MAGNETRON SPUTTERING OF ALUMINUM

Reference:

Work piece to be coated with Al

Ar⁺ Ions

Al Target atoms

Al Target
SPUTTERING MAGNETRON REVIEW

+ Magnets behind target
+ Electrons confined by ExB → $B \approx$ parallel, $E \approx$ normal to target surface

+ Aluminum target
INDUSTRY-LEADING TECHNOLOGY: DUAL MAGNETRON SPUTTERING (DMS)

- The predominant choice for new systems
- Planar or rotatable magnetrons
ROTATABLE MAGNETRON

The magnet is stationary and the target material rotates.

Racetrack
Magnets with flux lines shown
Target material
Turnaround
REACTIVE DMS CO-SPUTTERING
WHAT IS REACTIVE CO-SPUTTERING?

+ Multiple targets being sputtered in the presence of reactive gas
MOTIVATION FOR REACTIVE CO-SPUTTERING

+ Composition options are essentially unlimited, stoichiometry not required
+ Maybe the only option for some compounds
+ Material properties can be tailored to the application
REACTIVE CO-SPUTTERING: PRINCIPLES

+ Index of refraction depends on atomic fraction of the two target materials

+ Example: $\text{Al}_x\text{Ti}_y\text{O}$, with $1.66 < n < 2.4$

+ Vary atomic fraction of materials by varying power to each magnetron ($\sim$ rate from each magnetron)
DC REACTIVE CO-SPUTTERING WITH LARGE ROTATING MAGNETRONS

+ A. Belkind, et al., JVST A(9) 3, 1991
+ R. Laird, et al., JVST A(10) 4, 1992
DUAL-MAGNETRON REACTIVE SPUTTERING

- Magnetrons alternate roles as anode and cathode
- Eliminates “disappearing anode” problem
- Dielectric deposited during anode phase sputtered during cathode phase
- Need isolated bipolar supply
POWER SUPPLY REQUIREMENTS FOR DUAL MAGNETRON REACTIVE CO-SPUTTERING

- Regulate power, voltage, or current to each magnetron independently
- Magnetron targets are different materials, for example, Ti and Al
- Apply power differentially across magnetrons
MODELING REACTIVE DMS CO-SPUTTERING

+ Model based on:


+ Details published in SVC Bulletin Fall 2015 and Spring 2016 😊

+ Static model, no dynamics

+ Looked at pressure, composition, and rate as a function of partial pressure

+ Example model calculations for Al, Ti, O₂
TWO INDEPENDENT SPUTTERING SOURCES: A LOT HAPPENING

INDIVIDUAL TRANSITION CURVES FOR DUAL MAGNETRON SPUTTERING (DMS) ARRANGEMENT

DMS CO-SPUTTERING PROCESS CONTROL

- Highest performance: Control the power and working point for each cathode
- Power and working point control together provide for control of composition, absorption, and rate
- Use voltage to monitor working points A and B independently
**BASELINE WAVEFORM**

For voltage read back: AE DMS uses voltage in this interval ⇒ represents quasi-DC discharge voltage

- **Turn-on**
- **Turn-off**
- **End boost**
- **Dead/Clamp time**
- **Process voltage**

**CURRENT:**
Fast slew rate and higher start up threshold are desired

**V boost**

- **v (V)**
- **i (A)**

**T (us)**
MODELING RESULTS

+ Rate versus pressure curve has classic “S” shape
+ Rate varies strongly with partial pressure in transition region, varies significantly in poisoned region
+ Composition varies strongly with partial pressure in transition region, essentially flat in poisoned region
+ Graphs from model calculations follow…
## CO-SPUTTERING MODEL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti sputtering yield</td>
<td>$S_{M1}$</td>
<td>0.5</td>
<td>[3]</td>
</tr>
<tr>
<td>TiO$_2$ sputtering yield</td>
<td>$S_{C1}$</td>
<td>0.017</td>
<td>[3]</td>
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<tr>
<td>Al sputtering yield</td>
<td>$S_{M2}$</td>
<td>0.8</td>
<td>[5]</td>
</tr>
<tr>
<td>Al$_2$O$_3$ sputtering yield</td>
<td>$S_{C2}$</td>
<td>0.025</td>
<td>[4]</td>
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<tr>
<td>Sticking coefficients (all)</td>
<td>$\alpha_{xy}$</td>
<td>1</td>
<td>[1-3]</td>
</tr>
<tr>
<td>Ti target area</td>
<td>$A_{t1}$</td>
<td>0.068 m$^2$</td>
<td>Estimated</td>
</tr>
<tr>
<td>Al target area</td>
<td>$A_{t2}$</td>
<td>0.068 m$^2$</td>
<td>Estimated</td>
</tr>
<tr>
<td>Chamber area</td>
<td>$A_x$</td>
<td>1.46 m$^2$</td>
<td>Estimated</td>
</tr>
<tr>
<td>Ti target current density</td>
<td>$J_1$</td>
<td>294 A/m$^2$</td>
<td>1 kW, 500 V</td>
</tr>
<tr>
<td>Al target current density</td>
<td>$J_2$</td>
<td>367 A/m$^2$</td>
<td>1 kW, 400 V</td>
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<tr>
<td>Pumping speed</td>
<td>$S_p$</td>
<td>465 l/sec</td>
<td>Measured</td>
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<tr>
<td>Gas</td>
<td>n/a</td>
<td>O$_2$</td>
<td>Known</td>
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<tr>
<td>Temperature</td>
<td>$T$</td>
<td>300 K</td>
<td>Estimated</td>
</tr>
</tbody>
</table>
REFERENCES FOR MODEL PARAMETERS

MODEL CALCULATION

Rate (A.U.) vs. Oxygen flow

Rate (A.U.)

Oxygen flow (sccm)
MODEL CALCULATION

Oxygen flow (sccm) vs. partial pressure

Oxygen flow (sccm)

Oxygen partial pressure (mTorr)
MODEL CALCULATION

Ti fraction vs. oxygen partial pressure

Ti fraction (Ti/(Ti + Al))

Oxygen partial pressure (mTorr)
MODEL CALCULATION

Rate (A.U.) vs. Oxygen partial pressure

Rate (A.U.)

Oxygen partial pressure (mTorr)
EXPERIMENTAL CONDITIONS

- Ar flow 50 sccm
- Ar pressure 1.5 mTorr
- Base pressure < 1 x 10^-6 Torr
- Turbo-molecular pumped
- 2000 W total, varied fraction to Ti and Al targets
### EXPERIMENTAL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Ar flow</td>
<td>50 sccm</td>
<td></td>
</tr>
<tr>
<td>Ar pressure</td>
<td>≈ 1.5 mTorr</td>
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<tr>
<td>Substrate angle</td>
<td>45 deg</td>
<td>To Ti and Al target surface normals</td>
</tr>
<tr>
<td>Ti target to Al target angle</td>
<td>90 deg</td>
<td>Angle between surface normals</td>
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<tr>
<td>Ti target to sample distance</td>
<td>0.254 m</td>
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</tr>
<tr>
<td>Al target to sample distance</td>
<td>0.185 m</td>
<td></td>
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<tr>
<td>Pulse frequency</td>
<td>50 kHz</td>
<td></td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>50 %</td>
<td></td>
</tr>
</tbody>
</table>
O2 FLOW AS A FUNCTION OF PRESSURE PARAMETERIZED BY POWER BALANCE

AlOx Power/TiOx Power: Oxygen Flow versus Pressure

- Oxygen Flow (SCCM) vs. Oxygen Partial Pressure (mTorr)
- Curves for different power combinations:
  - 1950 W/50 W
  - 1333 W/667 W
  - 1000 W/1000 W
  - 667 W/1333 W
  - 50 W/1950 W
EXPERIMENTAL RESULTS

+ Deposited films with $1.7 < n < 2.3$
  by pulsed dual magnetron reactive co-sputtering with partial pressure control

+ Showed variation of index of refraction with reactive gas partial pressure

+ Showed variation of deposition rate with reactive gas partial pressure

+ Let’s look at the data …
Ti 1333 Watts, Al 667 Watts

Deposition Rate (Ang./sec)

Oxygen partial pressure (mTorr)
CONCEPTUALLY: DC-LIKE SPUTTERING FOR DMS SYSTEMS

AE AMS
DC Power Supplies

AE DMS
Dual Magnetron Sputtering Accessories

Optimized Bi-Polar Waveform for Dual Magnetron Sputtering Applications
WHY PULSED DC?

• The basics:
  – Creates pulsed quasi-DC conditions
  – Enables reactive sputtering in single magnetron system
  – Prevents or greatly reduces arcing (by reversing voltage)
  – Minimizes arc energy (by reversing voltage)

• And…
  – Provides higher ion energies to the substrate than DC sputtering
  – Enables control of some film properties and performance
BASELINE WAVEFORM

For voltage read back:
AE DMS uses voltage in this interval
⇒ represents quasi-DC discharge voltage

- Turn-on
- End boost
- Turn-off
- Dead/Clamp time

CURRENT:
Fast slew rate and higher start up threshold are desired

V boost
Process voltage

AE DMS uses voltage in this interval
⇒ represents quasi-DC discharge voltage

v (V)
i (A)
CURRENT SOURCE PULSED DMS SYSTEMS
RUN ALL COMMERCIAL PROCESSES

+ SiOx
+ SiNx
+ TiOx
+ AlOx
+ ZnOx
+ SnOx
+ Metal barrier layers
+ Etc…
DMS SYSTEMS

- Power, current, or voltage regulation
- Modular and scalable
- Optimal installation (rack or near/on cathode lid)
- Frequencies from 500 Hz to 50 kHz (fixed, user-selectable)
- Independent power regulation for each magnetron
- CEX (phase synchronization)
REACTIVE DMS CO-SPUTTERING: CONCLUSIONS

+ Modeling shows variation of composition and deposition rate with reactive gas partial pressure as well as power balance

+ Pulsed current source DMS supplies and reactive sputtering working point control are enabling technologies for DMS reactive co-sputtering
ROLL TO ROLL CO-SPUTTERING: INSIGHTS ON POWER AND CONTROL

AIMCAL Web Coating and Handling Conference

David Christie