Title: Reactive High Power Impulse Magnetron Sputtering with Positive Cathode Reversal Using a Rotary Magnetron

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This work investigates the novel sputtering technology of HiPIMS with positive cathode reversal (Positive Kick^{TM}), herein referred to as HiPIMS+CR, on rotary magnetrons for reactive sputtering. As compared to DC, HiPIMS provides the advantage of higher ion fractions at the target[1] and at the substrate[2]. As compared to standard HiPIMS, positive cathode reversal allows for control of the ion energy at the substrate, allowing for tuning of film properties such as stress as well as increased deposition rate overall[3]. In this work, the deposited film is aluminum nitride (AlN), which has applications in resonator devices, piezoelectric devices, and as a thermal spreader for heat management.[4] Many large-area industrial coating processes utilize rotary magnetrons instead of planar magnetrons, as they offer increased target utilization and higher power throughput due to better heat removal. It has been shown with DC that rotary magnetrons offer some benefits and differing deposition physics when compared to planar targets because of the target shape and rotation.[5] This work characterizes HiPIMS+CR applied to a rotary magnetron with target length of 430mm and target outer diameter of 145mm, identifying where the rotary configuration may offer benefit through a research-scale system.

HiPIMS+CR AlN reactive sputtering in the rotary magnetron configuration is characterized by both plasma diagnostics and film characteristics. To characterize the plasma, a Hiden Analytical PSM probe was used to gather time and energy resolved spectra of each ion species at the substrate location versus various plasma parameters. Whether the target was rotating or not rotating affected both the Al^+ and N^+ ion counts without changing the Ar^+ and N_2^+ counts (see Figures 1 and 2), where the N^+/Al^+ ratio increased by over 50% by simply rotating the target and keeping all other process parameters constant. This indicates target rotation does affect the system and adds another variable to adjust film properties such as stoichiometry. Hysteresis curves were generated at various target rotation speeds to understand how the poisoning point was affected by rotation speed in HiPIMS+CR.

AlN film characterization will be presented across varying HiPIMS+CR process recipe parameters, as well as target rotation speed, for the critical characteristics of the applications of AlN. Characteristics measured include film stoichiometry (including oxygen contamination), crystal structure and orientation measured with X-ray diffraction (XRD), and film density

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[1] J. Bohlmark *et al.*, "The ion energy distributions and ion flux composition from a high power impulse magnetron sputtering discharge," *Thin Solid Films*, vol. 515, no. 4, pp. 1522–1526, Dec. 2006, doi: 10.1016/j.tsf.2006.04.051.
[2] J. McLain *et al.*, "Linear magnetron HiPIMS high deposition rate magnet pack," *Vacuum*, vol. 155, pp. 559–565, Sept. 2018, doi: 10.1016/j.vacuum.2018.06.023.
[3] B. Wu *et al.*, "Cu films prepared by bipolar pulsed high power impulse magnetron sputtering," *Vacuum*, vol. 150, pp. 216–221, Apr. 2018, doi: 10.1016/j.vacuum.2018.01.011.
[4] C. L.A. Cunha, T. C. Pimenta, and M. Amorim Fraga, "Development and Applications of Aluminum Nitride Thin Film Technology," in *Thin Films - Deposition Methods and Applications*, D. Yang, Ed., IntechOpen, 2023. doi: 10.5772/intechopen.106288.
[5] R. De Gryse, J. Haemers, W. P. Leroy, and D. Depla, "Thirty years of rotatable magnetrons," *Thin Solid Films*, vol. 520, no. 18, pp. 5833–5845, July 2012, doi: 10.1016/j.tsf.2012.04.065.

measured with X-ray reflectivity (XRR). Thermal conductivity measurements are also made using time-domain thermoreflectance (TDTR).

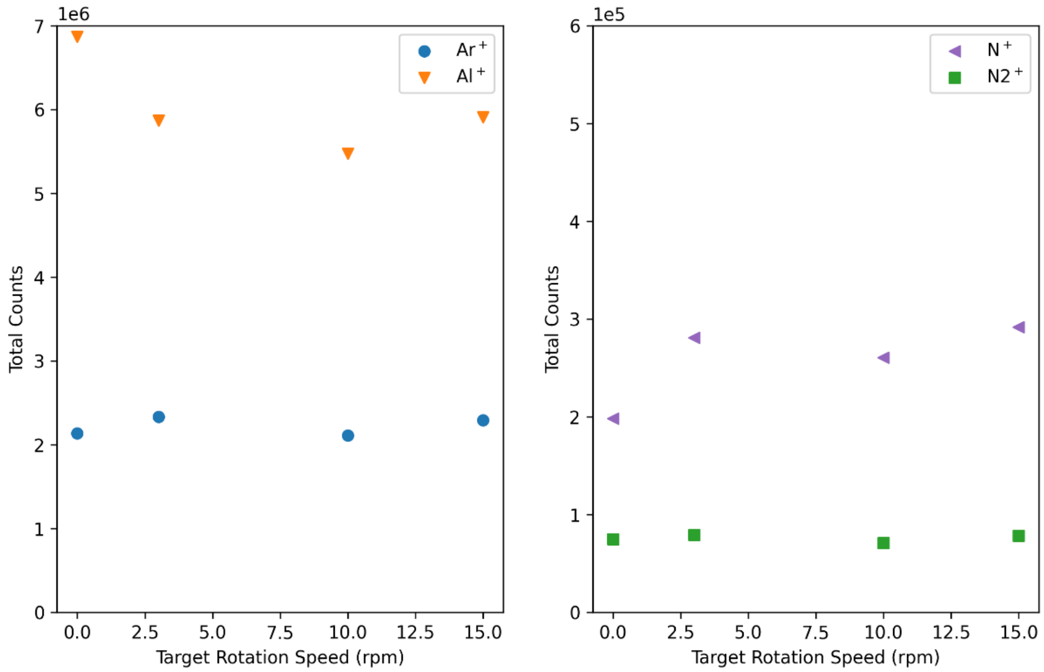

Figure 1. Total ion counts collected over the course of a HiPIMS+CR pulse versus the target rotation speed. The two windows have different scale values.

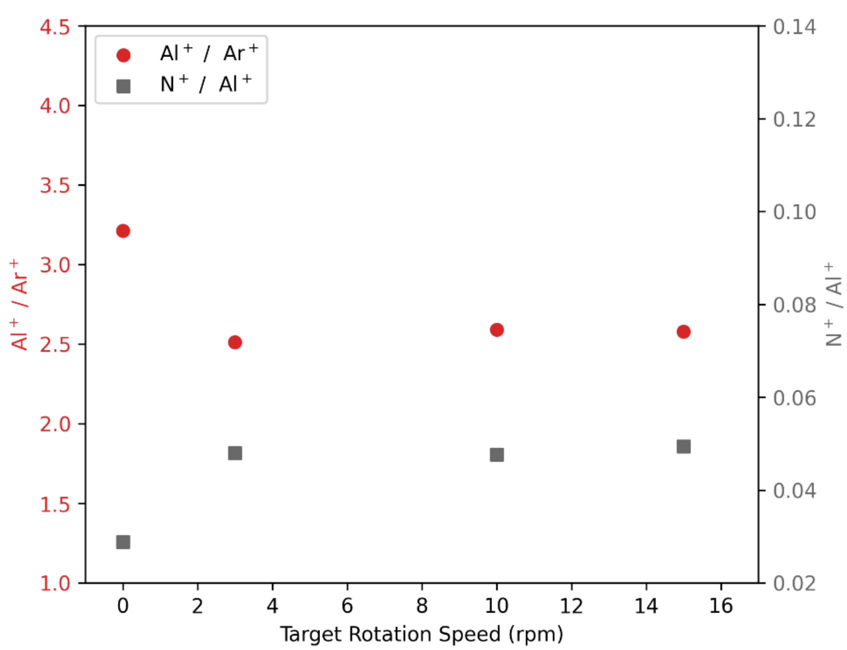

Figure 2. Ratios of total counts collected over a HiPIMS+CR pulse for Al^+/Ar^+ and N^+/Al^+ versus the target rotation speed.