Rotatable Magnetron Sputtering in R2R Web Coating of Optical Layer Stacks

Holger Proehl, Martin Dimer, Michael Hentschel, Falk Otto, Johannes Struempfel

VON ARDENNE Anlagentechnik GmbH, Dresden

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VON ARDENNE Expertise
Main Product Lines for Large Area Coating

PIAnova for glass coating

GC60V for glass coating

GC330H for large-area glass coating

MSC1250 for metal strip coating
Rotatable Magnetron Sputtering in R2R Web Coating of Optical Layer Stacks

Outline

• Rotatable Magnetron Sputtering
• AC Sputtering of Dielectric Films
  • SiO₂ Sputtering (Impedance Control)
  • TiO₂, Nb₂O₅ Sputtering (Ceramic)
• DC Sputtering (TCO)
  • Aspects of ITO Sputtering
• Sputter Roll Coater for Polymer Films
  • Process Flexibility
  • Concepts of Compartment Units
• Summary
Rotatable Magnetron Process in DC or AC Mode

Overall Advantages

- **Lower running costs**
  - Better target usage (≥ 85% compared to ≤ 40% for planar targets)
  - Longer sputter campaigns
  - Higher deposition rates (higher max. power due to direct cooling)

- **Better process performance and stability**
  - No re-deposition zones → less particles, less arcing
  - No cross contamination by sputtering of target clamps
  - Easy adjustable magnetic fields
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Coating Technology – Process in AC Mode
Rotatable Dual Magnetron (RDM)

AC
Conductive targets ($\rho \leq 1 \ \Omega\text{cm}$), conductive and insulating layers
long-term stable processes (e.g. ZnO, SnO$_2$ or Si$_3$N$_4$)
Low Index Material SiO$_2$
Silicon Target with Reactive AC Sputtering

Planar with Re-deposition
Flaking $\rightarrow$ Maintenance

Rotatable w/o Re-deposition
w/o Nodules less Maintenance

- Si planar target,
- Target thickness 10mm
- **AC** power density $< 15$ kW/m
- $ddr = 50$ nm*m/min per SDM
- Cleaning of target periodically
- **Severe re-deposition, flaking**

- Si rotatable target,
- Target thickness 9mm
- **AC** power density $\approx 20$ kW/m
- $ddr = 140$ nm*m/min per RDM
- Clean target, minor maintenance
- **No flaking, no nodules**
Working Ranges for High Rate Reactive Sputtering

• Hysteresis for power $P = \text{constant}$

metallic mode

transition mode stabilization by fast control of reactive gas flow, only

reactive mode

voltage, rate, intensity

reactive gas flow

metallic mode

ITO
ZAO

TiO$_2$, Ta$_2$O$_5$, Nb$_2$O$_5$

TiN

SiO$_2$,

$\tau \approx 200 \text{ ms}$, $\text{only}$

In$_2$O$_3$, ZnO, Si$_3$N$_4$, SnO$_2$
Reactive **AC** Sputtering of SiO₂
Characteristics of O₂ Flow vs. AC Voltage

![Graph showing the relationship between O₂ Flow and AC Voltage for different power levels: 20 kW, 18 kW, 16 kW, and 14 kW. The graph has a horizontal line at 500V.]
Voltage Fed for Stabilization Working Points
– Simple Control Scheme –

Power setpoint → PID controlled gas inlet → Gas manifold → Sputter Process

Voltage setpoint → Power Supply controlled voltage → Target

Slow control loop, $\tau \sim 1\,\text{min}$

Fastest control loop, dependent on power supply, typ. $\tau \sim \text{ms range}$
Reactive AC Sputtering of SiO$_2$
O$_2$ Flow vs. Power, @ 500 V (no Hysteresis)

- Increased flow @ constant voltage
- $\rightarrow$ Current / power increase $\rightarrow$ Dep. rate increase
Voltage Fed Working Point Stabilization
– Gas Trimming –

• 5 Segmented fast acting gas inlet manifold
  ➔ Tuning of deposition rate homogeneously
  ➔ Tuning of reactive gas pumping locally
  ➔ Same reactive working points at all sites of target

Pumping speed at target end influenced by chamber geometry

Sputter rate slightly different due to deviations in target geometry (B-field strength varies with distance)
Reactive **AC** Sputtering of SiO$_2$
Partial Pressure Control ($\lambda$-probe)

- Dependency of deposition date (AC-MF) on lambda probe voltage $U_\lambda$

![Graph showing the relationship between lambda voltage and deposition rate.](image)
Reactive AC Sputtering of SiO$_2$
Partial Pressure Control: $\lambda$-probe

- Lambda Probe is an galvanic cell
  - Cell voltage = lambda voltage $U_{\lambda}$ → Nernst Formula:

$$U_{\lambda} \sim \text{const.} \times \ln \left( \frac{p_{O_2}(\text{ambient})}{p_{O_2}(\text{process})} \right)$$
Reactive **AC** Sputtering of SiO₂
Partial Pressure Control \((\lambda\text{-probe})\)

- Dependency of cathode (AC) voltage and O₂ Flow on \(U_\lambda\)

Addition of some N₂ may be necessary to stabilize the process control at aggressive working points.
Reactive AC Sputtering of SiO$_2$
Segmented Fast Gas Inlet System

Fast Binary Manifold with 5 Segments
for fast response and precisely controlled gas inlet
with minimized stored amount of gas

Unpressurized $\Leftrightarrow$ minimized amount of gas $pV$: pressure $\times$ Volume
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High index Materials – Ceramic Targets
Uniformity Examples from Production

**Nb\textsubscript{2}O\textsubscript{5}**
- ddr up to 90nm*m/min w/o absorption
- Example: RDM 3750 (AC)

**TiO\textsubscript{2}**
- ddr ~ 55nm*m/min w/o absorption
- Example: RDM 3750 (AC)

→ Max. Deposition Rate is limited by max. applicable power (target / substrate)

compare T. Preussner et al., Nb\textsubscript{2}O\textsubscript{5} and TiO\textsubscript{2} thin films deposited by pulse magnetron of cylindrical ceramic targets, ICCG9 (2012)
Ceramic TiO2: AC vs. DC
Energy Impact at Substrate

**AC dual**
- $ddr \sim 55\text{nm}^*\text{m/min}$
- $T_{\text{web(max)}} \sim ?$

**DC dual**
- $ddr \sim 60\text{nm}^*\text{m/min}$
- $T_{\text{web(max)}} \sim ?$

Assumptions: PET 50µ, **Cooling drum: $T_{\text{CD}} = 0°C$**, heat transfer: $\alpha = 100 \text{ W/(m}^2\text{K)}$, 2m/min
Ceramic TiO2: AC vs. DC
Energy Impact at Substrate

**AC dual (RDM)**
- ddr \(\sim 55\text{nm*mm/min} \)
- \(T_{\text{web(max)}} \sim 61°C\)

**DC dual (RSM-RSM)**
- ddr \(\sim 58\text{nm*mm/min} \)
- \(T_{\text{web(max)}} \sim 29°C\)

Assumptions: PET 50\(\mu\), **Cooling drum**: \(T_{\text{CD}} = 0°C\), heat transfer: \(\alpha = 100 \text{ W/(m}^2\text{K)}\), 2m/min
Dual Anode Sputtering (DAS®)
Example: Dual DC Magnetron Lid (RSM-RSM)

• DC Sputter: up to 50% less energy impact to substrate
  ▶ Solution would be ideal for plastic webs and metal foils

• DC sputtering of transparent dielectrics: disappearing Anode problem
  ▶ Solution: Dual Anode Sputtering (DAS® / RAS) - Proven for planar and rotatable
Dual Anode Sputtering (DAS®)
Using a DC Power Supply and Active Switches
Industrial Application of DAS®
Ceramic Planar, Ceramic Rotatable

- i-ZnO with DC-pulse (rotatable)
- Example Nb₂O₅ (planar)

Thickness Uniformity (WSM2250)

G. Teschner et al., Dual Anode Magnetron Sputtering, 50th Annual SVC Technical Conference, 2007
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Coating Technology- Process in **DC** Mode

Dual **DC** Magnetron

**DC, DC-DC**

Conductive targets ($\rho \leq 1 \, \Omega \text{cm}$), layers with (residual) conductivity long-term stable TCO processes (e.g. ITO or ZnO:Al$_2$O$_3$)
ITO Ceramic Targets with **DC** Sputtering

Planar with Re-deposition
Nodules, Powder → Maintenance

<table>
<thead>
<tr>
<th>Rotatable w/o Re-deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>no Nodules, less Maintenance</td>
</tr>
</tbody>
</table>

- ITO ceramic planar target
- Target thickness 10 mm
- Target utilization 25%
- DC power density < 5 kW/m
- \( ddr = 34 \text{ nm} \times \text{m/min per SSM} \)
- Cleaning of target periodically,
- **nodule formation may occur**

- ITO Ceramic rotatable target
- Target thickness 6 mm
- Target utilization 80%
- DC power density > 10 kW/m
- \( ddr \) up to 100 nm\( \times \)m/min
- Robust process, clean target,
- **no nodules**
Main requirements

- Sheet resistance $R_{sq} \leq 150$ Ohm for standard panel sizes
  - Trend to $R_{sq} < 100$ Ohm for larger (>10”) panels
- Thickness 20...25 nm for invisibility (index matching)
  - Higher thickness = cost + more efforts for index matching
- Low absorption

Can these requirements be reached by rotatable magnetron technology at high rates for ITO?
Sheet resistance depends on the substrate
- Wafer: 130 Ohm
- PET with HC: 147 Ohm
- Glass with SiO₂: 179 Ohm
- Deposition rate: 37 nm m/min

ITO thicknesses: around 23 nm

60 min annealed at 150°C
ITO-Sputtering from Rotatable Targets
PET - Substrate Variation

- PET is not PET (who’d ever believed)
  - pretreatment, seed layers may help or not…

~30nm ITO on PET, annealed at 150°C

specific resistivity ($\mu$Ohmcm)

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VON ARDENNE - AIMCAL Web Coating & Handling Conference 2013 - Charleston
ITO-Sputtering from Rotatable Targets
High Rate Sputtering

• ITO on standard PET/HC
  ▶ High rate: lower resistivity (annealed), wider process window

![Power variation (PET)](image_url)
Before annealing
- Between 15 and 35° significant intensity → nanocrystalline structures

After annealing
- Polycrystalline structure with preferred (222) orientation
ITO-Sputtering with Rotatable Targets
Carrier Density and Mobility

- **Annealing**: carrier density increases from 4 to $7 \times 10^{20}\text{cm}^3 (+42\%)$
  - At 2.5% O$_2$ (optimum): only a minor change in the mobility by annealing
- **O$_2$-Flow**: Only a small increase of the carrier density by increasing of the oxygen flow
  - But a strong increase of the mobility with increasing oxygen content
Outlook: Low Ohm ITO on Dry IM Coating for Touch Panel Application

- **Finding:** \( R_{sq} 117 \, \Omega @ 25 \, \text{nm}, \text{ann.} 150^\circ \text{C}, 90 \, \text{min} \to 290 \, \mu\Omega \text{cm} \\
  \Rightarrow \text{Task: Optimize IM layers and ITO process for best ITO}

Goal:
\( R_{sq} < 100 \, \text{Ohm} \)
\( b^* \approx 0.8, \, T \approx 89.5\% \)
\( \Delta E^*(\text{etch}) = 0.9 \)
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Sputter Web Coater
FOSA 1300D10

- Two drum system
- Planar magnetron technology
- Box-in-box principle
New FOSA1600 Web Coating System

- Modular design, multi-chamber platform for R2R vacuum coatings
- Deposition of high-quality layers using advanced sputtering technology
- Flexible substrates, polymer films with multiple coil handling
- Based on proven FOSA1300 concept
Systems and Features
FOSA1600 D8  Dual Drum Web Coater
Modularity of Multi-Chamber System

- 1x unwinding, 1x rewinding, 1 to 3x process chambers
- 1 drum (heated/chilled) per process chamber
- Concept allows up to 24 DC-magnetrons

System

FOSA1600S4
FOSA1600D8
FOSA1600 T12
FOSA1600 Web Coating System
Inner Concept

Compartment Unit

• Box-in-box principle
• Undisturbed process vacuum
FOSA1600 Web Coating System
Inner Concept

**Compartment Unit**
- Box-in-box principle
- Undisturbed process vacuum
FOSA1600 Web Coating System

QC, Metrology

In-Situ Measurement

- Multi-track optical measurement (transmit., reflectance)
- Non contact sheet resistance measurement
- Optical emission spectroscopy
- Marker device

Process Control

- Impedance / lambda control for $\text{SiO}_x\text{N}_y$ etc. (VAprocos®)
FOSA1600 Web Coating System
QC, Metrology

- QC: position related data are preferred
  - Movement controlled real time triggering of data acquisition depending on measurement position
  - Subsequent, independent data evaluation
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Rotatable Magnetron Sputtering in R2R Web

Summary

- Rotatable Magnetrons are superior in use for mass production: higher dep. rates, reduced flaking, longer campaign duration
- Flexibility of Rotatable Magnetrons is obvious for R2R web coatings with ITO and dielectrics SiO$_2$, Nb$_2$O$_5$, TiO$_2$
- Uniformities of $\Delta d/d \leq \pm 2\%$ in TD and MD are achievable

- **Goal:** ITO touch panel films with $\rho < 250$ $\mu\Omega$cm and $T > 90\%$
  - Machine concepts shall assure and reliable process conditions combined with flexibility
Thank you | Danke für Ihre Aufmerksamkeit
Auf Wiedersehen | See You in Dresden 2014!

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Cordial Invitation

10th International Conference on Coatings on Glass and Plastics
June 22 – 26, 2014, Dresden, Germany