Substrate Thermal Heating Rates as a Function of Magnetically Controlled Plasma Impedance on Rotary Cathodes

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Abstract: The thermal budget for web based polymer substrates is a critical parameter to consider whenever depositing sputtered thin films. Electron heating and bombardment of high energy particles are commonly thought to be the primary source of substrate heating in a rotary magnetron sputtering process. The rate of energy transfer between the target and substrate as a function of plasma impedance is explored using a remotely adjustable magnet bar to control the positions of the magnets relative to the target surface.

Introduction: When sputtering on polymer web based substrates with rotary cathodes, manufactures often find themselves needing to push substrate thermal budgets to the very limits. Reductions in energy transferred to substrates during a deposition process even when modest can end up determining if a process is possible or not. New advancements in rotary cathode magnet bar technology now allows for the modification of the magnetic field strength on the surface of the target during the sputtering process. This new capability enables the control the plasma impedance throughout the lifetime of the target material. Changes in the cathode impedance over time create measurable changes in the amount of energy transferred to the substrate and those changes are the focus of this paper.

Theory: In addition to making local magnetic changes to compensate for sputtering uniformity issues the global position of entire magnet bar can be modified to control the thermal heat transfer to the substrate over the lifetime of the target. Modifying the plasma impedance and the net energy of the active species in the plasma should change the energy transfer rate to the substrate. The primary sources for heat transfer to the substrate are thermal radiation, bombardment from gas species that were heated by the sputtering process, and electron bombardment. Electrons are primarily going to be directed to the anode. Plastic substrates are insulators so in this analysis the substrate hearing from electrons is assumed to be insignificant.

Plasmas are assumed to have a mostly neutral net charge and thus would contain appropriately the same number of electrons and ions. The energy transferred to the ions and electrons is going to be a function of how many of each species are created for a set power level. If the plasma impedance is low then the discharge current will be very high and a lot of species will be created but the net energy transferred to them will be low. If the plasma impedance is high then the discharge current will be lower and less species will be created but the net energy transfer to each species will be much higher. The sputter yield of the target material is a function of the ion energy and directly affects how much energy can be left in an ion after collision with the target material. For sputter yields less than 1, more than one ion is required to impact a target atom before sputtering occurs. When the ion energy and sputter yield energy have a large mismatch then the ions are left with more energy after sputtering has occurred and they are no longer ionized. The energy of the hot gas species left over from the sputtering process is also going to be a function of the process pressure since they have to travel from the target surface to the
substrate. The more collisions that the hot gas species make with lower temperature gas species before they reach the substrate the cooler they will become. These assumptions can be used to create a process approximation for a constant deposition power:

\[
E_{Active \, Species} \propto \frac{V_{Cathode}}{SY + P}
\]

The energy of the ions in the process is proportional to voltage of the cathode and the sputter yield is proportional to the ion energy. The energy transferred to the sputtered species would also follow the same process approximation:

\[
E_{sputter \, flux} \propto \frac{V_{cathode}}{SY + P}
\]

For an aluminum sputtering process with a cathode voltage range of 400V to 470V at a constant pressure the energy of the sputter flux and active species would change as shown in the following graph.

Since the energy approximations equations are identical for the sputter flux and the active gas species the total energy change as a function of voltage should be:

\[
E_{f(V)} \propto 2 \times \frac{V_{cathode}}{SY}
\]

This means that the total change in energy delivered to the substrate as a function of the cathode voltage for a aluminum sputtering process with a voltage range of 400V to 470V should be roughly 7.2%.

**Testing Procedure:** To determine if the energy transfer to a substrate would change as a function of the plasma impedance a water cooled copper plate was set up in the place of a substrate and the a RAM Bar was used to adjust the 1110mm long QRM magnet bar position from the surface of the substrate. The water cooled plate was 200mm wide and had a ¼” copper water cooling trace located on the backside of the plate. In the very center of the plate both horizontally and vertically a thermocouple was placed to record the temperature of the plate. Additional thermocouples were used to measure the input and output water temperatures for the plate and the cathode. Flow meters were also used to accurately control the water flow rate through the cathode and the water cooled plate.
The 1110mm long monolithic aluminum target was run with a DC power supply at a power level of 15kW at 4mTorr with argon and with 62LPM of cooling water flowing through the target tube. The flow rate through the copper cooling line on the copper plate was 1.25LPM. The RAM bar was adjusted from the closest position to the target (20mm) to the furthest position away from the target surface (0mm). The power supply was able to log the voltage and current while a separate logging program was used to log the thermocouple temperatures.

**Results:** The calculated power being removed from the copper plate at 400V (20mm position) averaged out to 190W and the 470V (0mm position) averaged out to 140W as shown in figure 3. These results are opposite of the hypothesis and are at direct odds with the thermocouple readings from the copper plate as shown in figure 4. In figures 3 and 4 the green boxes indicate when the RAM bar was set to 20mm, the yellow boxes indicate when the magnet bar was actively moving from 20mm to 0mm, and the red boxes indicate when the RAM bar was at 0mm.
The two readings being at odds with each other suggested that there must be another driving effect. When the magnet bar moves from the 20mm to the 0mm position the location of the erosion zone where the sputtering takes place on the surface of the target tube moves. This movement changes where the sputtered particles are distributed and can reduce the number of sputtered particles that end up on the copper plate. To figure out the approximate sputter angle and deposition profiles the magnetic field was modeled to determine the location of the plasma on the target surface and then the sputter flux distribution was modeled to determine the collection efficiency. The results of the sputter flux collection efficiency study are shown in figure 5.

The sputter flux collection efficiency is decreasing as a function of the magnet bar position. A decrease in the sputter flux collection efficiency on the copper plate would decrease the total power transferred to the plate. When the thermal power removed from the copper plate data is multiplied by the sputter flux collection efficiency the temperature results from the copper plate agree with the corrected power removal data as shown in figure 6.

**Conclusion:** When correcting the data for a 100% sputter flux collection efficiency the resulting change in power is 7.6% for a 14.9% change in voltage much like the proportionality equations assumed in the hypothesis.

\[ E_f(V) \propto 2 \times \frac{V_{\text{cathode}}}{SV} \]

\[ P_{\text{Total}} = \frac{P_{\text{Removed}}}{CE\%} \]
Global changes in the RAM Bar’s position can be used to control the amount of energy delivered to the substrate over the lifetime of the target materials. In addition to maintaining constant temperatures, the energy transfer rate to the substrate can be tuned to allow the user to form specific temperature sensitive coating properties for materials such as ITO. Lastly controlling the deposition temperature can allow process engineers to maximize the deposition rate for a process by enabling them to deliver the maximum deposition power possible without exceeding the substrate’s thermal budget.