Beneq

Equipment and Technology
for
Functional Surfaces

Atomic Layer Deposition for Thin Film Research and New Emerging Applications

Turning Innovations into Success

Outline

- Beneq
- Thin Film market outlook
- Atomic Layer Deposition (ALD) Technology
- ALD New Applications
- ALD in Photovoltaics
- Beneq ALD Systems for Industry and Research
- Turning Innovations into Success

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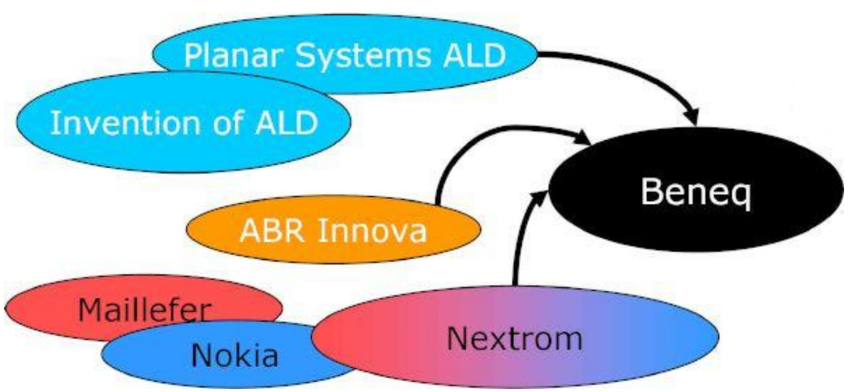
Beneq in Short

Established: 2005 MBO spin out from Nextrom (ex. Nokia-Maillefer) with focus on Equipment and Technology for Functional Surfaces.

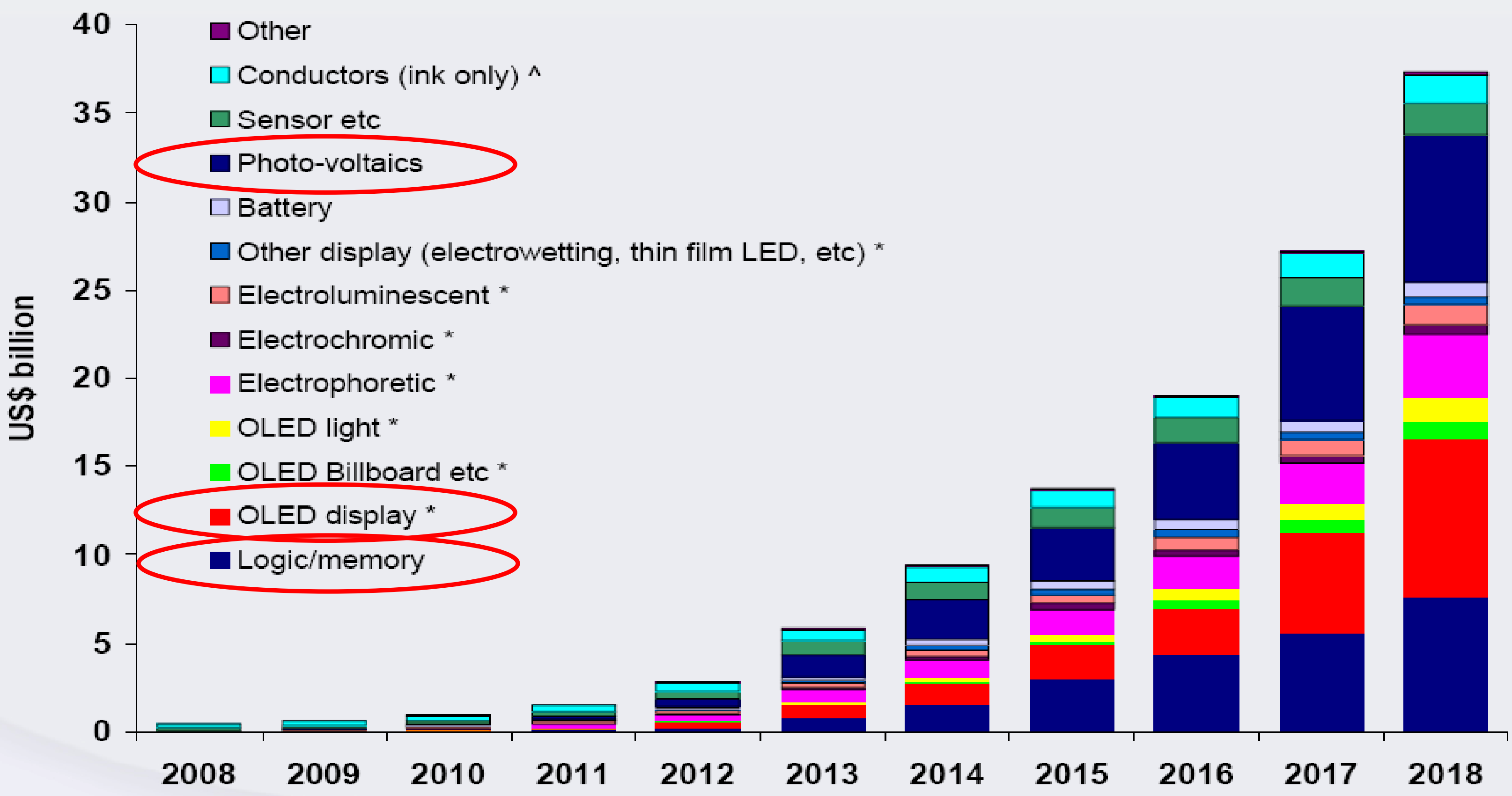
Ownership: Privately owned
Domicile: Vantaa, Finland

Products: Industrial and R&D Equipment for coatings based on
- Atomic Layer Deposition (ALD)
- atmospheric pressure Aerosol Technologies

Sales Offices: Germany (Europe), China, USA; representatives and customer support globally

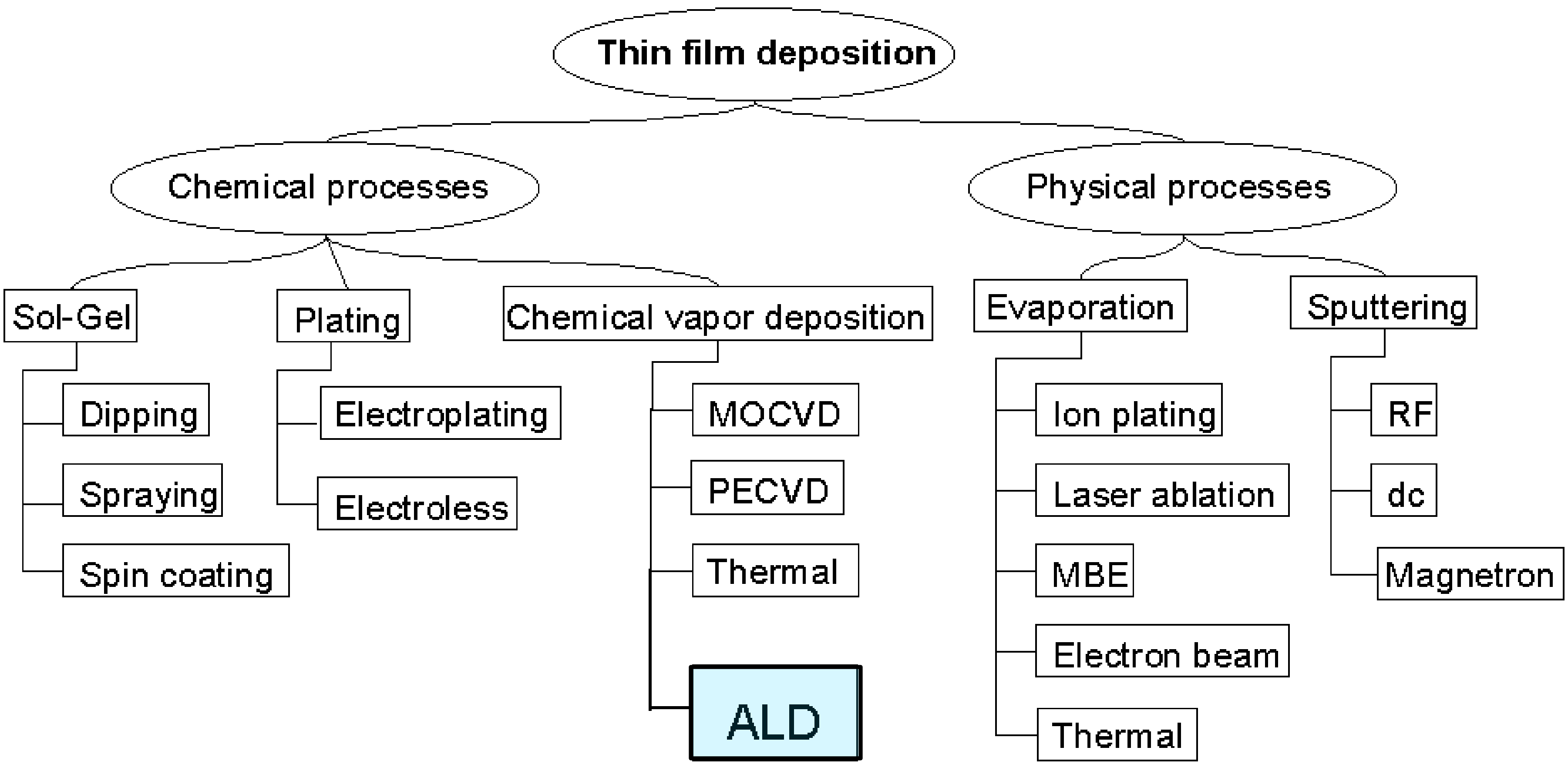


Market by sector 2008-2018



Market growth of thin film enabled industries.
Source: IDTechEx, Dresden, April, 2008

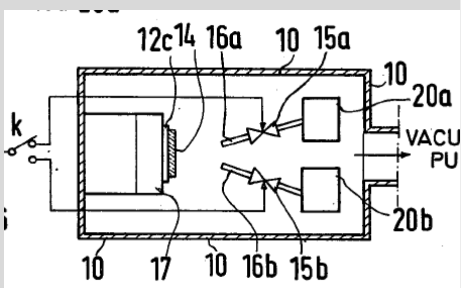
Thin Film Deposition Techniques



ALD Development History

1970

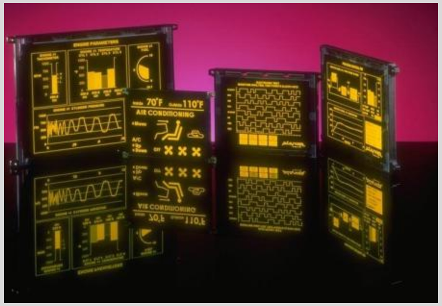
1974 ALD was invented by Dr. Suntola and co-workers



US 4058430

1980

1985 Thin film electroluminescence (TFEL) displays were the first ALD enabled products



Courtesy of Planar Systems Inc.

1990

Early 90's more R&D groups arrived to the scene notably from Korea, USA, and Finland

In the 90's IC industry recognizes ALD for new DRAM and gate oxide/metal systems

Late 90's DENSO starts manufacturing transparent TFEL displays for automotive markets using ALD

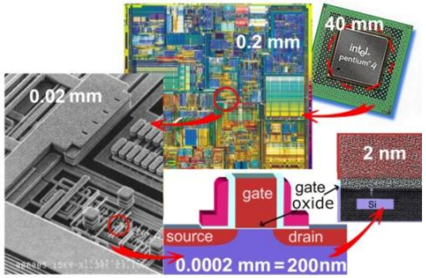
Front view

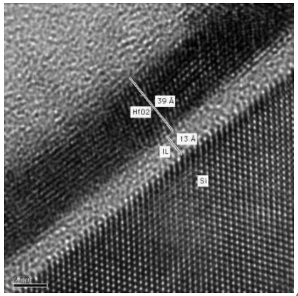
2000

Early 2000's major IC deposition tool vendors offer ALD tools. ALD is part of R&D at every major IC house.

Early 2000's ALD is applied to hard disc manufacturing

2007 First microprocessor products with ALD



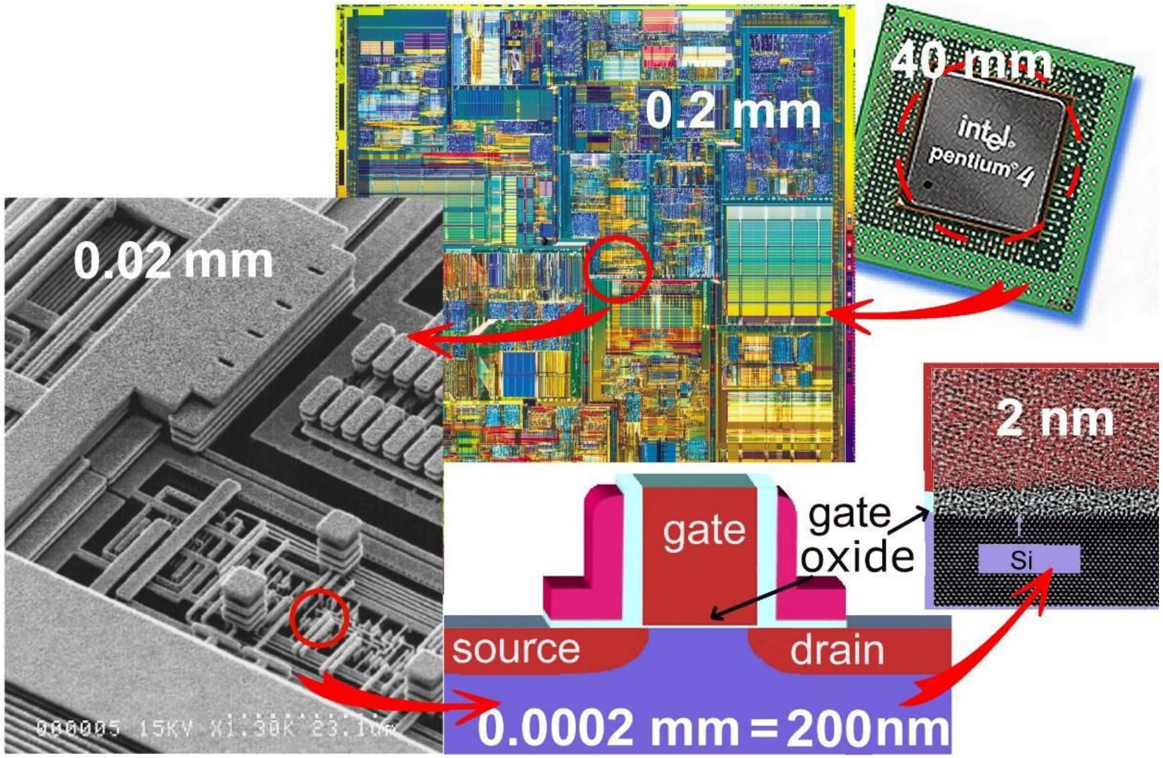


Examples of IC Applications

- Gate oxide
- Barrier layers
- Primer layers
- Gate electrode

Examples of non-IC Applications

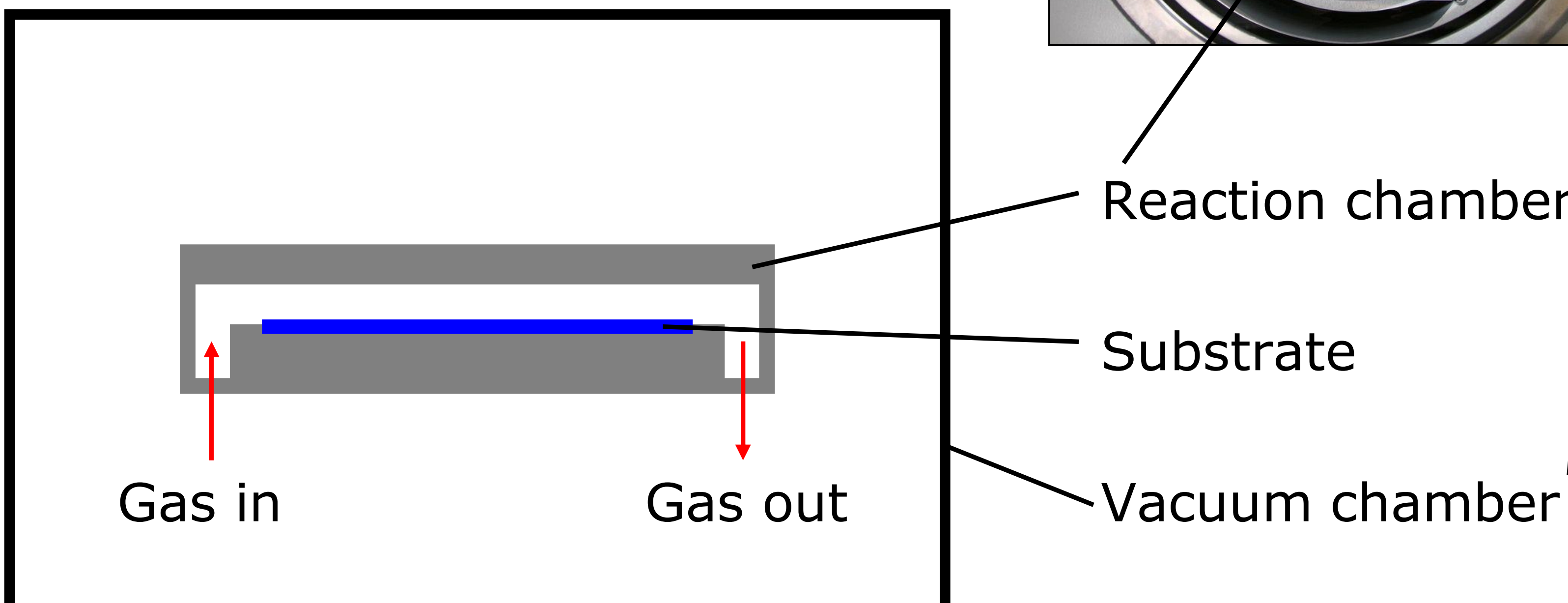
- Sensors
- Flat Panel Displays
- Solar panels
- Magnetic heads
- Memories
- Fuel cells



ALD Process

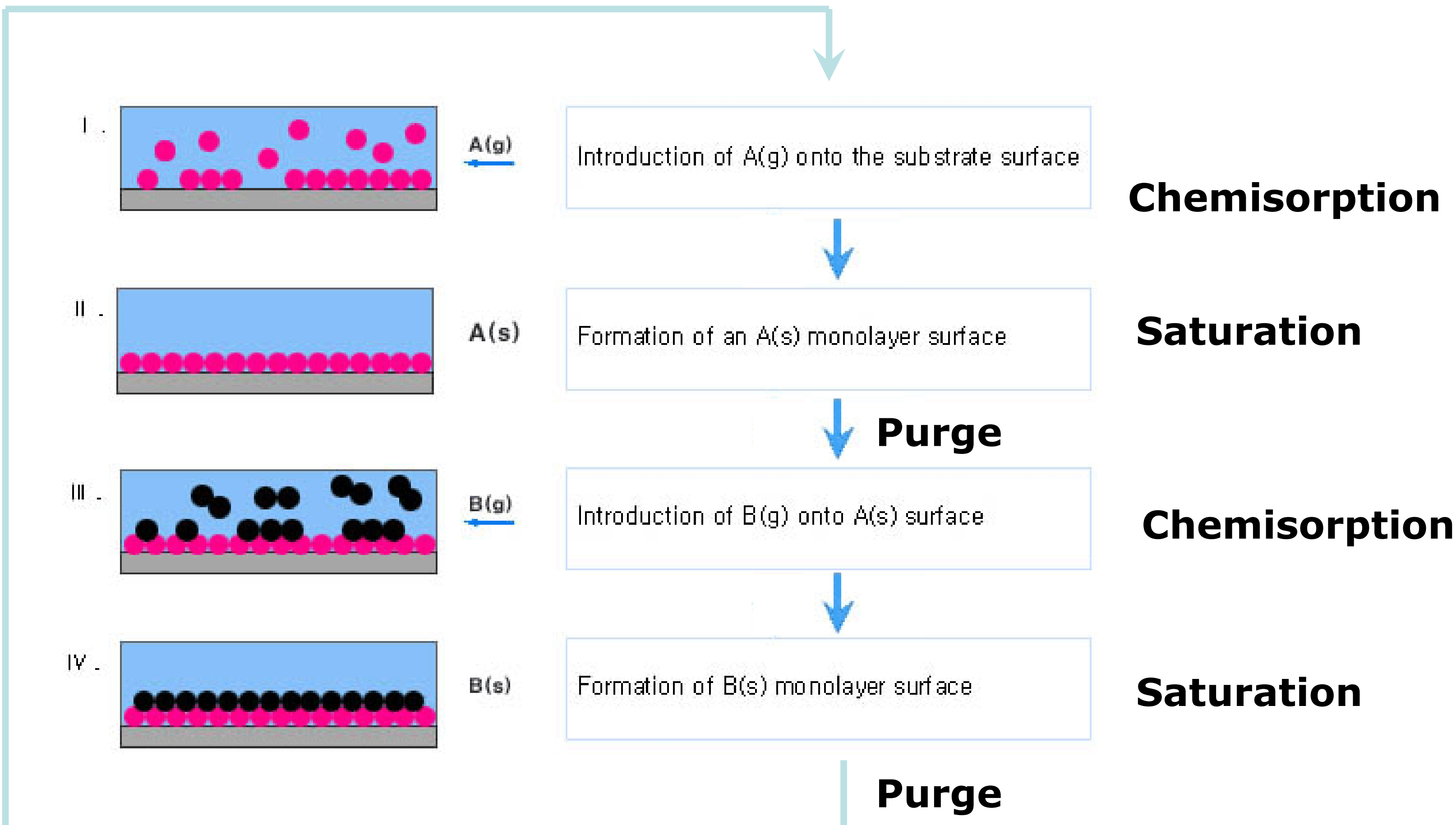
Process features:

- Pressure 0.1-5 mbar
- Temperature 60-500ºC
- Gas flow 0.3-1.0 SLM



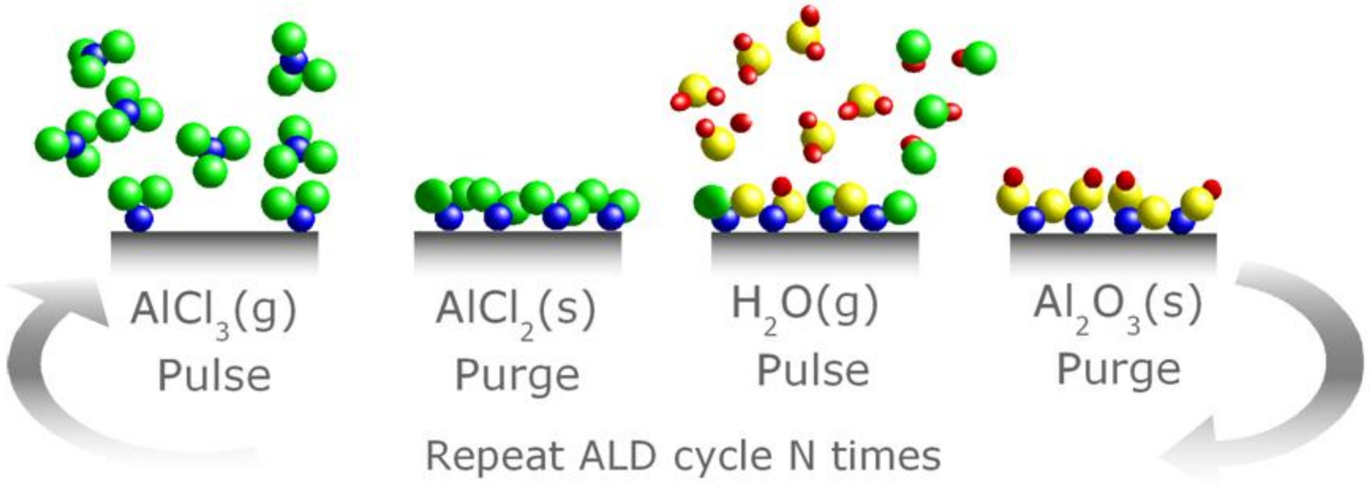
ALD Process Steps

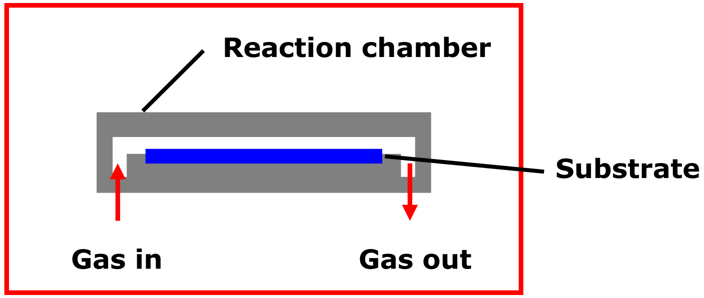
Sequential process

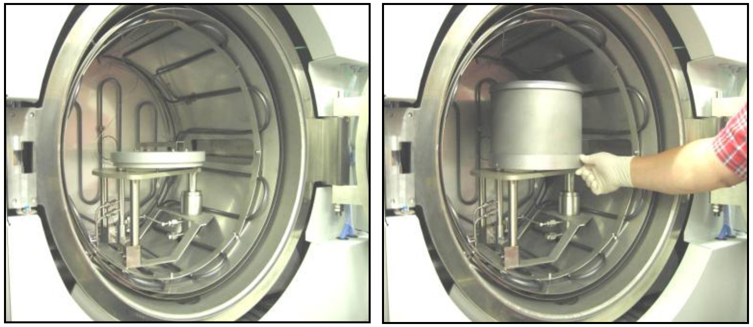


Surface controlled growth

$$2\,AlCl_3\,(g) + 3\,H_2O\,(g) \rightarrow Al_2O_3(s) + 6\,HCl\,(g)$$







ALD versus CVD versus PVD

CVD	ALD	PVD
Analog (µm/min) High growth rate	Digital (Å/cycle) High accuracy and repeatability	Analog (µm/min) High growth rate
Plenty of different materials	Oxides, nitrides, doped layers	Plenty of different materials including metals
Process parameter controlled	Surface controlled	Process parameter controlled Substrate movements
Mixable source materials	Highly reactive source materials	Physical transportation of the film material
Process parameter accuracy important	Flow dynamics important	High vacuum Process parameter accuracy important
Pieces with large surfaces 2-D surfaces	Pieces with large surfaces 3-D pieces Mixed structures	Small size pieces

Overview of ALD Materials

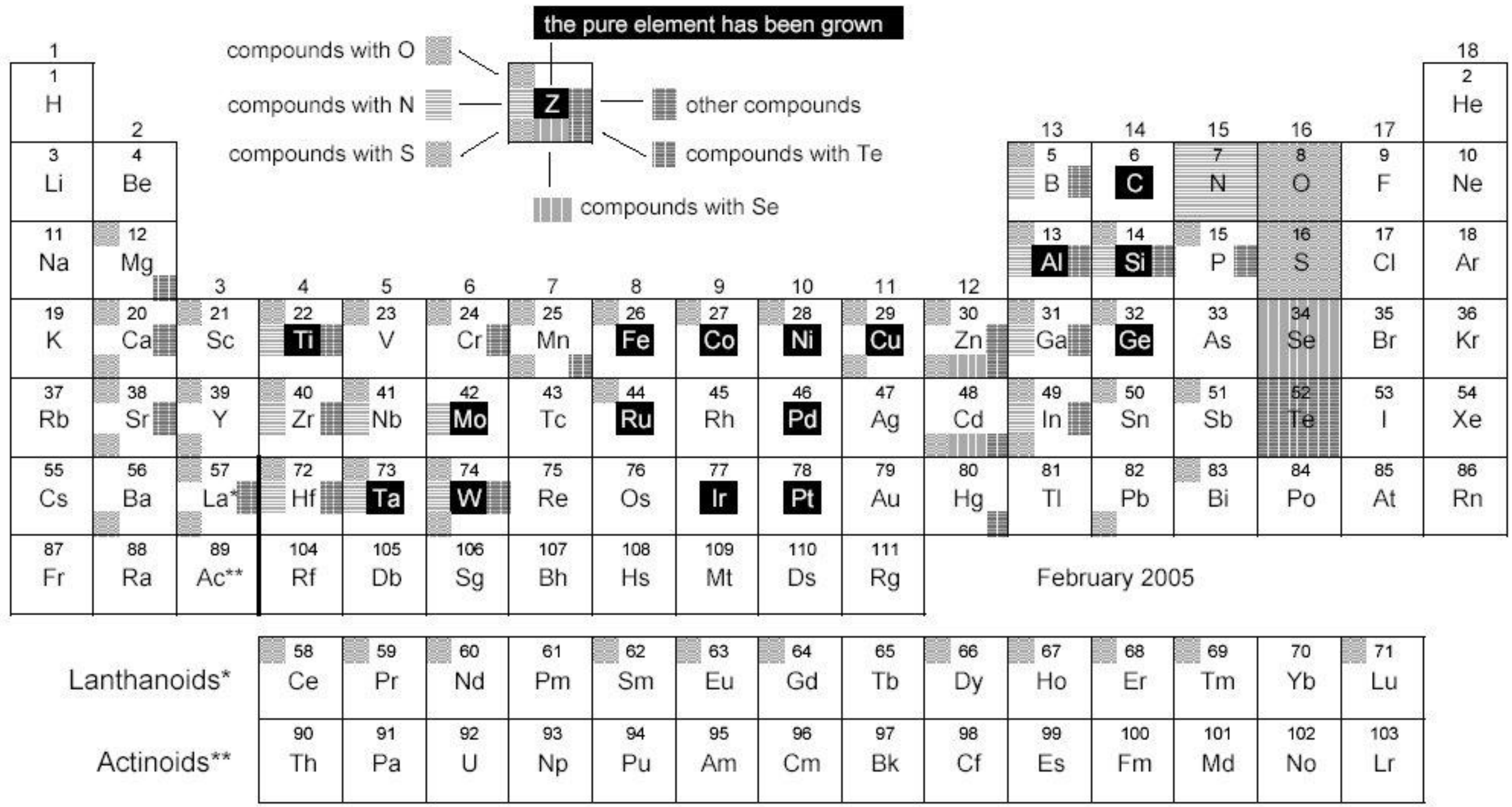


Figure 3: Overview of the materials grown by ALD. Classification according to Reactant A, with details of the investigations in Table III. Growth of pure elements as well as compounds with oxygen, nitrogen, sulphur, selenium, tellurium, and other compounds grouped together are indicated through shadings of different types at different positions. The elements are named according to the recommendations of The International Union of Pure and Applied Chemistry (IUPAC, http://www.iupac.org/reports/periodic_table/, dated 1 November 2004).

Ref. Riikka L. Puurunen J. Appl. Phys. 97 (2005) 121301-1 : **Surface chemistry of atomic layer deposition: a case study for the trimethylaluminum/water process**

Examples of ALD Materials

- **Oxides:** Al_2O_3, TiO_2, Ta_2O_5, Nb_2O_5, ZrO_2, HfO_2, SiO_2(Al), SnO_2, In_2O_3, ZnO, MgO, La_2O_3, Y_2O_3, CeO_2, Sc_2O_3, Cr_2O_3, SrO, Er_2O_3, VO_2, B_2O_3, Co_2O_3, CuO, Fe_2O_3, NiO, Ga_2O_3, WO_3, …
- **Nitrides:** AlN, TaNx, NbN, TiN, MoN, ZrN, HfN, GaN, WxN, InN, SiNx, …
- **Carbides:** TiC, NbC, TaC, …
- **Metals:** Pt, Ru, Ir, Pd, Cu, Fe, Co, Ni, W, …
- **Sulfides:** ZnS, SrS, CaS, PbS, …
- **Fluorides:** CaF_2, SrF_2, ZnF_2, …
- **Biomaterials:** TiO_2, $Ca_{10}(PO_4)_6(OH)_2$ (hydroxyapatite)
- **Polymers/ Organic :** Polyimides (PMDA-ODA, PMDA-DAH), 3-aminopropyltrimethoxysilane, ...

- **Doping:** ZnO:Al, ZnS:Mn, SrS:Ce, Al_2O_3:Er, YSZ, …
- **Nanolaminates:** HfO_2/Ta_2O_5, TiO_2/Ta_2O_5, TiO_2/Al_2O_3, ZnS/Al_2O_3, …
- **Mixed structures:** TiAlN, TaAlN, ATO (AlTiO), TiCrOx, SiON, LaAlO, STO, …

- Substrate temperature between 25 ºC and 500 ºC.
- Metal precursor compounds include: halides, organometals, alkoxides, metallocenes, beta diketonates, N-coordinated precursors (amides, amidinates), …

ALD benefits driven by surface reactions

Saturation and surface control

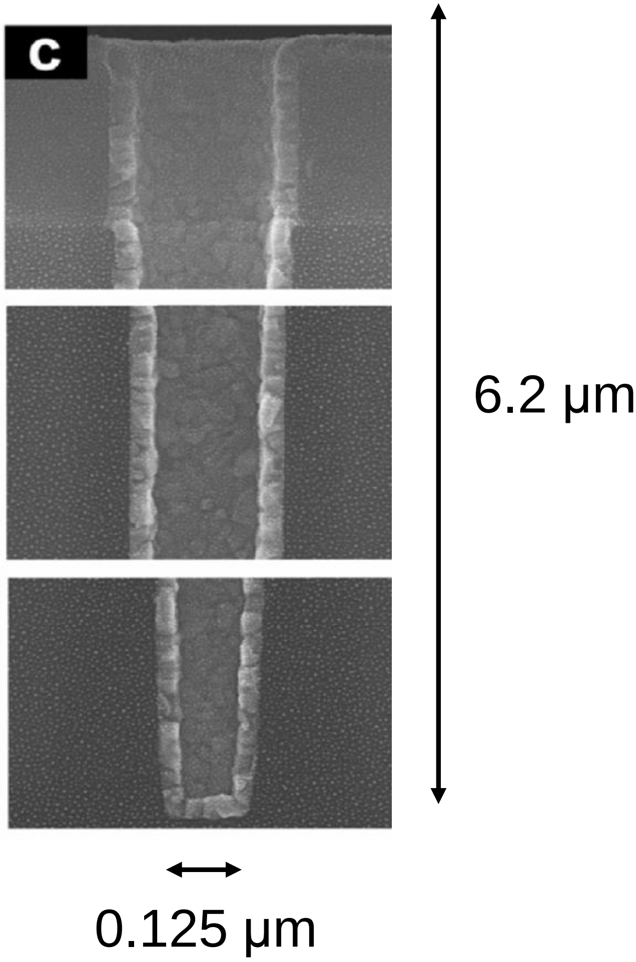
- Excellent step coverage (trenches, 3D)
- High conformality (thickness, composition)
- Pinhole free structures

Chemisorption

- Primer layers
- Surface modifications

Sequential

- Multi-layers in one process
- Nanolaminates
- Even gradual composition changes in nanoscale



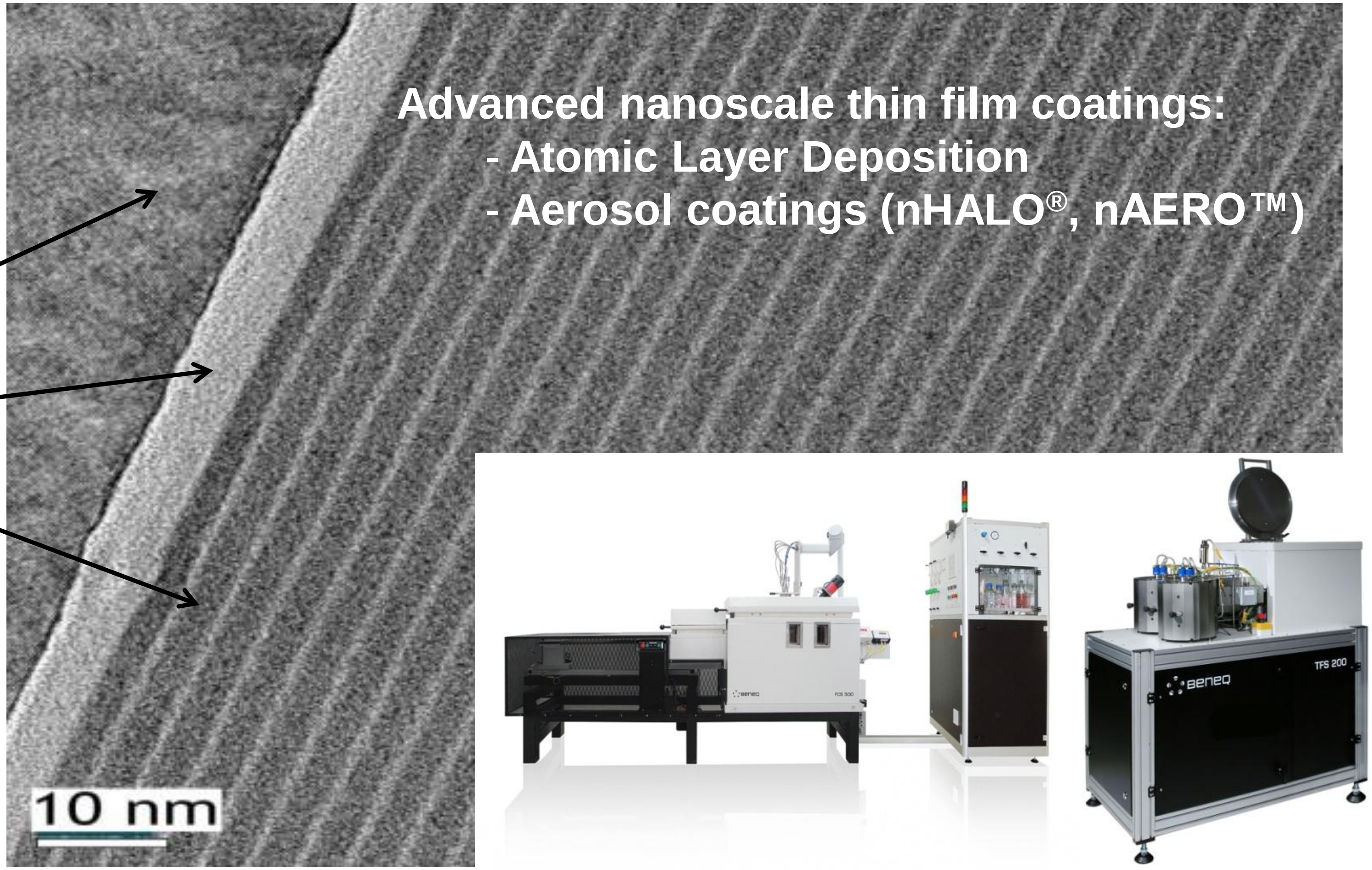
Strengths of ALD

- **Extreme surface conformality –** The best technology to deposit conformal films with superior uniformity
- **Pinhole free films –** ALD is naturally pinhole free; excellent for passivation, barriers and insulators
- **Repeatability, precision –** without in-situ feedback and control
- **Scalability –** straightforward to scale-up
- **Thin, dense, smooth films <2nm –** Films formed one atomic layer at a time
- **Artificial materials –** Digital control of ALD provides a way to create artificial materials; a critical benefit in many innovative R&D applications

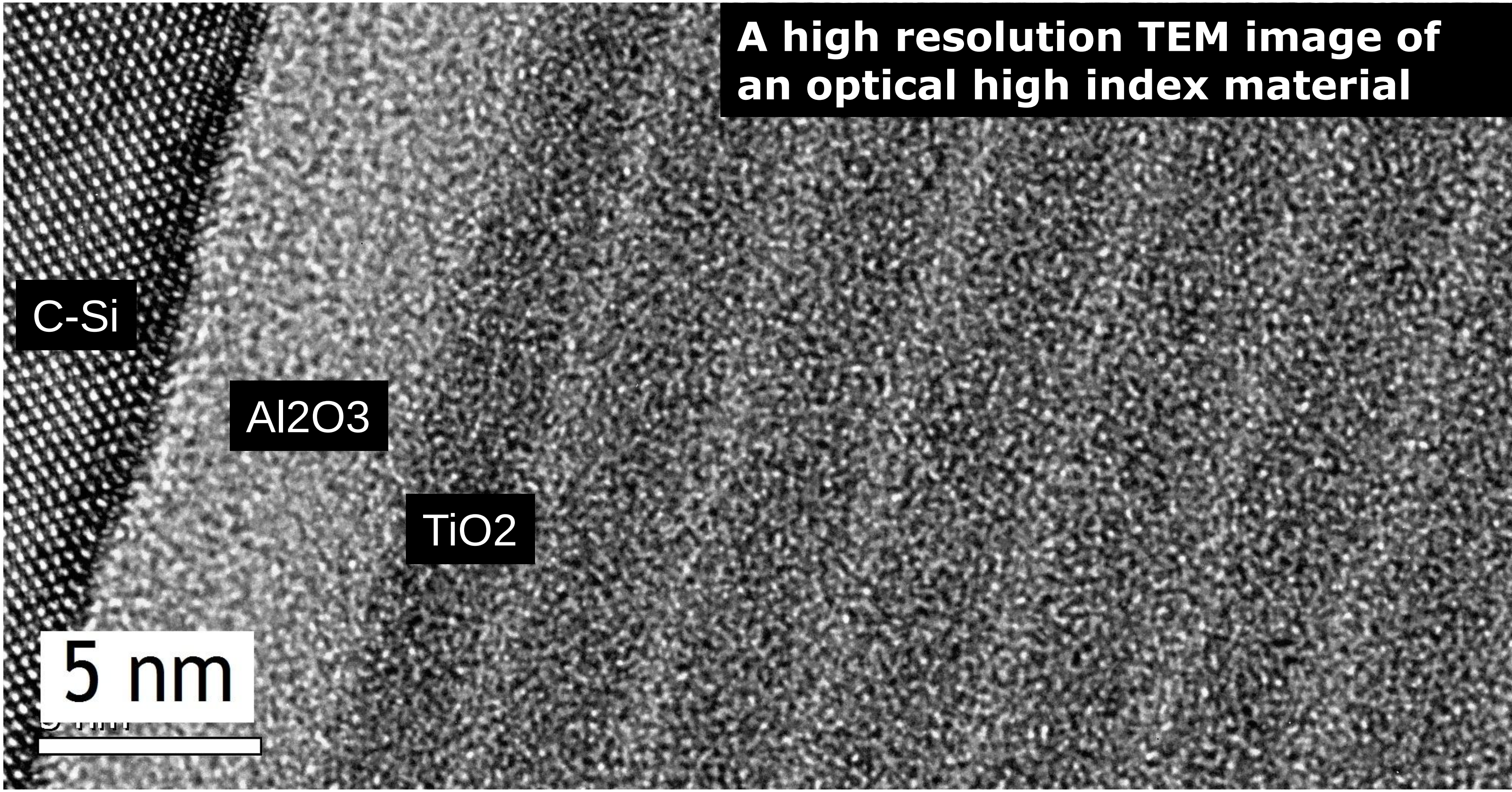
Artificial Materials by ALD

Advanced nanoscale thin film coatings:

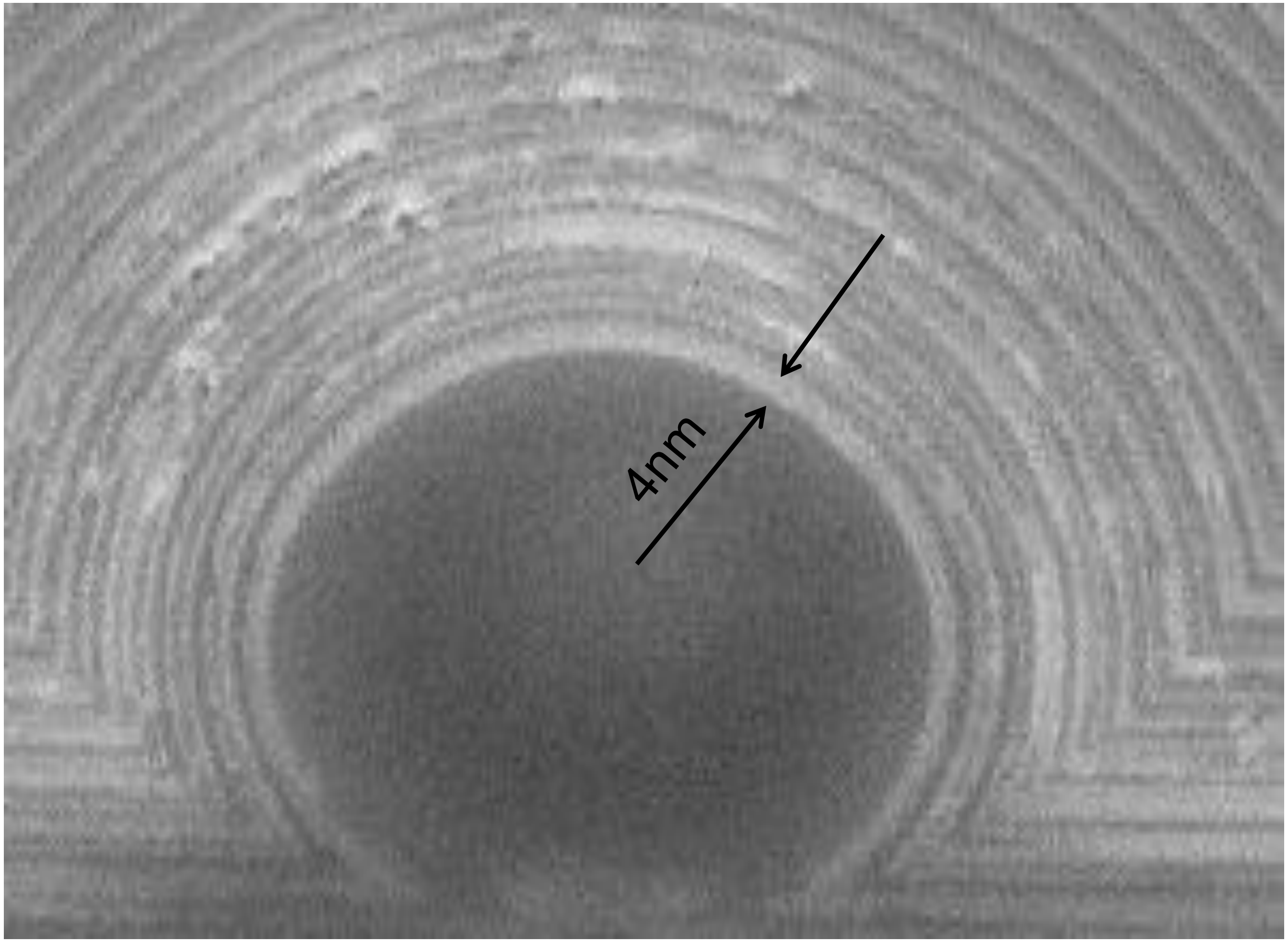
- **Atomic Layer Deposition**
- **Aerosol coatings (nHALO®, nAERO™)**



Artificial Materials by ALD



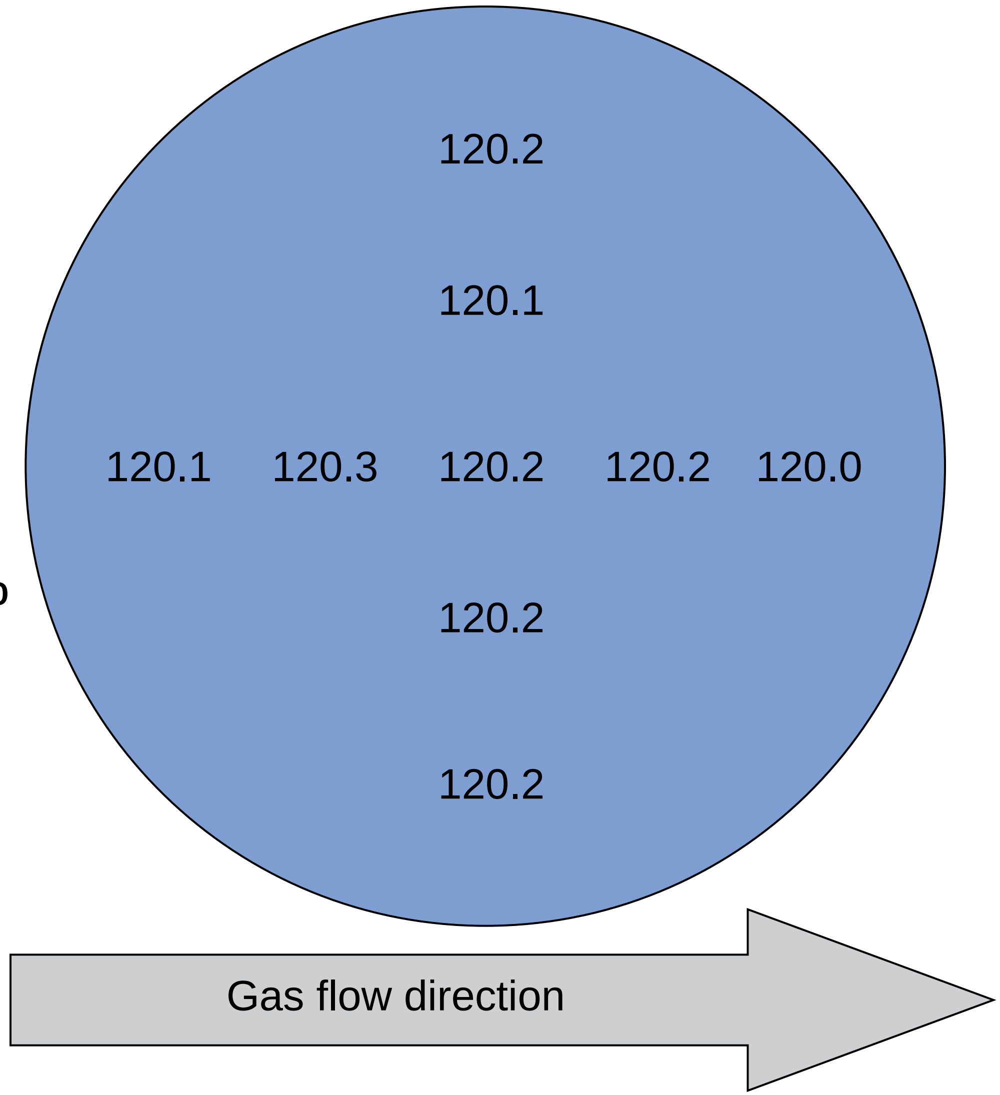
Artificial Materials by ALD for 3D substrates



Film Thickness Uniformity

9-point measurement

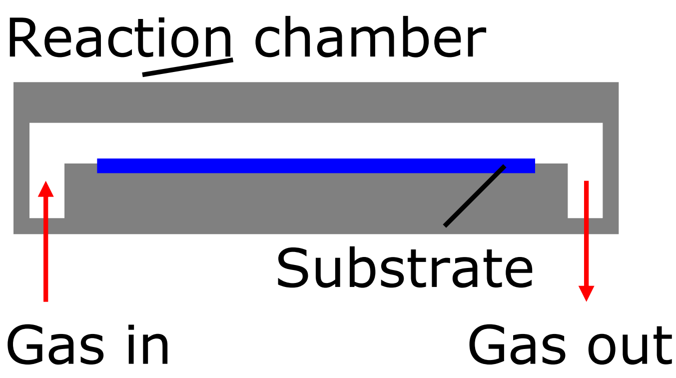
- 100 mm wafer
- Al_2O_3 with TMA + H_2O
- 2 second cycle time
- Thickness variation 0.25% (from 120.0 to 120.3 nm)

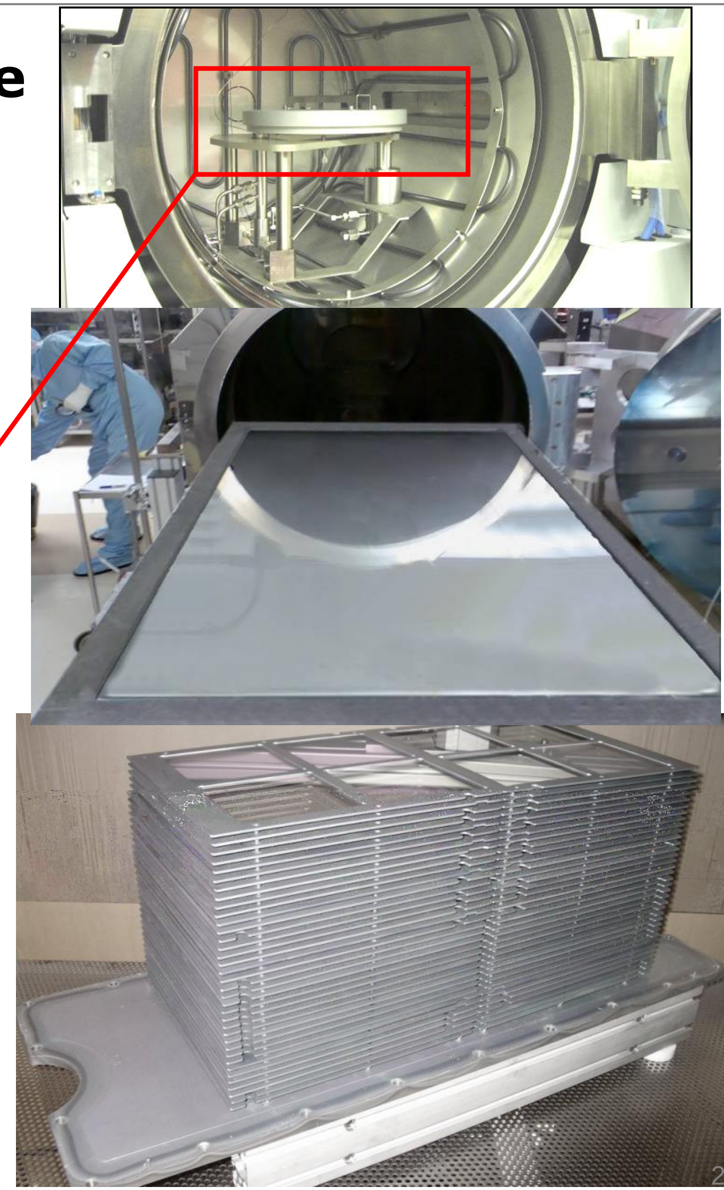


ALD Process scalability

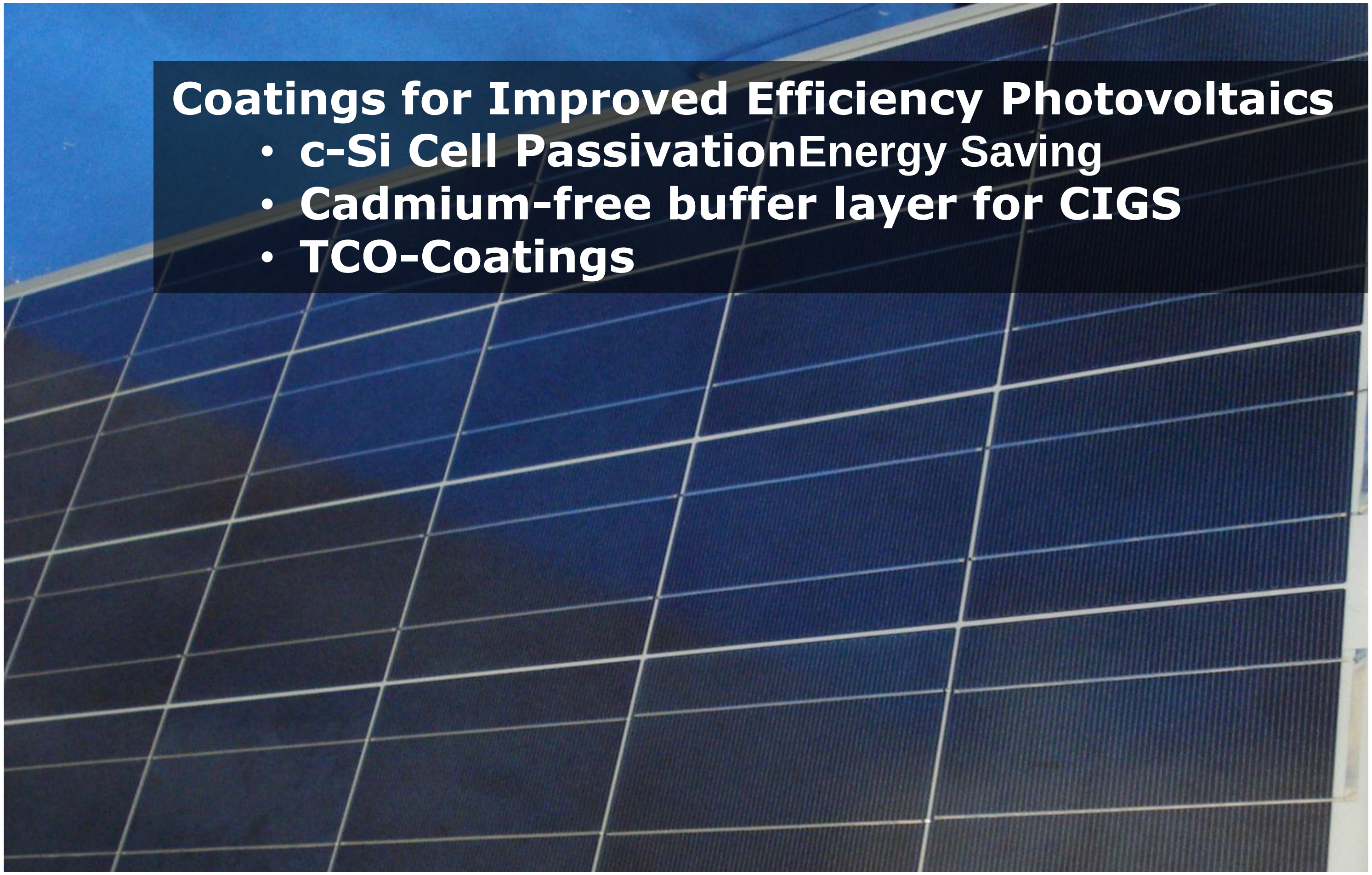
If something works in small scale it should work also on industrial scale ???

- performance, integration
- deposition speed
- price



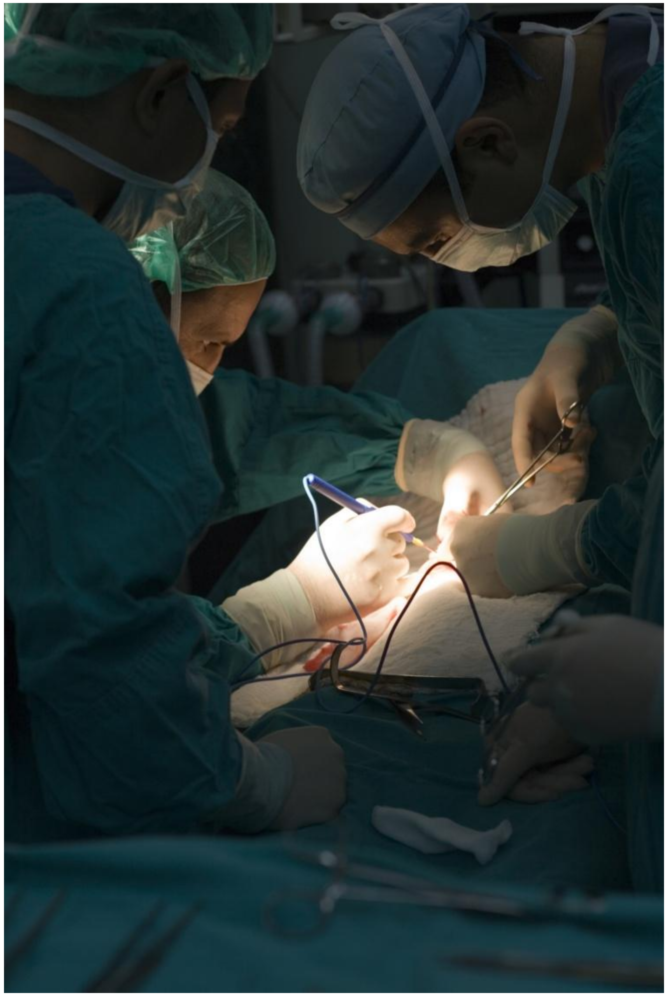


Renewable energy - Photovoltaics

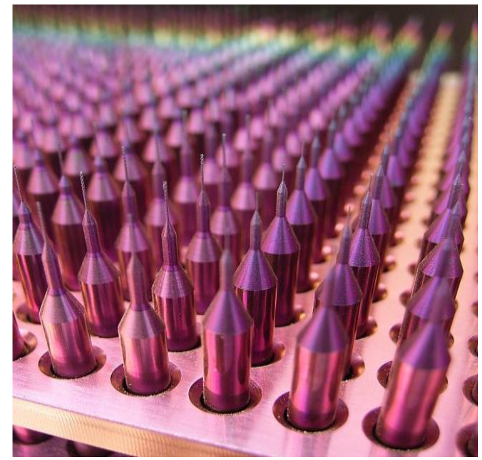


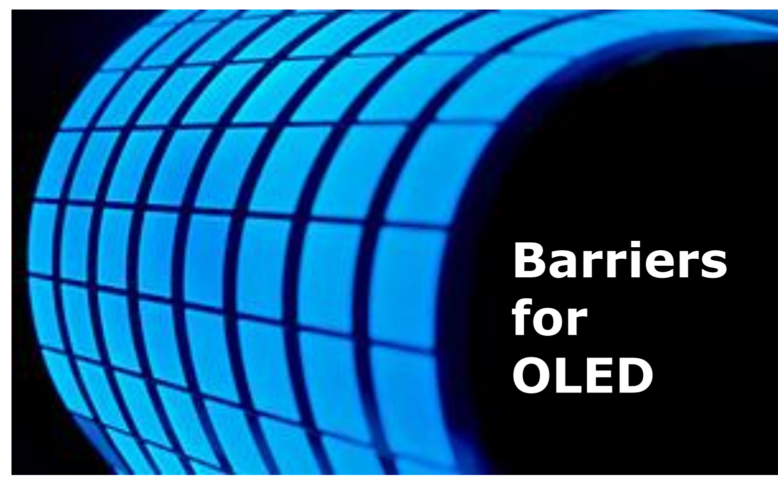
Medical industry

Biocompatible thin film coatings

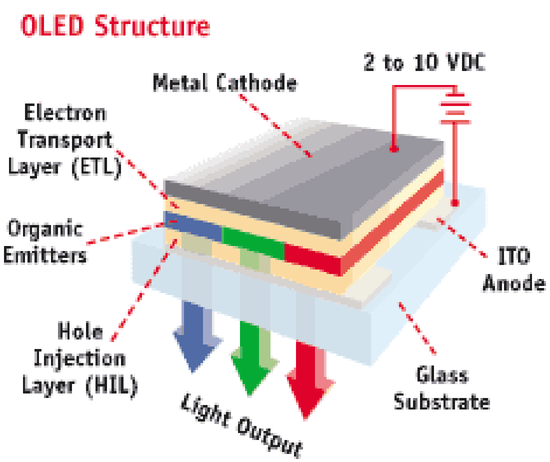


Industrial thin film coatings

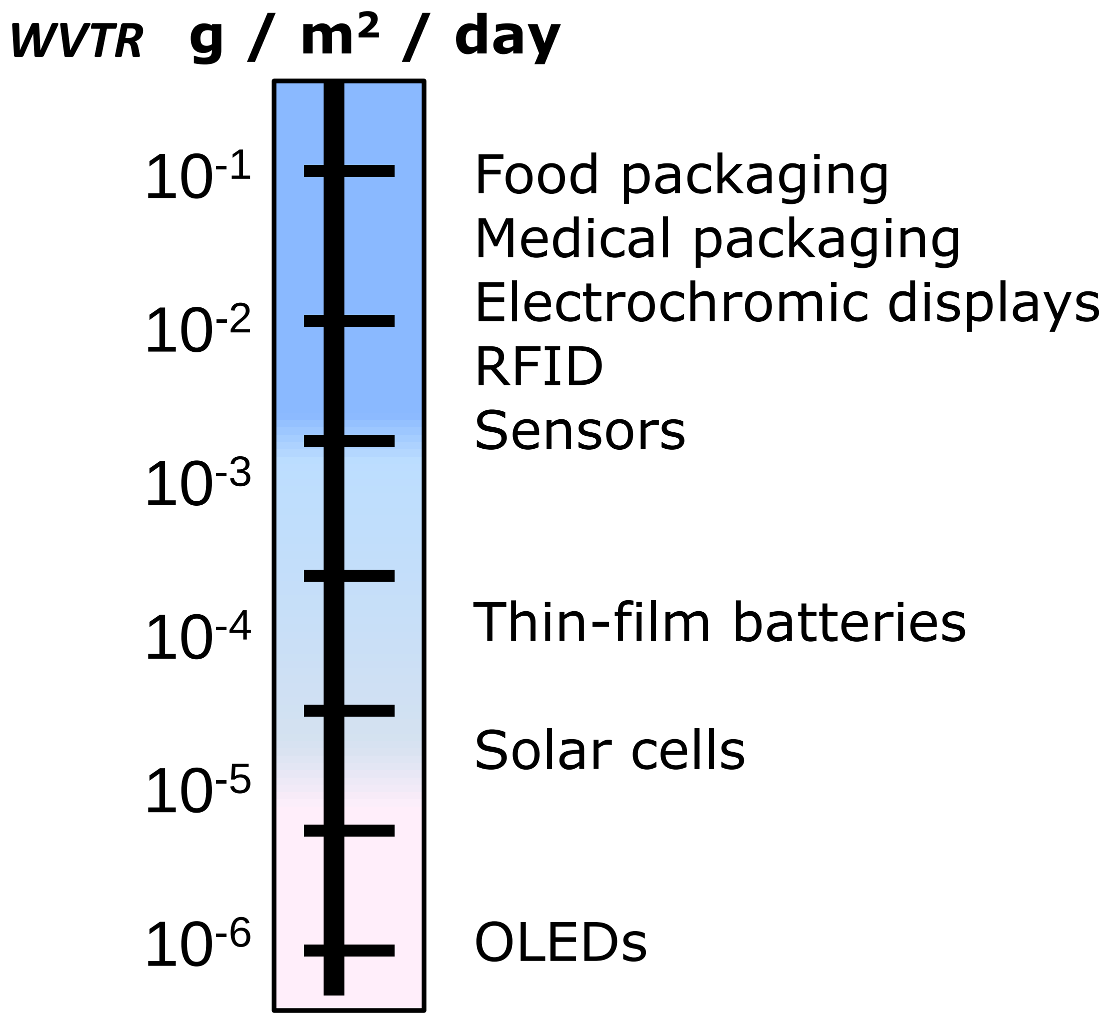




Barrier applications



www.oled-display.net

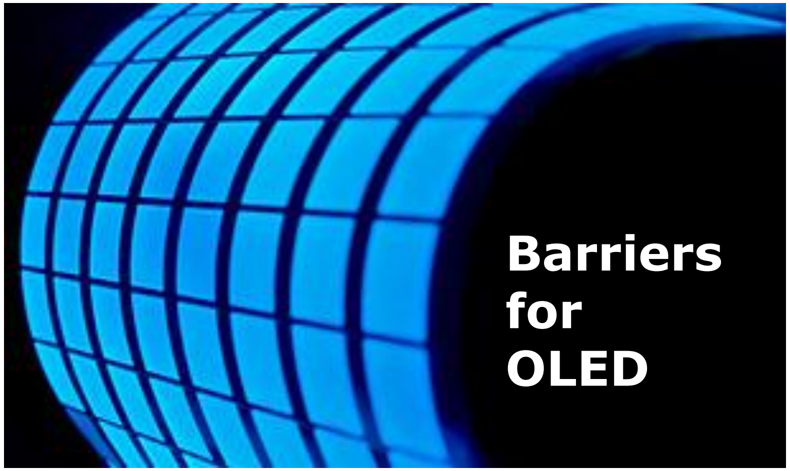


Superior Barrier Layer Against Moisture

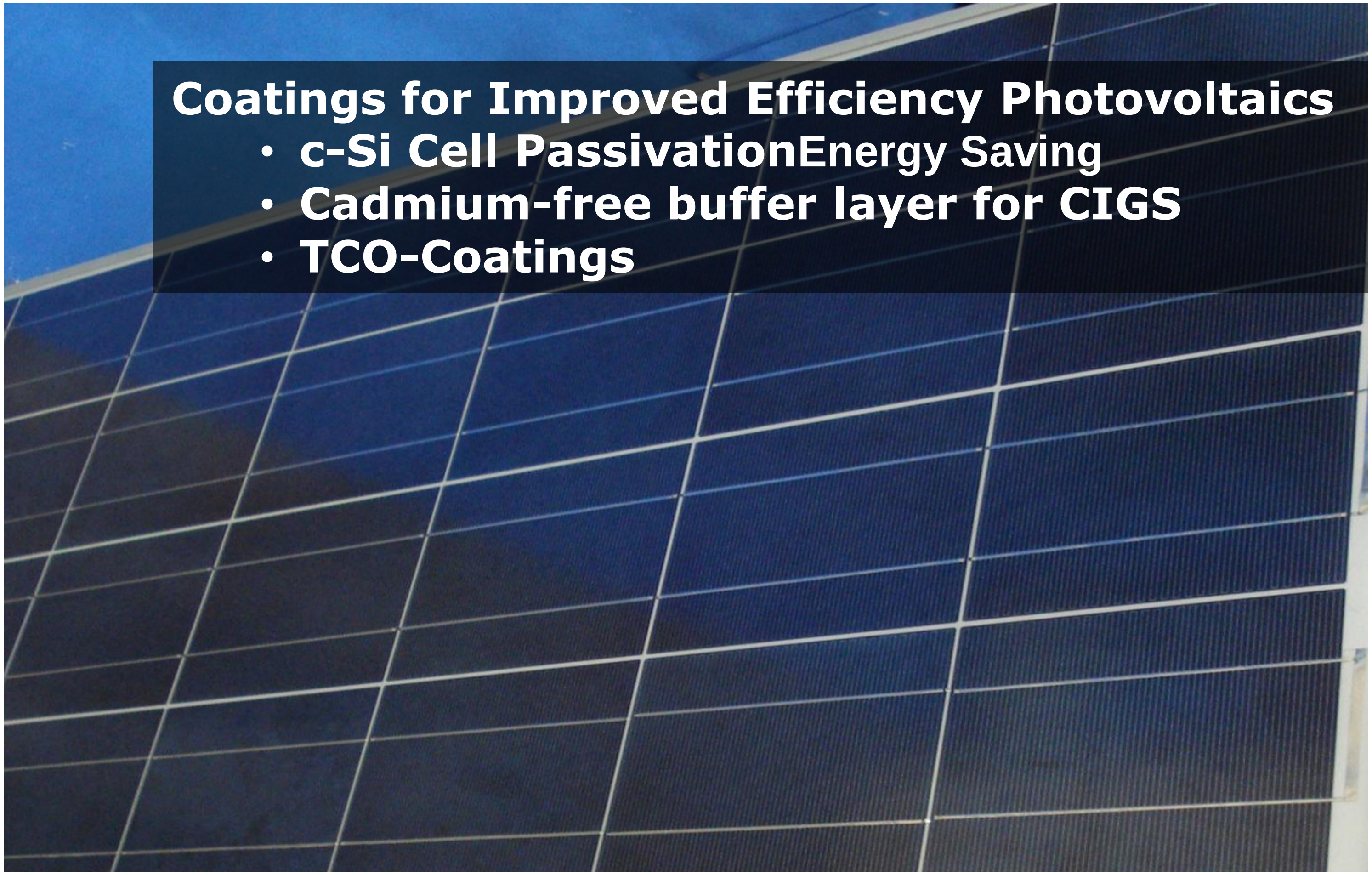
Ca-test, WVTR (g/day·m^2)

Substrate	Process temperature	Condition 80°C/80%
Ca	120 °C	$8x10^{-5}$ *

* Corresponds < 10^{-6} g/m^2 day @ RT
test performed at TU Braunschweig



ALD in Photovoltaics

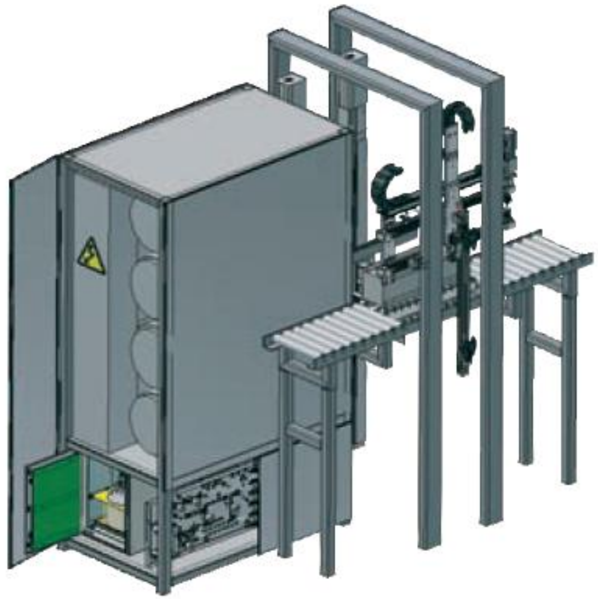


Rear Surface Passivation of c-Si Solar Cells

Back surface passivation of thin c-Si cell wafers improves efficiency, through increased effective lifetime of charge carriers

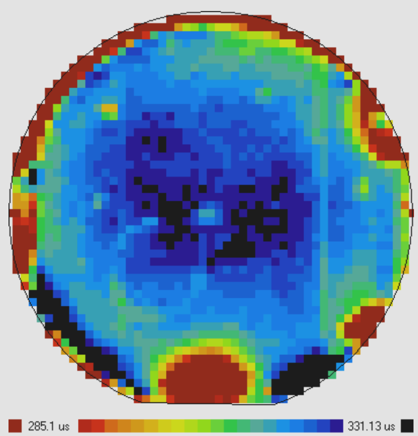
ALD Al_2O_3 gives 1-2%-unit higher efficiency

- proven in cell scale



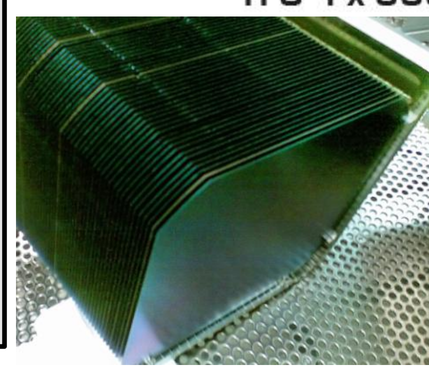
TFS 4 x 300

Thermal ALD Al_2O_3 coated 2 ohm·cm <111> p-type 4” wafer



295 µs **331 µs**

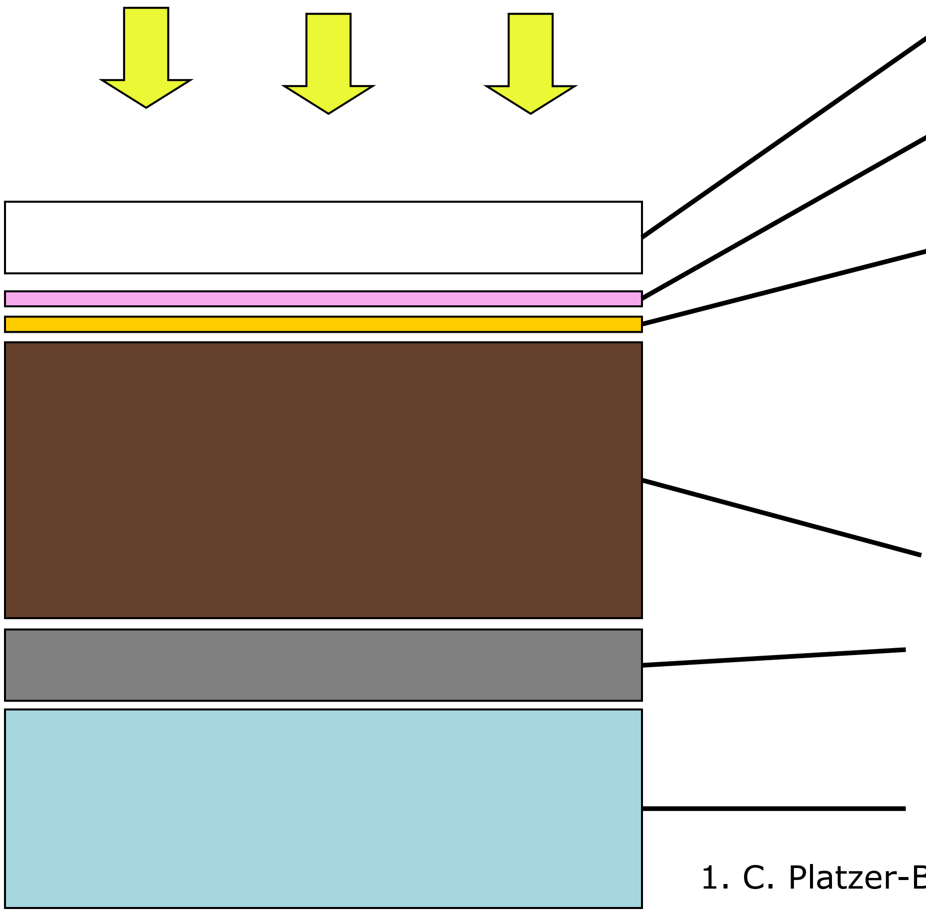
Measurement: Semilab, WT-85 µPCD



- $156x156mm^2$ wafer
- Batch size 500w
- Thru-put 1500w/h

Buffer Layer for CIGS Solar Cells

ALD Zn(O,S) buffer layer gives 1%-unit higher efficiency compared to conventional CdS



TCO: ZnO:Al (0.5 – 1.0 µm)

Window layer: ZnO (50 – 100 nm)

Buffer layer:
CdS (n-type; 50 nm) or
Cd-free window layer: Zn(O,S), (Zn,Mg)O, In2S3 (10-50 nm)[1]

Cu(In,Ga)Se_2 (p-type; 1.5 µm)

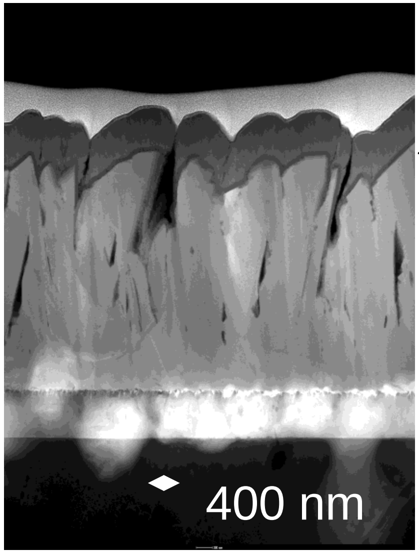
Back electrode: Mo 0.3 – 0.4 µm

Substrate: soda lime glass

1. C. Platzer-Björkman et. al. J. Appl. Phys. 100, (2006) 044506

ALD Zn(O,S) buffer layer for CIGS solar cells
- Improved transmission vs. CdS
- Highly conformal
- Enhanced blocking of pin-holes in the CIGS layer

→ 1%-unit higher efficiency

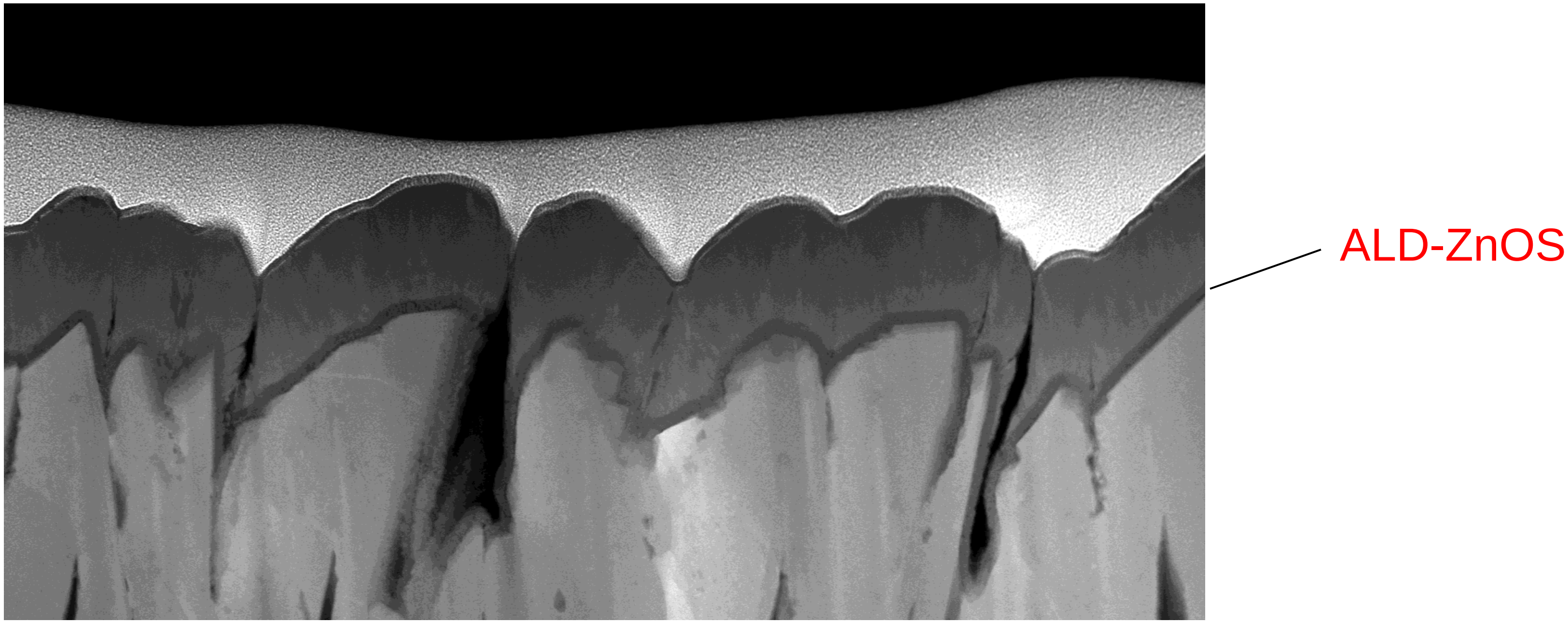


TEM from Uppsala University

Beneq TFS 1200 in-line production ALD system

ALD Buffer Layer for CIGS Solar Cells

ALD Zn(O,S) buffer layer for CIGS solar cells
- Highly conformal and excellent step coverage

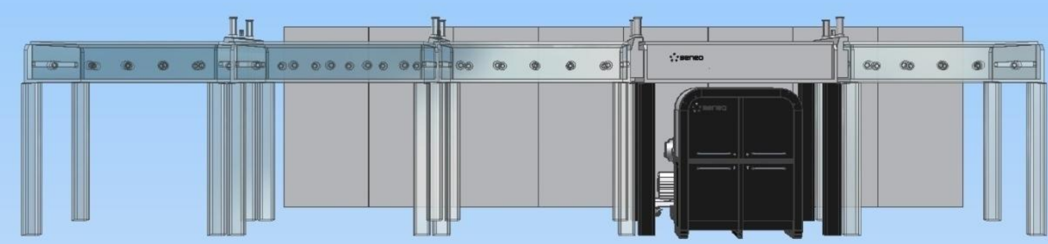


TEM from Uppsala University

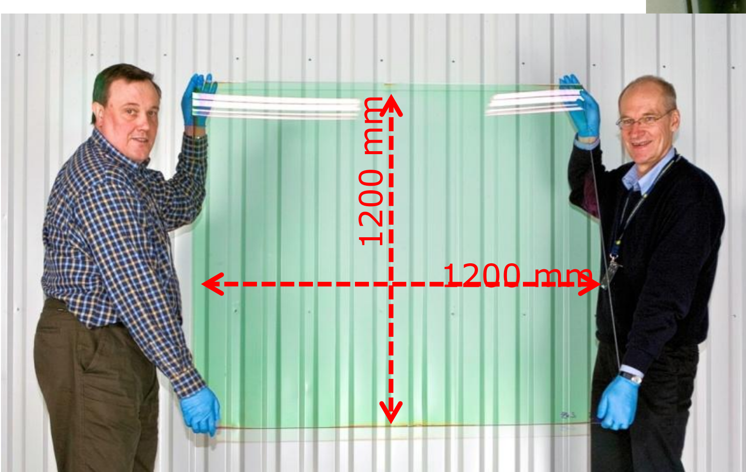
Buffer Layer for CIGS Solar Cells

Beneq TFS 1200 In-line ALD module

- Substrate 600x1200mm^2
- Batch size 2 substrates
- Batch time 5 min
- Thru-put 24pcs/h



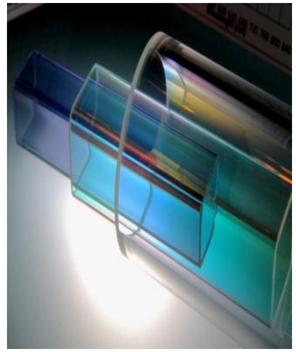
Beneq TFS 1200 in-line production ALD system

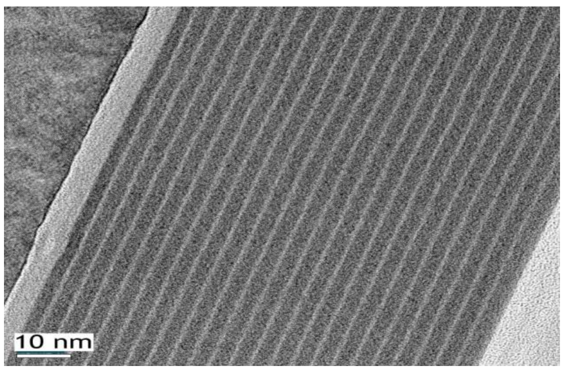


For substrates up to 1200x1200mm^2

The largest substrate ever coated with ALD!

Beneq ALD Equipment and Technology





Application examples:

- nOPTO – Optical coatings
- nERGY – Photovoltaic applications
- nSILVER – Anti-tarnishing coatings on silver
- nCLEAR – Passivation and hermetic barrier coatings
- nTRIBO – Tribological coatings for precision parts
- nPRIMER – Primering applications
- Glass strengthening

Equipment range:

- **TFS 200** – Thermal/plasma ALD tool for R&D purposes
- **TFS 500** – Thermal/plasma ALD equipment for batch production
- **TFS 4x300** – Batch ALD equipment for PV
- **TFS 600** – For PV and display industry
- **TFS 1200** – In-line ALD equipment for PV
- **P400A, P800** – Batch ALD equipment for manufacturing

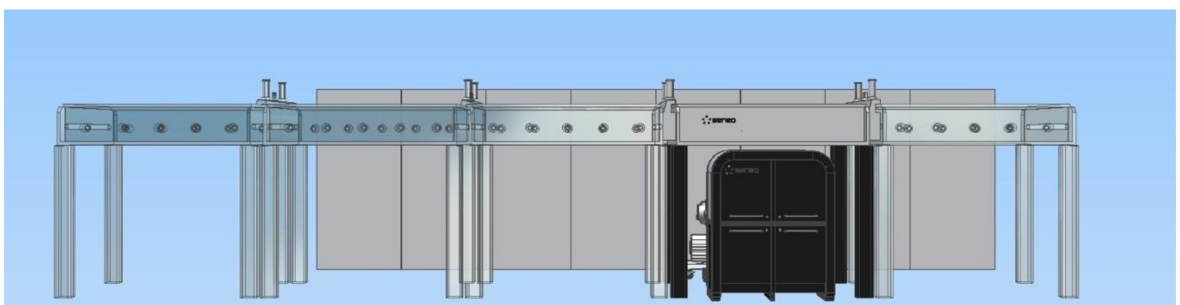
Beneq

Industrial scale up

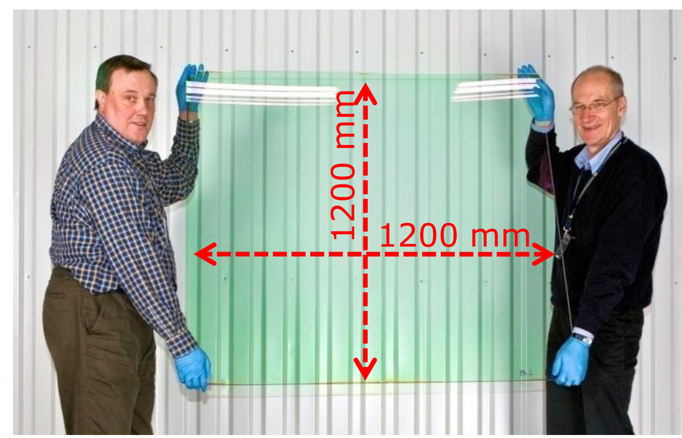
The Myth: ALD is slow and only for ultra-thin films

The Answer: Growth on surface => scale up by expanding surface

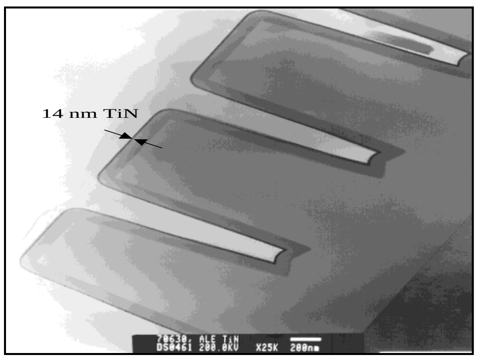
ALD is a slow in nm/s, but fast in m²/s.



In-line: 20nm/5min **TFS 1200**



Turning Innovations into Success



Application specific coating and material development services

Verification and pilot production services

Coating equipment

Thin Film System – TFS 200

Advanced tool for advanced ALD research

Thank You !

Mr. Mikko Saikkonen
e-mail:mikko.saikkonen@beneq.com