Roll-to-roll equipment for atmospheric ALD for solar applications

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VDL Group

- Established in 19 countries
- 85 operating companies
- > 10,000 employees, privately owned
- Turnover 1.8 billion (2013)

Subcontracting:
- Mechatronic systems
- Module assembly
- Part and sheet metal
- Surface treatments
- Plastic processing
- Other specialties

Bus group:
- Touring cars
- Public transport bus
- Mini and midi busses
- Chassis modules
- Second hand trade

Finished products:
- Medical equipment
- Process installations
- Consumer products
- Production automation
- Various products
- Packaging equipment

Car assembly:
- NedCar
The Rise of Printed, Flexible, and Organic Electronics
High-precision R2R Printing & Coating

R&D and pilot/mass production of:
- Flexible OPV and CIGS solar cells
- Large-area OLED lighting
- Flexible displays
- Flexible batteries
- Flexible sensors, circuits, and systems

Grey-room production environment

Cleanroom class 100
Compact R2R Printing & Coating
Purged R2R Lamination Line
Outline

• Introduction Spatial Atomic Layer Deposition
• Spatial ALD for increased throughput
• Application: CIGS solar cell buffer layer
• ALD on flexible substrates
• Results
• Conclusions
What is Atomic Layer Deposition?

Example: Tri-methyl Aluminium + H₂O → Al₂O₃

- Excellent conformality
- Extreme layer thickness control
- Wide variety of materials
- Reactor geometry, flow layout & temperature less critical
- Low contamination

- Low deposition rate
- Inefficient precursor use
- Backside deposition & coating on walls reactor
- Not economically feasible for many applications

**ALD reactor**

Step 1: Pulse A

Step 2: Purge

Step 3: Pulse B

Step 4: Purge
**What is “slow”?**

<table>
<thead>
<tr>
<th>“Fast” ALD</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Hair</td>
<td>1.25 cm/month</td>
<td>5 nm/s</td>
</tr>
<tr>
<td>Nails</td>
<td>0.1 mm/day</td>
<td>1 nm/s</td>
</tr>
<tr>
<td>Mount Everest</td>
<td>1 cm/year</td>
<td>0.3 nm/s</td>
</tr>
<tr>
<td>Lichen</td>
<td>1 mm/year</td>
<td>0.03 nm/s</td>
</tr>
<tr>
<td>Stalactites</td>
<td>0.13 mm/year</td>
<td>0.004 nm/s</td>
</tr>
</tbody>
</table>
Spatial separation of half-reactions

How to keep reactions separated?

How to do the mechanics?
Spatial ALD with gas bearings

- Gas bearing gap: ~ 20 μm, providing excellent diffusion barrier
- No deposition on reactor walls
- Small reactor volume, high precursor yield
- Atmospheric pressure
- No purge + fast reactions: high deposition rate
ALD for flexible electronics
Thin film encapsulation

Water vapor infiltration: major reliability issue in large area electronics (e.g. ZnO in CIGS, cathode in OLEDs, organic semiconductors)

Encapsulant is required to provide barrier against water diffusion

Benchmarks are: - Water Vapor Transmission Rate (WVTR, g/m²/day) - Oxygen Transmission rate (OTR, cm³/m²/day/atm)
CIGS buffer layer

EU FP7 project R2R CIGS:
- Buffer layer: thin, conformal layer
  - CdS < 50 nm
- Replace CdS in stack with Zn(O,S)
- ALD of Zn(O,S):
  - ZnO using diethylzinc (DEZ) and H₂O
  - ZnS using diethylzinc (DEZ) and H₂S
- Mixed compound
  → O : S ratio enabled by spatial processing
Spatial ALD and premixing of precursors

- Premixing of precursors for mixed compounds: Zn(O,S), ...

- Conventional ALD:
  - Self limiting character of ALD + concurrent reaction kinetics → prevents mixed compounds

- Spatial ALD:
  - Enabler for premixing because of limited exposure time
  - Fine tuning of layer composition, morphology and electrical properties

Spatial ALD and premixing of precursors
Spatial ALD on flexible substrates

Spatial ALD is mainly used on rigid substrates

**Does it work for flexible substrates?**

Challenges:

- Web deformation and strain
- Contamination
- Thick films
  (as compared to e.g. passivation layers)
- Large substrates
- Temperature limitations
- High-throughput / low cost
Roll-to-roll Spatial ALD: TNO concept

• Center piece: Web surrounding a drum with several reaction zones and gas-bearings
• Web moves left to right (slowly)
• Fast ALD injector rotates right to left (fast)
• Combination gives high deposition rate

• No mechanical contact on deposition side
• Flexibility in web and layer thickness
• Compact

Patents pending
R2R ALD for CIGS tool
R2R ALD for CIGS tool

- Enclosures for thermal insulation and H$_2$S safety
Results

- R2R ALD tool developed for deposition of Zn(O,S) buffer layers
- Contactless gas feedthrough
- Gas bearing of web
- Precursor separation
- Deposition of ZnO and Zn(O,S) done on PI foils, including PI with Mo and CIGS
- Functioning solar cell was made using ALD deposited Zn(O,S) buffer layer
Conclusions & outlook

• Spatial ALD enables thin film deposition rates > 1 nm/s
• This enables application of ALD in low cost applications / R2R
• Mixed compounds such as Zn(O,S) can be made using spatial ALD
• R2R ALD tool (2nd generation) is developed aimed at deposition of Zn(O,S) buffer layers as part of EU FP7 Project R2R CIGS:
  see also http://r2r-cigs.com/
• Deposition of ZnO and Zn(O,S) done on PI foils, including PI with Mo and CIGS
• Functioning solar cell was made using ALD deposited Zn(O,S) buffer layer
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Questions