Robust and Reliable Thin-Film OLED Encapsulation

Bay Area SID Seminar – July 16th 2019

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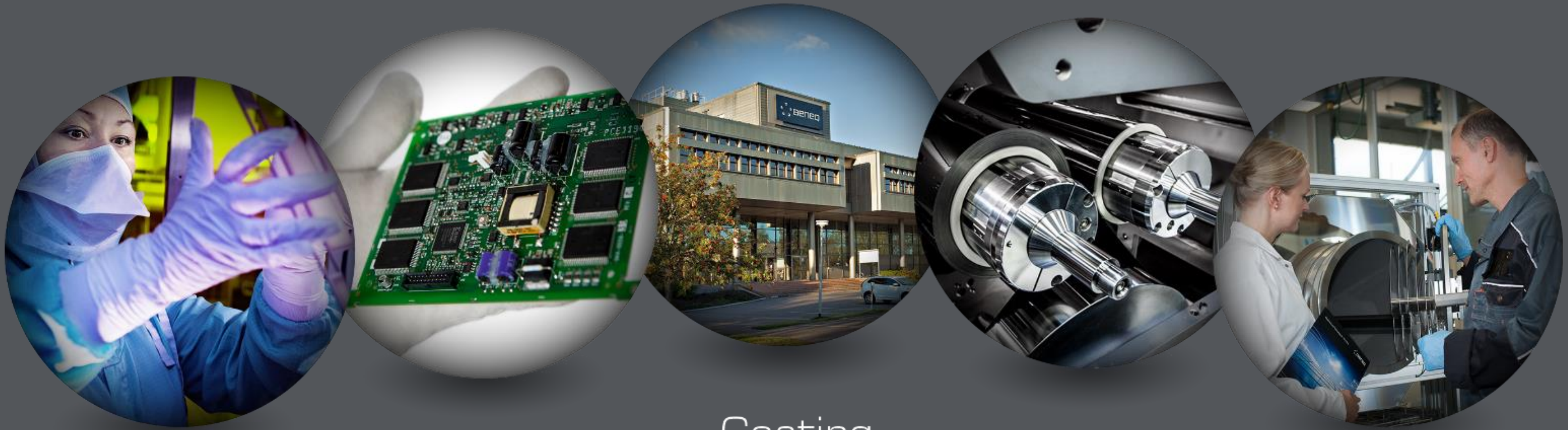
Company confidential

Beneq

OUTLINE

- Brief company introduction
- Beneq ALD equipment portfolio
- Beneq ALD technology for moisture barriers and OLED encapsulation
- Discussion

ONE STOP FOR ALL ALD



Research

Development Services

Coating Services

Thin Film Equipment

Lifecycle Services

BENEQ – HOME OF ALD

Instrumentarium: 1974

- Tuomo Suntola introduces Atomic Layer Epitaxy for the production of Thin Film Electroluminescent (TFEL) displays

↓

Finlux / Lohja: ~1984-1993

- Development of processes for TFEL displays based upon home built ALD systems (P400)

↓

Planar Systems: 1993-2012

- Continues TFEL business.
- Starts to sell P400 systems in 2005

↓

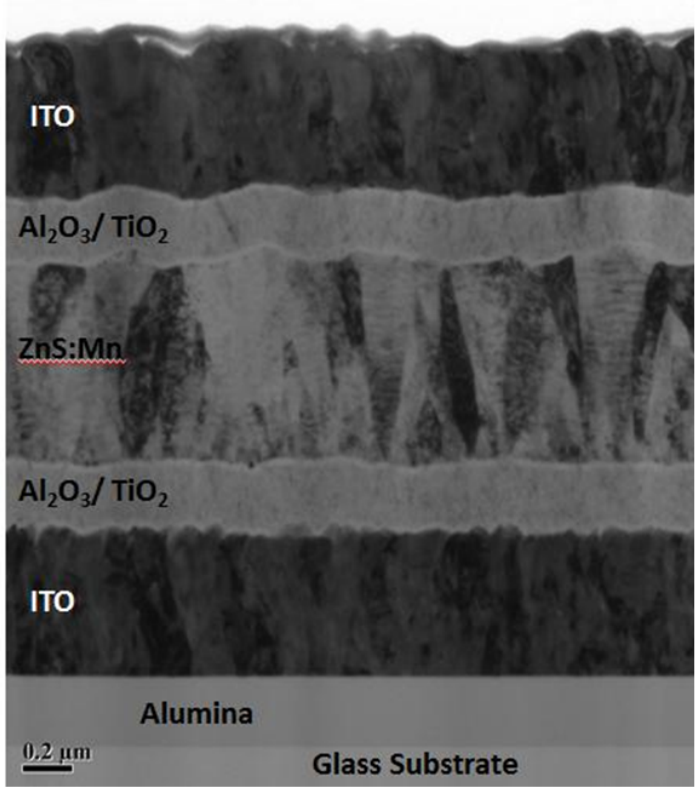
Beneq

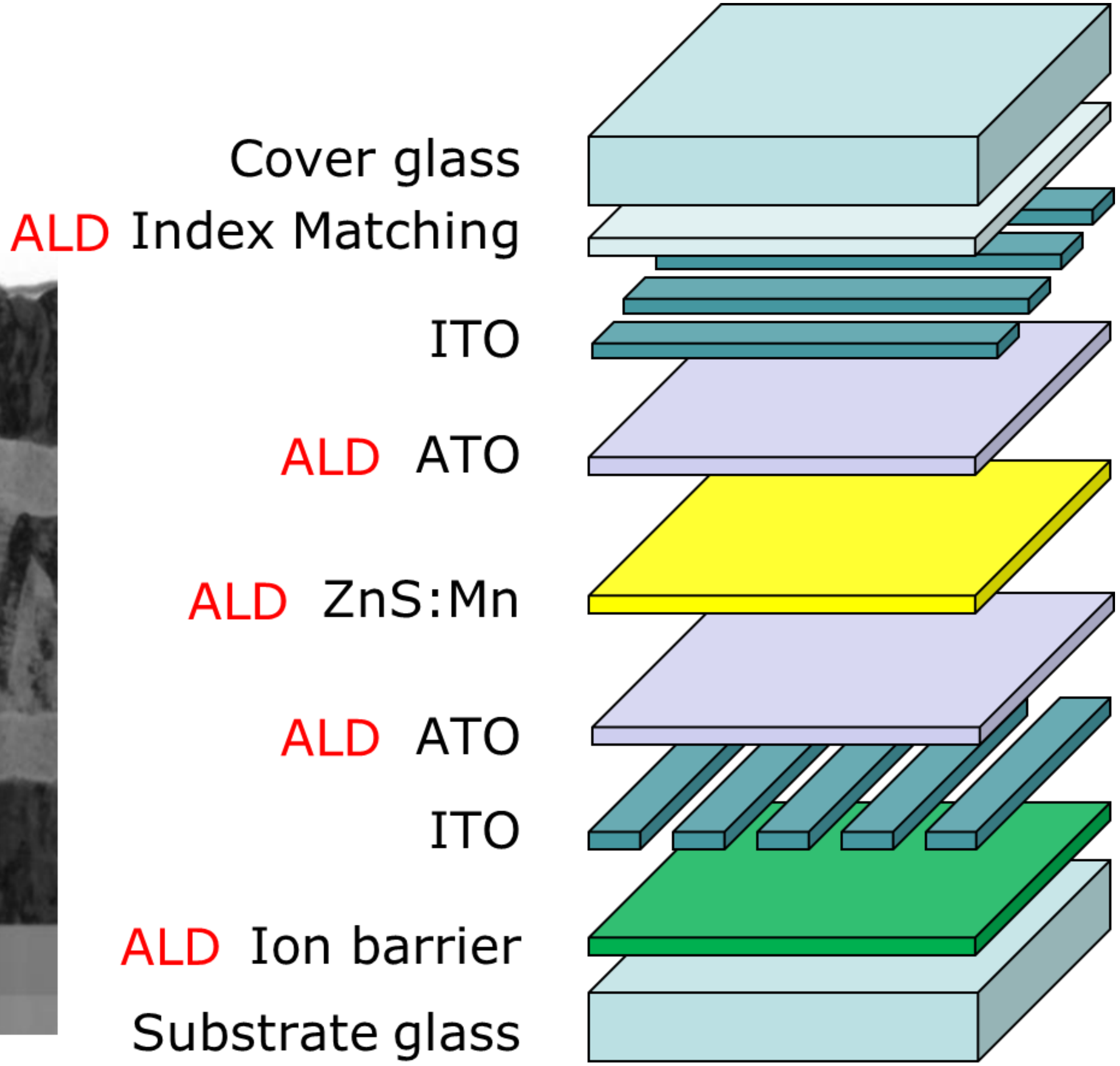
- Starts ALD equipment business in 2005
- Purchases ALD Business from Planar – 2007
- Purchases TFEL Business and factory from Planar - 2012

BENEQ ALD

- Leading supplier of Atomic Layer Deposition (ALD) equipment for industrial and R&D
- Headquarters & ALD Fab in Espoo, Finland
- Operating world’s largest ALD dedicated plant, with more than 40 ALD production systems
- Extended service and demo capabilities, from proof-of-concept to pilot production
- 30+ years of industrial ALD experience at your service

TRANSPARENT EL DISPLAY STRUCTURE





Focus application areas

Wafer Processing ALD

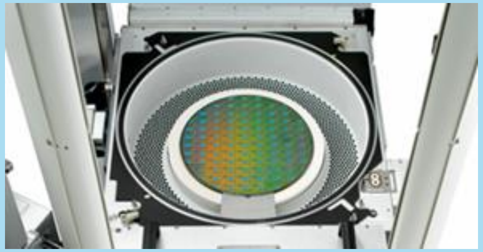
Various More-than-Moore applications

Research

Academic research, research institute, corporate R&D

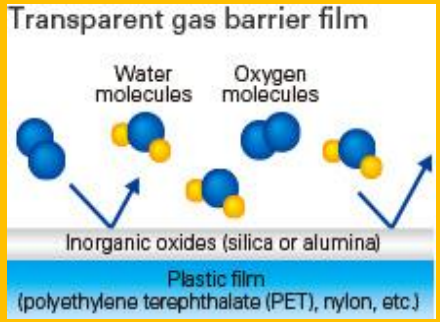
Batch

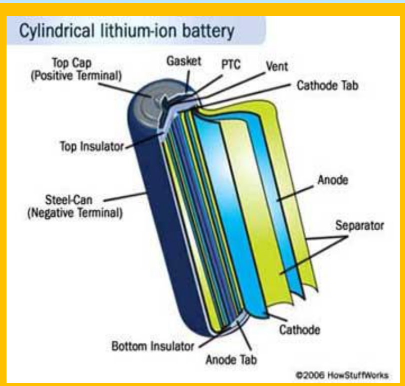
1. Encapsulation
2. Optics
3. Anticorrosion, passivation



Spatial

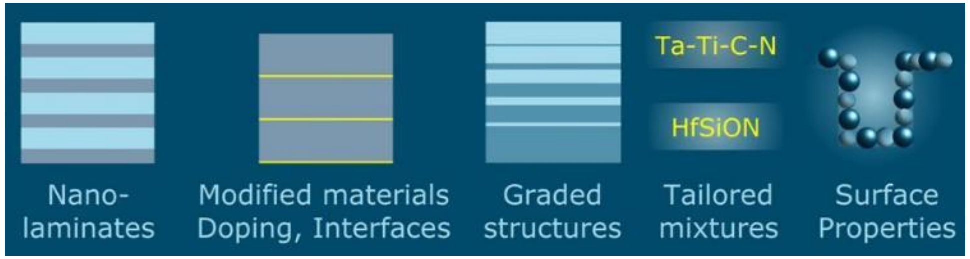
1. Moisture barrier
2. Energy storage

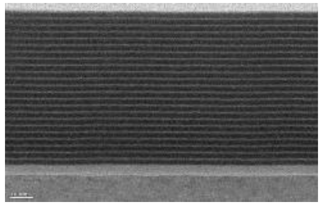


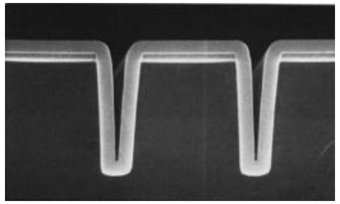


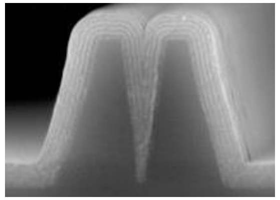
BENEQ ALD COMPETENCE

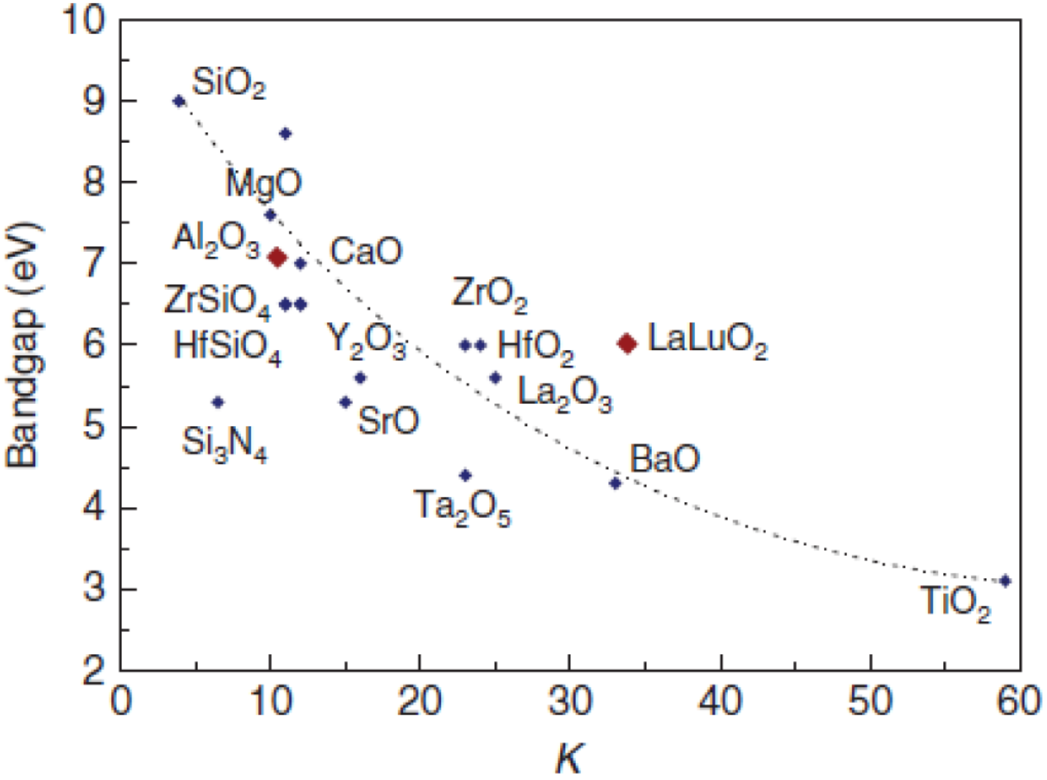
- ALD factory with more than 40 ALD systems
- Production of thin-film electroluminescence displays (since -85)
- Installed base of more than 240 ALD systems
- Dedicated process development and coating service teams
- Extensive process library with 100+ chemistries
- High-k materials: Al_2O_3, HfO_2, ZrO_2, Ta_2O_5, TiO_2...
- Nitrides and metals











ALD THIN FILM ENCAPSULATION EXAMPLES

OLED lighting
- *Eliminated black-spots*
- *Allowed new designs*
- *Large-batch TFS 600 system in production*

Automotive OLED
- *Passed 1000h 85/85*
- *New zero bezel design*
- *Lower CoO (than CVD)*
- *Multiple TFS 500 in production*

PCB
- Improved corrosion resistance
- In production

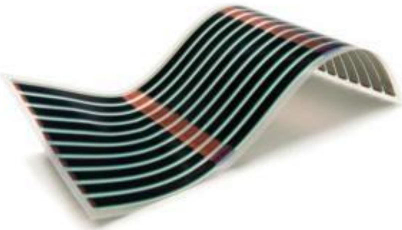
OLED and LCD displays
- In pilot production

Medical imaging (Scintillator)
- High surface area barrier
- Excellent conformality & WVTR
- In job coating & multiple P800 batch systems

FLEXIBLE ELECTRONICS OPPORTUNITY

Source: Plastic Logic

Source: Samsung



Source: Hanergy

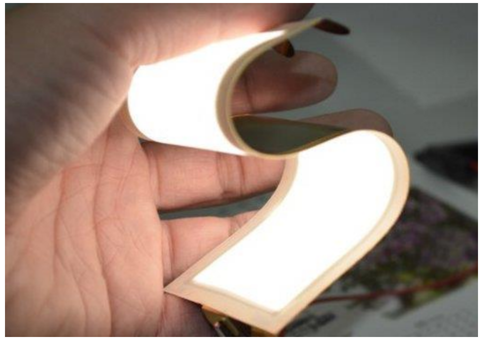
FEATURES:

- new designs & form factors
- no glass –> unbreakable
- conformal/bendable/rollable...
- ultra-light weigth & flat
- edgeless

Source: FlexEnable

Source: LG

Source: Microsoft



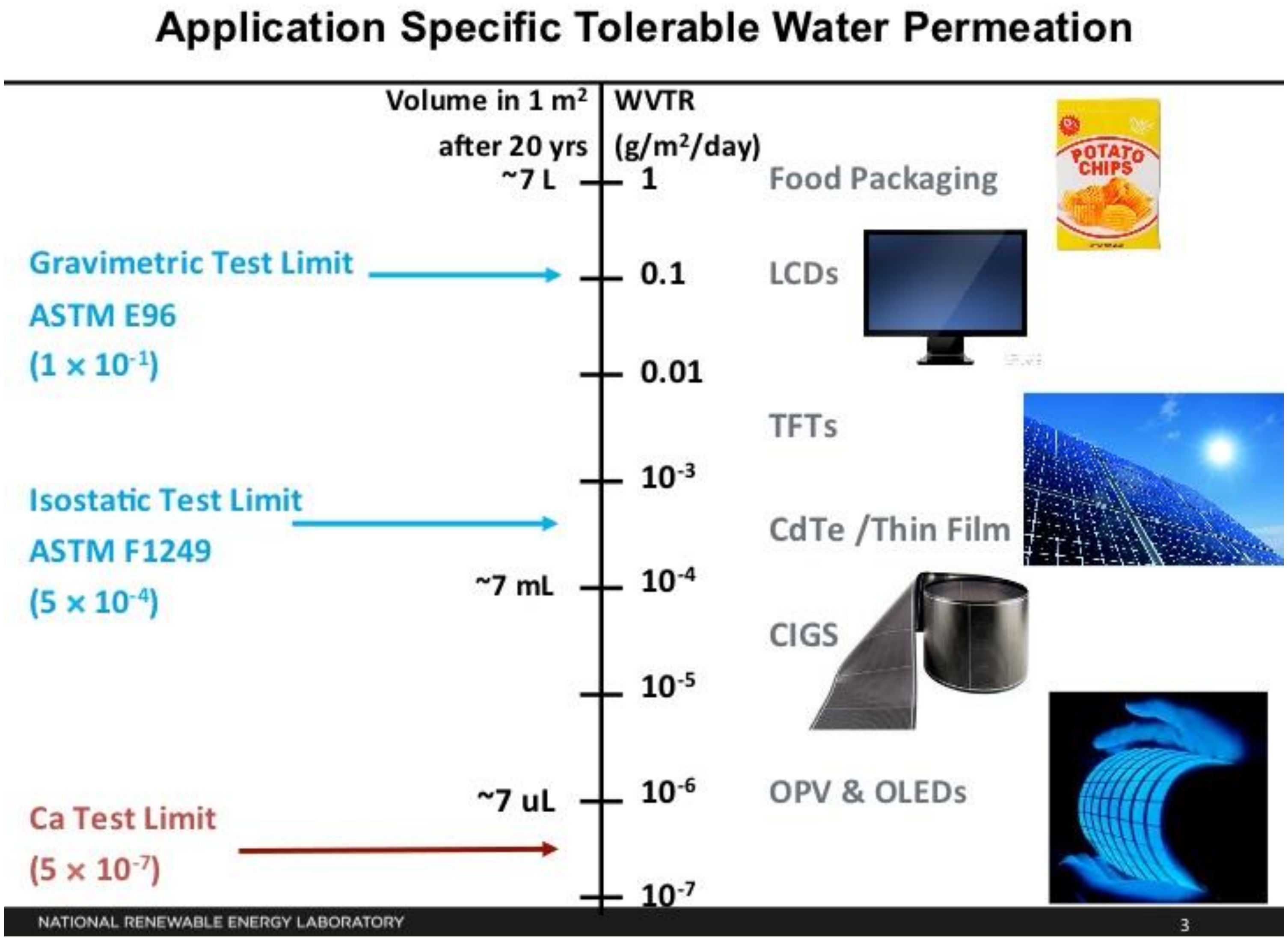
Source: Konica Minolta

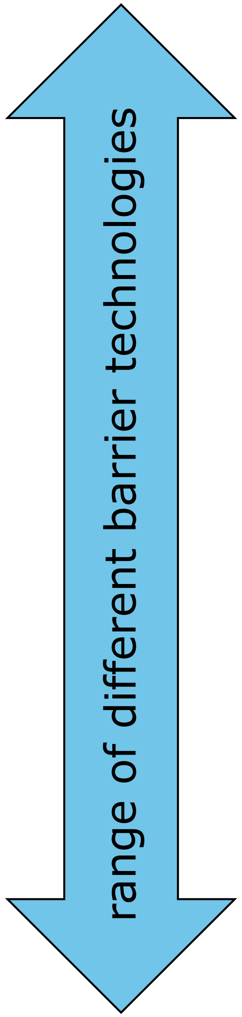
Source: Samsung

Source: BMW

H_2O - ”The ENEMY”

WATER VAPOR TRANSMISSION RATE





FLEXIBLE ENCAPSULATION APPROACHES

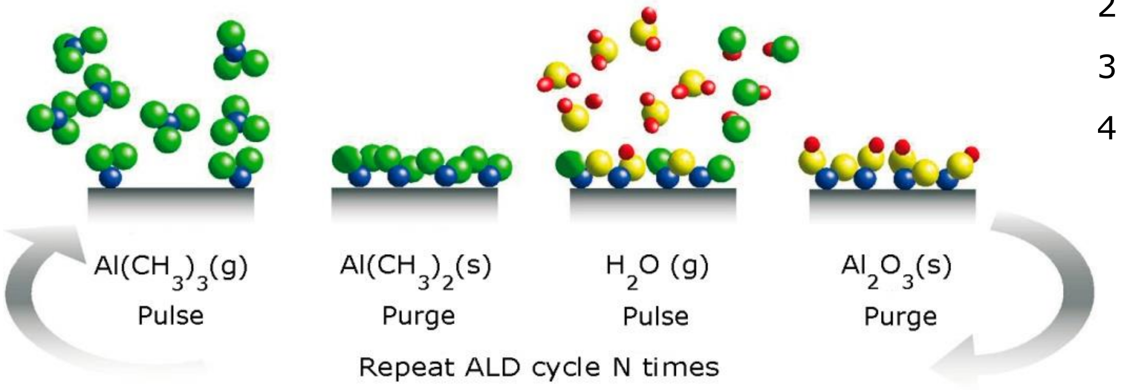
Type	Barrier component	Deposition method	Thickness
Glass	Borosilicate	Frit sealing + dessicant	<200 μm
Inorg./org. Multilayer	Al_2O_3	CVD	3-5 μm
Inorganic	SiNx	PECVD	<1 μm
ALD	Al_2O_3	ALD	10-50 nm

- Flexible glass does not apprear to be a robust solution
- Commercial inorganic/organic multilayer requires thick stack, sells for a prohibitively high price
- PECVD + organic currently applied, but not flexible enough
- ALD value proposition: ultra-thin & flexible

Common question: can ALD meet / scale to industral large-area needs?

ATOMIC LAYER DEPOSITION

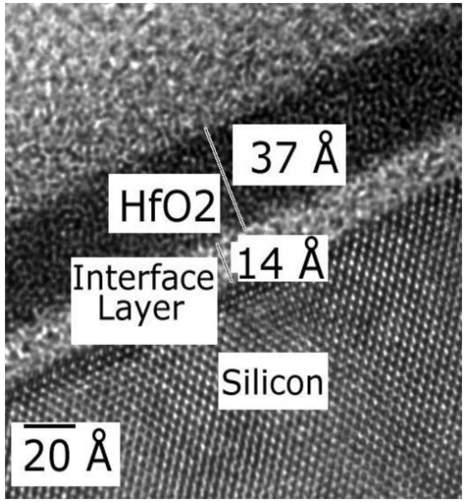
Al_2O_3: ~0.1 nm /cycle

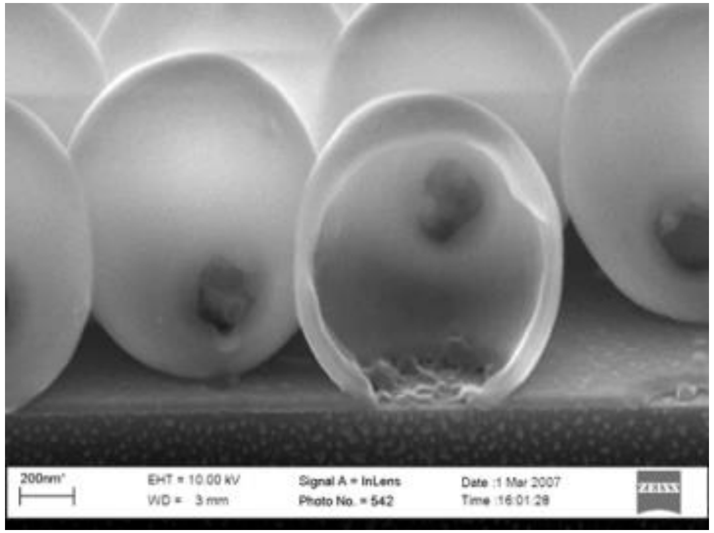


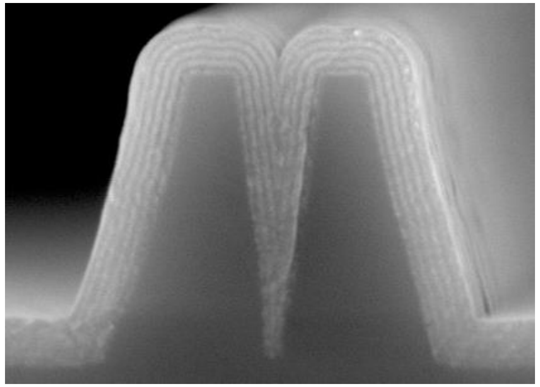
1. Sequential ("A"-purge-"B"-purge)
2. Chemisorption
3. Surface controlled reactions
4. Saturation

BENEFITS:

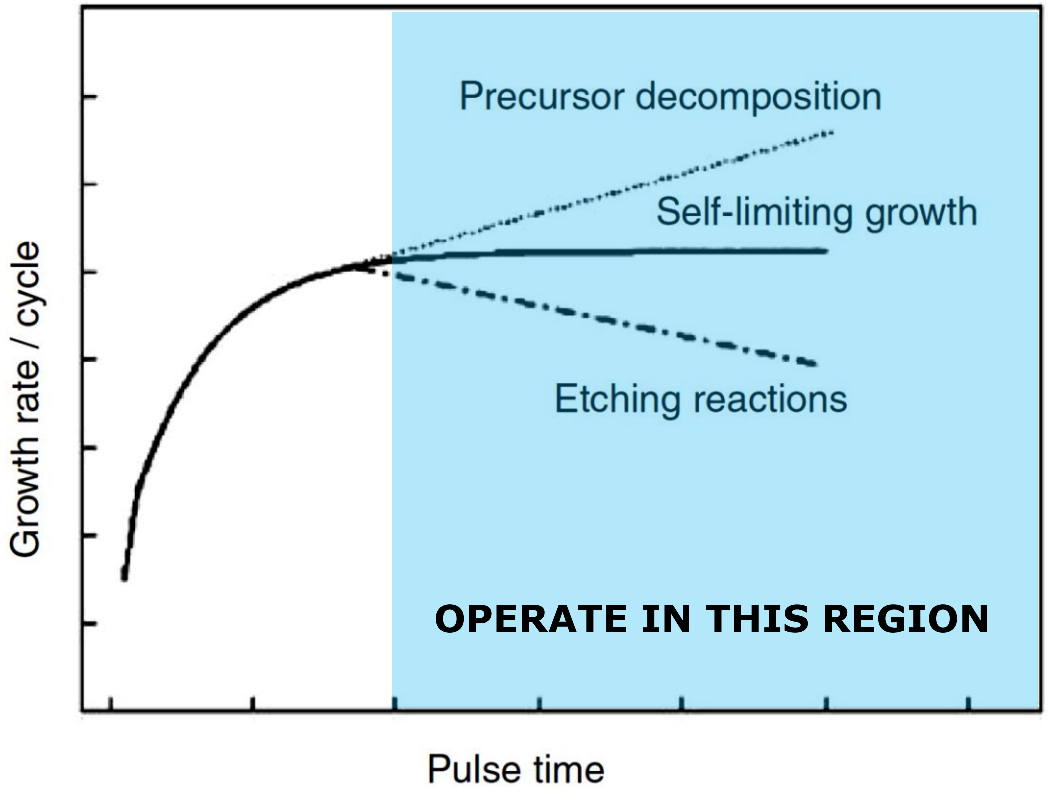
- ✓ Nanoscale thickness accuracy
- ✓ Dense, conformal, pinhole-free
- ✓ Low process temperature (< 100 C)
- ✓ Good adhesion
- ✓ Engineered material properties
- ✓ Robust process





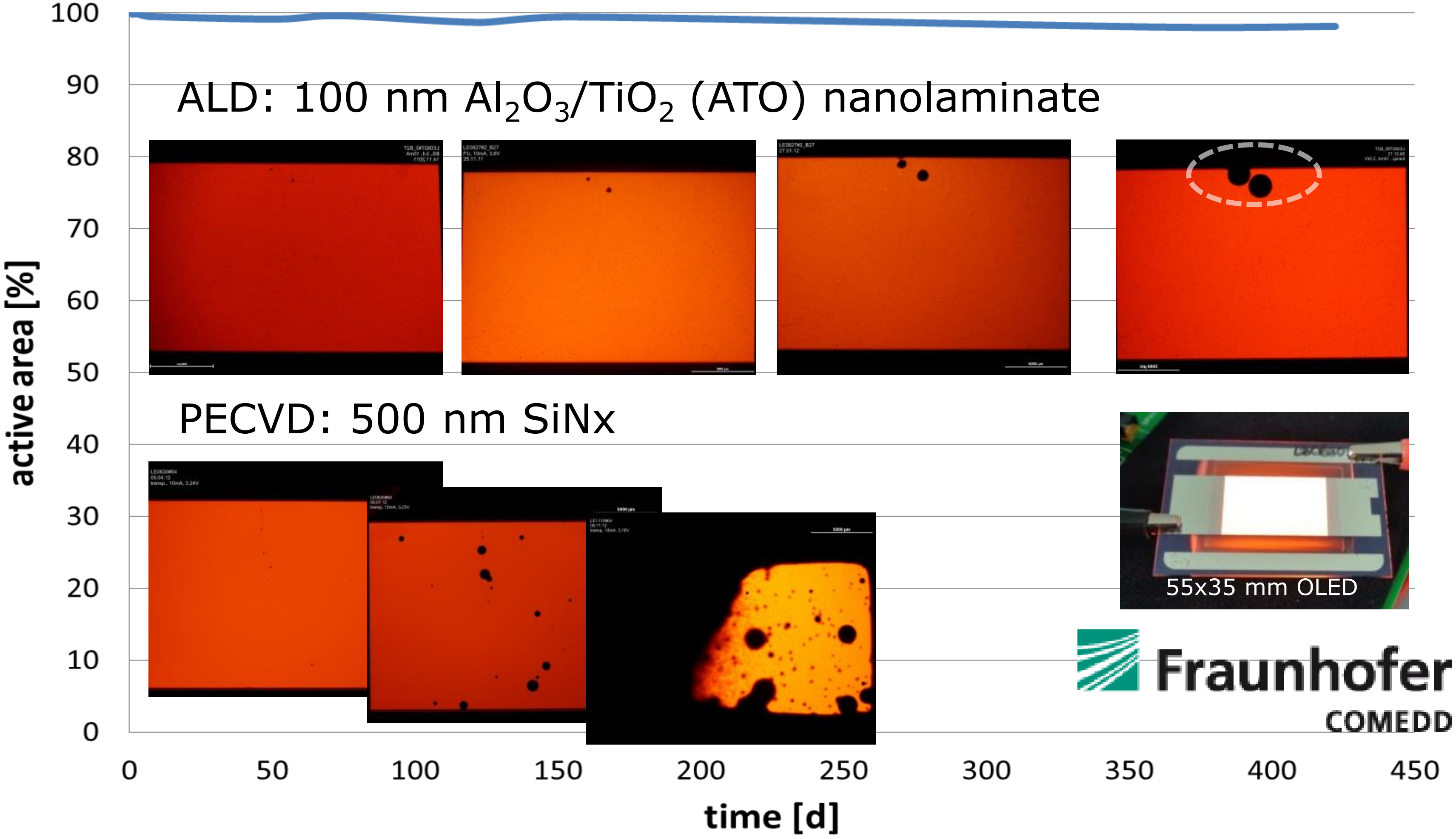


THE CORE OF ALD – SATURATIVE SURFACE REACTIONS



- Ideally the surface reactions are self-limiting and irreversible
  - ➢ The film growth is surface controlled
- Typically some level of ”overdosing” is used

ALD VERSUS PECVD ENCAPSULATION



Intrinsic WVTR is ≤10^{-6}, particles can be addressed (e.g. planarization)

C. Keibler *et al*, "Direct encapsulation of OLEDs with different thin film methods", LOPE-C 2013, Munich, Germany

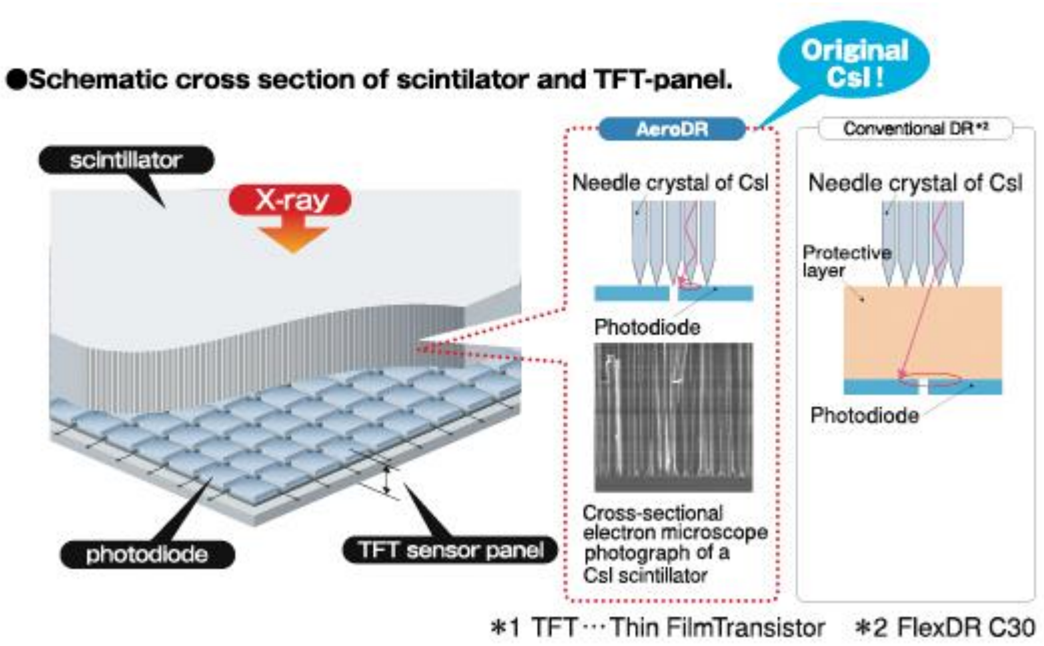
CASE : SCINTILLATOR

Customer: A Leading medical scintillator manufacturer
Application: Thin film encapsulation
System: Beneq coating services using Beneq P400 batch ALD
Status: Currently 5 years in production through Beneq coating services

ALD FOR SCINTILLATORS

ALD has two unique features making it ideal moisture barrier for scintillators

- Best moisture barrier properties of all thin films
- Extreme conformality on high aspect ratio structures
  - Works directly on scintillator needle structure
  - Works on a planarized scintillator structure (parylene etc.)



www.konicaminolta.com/healthcare/products/dr/aerodr/feature.html

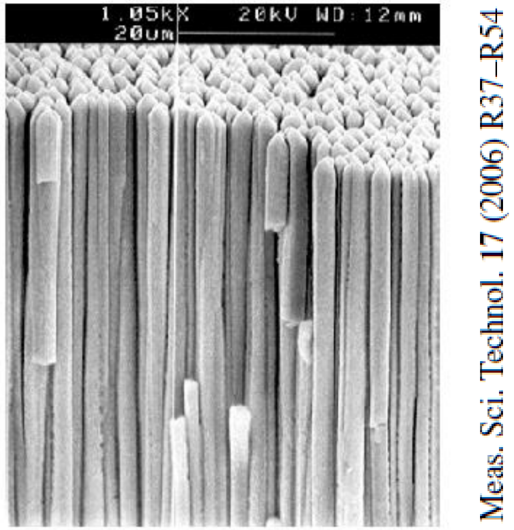
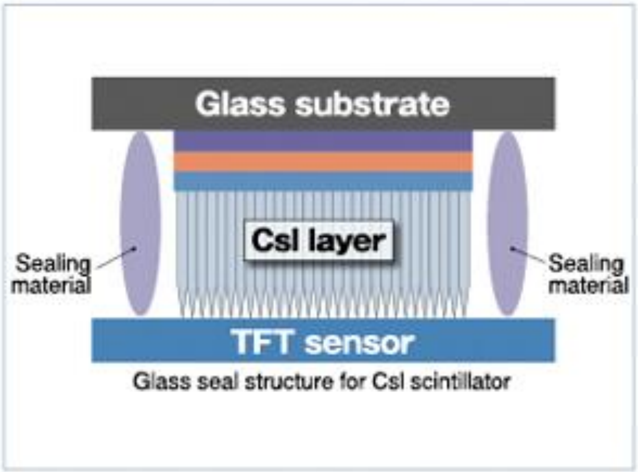


Figure 6. Vapour deposited column-shaped CsI:Tl scintillation crystals of very smooth structure. Diameter ~3 μm, length >0.5 mm. Reprinted from [13] with permission (courtesy Philips Research Laboratories, Aachen).



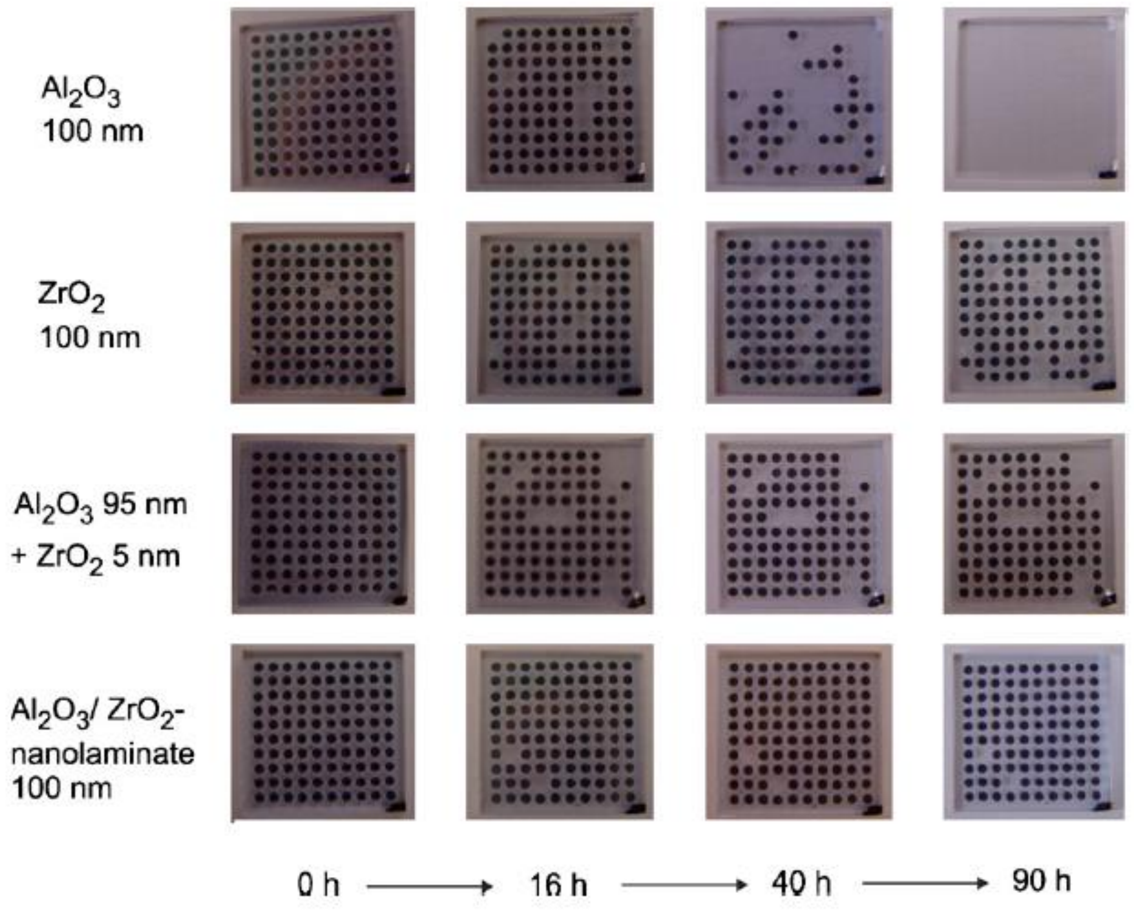
ALD VERSUS PARYLENE COATING

- Comparison to parylene coating

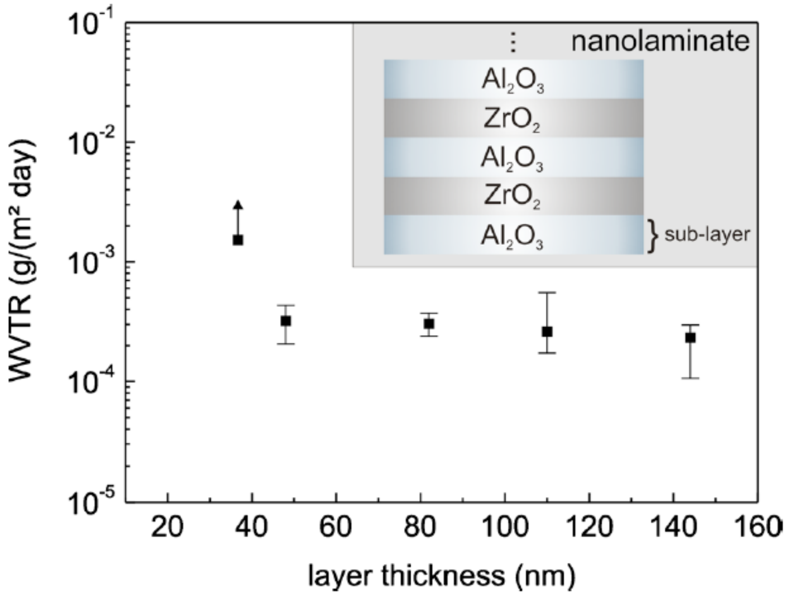
	Parylene	Beneq nCLEAR	Factor nCLEAR vs Parylene
Thickness	20 µm	0.02 µm	1 000
WVTR or MTR (g/m^2day)	4	0.000004	1 000 000
TOTAL			1 000 000 000

- A billion times better barrier!

WHY ALD NANOLAMINATES



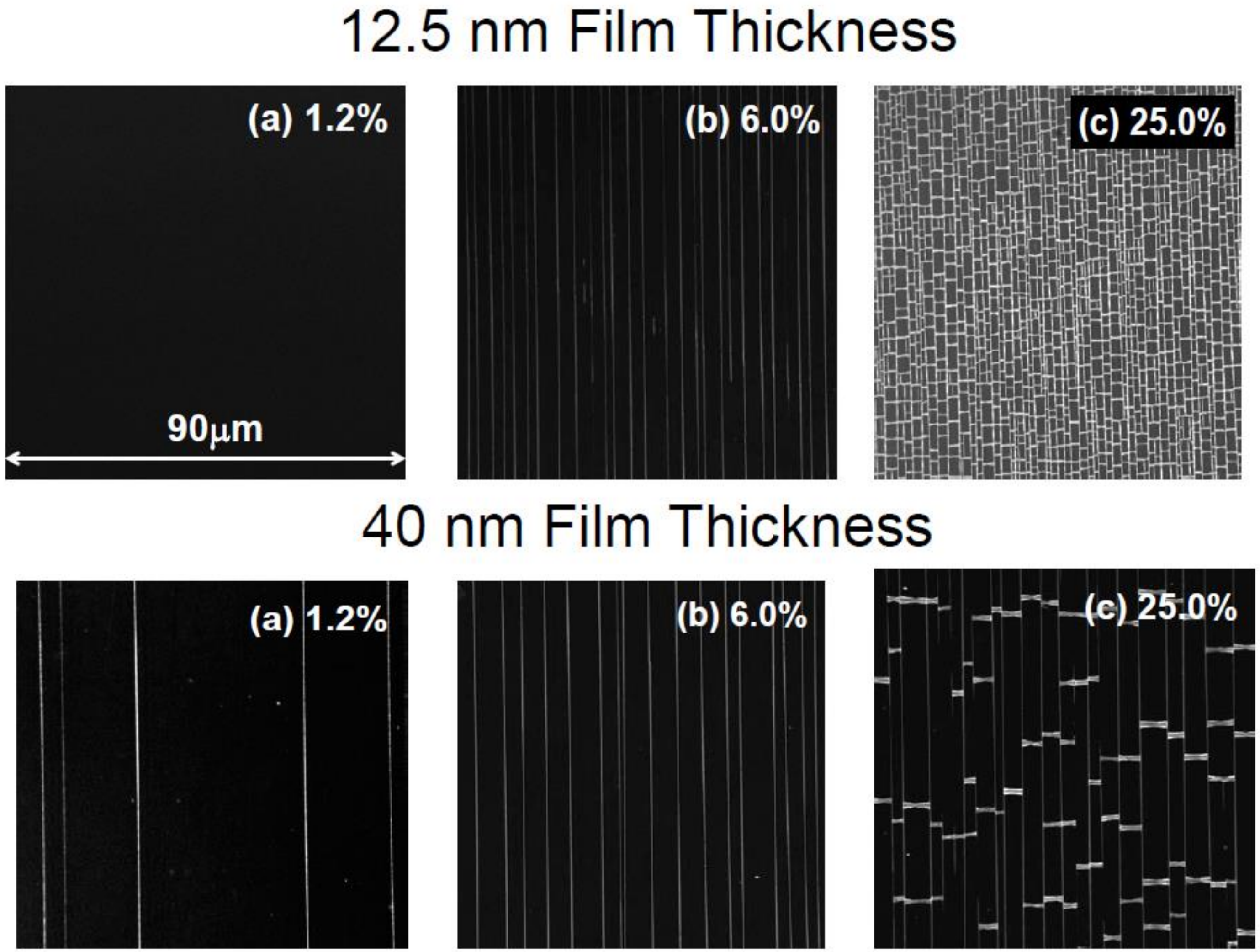
Condition: 80 °C / 80 % RH



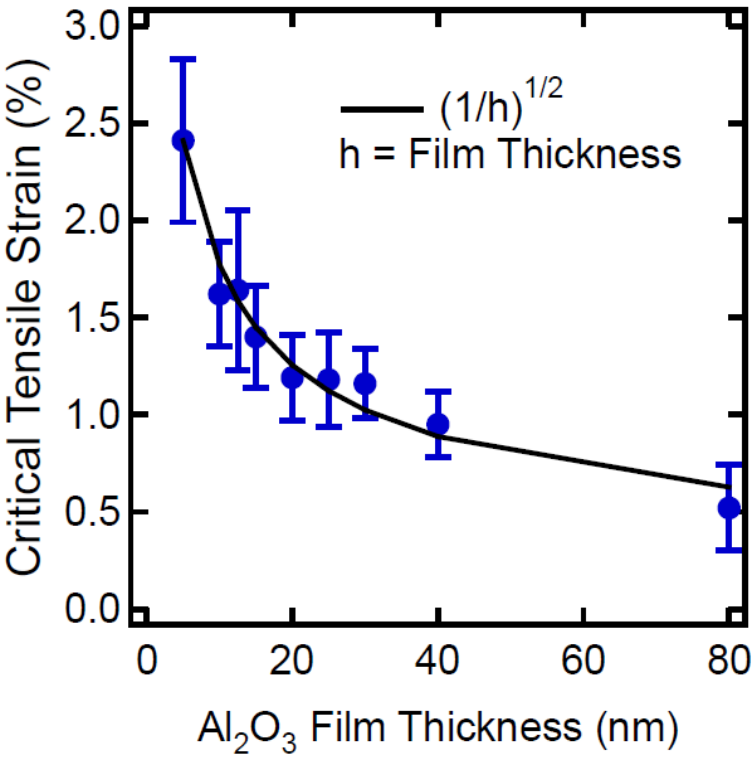
J. Meyer et al, Appl. Phys. Lett. **96**, 243308 (2010)

- Plain and unprotected Al_2O_3 etches quickly
- 50 nm thick laminate appears to be robust

FLEXIBILITY OF ALD BARRIER FILMS



FLEXIBILITY OF ALD BARRIER FILMS



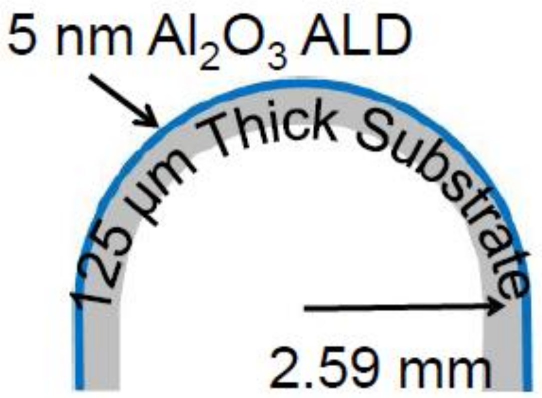
Fracture mechanics modeling predicts critical tensile strain α $(1/h)^{1/2}$

h is film thickness

Based on work & strain energy in film

N. Laws & G.J. Dvorak, *J. Compos. Mater.* **22**, 900 (1988).

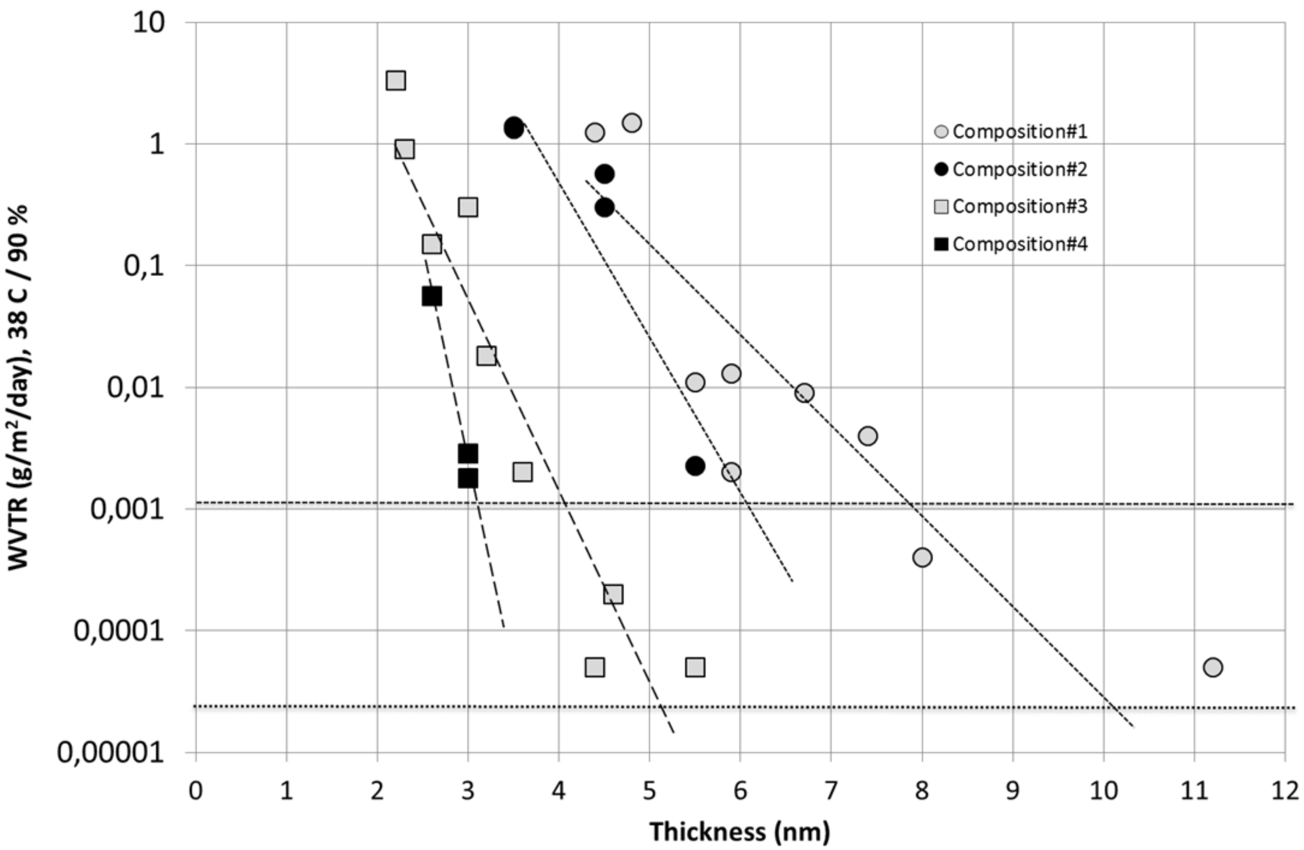
Strain, ε = D/2R where D is substrate thickness



For 50 nm Al_2O_3, R = ~8 mm

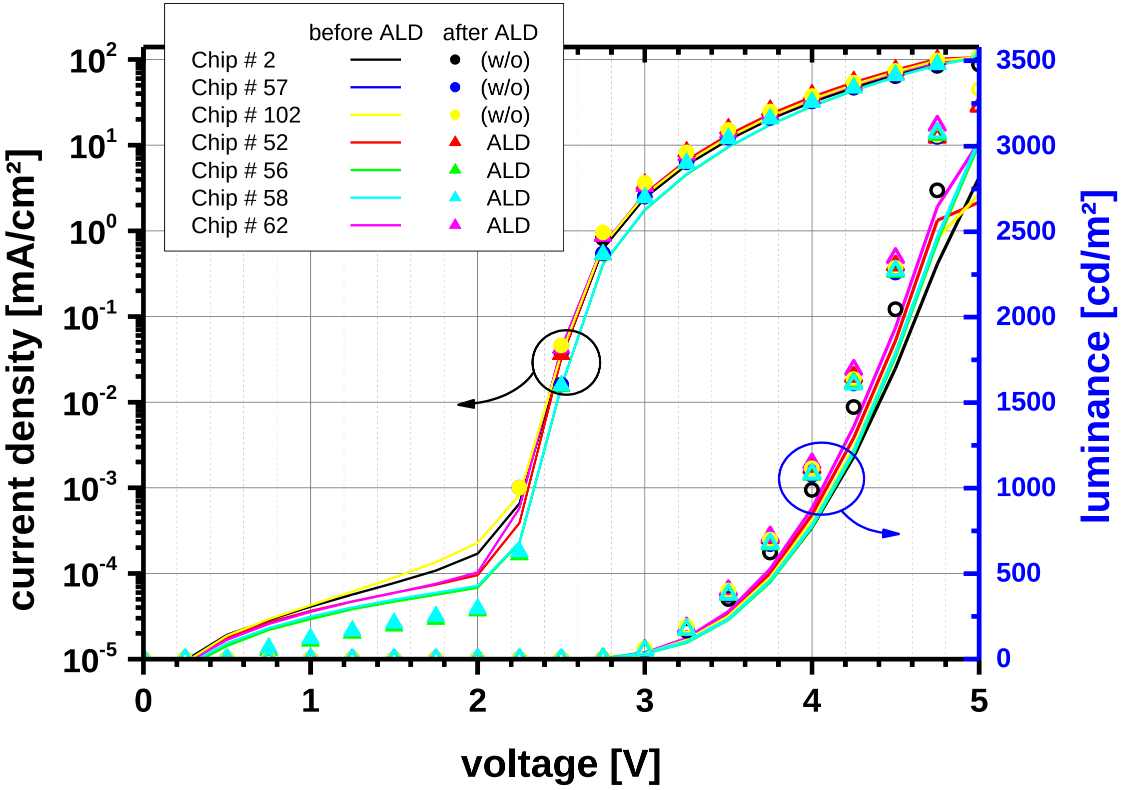
FLEXIBILITY OF ALD BARRIER FILMS

PE-ALD on a low-cost PET film @ 120 C

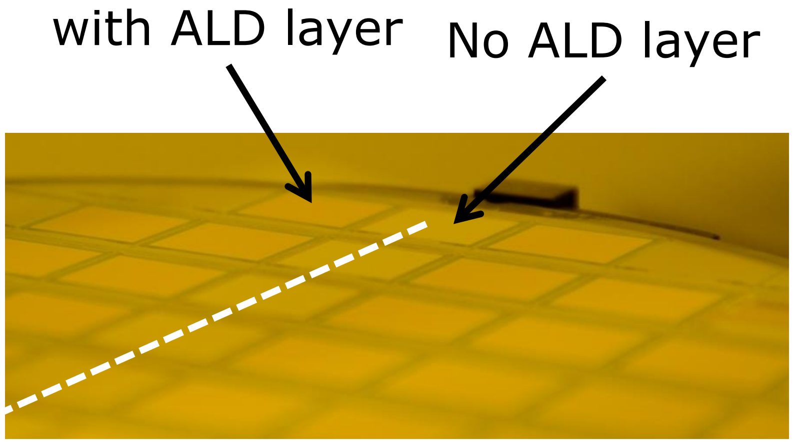


Combining PE-ALD and Parylene top-coating (by AIXTRON) WVTR of **$8*10^{-5}$ g/(m^2 day)** achieved with **14 nm Al_2O_3**, +400 h at **38°C/90 % RH**.

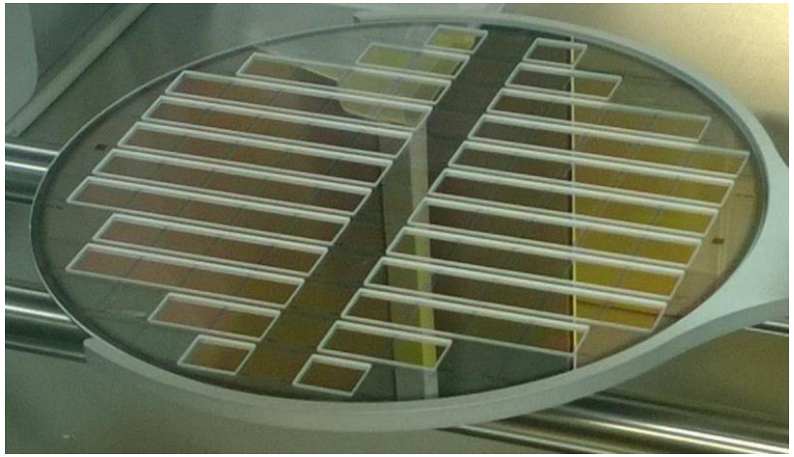
ALD FOR OLED MICRODISPLAYS



- PEALD process utilized for patterning
- Deposition of an ALD layer using a shadow mask directly onto an OLED-microdisplay wafer
- Unchanged OLED performance
- No coverage of bond pads by ALD process



Chips with and without structured ALD layer



Glass shadow mask attached to OLED-CMOS wafer

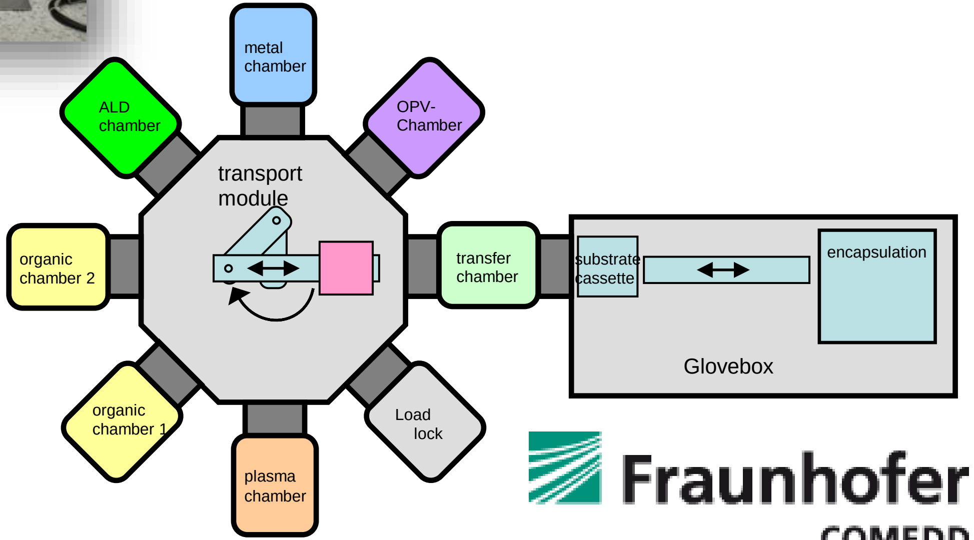
ALD FOR OLED MICRODISPLAYS

Globox integrated systems with MBraun

Cluster integrated systems (@ COMEDD)

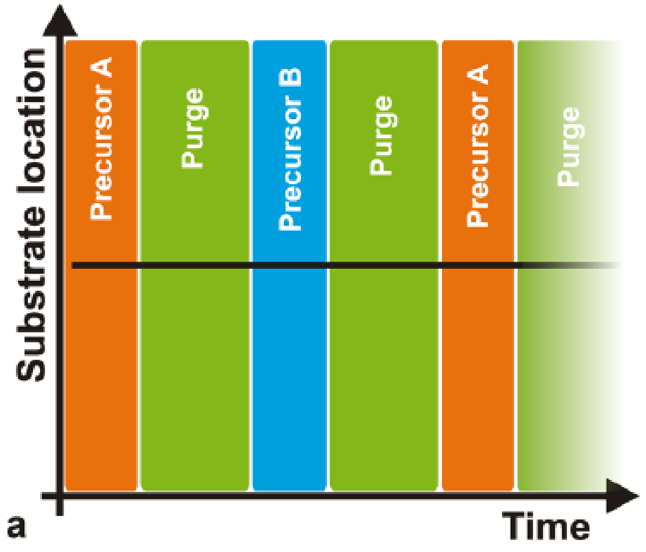
- Beneq ALD systems are widely used in OLED encapsulation – the most demanding moisture barrier application

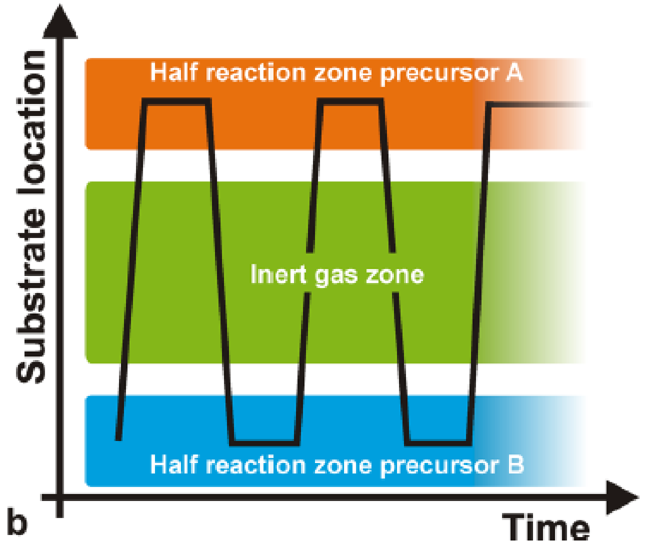
- Substrate sizes from 200mm to 370x470mm



Fraunhofer COMEDD

METHODS FOR SCALING ALD THROUGHPUT





P. Poodt et al., J. Vac. Sci. Technol. A 30(1), Jan/Feb 2012

Convential time-separated ALD

- Precursors separated in time
- Substrate is stationary
- Separation by inert gas purge step
- Scaling by **batch processing**
- Suitable for rigid sheets / wafers

Spatially-separated ALD

- Precursors separated in space
- Substrate is in relative movement
- No purge step -> fast process
- Scalable in process speed & width
- Especially well suited for scaling to **large sheets and roll-to-roll**

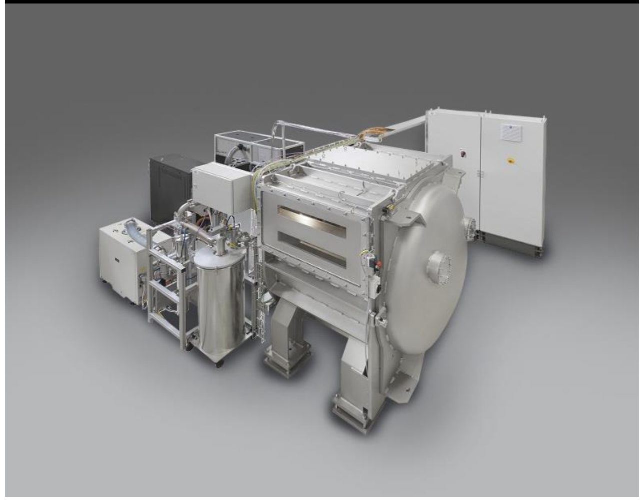
ALD EQUIPMENT FOR R&D AND MANUFACTURING

Beneq TFS 200

Beneq TFS 500

Beneq P400A and P800

Beneq WSC 600



Beneq C3R

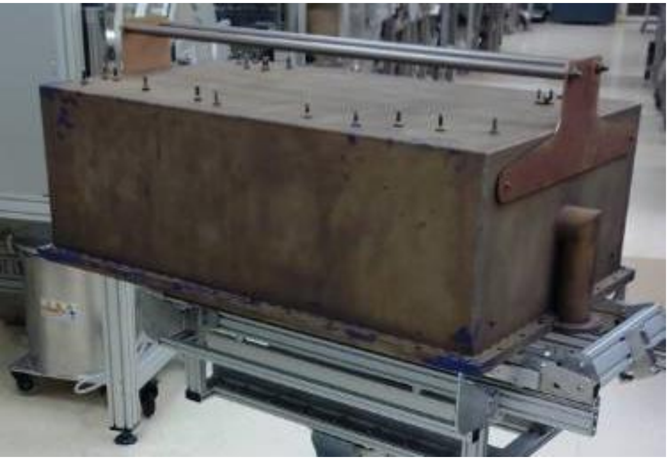
Beneq C2

BENEQ P400A AND P800 BACK END EQUIPMENT

ALD SYSTEM FOR BATCH PRODUCTION, SPECIALIZED FOR THICKER FILM STACKS

PROCESS TYPE	• thermal ALD
USAGE	• production
SUBSTRATE TYPE	• wafers • glass and metal sheets • 3D-parts • Max substrate size: P400A: 370x470 mm P800: 730x1200 mm
SUBSTRATE LOADING	• manual
MAIN DIMENSIONS	• P400A: 2400×930×2420 mm • P800: 3200×1340×2460 mm
INTEGRATION	• stand-alone

P800 AND P400 REACTION CHAMBERS



EXAMPLES OF REACTION CHAMBERS FOR BATCH PRODUCTION (SUBSTRATE SPACE, WxHxL):

- 550 × 350 × 1100 mm
- 380 x 380 x 900 mm
- 600 x 300 x 800 mm
- 730 × 10 x 1200 mm

ALD EQUIPMENT FOR WAFER PRODUCTION

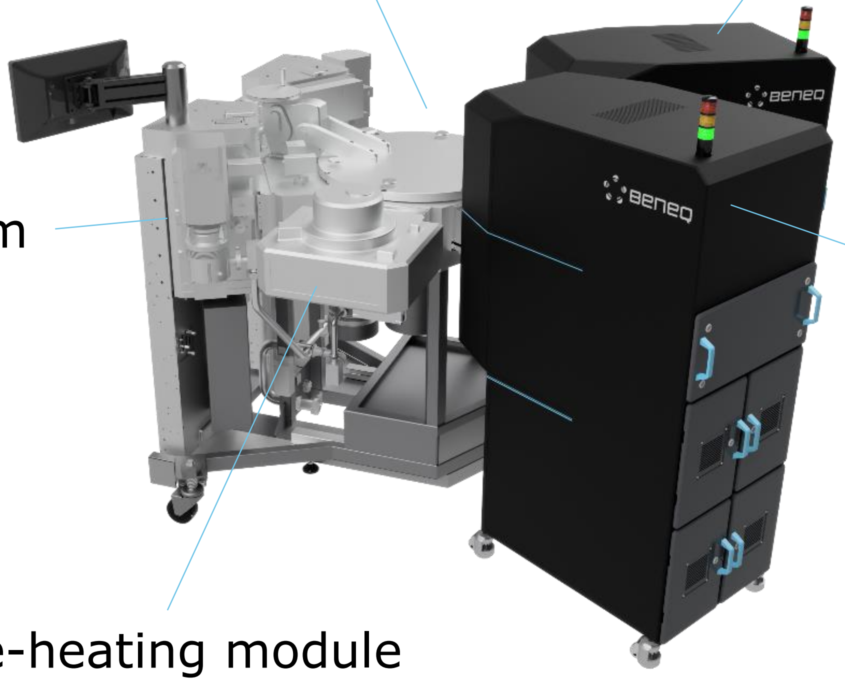
CSindustry awards

BENEQ ALD3 & ALD4

Front End Cluster Tool

BENEQ ALD CLUSTER TOOL

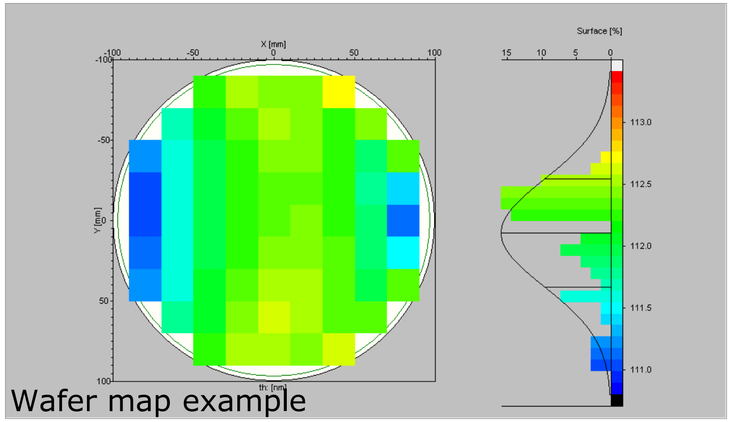
Configuration example



- Solution for turn-key production and flexible development/pilot line with ALD3 & ALD4
- Proprietary single wafer and/or batch C2 ALD process modules
- Smallest footprint, highest capacity per cleanroom area and lowest CoO
- Ideally suited for all More than Moore applications

BENEQ BATCH ALD – Al_2O_3 EXAMPLE

Wafer	Wafer average thickness (nm)	Wafer σ/ave (%)	Refractive index, ave @633 nm
1	112,08	0,49	1,6465
2	112,06	0,51	1,6465
3	112,08	0,46	1,6464
4	112,11	0,39	1,6464
5	112,09	0,44	1,6464
6	112,10	0,37	1,6463
7	112,12	0,41	1,6464
8	112,11	0,45	1,6463
9	112,09	0,42	1,6463
10	112,13	0,42	1,6463
11	112,14	0,41	1,6462
12	112,11	0,39	1,6462
13	112,15	0,38	1,6463
14	112,18	0,36	1,6462
15	112,20	0,37	1,6464
16	112,23	0,35	1,6463
17	112,22	0,32	1,6462
18	112,26	0,33	1,6462
19	112,33	0,36	1,6462
20	112,36	0,38	1,6463
21	112,40	0,35	1,6462
22	112,46	0,33	1,6463
23	112,52	0,37	1,6463
24	112,62	0,36	1,6462
25	112,67	0,34	1,6463
Ave	***112,23***	***0,39***	***1,6463***



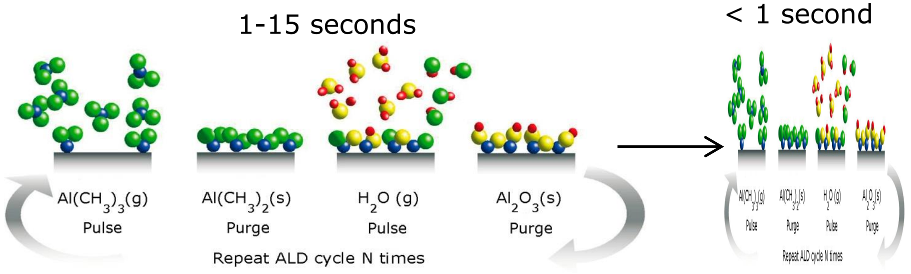
Wafer map example

- Al_2O_3 at 200°C using TMA + H_2O process
- Batch size: 25 pcs of 200mm wafers
- Cycle time 7.8s, 1000 cycles
- Within wafer thickness variation: 0.39%
- Wafer-to-wafer thickness variation: 0.16%
- Wafer-to-wafer index variation: 0.01%

SPATIAL ALD – HIGH THROUGHPUT

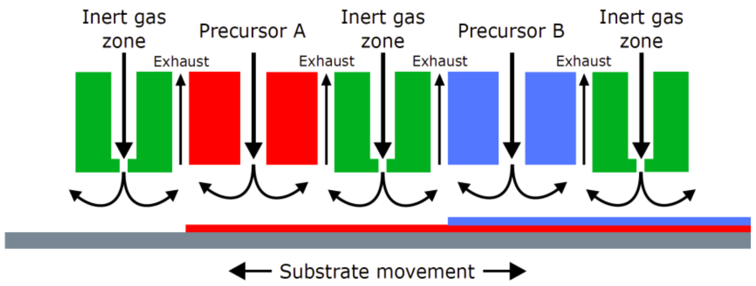
1. Throughput: 10-100 faster ALD cycle

- By rapid substrate translation



3. Insitu monitoring possibilities

+ Thickness measurement (inline/in-head)
+ Accurate MFC control of precursor feed
+ Exhaust monitoring by RGA



- Spatially separated precursor ”zones”
- Continuous (not pulsed) flows through injector
- Gap control

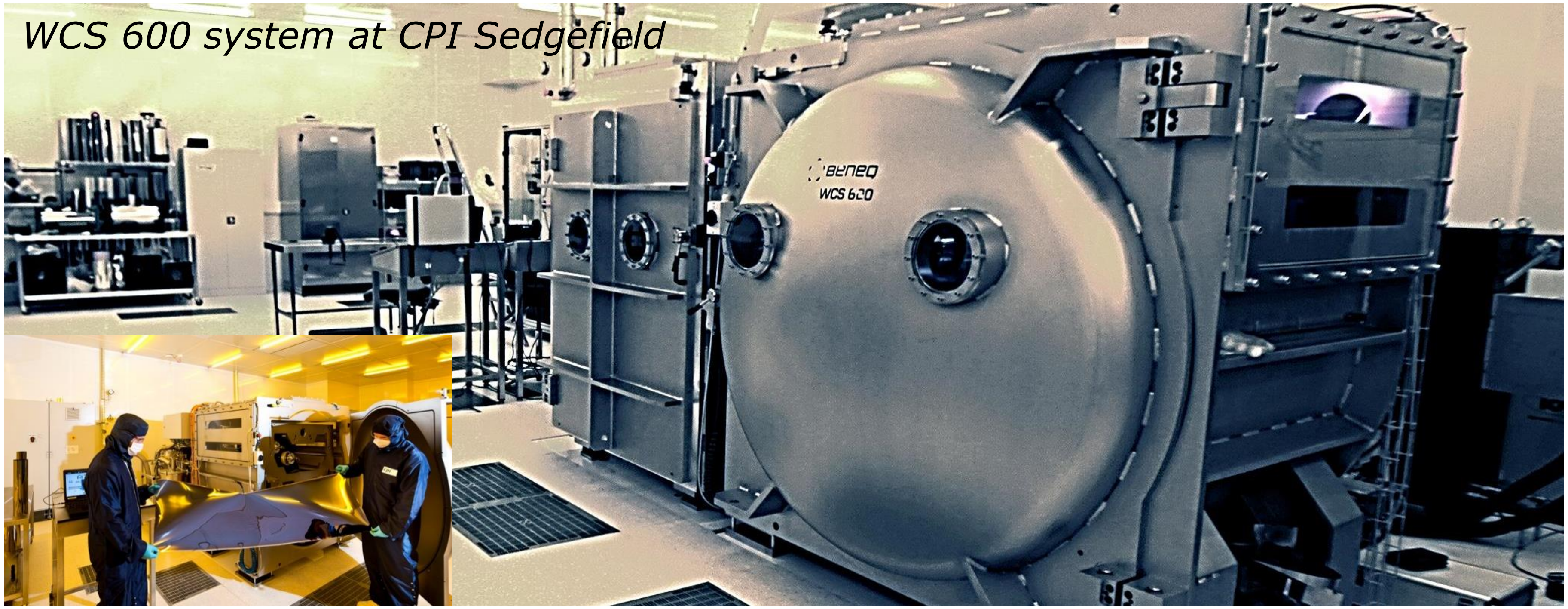
2. Scale-up in size

+Injector scales modularly in width & length
+high uniformity in ”machine/movement direction” -> focus on transverse injector design

4. Low maintenance requirement

+ only the substrate ”sees” the two precursors
+ no parasitic deposition in chamber

SPATIAL ROLL-TO-ROLL ALD



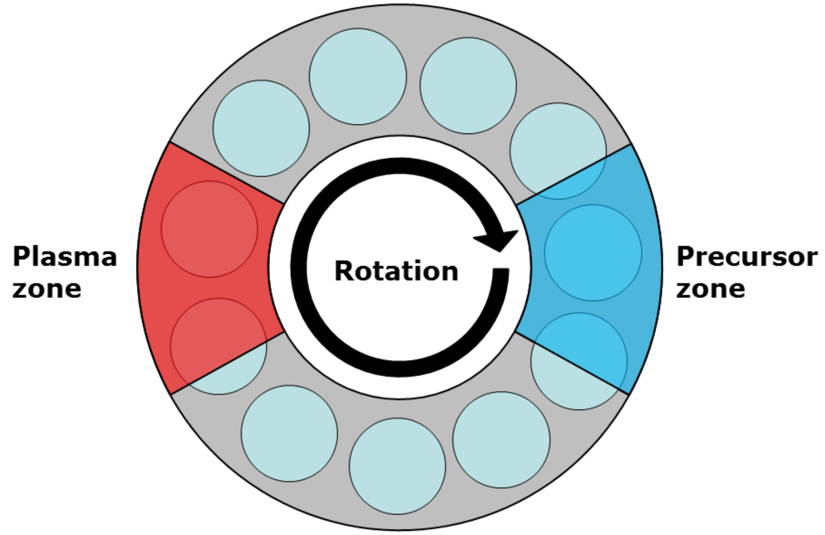
WCS 600 system at CPI Sedgefield

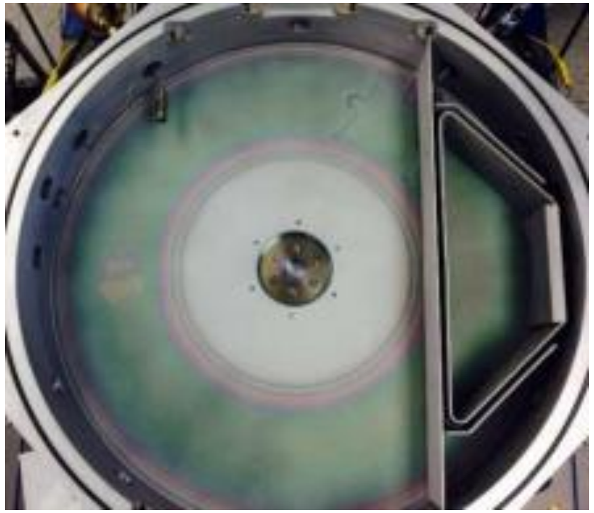
- Roll-to-roll ALD system for moisture barrier development & piloting
- Collaboration with CPI Sedgefield for turn-key equipment solution
  - WCS 600 (roll-to-roll) and TFS 500 (large batch) systems installed
- WVTR < $5*10^{-4}$ (g/m^2 day) achieved on low cost PET film, ~10^{-6} (g/m^2 day) demonstrated on PEN (J. Vac. Sci. Technol. A 32(5) Sep/Oct2014)
- Combined ALD/organic stack deposition in the same system

ROTARY ALD FOR WAFERS

Features of rotary spatial ALD

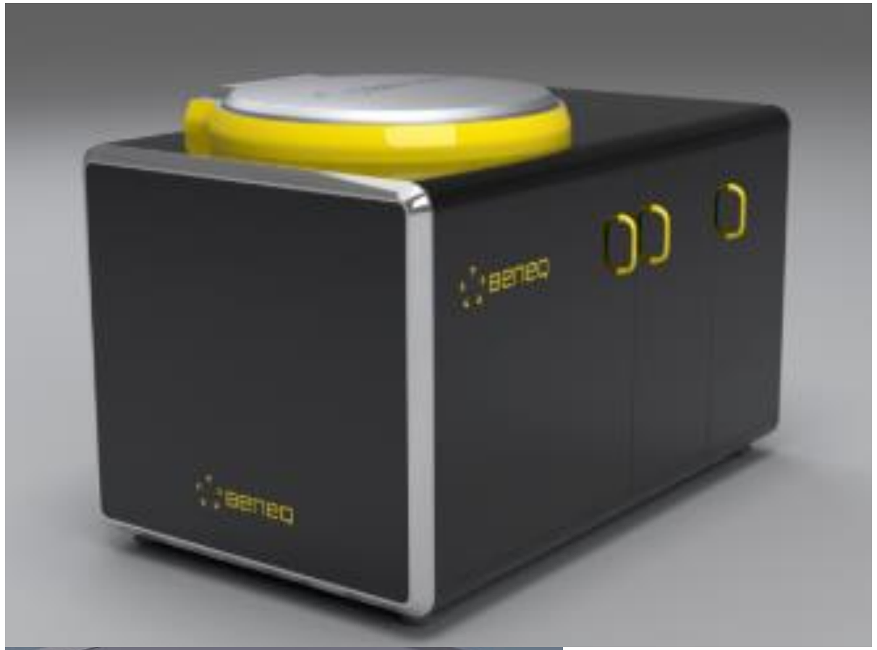
- Based on spatial separation of reactants
- High deposition rates (µm/h)
- Enables use of plasma enhanced ALD (PEALD) in batch mode, allowing new materials for production scale
- Very low maintenance needs, only the donut-shaped area gets coated
- Allows single-side coating, with minimized wrap-round

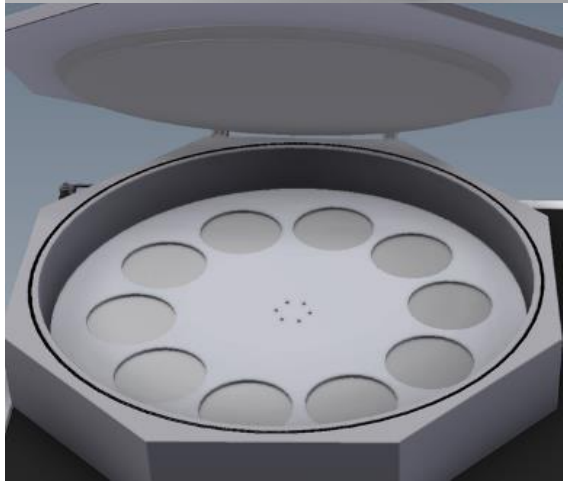




ROTARY ALD FOR WAFERS – BENEQ C2R

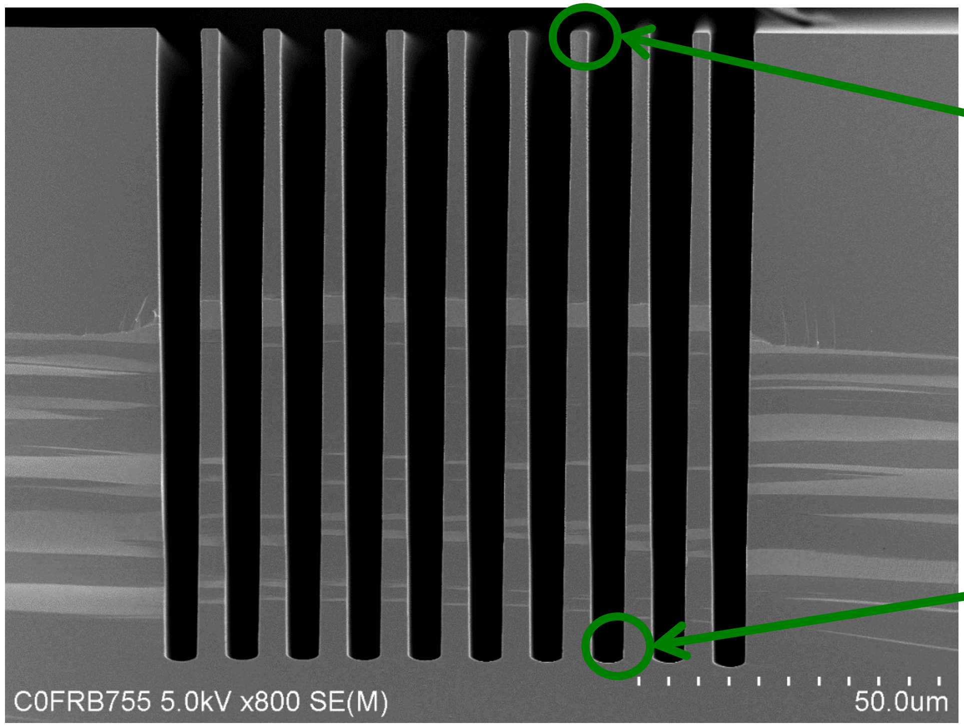
Item	Specification
Batch size	- 10 pcs of 200mm wafers - 30 pcs of 100x100mm sheets - 416 pcs of 25mm wafers
Deposition rate	-SiO_2 24nm/min 1.4µm/h -Al_2O_3 40nm/min 2.4µm/h -TiO_2 18nm/min 1.1µm/h -Ta_2O_5 33nm/min 2.0µm/h
Process temperature	25-200 °C
Process pressure	1 mbar
Substrate orientation	Face down
Rotary table diameter	1100 mm



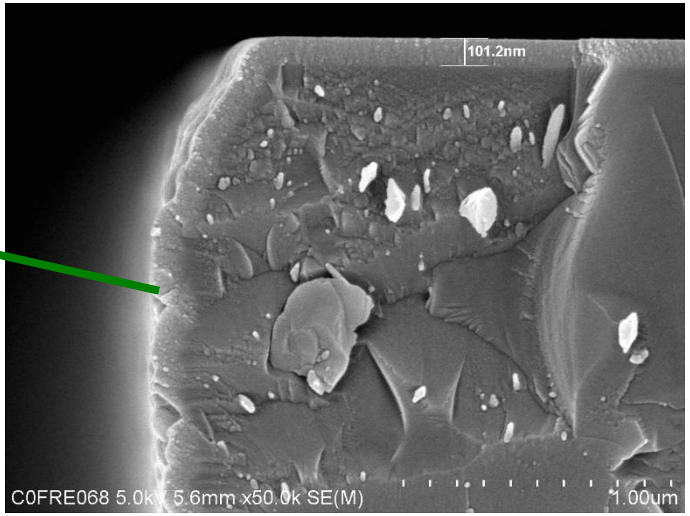


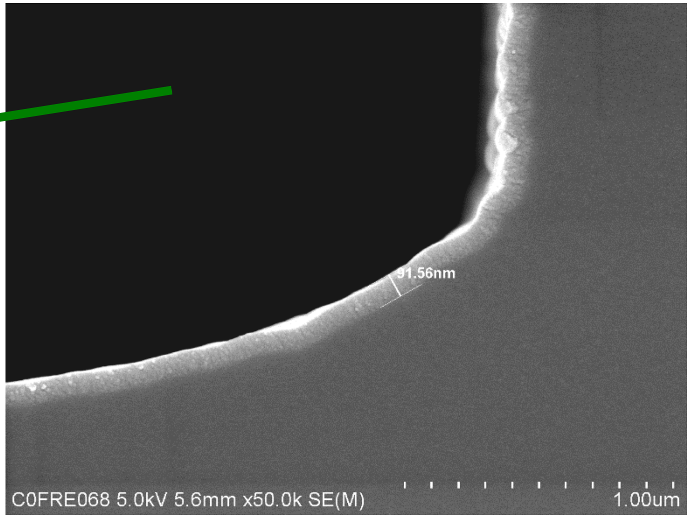
ROTARY ALD FOR WAFERS - CONFORMALITY

Compare the coating thickness at the bottom and top of trench



Ta_2O_5 Deposited at 150 RPM



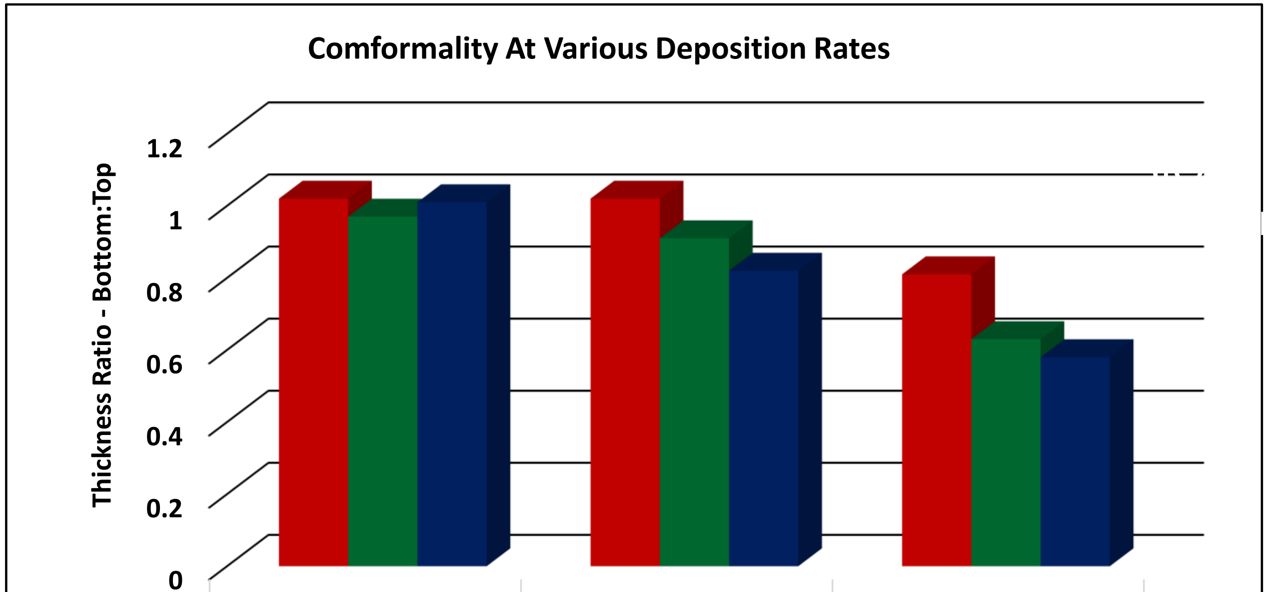


- Silicon substrates prepared using “Bosch” Deep Reactive Ion Etch to mill trenches
  - Nominally 5-7μ wide by ~ 120μ deep

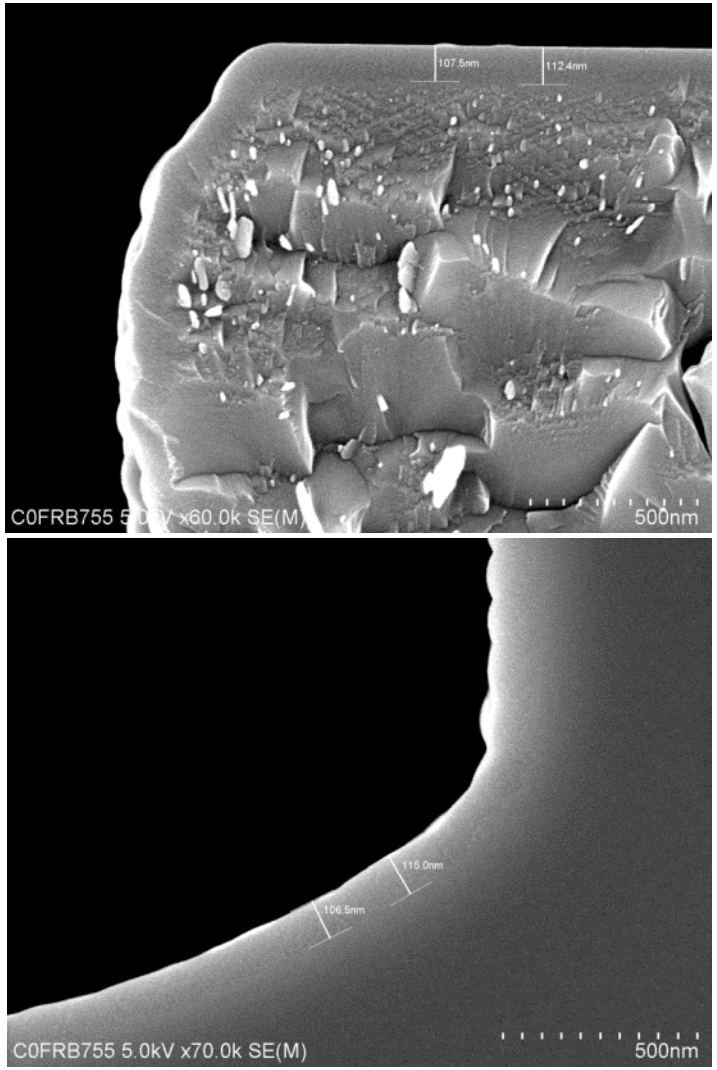
ROTARY ALD FOR WAFERS - CONFORMALITY

300 RPM = 300 ALD cycles / minute
= 300 cycles x 0.08 nm/ cycle / minute =

24 nm/minute for 1:20 aspect ratio



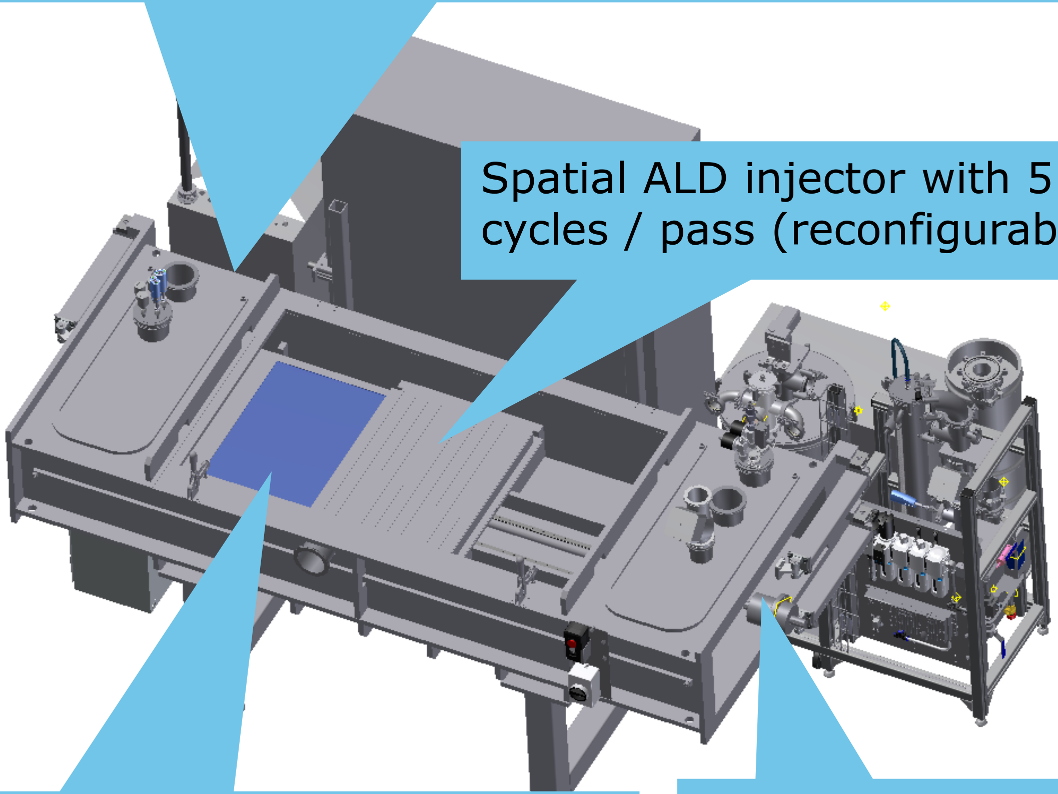
	SiO2	Ta2O5	TiO2
60 RPM	1.02	1.02	0.81
150 RPM	0.97	0.91	0.63
300 RPM	1.01	0.82	0.58



LARGE AREA SPATIAL ALD - PROTOTYPE

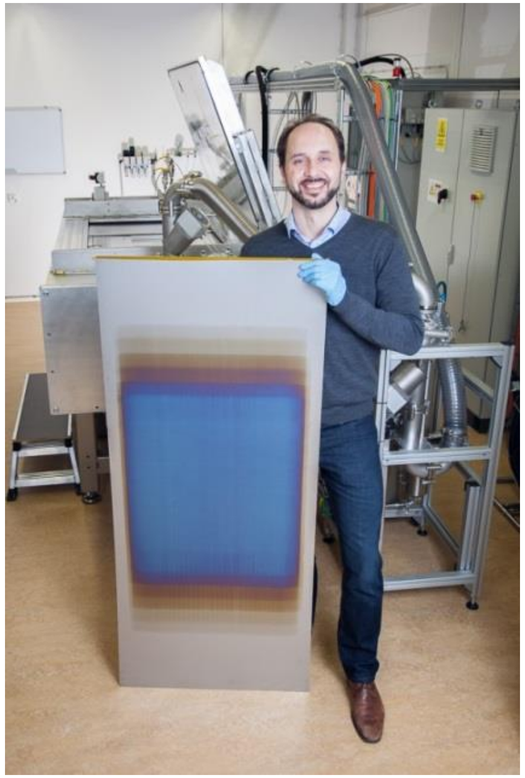
Near-atmospheric pressure spatial ALD prototype
Al_2O_3, TiO_2, ZnS, Zn(O,S) processes demonstrated

Spatial ALD injector with 5 cycles / pass (reconfigurable)



Substrate Gen2.5 glass, or multiple wafers, placed on a moving carrier

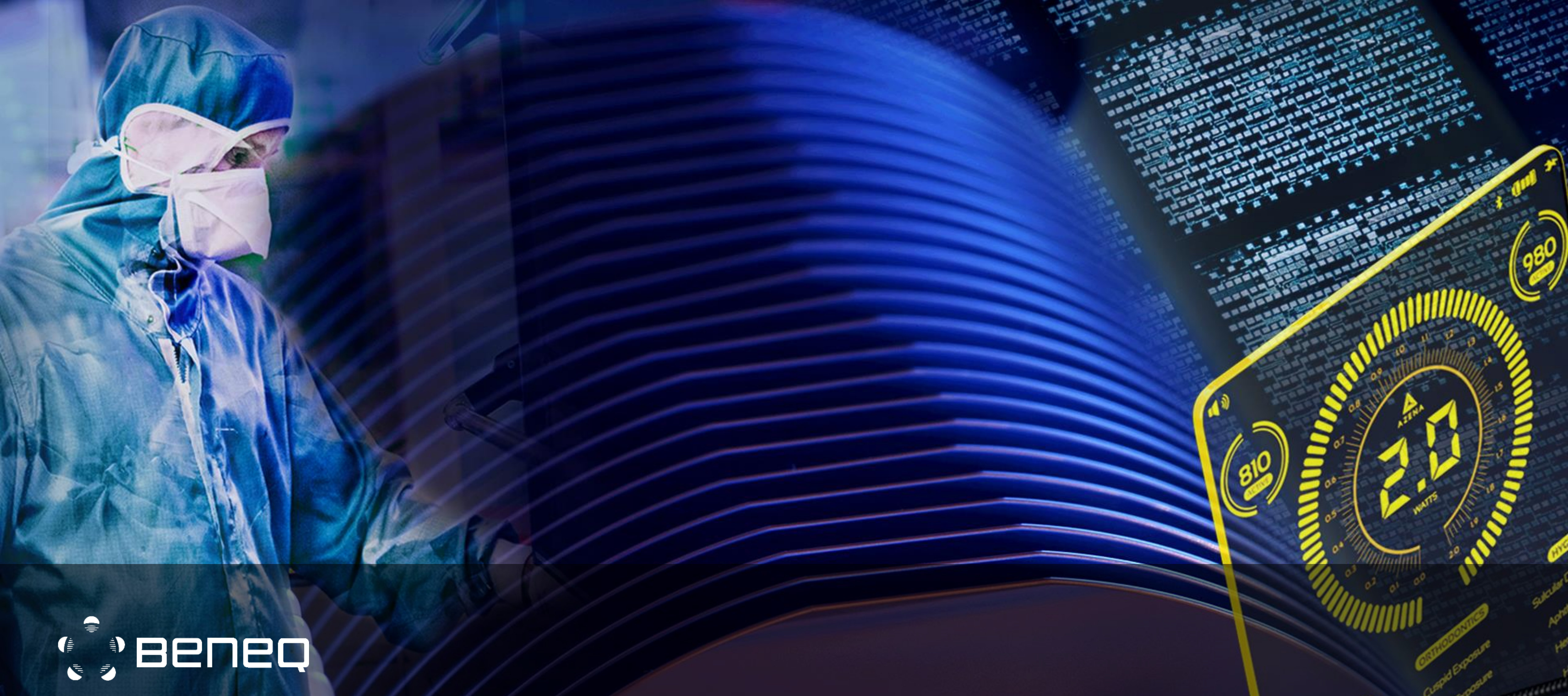
Motor for up to 30 m/min translation speeds



Demonstration of fast & large-area Al_2O_3 coating on 1500 x 640 mm sheet

SUMMARY

- Flexible electronics drives a transition from glass to polymer-based devices -> demand for barrier coatings
- Ultra-thin and pinhole-free ALD coatings demonstrate excellent moisture barrier properties
- On wafer-scale batch ALD can meet the demands on capasity e.g. for micro-OLED displays
- Spatial ALD method is an enabler for addressing large surface areas, and roll-to-roll processing, providing
  - High deposition rate (> 10 nm / min)
  - Scalability (gen 5.5 and beyond)
  - In-situ monitoring
  - Low maintenance (months of continuous processing)
- Flexible electronics requires not only barriers, but also other high quality layers (di-electrics,...)



Beneq® is a leading supplier of production and research equipment for atomic layer deposition (ALD), a provider of thin film coating services, and the world’s premier manufacturer of thin film electroluminescent (TFEL and TASEL) displays.

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