## Improved properties of the atomic layer deposited Ru electrode for dynamic random-access memory capacitor using discrete feeding method

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**Figure S1.** XP spectra of the Ru films after the *in-situ* surface etching (~1 nm) grown by (a) Conventional ALD, (b) DFM-ALD, and (c) Sputtered.



**Figure S2.** The distribution of the grain size of the  $TiO_2$  films (~24 nm) on the Ru films grown via different conditions.



Figure S3. TEM-EDS images of Pt/TiO<sub>2</sub>/Ru capacitors, where the Ru film was grown by

(a) conventional ALD, (b) DFM-ALD, (c) sputtering.



Figure S4. Enlarged GAXRD patterns of 24 nm-thick TiO<sub>2</sub> films ranging from 25° to 30°.



**Figure S5.** Cross-sectional TEM images (50 k) of Pt/TiO<sub>2</sub>/Ru, where the Ru film was grown by (a) conventional ALD, (b) DFM-ALD, (c) sputtering. (scale bar: 100 nm)



**Figure S6.** Surface morphology of TiO<sub>2</sub> films (~2.5 nm and ~ 4 nm-thick) on the Ru substrates deposited by different methods (scale bar: 200 nm).

Figure S6 shows SEM images of thin TiO<sub>2</sub> films (~2.5 and ~4 nm), corresponding to the initial growth stage of TiO<sub>2</sub> films, on the different Ru substrates. Also, roughness values obtained by AFM analysis were indicated in each SEM image. Several local protrusions corresponding to new grains of TiO<sub>2</sub> were formed on the conventional ALD and sputtered Ru films as the TiO<sub>2</sub> film became thicker. The coarsening of the new grains was severe in the conventional ALD method, which might be caused by the higher surface roughness of the Ru film. However, the matrix regions (black boxes in the images) showed similar surface morphologies on each Ru film. Unlike the conventional ALD and sputtered Ru films, the TiO<sub>2</sub> film grown on the DFM-ALD Ru film showed smooth surface morphology without local protrusions. This finding suggests that the local epitaxial growth of the TiO<sub>2</sub> could be retained up to a thicker thickness on the DFM-ALD Ru film. These results indicate that the characteristics of Ru substrates substantially affected the epitaxial growth behavior of TiO<sub>2</sub> film.



Figure S7. (a) I-V curve of  $Pt/TiO_2$  (24 nm)/Ru capacitor. (b) C-V curve of  $Pt/TiO_2$  (24 nm)/Ru capacitor.