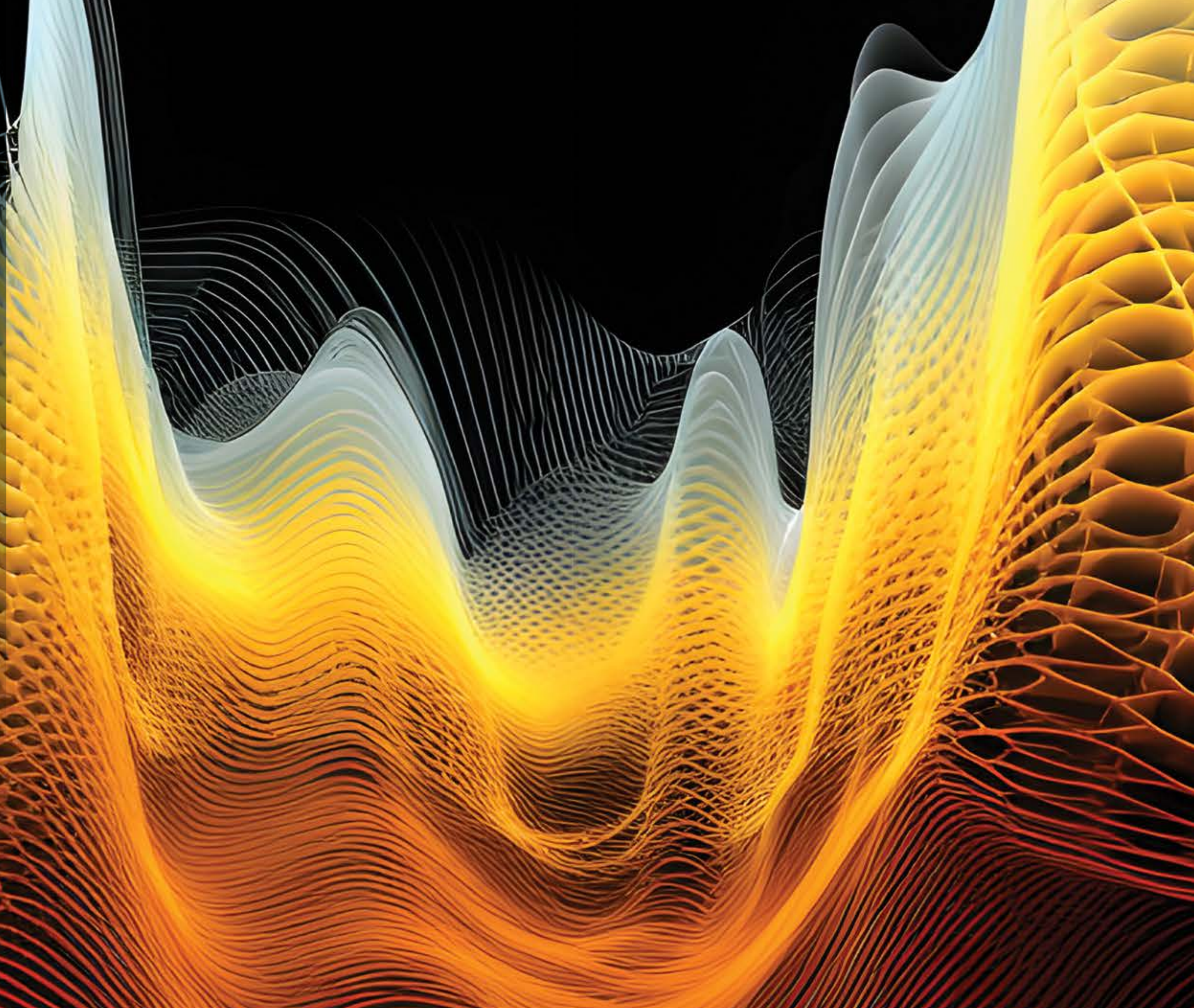
# PEALD

## The smartest plasma, the purest films

**Dr. Julian Pilz** and **Shiv Jyotindra-Bhudia** of Silicon Austria Labs and **Dominik Hartmann**, Manager Technology Development at Evatec, report recent results showing how a novel Microwave Electron Cyclotron Resonance (ECR) Plasma Source delivers Ultra-Pure, Damage-Free films in Plasma Enhanced Atomic Layer Deposition (PEALD).

### Why PEALD

PEALD has become a key technology in the semiconductor industry to produce advanced electronic and structural thin films in the nm range. However, when film purity, low-temperature growth and structural control are all required at once, conventional plasma sources often reach their limits. In LAYERS 8, Evatec introduced its new PEALD module for integration on CLUSTERLINE® 200 and highlighted the benefits of ECR source technology. Now we can report recent results demonstrating the system's ability to meet key industry demands by enabling the production of ultra-pure $Al_2O_3$ for advanced gate dielectrics in logic and memory devices, as well as highly crystalline AlN films for piezoelectric MEMS, thermal interface layers, and dielectric components for RF and power applications.



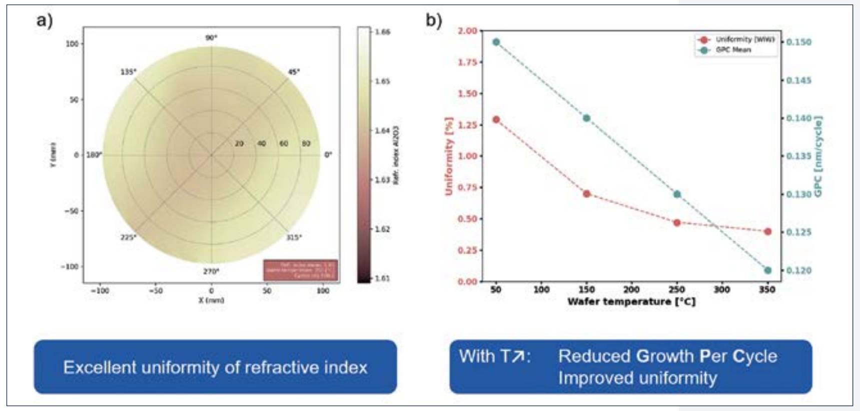



*Figure 1: Single wafer process $Al_2O_3$ layer characteristics. a) The refractive index map is shown for the 250 °C process, which shows excellent uniformity across the entire wafer at a refractive index of 1.65 in most areas. b) The thickness uniformity and GPC as a function of temperature illustrate how uniformity gets better, while GPC decreases at increasing temperature.*

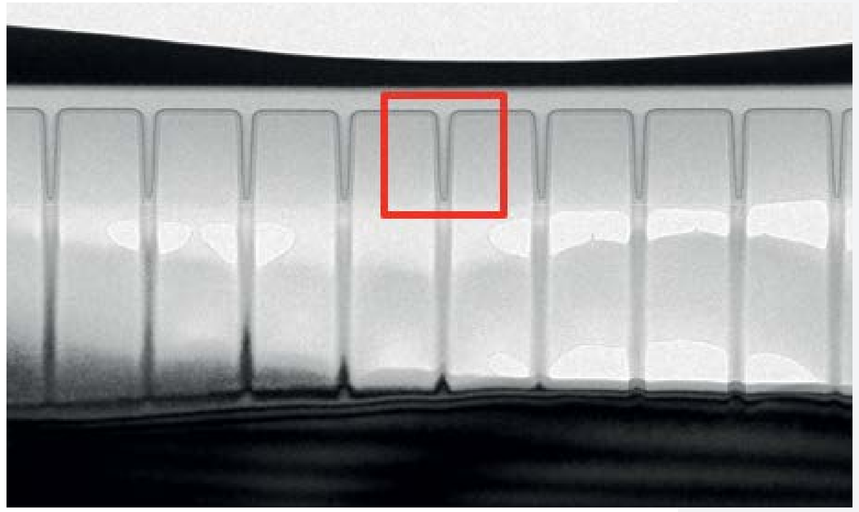


*Figure 2: a) TEM measurements of $Al_2O_3$ on high aspect ratio structure, Large scale image of multiple vias.*

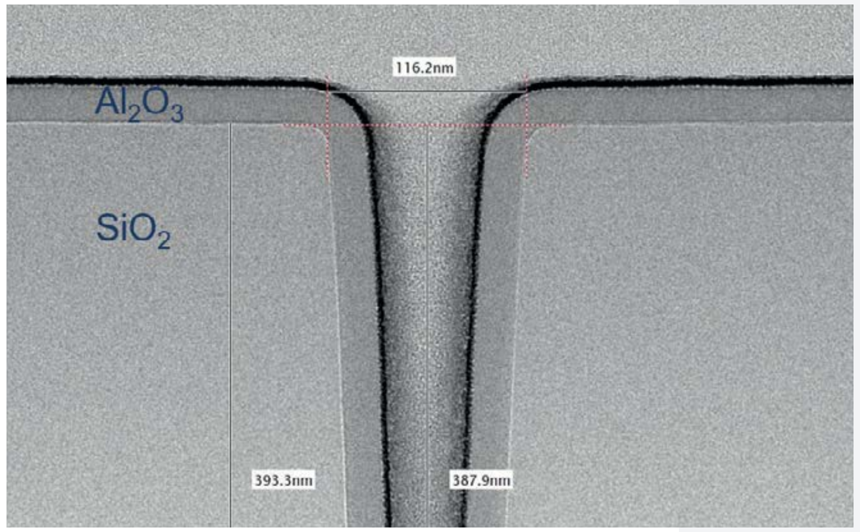



*Figure 2: b) Zoomed in on a 4:1 structure shows a highly conformal layer.*

## $Al_2O_3$ - Precise layers and high throughput

Single wafer processes, where $Al_2O_3$ is deposited for 25 wafers in a batch, shows excellent thickness uniformity across the 200 mm silicon substrates, with variations below 0.5% and stable refractive index values around 1.65 at 633 nm.

At a growth rate of 1.8 nm/min, 50 nm $Al_2O_3$ coatings can be processed in under 30 min, leading to the entire batch processed within half a day, while in-film particle (>0.3 µm) generation is kept low at < 50. Figure 1 illustrates how the refractive index, thickness uniformity and growth per cycle (GPC) behave as a function of temperature showing that elevated temperature can smoothen and densify the $Al_2O_3$. This can be helpful in applications such as hydrogen diffusion barriers.

Micrographs in Figure 2 also show how the process can deliver highly conformal coatings, with high aspect ratios > 4:1. Pre-etched $SiO_2$ structures were coated with 20 nm of $Al_2O_3$, showing that the same throughput could also be achieved on structured wafers with outstanding conformality.

## AlN Films – High purity and tuneable crystallinity

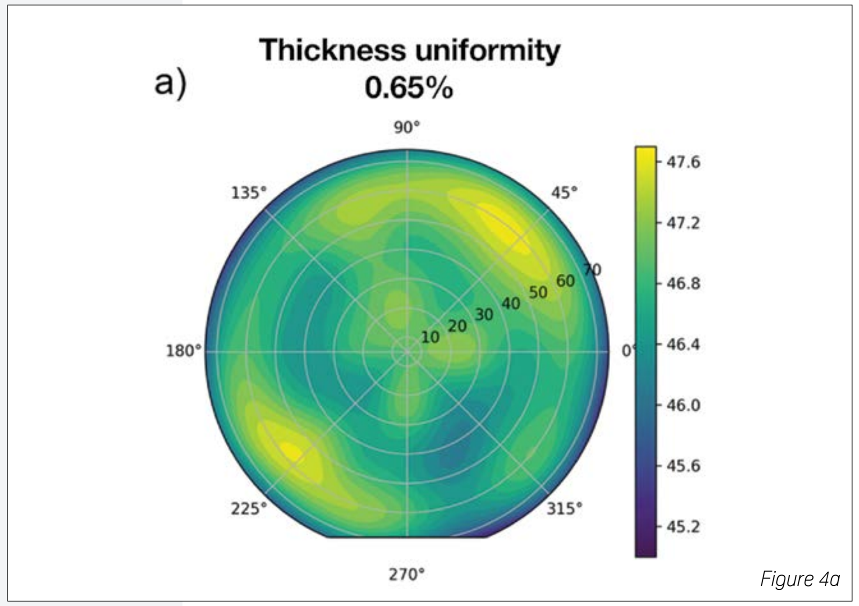
Aluminium nitride is a key material in advanced microelectronic devices. It is used in piezoelectric MEMS, thermal interface layers and dielectric components for RF and power applications [1, 2]. Material quality is of the highest importance, and especially crystallinity, stoichiometry, and impurity levels which have decisive impacts on the device performance [3].

Highly oriented AlN films are typically grown using methods such as metalorganic chemical vapor deposition [4] or reactive sputtering [5]. However, these approaches often lack the process control and integration flexibility needed for modern device architectures. Whilst Plasma-enhanced atomic layer deposition offers a promising alternative [6-8], the challenge there has been to achieve similar structural quality while keeping oxygen and carbon impurities to a minimum [9, 10].

In these trials, we used our newly developed microwave-based PEALD system to grow AlN on 200 mm Si (111) wafers. The process combines trimethylaluminum (TMA) with ammonia ($NH_3$) plasma. The high-density microwave plasma allows precise tuning of energy input by varying the microwave power between 50-500W. Furthermore, various other parameters in the process, such as pressure, NH3 flow, and exposure time can be individually adjusted to tune the desired properties. This gives full control over film growth, chemistry and structure.

Figure 4 shows the layer characteristics as measured by ellipsometry at 633 nm. In Figure 4a, thickness uniformities <1% can be achieved at T = 200°C (chuck temperature) for a 500 cycle process. The refractive index uniformity is illustrated in Figure 4b. The wafer shows polycrystalline regions especially in the outward regions, which can be identified from high refractive indices > 1.9.

X-ray photoelectron spectroscopy (Figure 5) confirms excellent purity, where oxygen and carbon levels are extremely low and almost not detectable. Figure 5 shows the bulk composition of AlN grown with different plasma cycle doses at different radial positions on the wafer. To compare the composition, the reference values for bulk AlN are also shown on the right side. Of significant note is that the AlN structure has reached an almost identical composition to the bulk reference case after only 10 s, which proves its exceptional quality. There is



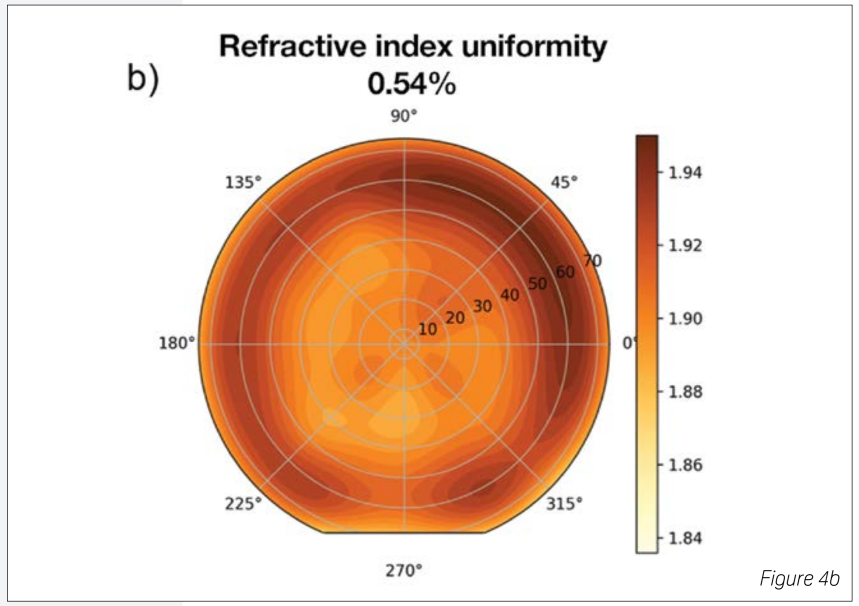




*Figure 4: AlN layer characteristics measured by ellipsometry at 633 nm.*
*a) Thickness uniformity*
*b) Refractive index uniformity. Process: 200°C, 500 cycles.*

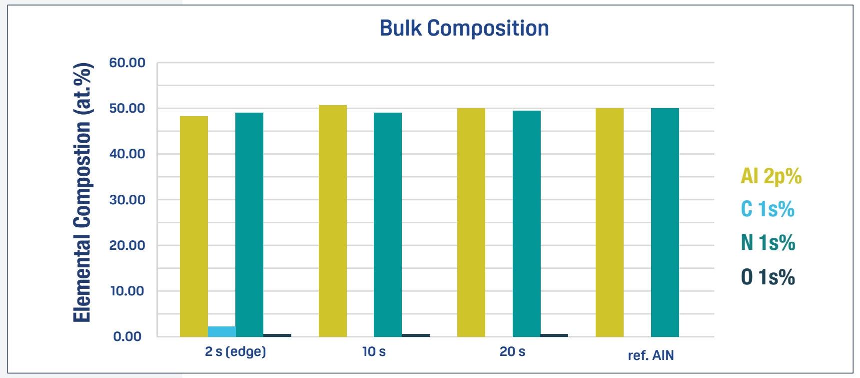



*Figure 5: Elemental composition of AlN measured by XPS for different plasma times on different radial positions of the wafer. After 10s there is no C detected anymore, which is an excellent proof of high quality PEALD environment. There is only a minimal amount of oxygen detected, which is due to surface oxidation. As a reference the AlN elemental ratios (1:1) are shown.*

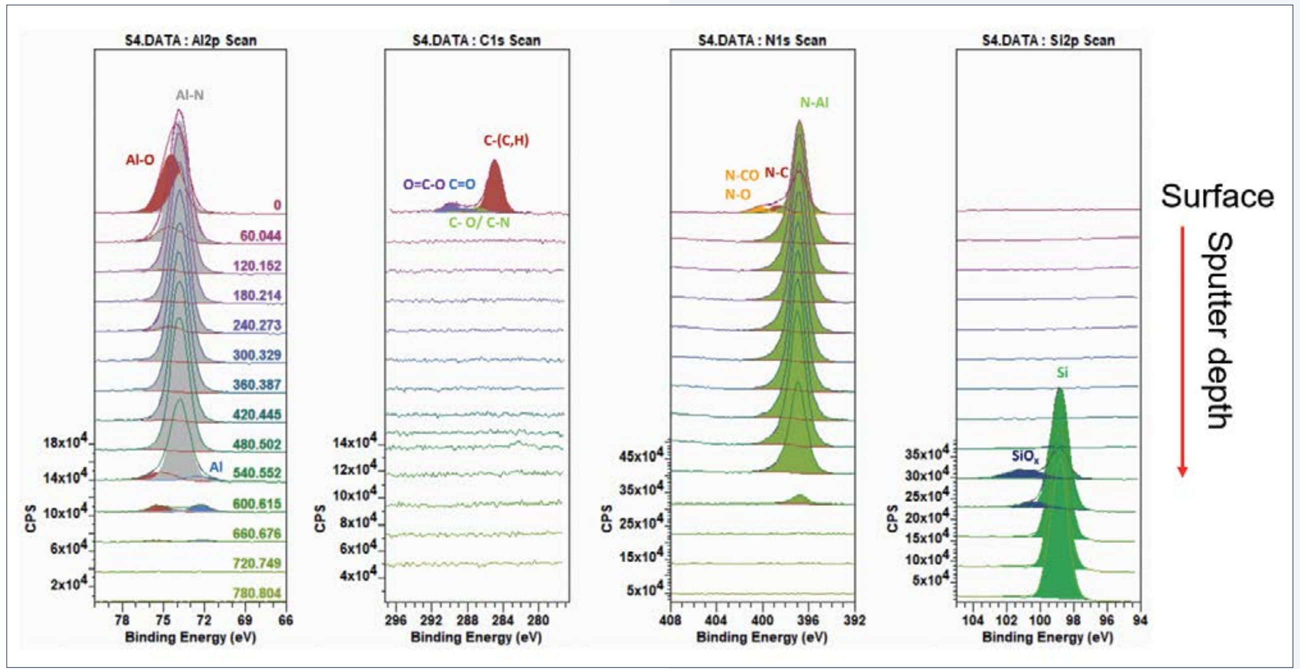



*Figure 6: XPS depth profiles shown for Al, O , N, and Si. The number in different colors form purple to green show the sputter times. There is no detectable C in the bulk of the material (second plot), which is a great sign of quality nitride layers.*

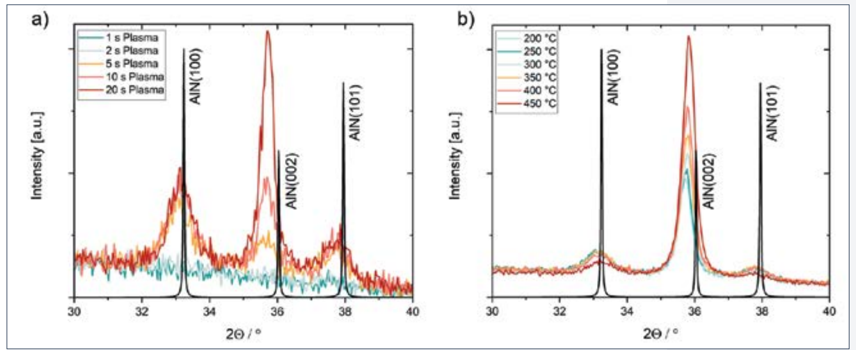



*Figure 7: XRD Grazing incidence scans of processed AlN layers with different plasma times (a) and at different temperatures (b).*

**References:** [1] La Spina, L. et al., Solid-State Electronics, 1359–1363 (2008). [2] Haider, S. T. et al., IEEE Access, 58779–58795 (2023). [3] Strnad, N. A. et al., Journal of Vacuum Science & Technology A, 40(4) (2022). [4] Demir, I. et al., Journal of Physics D: Applied Physics, 51(8), 085104 (2018). [5] Dadgar, A. et al., Physica Status Solidi (a), 220(8), 2200609 (2023). [6] Österlund, E. et al., Journal of Vacuum Science & Technology A, 39(3) (2021). [7] Ueda, S. T. et al., Journal of Materials Chemistry C, 10(14), 5707–5715 (2022). [8] Goswami, R. et al., Coatings, 11(4), 482 (2021). [9] Zhang, X. Y. et al., Journal of Materials Research and Technology, 27, 4213–4223 (2023). [10] Gungor, N. & Alevli, M., Journal of Vacuum Science & Technology A, 40(2) (2022). [11] Lau, W. S. et al., Applied Physics Letters, 87, 123505 (2005). [12] Manzeli, S. et al., Nature Reviews Materials, 2, 17033 (2017). [13] Radisavljevic, B. et al., Nature Nanotechnology, 6, 147 (2011). [14] Chowdhury, S. & Mishra, U., IEEE Transactions on Electron Devices, 60, 3060 (2013).

only minor surface oxidation caused by post-deposition air exposure. Depth profiling (Figure 6) further confirms that contamination is confined to the surface, highlighting the cleanliness and reliability of the process. We have further analysed the crystal structure using X-ray diffraction. Figure 7a shows that increasing the ammonia plasma duration enhances the (002) peak intensity, indicating stronger c-axis texture. This trend continues with higher substrate temperatures, as seen in Figure 7b. Even at just 200 °C the tool delivers highly oriented films. This level of control enables fabs to adapt the process to match their device and integration needs.

### Process integration on a single platform

One of the main advantages of the Evatec PEALD system is its integration into the CLUSTERLINE® 200 platform, where it can be combined with PECVD, sputtering, and plasma etching technologies without interrupting the vacuum process throughout the entire process flow. This configuration enables complete, multi-step device fabrication without exposing the wafer to ambient conditions.

Surface pretreatment, seed layer deposition, film growth and encapsulation can be carried out in a connected and controlled vacuum and process flow. This high degree of integration opens new options for advanced device fabrication, e.g. high-κ metal gate stacks (HKMG) benefit from clean, sequential deposition of dielectrics and metals in one tool environment [11]. 2D materials like $MoS_2$ and graphene need damage-free surface pretreatment and careful encapsulation to retain their electrical performance [12,13]. GaN on diamond for high power devices relies on low-temperature, conformal coatings with tight interface control [14]. VCSELs and Micro-LEDs require precise control of multilayer thickness and stress for optimal optical performance.

Figure 8 shows a possible configuration of the CLUSTERLINE® 200 with PEALD, PECVD, sputter, and etch modules connected to a central wafer handling system. Each module can be adapted for specific materials or coating processes. Depending on requirements, the system can be equipped with multiple PEALD modules with numerous precursor lines.

### So what's next?

The Evatec team is already exploring advanced materials such as AlScN, InGaN etc. and how a newly developed RF chuck can tune crystallinity and other important properties through super-cycle processing. With all these capabilities in one platform, we are ready to support our customer's innovations in logic, power devices, optical coatings, optoelectronics and sensor technologies from R&D to high-volume manufacturing.

*Acknowledgement:*
*XPS measurements have been performed at the Luxembourg Institute of Science and Technology.*

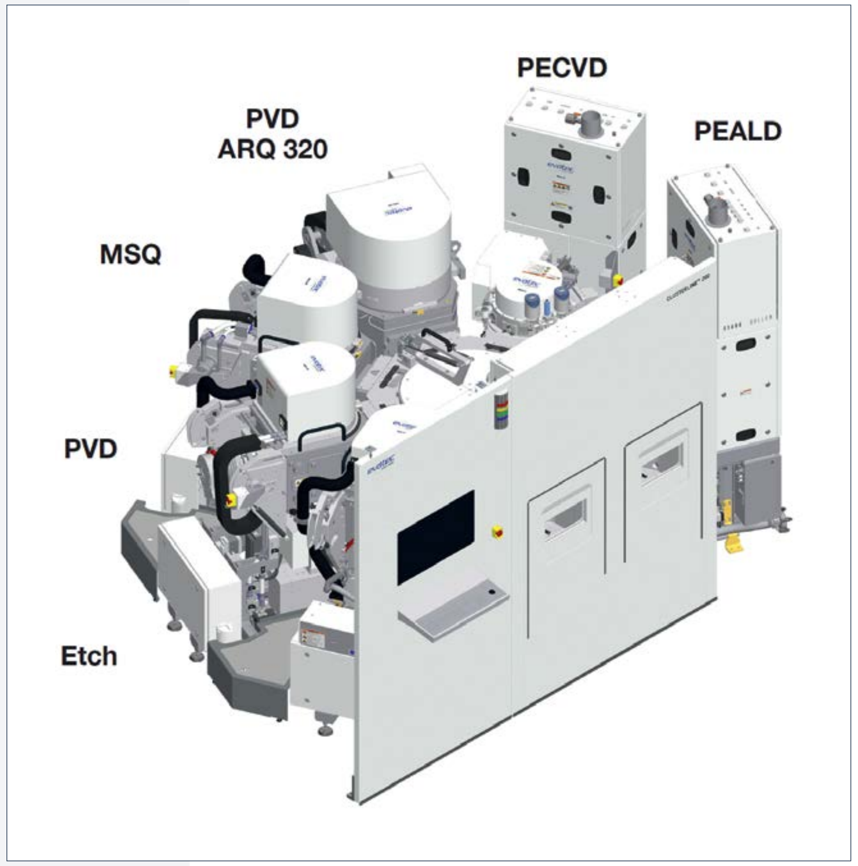



*Figure 8: CLUSTERLINE® 200 combines many advanced technologies for advanced device fabrication without breaking vacuum.*

**"With this new platform, Evatec brings a highly flexible and scalable PEALD solution to the market. It delivers high-purity, crystalline AlN films on full 200 mm wafers. The tool is ready to support a wide range of applications, from next-generation piezoelectric components to thermal and dielectric layers in RF and power devices. For customers looking to combine high performance with process control, this system offers a clear path forward"**

***Dr. Julian Pilz, Silicon Austria Labs (SAL)***