Center for Energy Efficient Electronics Science

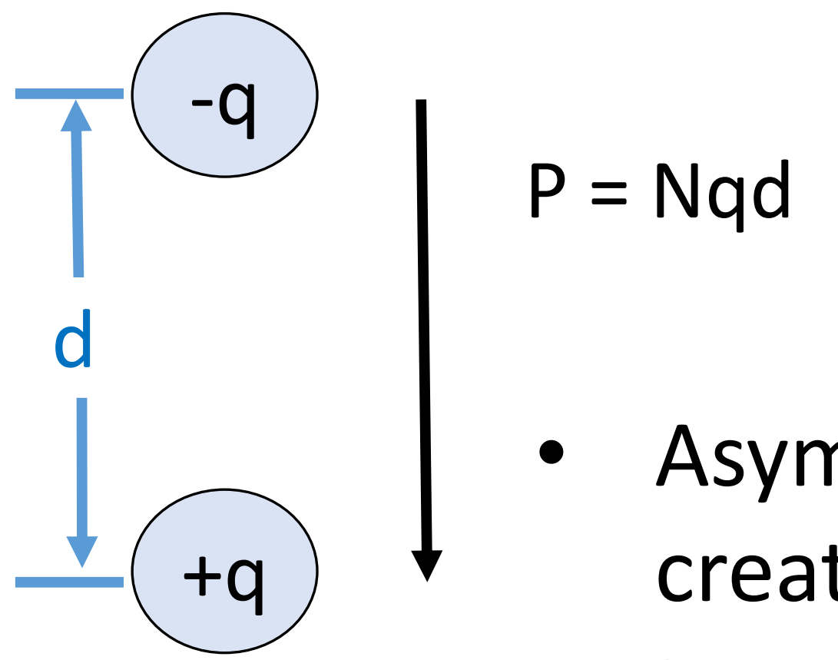
Terahertz Switching in Ferroelectric HfO_2

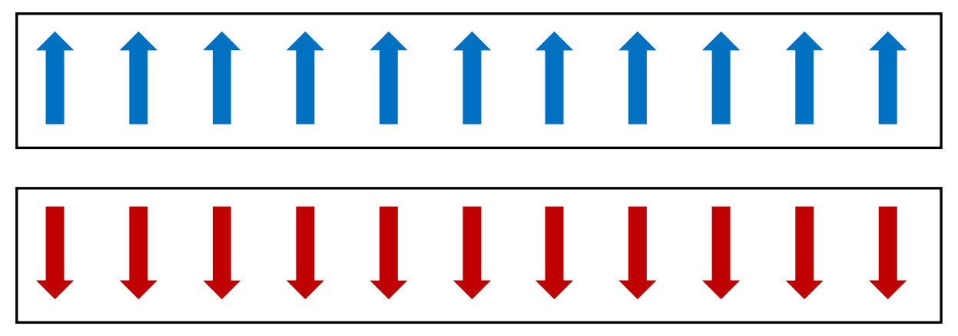
Alexander Rosner[1], Korok Chatterjee[2], and Sayeef Salahuddin[2]
[1]University of Notre Dame, [2]University of California, Berkeley

Abstract

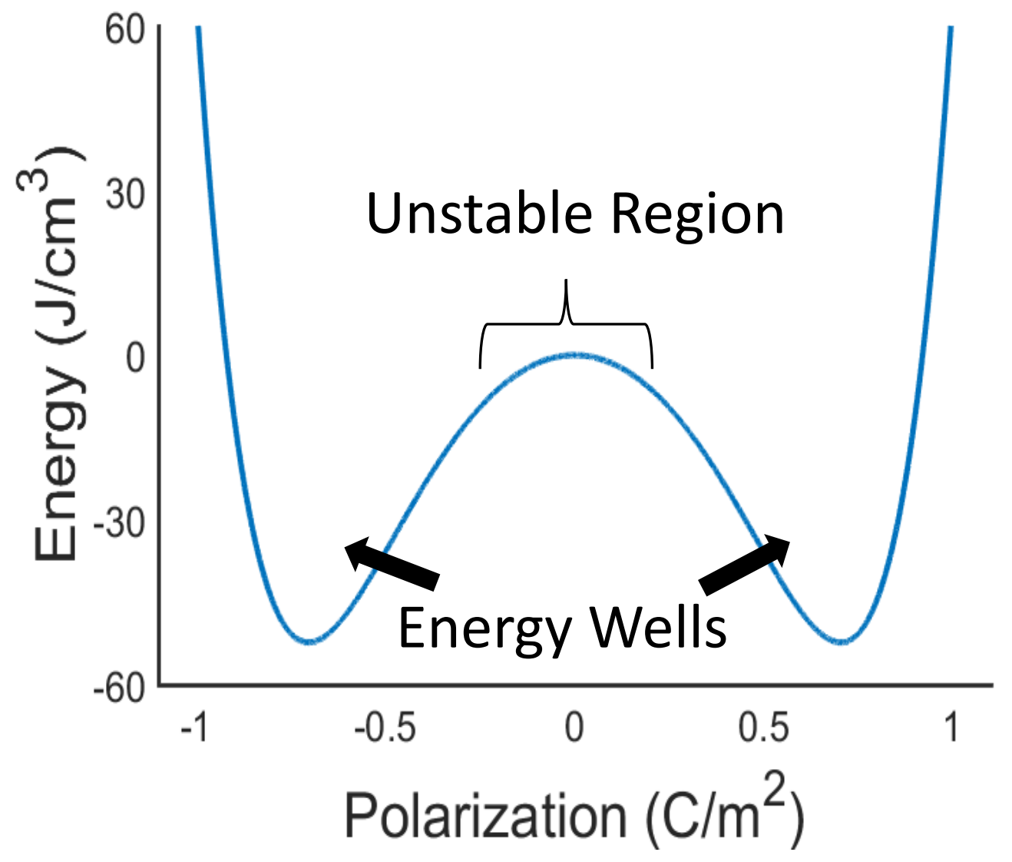
Hafnium Oxide's (HfO_2) compatibility with the CMOS process and its ferroelectric phase make it a desirable material for the gate of a transistor in order to create more efficient memory. However, its response time when it switches polarization may limit its application in certain high-performance devices. By introducing an induction term in the Landau-Khalatnikov equation, which describes the dynamic motion of ferroelectric polarization, we hope to better understand the frequency response of HfO_2 and its limitations. The classical damped oscillator model also can model polarization and be fitted to optical data to determine its coefficients. Together, these two models can predict an internal resistance that determines the fastest switching time of HfO_2.

Ferroelectricity



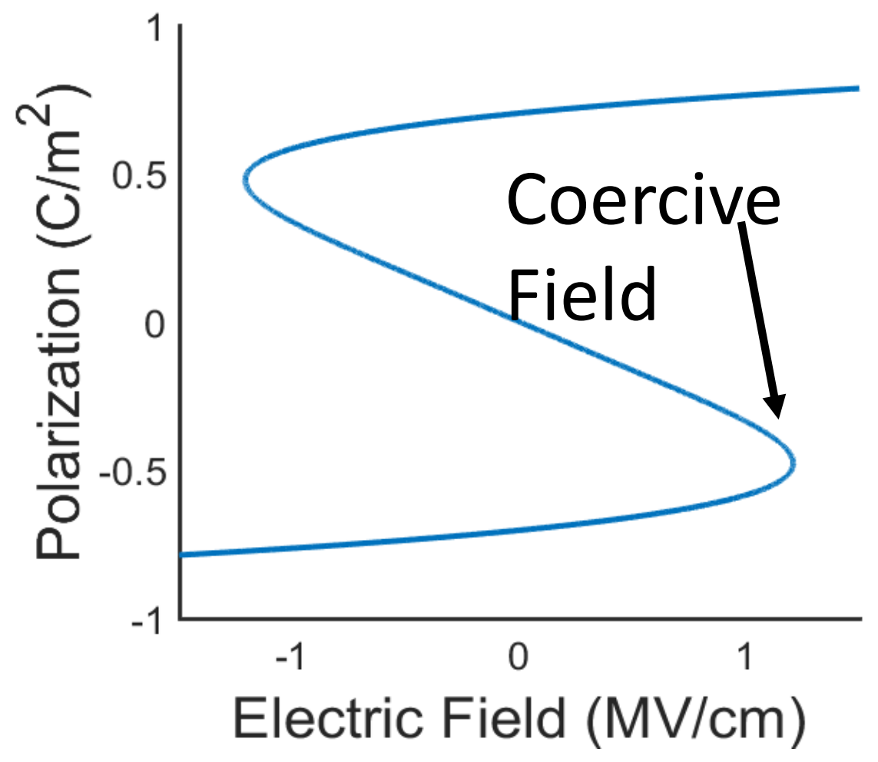


- Asymmetric distortion of molecules creates separation of charge (left). The two polarization states of a ferroelectric result from the two orientations (above).



- Two energy wells represent the two polarization states
- Unstable region is the barrier between the states

- Q = CV C = dQ/dV
- Negative capacitance in unstable region
- Coercive field needed to switch states



Circuit Equations

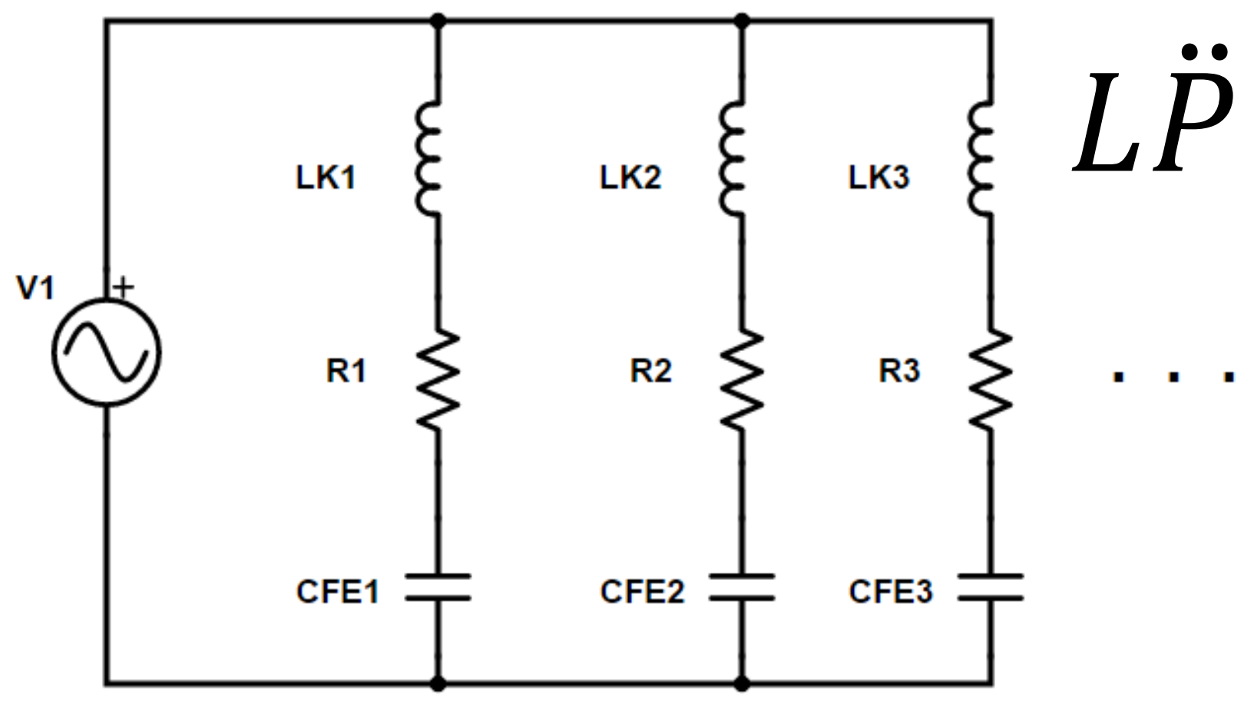
$$F = \alpha P^2 + \beta P^4 + \gamma P^6$$

- The Landau free energy equation gives the capacitance after taking the second derivative and is symmetric with polarization. A, β, and γ are fitted experimentally.

$$L_K = \frac{m t_{ins}}{n q^2 A}$$

- Kinetic inductance is due to the inertia of atoms which resist change in motion. Inductance increases with mass(m) and decreases with higher charge (q) and density (n).

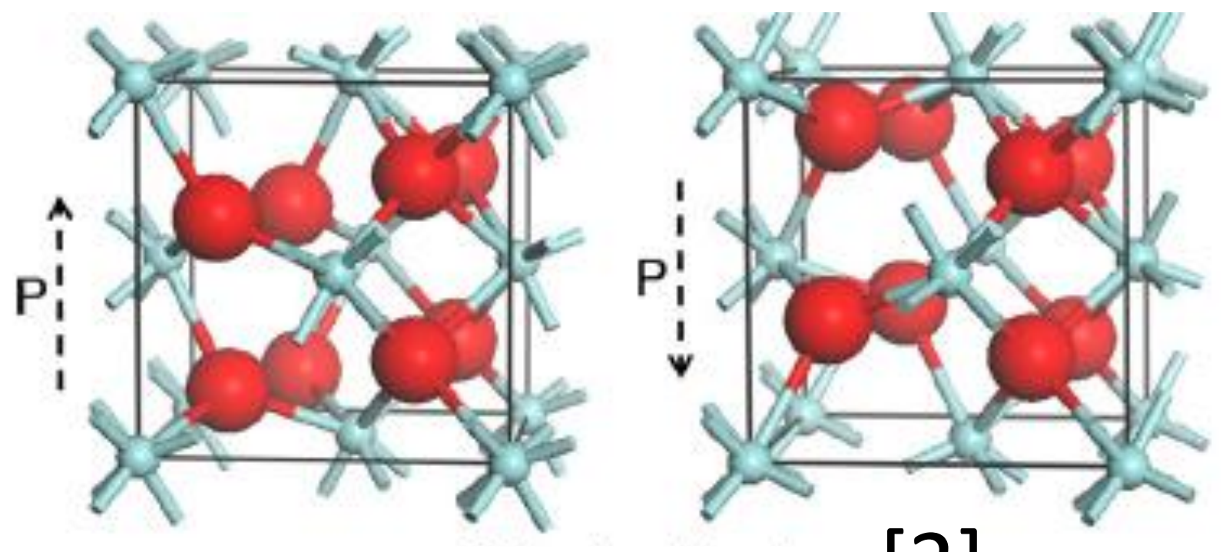
RLC and Damped Oscillator



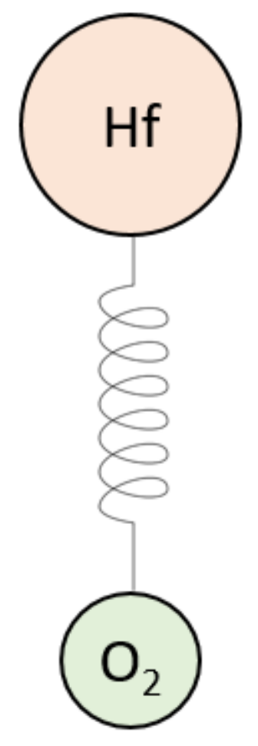
$$L\ddot{P} + \rho\dot{P} + \nabla_P F = E$$

- The LK equation (above) models a ferroelectric as a RLC circuit [1]
- Each series RLC represents a domain

- Displacement of oxygen shows change in polarization state and is the source of kinetic inductance



[2]



$$m\ddot{x} + \beta\dot{x} + kx = eE_x$$

- Classical model of oscillating dipoles. It can be fitted to optical measurements to determine coefficients.
- Predicted mass of 13.5 amu (oxygen has 16 amu) [3]

Conclusion and Future Work

We were able to find the phonon resonance of PZT and determine the maximum allowable resistivity to achieve terahertz switching with the LK equation. Future work includes repeating the procedure with HfO_2 and further investigating parameters controlling the resistivity to evaluate whether our prediction is realistic for a ferroelectric thin film. Success could entail faster switching for ferroelectric transistors.

Alex Rosner
arosner@nd.edu
(480)-278-9365

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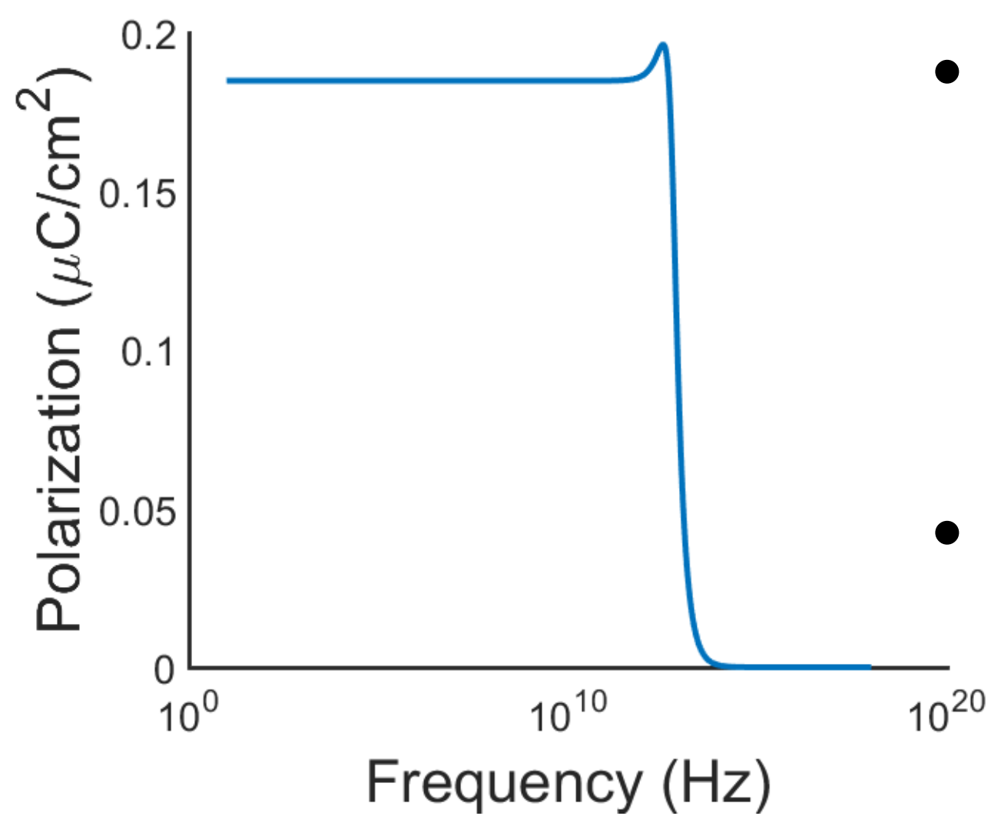
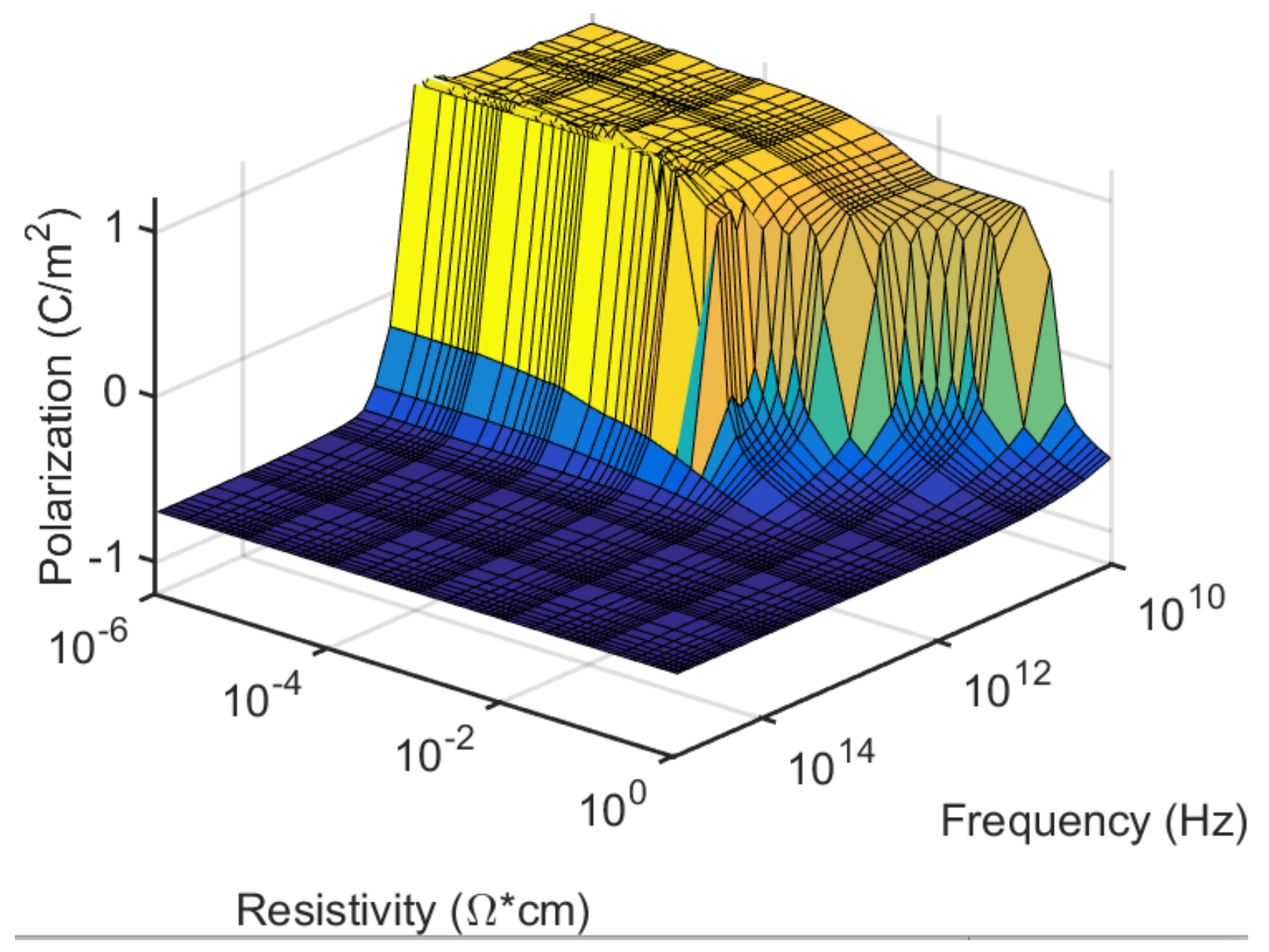
Results



- Frequency response given by the damped oscillator model using fitted parameters.
- Resonance is around 5 THz.

- RLC surface plot showing whether switching is possible for different inputs
- PZT coefficients used because HfO_2's were not available



- Limit of .003 Ω*cm to switch at 1 THz for PZT

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