Recent Advances in ALD Technology

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One Stop for All ALD

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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
- Anti-reflection coatings
- Surface passivation
- Powder functionalization
- Flexible moisture barrier films
- AMOLED
- LED
- Photovoltaic
- Buffer/interface layers
- Quantum Dot TV
Large-area industrial ALD opportunities

- To address these markets, innovations required in:
  1. Large-area sheet systems
  2. Roll-to-roll processing
  3. High capacity 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!

Spatial large sheet ALD equipment

• For large (m²) 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 + $\text{H}_2\text{O}$ at both ends

70 nm on ZnO on stainless steel showing effective coating area

"The Team Spatial"
Spatial sheet ALD highlights

- Fast Al$_2$O$_3$ process developed for e.g. thin-film encapsulation of OLEDs and rear-surface passivation

Al$_2$O$_3$ @ 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**

- $n (633 \text{ nm}) = 1.9556$

**ZnS @ 110 °C**

- $n (633 \text{ nm}) = 2.401$
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 principle 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 $\text{Al}_2\text{O}_3$ layer deposited at $@ 105 \, ^\circ\text{C}$

Water vapor transmission rate (WVTR) $\sim 5 \times 10^{-6} \, \text{g/m}^2 \, \text{day}$

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

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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 $\text{Al}_2\text{O}_3$ 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 licenced 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 tetraethylsilanediame (SAM-24) and O$_2$ plasma
  - TiO$_2$ from titanium tetraisopropoxide (TTIP) and N$_2$/O$_2$ plasma
  - Ta$_2$O$_5$ from Tris(ethylmethylamido)(tert-butylimido)tantalum (TBTEMT) and O$_2$ plasma

<table>
<thead>
<tr>
<th></th>
<th>Temperature (°C)</th>
<th>Rotation speed (RPM)</th>
<th>GPC (Å/cycle)</th>
<th>Refractive index (@550 nm)</th>
<th>Residual Carbon (at.%)</th>
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<td>SiO$_2$</td>
<td>85-100</td>
<td>200</td>
<td>1.2</td>
<td>1.45</td>
<td>&lt; 0.1</td>
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<tr>
<td>TiO$_2$</td>
<td>85-100</td>
<td>200</td>
<td>0.54</td>
<td>2.45</td>
<td>2.5</td>
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<tr>
<td>Ta$_2$O$_5$</td>
<td>150</td>
<td>120</td>
<td>0.82</td>
<td>2.17</td>
<td>2.0</td>
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</table>
Uniform ALD growth in high aspect ratio trenches (1:20)

<table>
<thead>
<tr>
<th>Thickness Ratio - Bottom:Top</th>
<th>SiO2</th>
<th>Ta2O5</th>
<th>TiO2</th>
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<tbody>
<tr>
<td>60 RPM</td>
<td>1.02</td>
<td>1.02</td>
<td>0.81</td>
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<tr>
<td>150 RPM</td>
<td>0.97</td>
<td>0.91</td>
<td>0.63</td>
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<tr>
<td>300 RPM</td>
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<td>0.58</td>
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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 design 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 $\text{Al}_2\text{O}_3$ coating on $\text{SiO}_2$ spheres
- Low amount of non-coated spheres ($< 5\%$)
Fluidized-bed ALD outlook

- Highly conformal Al$_2$O$_3$ coating of ~200 nm particles demonstrated
  - SnO$_2$ process also tested
- First 2$^{\text{nd}}$ 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 specific benefits are available
  - 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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