Supplementary Information

Precise Ion Energy Control with Tailored Waveform Biasing for Atomic Layer Etching

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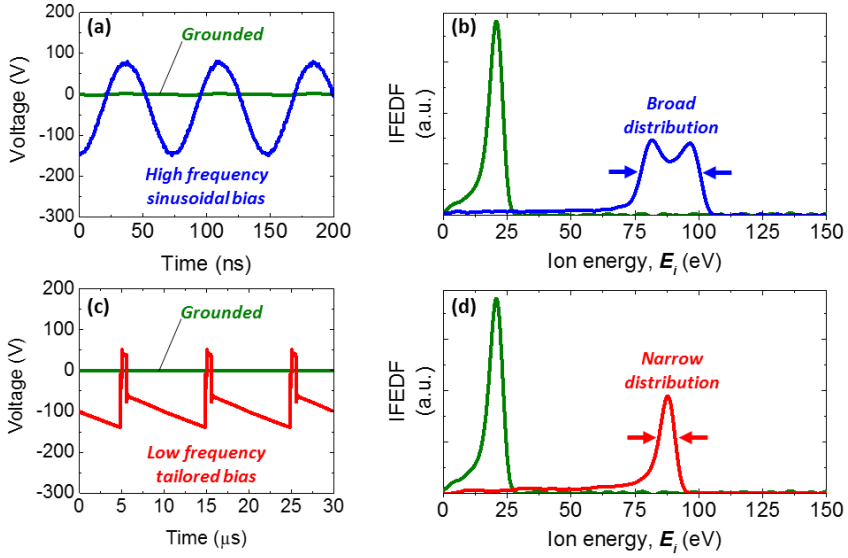

Figure 1. ***(a), (c)*** *Substrate voltage as a function of time and* ***(b), (d)*** *ion flux-energy distribution functions (IFEDFs) for grounded and biased dielectric substrates in an Ar plasma. Substrate biasing was performed using* ***(a), (b)*** *a sinusoidal radio-frequency (RF: 13.56 MHz) voltage waveform that produced a broad, bi-modal IFEDF and* ***(c), (d)*** *a low frequency (100 kHz) tailored voltage waveform that produced a narrow, mono-modal IFEDF.*

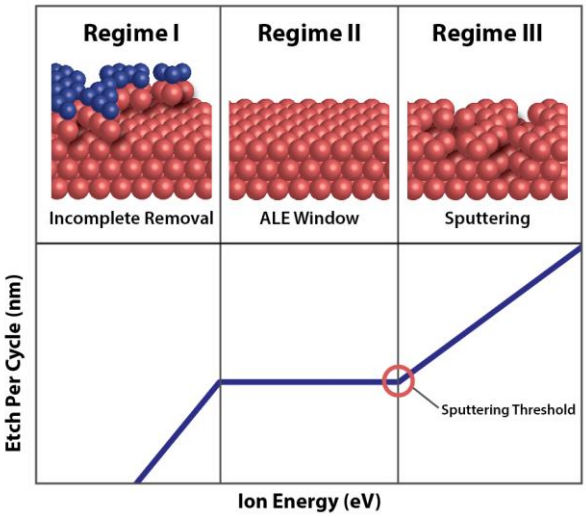

Figure 2. Schematic representation of the idealized etch rate per ALE cycle as a function of the ion energy depicting the ion energy window for an anisotropic plasma ALE process. In regime II, the ion energy lies below the upper limit of the ion energy window (i.e. sputter etch threshold of the target material) such that only the modified surface layer is completely removed. These thresholds can be accurately measured by sputtering materials using ions with narrow energy distributions obtained by tailored waveform biasing. In regime III, the ion energy exceeds the sputter etch threshold, so all of the modified surface layer is removed as well as some of the underlying bulk material. (adapted from Ref. 1 and 2)

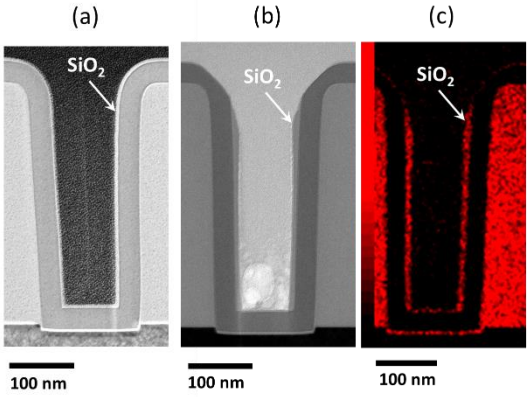

Figure 3. Cross-sectional TEM and EDX images of 3D trench nanostructures where the outermost layer is a thin film of SiO_2 ***(a)*** *before any sputter etching and* ***(b), (c)*** *after sputter etching using 100 eV ions generated by applying tailored waveform biasing to the substrate in an Ar plasma at 200 W ICP power and 3 mTorr pressure. EDX elemental mapping of oxygen is shown for the TEM image in* ***(b)*** *after sputter etching. The presence of a thicker SiO_2 layer at the vertical sidewalls compared to the horizontal top and bottom surfaces of the trench in images* ***(b)*** *and* ***(c)*** *demonstrate how tailored waveform biasing enables anisotropic plasma etching.*

[1] Kanarik *et al., J. Vac. Sci. Technol. A* **33**, 020802 (2015)

[2] Berry *et al., J. Vac. Sci. Technol. A* **36**, 01B105 (2018)