Ferroelectric Materials Tutorial:
What are we looking for?

Summary

A ferroelectric hysteresis is not a monolithic signal. Its function can be better understood by breaking it into components individually.

- *Proper interpretation of test results cannot occur without an understanding of the underlying physics.*

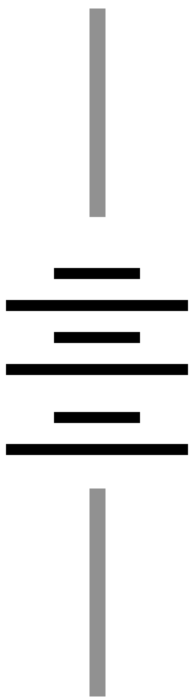
Contents

- What is Capacitance?
- The Component Model of the Ferroelectric Capacitor
- SBT vs PZT
- Component Fatigue
- Imprint
- Test Theory

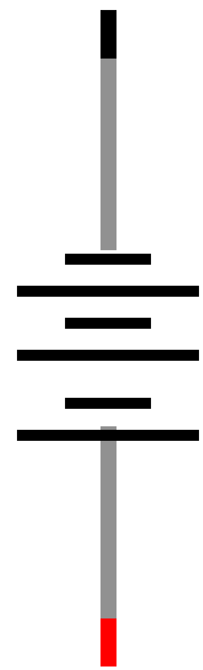
What is Capacitance?

Capacitance is the storage of energy in electric fields.

The Wire as a Capacitor

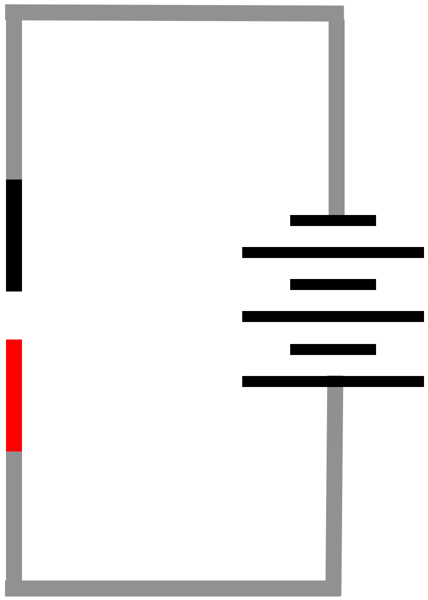


When a wire touches
the battery,
electrons move until
the force of
the uncovered protons
cancels the battery
voltage.



The Secret of Counteracting Fields!

If the wires tips approach each other, the opposite charges attract across the gap and more charge displacement is needed to counter the applied voltage.

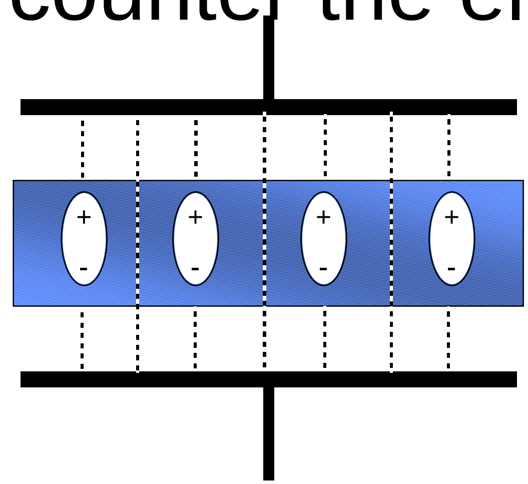


– The closer the tips are, the greater the compensation needed.

The Dielectric Continuum

Counteraction also takes place if we place a material between the plates of a capacitor. In this case, charges in the material displace to counter the electric field.

– electrons
– nuclei
– domains



Dielectric Electrons

The electrons in all materials will displace slightly from their orbits in an electric field. This makes sense because an electron orbit is really the locus of positions that minimize the electric fields the electron sees from the surrounding protons and electrons. An external field is just one more to deal with but it tips the balance.

Dielectric Nuclei

Atomic nuclei are positively charged. In some materials, their binding is loose enough such that they also move in an electric field.

- This means the material changes size!
- The definition of piezoelectric response
- But, the further it moves, the harder it is to move it!

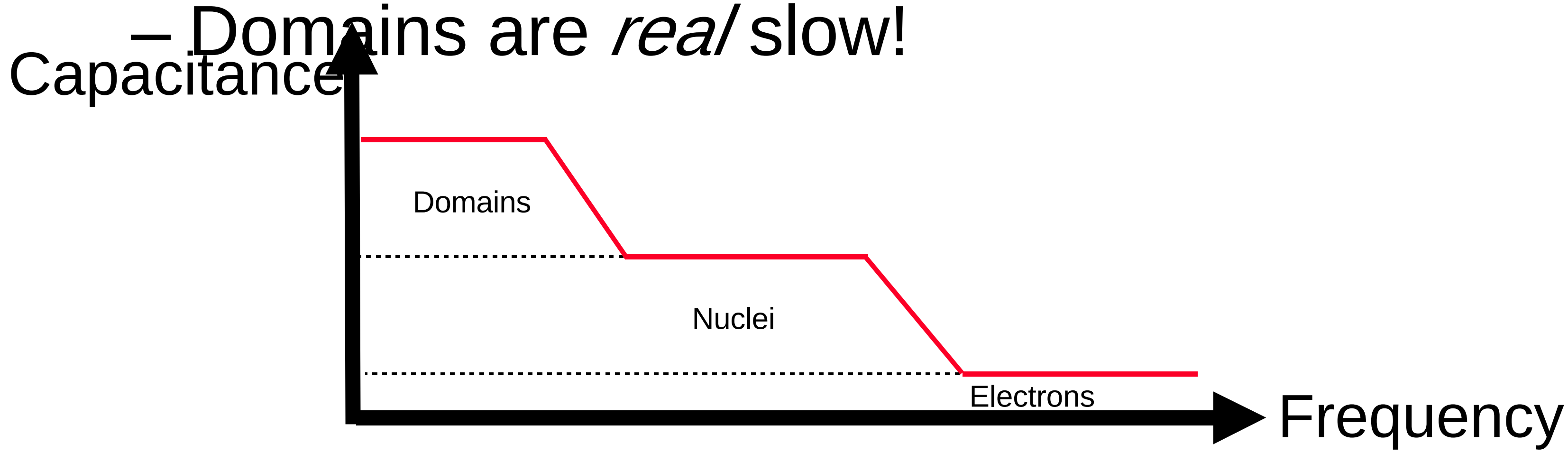
Dielectric Domains

In a few materials, the nuclei respond to the electric fields of their neighboring atoms. This long range coupling causes nuclei to couple together, leading to areas of spontaneous displacement: i.e. domains!

– The domains respond to external fields with huge polarizations, giving them gigantic dielectric and large piezoelectric responses.

Capacitance vs Frequency

- Capacitance is about *separation* of charge!
  - Electrons are fast (light speed!).
  - Atoms are slow!
  - Domains are *real* slow!



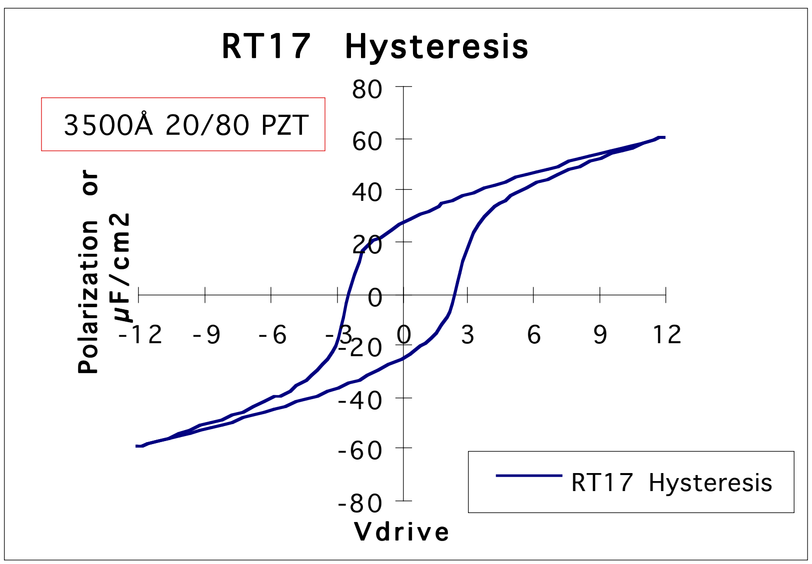
Component Modeling of Systems

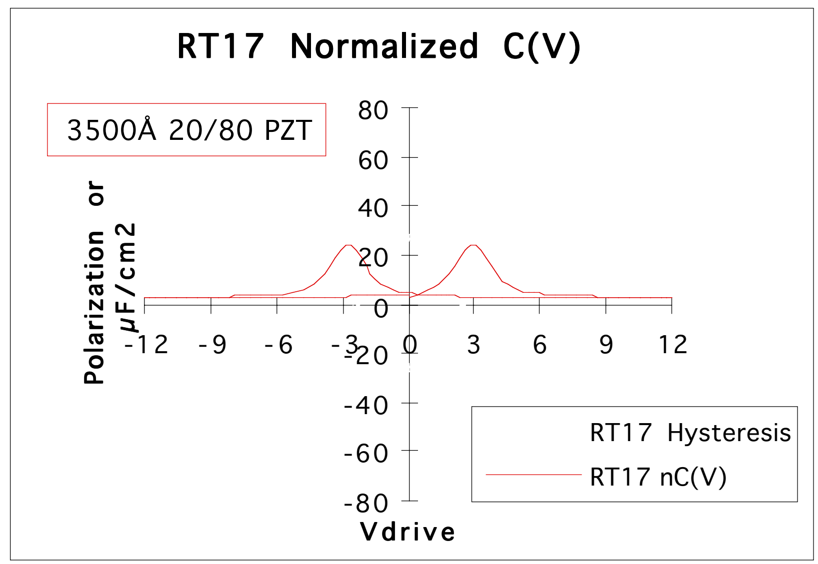
The most powerful tool of engineering is the concept that every complex system consists of more simple *components* which can be modeled and the responses added together to recreate the system.

– We will use this powerful tool to understand the ferroelectric hysteresis.

The Derivative as a Tool

The hysteresis is polarization as a function of voltage P(V). Its derivative with respect to voltage is δP/δV => (δQ/δV)/Area.





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The Component Model of the Ferroelectric Capacitor

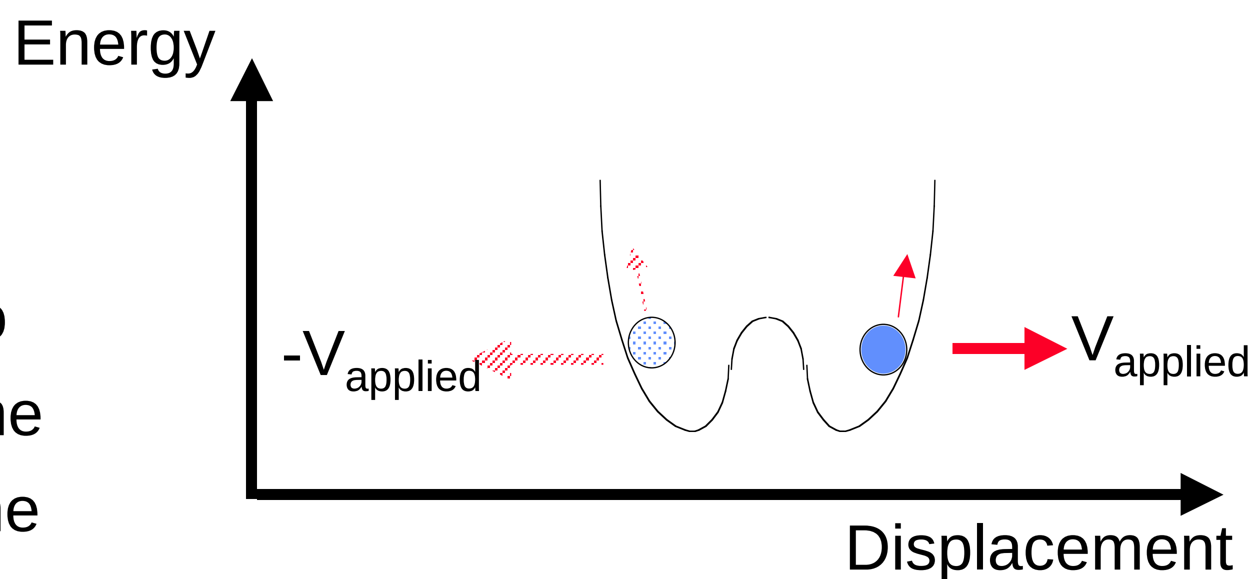
(Using PZT)

Components of a Ferroelectric Capacitor

- A ferroelectric capacitor should have three sources of charge:
  - Polarization of the dielectric material
  - Remanent polarization from domain memory
  - Leakage through the material.

Dielectric Response

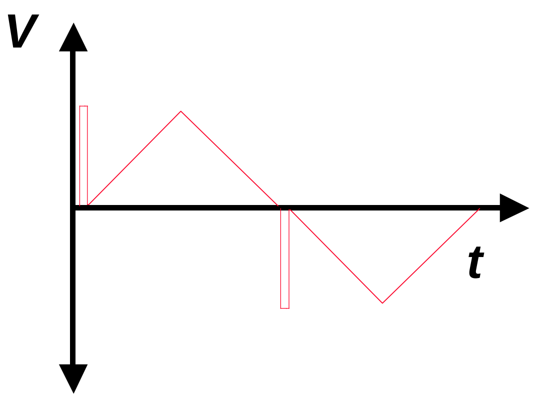
The dielectric response comes from the piezoelectric distortion of the ferroelectric crystal.

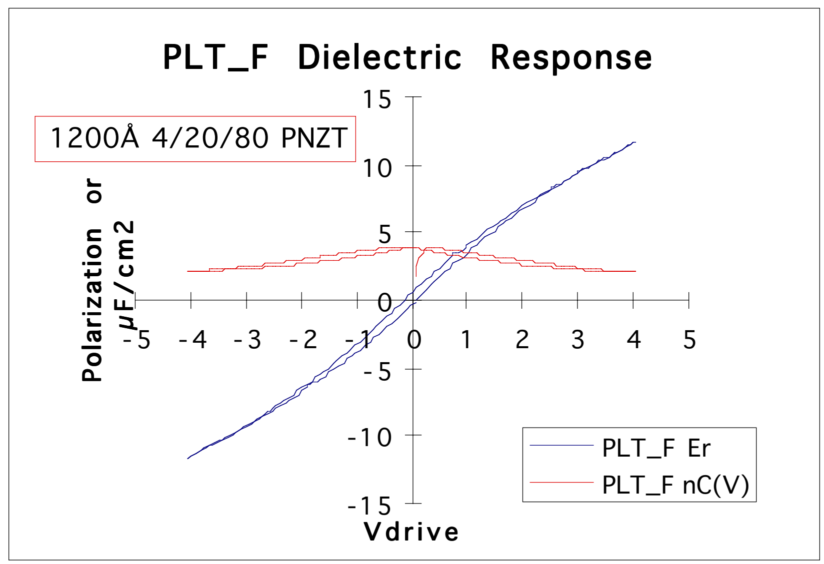


We want to measure the shape of the two sidewalls of the Landau energy diagram:

Measuring Dielectric Response

The dielectric response is measured using the small signal capacitance vs DC bias technique. It is imperative that leakage current be measured and subtracted out.

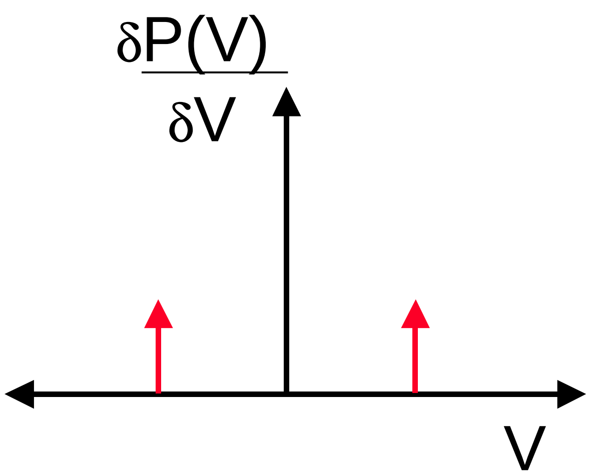


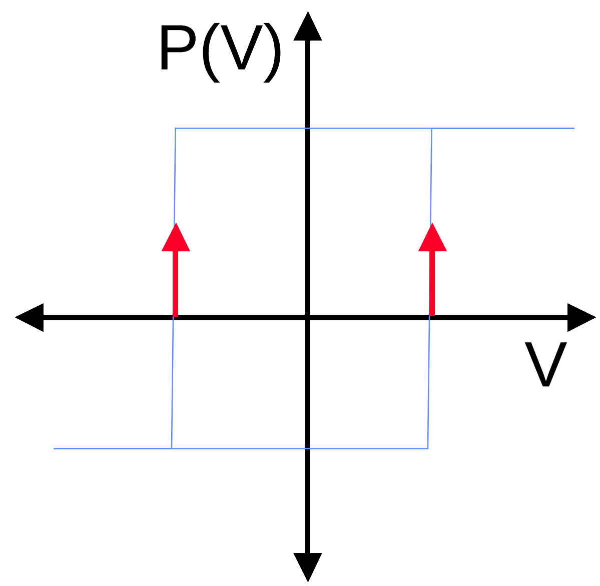


Remanent Memory

Imagine a unit dipole in space with $\varepsilon_r=0$

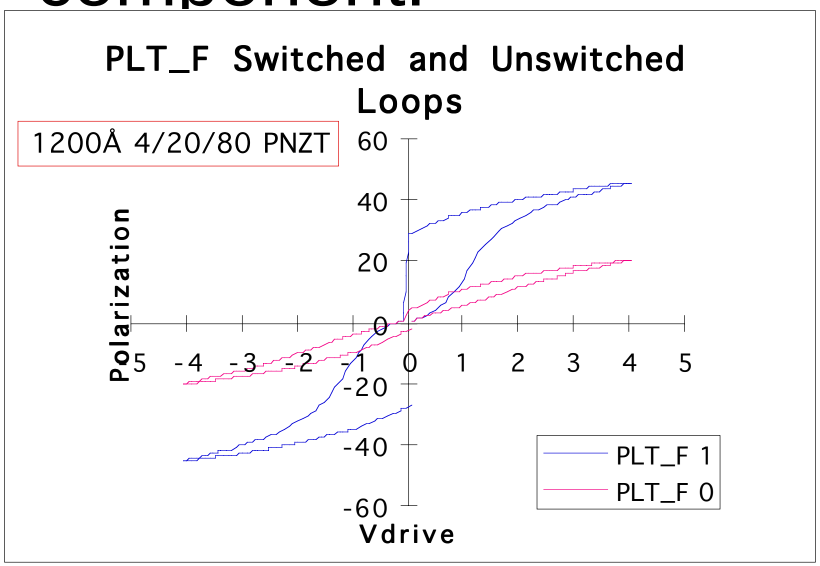
and a switching threshold. It makes the perfectly square hysteresis. That is memory!

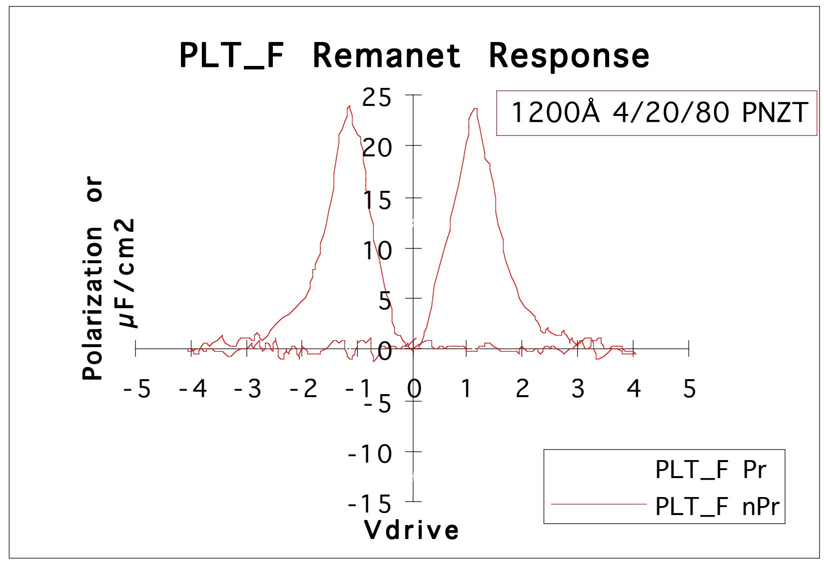




Measuring Remanent Memory

The ferroelectric material has a population of domain dipoles. By measuring the switching and non-switching hysteresis and subtracting them, you get the remanent polarization component.



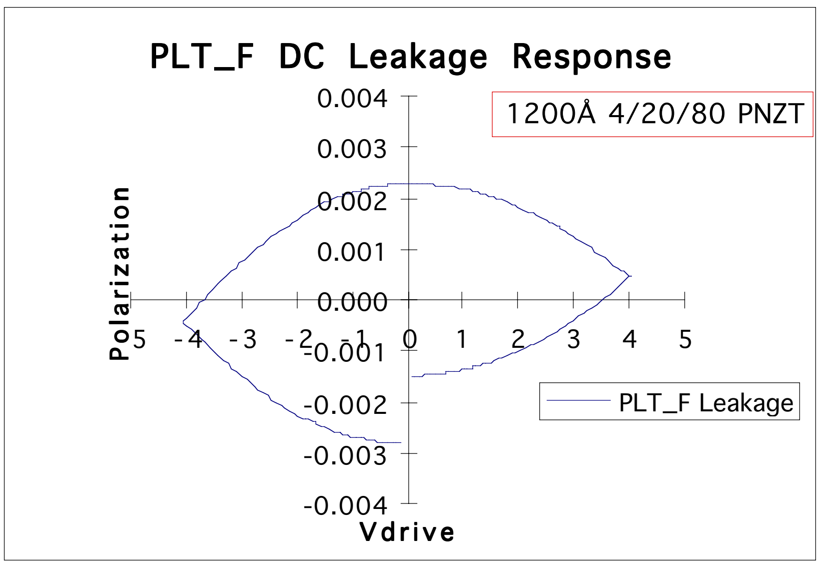


Resistive Leakage in a Hysteresis Loop

Resistance is easy for a triangle wave:

$$P=(Current \bullet time)/Area$$

$$\therefore P=(\Sigma^{k}_{n=0} n\ \Delta V/R \bullet \Delta time)/Area$$



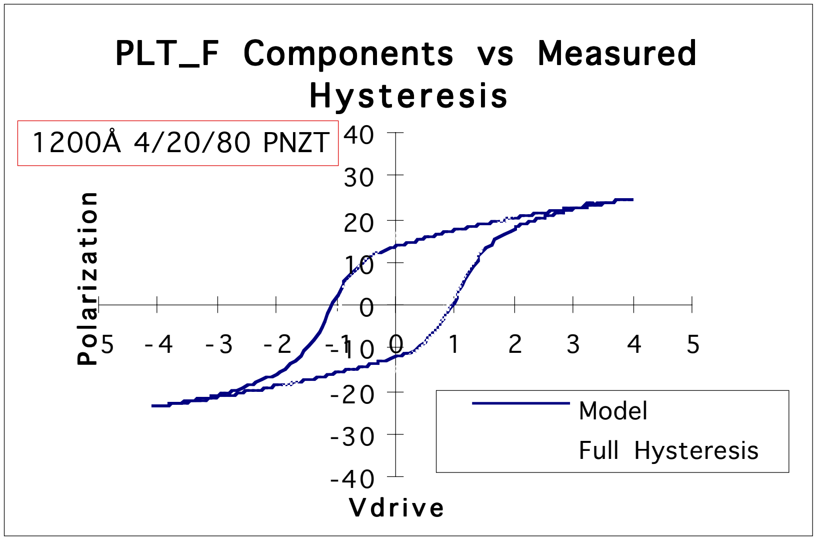
Δtime=time step per point

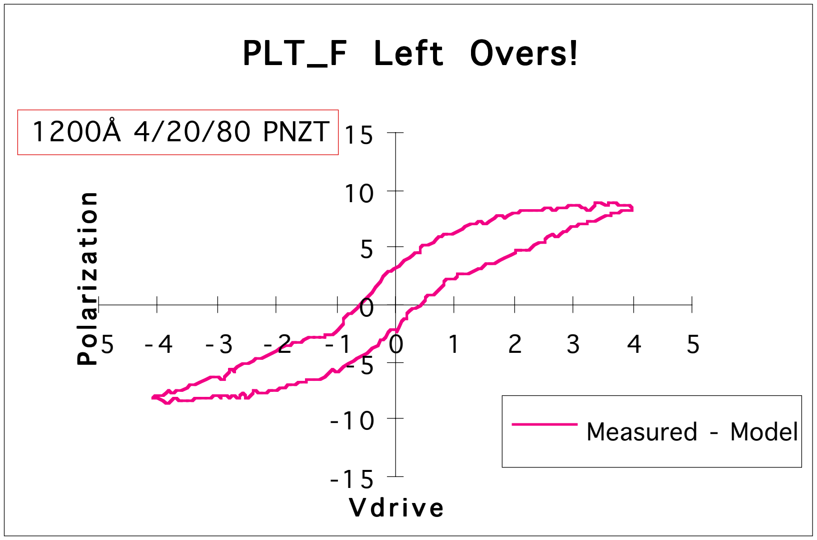
Δ V=voltage step of wave

n = point number of digitized triangle wave

Model vs Reality: Reality is Greater

If we measure the three components and subtract them out, we have something left over:





It is the “gap” in the hysteresis loop!

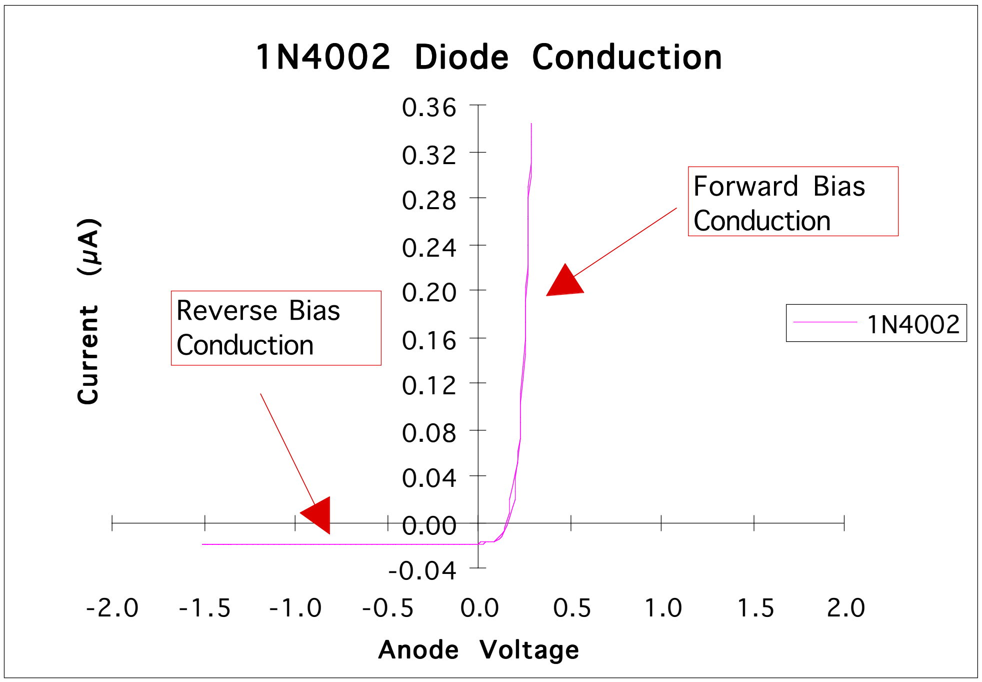
Speculation on the Components of the Non-remanent Component

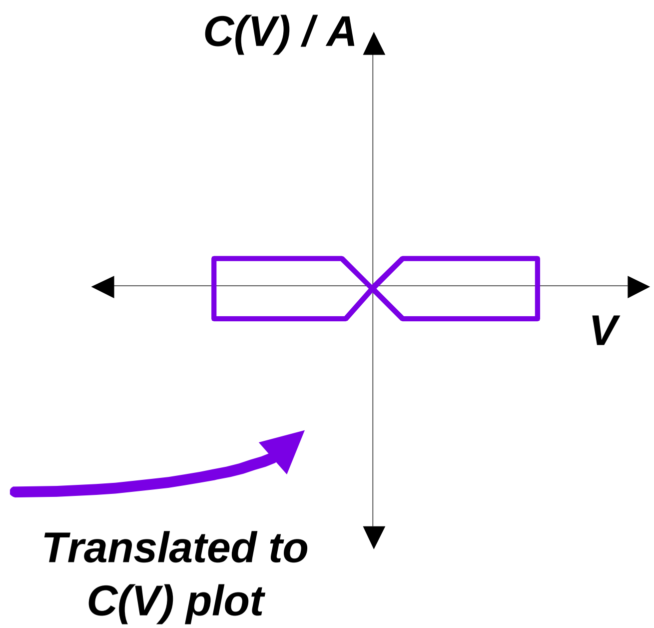
1. Domain relaxation
   – During voltage application, domains swell piezoelectrically. After voltage removal, they shrink slowly as stress is equalized.

2. Dynamic diode leakage
   – Reverse biased diode leakage current contributes to measured polarization.

Diode Leakage Model

- A platinum electrode based capacitor has two opposing diodes, one of which is always turned off.

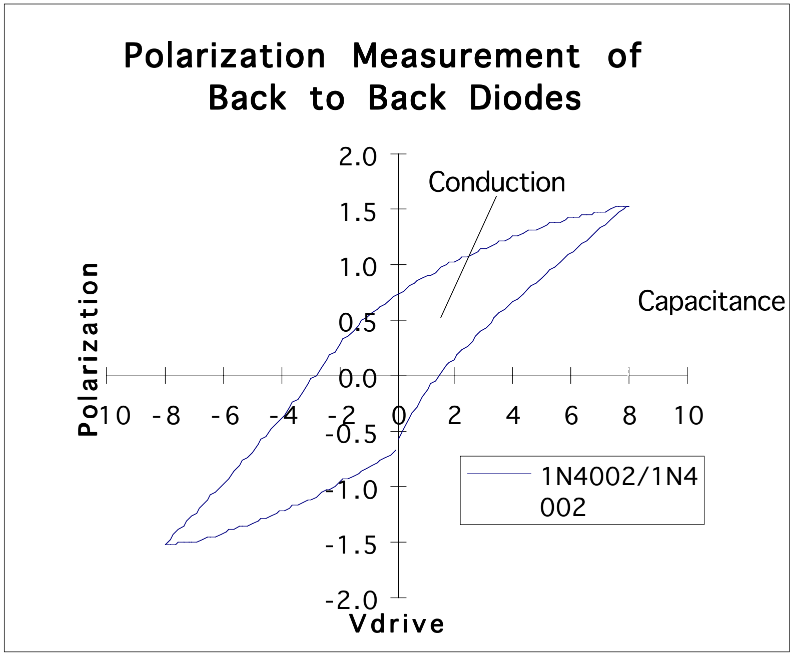


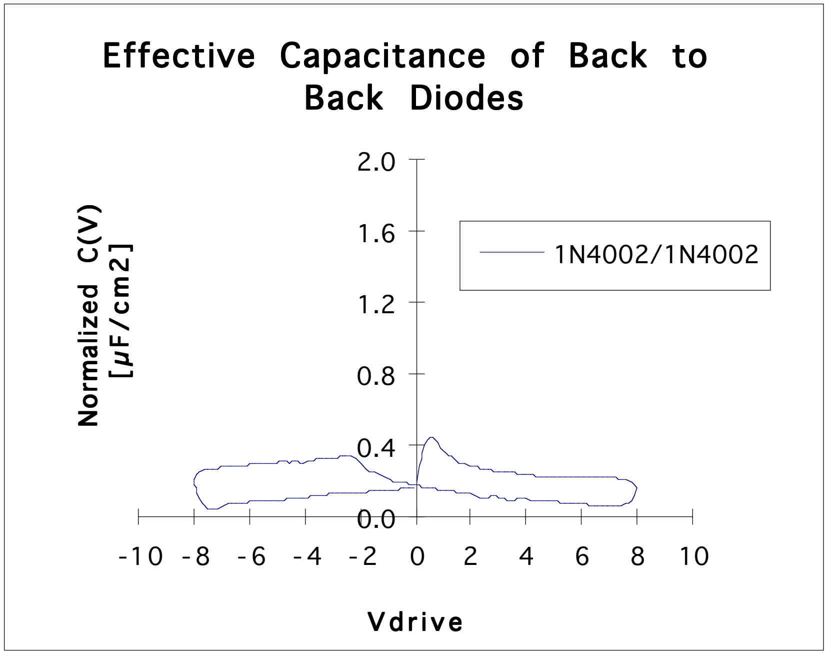


- In reverse bias, a diode has a constant current INDEPENDENT of voltage.

Diode Leakage Model

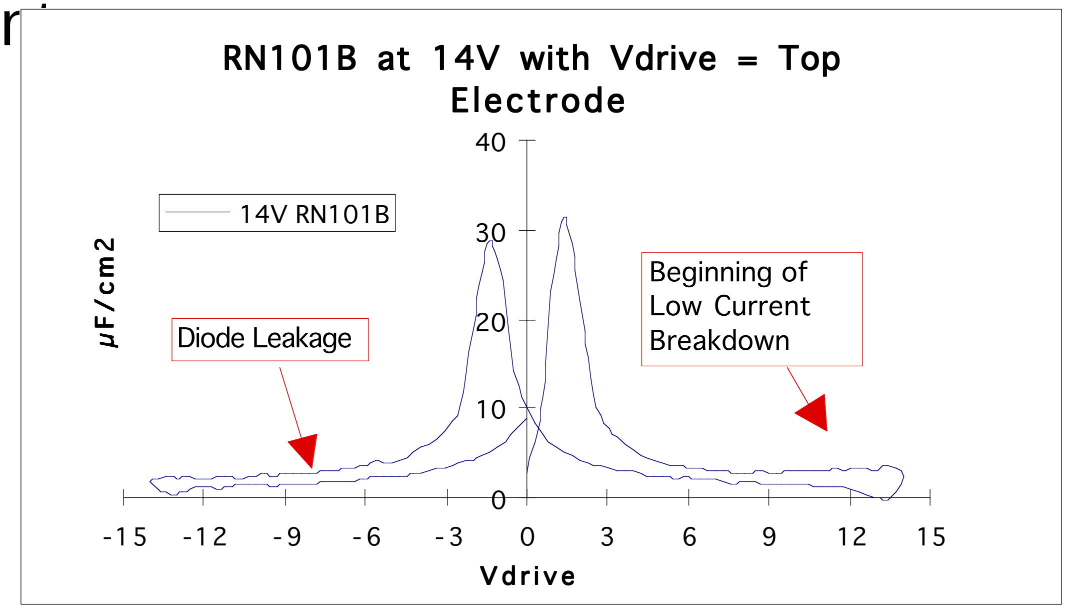
- A pair of back to back diodes have a unique signature on a virtual ground test system which uses a triangular drive voltage.





Diode Leakage Model

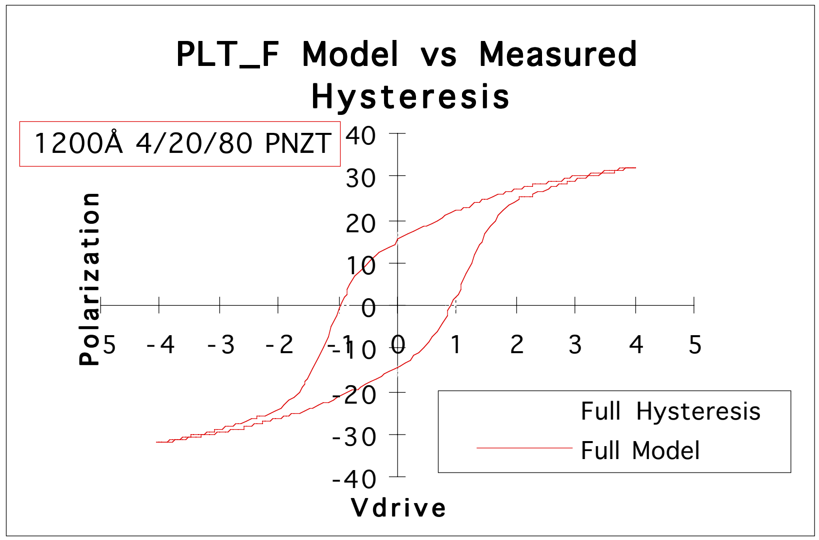
- The derivative of a polarization hysteresis loop can clearly show the diode reverse biased leakage if it is present.



The effect of diode leakage can be identified in the plot of a 1200Å 4/20/80 PNZT film above.

Fitting the Hysteresis Model

Fitting the four components makes a pretty good fit. And, the model predicts partial switching.



Dielectric Component

+

Remanent Component

+

Leakage Component

+

Non-remanent Component = Total Polarization!

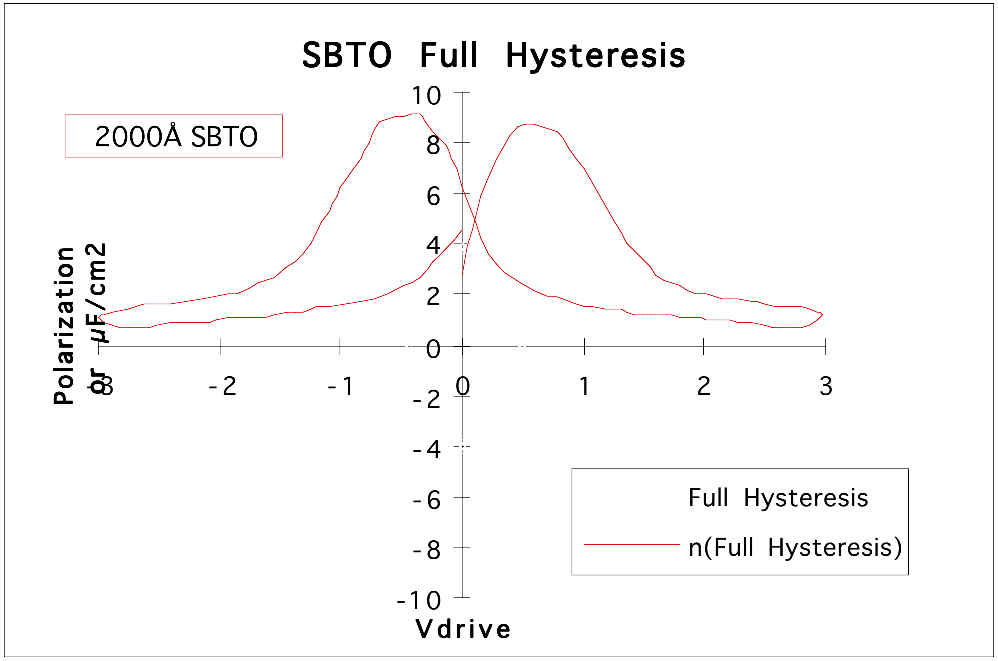
The SBT Capacitor

Is this model unique to PZT or does it apply to all ferroelectric materials?

– *>It Applies to them All!*

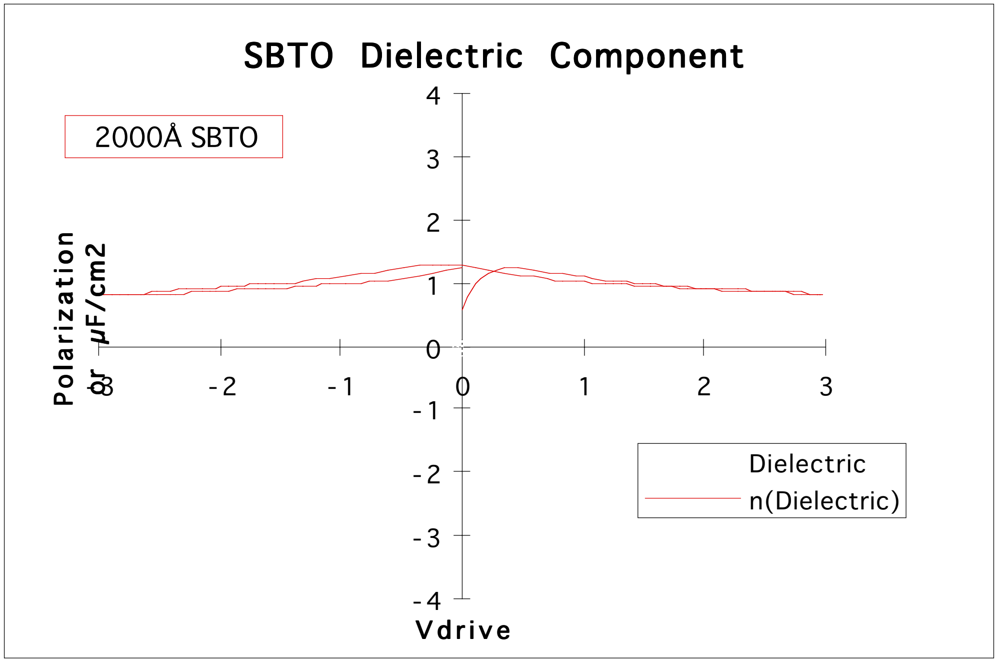
The SBT Full Hysteresis

- 2000Å Strontium Bismuth Tantalate



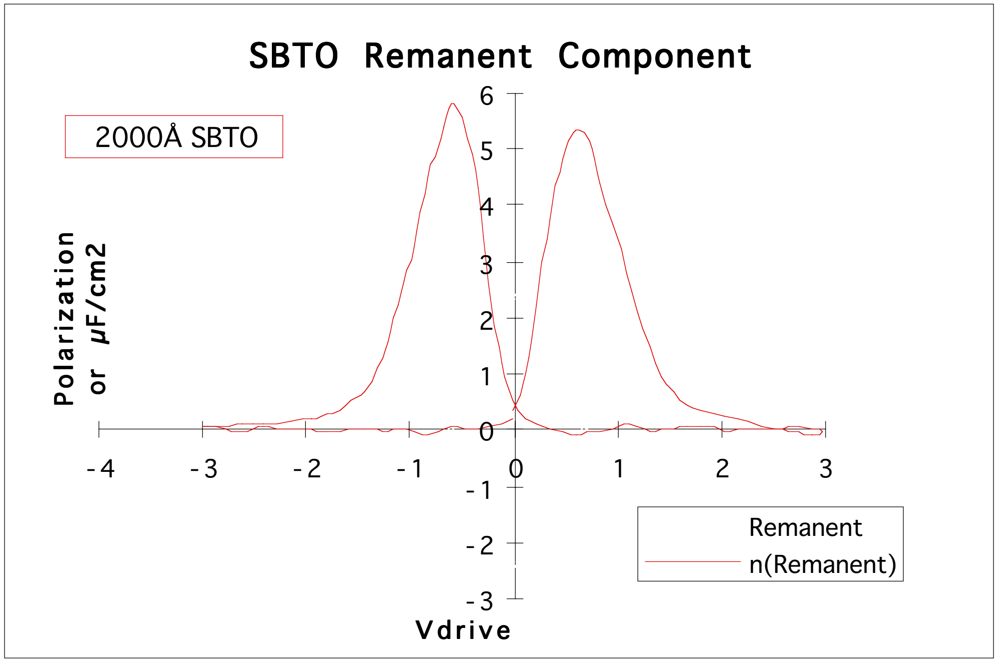
SBT Dielectric Response

- 2000Å Strontium Bismuth Tantalate



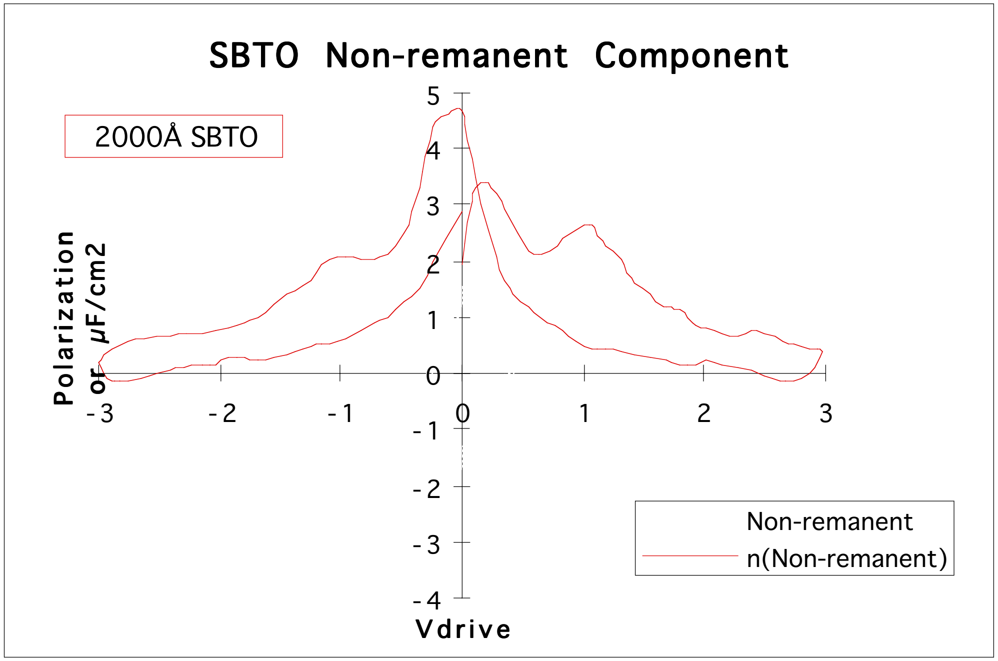
SBT Remanent Response

- 2000Å Strontium Bismuth Tantalate



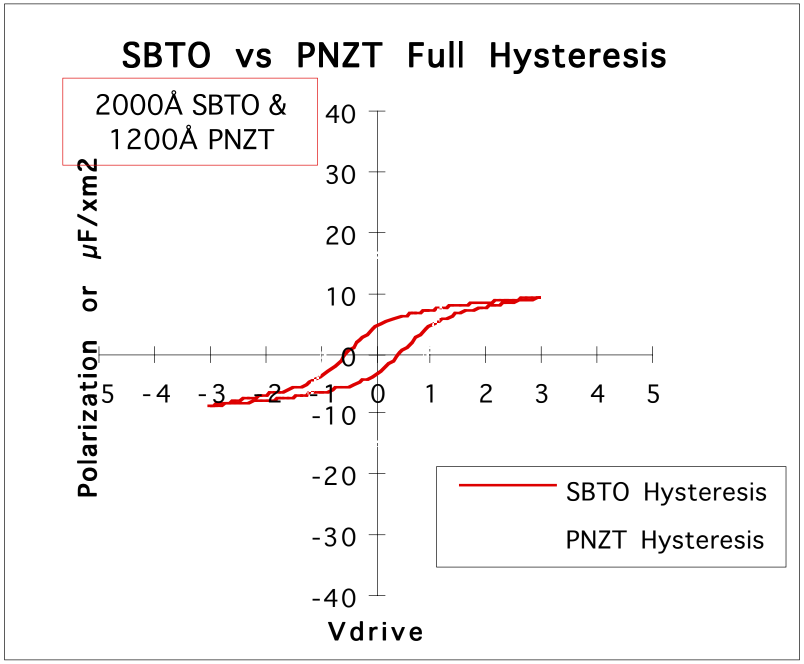
SBT Non-remanent Response

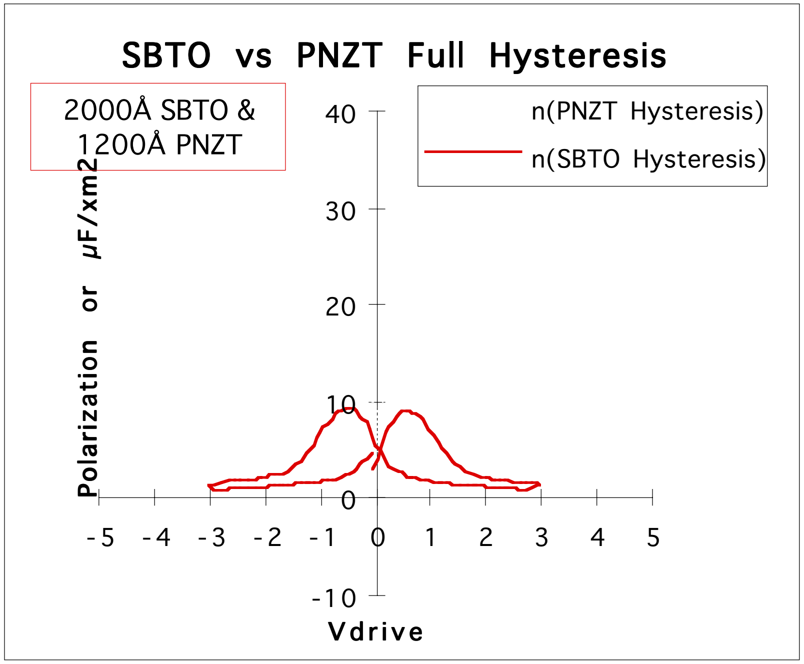
- 2000Å Strontium Bismuth Tantalate



SBT vs PZT: Full Hysteresis

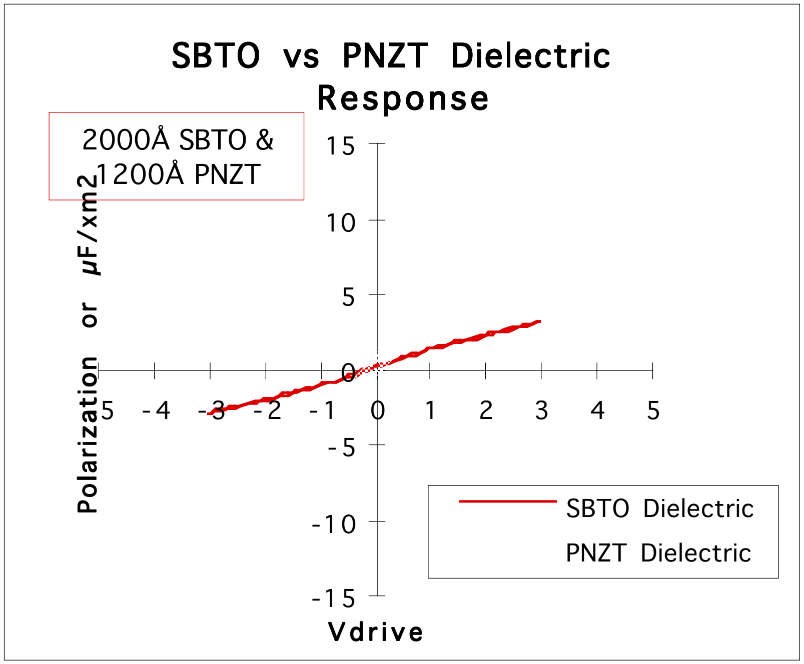
1200Å 4/20/80 PNZT vs 2000Å SBT sample:

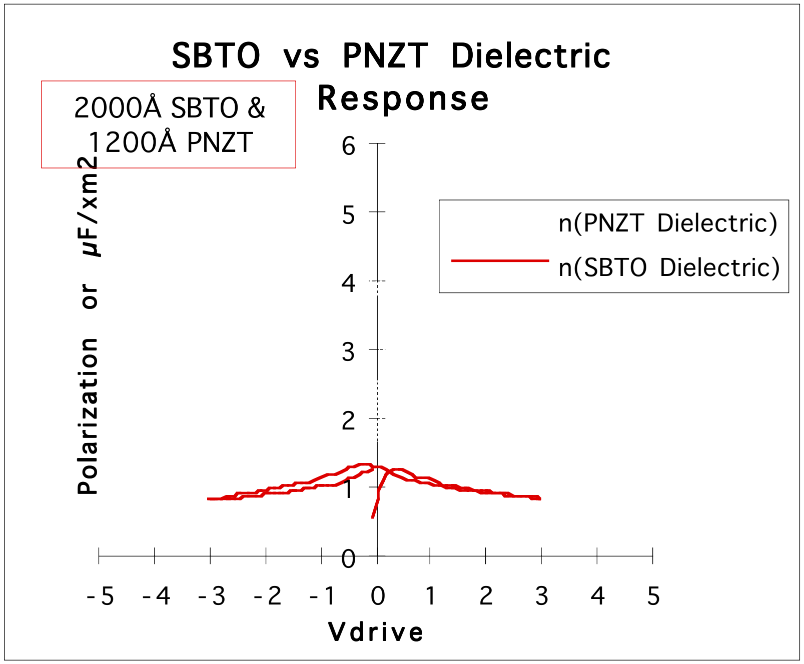




SBT vs PZT: Dielectric Response

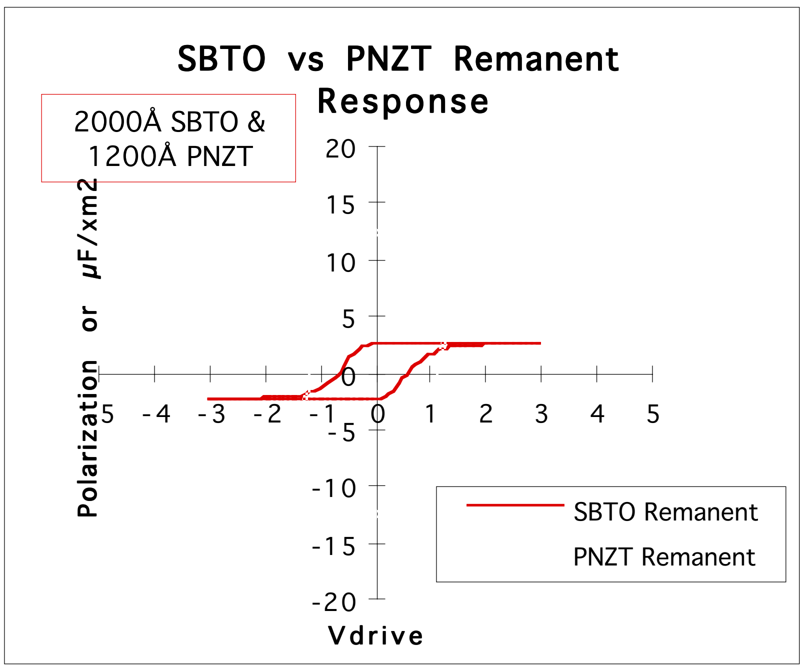
1200Å 4/20/80 PNZT vs 2000Å SBT sample:

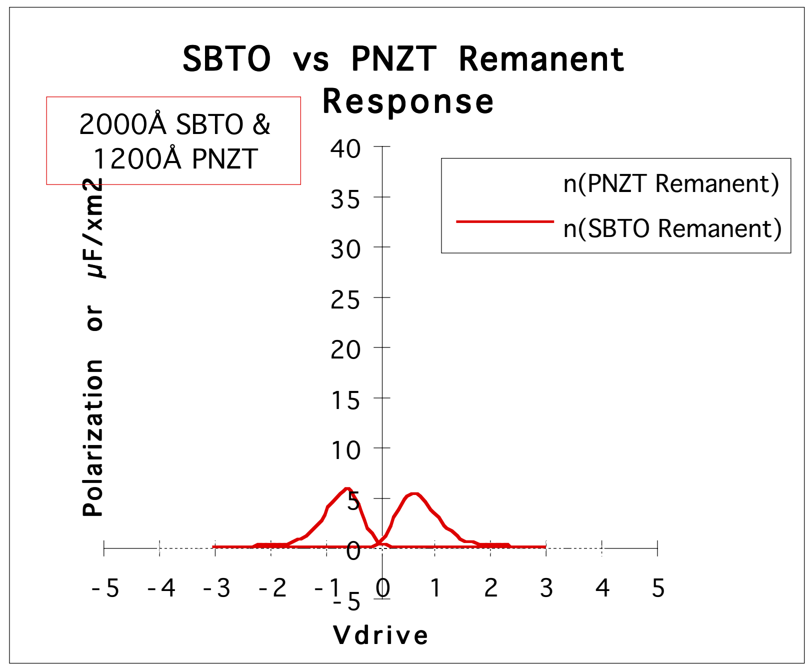




SBT vs PZT: Remanent Response

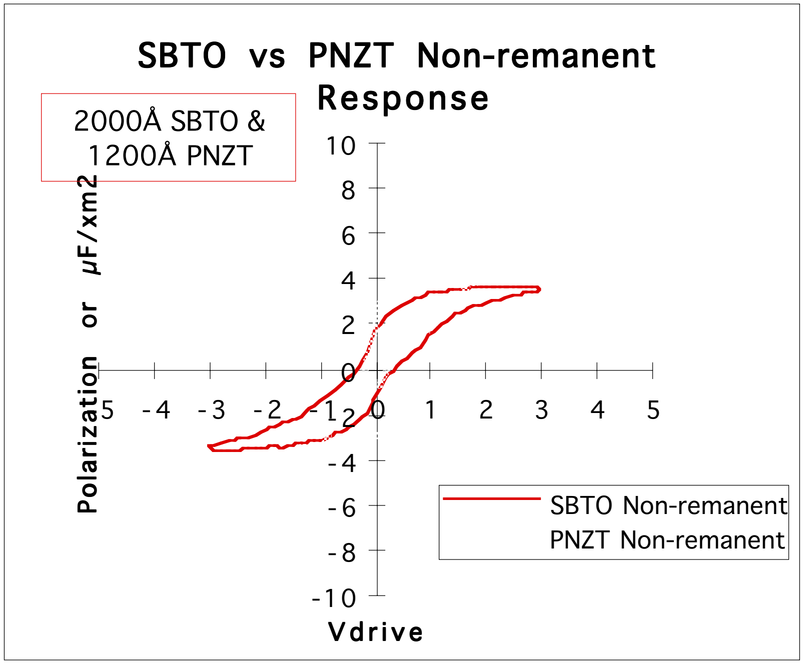
1200Å 4/20/80 PNZT vs 2000Å SBT sample:

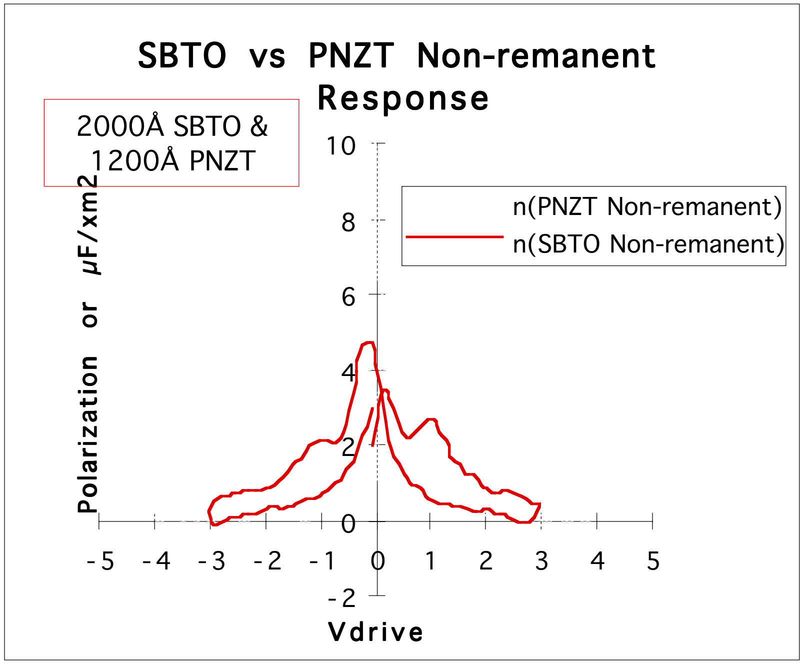




SBT vs PZT: Non-remanent Response

1200Å 4/20/80 PNZT vs 2000Å SBT sample:





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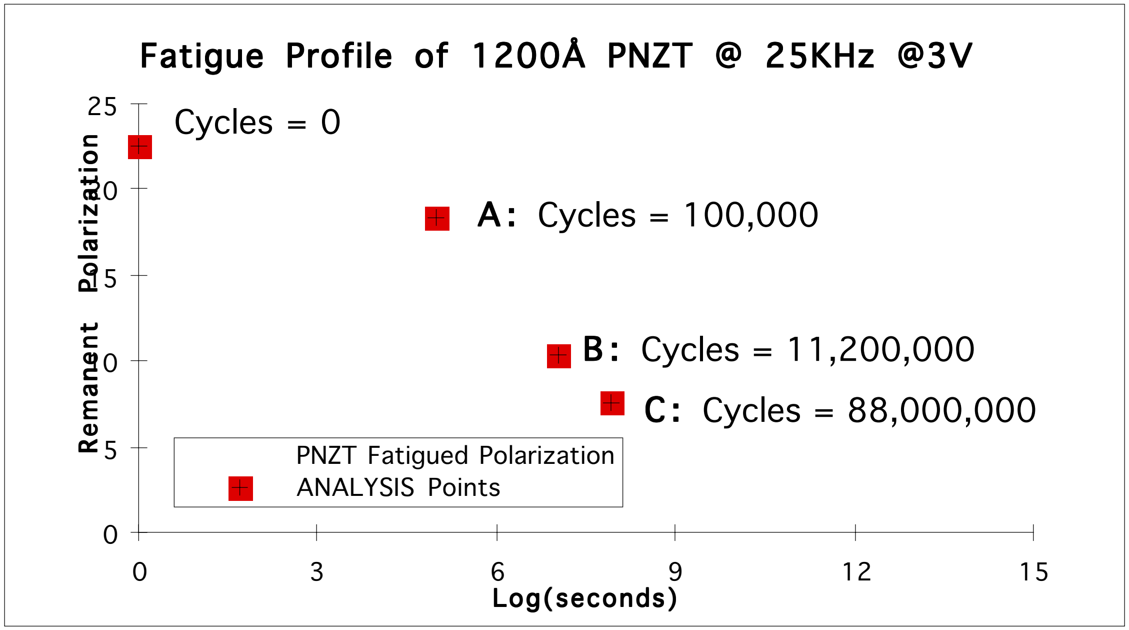
Fatigue in the Component Way

We can gain important insights to the nature of fatigue by examining fatigue of the components:

- Does internal stress change the dielectric response?
- Does the coercive voltage of the remanent polarization go down or up?
- What happens to the parasitics?

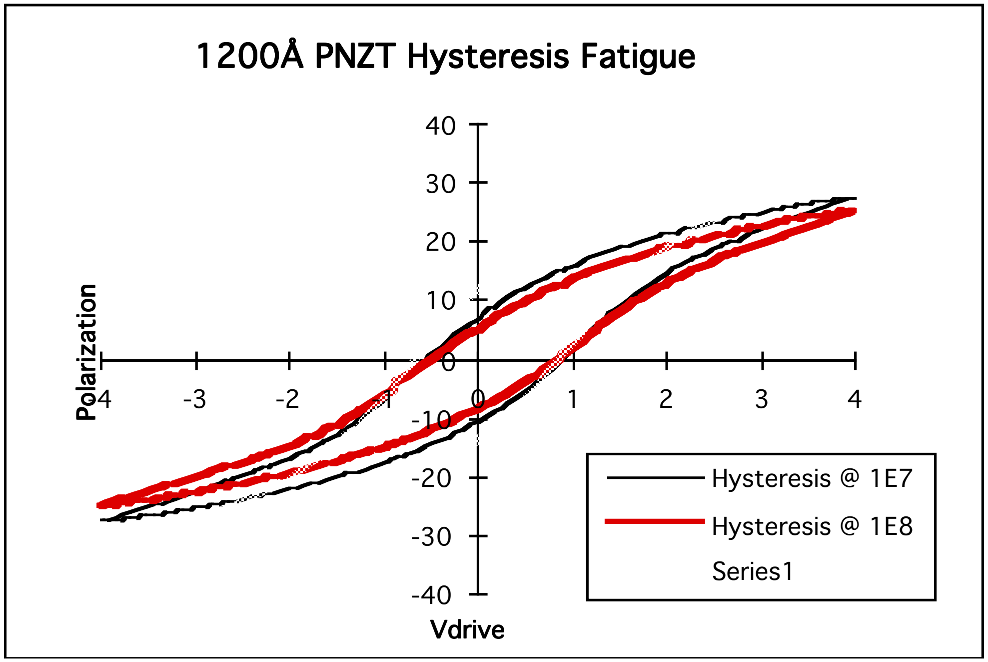
The Fatigue Profile

25KHz at 3V at Room Temperature



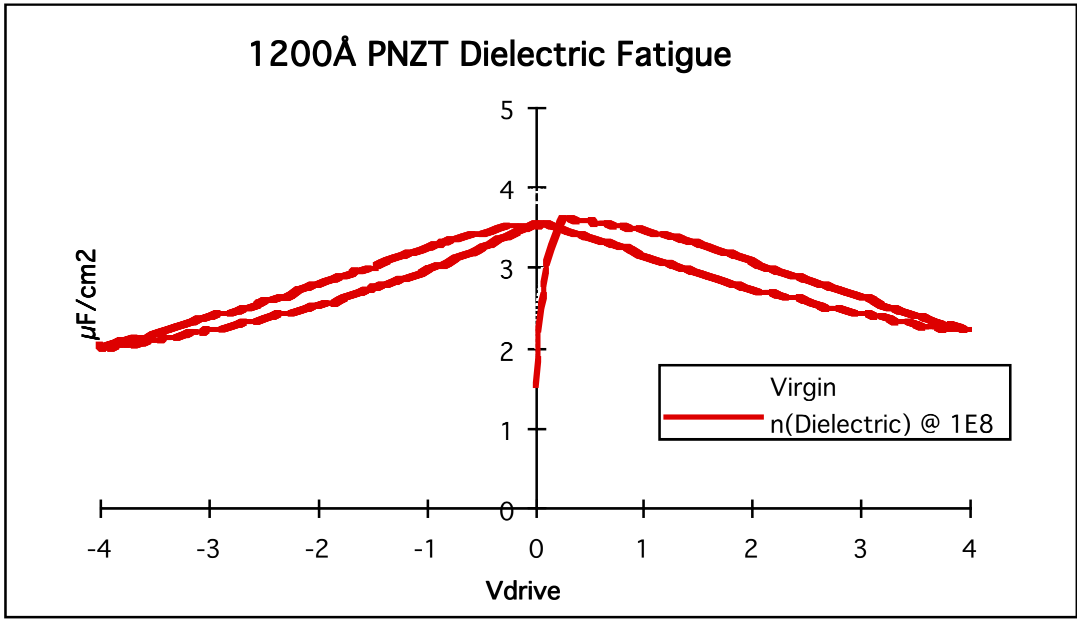
Full Hysteresis Fatigue

- Before and After Fatigue of a 1200Å 4/20/80 PNZT film:



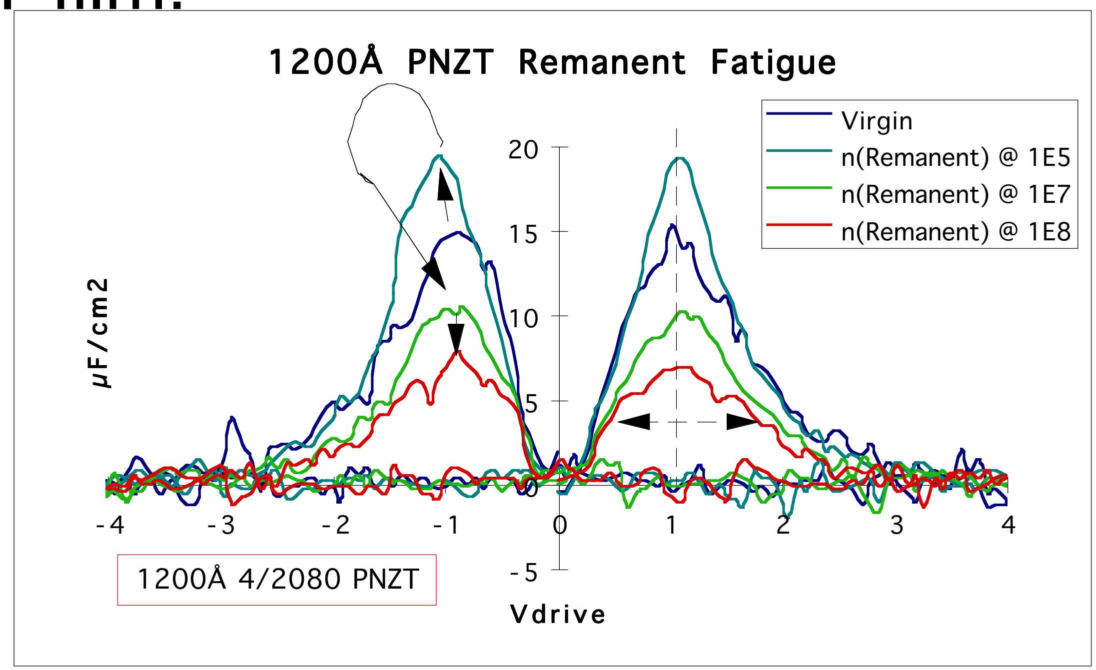
Dielectric Component Fatigue

- Before and After Fatigue of a 1200Å 4/20/80 PNZT film:



Remanent Component Fatigue

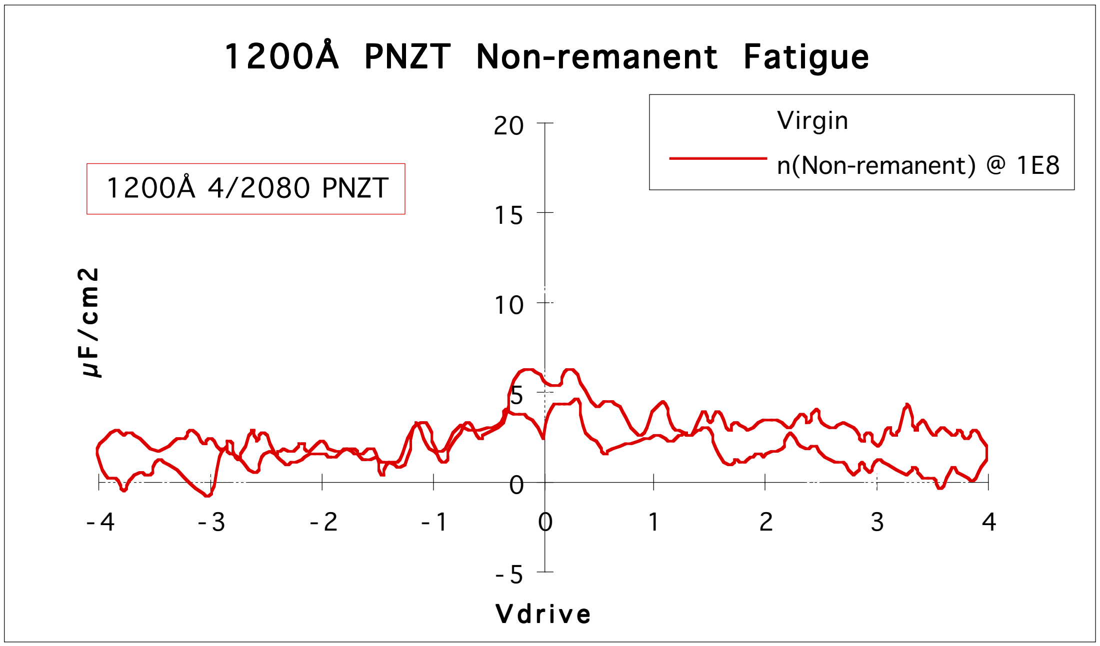
- Before and After Fatigue of a 1200Å 4/20/80 PNZT film:



- Note: Vc and switching distribution do not change with fatigue.

Non-remanent Component Fatigue

- Before and After Fatigue of a 1200Å 4/20/80 PNZT film:



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Conclusions about Fatigue

- Dielectric Response does not change above 1V.
- Non-remanent polarization does not change.
- Only the population of switching domains changes greatly.   Domain switching parameters, such as Vc, do not change.

IMPRINT

The leading issue preventing manufacturing!

Definition: *The mechanism by which a stored state becomes permanent in its memory location.*

– i.e. The memory becomes "read only" and quits being random access.

i.i.e. Imprint Lifetime Product Lifetime

Thermal Imprint Test Definition

Imprint is accelerate by temperature.

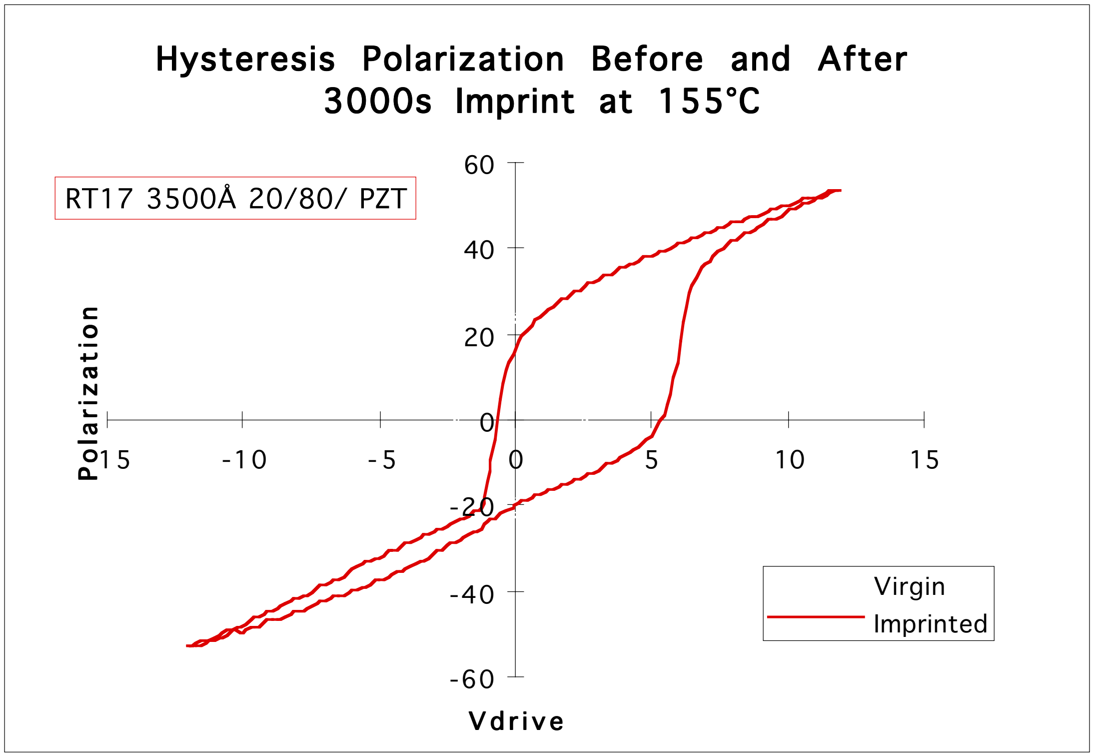
Write Capacitor

Thermal Stress

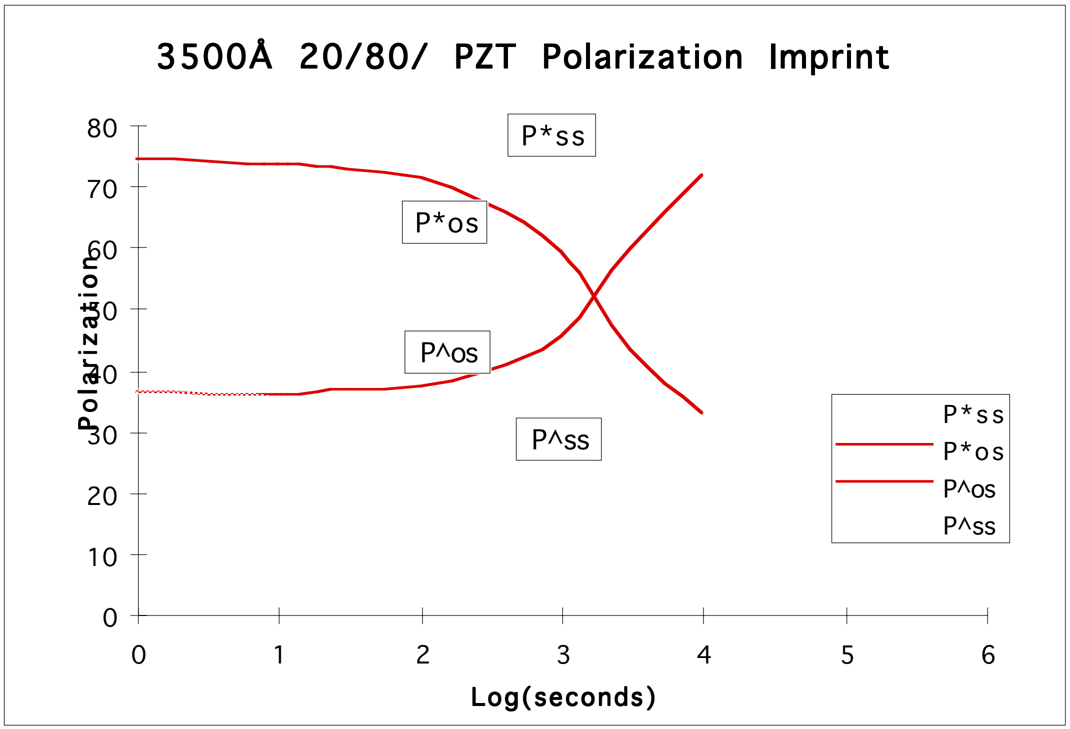
Write Capacitor Opposite State

Read Capacitor Opposite State

Imprint of the Hysteresis



Imprint of the Polarization



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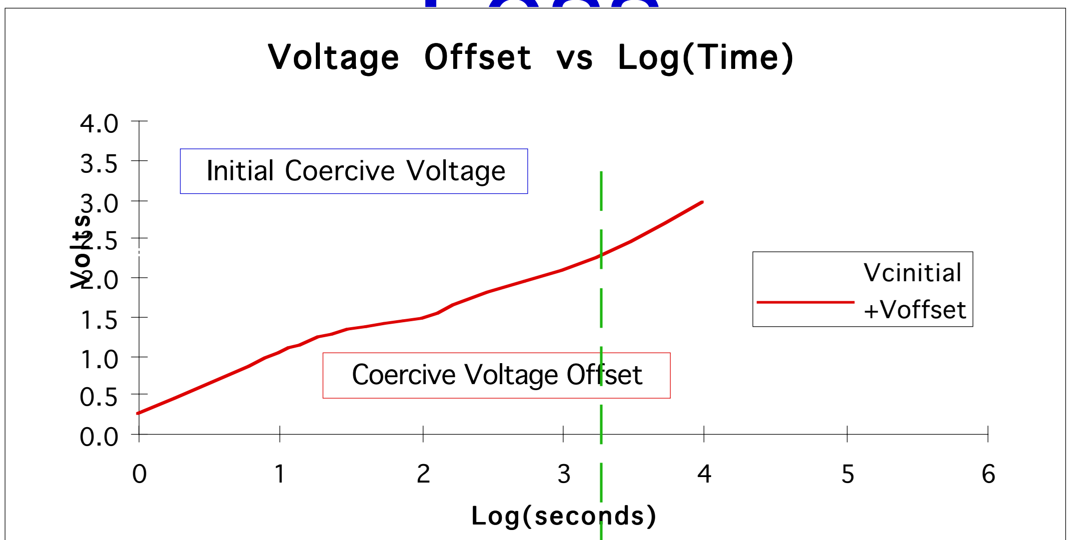
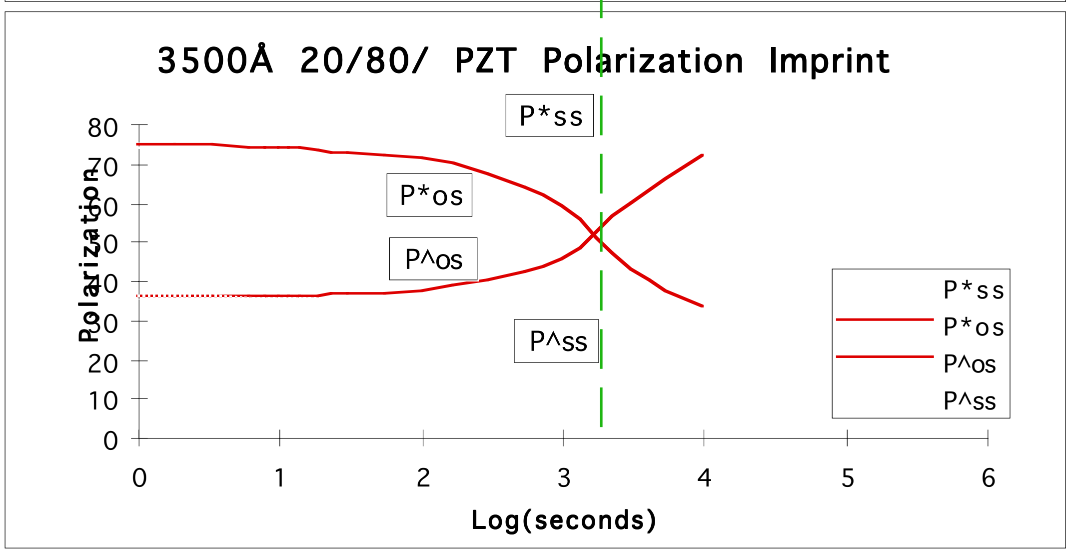
Offset Field vs Polarization Loss





Conclusions about Imprint

Clearly, hysteresis offset and opposite state polarization loss are related!

Controlling the rate of imprint offset is the key process parameter the test engineer must monitor in-process!

Objective for IC FeCap Parameters

> Maintain a minimum deltaP for all conditions during life and at end of life!

– 5µC/cm^2 is a commonly discussed value

> Verification Test Suite:

– Vsat (< 3V)

– Pulse > 5µC/cm^2 @ 50ns @ 125°C

– Fatigue > 75% @10^{12} cycles @ 3V @ 25°C

– Thermal Imprint > 10 years @ 150°C

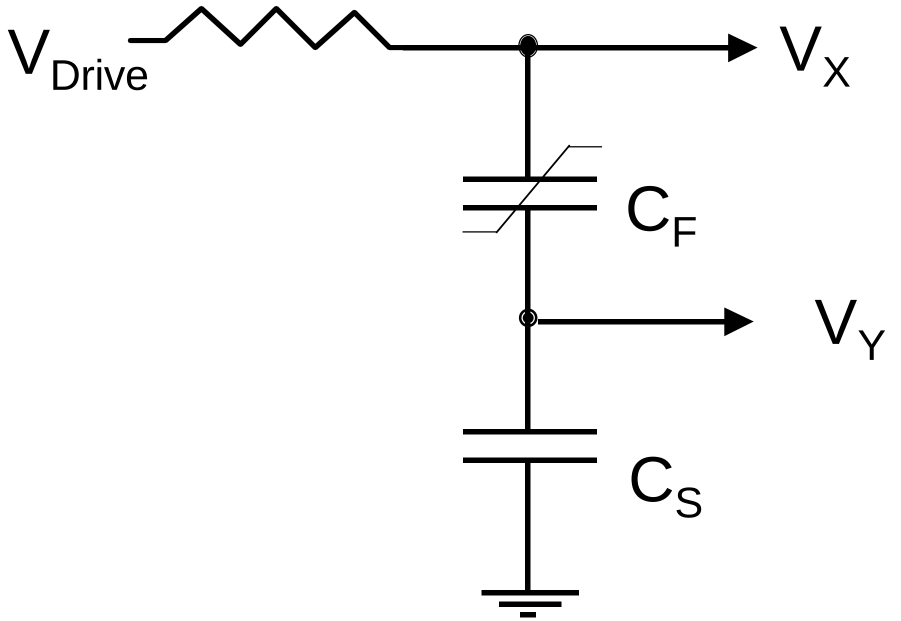
– Dynamic Imprint > 10^{12} cycles @ 150°C @ 3V

– Retention > 10 years @ 150°C @ 1.5V

– Thermal Shock @ 150°C

Test Theory

The Sawyer-Tower Circuit



$$Q_F = Q_S$$

$$C_F V_F = C_S V_S$$

$$\frac{C_F V_F}{C_S} = V_S$$

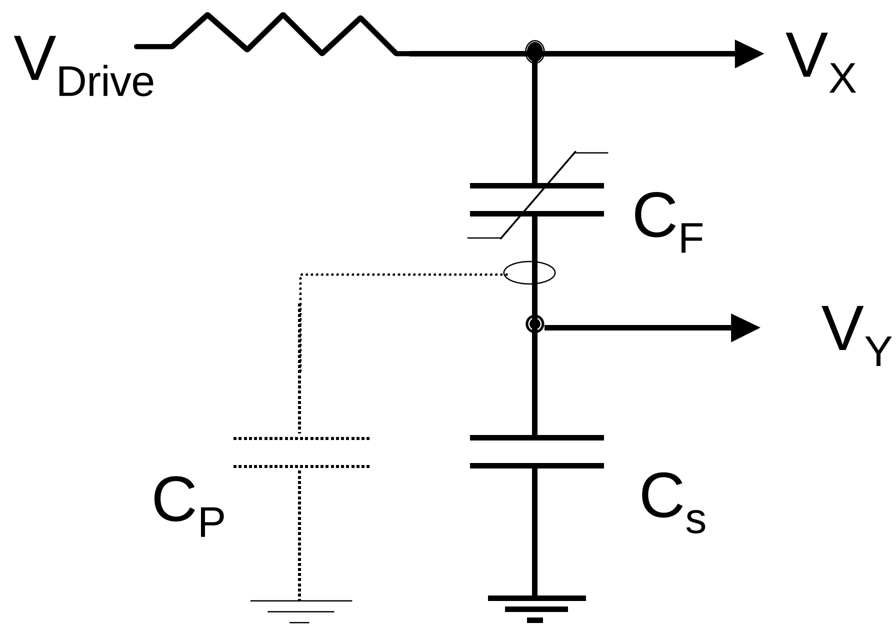
Advantages & Disadvantages

<u>Advantages</u>

- Fast
- Simple

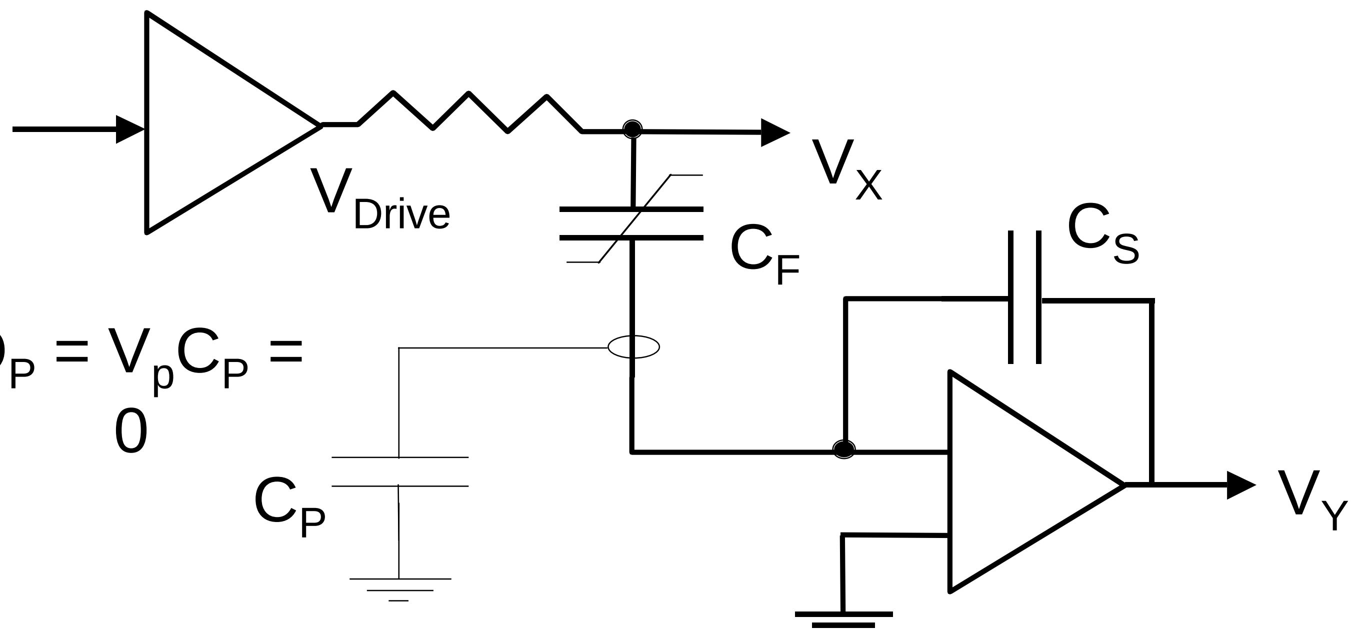
<u>Disadvantages</u>

- Parasitics
- Back voltage



$V_F = V_{Drive} - V_S$

Virtual Ground



$Q_P = V_p C_P = 0$

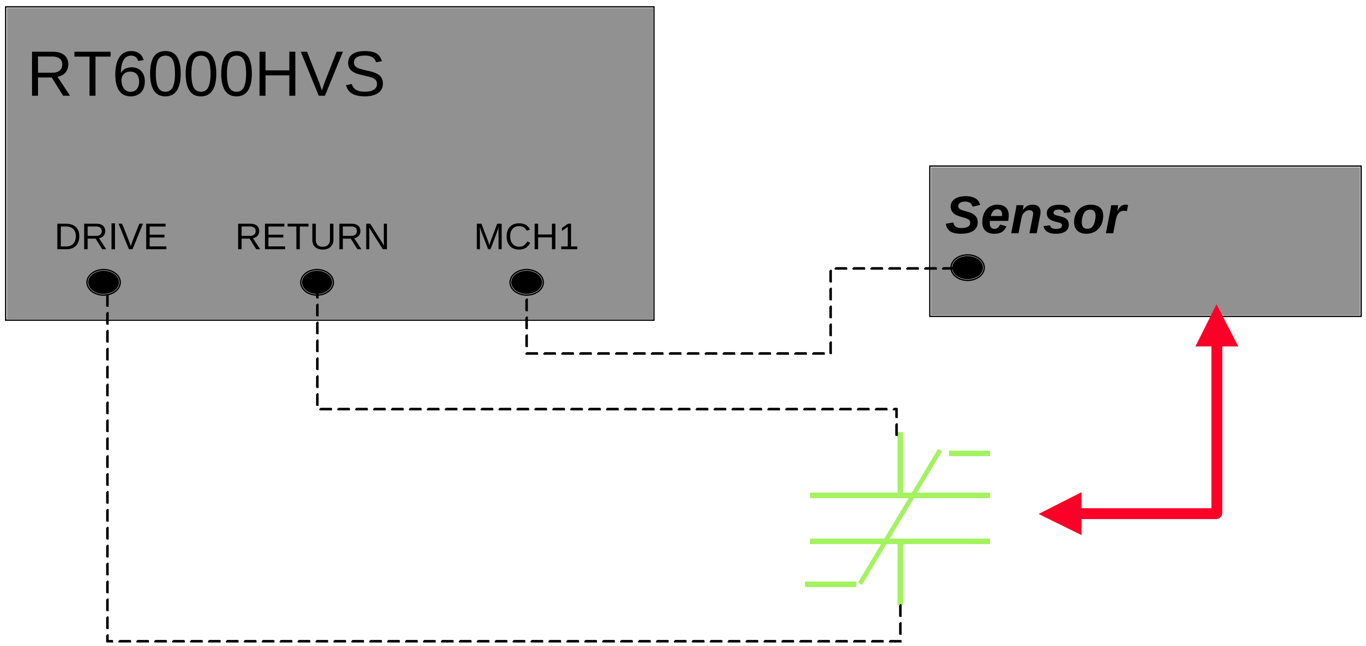
- The virtual ground is a specialized Sawyer-Tower circuit that eliminates parasitic capacitance and back voltage.

IMPEDANCE: It Changes the Loop!

- Impedance effects can be desribed as shifting the Y axis with respect to the X-axis.

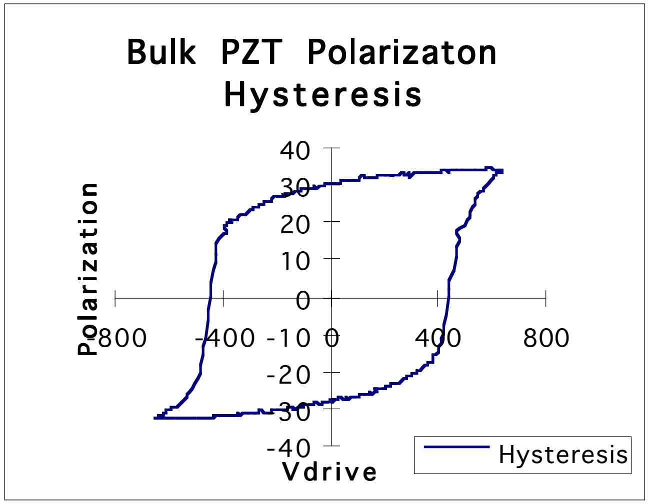
- To see the true shape of the loop, impedance effects must be avoided!

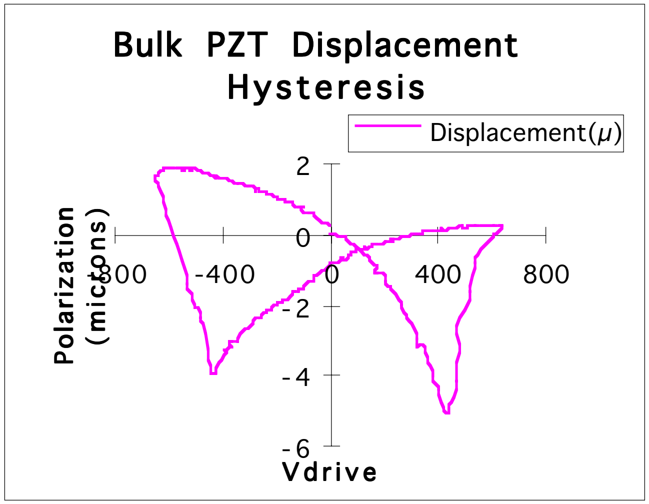
Piezoelectric Measurement

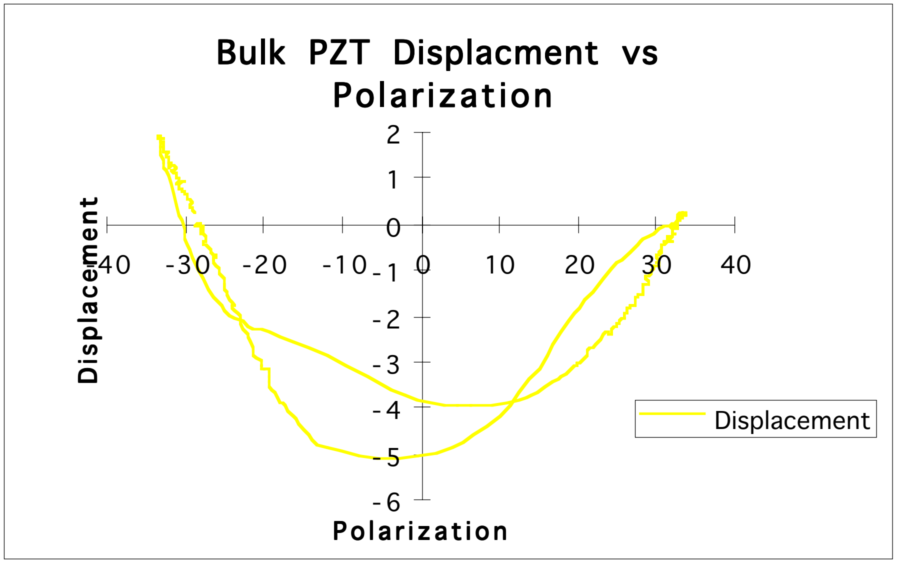


PIEZO software takes input on the Multichannel from displacement or force sensors to collect piezoelectric properties simultaneously with electric properties.

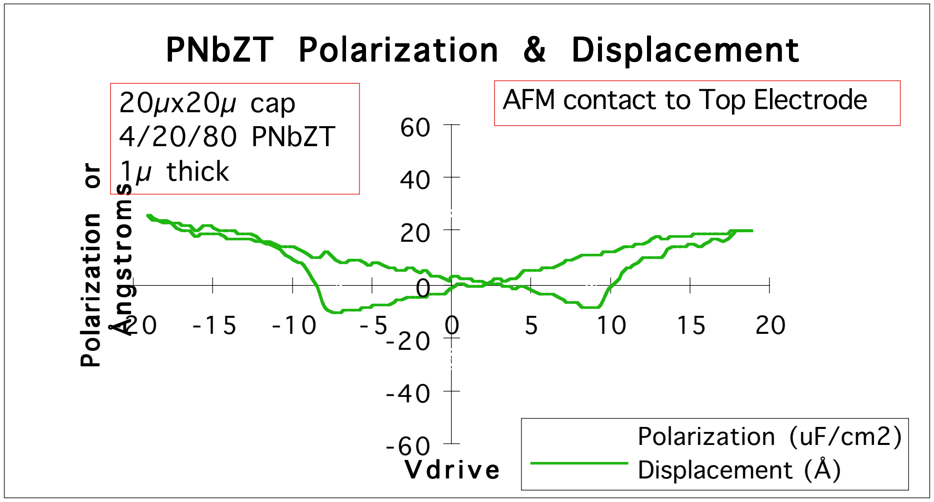
Piezoelectric Response of Bulk PZT

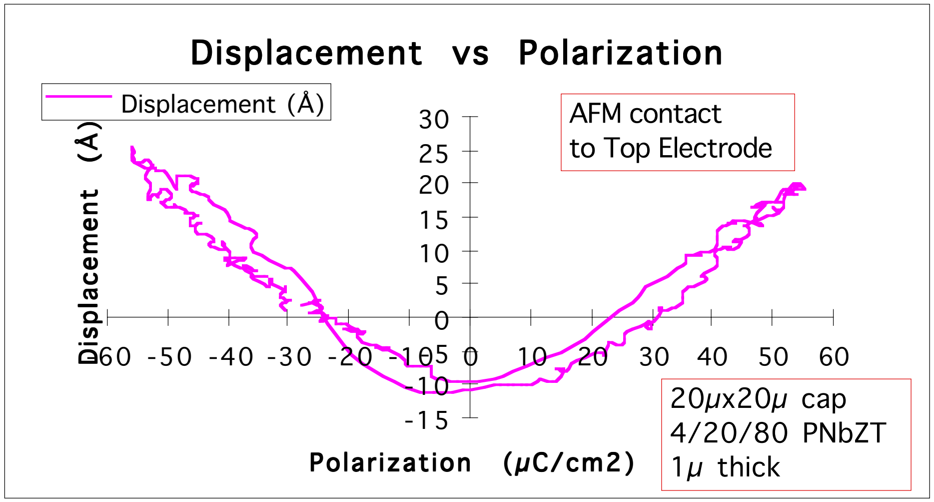




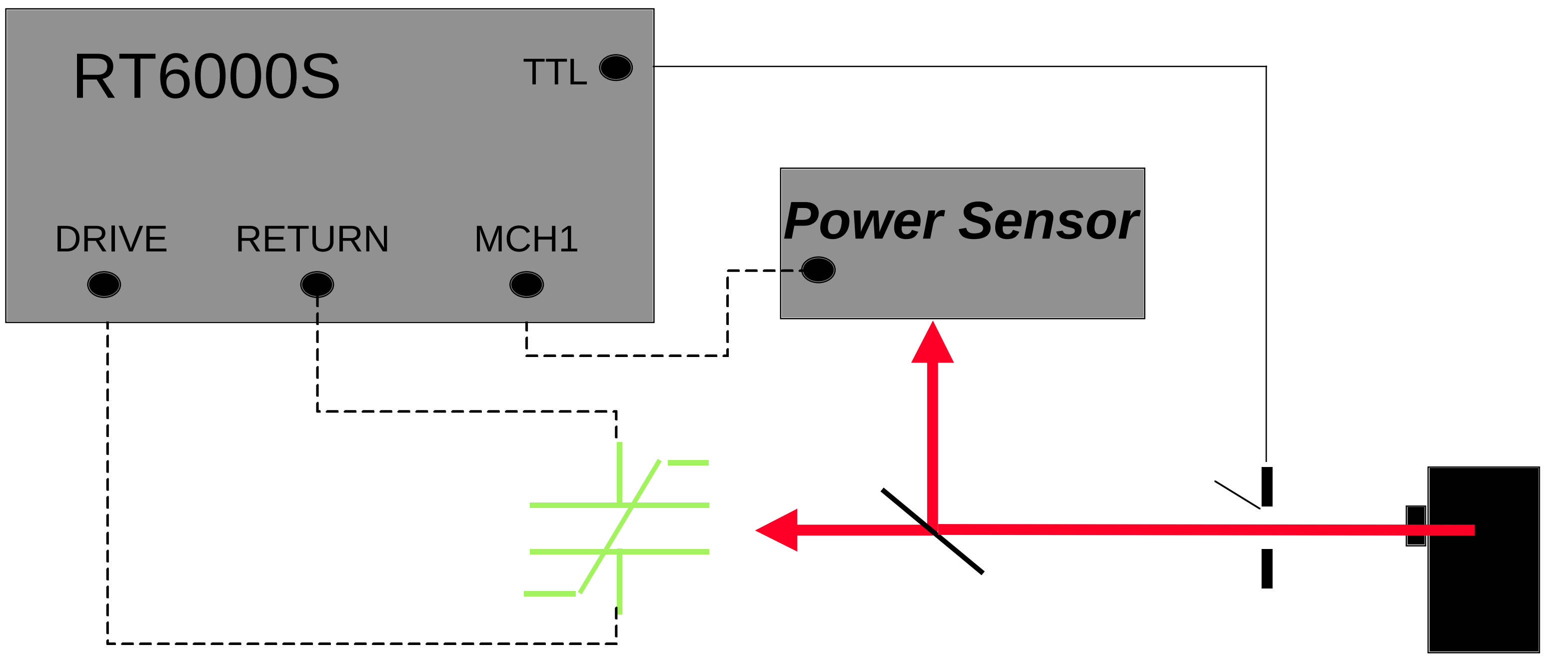


Piezoelectric Response of Thin Film PNZT



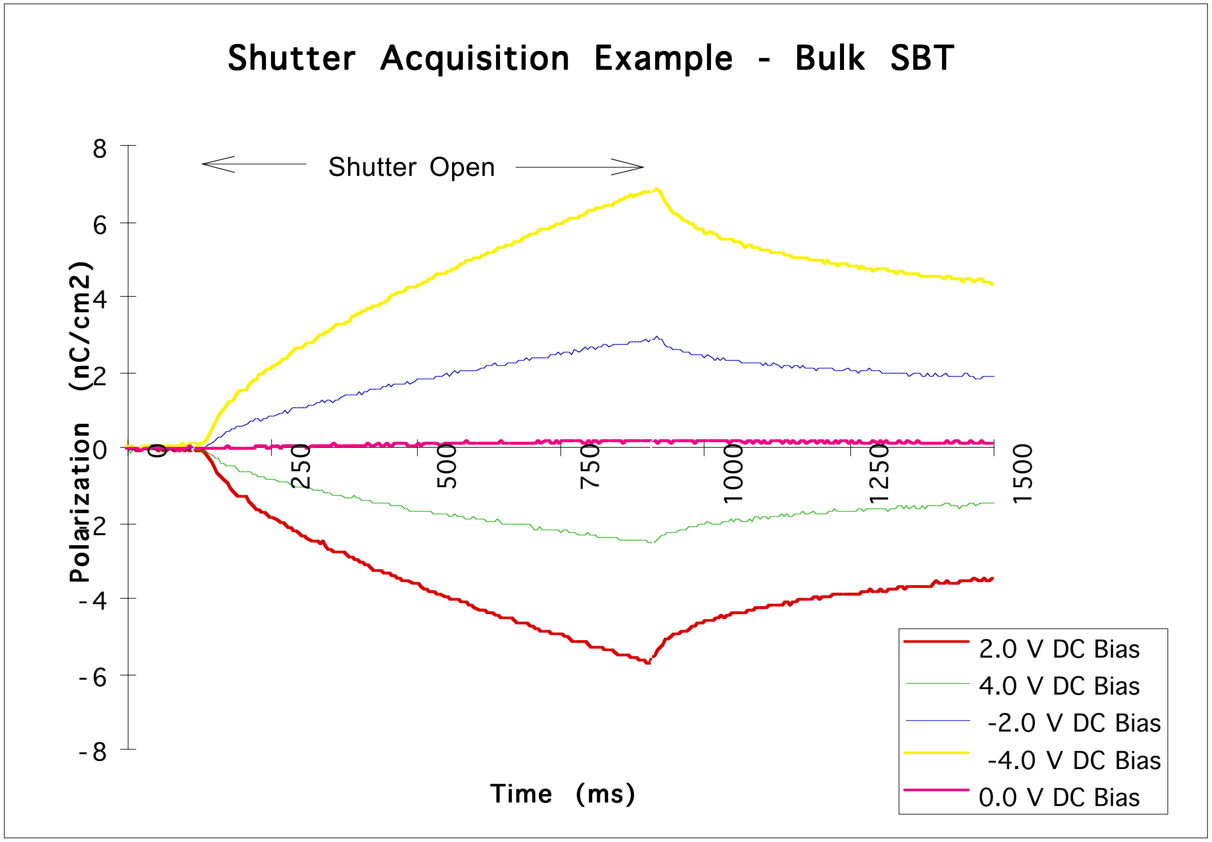


Pyroelectric Measurement



PIEZO software takes input on the Multichannel from displacement or force sensors to collect piezoelectric properties simultaneously with electric properties.

Pyroelectric Response of BST



Conclusion

- Proper interpretation of test results cannot occur without an understanding of the underlying physics.

- A good test procedure is like fine wine:
  - *It takes time to mature!*
  - *Practice makes perfect!*
  - *It requires understanding of the equipment impact on the measurements*