**Supplementary Figure S1 | TEM and STEM characterization.** (a) STEM image of PZT/SRO/DSO heterostructure. The scale bar corresponds to 100 nm. (b) Selected area electron diffraction (SAED) pattern showing a single crystal c-oriented film. The ratio c/a is measured to be 1.05. The g=202 vector used to form the diffraction contrast images in this work is circled. (c) HAADF image depicting the epitaxial PZT/SRO interface. The scale bar is 1 nm.
Supplementary Figure S2 | Energy band diagrams of Tungsten/PZT/SRO. (a) Energy band diagram at thermal equilibrium of tungsten/PZT/SRO heterostructure, where \( V_{b1} \) and \( V_{b2} \) are the built-in potentials for the contacts, SRO/PZT and tungsten/PZT, respectively. (b) Distribution of built-in electrical field in such a tungsten/PZT/SRO structure. (c) The built-in potential profile, assuming that the PZT is fully depleted of carriers. (d) The corresponding built-in electrical field. The maximum values are \( E_{m1}=39.6 \) MV/m at the interface of SRO/PZT and \( E_{m2}=47.6 \) MV/m at the interface of tungsten/PZT.
Supplementary Figure S3 | Tip effect and electric field distribution. (a) The distribution of external electrical field in PZT with the tip diameter ~50 nm and bias ~ -4.8 V. The Scale bar is 50 nm. (b) The corresponding potential profiles of the total electric field directly below the tip under zero bias (black), and under the negative (0.4 V – red) and positive (-4.8 V – blue) field nucleation biases.