Center for Energy Efficient Electronics Science

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Ferroelectric Switching Dynamics

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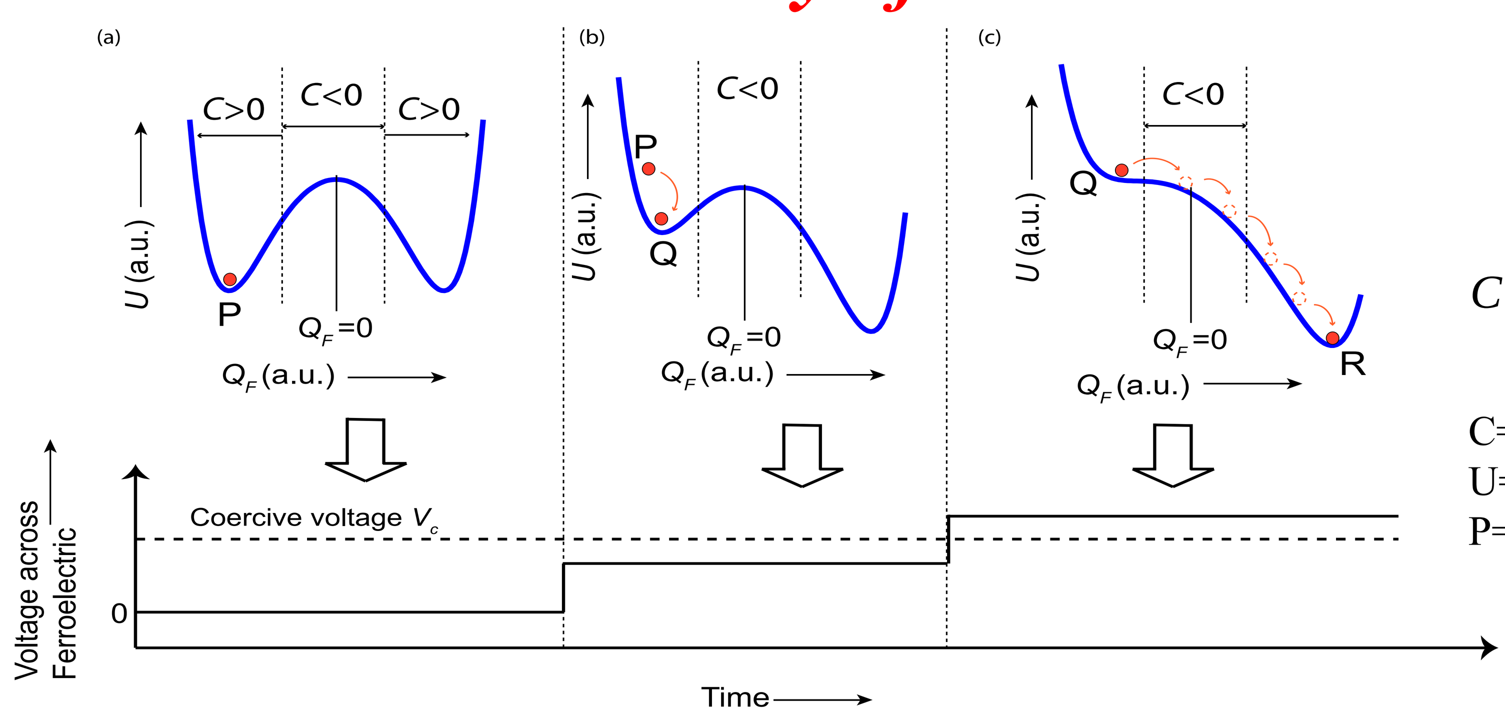
Abstract

Negative capacitance effect in ferroelectric capacitors have recently been directly observed in ferroelectric capacitors via time dynamic measurements during polarization switching. However, the effect of switching dynamics, specifically that of a multi-domain switching on the negative capacitance is not yet fully understood. In this work, we study the multi-domain switching dynamics by numerically solving the Landau-Khalatnikov equation. Multi-domain switching is modeled by parallel connected ferroelectric capacitors with varying internal resistances. The results suggest that the negative capacitance time scale becomes much shorter when the switching occurs through multiple domains as opposed to in the single domain fashion.

Theory of Negative Capacitance

Landau Theory of Ferroelectrics



Capacitance:

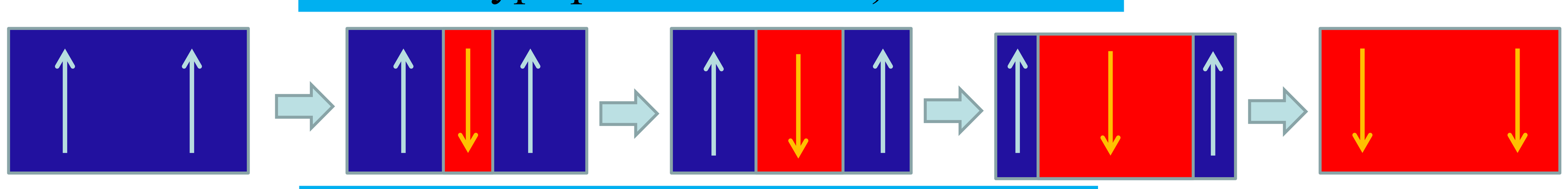
$$C = \left[\frac{d^2U}{dP^2}\right]^{-1}$$

C= Capacitance
U= Stored energy
P= Stored charge

The negative capacitance state is unstable. The negative capacitance states can be accessed during ferroelectric polarization switching.

Switching Mechanism in Ferroelectric

Domain Nucleated Switching (Order disorder type phase transition)



Continuous or Landau type Switching (Coherent Phase transition)

Simulation Ferroelectric Switching Dynamics

Multi-domain switching dynamics numerically simulated using Runga-Kutta-4 method.

Model of Ferroelectric Switching

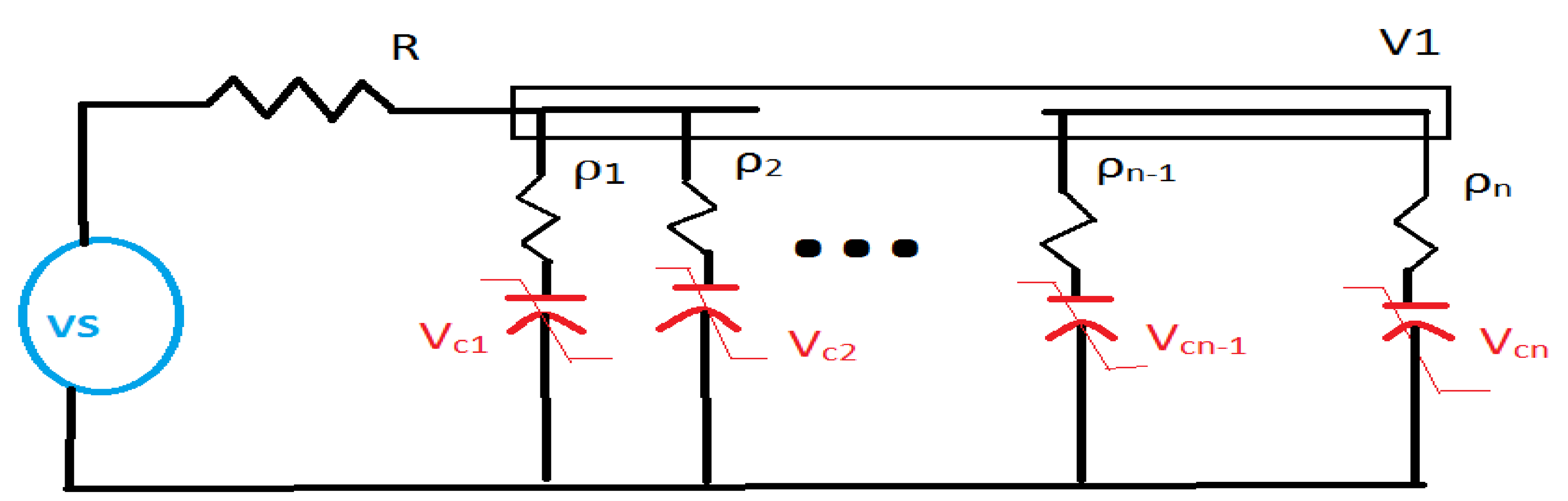
$$U = \alpha Q^2 + \beta Q^4 + \gamma Q^6 - EQ$$

$$V_{ci} = 2\alpha' Q + 4\beta' Q^3 + 6\gamma' Q^5$$

$$\rho \frac{dQ_F}{dt} = -\frac{dU}{dQ_F}$$

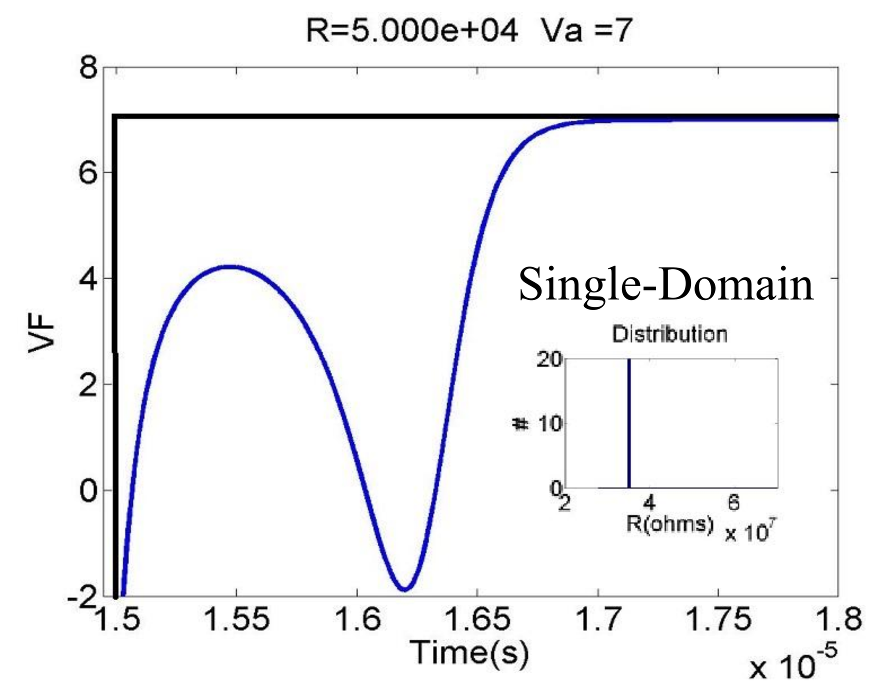
$$V_1 = \frac{Vs + \sum \frac{Vc_i}{\rho_i}}{\frac{1}{R} + \sum \frac{1}{\rho_i}}$$

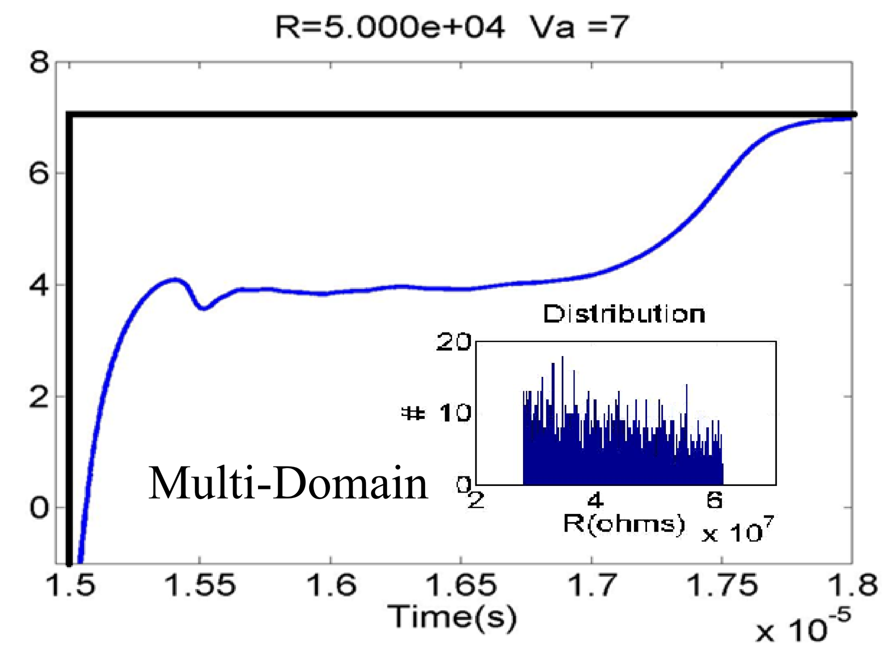
$$Ic_i = \frac{V_1 - Vc_i}{\rho_i}$$

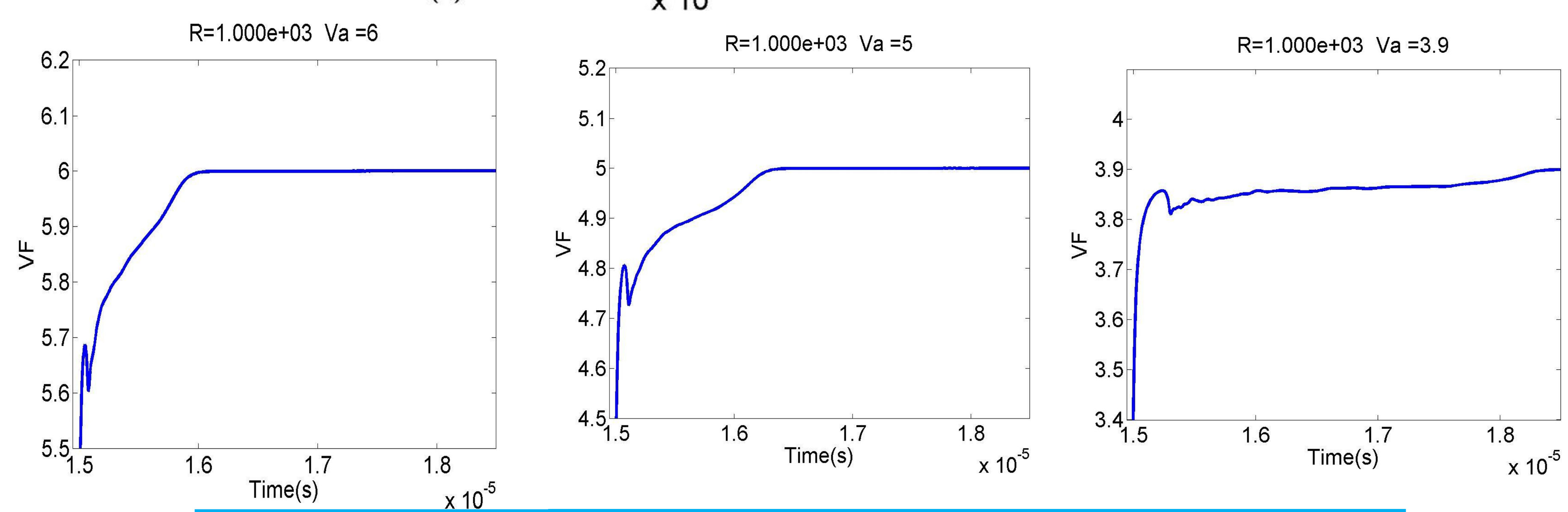


Results and Discussion

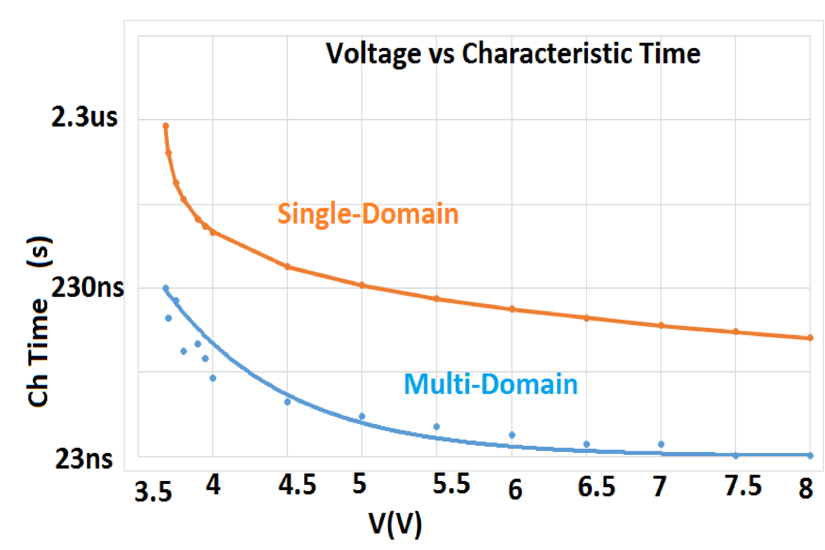
Simulated transient ferroelectric voltage (blue) under applied voltage (black) single value of ρ vs wide normal distribution.

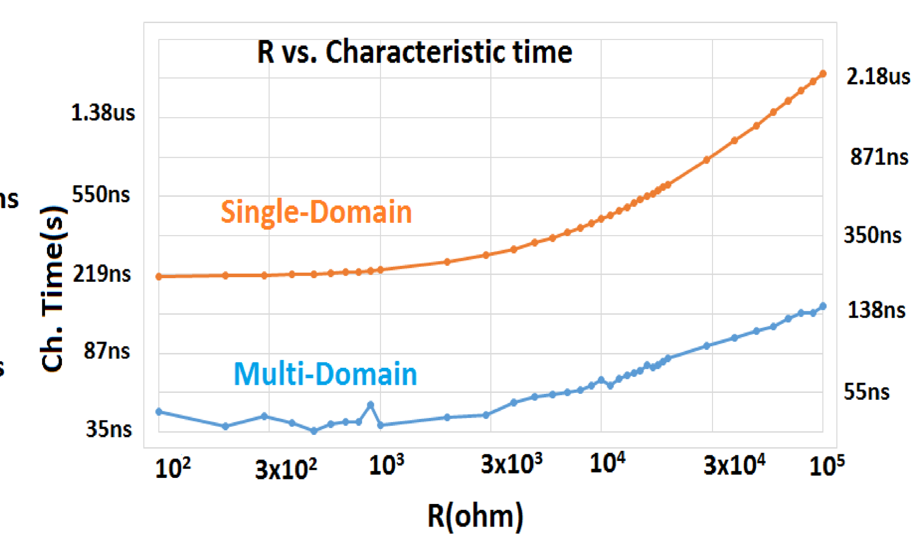






Characteristic negative capacitance transients under applied voltages of 6V, 5V, and 3.9V





Characteristic times from the 1st voltage maximum to the minimum vs. applied voltage and resistance.

Conclusions

- Simulations including switching time variance more closely match experimental measurements
- The observed negative capacitance effect could be much stronger if domain switching times can be homogenized.

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