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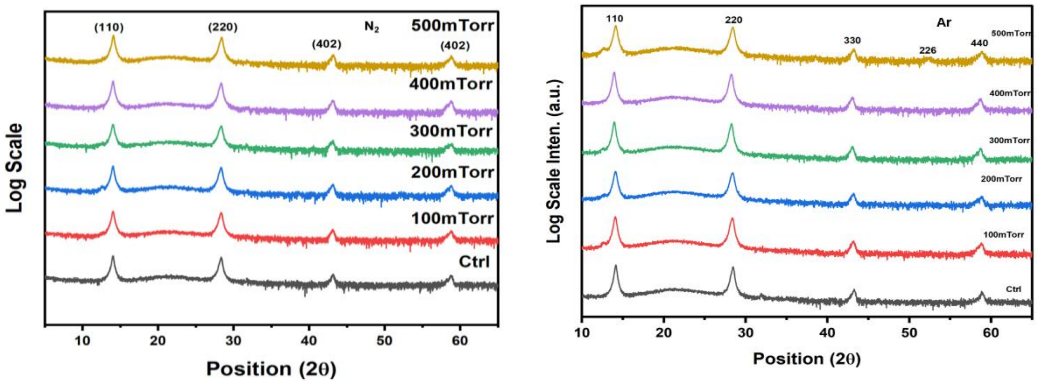

Figure 1. XRD patterns of $MAPbI_3$ films deposited under varying N_2 and Ar background pressures (control represents active vacuum) during RIR-MAPLE processes. All films exhibit the characteristic tetragonal reflections dominated by the (110) and (220) planes, confirming the perovskite structure across the deposition conditions. Films deposited under N_2 generally exhibit improved peak definition, while Ar-grown films demonstrate additional peaks near ~13° for 100, 300, and 500 mTorr, and higher angle reflection (226) at ~53° for the 500mTorr film. These variations suggest atmosphere-dependent modifications in crystallization behavior, preferred orientation, and possible secondary-phase formation associated with stronger plume-scattering effects under Ar environments.

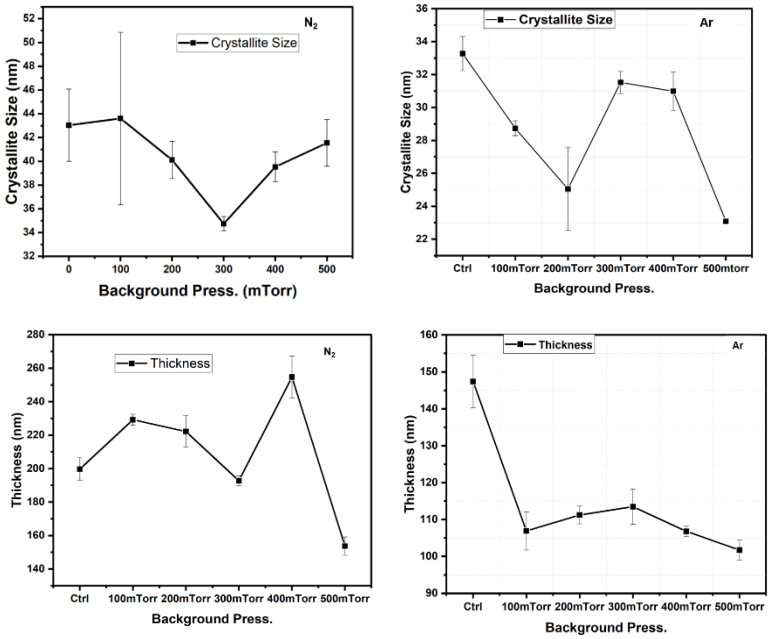

Figure 2. Pressure-dependent evolution of crystallite size and film thickness for $MAPbI_3$ thin films deposited under N_2 and Ar background environments during RIR-MAPLE growth. N_2-grown films exhibit comparatively larger crystallite sizes and greater thicknesses across most deposition pressures, indicating enhanced precursor retention

and more favorable crystal growth conditions. The N_2 environment also shows maximum film thickness at 400 mTorr, followed by a sharp decrease at 500 mTorr, suggesting the onset of high plume scattering. However, Ar-grown films generally demonstrate reduced thickness and smaller crystallite sizes, consistent with enhanced collisional scattering and reduced precursor flux reaching the substrate. Crystallite size was calculated using the first two diffraction peaks, and error bars represent the standard deviation from three independent measurements, while thickness values correspond to the average of four measurements for each sample.