Supplementary information

Substantially improved energy density of SrTiO$_3$ thin film by cyclic cooling-heating and interfacial blocking effect

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Fig. S1. The anodic oxidation reaction model of the SrTiO$_3$ film with Al electrode.

Fig. S2. Weibull plots for Au and Al electrode.
Fig. S3 Observation of breakdown process for Au electrode with an optical microscopy system.

Fig. S4 (a) XRD pattern of generated Al₂O₃ layer. (b)–(c) Selected path of EDS for linear scanning

S5. According to the TSDC theory, dipole polarization can be described with a single relaxation with the classical Debye model and thermally stimulated depolarization process was shown in equation (S1). The corresponding parameters of T is the absolute temperature, p is polarization intensity, β is the heating rate, k is Boltzmann constant, τ₀ is the relaxation time at infinite temperature and H is the activation energy.

\[
I(TSDC) = -\beta \frac{dp(T)}{dT} = \frac{p_0(T_0)}{\tau_0} \exp \left( -\frac{H}{kT} - \frac{1}{\beta \tau_0} \int_{T_0}^{T} e^{-\frac{H}{kT}} dT \right) \]  \hspace{1cm} (S1)

The characteristics of dipole polarization can be figured out clearly in equation (S3) and (S4) which originated from derivation process in equation (S2). Equation (S3)
displays that peak temperature \(T_m\) is independent of poling field \((E)\) while equation (S4) exhibits a linear relation of peak current \(I_m\) with the poling field \((E)\). For the terms in the pre-exponential factor in equation (S4), \(N\) is the dipole density, \(\mu\) is dipole moment, \(E\) is poling field, and \(T_b\) is poling temperature.

\[
\frac{dI(TSDC)}{dT} = \frac{P_0}{\tau_0} \exp\left(-\frac{H}{kT}\right) \times \frac{1}{\beta \tau_0} \int_{T_0}^{T} e^{\frac{-H}{kT}} dT \times \left(\frac{1}{\beta \tau_0} - \frac{1}{\beta \tau_0} e^{\frac{-H}{kT}}\right) = 0 \quad (S2)
\]

\[
\frac{H_0}{kT_m^2} = \frac{1}{\beta \tau_0} e^{\frac{-H_0}{kT_m}} \quad (S3)
\]

\[
I_m = \frac{N \mu^2 E}{3kT_b \tau_0} \exp\left(-\frac{H_0}{kT_m} - \frac{1}{\beta \tau_0} \int_{T_0}^{T} e^{\frac{-H_e}{kT}} dT\right) \quad (S4)
\]

The total charge of ionic polarization should accord with the form of sinh function, as shown in equation (S5), where \(q\) is the ionic charge, \(N\) is the density of the moving ions and \(a\) is the separation.

\[
Q_{ISC} = p(t_b) = \frac{1}{\beta} \int I(T)dT = Q_0 \sinh\left(\frac{qaE_b}{2kT_b}\right) \quad (S5)
\]