuration the system can also be configured with manual segment loading and removal, but still with the same LLTM technology to retain the benefits of higher throughput and reduced energy consumption.

- The complete process chamber remains under vacuum continuously, delivering the most stable process environment possible for even greater levels of process repeatability when required
- The only elements entering and leaving the process chamber during production are segments loaded with wafers. They enter and leave the process chamber via a LLTM
- Rapid pump and transfer in this step offers a great opportunity to make additional overall gains in throughput
- Sources replenished by the wire feeder remain under vacuum in a ready state for the highest stability. Opening of the process chamber itself is then limited to periodic maintenance such as pocket cleaning and shield change
- An operator loads and unloads the uncoated and coated segments at the front end



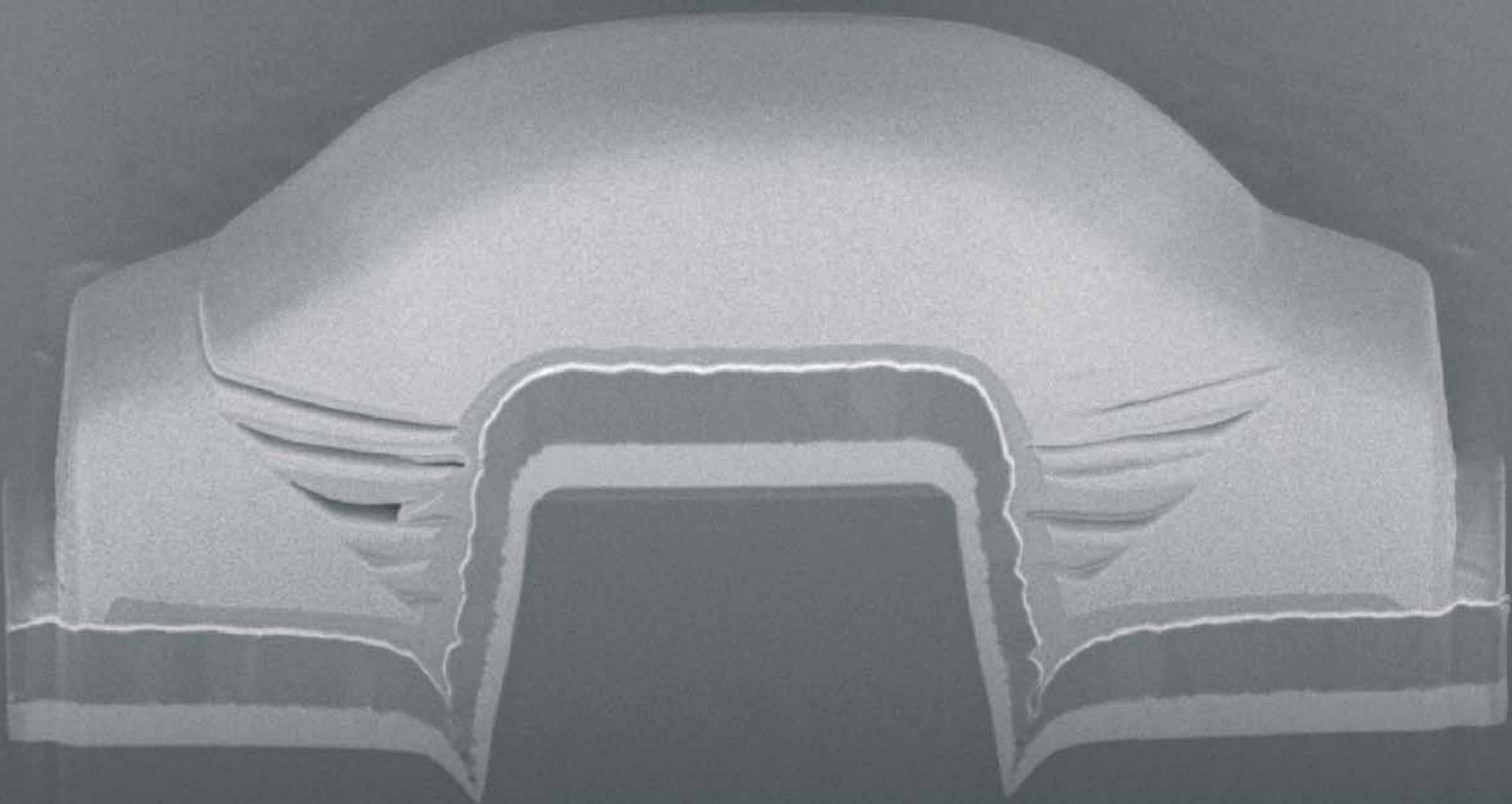
Watch the BAK 911 video

Want to know more about the Multi BAK?

Contact your local Evatec sales and service office to find out more.

Side Wall coverage – maximizing performance in new generation optoelectronic devices

Head of Business Field Compound & Photonics, ***Jakob Bollhalder*** explains why device side wall coverage is becoming important for thin film processes in Optoelectronic applications like Micro LED and how Evatec thin film solutions on CLUSTERLINE® can deliver just the performance required.



It's all about maximizing device performance

As device architectures get smaller, the output area of the device front surface gets smaller too, and that means that any light losses from side walls which would normally not be critical for larger devices start to represent a bigger and bigger proportion of the overall light output. But there are other factors to consider too! As device architectures shrink to 50 microns and lower, so does device volume to surface area ratio. Protecting the device by effective side wall coverage becomes important to avoid device performance degradation and maximize lifetime.

Figure 1a: CLUSTERLINE® 200 equipped with single process modules and FOUP

Figure 1b: CLUSTERLINE® 200 BPM equipped with Batch Process Module

CLUSTERLINE® 200 is the solution

Evatec's CLUSTERLINE® family is already a proven workhorse in the optoelectronics industry for applications including Micro LED, Mini LED and Edge-emitting Lasers (EELs). Processing of 200mm wafers either direct or on carriers makes it a flexible choice for sputter deposition of metals, TCOs, DBRs and passivation layers. Cassette-to-cassette configuration eliminates manual handling avoiding the risk of wafer breakage and reduces particles to the levels essential for high yield production of small scale devices. Different typical system layout for applications in optoelectonics are shown in Figure 1 for either single substrate or batch processing. Systems can be equipped with Advanced Process Control techniques like GSM broadband optical monitoring for layer termination and PEM plasma emission monitoring for control of film stoichiometry and maximizing deposition rates according to customer process. The systems are equipped with Evatec's proprietary cathode technology to deliver optimized side wall coverage.

Characterizing side wall coverage process performance

Every customer has their own unique device architectures and process requirements. Mapping performance of our tool and processes helps us be ready for whatever requests come our way. Figure 2 shows how we typically map side wall coverage performance on 8 inch substrates using a series of structures – pillars, trenches or vias of different dimensions.

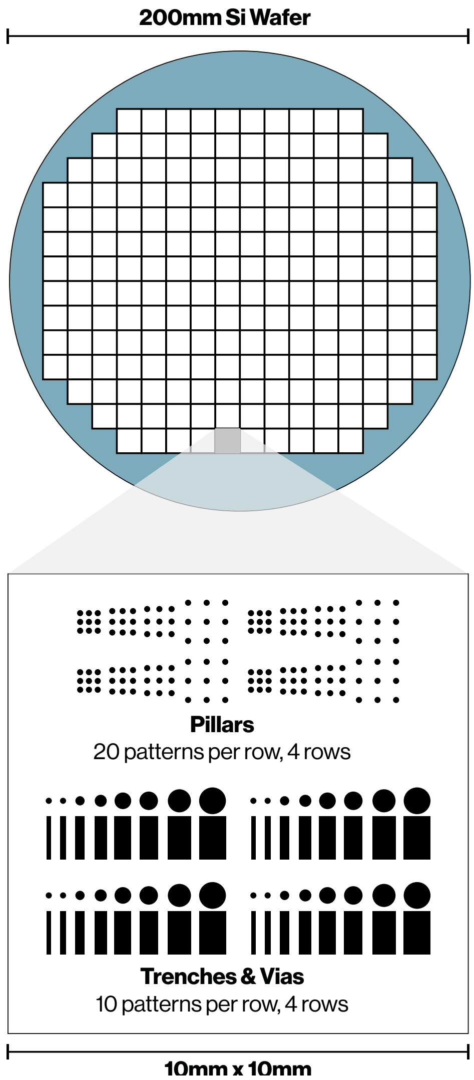


Figure 2: Side wall coverage performance test structures on wafer

Results so far

MicroLED technology

Figure 3a shows the architecture of a typical Micro LED while Figure 3b shows the excellent side wall coverage for ITO and metal layers when deposited on test structures using Evatec's propriety cathode technology.

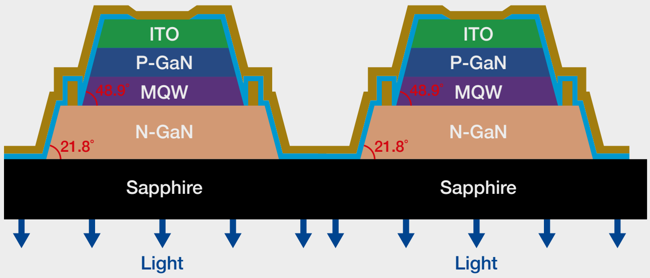


Figure 3a: Typical MicroLED architecture with side wall coverage for improved light extraction efficiency and passivation layer for device protection

EEL technology

MicroLED is just one area where innovations in coating processes for side wall coverage can be beneficial. New wafer level manufacturing approaches for edge emitting lasers eliminate the need for the processing of so called "laser bars" within complex mechanical jigs. Diode structures can be created within the wafer itself by lithography, etch and deposition stages and can then can have opposing facets (side walls) coated with the required high reflectivity (HR) or antireflection (AR) coatings whilst still at wafer level.

Figure 4 illustrates a typical process flow for EEL manufacturing according to two different manufacturing methods. In a traditional approach so called laser bars have to be assembled in a jig, coated on the first side then flipped and coated on the second side. In the Wafer Level Approach, photo-lithograph and etch steps are followed by coating steps to prepare devices over the whole wafer before final testing and dicing.

Traditional approach

*In a **traditional** approach so called laser bars have to be assembled in a jig, coated on the first side then flipped and coated on the second side.*

Wafer level approach

*In the **Wafer Level** approach coating technology for effective side wall coverage enables elimination of complex tooling and reduces overall process complexity.*

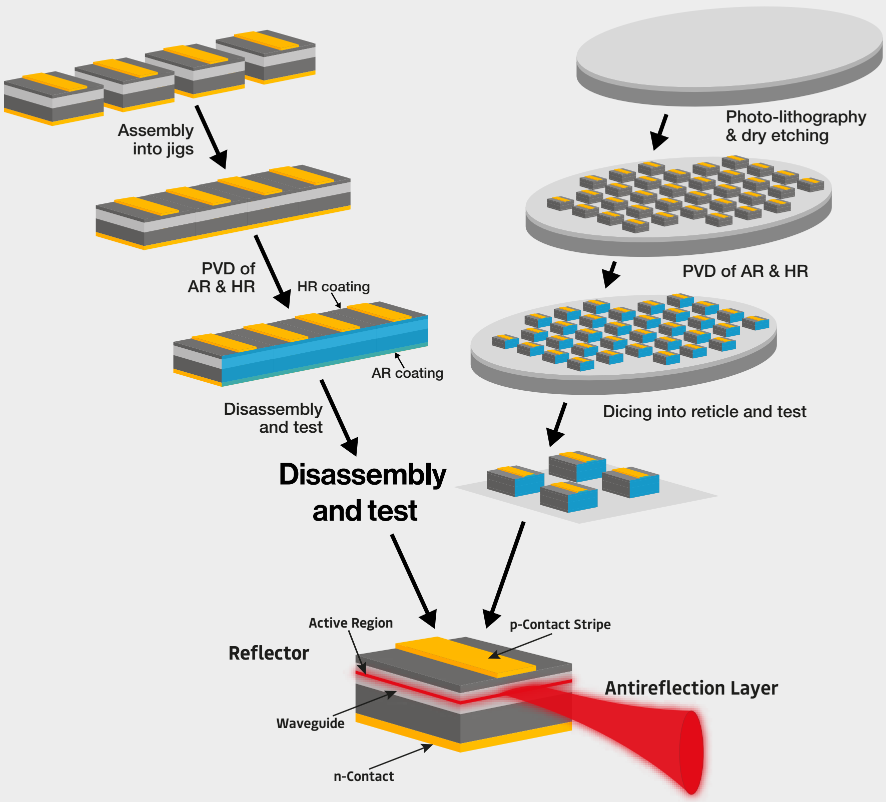


Figure 4: Typical process flow for EEL manufacturing

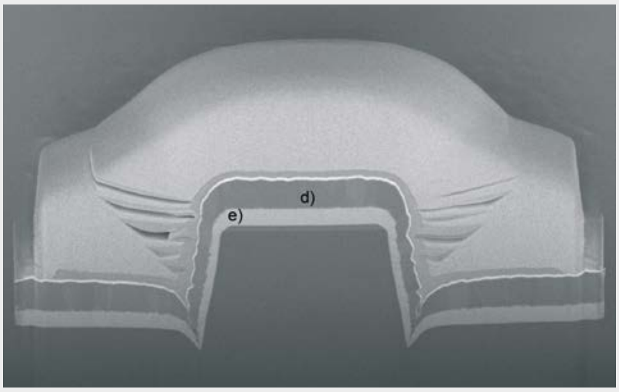
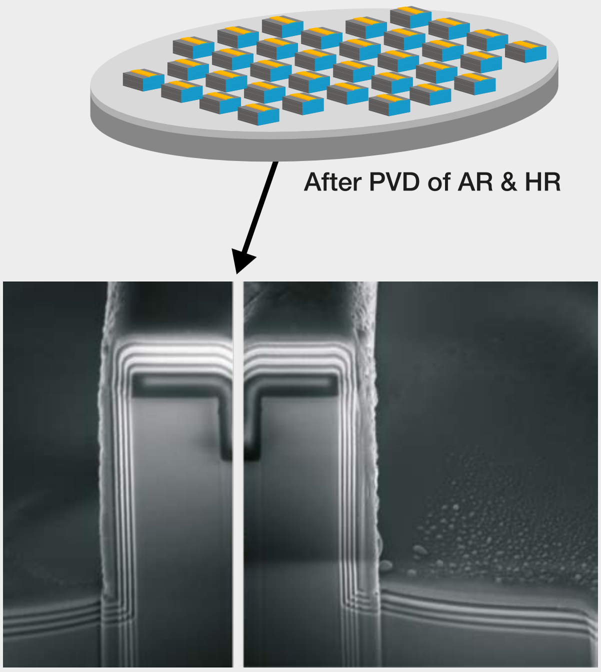


Figure 3b: Test structure deposition – d) Evatec Al; e) Evatec ITO



- Same result for both active sides
- Clear and smooth layer separation
- Equal single layer thickness on side wall
- Side wall coverage 60% of top thickness

Want to know more?

Our applications team would love to talk to you about the work we have been doing and find out how new approaches can support your own efforts in driving down manufacturing costs or improving process performance.

Contact us via your local Evatec sales and service office for more information
https://evatecnet.com/about-us/sales-service/

CLUSTERLINE® Family

YouTube

CLUSTERLINE® 200 BPM

YouTube

Hybrid DBRs – One process change brings two benefits for Micro LED production

Evatec Senior Product Marketing Manager ***Dr. Chongqi Yu*** talks about Evatec's latest process developments in Micro LED technology delivering both, 1 the lower cost of ownership and 2, the more compact structures that will help drive growth of mass market applications exploiting the benefits of Micro LED technology.

Micro LED – The benefits are clear

The performance advantages of emerging Micro LED including excellent brightness, contrast, and viewing angle are already well documented (Figure 1), but that doesn't mean we don't need to support our partners around the globe with process innovations that enable the introduction of the technology across mass market applications including Augmented Reality in 2025 and beyond.

Micro LED technology and production trends reported by both leading players in the industry and confirmed by analysts like Yole Group are calling for both smaller and smaller device sizes and the lowering of manufacturing costs. Production on larger wafer sizes is just one aspect driving down manufacturing costs but the introduction of so called "Hybrid DBR" process technology is an exciting next step with double benefits, on one hand enabling thinner structure / total device thickness and on the other reducing the normal process times for DBR deposition.

"Hybrid DBR processes – Increasing wafer throughput by 50% and reducing the total thickness by half"

MicroLED vs. OLED and LCD

	LCDs	OLEDs	MicroLEDs
Energy consumption	Medium	Medium	Medium to Low
Pixel density	Up to 1000 PPI	Up to 4,000 PPI (RGB for micordisplays)	> to 20,00 PPI monochrome demonstrated >4,500 PPI RGB demonstrated
Brightness	High (3000 nits peak on commercial TV)	Lowest [1]	Highest (up to 10^6cd/m^2 for microdisplays)
Contrast	Low to medium	High (true black)	Very high (true black + high brightness)
Color gamut	Wide with QDs	Wide with filters, resonant cavities	Wide (better with QD color conversions)
Lifetime	Good	Medium	Best
Environmental stability	Good	Medium with appropriate encapsulation	Best
Operating temperature	-40ºC to 100ºC	-30ºC to 85ºC	-100ºC to 120ºC
Switching speed	Low - ms	High - µs	Very high - ns
Viewing angles	Low to medium	Medium to high	High
Flexibility	Low	High	Medium
Maturity	High	Medium	Low
Cost	Low	Medium	High (2022)

Figure 1: Comparison of competing display technologies in consumer applications (Courtesy of Yole Group)

DBRs – Choosing the right thin film production platform architecture as a starting point

Process yield is also one of the significant drivers in driving down manufacturing costs, and that means using fully automated cassette-to-cassette processing for the lowest particle levels. But that's not the end of the story, the growing demand for sputter technology, with its higher film densities and process stability offers the potential for the best process repeatabilities.

Evatec's CLUSTERLINE® 200 BPM is already established as an industry standard sputter solution in the LED business for deposition of low damage TCOs and now its time to use the latest hybrid DBR process solutions for driving down manufacturing costs and thinning down the total layer thickness for high performance reflector layers too. A typical tool layout for Hybrid DBR processes is shown in Figure 2.

Hybrid DBRs – More throughput and thinner total thickness without compromise in optical performance

Hybrid DBR process technology delivers the required optical performance by combining a dielectric stack with a metal layer on either front or backside according to the Micro LED manufacturers preferred architecture. Less layers means shorter process times, higher throughputs and smaller scale device architectures. The typical RGB optical performance for Hybrid DBRs combining traditional dielectric stack with a silver layer is show in Figure 3.

In Figure 4 we see a comparison of overall stack thickness, process time and throughput for hybrid vs traditional sputtered DBRs on Evatec's CLUSTERLINE® 200 BPM configured for 8 inch processing. Throughput can typical be enhanced by 50% or more across all colours on 6 or 8 inch processing, and the total layer thickness of the mirror can be reduced by 50%. The results reported in Figure 4 are for hybrid DBRs utilizing silver, but for those customers preferring aluminium we can offer process solutions too – all you need to do is ask!

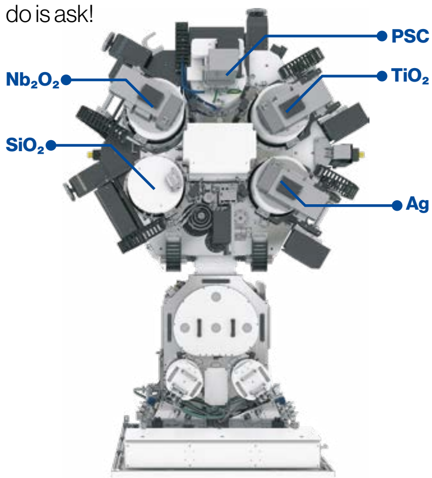


Figure 2: CLUSTERLINE® 200 BPM equipped with up to 5 process modules for depositon or etch or optical thin films with advanced process control technologies including broad band optical monitoring and plasma emission monitoring.

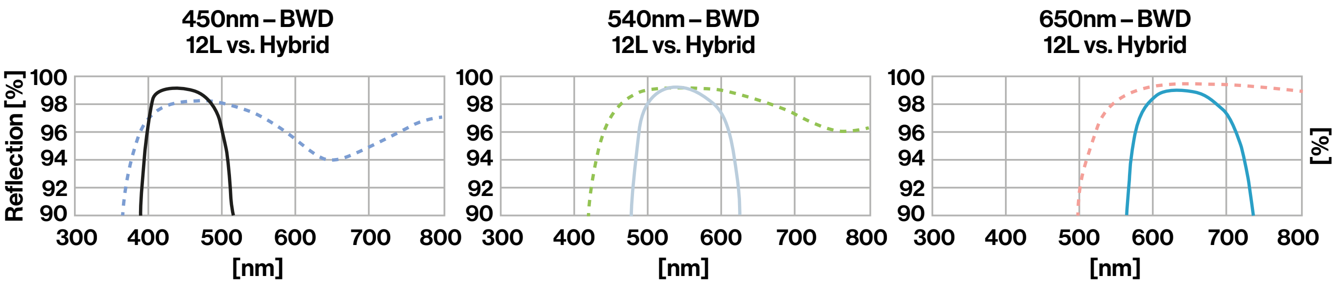


Figure 3: Optical performance of Hybrid stacks (- - -) for blue, green and red vs traditional DBRs (—)

	Blue – 450nm		Green – 540nm		Red – 650nm	
	12L	Hybrid 5L	12L	Hybrid 5L	12L	Hybrid 5L
End layer	SiO_2	Ag incl. Capping	SiO_2	Ag incl. Capping	SiO_2	Ag incl. Capping
Number of dielectric DBR layers	12	4	12	4	12	4
Total thickness (including Capping)	797.4 nm	529.8 nm	987.3 nm	586.96 nm	1177.2 nm	622.02 nm
Process time (tool time w/o handling) + Ag Capping	01:11:23	00:38:32	01:20:53	00:41:33	01:30:43	00:43:10
Resuts Sputtering on D263						
Max Reflectivity @nm	99.33% @ 437nm	98.90% @ 461nm	98.99% @539nm	99.30% @ 552nm	98.77 @ 637nm	99.54% @ 664nm
Reflectivity @nm – (Bwd)	99.23%	98.85%	98.96%	99.26%	98.65%	99.50%
Range of Reflectivity	>98% @ 405-483nm >99% @ 417-463nm	>98% @ 399-554nm	>98.8% @ 517-556nm	>99% @ 487-622nm	>98% @ 597-678nm	>99% @ 553-819nm
Stopband width	78nm @98% 46nm @99%	155nm @98%	39nm @99%	135nm @99%	81nm @98%	266nm @99%
Throughput 8”						
Substrates / h	9.1	13.7	8.2	13.1	7.5	12.6
Substrates / month (48 weeks/y, 85% uptime)	5198	7825	4684	7483	4284	7197
Throughput 6”						
Substrates / h	12.1	17.6	11	16.9	10	16.4
Substrates / month (48 weeks/y, 85% uptime)	6912	10053	6283	9653	5712	9368

Figure 4: Comparison of throughput for standard vs hybrid DBR

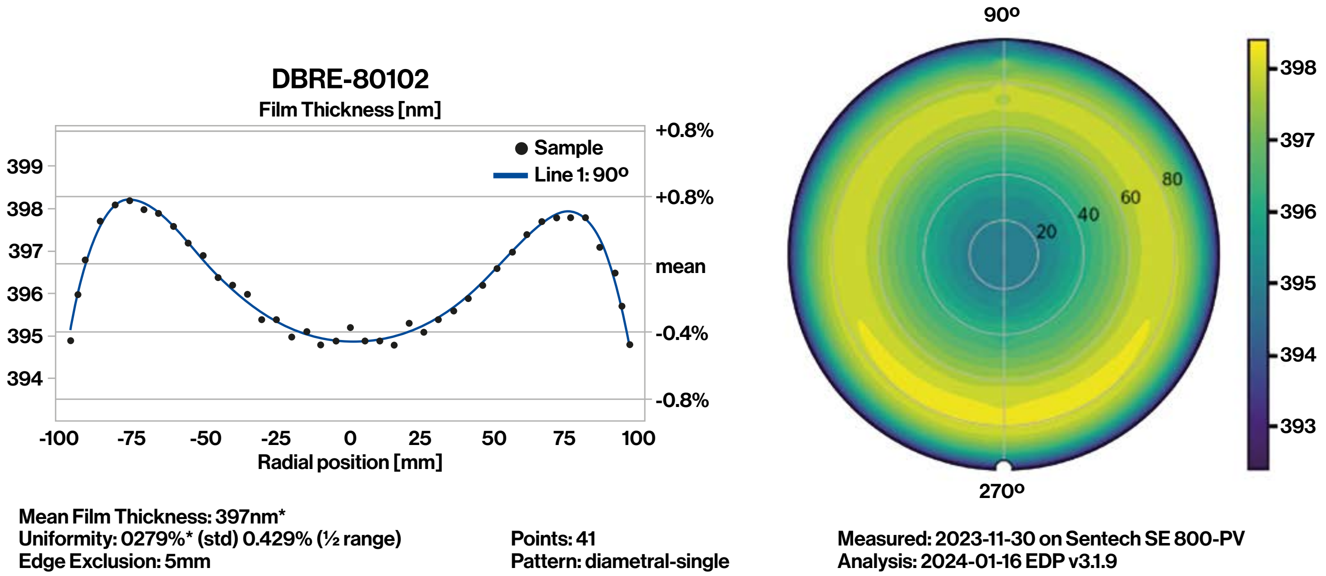


Figure 5: Deposition uniformity of SiO_2 on CLUSTERLINE® 200 BPM < ± 0.5% over 8 inch.

Base system performance is key

The benefits of reduced process times, high deposition rates and enhanced throughput can only be achieved if base system performance including deposition uniformities and run to run process repeatability meet the required Micro LED standards. CLUSTERLINE® 200 BPM uses advanced process control (APC) technologies including in-situ broadband optical monitoring (GSM) of the substrate itself plus plasma emission monitoring (PEM) combined with dynamic sputter architecture without shapers to deliver the levels of process control required.

Figure 5 illustrates typical film thickness uniformity for deposition of dielectrics of better than ± 0.5% on 8 inch.

Figure 6a shows typical wafer in wafer, wafer to wafer and run to run repeatabilities on 6 inch of less than ± 0.6%. Figure 6b shows optical performance repeatability.

Material	Layer thickness	Thickness uniformity $U(Max\ Min)\,[\pm\%] = \frac{(Max - Min)}{2 \cdot Avg} \cdot 100$		
		WiW	WtW	RTR
SiO_2*	300nm	<±0.5%	<±0.5%	<±0.5%
Nb_2O_5*	300nm	<±0.5%	<±0.5%	<±0.5%
TiO_2*	300nm	<±0.5%	<±0.5%	<±0.5%

*with rotating Chuck, PEM & GSM

Figure 6a: Deposition uniformity achievements for single layers on 6" substrates

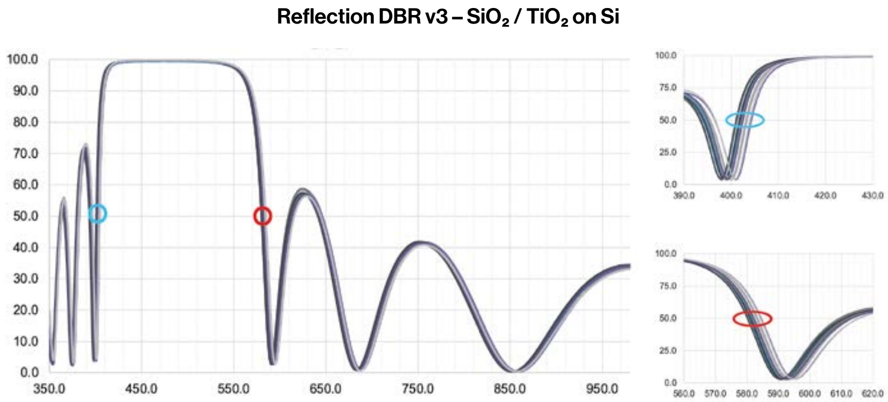


Figure 6b: Optical performance repeatability

How can we help you?

Every manufacturer has different device architectures and therefore requirements. Our LED process specialists are here to help not just with DBR solutions but also with metals and TCOs too.
Contact your local Evatec sales and service office to find out more.

A view from Yole Group

As OLED keeps improving, Apple's withdrawal increases sense of urgency for MicroLED commercialization

Apple created the MicroLED industry when it acquired startup Luxvue in 2014. It then spent ten years and $3 billion developing the technology. If it hadn't been for that keen interest, the enthusiasm since shown in MicroLED by most OEMs and display makers would have been much more subdued.

Osram completed a $1.3 billion 200 mm MicroLED fab to meet Apple's needs, and an Apple watch was scheduled for release in 2026. But in February 2024, Apple canceled the project, sending shockwaves into the industry and seriously undermining its prospects. Two years ago, this could have been the death of MicroLED. However, Yole Group believes it has now gained sufficient momentum of its own to keep going.

Exiting 2023, the industry had spent $12 billion in MicroLED directly and another $2 billion in M&As. About 40% of that total is related to Apple. Yet, other players have spent $7 billion non-related to Apple's efforts. MicroLED remains critical for the long-term strategies of Taiwanese companies such as AUO. The ecosystem is strengthening further, and MicroLEDs had a strong showing at the recent Touch Taiwan and Display Week industry events.

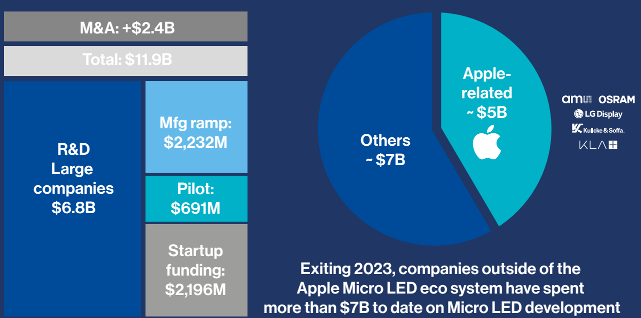
To succeed, MicroLED must reach a similar cost structure to OLED while delivering strong performance differentiation. With Apple gone, MicroLED will focus on applications with clear differentiation against OLED: AR, automotive, and various specialty applications such as transparent displays. Smartwatch forecasts are cut drastically but remain the low-hanging fruit for MicroLED in terms of consumer applications. AUO started shipping small volumes for luxury watches.

Despite Apple's project cancellation, there's still good momentum, but also a sense of urgency to accelerate commercialization. With Apple gone, the central question is how to incubate the industry. Can low-volume smartwatches, automotive, and various niche applications bootstrap the industry to achieve the economies of scale required to enable higher-volume consumer applications? This is reminiscent of OLED's situation until 2007, when Samsung bit the bullet and built the first AM-OLED fab, at a time when benefits compared to LCD were still very questionable. That's what the industry was hoping Apple would do for MicroLEDs.

The next 18 months will be critical. Will Samsung remain committed to MicroLED TVs? Can other champions emerge? For now, the industry's center of gravity has shifted toward Taiwan, but China could once again surprise us.

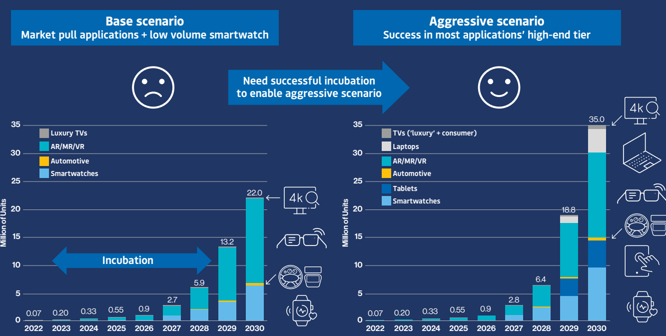
Micro LED development and industrialization effort

Source: Micro LED 2023 report, Yole Intelligence – June 2024 update



Consumer MicroLED volume forecast - intermediate 2024 analysis

Source: MicroLED 2023 report, Yole Intelligence – June 2024 update

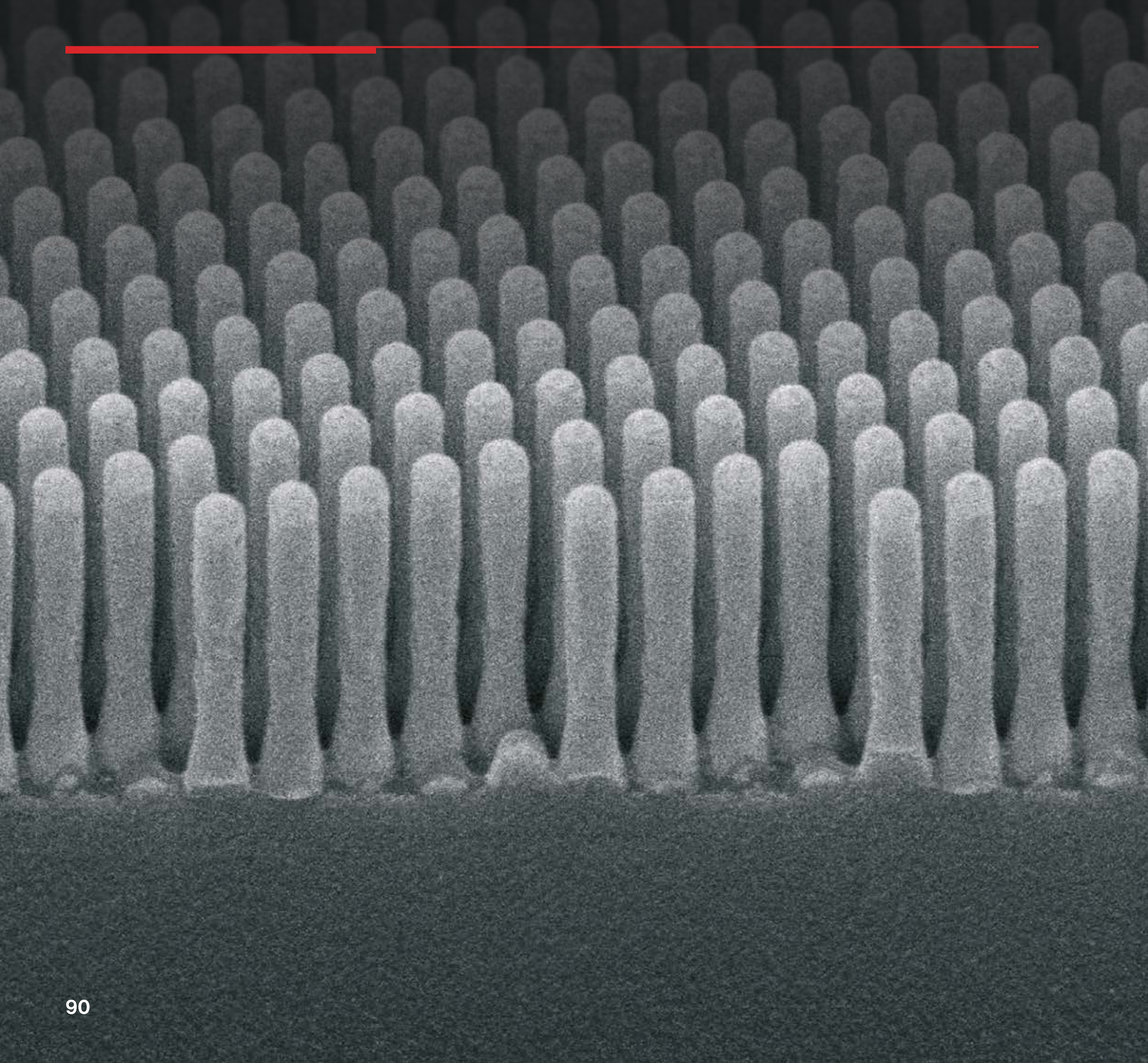


About the author

As Principal Analyst, Display at Yole Group, **Eric Virey, Ph.D.**, is a daily contributor to the development of LED, OLED, and display activities. He has authored an extensive collection of market and technology products as well as multiple custom consulting projects on subjects including business strategy, identification of investments or acquisition targets, due diligence in buying and selling, market and technology analyses, cost modeling, and technology scouting. Thanks to his deep knowledge of the LED/OLED and display industries, Eric has spoken at more than thirty industry conferences worldwide over the last five years. He has been interviewed and quoted by leading media all over the world. Eric Virey holds a Ph.D. in Optoelectronics from the National Polytechnic Institute of Grenoble.

Metalenses – a world of opportunity

Metalenses are tiny optical elements that can manipulate light like traditional lenses, but their small size, and “flat” architecture offers the potential for cost-effective manufacture at large scale using a “wafer level optics” approach at substrate sizes up to 12 inch. Senior Product Marketing Manager ***Dr. Clau Maissen*** explains how Evatec process know-how is helping customers deliver the sputtered layer qualities and process repeatability required for mass market applications



A technology with huge potential

Metalenses are at the forefront of optical innovation, transforming the way we manipulate light with their ultra-thin, flat structures. Unlike traditional bulky lenses, metalenses utilize nanostructured surfaces to precisely control light, offering unprecedented advantages in miniaturization and performance. This breakthrough technology is poised to revolutionize a wide range of applications, from enhancing the imaging capabilities of smartphone cameras and augmented reality glasses to advancing medical imaging devices with greater precision and clarity. Figure 1 illustrates how a traditional optical assembly can be simplified significantly using a metalense approach.

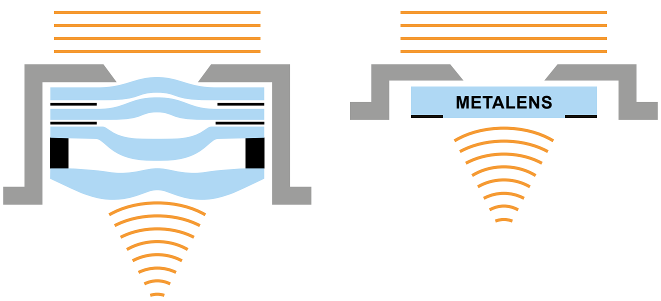


Figure 1: Metalens enable simplification

Thin film technology and wafer level optics are key

Evatec's expertise in the deposition of high-index material layers plays a crucial role in the fabrication of these advanced lenses, ensuring the uniformity and repeatability needed for high-performance optical systems. By leveraging Evatec's specialized processes, manufacturers can achieve the exacting standards required for mass-market adoption of metalenses, paving the way for a new era of optical technology.

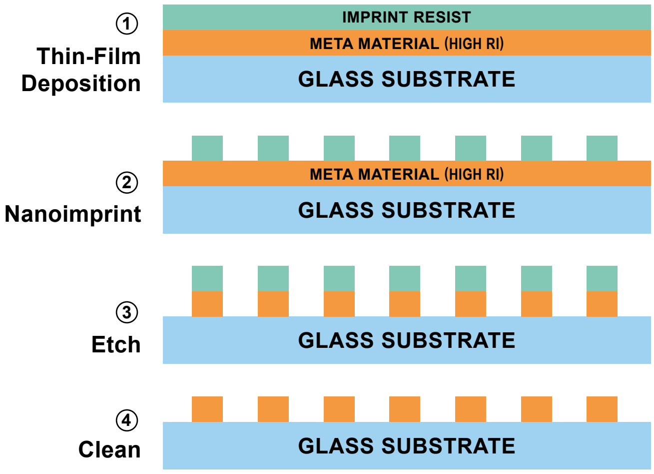


Figure 2: Example manufacturing process flow

A key advantage of metalens technology is the ability to start from a wafer. Following deposition of a high index material such as amorphous Si or metal oxides, manufacturing technologies such Nanoimprint and etch are then used to create the functional pillars "so called metaatoms" at the heart of the device. AR coatings and encapsulation layers then follow before the whole wafer is then diced to give final individual devices. Figure 2 illustrates a typical process flow.

The high index materials (e.g. amorphous hydrogenated Si for Near IR, Nb_2O_5 for visible) and pillar architectures will of course vary according to application and operating wavelength requirements. Irrespective of the application however, the ability to deposit highly uniform repeatable films of the index material up to 12 inch substrates is key.

Evatec know-how for deposition of high index materials

Evatec has long know-how in sputter deposition of high index materials on both its MSP and CLUSTERLINE® 200 BPM platforms. Use of advanced process control technologies like plasma emission monitoring ensures correct stoichiometry and high deposition rates whilst GSM optical broadband monitoring delivers precise film thickness. Typical deposition results on 8 and 12 inch substrates are shown in Figures 3a & 3b.

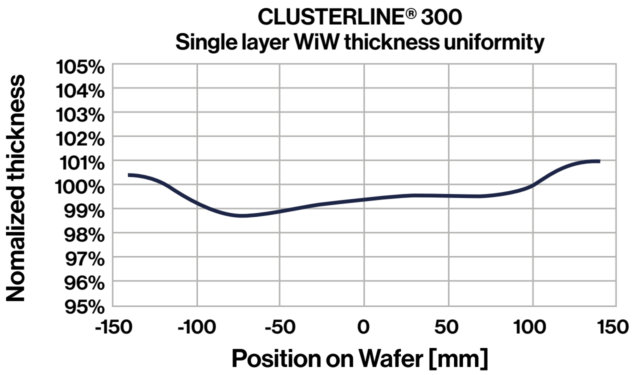


Figure 3a: aSi:H on CLUSTERLINE® 300 thickness uniformity

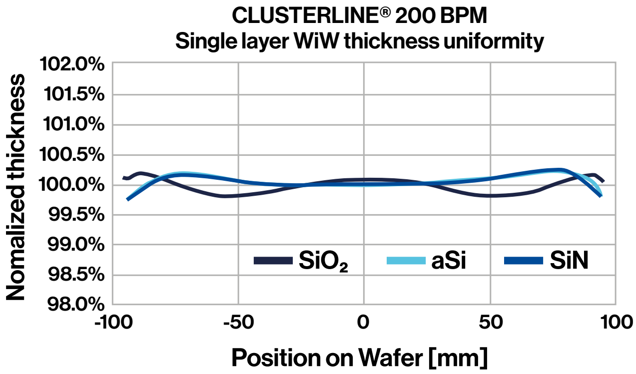


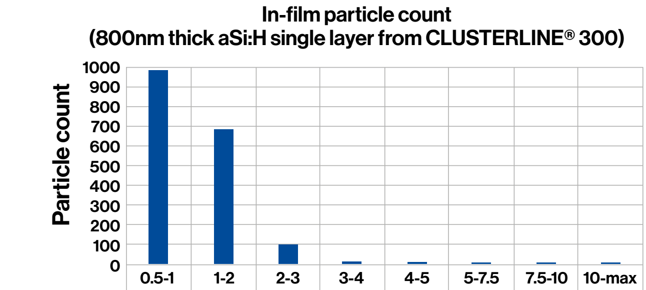
Figure 3b: SiO_2, aSi, SiN on CLUSTERLINE® 200 BPM thickness uniformity

Images in Figures 1 and 2 plus cover image courtesy of Moxtek.

Control of particles is key

Single particles can have an impact on the performance of a lens over an area up to 10x larger than the particle itself depending on the technology used to fabricate the lens. So particle control is key. Tools like Evatec's MSP or CLUSTERLINE® family which eliminate uniformity shapers from the sputter system not only enable higher deposition rates but also eliminate a significant source of particles too.

For those customers with even more demanding particle specifications the automated cassette-to-cassette handling systems of CLUSTERLINE® can improve further particle managment even more. Figure 4 illustrates typical particle data for single layer deposition on CLUSTERLINE® 300.



	0.5-1	1-2	2-3	3-4	4-5	5-7.5	7.5-10	10-max
800nm aSi:H	994	689	104	11	10	9	2	9

Figure 4: Particle data of single layer aSi

Want to know more?

For more information about Evatec coating solutions for metalense applications contact your local Evatec sales and service office at: **https://evatecnet.com/about-us/sales-service/**

MOXTEK

About Moxtek*

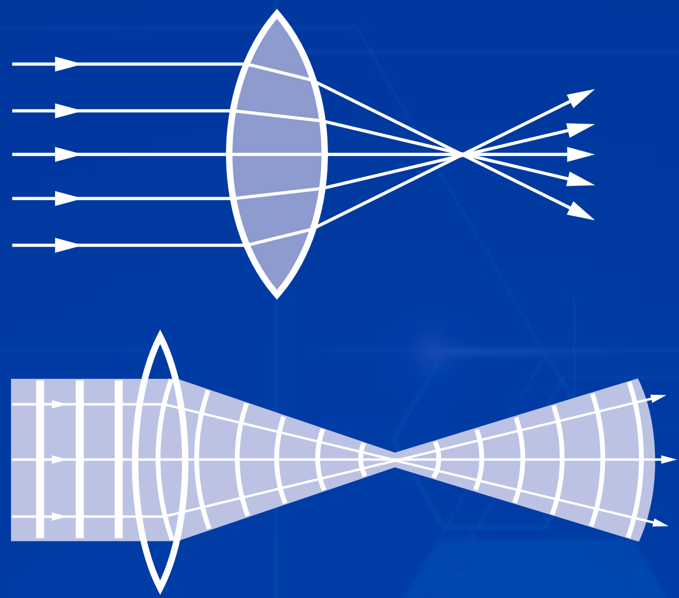
MOXTEK® is a leading developer and manufacturer of advanced nano-optical and x-ray components used in display electronics, imaging, and analytical instrumentation. Moxtek produces high volume, innovative, solution-based products that enable many new scientific discoveries and improve the quality of everyday life. Moxtek manufactures functional metasurfaces including: metalens, patterned nanostructures, Meta-Optical Elements (MOE), Diffractive Optical Elements (DOE), waveguides, photonics crystals, and biosensor arrays. Please visit their website to learn more.

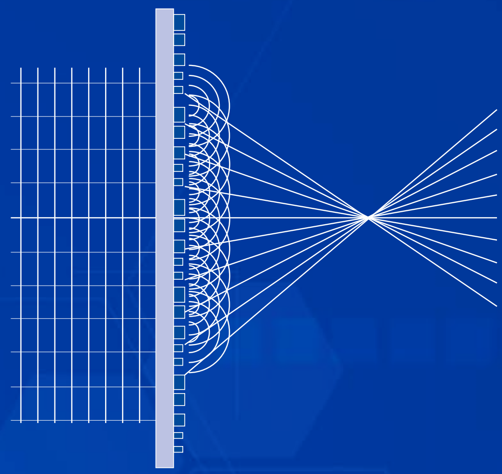
For more information visit **https://moxtek.com**

**Source: Moxtek website*

SPOTLIGHT ...METALENSES

An introduction to Metalenses





Left: Conventional refractive lens: refraction at the interface between air and lens directs the light to a focal point. Another view to the same effect is: a plane wave is converted to a spherical wave.

Right: Shows a metalens. A plane wave is converted to a spherical wave via the response of nanostructures (nanoantennas) built on the surface of the substrate. The surface is a quasi-periodic structure with subwavelength dimensions.

Metalenses – Potential benefits

Benefit		
Miniaturization	✓	Metalenses allow for the creation of smaller, lighter optical devices, which is especially beneficial for applications in consumer electronics such as smartphones and AR glasses. For instance, Samsung is researching metalenses to integrate into their smartphone cameras, aiming for improved image quality and reduced lens size. Similarly, Apple is reportedly investigating the use of metalenses for future iPhones and AR glasses to achieve superior optical performance and device miniaturization .
Smaller optical packages with more functionality	✓	Meta Optical Elements (MOEs) enable the development of smaller optical packages with multiple functions , making them ideal for compact devices with advanced optical requirements. This multifunctionality is particularly advantageous in compact devices where space is at a premium.
Reduced complexity and cost of optical assemblies	✓	Metalenses simplify optical system design by reducing the number of elements required since metalenses do not suffer from spherical abberation, thereby lowering the overall cost and complexity of optical assemblies such as camera lenses. Unlike traditional lenses, metalenses are less sensitive to alignment issues, which simplifies manufacturing and assembly processes.
High Numerical Aperture (NA)	✓	Metalenses achieve high NA values, which are crucial for applications requiring high resolution, such as microscopy and high-end cameras.
Thermal stability	✓	They exhibit high thermal stability, essential for high-power laser systems and harsh environments.
Polarization control	✓	Metalenses can be engineered to control the polarization state of light, beneficial in optical communication and sensing applications .
Reduction of chromatic aberrations	✓	Chromatic aberration can be an issue with metalenses, but newer approaches have significantly reduced these aberrations. Advanced designs enable metalenses to achieve high Numerical Aperture (NA), improving image clarity and color accuracy.

Europe – A powerhouse in III-V solar cells manufacturing

Evatec Europe Sales Manager, ***Frank Wette*** and Head of Sales Europe ***Sandro Bertelli*** explain how Evatec evaporation solutions on the BAK and the latest substrate handling options are helping customers deliver the process repeatabilities and high production yields essential for successful manufacture of III-V solar cells.

Why III-V semiconductors for space applications?

III-V semiconductor-based photovoltaics play a crucial role in space applications due to their unique properties. Here are just some of the reasons why III-V solar cells are favoured for use in space:

- **High Efficiency:**
  III-V multi-junction solar cells exhibit exceptional efficiency compared to traditional silicon-based cells. For instance, a combination of InGaP with a bandgap of 1.9 eV, InGaAs with a bandgap of 1.4 eV and Ge with a bandgap of 0.7 eV allows III-V cells to absorb a broader range of photons at energies close to the individual bandgaps, making them highly efficient. Higher efficiency translates to smaller arrays, reduced weight, and increased payload capacity for spacecraft.
- **High Voltage:**
  Due to the serial combination of several III-V semiconductor absorbers within a multi-junction solar cell, the output voltage of an individual cell rises considerably. The high thermal stability of the III-V cell voltage compared to Silicon allows for the design of relatively short solar cell strings on a satellite panel, making the solar array design more flexible and reliable.
- **Radiation Resistance:**
  Space environments expose solar cells to cosmic radiation, which can degrade their performance. III-V materials have demonstrated superior radiation resistance compared to other materials. Additional concepts, such as distributed Bragg reflectors (fully patent protected by AZUR SPACE) within the semiconductor stack further enhance the radiation resistance of the III-V solar cell devices. They maintain efficiency even in harsh conditions.
- **Space Heritage:**
  III-V solar cells have been widely used in space systems for decades. Their reliability and proven track record make them a trusted choice.

In summary, III-V-based solar cells offer a compelling combination of efficiency, radiation resistance, and historical success in space applications. Their lightweight and flexible nature make them ideal for powering satellites and spacecraft.

Thin film process repeatability is key

Of course each manufacturer has their own cell designs and process requirements but Evatec typically supports customers with process solutions for deposition of either dielectrics for antireflection coatings or with process solutions for metals. The high added value of typical 6 inch substrates prior to coating call for both coating systems and processes that are robust for the reliable and stable repeatable deposition of layers without failures. Secure wafer handling is needed to eliminate risk of substrate damage and even breakage and coating process technology itself needs to avoid substrate damage due to stray electrons / ions.

Europe – A solar cell production powerhouse

We are very happy that our European region already has a number of well-established manufacturers including **AZUR SPACE** and **CESI** supporting a strongly growing global market.

AZUR SPACE
A 5N PLUS COMPANY

"More than 11 MW space qualified solar cells & CICs in space"
www.azurspace.com

CESI
Inspired with innovation

"Enabling four junction cells with space efficiencies beyond 35%"
www.cesi.it/space-solar-cells

The BAK Evaporator Family – A long history and an exciting future

The original BAK evaporator concept may well be 50 years old but its flexible tool architecture combined with modern process source and control technology enables customers to manage manufacturing and recording of actual production process data according to the strict standards of the solar industry.

BAK platforms are currently available in a range of sizes from 0.5 to 1.4 meters optimized according to customer's substrate size, batch processing size and throughput. The layout of a BAK1101, a typical size used by the solar industry, is shown in Figure 1. In addition to the usual e-gun technology there is plenty of space for integration of additional equipment such as plasma sources plus process accessories like heating. Platform control and process data logging is managed by Evatec's Khan and a host integration option gives customers the control they need within the fab.

Whilst the solar cell industry may call for rigorous long term process repeatability and stability of the manufacturing environment that doesn't mean there is no appetite for improving efficiency. For many manufacturers the road to driving down costs involves the increasing use of automation for substate handling. Figure 2 illustrates how the latest generation of BAK evaporators can be equipped with a range of different semi or fully automated load options according to the substrate and platform size.

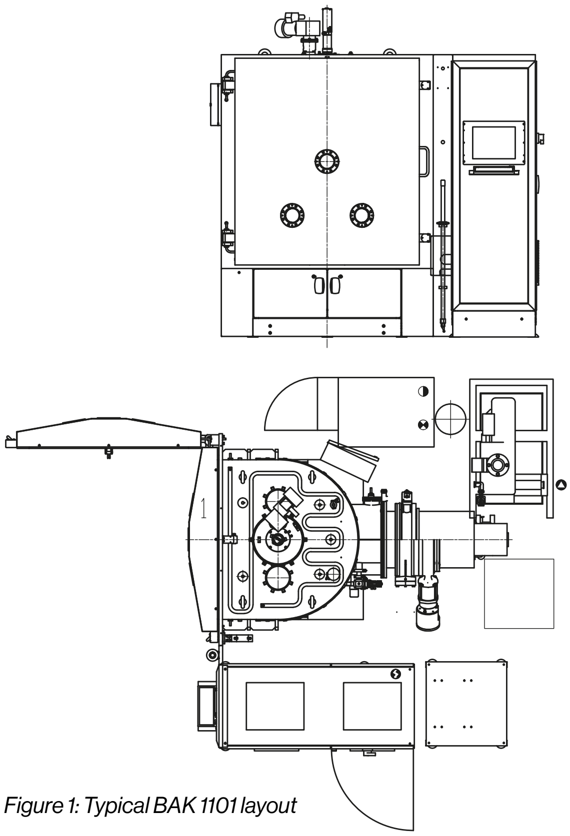


Figure 1: Typical BAK 1101 layout

A wealth of substrate handling options for the BAK family

Manual load / unload

- Either wafer direct to calotte in chamber or manual load of preloaded segment.

Semi automated

- Manual load of calotte-robot load / unload of calotte to chamber. Loading capacity per batch can be increased through unsegmented dome design.

Semi automated

- Manual load of calotte-robot load / unload of calotte to chamber via vacuum load lock. Reducing batch times through quicker unload / loading, faster pumping.

Fully automated

- Cassette-to-cassette (or FOUP to FOUP) via intermediate loadlock as featured on Multi BAK.

Increasing levels of handling automation

Figure 2: Semi or fully automated load options for BAK evaporators

Want to know more about the solar production solutions on the BAK platform?

Our application specialists would love to talk to you. Simply contact your local sales organization **https://evatecnet.com/about-us/contact-us/**

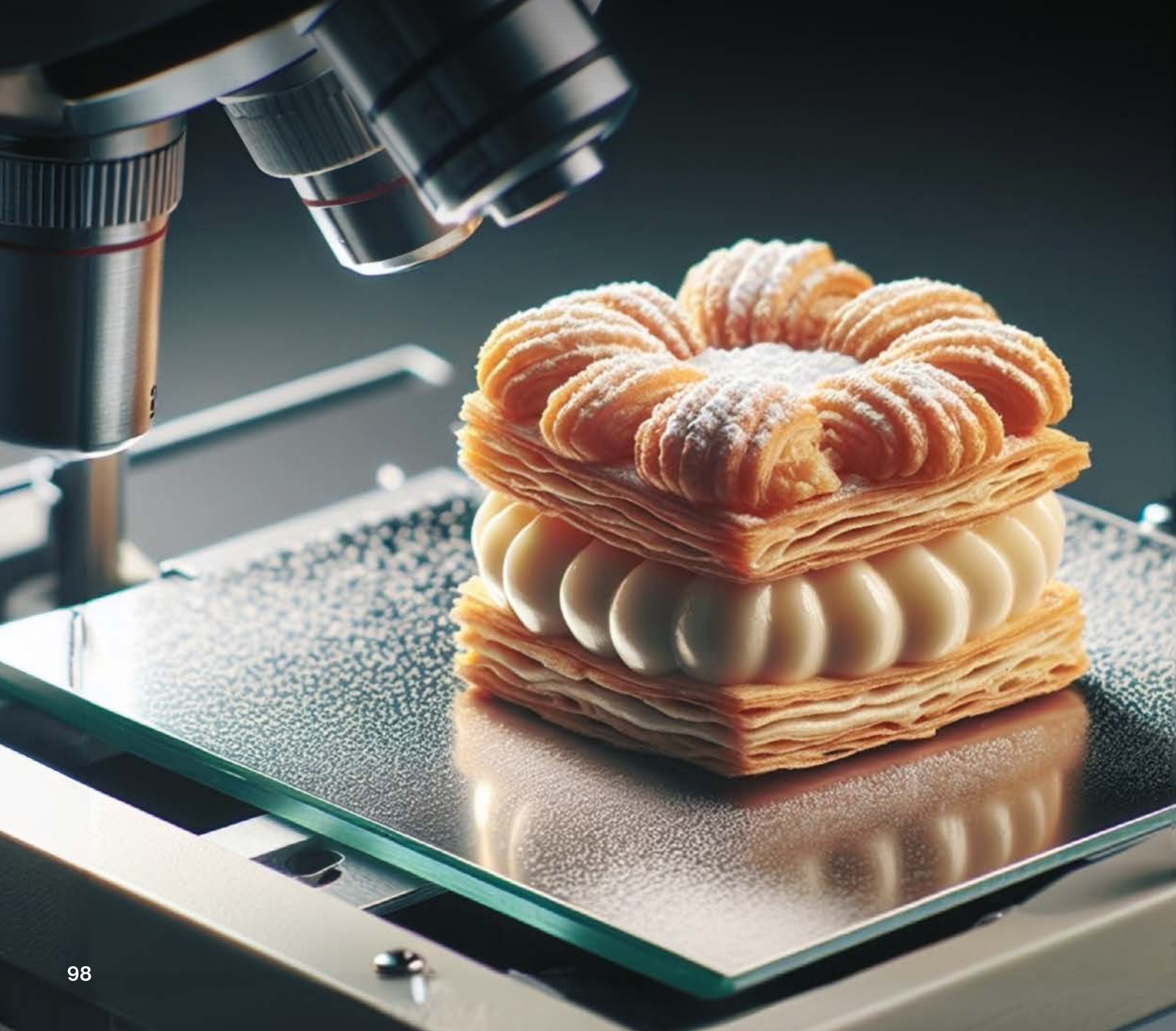
Access the latest brochure to learn more about the BAK family

Watch the Multi BAK video to learn how you can increase throughput and reduce energy costs

Quantized Nanolaminates through the microscope -

A step forward in optical thin film technology?

Evatec's Principal Scientist ***Dr. Silvia Schwyn Thoeny*** introduces quantized nanolaminates, tells us the potential benefits for optical thin film production and how they can be manufactured effectively by sputter technology on CLUSTERLINE® 200 BPM.



Why Quantized Nanolaminates?

Optical interference coatings such as anti-reflection, mirror or filter coatings are based on stacks of materials with at least 2 different refractive indices, n. The interference effect is stronger if the difference in refractive index between materials is larger. Hence, a stack design based on materials with a larger difference in refractive index requires a smaller number of individual layers and thus less overall thickness to fulfill the same specification as a design based on materials with a smaller difference. In addition to the refractive index, the materials have to fulfill other requirements, among those being transparency with negligible losses in the wavelength range of interest.

However, in dielectric materials the refractive index and absorption edge are linked. Materials with high refractive index have their absorption edge at a long wavelength, while low refractive index materials have the absorption edge at a short wavelength. TiO_2 is the dielectric material with the highest refractive index, which is transparent in the visible range of the spectrum starting to transmit at ca. 400 nm. Having a material at disposition with a higher refractive index while being transparent in the VIS would be of broad practical relevance, since it would allow interference designs with a lower number of layers and reduced overall thickness.

An approach to overcome the connection between the two characteristics is Quantized Nano Laminates (QNL). In this concept thin layers of high and low refractive index with a thickness in the nanometer range or below are stacked. The limited structure size leads to a change of the energy gap, which can be adjusted by the physical thickness of the materials, whereas the thickness ratio of the materials determines the effective refractive index of the QNL.

In optical interference coatings, the decoupling of band gap and refractive index potentially offers the advantage of using the QNL material combination instead of using a specific material. The stack structure of a typical coating with QNL in comparison with standard interference is illustrated in Figure 1.

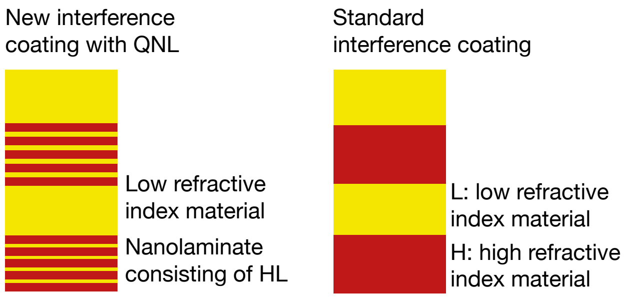


Figure 1: Comparison of film structure

As an example, in the UV range the band gap of Ta_2O_5 can be pushed towards shorter wavelength and can thus replace the use of HfO_2. This is desirable since hafnium targets are expensive and because HfO_2 has a tendency to form polycrystalline films with grain boundaries which can cause losses by straylight. Another very interesting material combination is QNL composed of amorphous silicon and SiO_2 which offers a higher effective index than TiO_2 with being transparent well into the visible part of the spectrum.

Nanolaminates Benefits

Table 1 summarizes the potential benefits of nanolaminates when it comes to optical thin film production. Key to commercial realization is finding a practical production technique and that's where sputtering comes in. Although ALD and IBS lead to good results, they do have drawbacks with regard to volume production, whereas magnetron sputtering achieves deposition rates comparable to standard optical thin film production processes.

Potential benefits of quantized nanolaminates
✔ Decoupling of refractive index and absorption edge
✔ Extending useful range of high index materials
✔ Improved film performance
✔ Comparable results achieved with less complex stacks / shorter process times
✔ Replacement of expensive materials
✔ In-situ PEM and optical monitoring can be used just like in classical processes

Table 1: Potential benefits of Quantized Nanolaminates

Now you really can 'have your cake and eat it'

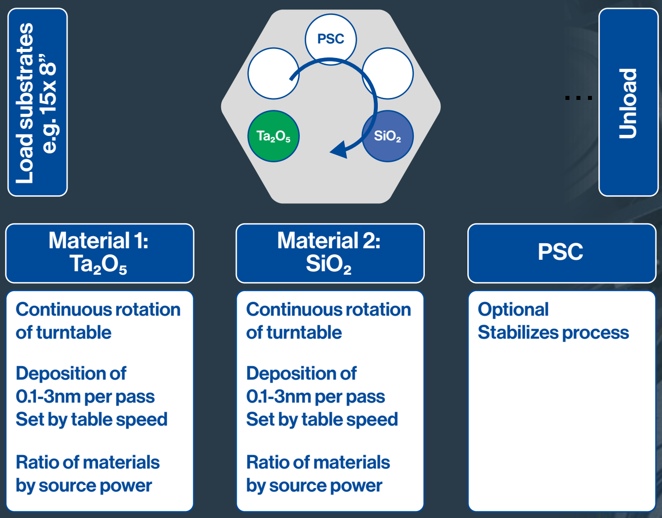
Production solutions on CLUSTERLINE® 200 BPM

Evatec's CLUSTERLINE® 200 BPM dynamic sputter tool with its large substrate table is well suited to nanolaminates deposition. The deposition system has a capacity of 15 substrates of diameter 200mm. Substrate loading and unloading is executed automatically through a vacuum transfer module and load-lock. The system is also equipped with broad band and monochromatic optical monitoring.

For the deposition of aSi - SiO_2 QNL one sputter source was equipped with a silicon target with the purpose to deposit an amorphous silicon layer. The SiO_2 layer is formed by the plasma source (PSC), where the aSi film partially gets oxidized by the oxygen plasma. The plasma source is a RF-driven capacitively coupled discharge, where oxygen as operating gas is partially dissociated and ionized. The schematic tool configuration is shown in Figure 2.

When depositing the long pass filter consisting of aSi - SiO_2 QNL as the high refractive index material and SiO_2 for the low refractive index material, a second sputter station equipped with a silicon target was used to reactively deposit the low index SiO_2 layers.

The turntable configuration is perfectly suited for the deposition of QNLs. The substrates pass repeatedly beneath the active sources, thereby exposing the substrates to both the sputter (Si & Ta) and the plasma source with each rotation. The total thickness deposited in one turn is determined by the rotation speed of the table, a parameter which can easily be varied in a wide range, and the deposition rate. The thickness ratio of the aSi and SiO_2 materials is determined by the sputter and the plasma source power, which can be adjusted individually. Deposition rates for QNL layers tend to be as high as those for single aSi since the active source is run at standard conditions.



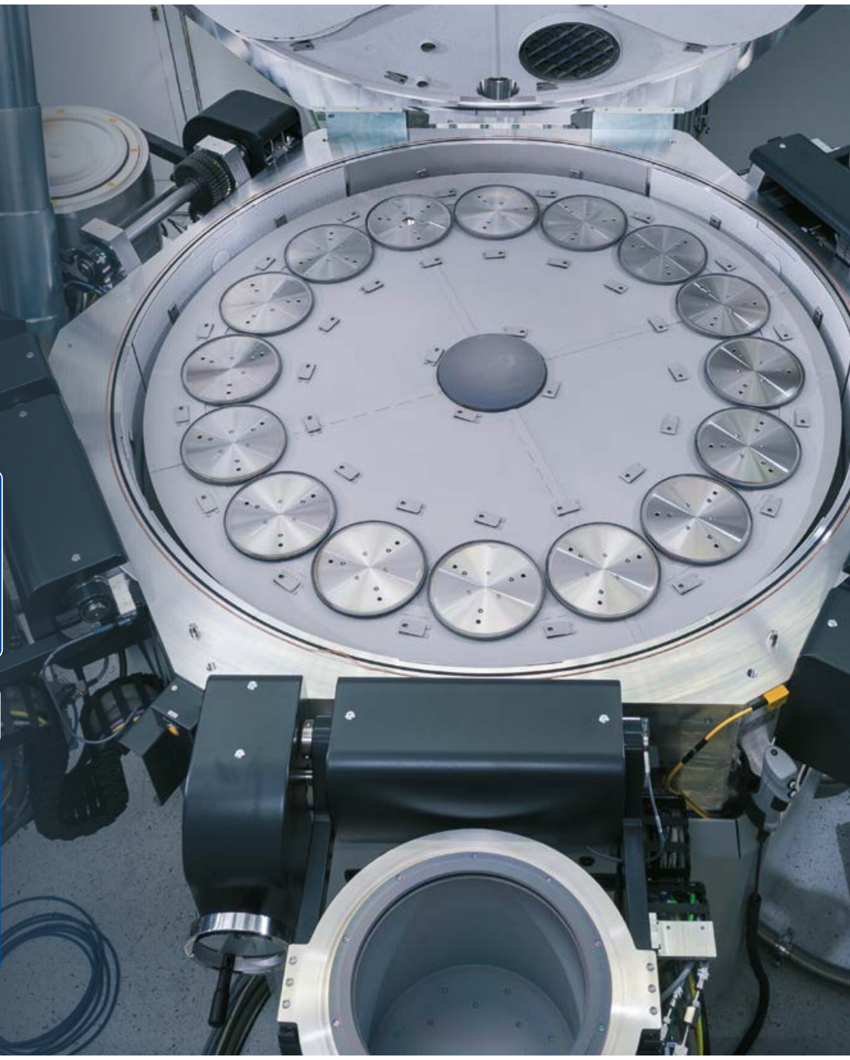


Figure 2: CLUSTERLINE® 200 BPM

Experimental results

1. Illustrating the quantized nanolaminate effect

In a first experiment, the Si and Ta sources were run at fixed powers. The table speed was varied from 3 to 15 seconds per pass, which means that the thickness ratio of high to low layers stayed constant, but the individual layer thickness increased with the slower table speed. The well thickness, i.e. thickness of Ta_2O_5 was determined to be in the range of 0.2-1 nm. According to the theory it was expected that the absorption edge would shift towards shorter wavelengths the thinner the individual well layers became, whereas the effective refractive index would remain constant for all five samples. This behavior was indeed seen in the transmission measurements. The absorption edge of the 3s/pass sample lies at the shortest wavelength, whereas the 15s/pass results in the longest wavelength edge with a difference of 18 nm between the samples (see Figure 3). For reference the absorption edge of a Ta_2O_5 layer is indicated by a dotted line. In the longer wavelength range above 280 nm, all curves overlay since they all have the same effective refractive index and optical thickness. Furthermore, they touch the solid line for ½ λ optical thickness indicating very low absorption of the QNLs in the longer wavelength range.

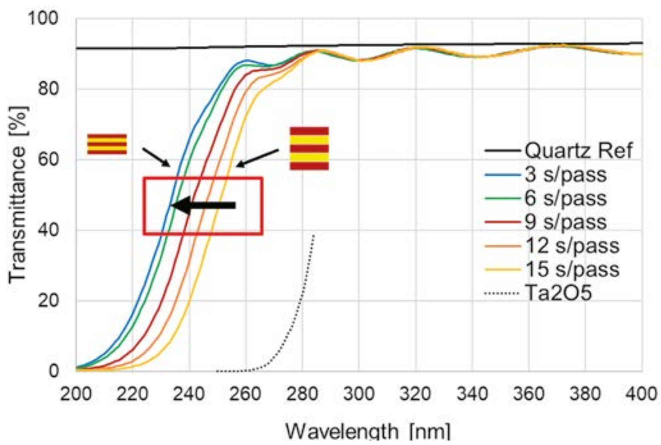


Figure 3: Transmittance of QNL layers with the same thickness ratio of Ta_2O_5 to SiO_2, but with increasing table speeds. The thinnest layers deposited with the highest table speed show the largest shift in absorption edge to shorter wavelength.

2. AR Coating

In a second experiment, a UV AR coating centered on 266nm was deposited on silica substrates using a stack comprising SiO_2 and QNL of TaO_2/SiO_2 showing an effective coating without the use of Hafnia. The reflectance and transmission performance on a double side coated sample are shown in Figure 4.

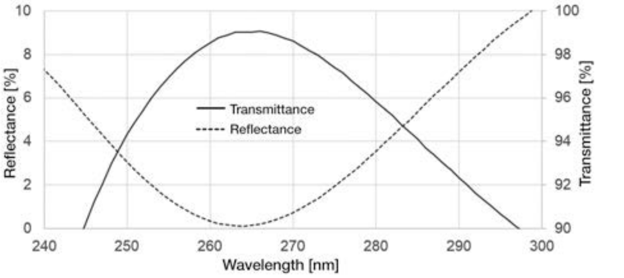


Figure 4: Transmittance and reflectance measurements of the antireflective coating of SiO_2 and QNL layers showing excellent transmission at 266 nm

3. Mirror at 355nm with short pass filter

Figure 5 shows a comparison of performance for two short pass filters: the curve in red is a standard SiO_2-Ta_2O_5 coating. Both designs reflect at 355nm and transmit light at shorter wavelength, but transmittance falls off rapidly below 300nm using standard filter designs whereas quantized nanolaminate structure enables significantly higher light output down close to 280nm.

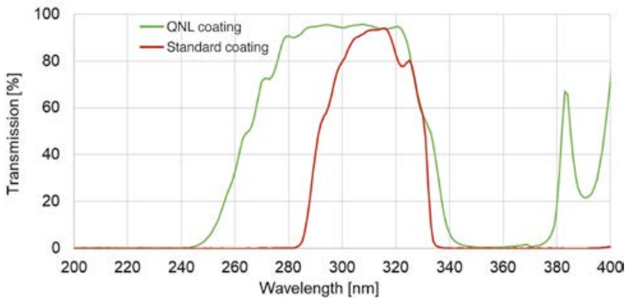


Figure 5: Short pass filter transmittance of a design using SiO_2-QNL (green) compared to standard coating (red) using SiO_2-Ta_2O_5

4. Long pass filter

In Figure 6 we see a comparison between long pas filters both having 16 layers. The classical design using TiO_2 / SiO_2 blocks only from 520 to 670nm and would require twice the number of layers to give equivalent performance to the QNL design using aSi/SiO_2. This shows how QNL structures can reduce overall coating thickness, deposition times and manufacturing costs.

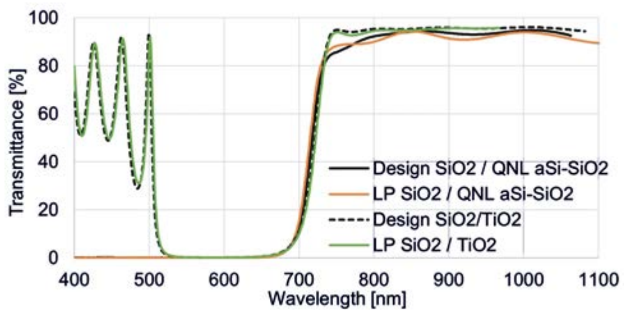


Figure 6: Transmittance of a long pass filter based on SiO_2/QNL aSi-SiO_2 and on SiO_2-TiO_2 for comparison

Quantized nanolaminate: the theory

In standard dielectric materials the refractive index and the energy of the absorption gap are fundamentally linked. Quantized nanolaminates however allow us to set the refractive index and the absorption edge independently within the limits given by the bulk properties of the high and low index material.

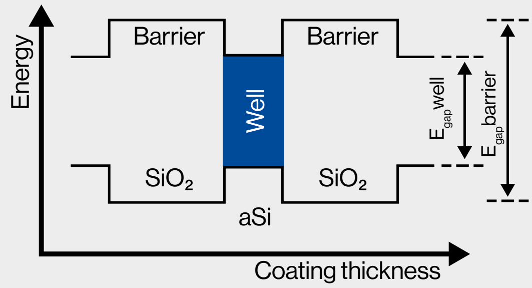


Figure 7: Periodic structure of high and low band gap areas, which limit the electron mobility

The theory of the quantized nanolaminates has already been detailed in other publications but here is a quick summary. As already mentioned, optical coatings mostly produce amorphous or polycrystalline materials whose band structure is not clearly defined, nevertheless an energy gap between quasi-free ground states and higher conduction states is present. Thus, the band gap itself can be regarded as a depletion zone of states and the densities between bound and free states are so low that they can be neglected. Thus, the potential well, which is necessary for the quantization is clearly defined.

The electron mobility can be limited in the growth direction if two materials with high and low band gap are combined in a thin periodic structure. In this case the low index material will act as a barrier, whereas the high index material acts as the quantum well, as illustrated in Figure 7. Since this is a simple potential consideration, even non-closed atomic layers can lead to a suitable periodic potential.

The thickness of the quantum well will determine the shift in band gap, whereas the thickness ratio of high to low bandgap material will determine the refractive index. Thus, the novel concept of so-called quantizing nanolaminates (QNLs) allows for independent adjustment of the optical band gap and the refractive index. To give an idea of the thicknesses required we turn to data published for SiO_2-Ta_2O_5 which shows that the quantum well layers should be much smaller than 2 nm to achieve a shift which is of practical use.

Please take a look at the open access paper published in *Optics Express and Advanced Photonic Research* to access more references of previous work reported in the literature about Quantized Nanolaminates and more results for the work being done at Evatec.

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