A METHOD FOR SCALING DYNAMIC DEPOSITION RATES BETWEEN
PLANAR TO ROTARY MAGNETRONS, AND STUDY OF HEAT LOAD
INCIDENT UPON SUBSTRATE FOR EACH
OVERVIEW

- Process engineers tasked with estimating throughput need to know something about deposition rates and heat loads

- We will investigate planar vs. rotary magnetrons

- Deposition Rate Scaling From Planar to Rotary
  - Characterize deposition rates
  - Normalize total target power or current to the plasma racetrack dimensions
    - Measure erosion groove
  - Investigate ways to scale the deposition rate from planar to rotary magnetron

- Heat Load Comparison
  - Develop scheme for placing thermocouples on the temperature controlled coating drum for in-situ temperature measurements
  - Compare the thermocouple readings at equal deposition rates, thereby indicating the heat load on the substrate
DEPOSITION RATE SCALING
BACKGROUND / NEED

- **Goal**
  - Develop a method to transfer a known dynamic deposition rate (DDR) for a planar magnetron to an estimated DDR for a rotary magnetron

- **Assumptions**
  - Deposition profile follows a cosine distribution
  - Sputter flux per amp is equal (While holding constant: target material, working gas, pressure)

- **Approach**
  - Characterize the planar magnetron DDR at known process conditions [nm-m/min]
  - Measure the planar target erosion groove length [m]
  - Normalize the DDR to power or current per unit racetrack length [nm-m/min/(W/m)]
  - Determine system geometry
  - Calculate rotary DDR

- **Challenges**
  - How do I measure the plasma racetrack dimensions for my planar magnetron?
    - Measure the erosion groove.
  - How do I calculate the plasma racetrack dimensions for a rotatable magnetron? Let’s look at some options.

- **Questions**
  - Why use racetrack length instead of target area?
    - Because the physics happen in the plasma, not over the whole target area
**Deposition Rate Scaling Equipment Setup**

- **R2R330 Web Coating Tool**
  - 13” [330mm] coated width, 4 deposition zones, temperature controlled coating drum

- **Planar Magnetron Module: Zone 3**
  - 100mm wide x 500mm long target

- **Rotary Magnetron Module: Zone 2**
  - 100mm Diameter x 600mm long target

- **Target Material**
  - 6061 Aluminum Alloy

- **Power Supply**
  - DC (not pulsed)

- **Thickness Witness**
  - Glass microscope slides affixed to coating drum
Measure Target Erosion Pattern
- Burn the target long enough to see the erosion groove
- In the case of the rotary, do not spin the target during this test

Tape a string to the eroded target centerline, mark it, and measure per the diagram
- A: Straightaway length
- B: Turnaround length (one turnaround; half-circle shape)
- $2A + 2B = \text{total string length}$
- Total string length and straightaway are easiest to measure
  - $B = (\text{Total String Length} - 2A)/2$

<table>
<thead>
<tr>
<th>Magnetron</th>
<th>Target Dimensions</th>
<th>Target Area [cm²]</th>
<th>Erosion Groove Length [m]</th>
<th>Straightaway Length [m]</th>
<th>Turnaround Length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar</td>
<td>10cm x 50cm</td>
<td>500</td>
<td>0.96</td>
<td>0.36</td>
<td>0.11</td>
</tr>
<tr>
<td>Rotary</td>
<td>10cm dia x 60cm</td>
<td>1885</td>
<td>1.12</td>
<td>0.42</td>
<td>0.14</td>
</tr>
<tr>
<td>Ratio (Rot./Plan.)</td>
<td>N/A</td>
<td>3.77</td>
<td><strong>1.16</strong></td>
<td>1.14</td>
<td>1.24</td>
</tr>
</tbody>
</table>
DEPOSITION RATE SCALING
PLANAR MAGNETRON DDR/Amp

- **Multi-pass coating**
  - Copper deposited on a glass microscope slide, 3mT Argon
- **Thickness measured with step profilometer**
- **DDR/ Amp calculated:**
  - Average 5.2 \(\text{nm-m/min}/[\text{Amp/m}]\); Standard deviation 0.1 (1.2%)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Current [A]</th>
<th>Speed [m/min]</th>
<th>N Passes</th>
<th>Thickness [nm]</th>
<th>Racetrack Length [m]</th>
<th>DDR/ Amp/ m [nm-m/min/ [A/m]]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-1</td>
<td>4.52</td>
<td>0.373</td>
<td>3</td>
<td>188</td>
<td>0.96</td>
<td>4.96</td>
</tr>
<tr>
<td>P-2</td>
<td>4.52</td>
<td>0.373</td>
<td>3</td>
<td>190</td>
<td>0.96</td>
<td>5.03</td>
</tr>
<tr>
<td>P-3</td>
<td>4.52</td>
<td>0.326</td>
<td>3</td>
<td>215</td>
<td>0.96</td>
<td>4.97</td>
</tr>
<tr>
<td>P-4</td>
<td>4.52</td>
<td>0.326</td>
<td>3</td>
<td>220</td>
<td>0.96</td>
<td>5.09</td>
</tr>
</tbody>
</table>
Multi-pass coating
- Copper deposited on a glass microscope slide, 3mT Argon

Thickness measured with step profilometer

DDR/Amp calculated:
- Average 3.2 nm·m/min/[Amp/m]; Standard deviation 0.4 (4.4%)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Current [A]</th>
<th>Speed [m/min]</th>
<th>N Passes</th>
<th>Thickness [nm]</th>
<th>Racetrack Length [m]</th>
<th>DDR/Amp/m [nm·m/min/[Amp/m]]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>5</td>
<td>0.373</td>
<td>3</td>
<td>129</td>
<td>1.12</td>
<td>3.58</td>
</tr>
<tr>
<td>R-2</td>
<td>5</td>
<td>0.373</td>
<td>3</td>
<td>133</td>
<td>1.12</td>
<td>3.68</td>
</tr>
<tr>
<td>R-3</td>
<td>5</td>
<td>0.326</td>
<td>3</td>
<td>140</td>
<td>1.12</td>
<td>3.40</td>
</tr>
<tr>
<td>R-4</td>
<td>5</td>
<td>0.326</td>
<td>3</td>
<td>155</td>
<td>1.12</td>
<td>3.76</td>
</tr>
</tbody>
</table>
DEPOSITION RATE SCALING
OTHER CONSIDERATIONS

- **Planar Vs. rotary magnetrons**
  - Fundamental geometry difference; difference in direction of sputtered particles leaving the target

- **Geometry**
  - Downweb length of deposition window
  - Length of target beyond substrate width to give uniform coatings

- **Other things to consider:**
  - Magnet pack design
    - Single or multi-row
    - Balanced or unbalanced
    - Target surface field strength
In this instance, rotary requires 1.62 times the input power for equal DDR on the substrate:

- Planar: 5.2 nm-m/min/[Amp/m]
- Rotary: 3.2 nm-m/min/[Amp/m]

How can we scale this in a predictive manner?
**Deposition Rate Scaling Model**

- **Assumptions**
  - The quantity of sputtered particles is approximately equal per Amp, per unit plasma racetrack length, across planar and rotary magnetrons
    - While holding constant: target material, working gas, pressure
  - The sputtered particles are ejected from the target surface according to a cosine distribution during the sputter process

- **Model Inputs**
  - Planar magnetron data
  - Rotary magnetron target tube diameter & included angle of plasma
  - Coater deposition window geometry
• **Geometric analysis of sputter flux that reaches the substrate**
  - Assume cosine flux distribution as measured from the target normal at the plasma lobe center
  - Determine end point angles from this plasma lobe center
  - Integrate the cosine function over this angle to determine the fraction of particles that land on the substrate and are counted in the DDR
    - Solve the definite integral of the cosine over this interval; equal to the sine of the end angle minus the sine of the beginning angle
**Deposition Rate Scaling**

**Sputter Flux Distribution**

- **Ratio**
  - \( f_P / f_R = 2.57/1.75 = 1.47 \).
  - This times as much flux reaches the substrate in this planar geometry as this rotary geometry.

<table>
<thead>
<tr>
<th></th>
<th>Lower Angle</th>
<th>Upper Angle</th>
<th>2x Integral</th>
<th>Plan./ Rot.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar</td>
<td>-33.27</td>
<td>47.56</td>
<td>2.57</td>
<td>1</td>
</tr>
<tr>
<td>Rotary</td>
<td>6.44</td>
<td>81.74</td>
<td>1.75</td>
<td>1.47</td>
</tr>
</tbody>
</table>
Deposition Rate Scaling Outcome and Model Summary

- Calculation differs from actual result by 9.2%
- Relatively simple way to get a close estimate
- Useful for power supply sizing

<table>
<thead>
<tr>
<th></th>
<th>DDR/ Amp/m [nm-m/min/ [A/m]]</th>
<th>Integrated Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar</td>
<td>5.2</td>
<td>2.57</td>
</tr>
<tr>
<td>Rotary</td>
<td>3.2</td>
<td>1.75</td>
</tr>
<tr>
<td>Planar / Rotary Ratio</td>
<td>1.61</td>
<td>1.47</td>
</tr>
<tr>
<td>Percent Error</td>
<td>N/A</td>
<td>9.2%</td>
</tr>
</tbody>
</table>
Thermal load on the substrate is an important factor in vacuum coating.

Comparison of this thermal load between rotary and planar magnetrons is useful.

This is not an absolute comparison; there are other factors at play:
- Magnetic design; target cooling; others.
**Planar vs. Rotary Heat Load – Equipment Setup**

- **Same planar and rotary magnetrons as noted previously**
  - Planar target is indirectly cooled; rotary target is directly cooled

- **Direct thermocouple measurement between the substrate and the cooling drum**
  - In-line, with the drum rotating to coat continuous lengths of web

- **Use a thin substrate to minimize the effect of its heat capacity**
  - 10 micron thickness polymer web used in these tests

- **Tested 3 configurations, pictured on next slide**

**Clarification:** The aim here is to use a repeatable method; not to determine the actual temperature of the substrate

- The TC reading will not be equal to the web temperature
- The mere presence of the TC dramatically alters the heat transfer mechanics, and results in a much hotter web
- But, the data from the approach are deemed useful in comparing one substrate heat load to another
PLANAR VS. ROTARY HEAT LOAD – THERMOCOUPLE INTEGRATION

 AIMCAL R2R Conference 2017, Tampa, Florida

TC01 Config.
10µ Substrate
Thermocouple
Drum

TC02 Config.
10µ Substrate
Thermocouple
PI Tape
Drum

TC03 Config.
10µ Substrate
Thermocouple
Substrate
Drum
PLANAR VS. ROTARY HEAT LOAD – TEMPERATURE DATA

- TC02 approach selected because settling time is comparable to TC1, but signal is larger
- All data going forward uses TC02 approach

Back-side Web Temperature Response Across Four Heat Loads

![Graph showing temperature response over time for TC01, TC02, and TC03 across four heat loads.](image-url)
Three thermocouples attached to the drum at 120 degree intervals using the TC2 method

Arbitrarily chose the Planar magnetron power levels to use in the test

Calculated the rotary magnetron parameters that yield the same coating thickness
  • Using the actual measured DDR, not the calculated one

Compare the temperature responses and use these as indicators of the heat load on the substrate
  • The temperatures are not those of the substrate
HEAT LOAD DATA

- **Temperature rise measured under equal deposition rate conditions**
  - R-H-7 DDR is equal to P-H-7, etc

- **Planar magnetron found to have higher temperature rise in all cases**

<table>
<thead>
<tr>
<th>Run</th>
<th>Target</th>
<th>TCA Rise [°C]</th>
<th>TCB Rise [°C]</th>
<th>TCC Rise [°C]</th>
<th>Average [°C]</th>
<th>% Greater T Rise @ Planar</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-H-7</td>
<td>Rotary</td>
<td>2.78</td>
<td>3.33</td>
<td>2.50</td>
<td>2.87</td>
<td>18.7%</td>
</tr>
<tr>
<td>P-H-7</td>
<td>Planar</td>
<td>3.11</td>
<td>4.39</td>
<td>2.72</td>
<td>3.41</td>
<td></td>
</tr>
<tr>
<td>R-H-8</td>
<td>Rotary</td>
<td>2.33</td>
<td>2.72</td>
<td>2.22</td>
<td>2.43</td>
<td>32.1%</td>
</tr>
<tr>
<td>P-H-8</td>
<td>Planar</td>
<td>2.78</td>
<td>3.89</td>
<td>2.94</td>
<td>3.20</td>
<td></td>
</tr>
<tr>
<td>R-H-9</td>
<td>Rotary</td>
<td>5.11</td>
<td>5.28</td>
<td>4.78</td>
<td>5.06</td>
<td>25.6%</td>
</tr>
<tr>
<td>P-H-9</td>
<td>Planar</td>
<td>6.39</td>
<td>8.22</td>
<td>4.44</td>
<td>6.35</td>
<td></td>
</tr>
<tr>
<td>R-H-10</td>
<td>Rotary</td>
<td>4.67</td>
<td>4.89</td>
<td>5.11</td>
<td>4.89</td>
<td>36.4%</td>
</tr>
<tr>
<td>P-H-10</td>
<td>Planar</td>
<td>6.89</td>
<td>7.17</td>
<td>5.94</td>
<td>6.67</td>
<td></td>
</tr>
</tbody>
</table>
SUMMARY

- Characterized dynamic deposition rates of planar and rotary magnetrons via glass microscope slides affixed to the coating drum

- Showed a means of scaling a known planar magnetron target DDR to an estimated rotary magnetron DDR.
  - By normalizing sputter current to plasma racetrack length and analyzing the deposition window geometry

- Compare the heat load on the substrate for a planar and rotary magnetron operating at the same DDR

- Found the rotary magnetron to result in a lower heat load than the planar
  - At least some of this difference is attributable to the difference in target cooling design
Thank you for your attention!

- For more information, contact Mike Simmons
  msimmons@intelli-vation.com