Recent Advances in ALD Technology

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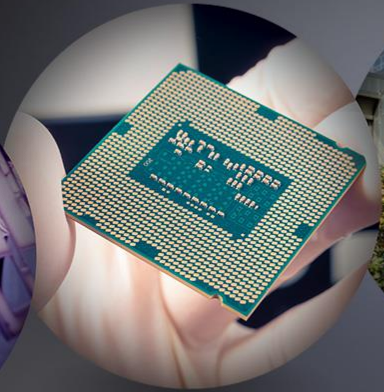
95
km/h
7213
RPM
Services
Equipment
Displays

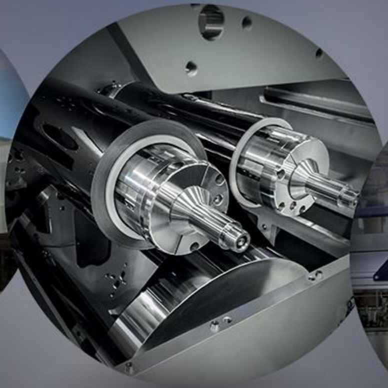
One Stop for All ALD

Research



Development Services

Coating Services



Industrial Equipment

Customer Services

Outline

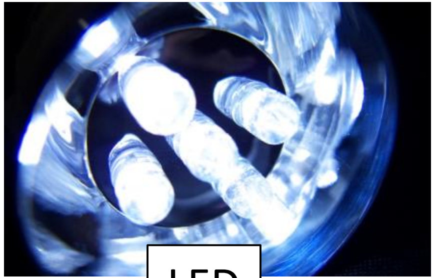
- Large-area industrial ALD technology trends
- Recent advances in ALD technology
  - Spatial ALD
    - Large sheet ALD
    - Roll-to-roll ALD
    - Rotary Plasma ALD
  - Fluidized-bed ALD
- Summary

Large-area industrial ALD opportunities

Thin-film encapsulation

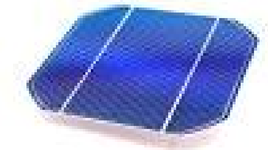
AMOLED

Anti-reflection coatings



LED

Surface passivation



Photovoltaic

Flexible moisture barrier films

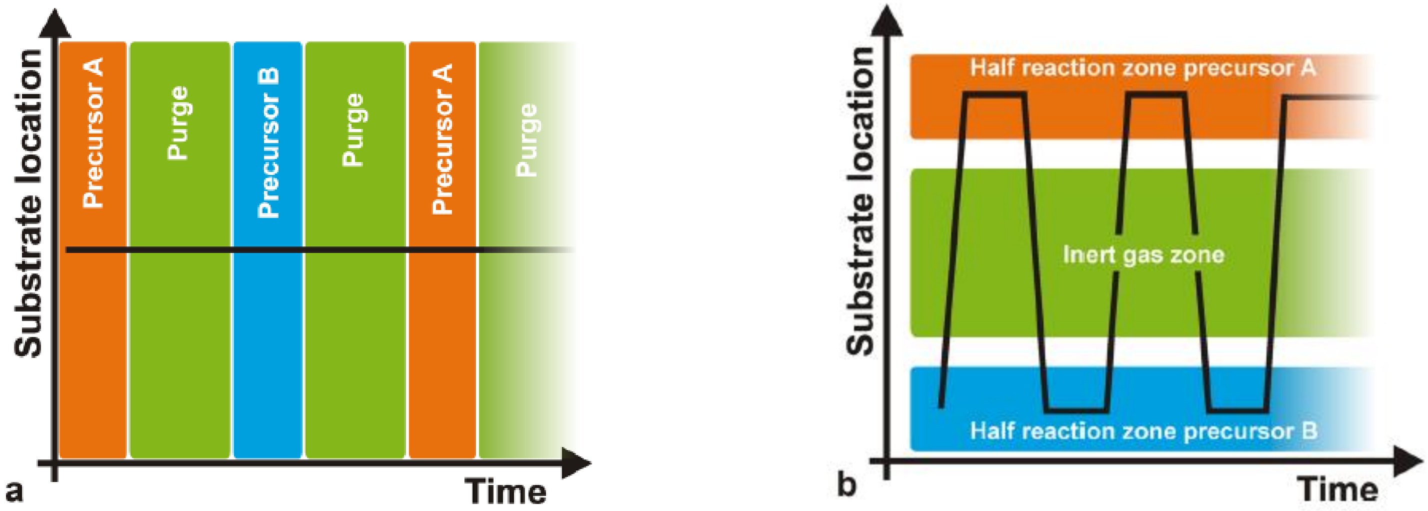
Powder functionalization

Buffer/interface layers

Large-area industrial ALD opportunities

- To address these markets, innovations required in:
  1. Large-area sheet systems
  2. Roll-to-roll processing
  3. High capasity wafer systems
  4. Powder coating methods
- 1. through 3. are achieved by Spatial ALD method
- Powder coating (4.) is achieved by fluidized-bed ALD
- In the following, equipment/performance/outlook is given for the above

Spatial ALD method

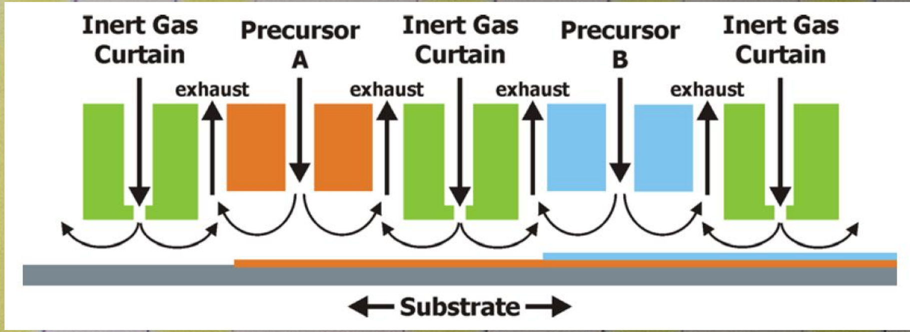


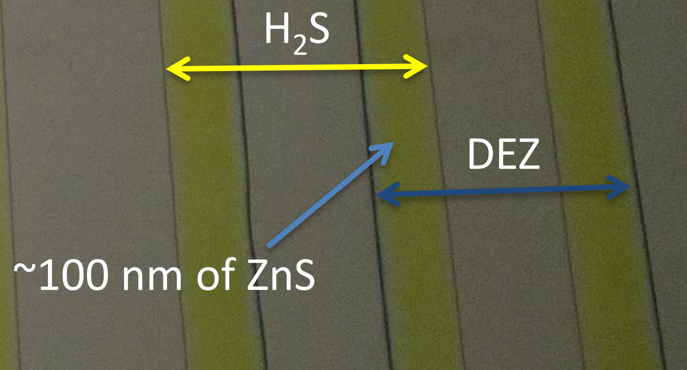
- High deposition rate by rapid relative movement!

[1]Poodt, P.; Cameron, D. C.; Dickey, E.; George, S. M.; Kuznetsov, V.; Parsons, G. N.; Roozeboom, F.; Sundaram, G. and Vermeer, A.; J. Vacuum Sci. Technol. A 30 (2012) 010802.

Spatial large sheet ALD equipment

- For large (m^2) planar substrates such as glass sheets
- Spatially separated metal and oxidising precursor zones
- Rapid substrate translation between the zones
- Processing at elevated pressures enabled with target for atmospheric processing
- In-line processing capability

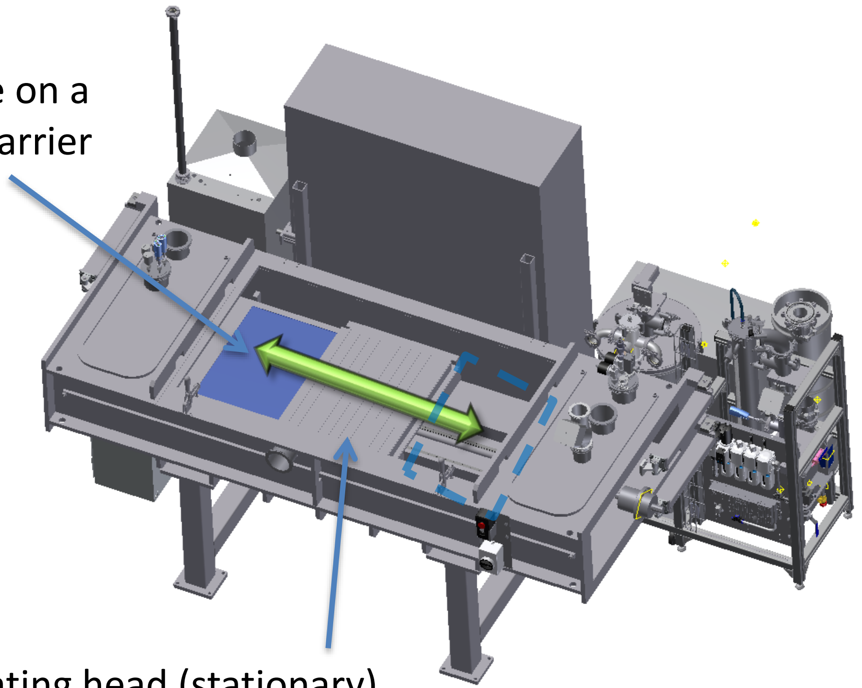




Picture showing ZnS ”stripes”, deposited to check performance of the coating system

Spatial sheet ALD highlights

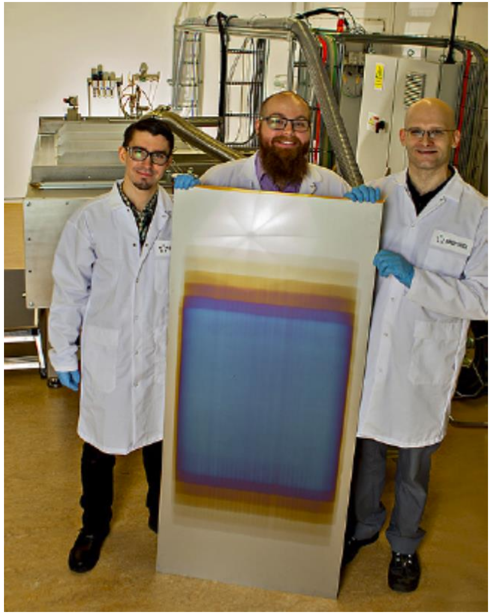
Substrate on a moving carrier



ALD coating head (stationary)

- 5 ALD cycles + H_2O at both ends

"The Team Spatial"



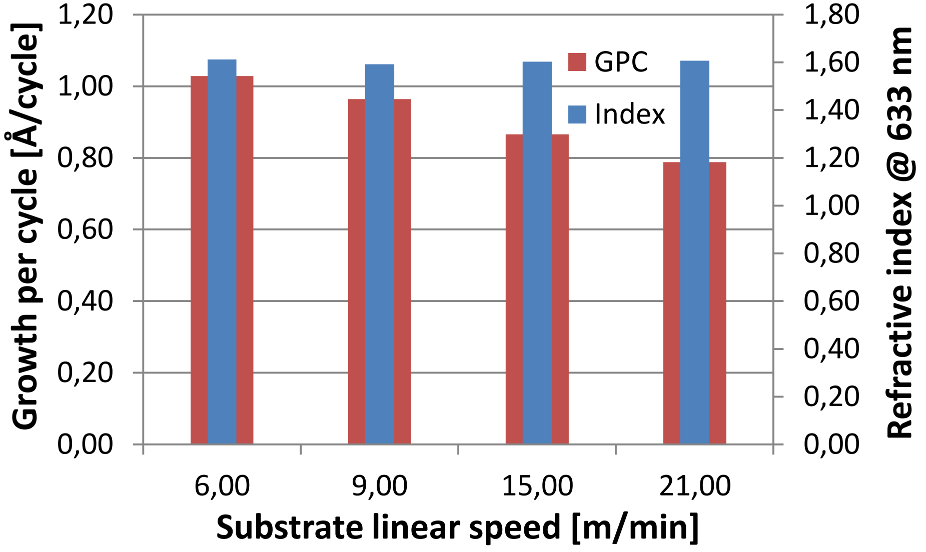
70 nm on ZnO on stainless steel showing effective coating area

Spatial sheet ALD highlights

- Fast Al_2O_3 process developed for e.g. thin-film encapsulation of OLEDs and rear-surface passivation

Al_2O_3 @ 110 °C

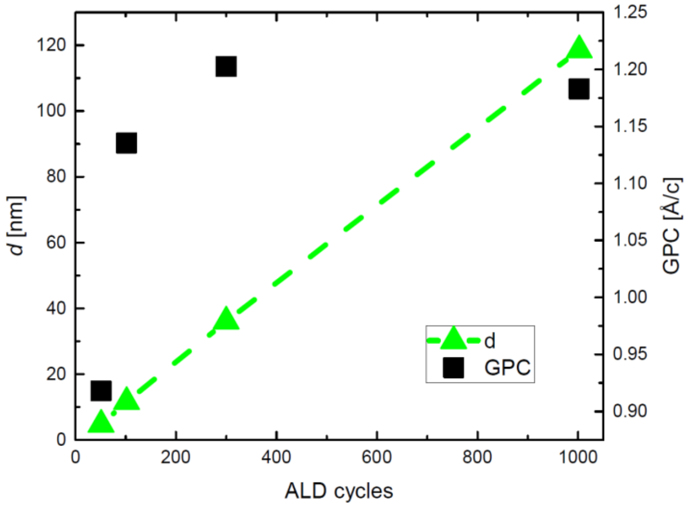
- ➢ Line speeds up to 21 m/min demonstrated
- ➢ Growth rate from 60 to 170 Å/min



Spatial sheet ALD highlights

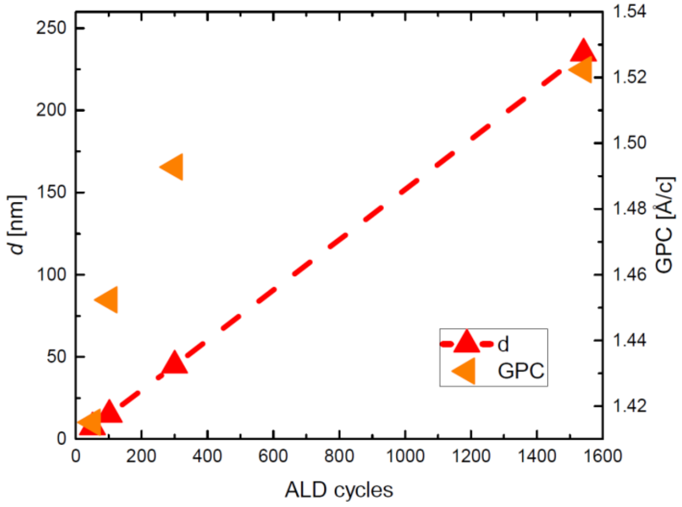
- Driving application is Zn(O,S) buffer for CIGS solar cells

ZnO @ 110 °C



n (633 nm) = 1.9556

ZnS @ 110 °C



n (633 nm) = 2.401

Spatial sheet ALD outlook

- Process exploration continued with prototype
- Zn(O,S) buffer trials on CIGS modules ongoing
- Low temperature OLED thin-film encapsulation work ongoing
- Spatial plasma oxidation to be implemented
- High partial pressure is beneficial for coating of highly porous substrates

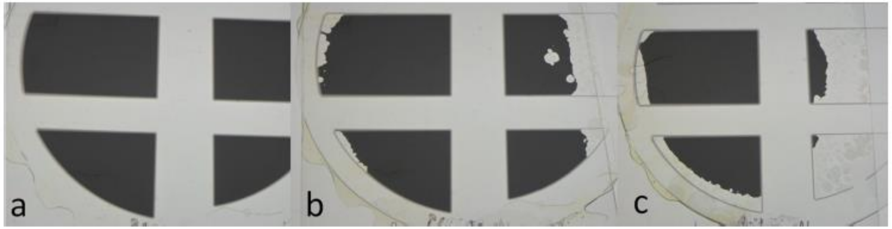
Spatial roll-to-roll ALD equipment

- Roll-to-roll process, with substrate tensioned on a process drum
- For continuous, flexible substrates (e.g. polymer, metal, paper)
  - Roll width 625 mm, length +1000 m
- Spatially separated metal and oxidizing precursor zones with operating principible similar to large sheet spatial ALD
- Rapid web translation (from 0.05 to 10 m/min)
- Line-integration to pre-and post-processing equipment

Image courtesy of Center for Process Innovation (UK)

Spatial roll-to-roll ALD highlights

- Driving application is flexible moisture barrier film
- Single 20 nm Al_2O_3 layer deposited at @ 105 °C[2]



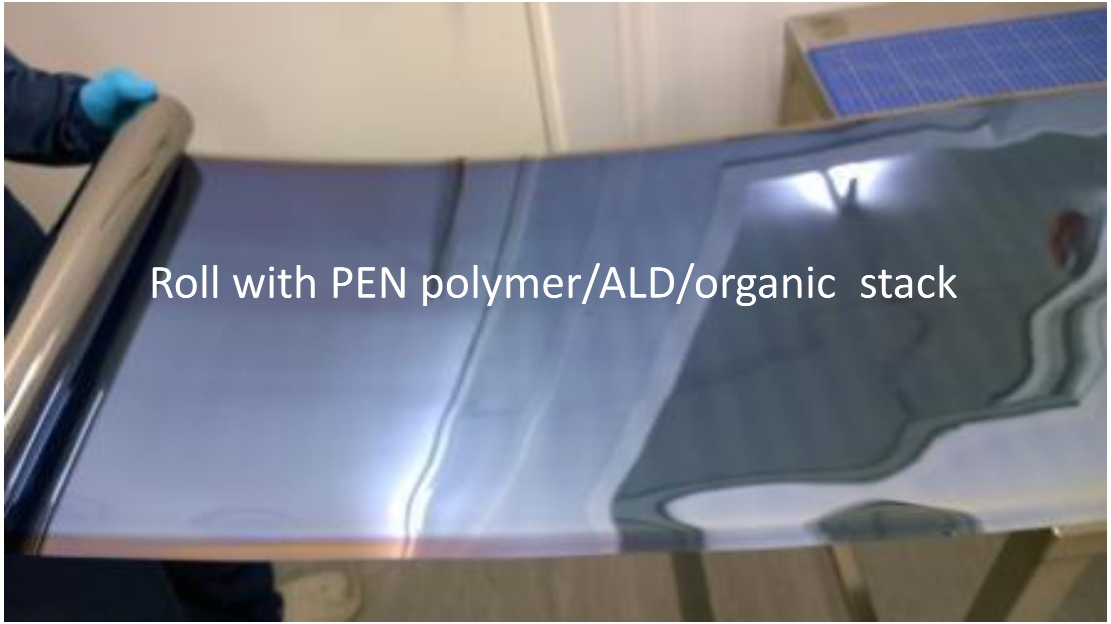
a) 185 hours at 40°C / 90 % RH
b) 468 hours at 85°C / 85 % RH
c) 800 hours at 85°C / 85 % RH

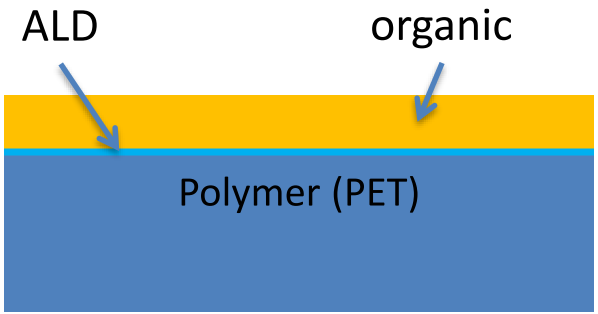
➡ Water vapor tranmission rate (WVTR) ~$5*10^{-6}$ g/m^2 day

[2]Maydannik, P. S.; Kääriäinen, T. O.; Kahtinen, K.; Cameron, D. C.; Söderlund, M.; Soininen, P.; Johansson, P.; Kuusipalo J.; Moro, L. and Zeng, X; J. Vacuum Sci. Technol. A, 32 (2014) 051603.

Spatial roll-to-roll ALD highlights

- Ongoing development of in-situ organic top-coating, for mechanical protection of sensitive ALD barrier coating





Spatial roll-to-roll ALD outlook

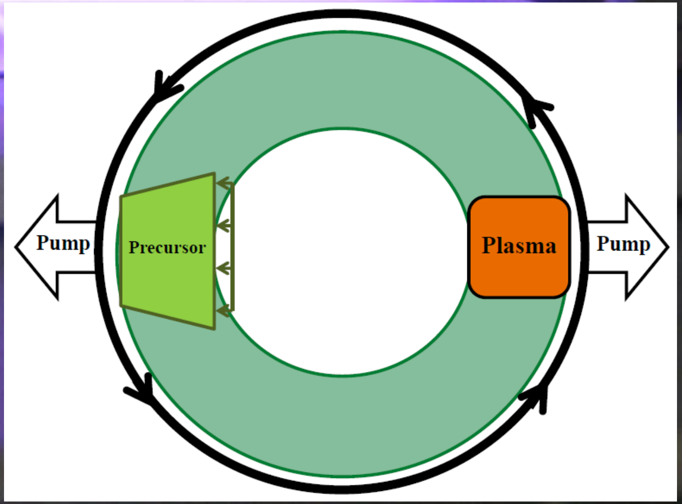
- True roll-to-roll ALD system is demonstrated, based on spatial ALD method
- Single-layer Al_2O_3 film for flexible moisture barriers is achieved @ 0.5 m/min
- Ongoing turn-key system development with organic top-coating of sensitive ALD layer
- Opportunity in emerging flexible AMOLED display barrier films
  - Conceptual design for 1.5 m wide webs

Rotary ALD equipment

- For wafers and other small substrates (e.g. optics lenses)
- Spatially separated metal organic and **plasma** zones
- DC plasma enabling low deposition temperatures (e.g. for plastics)
- Rapid wafer translation (300 RPM) between the zones

- 300 RPM = 300 ALD cycles/minute!

- Technology licended from Lotus Applied Technology



Images courtesy of Lotus Applied Technology

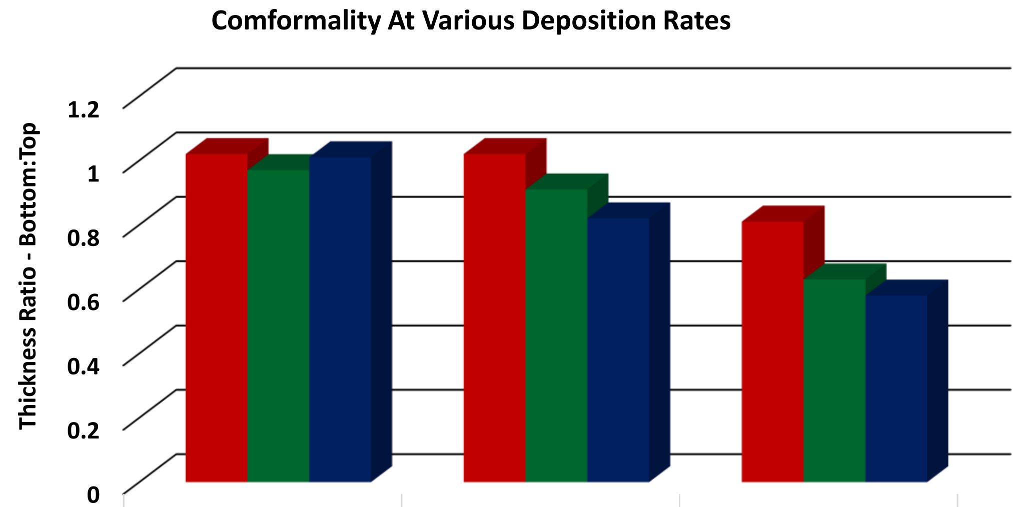
Rotary ALD highlights

- Driving application are thick optical HI/LO coatings
- Materials
  - SiO_2 from tetraethylsilanediamine (SAM-24) and O_2 plasma
  - TiO_2 from titanium tetraisopropoxide (TTIP) and N_2/O_2 plasma
  - Ta_2O_5 from Tris(ethylmethylamido)(tert-butylimido)tantalum (TBTEMT) and O_2 plasma

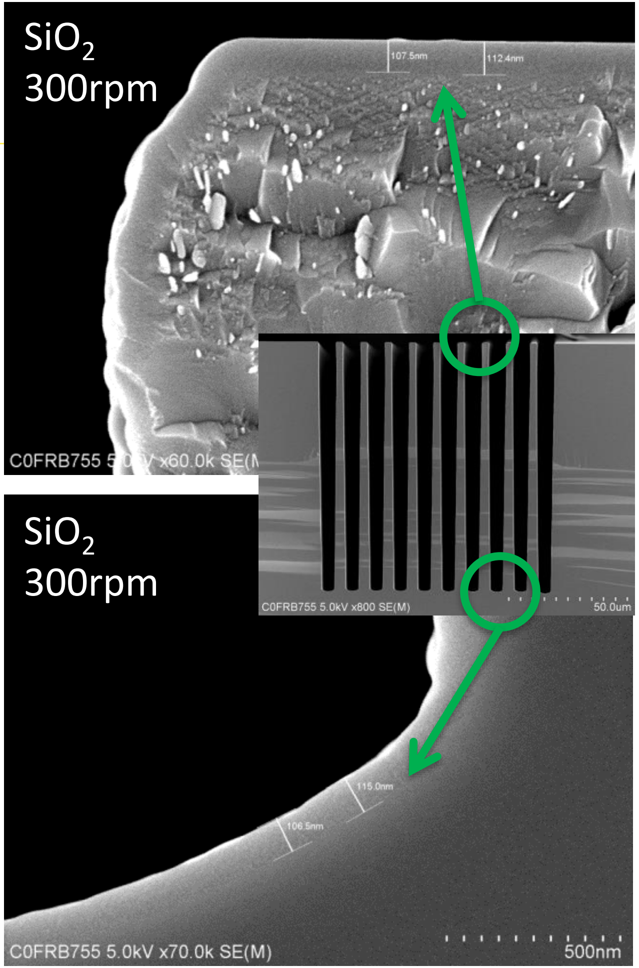
	Temperature (°C)	Rotation speed (RPM)	GPC (Å/cycle)	Refractive index (@550 nm)	Residual Carbon (at.%)
SiO_2	85-100	200	1.2	1.45	< 0.1
TiO_2	85-100	200	0.54	2.45	2.5
Ta_2O_5	150	120	0.82	2.17	2.0

Rotary ALD highlights

Uniform ALD growth in high aspect ratio trenches (1:20)



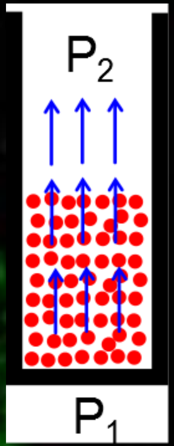
	SiO2	Ta2O5	TiO2
60 RPM	1.02	1.02	0.81
150 RPM	0.97	0.91	0.63
300 RPM	1.01	0.82	0.58



Rotary ALD outlook

- Low-temperature and high growth rate HI/LO refractive index processes developed
- AR-coating on plastic lenses demonstrated
- Realization of industrial scale platform (R11)
  - 1 µm/hour productivity target
- Expand on chemistries (e.g. SiN_x)
- Expand on applications

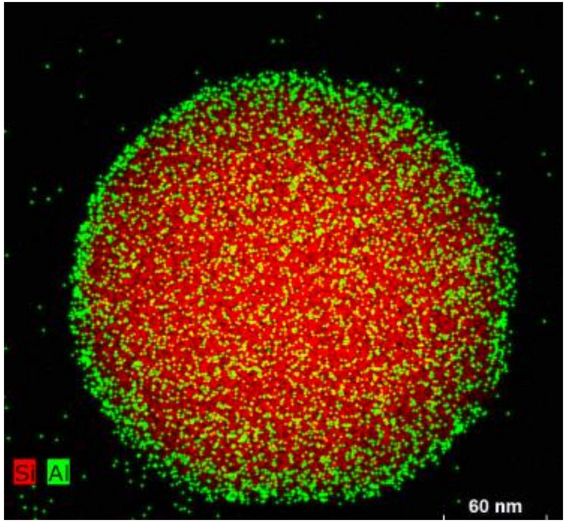
Fluidized-bed ALD equipment

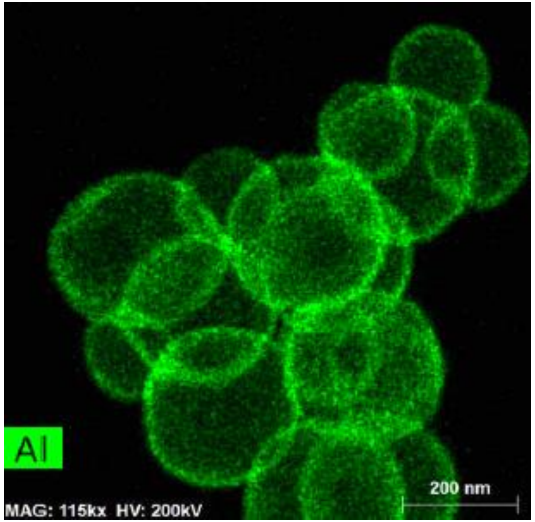


- For coating of powder (down to 10's nm)
- Based on fluidization of powder together with vibration
  - avoids static bed problems (e.g. channeling)
  - viable approach to scale for mass production
- Mass spectrometry for determining completeness of reaction
- Second generation FBR option for TFS 200 system
  - Chamber in chamber desing with isothermal conditions
  - Processing temperature up to 300 °C
  - Up to 5 grams of powder

Image courtesy of EPFL

Fluidized-bed ALD highlights





- Recent characterization results by EPFL, using HAADF STEM
- Highly conformal Al_2O_3 coating on SiO_2 spheres
- Low amount of non-coated spheres (< 5%)

Fluidized-bed ALD outlook

- Highly conformal Al_2O_3 coating of ~200 nm particles demonstrated
  - SnO$_2$ process also tested
- First 2nd generation FBR systems sold, deliveries in Q1/17
- Opportunity for ALD research community to adopt method for fine powder coating
- Potential industrial applications e.g. in improving robustness of phosphors & quantum dots.

Summary

- There is a growing need for technologies enabling ALD film growth on larger area substrates, faster and/or with higher capacity.
- Innovative solutions with system spesific benefits are avaible
  - Spatial large sheet ALD reactor for large planar substrates
  - Roll-to-roll ALD reactor for large flexible substrates
  - Rotary ALD reactor for ultra fast film growth
  - Fluidized-bed ALD reactor for powders

Thank you

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