Component Model of Ferroelectric Capacitors

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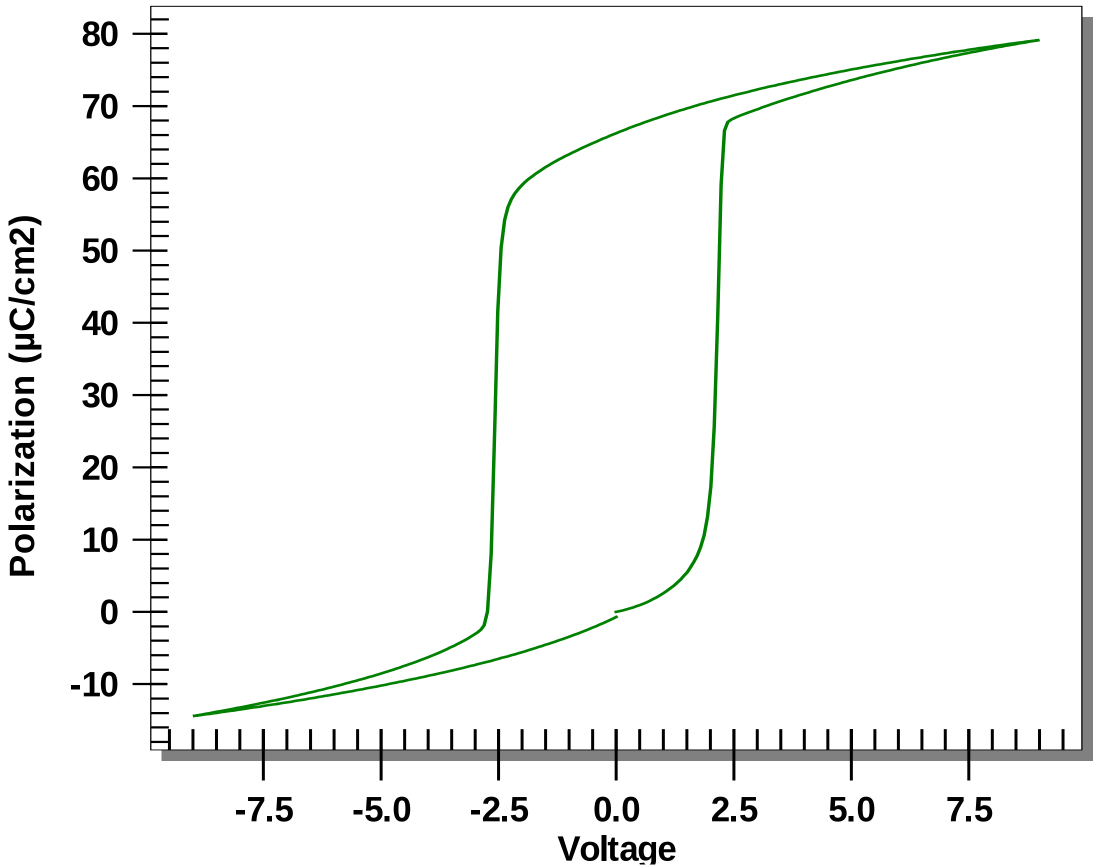
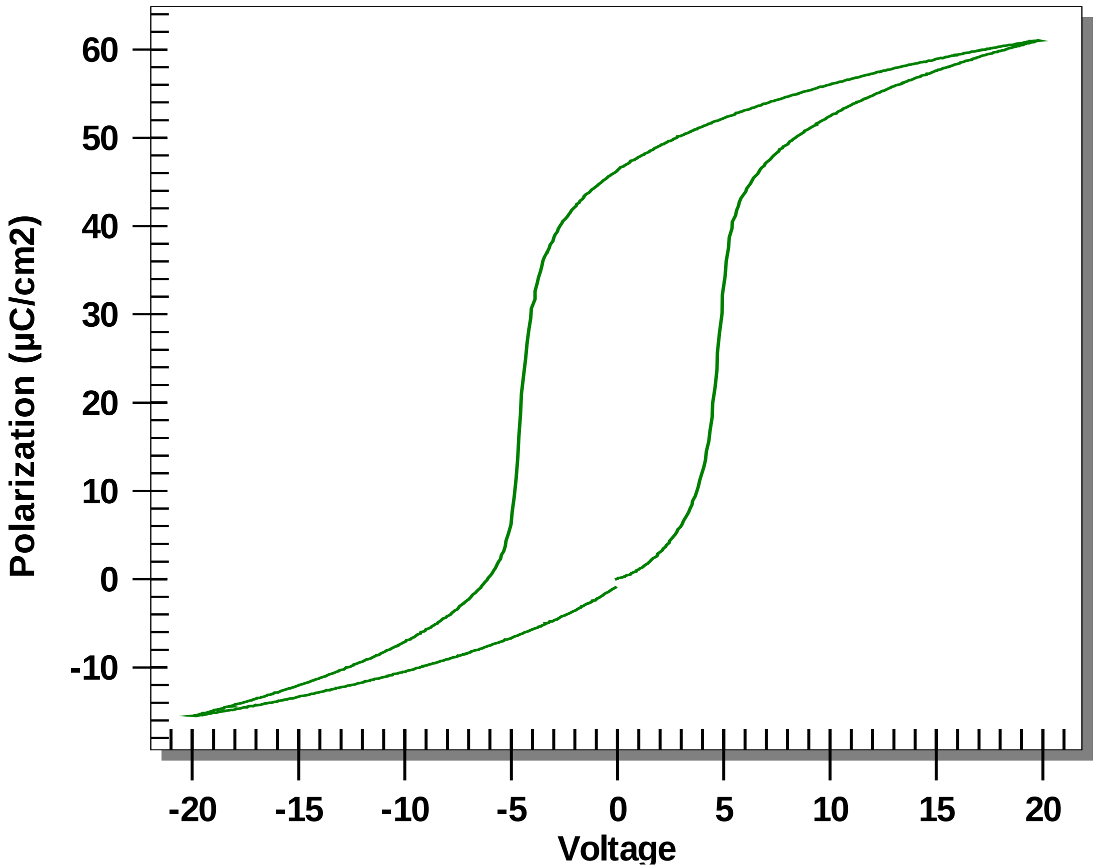
www.ferrodevices.com

An Excellent Hysteresis Loop



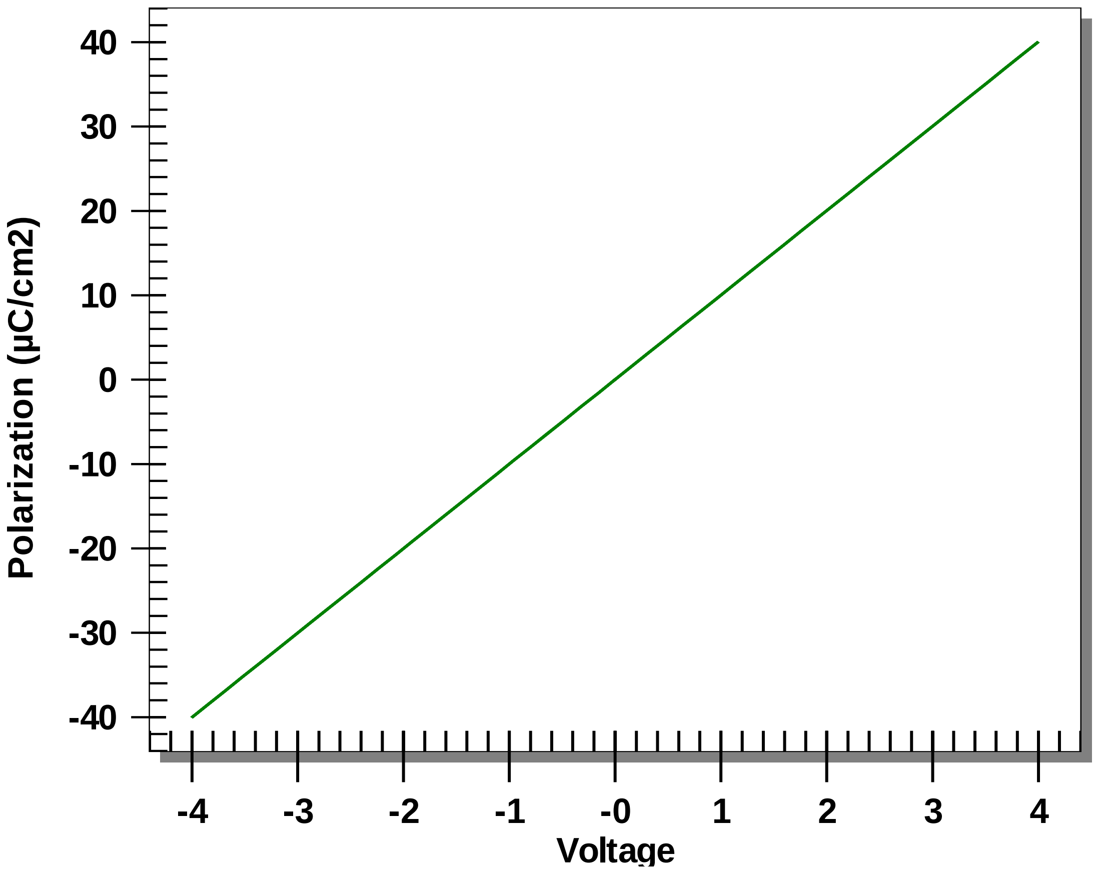
- This loop is nearly “perfect”. Most loops are not. After this presentation, you should be able to discern the difference upon inspection.

What is this?



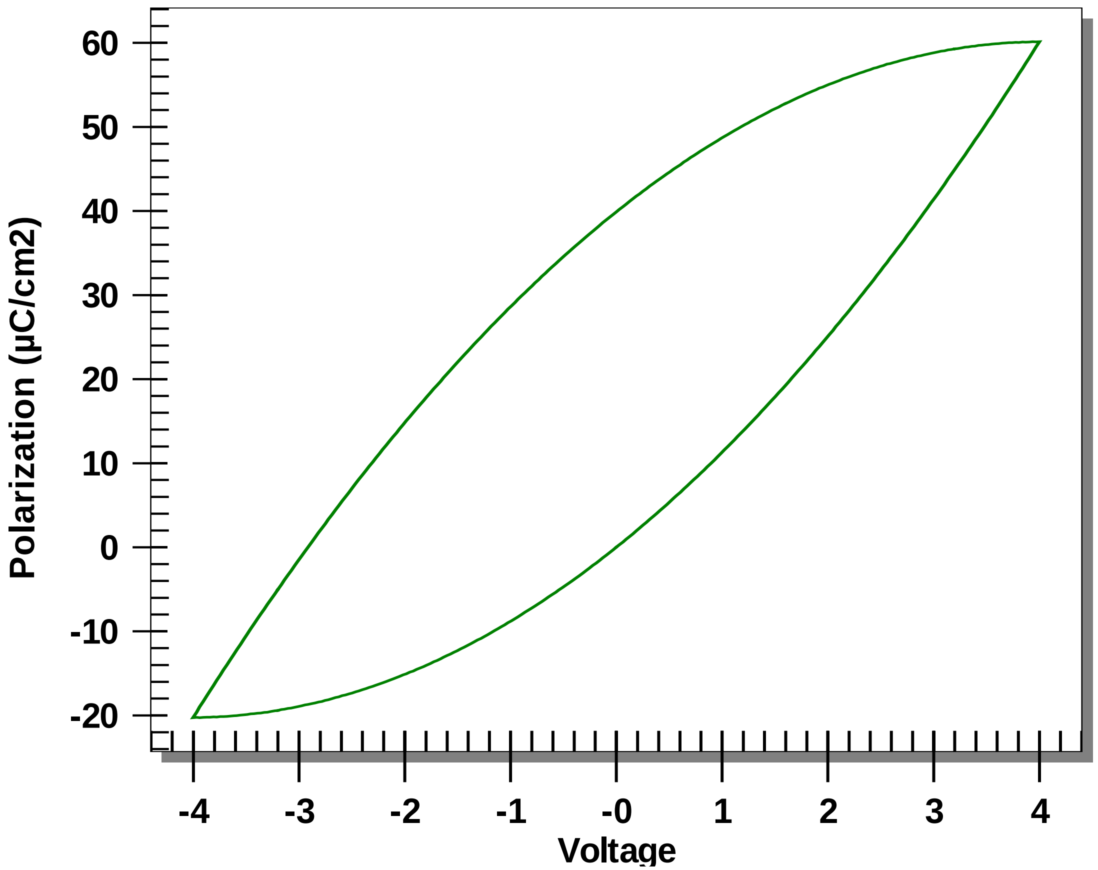
- Is this loop as good as the previous loop?

What is this?



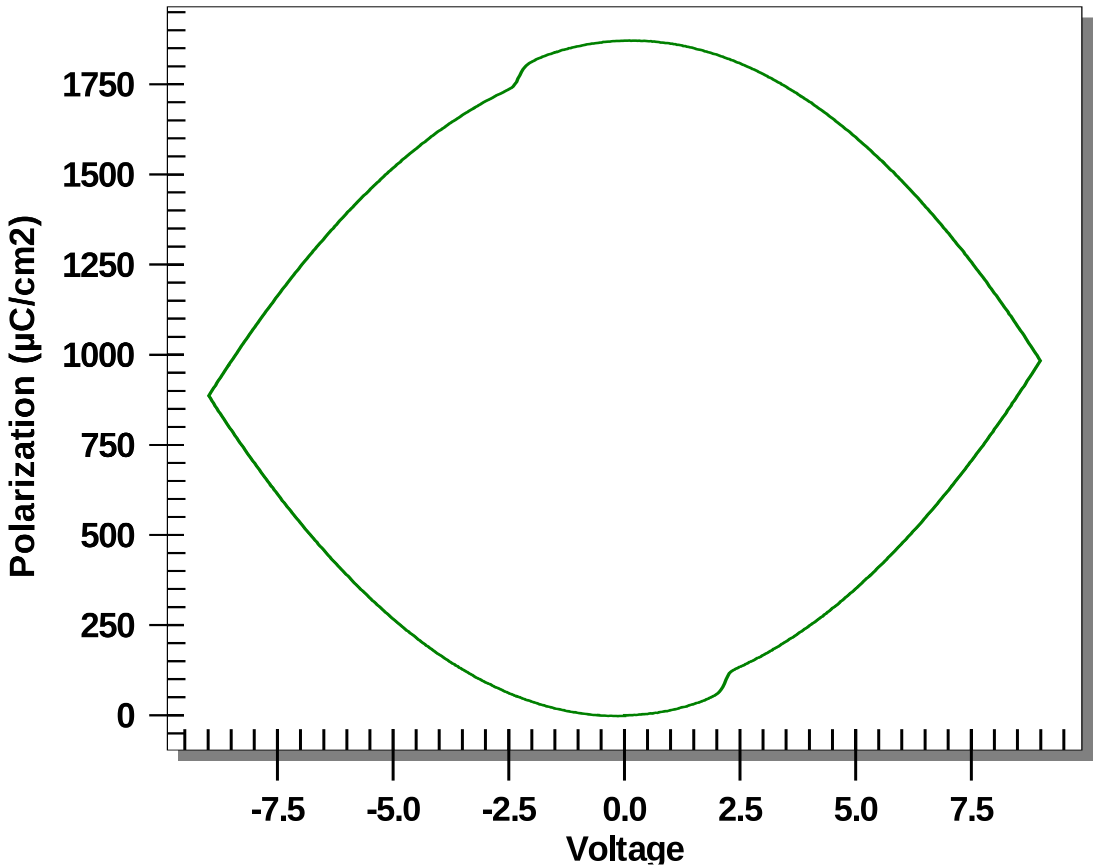
- Real clean. This one is easy.

A Harder One

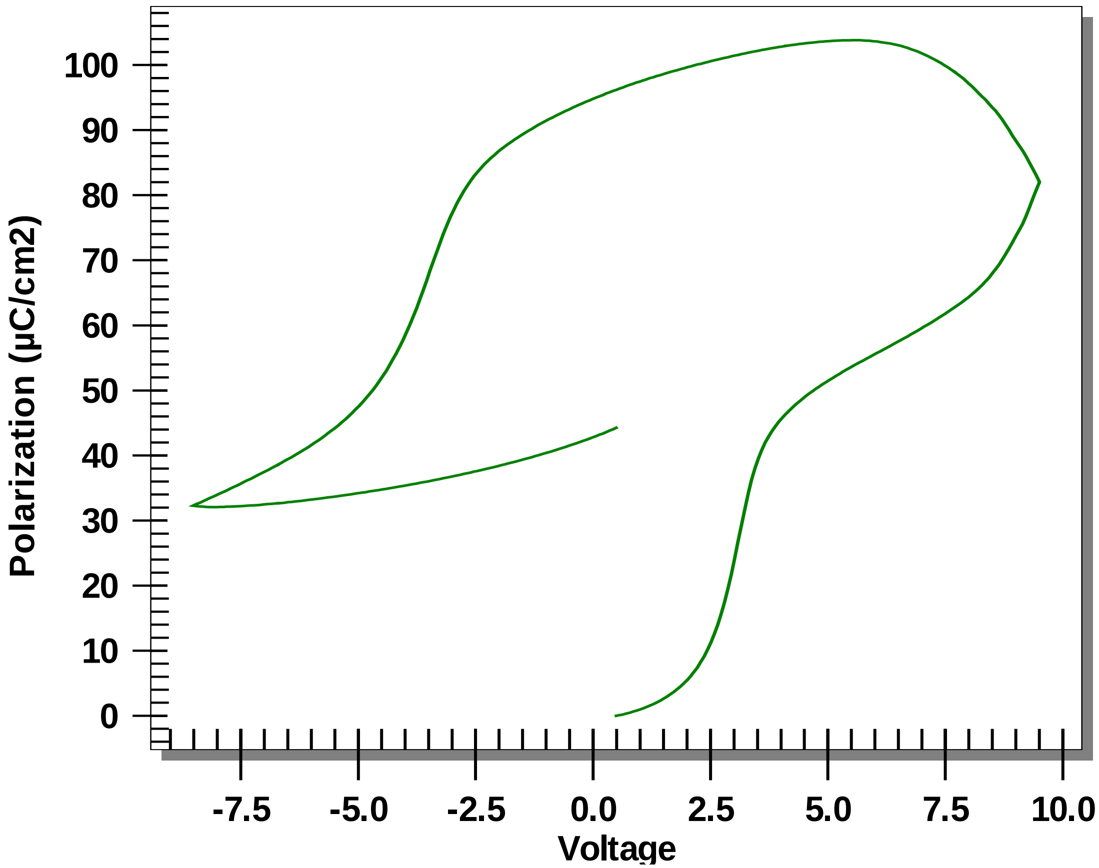


- Quite a few papers include loops that look like this.

Is this Ferroelectric?



What Happened Here?



Modeling Nonlinear Capacitance

- In electrical engineering, a fundamental approach to understanding a system is to break it into components and model each component.
  - Each component responds independently to the stimulus.
  - The output of a component is either the input to another component or is summed with the outputs of other components to form the response of the device.

The Components

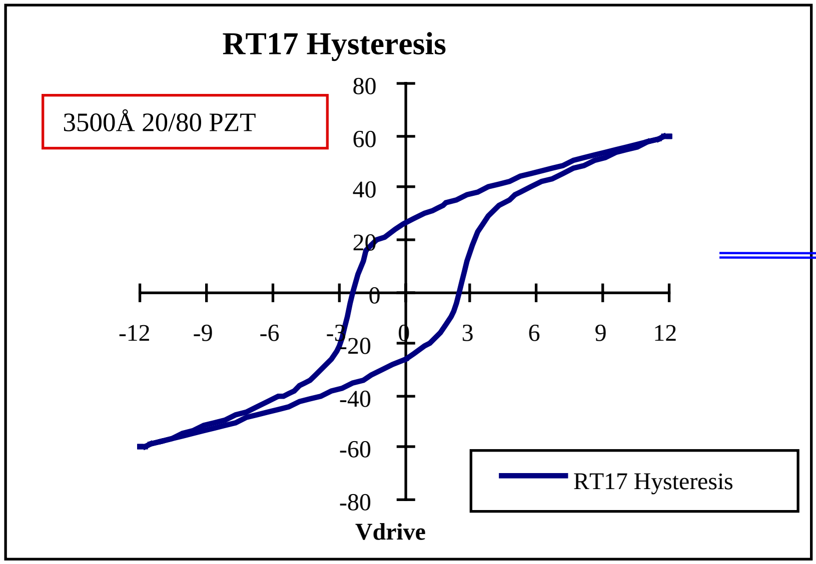
- According to Joe:
  - Linear capacitance
  - Non-linear capacitance
  - Remanent polarization
  - Remanent and nonremanent leakage
  - Remanent and nonremanent small signal capacitance
  - Reverse bias diode electrode interfaces
  - Left-overs

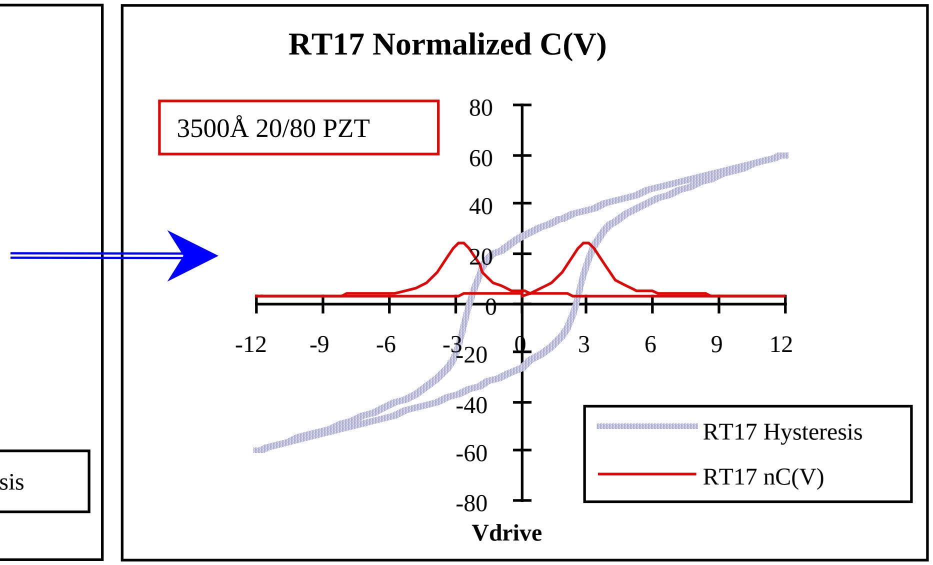
A Mathematical Tool

The hysteresis loop is polarization responding to applied voltage: P(V). Its derivative with respect to voltage is

$$\delta P/\delta V \Rightarrow (\delta Q/\delta V)/\text{Area}$$

which equals Large Signal Capacitance per Unit Area.





Normalized CV

The normalized CV [nCV] has the formula

$$\delta P/\delta V \Rightarrow (\delta Q/\delta V)/\text{Area}$$

and has the units of

$$\mu F/cm^2$$

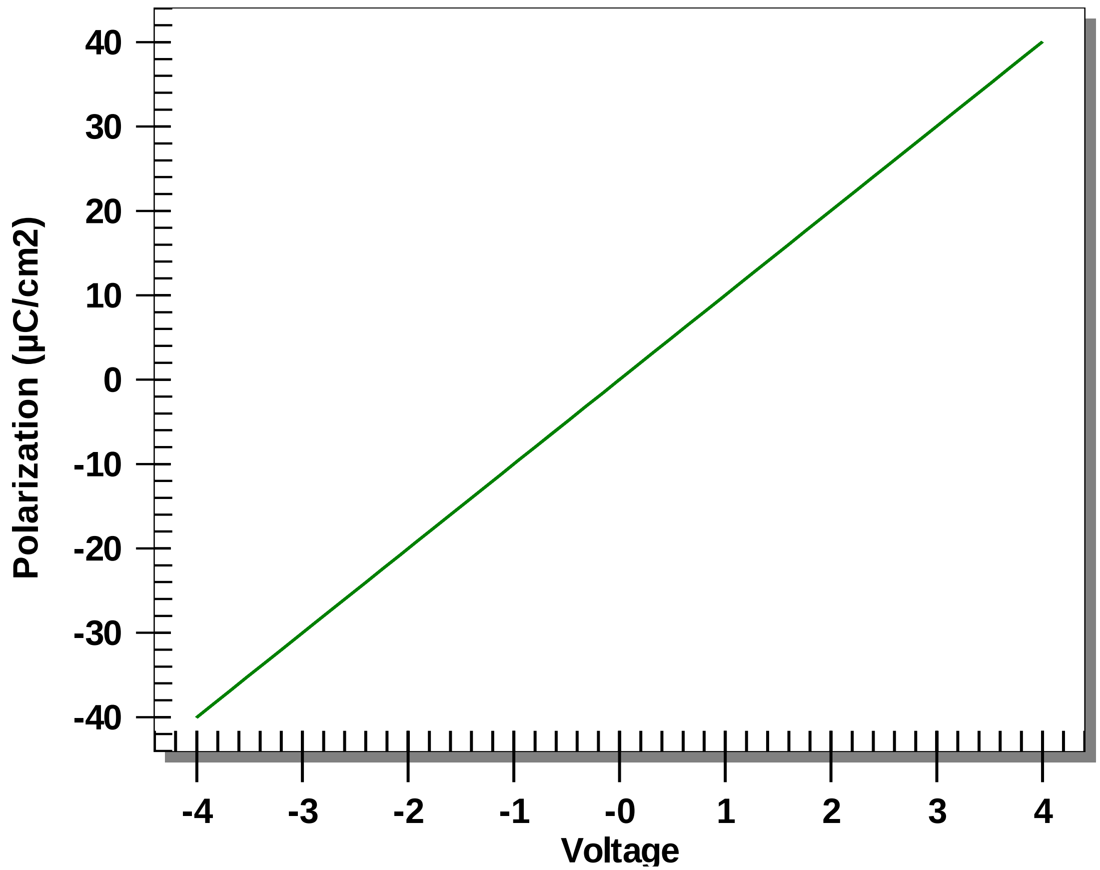
when the derivation is performed on the polarization units of

$$\mu C/cm^2.$$

Integration

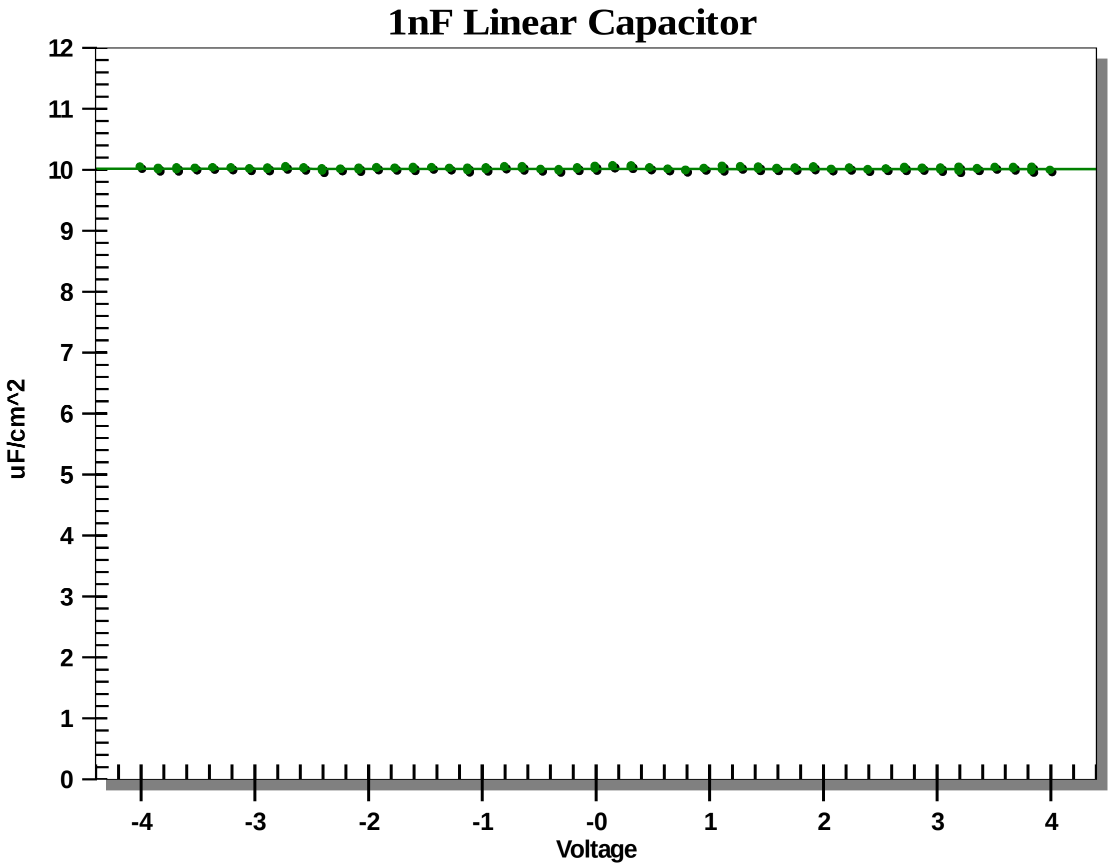
- Some measurements determine capacitance.
  – Small signal capacitance vs. Voltage
- Mathematical integration will convert the capacitance to its equivalent polarization contribution at each voltage.

Linear Capacitance



- Q = CxV where C is a constant

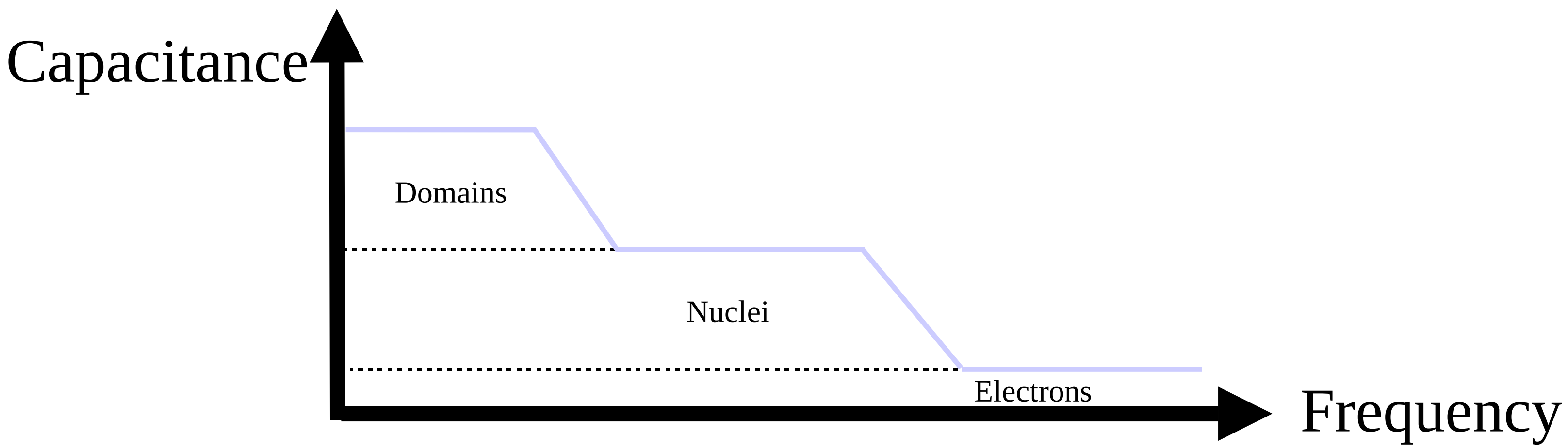
Derivative of Linear Capacitance



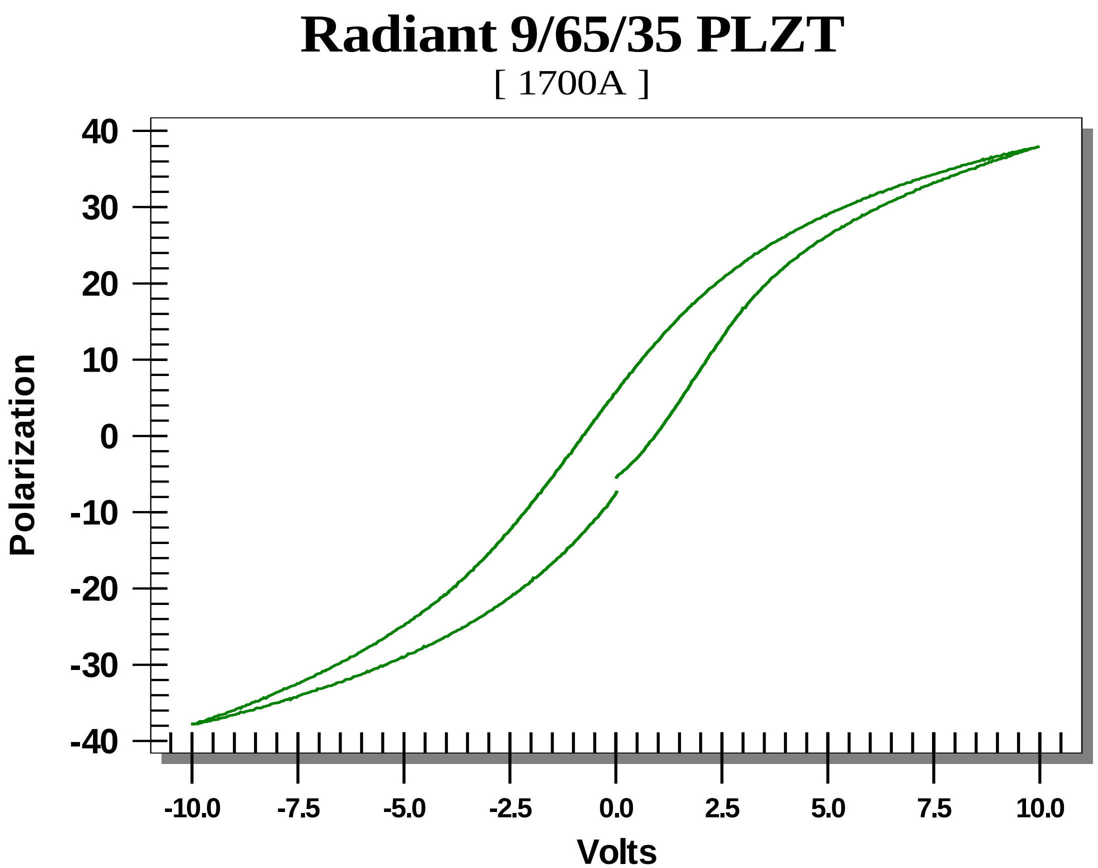
- C is a constant slope so the derivative of linear capacitance is simply a vertical offset on the nCV plot.

Capacitance vs Frequency

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

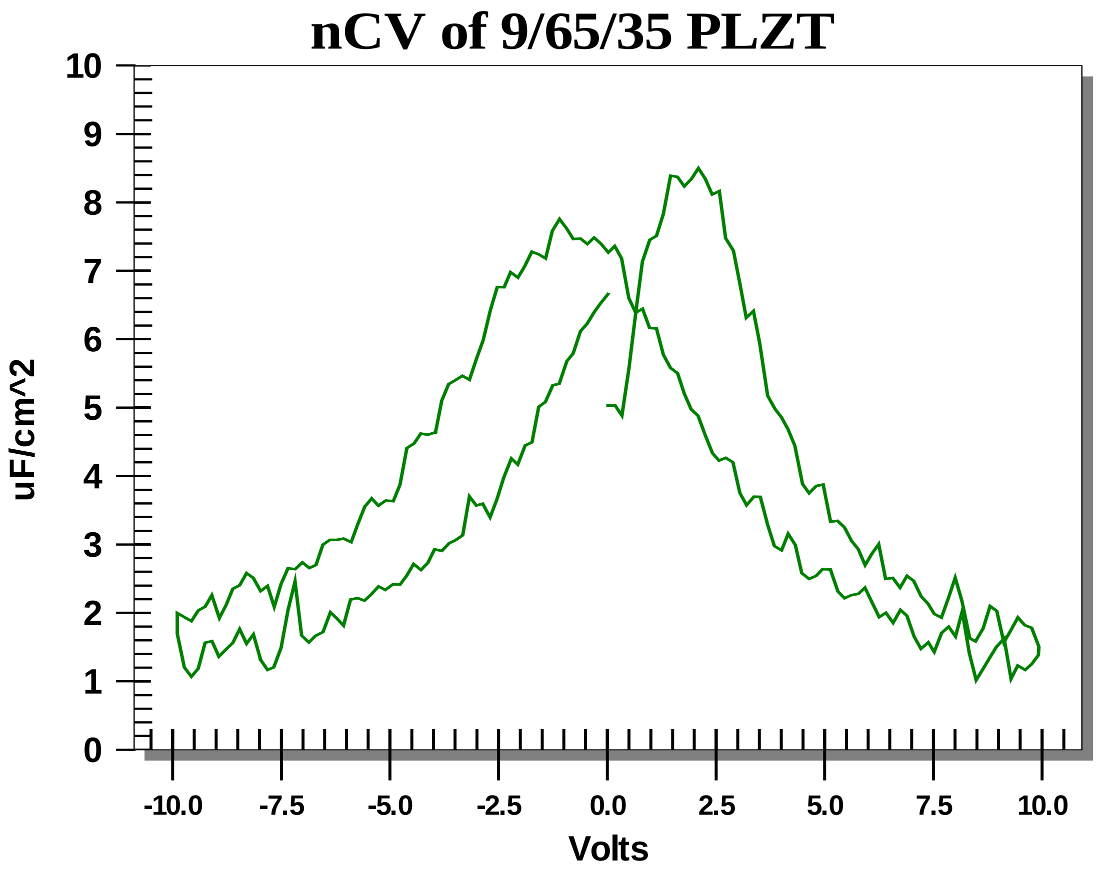


Non-linear Capacitance



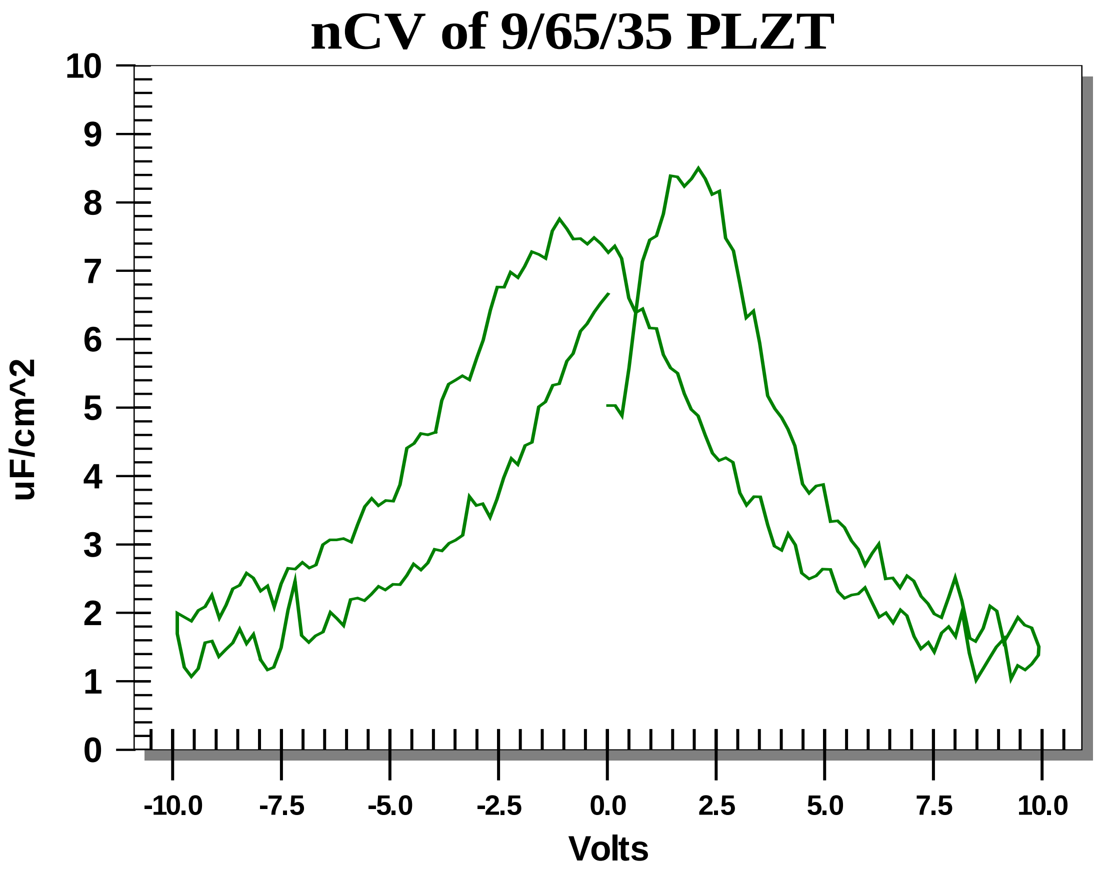
- When the electric field begins to move atoms in the lattice, the lattice stretches, changing its spring constant. Capacitance goes down.

The Derivative



A non-linear capacitor has decreasing capacitance as the applied voltage increases.

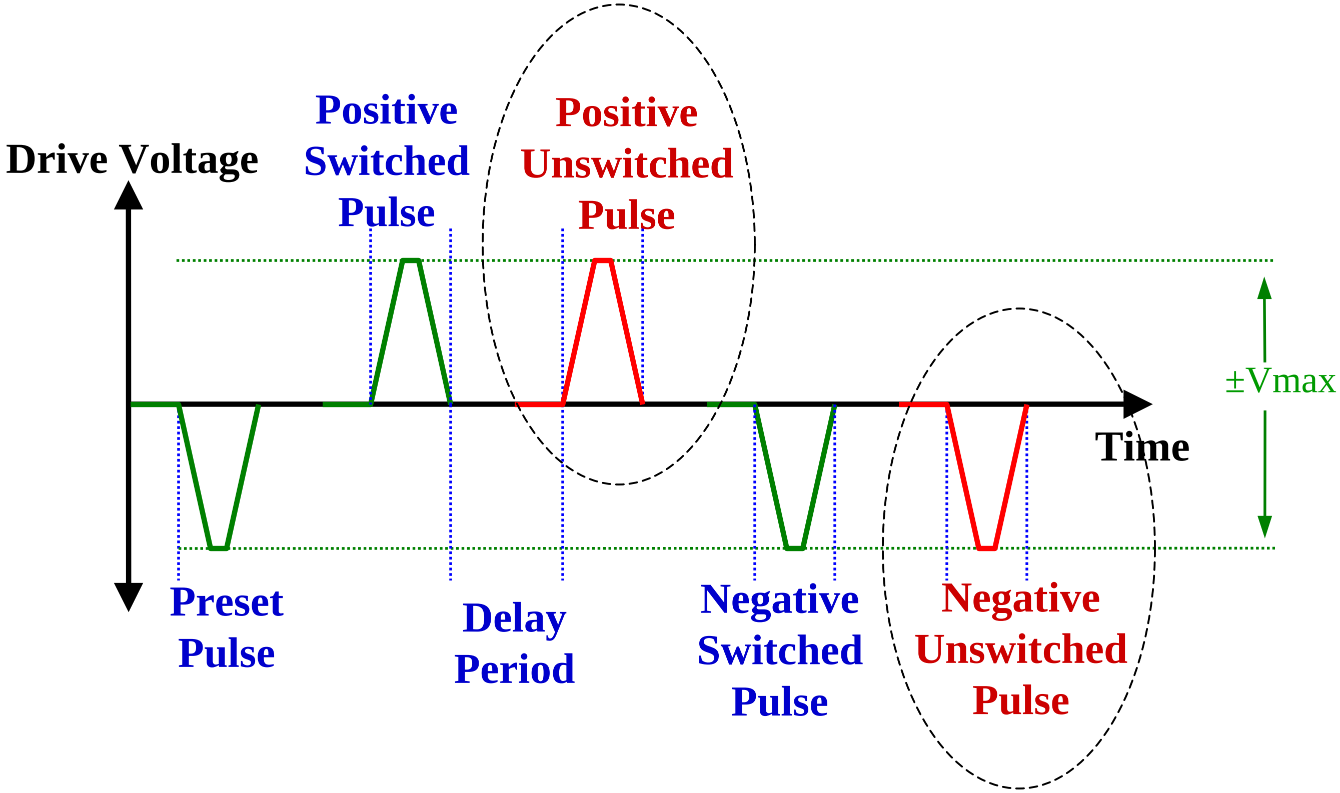
Linear vs. Non-linear Capacitance



This device has both linear and non-linear capacitance. The linear capacitance is the vertical offset of the nCV plot. The tips do not touch zero.

Remanent Polarization

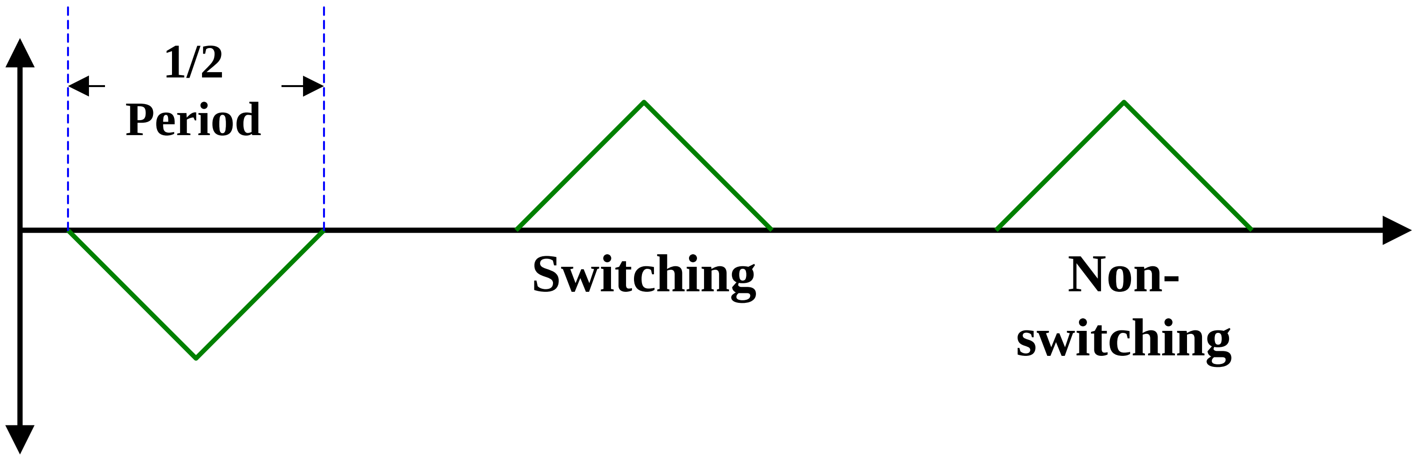
- The PUND test is a familiar measurement:



- Any matched pair of switched and non-switched pulses may be subtracted from each other to get the remanent polarization.

Remanent Hysteresis

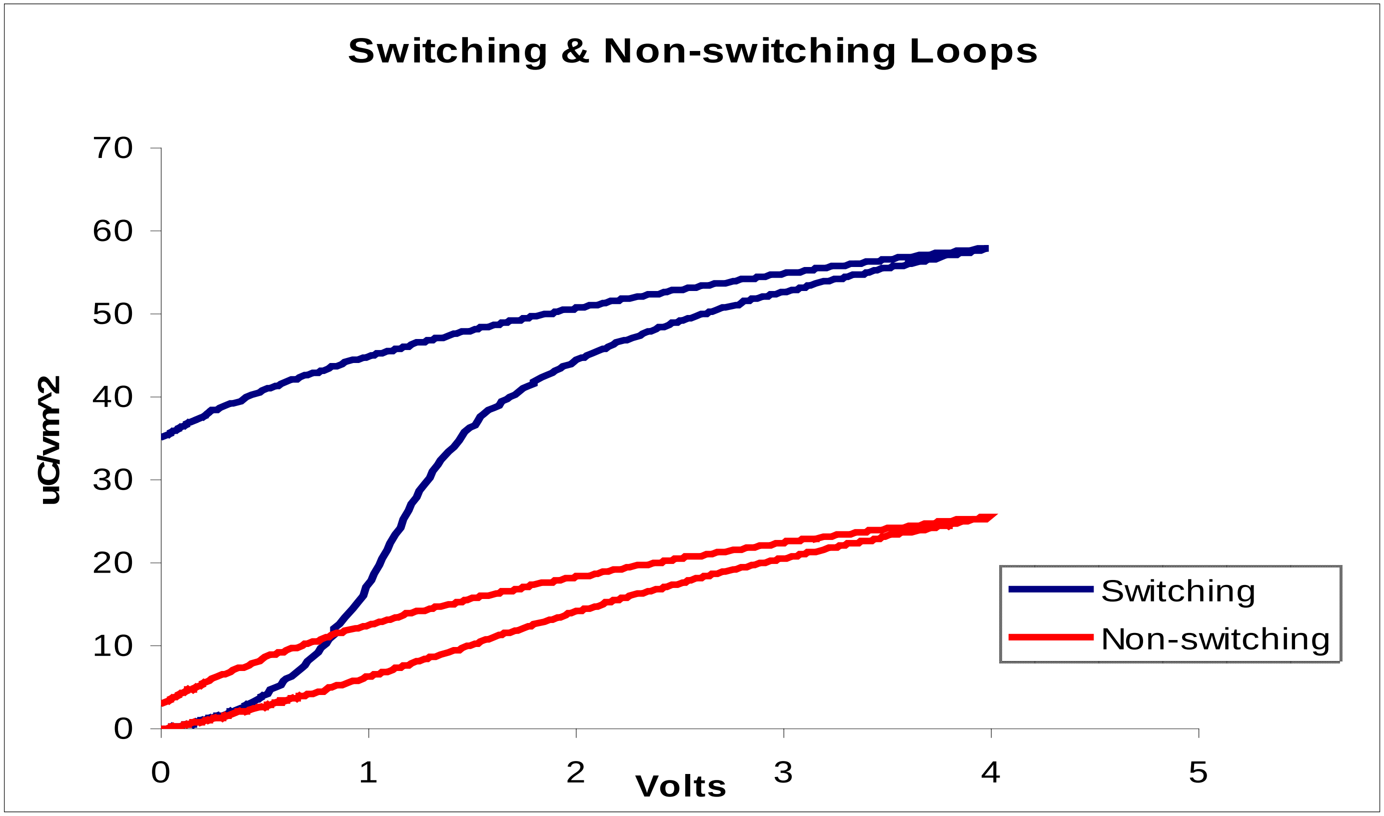
- The same measurement may be made using half-hysteresis loops instead of pulses:



- The difference between the switching and non-switching measurements will give the Remanent Polarization vs Voltage function.

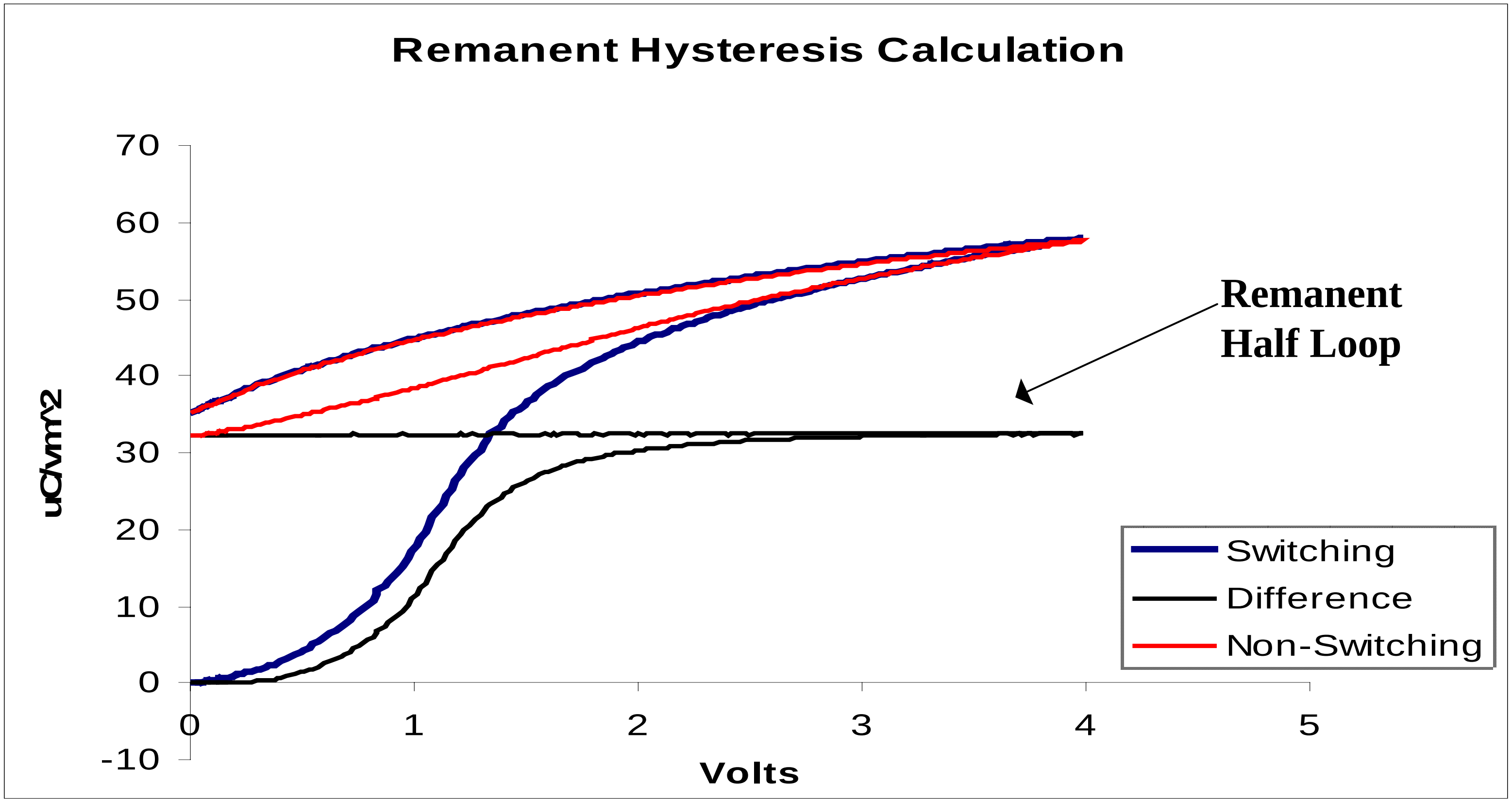
Remanent Hysteresis

Switching and Non-switching half loops:



Remanent Hysteresis

- PUND: P*r - P^r = dP = Qswitched
- Hysteresis: Switching - Non-switching = Remanence:



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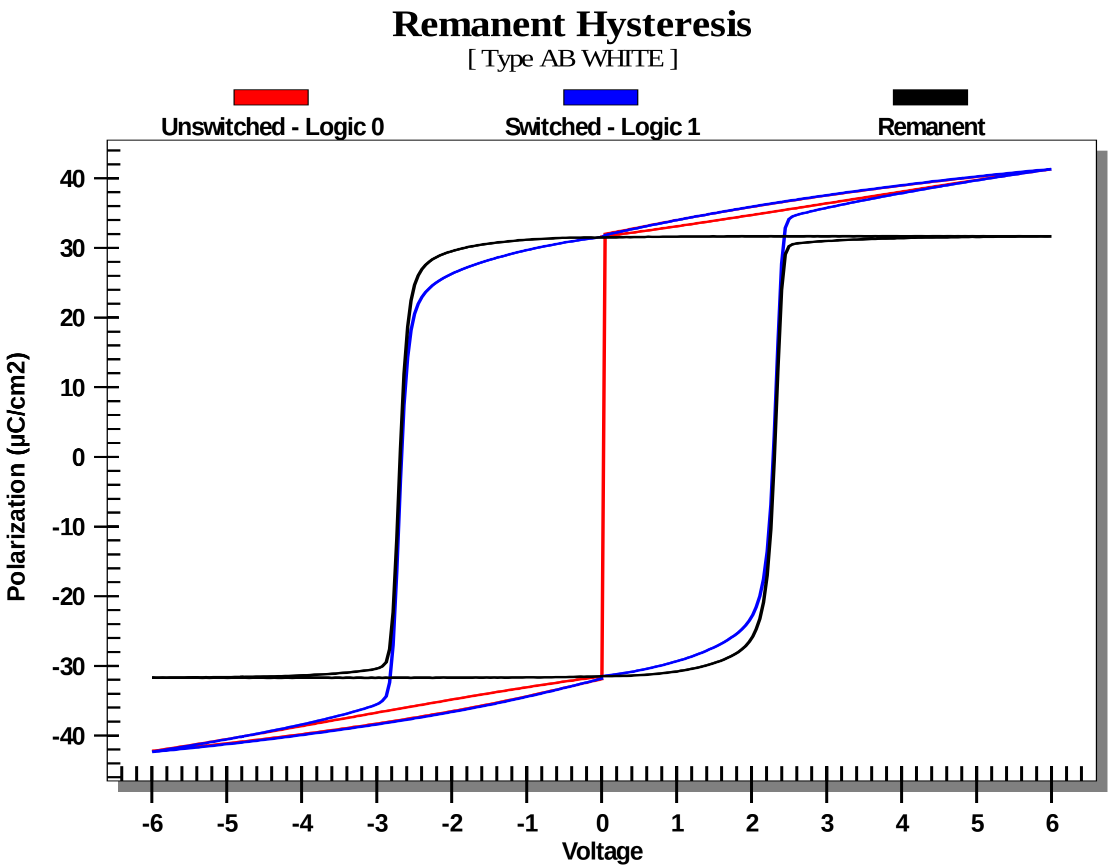
Remanent Hysteresis

- The test may be executed in both voltage directions and the two halves joined to show the switching of the remanent polarization that takes place *inside* the full loop.

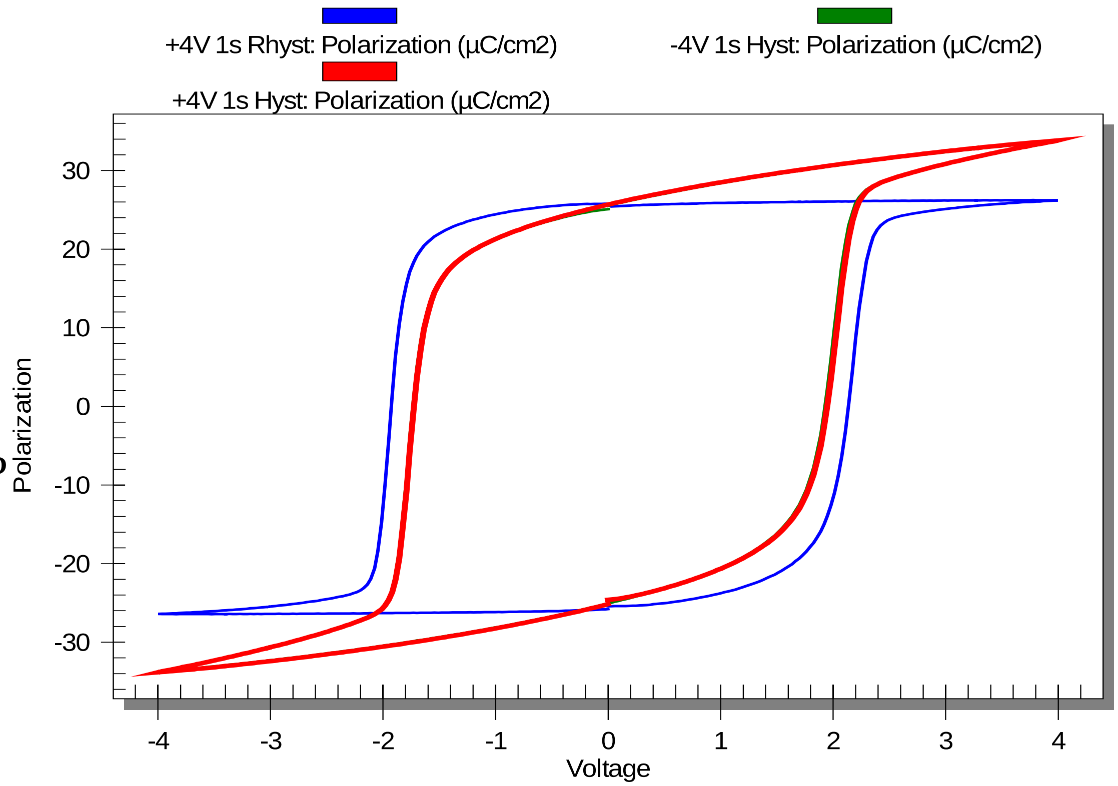


Remanent vs. Normal Hysteresis

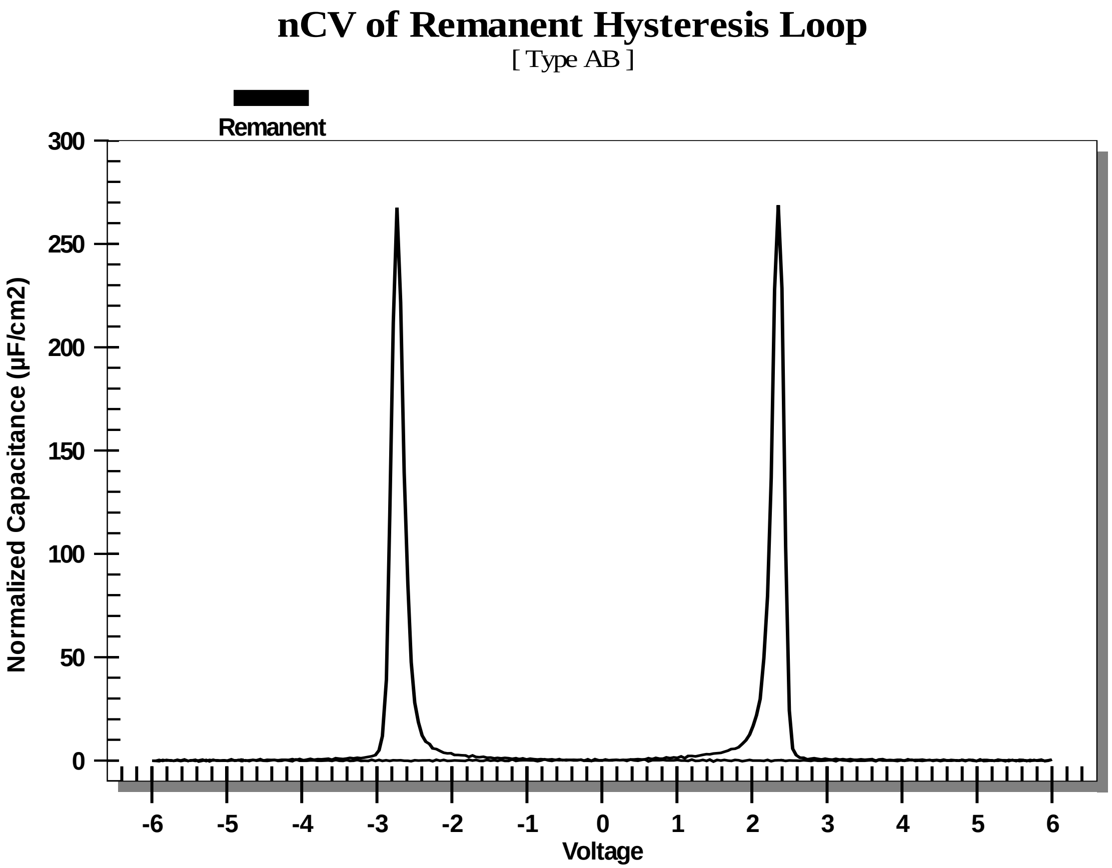
- The first stage of the experiment consisted of measuring two 4V hysteresis loops going in opposite directions (including their gaps) and a 4V remanent polarization loop.
  - The remanent hysteresis is in blue.
  - The full loops in opposite directions overlay exactly.
  - The Vc of the remanent loop lies outside that of the normal loops. Why? (Hint: the reason is purely mathematical.)
  - The Vc of the remanent loop is the true Vc.

1 Second Hyst vs 1 second Rhyst

[Radiant Type AB White, 9V preset]



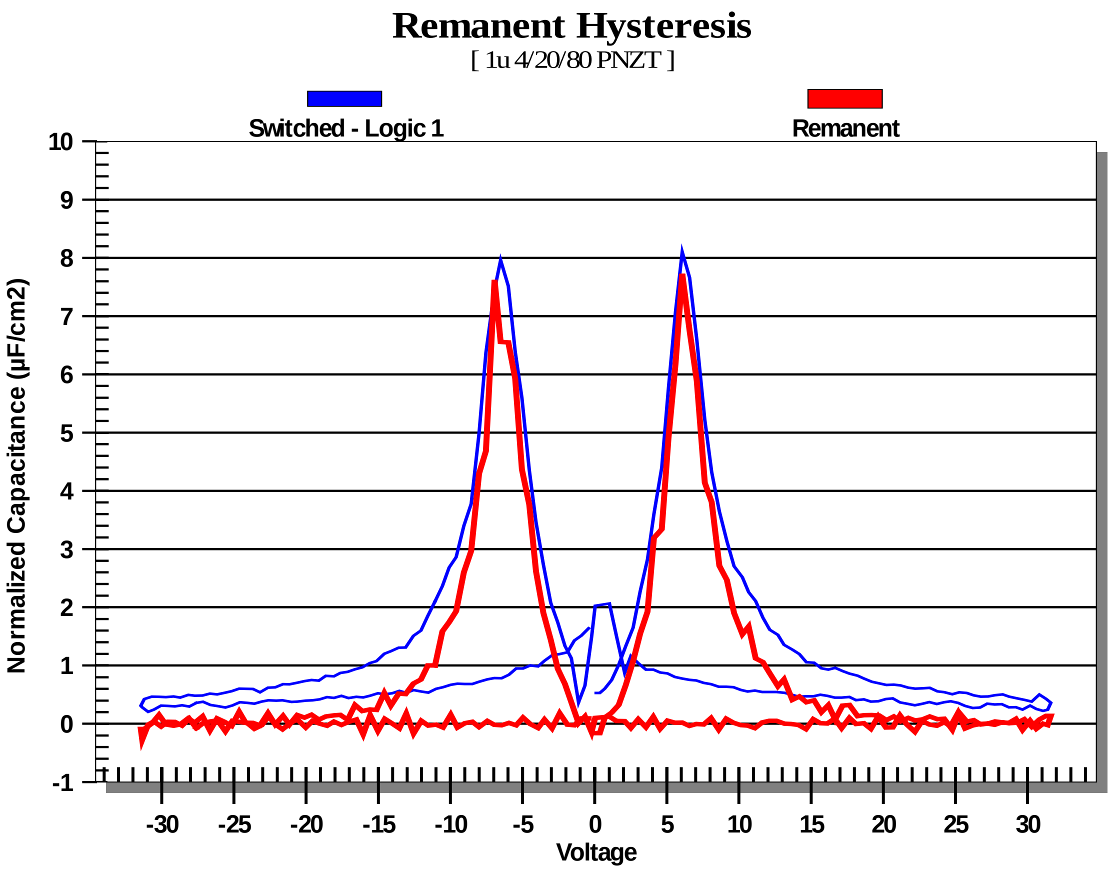
The Derivative



- The nCV of the remanent polarization loop rests on the X-axis because it has no capacitance on the re-trace.

The Perfect Capacitor

- A perfect capacitor combines non-linear capacitance with remanent polarization.



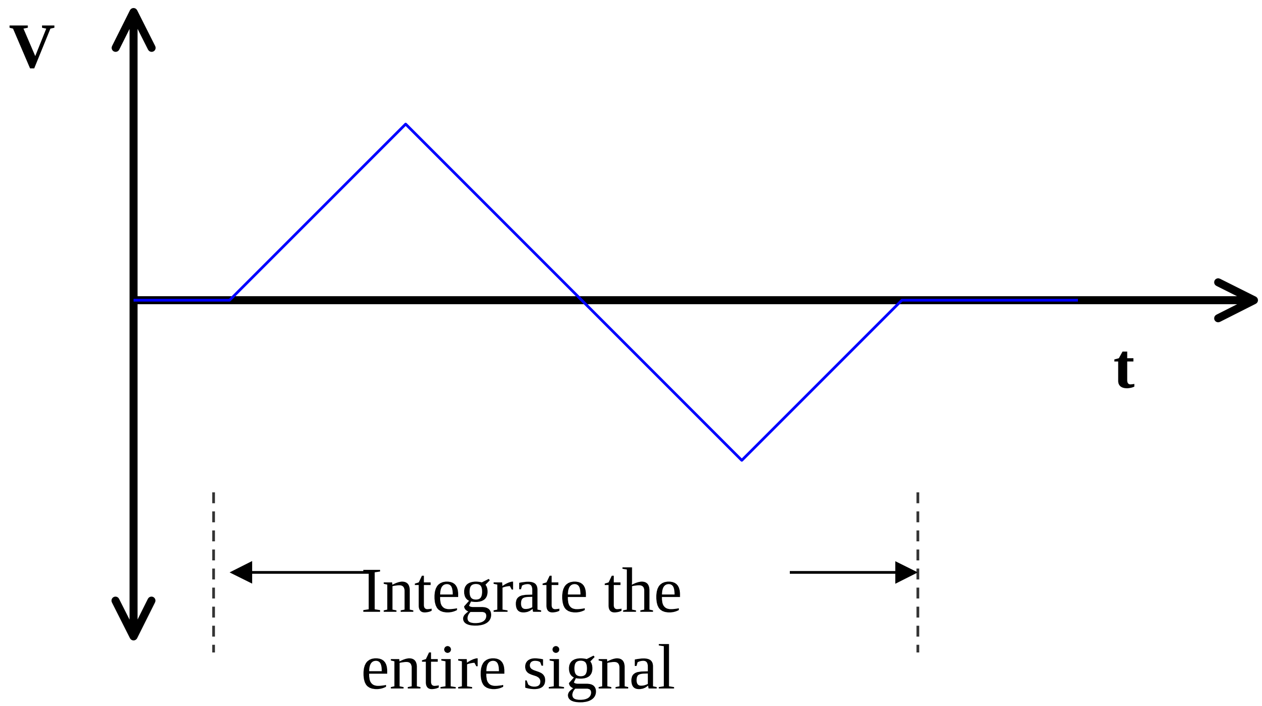
Hysteresis in Small Signal Capacitance

- The small signal capacitance versus bias voltage is determined by measuring the sample capacitance with a low amplitude signal at a series of bias voltages.
  - Theoretically, the signal amplitude should be small enough that it does not disturb the state of the capacitor.
- While this is a noble effort, it cannot be ignored that the remanent polarization modulates the small signal capacitance.
- The state of the remanent polarization must be managed during measurements of small signal capacitance.

Small Signal vs Large Signal

- The ferroelectric hysteresis measurement is defined at Radiant as a "large signal" measurement of the polarization properties of the sample.
- "Large signal" means that the test waveform has a large enough amplitude to switch dipoles in the ferroelectric material.
- As well, the "large signal" measurement captures and integrates all changes the sample experiences during the test waveform, showing its entire trajectory.
- The measurement result contains contributions from all components of the sample, including the remanent polarization and parasitics.

Small Signal vs Large Signal



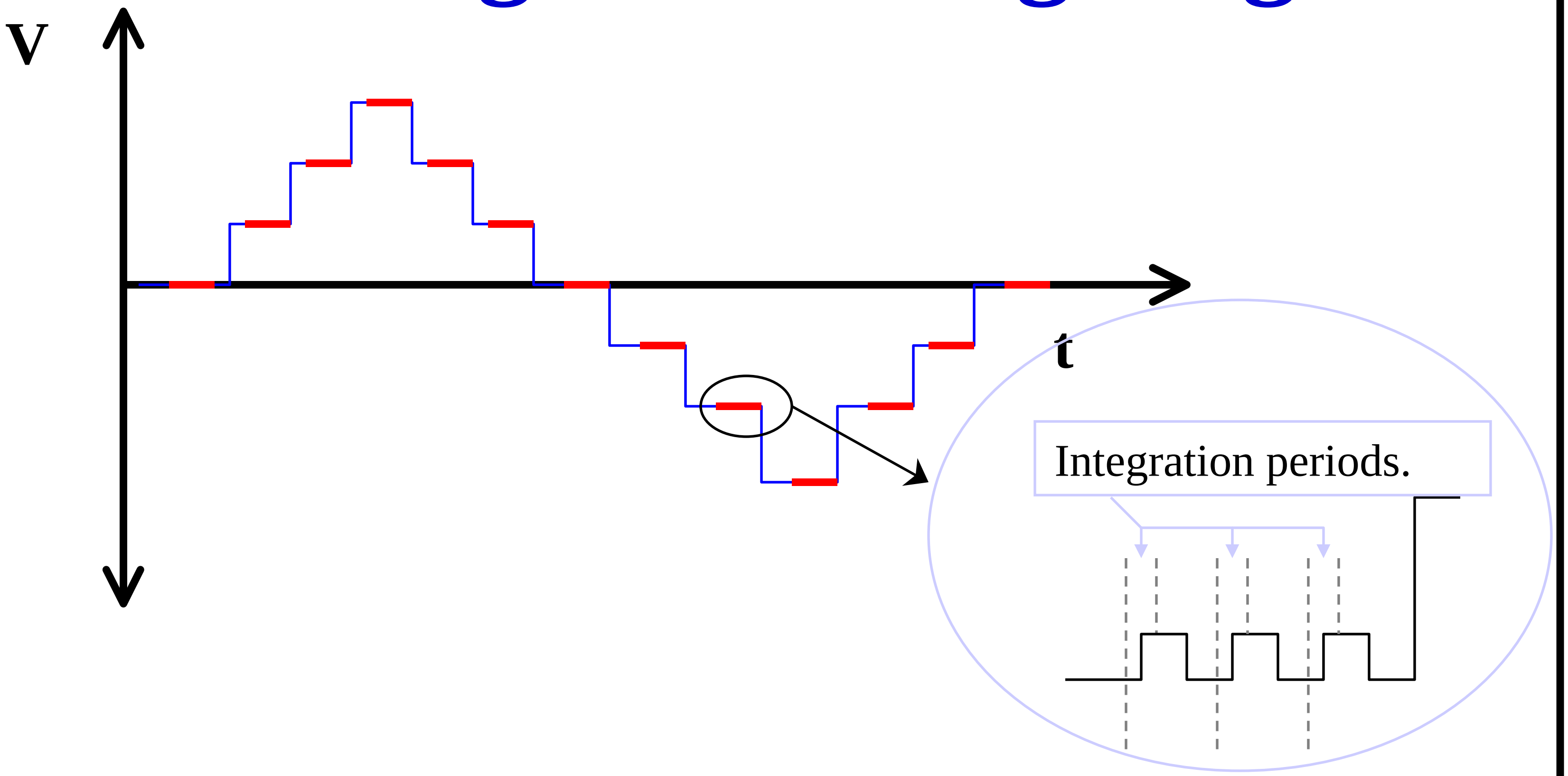
- A "large signal" measurement captures every electron that moves into or out of the capacitor during the stimulus waveform.

Small Signal vs Large Signal

- The “small signal” measurement is defined as one where the test amplitude is small compared to that required to switch remanent polarization in a ferroelectric capacitor.
- Since the response of a non-linear sample changes with the absolute value of the voltage applied and the remanent polarization state, the “small signal” measurement must also have a steady state voltage component as well as a remanent polarization pre-set procedure to put the sample in the appropriate state.
- Therefore, the “small signal” measurement captures and integrates <u>only</u> those changes the sample experiences during a small amplitude stimulation of the sample at a specified voltage and polarization state.

By definition, the “small signal” measurement contains no contribution from <u>switching</u> dipoles!

Small Signal vs Large Signal



- In “small signal” measurements, many small measurements are taken that capture only the small changes associated with small stimuli.
- In a “small signal” measurement, the sequence of DC bias values is the same as the voltage profile used for hysteresis so the two can be compared directly.

Small Signal vs Large Signal

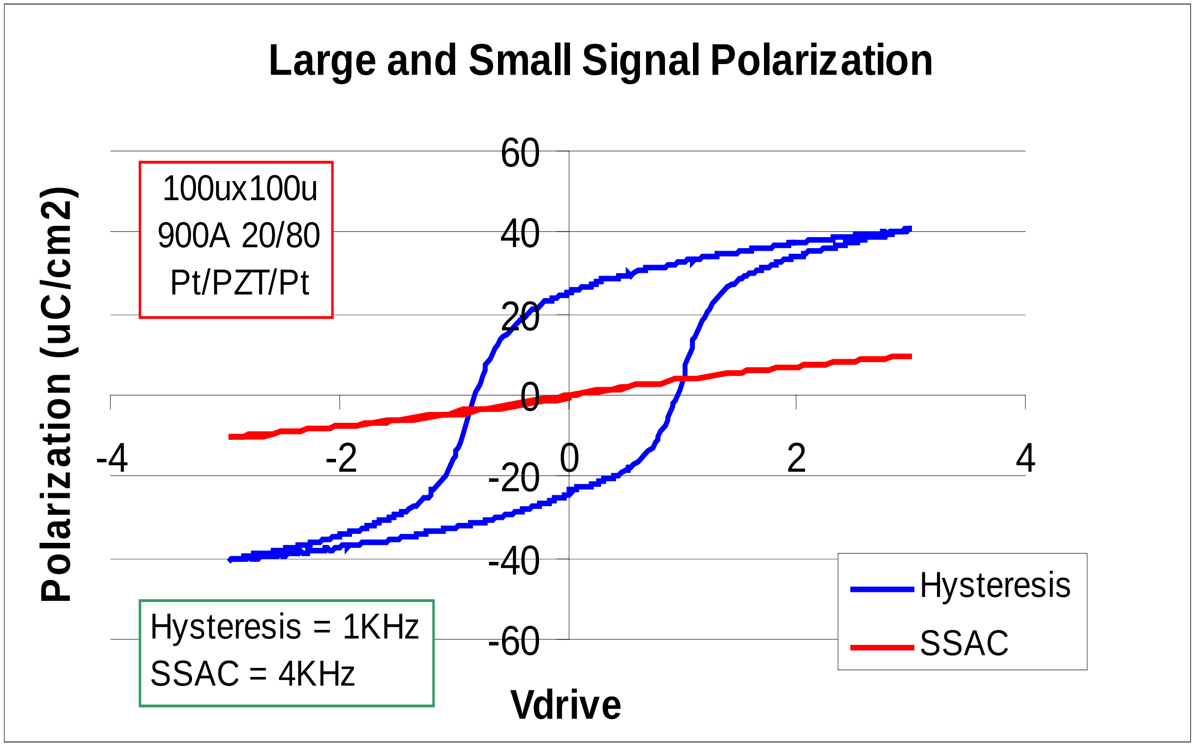
- Radiant testers execute both standard "large signal" hysteresis and "small signal" capacitance measurements.

  - "large signal" hysteresis results are normally given in units of polarization ($\mu C/cm^2$) but can be converted to capacitance using the CV or Normalized CV plotting functions of the Hysteresis Task or the Hysteresis Filter.

  - "small signal" measurements are normally given in units of capacitance (nF or $\mu F/cm^2$) but can be converted to equivalent polarization using the appropriate plotting function of the Advanced CV measurement task.

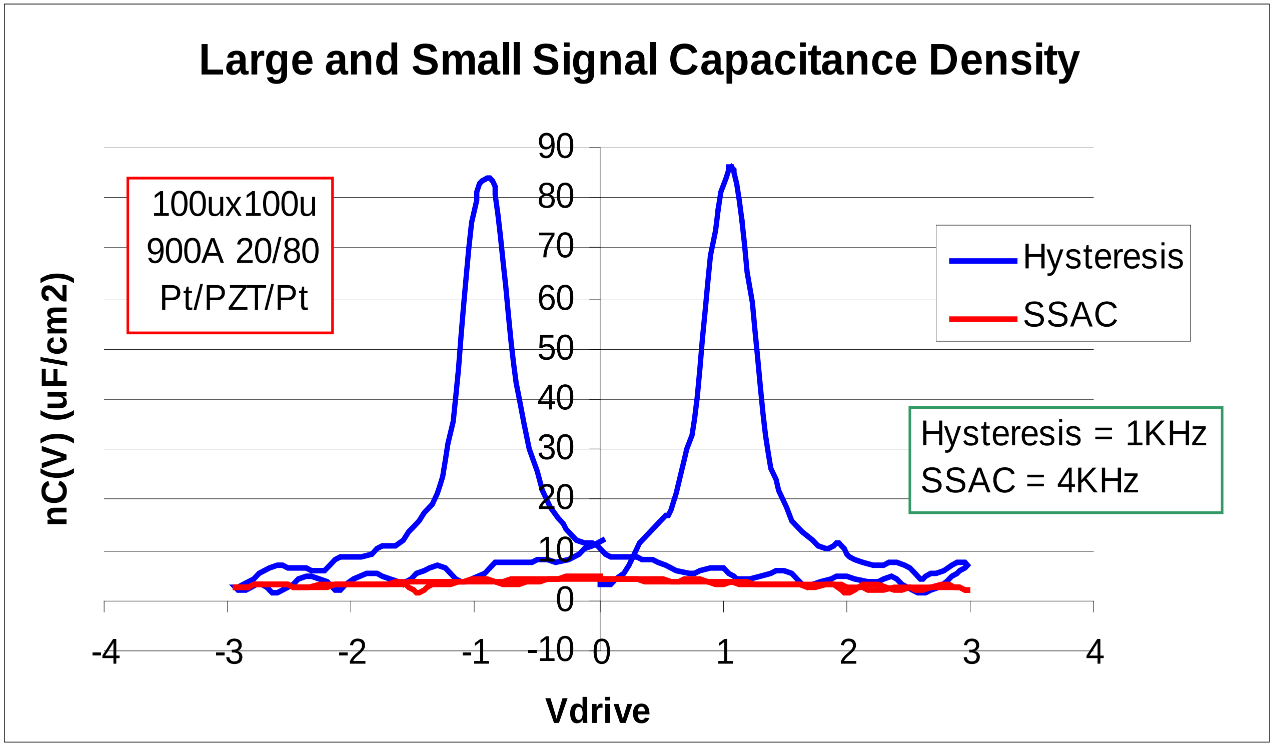
Small Signal vs Large Signal

- Comparison of the Hysteresis and Polarization of the Small Signal Capacitance is shown below:

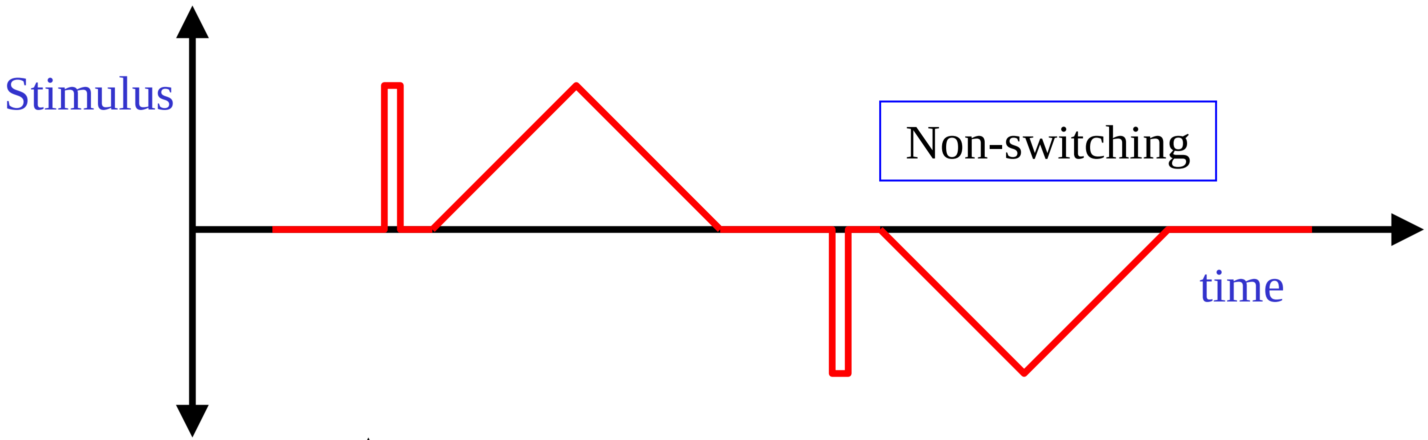


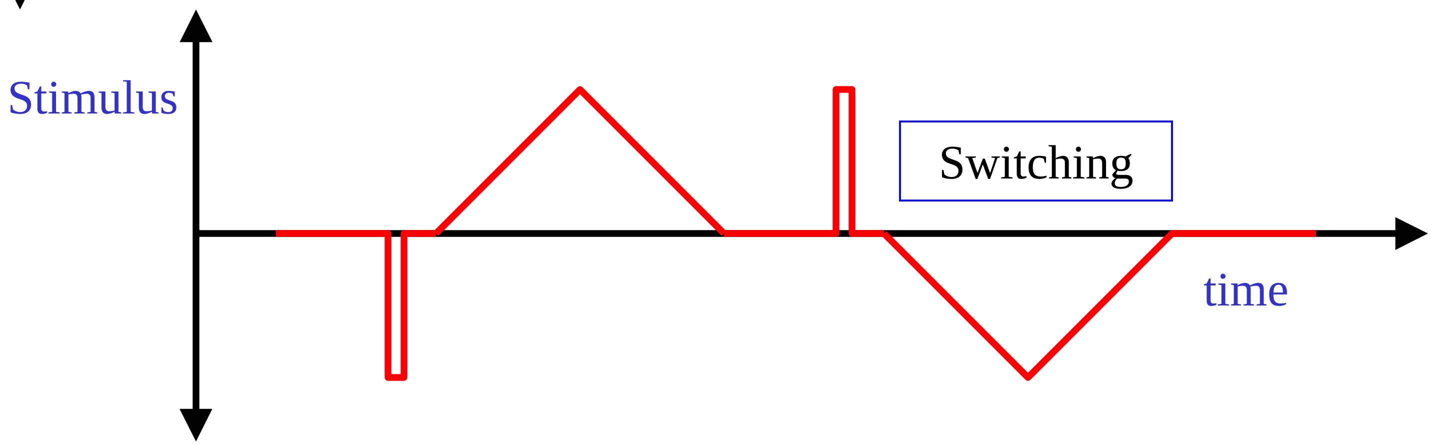
Small Signal vs Large Signal

- Comparison of the Large and and Small Signal Capacitance is shown below:

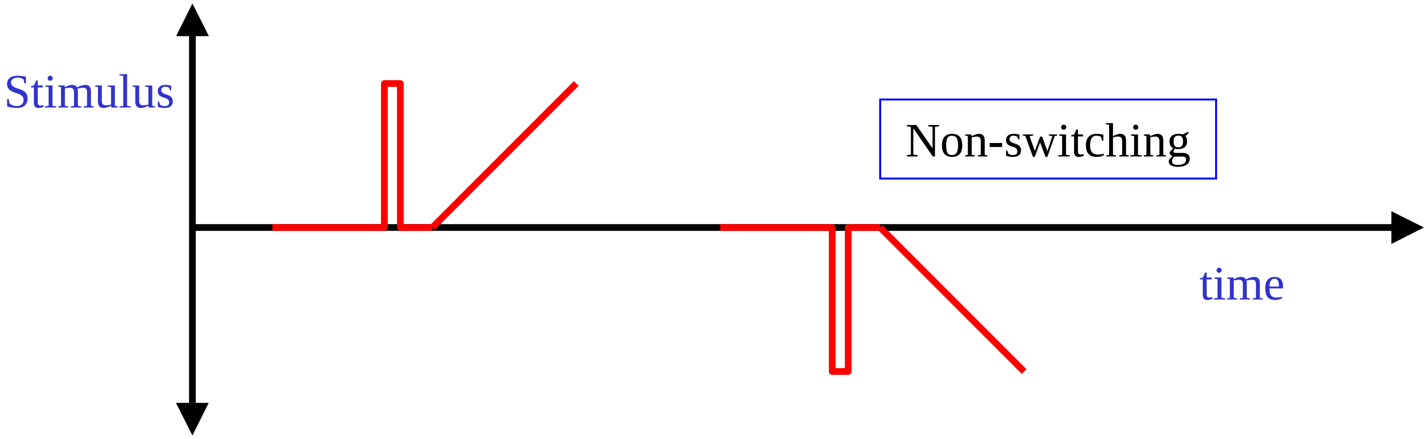


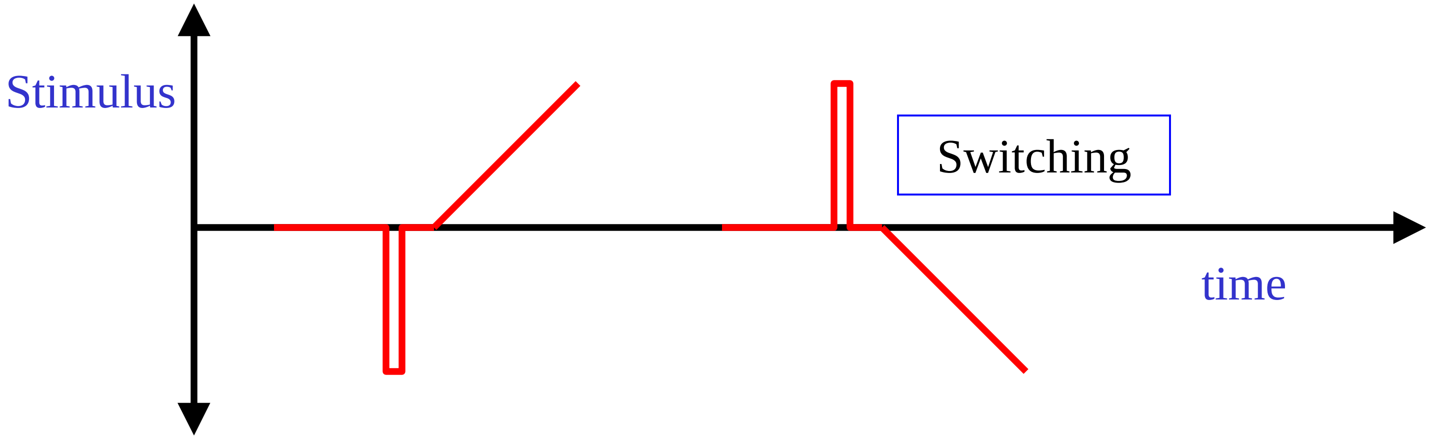
Hysteresis in Small Signal Capacitance





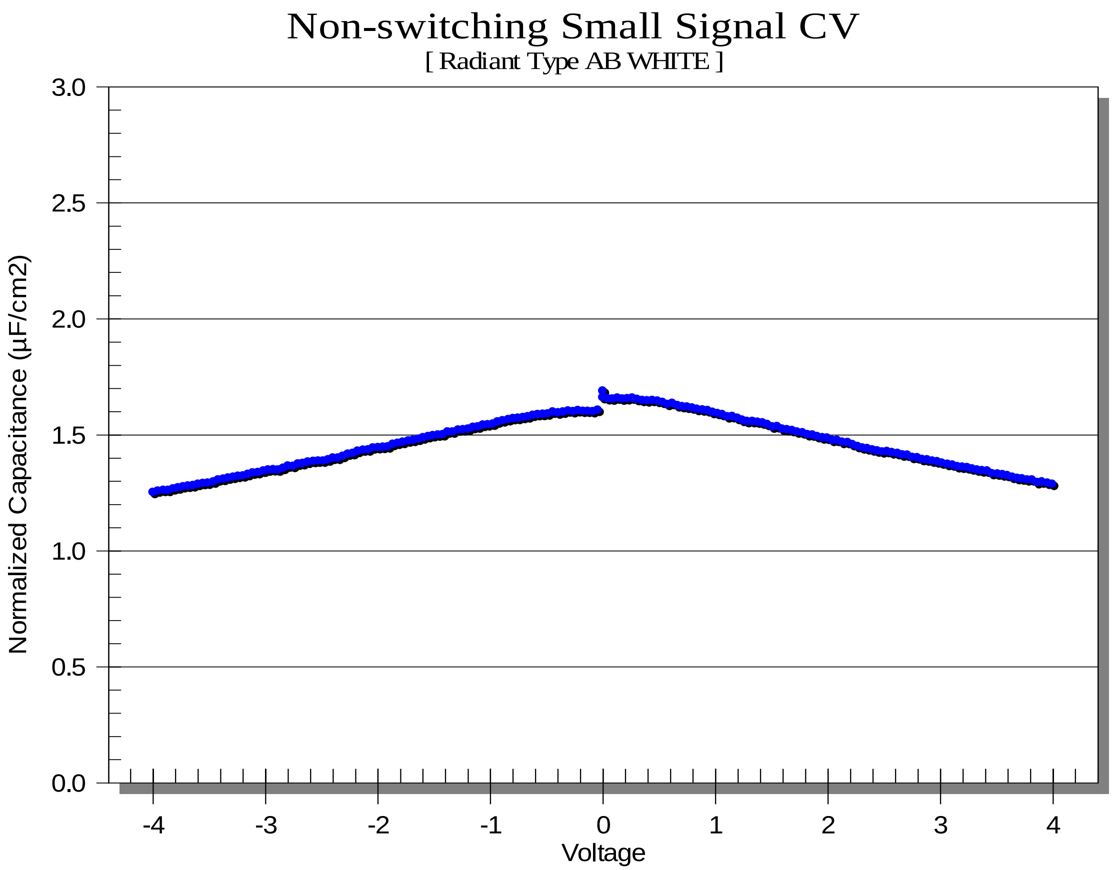
Hysteresis in Small Signal Capacitance





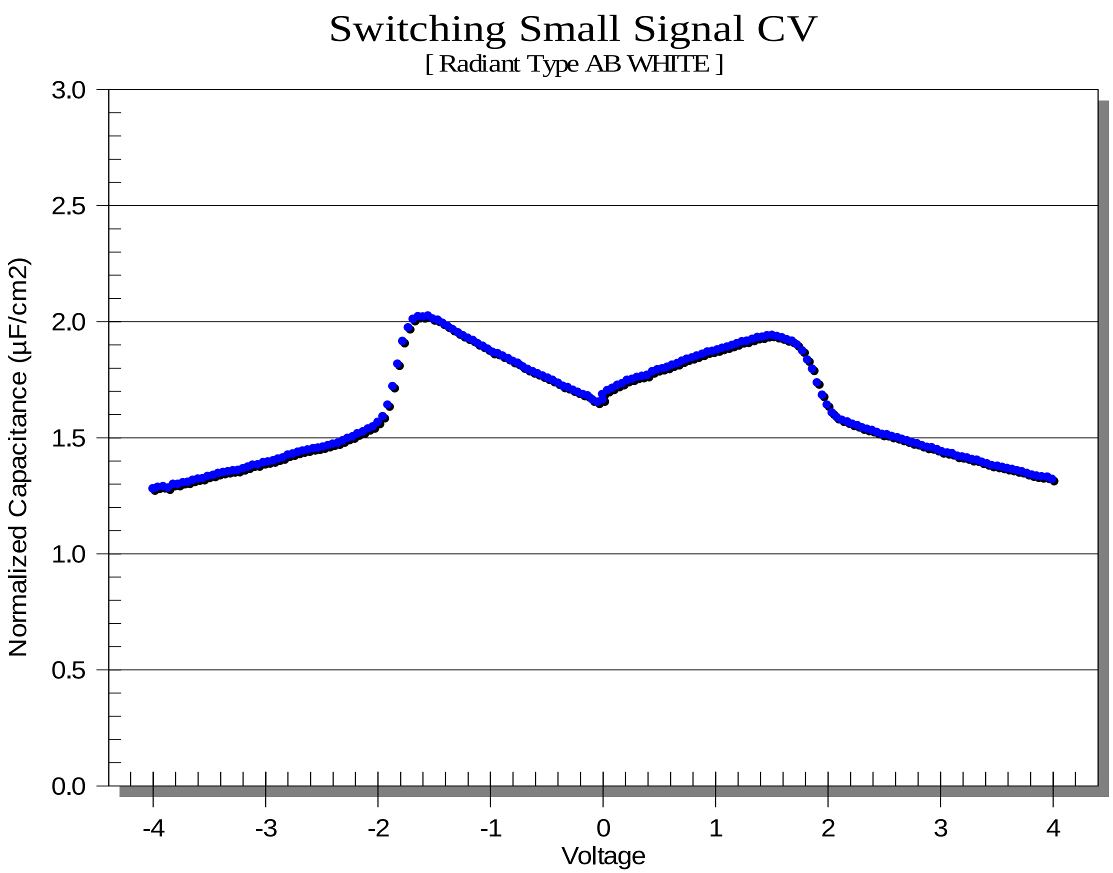
Non-switching CV for the Sample under Test

- 1KHz 0.2V test with 182 points



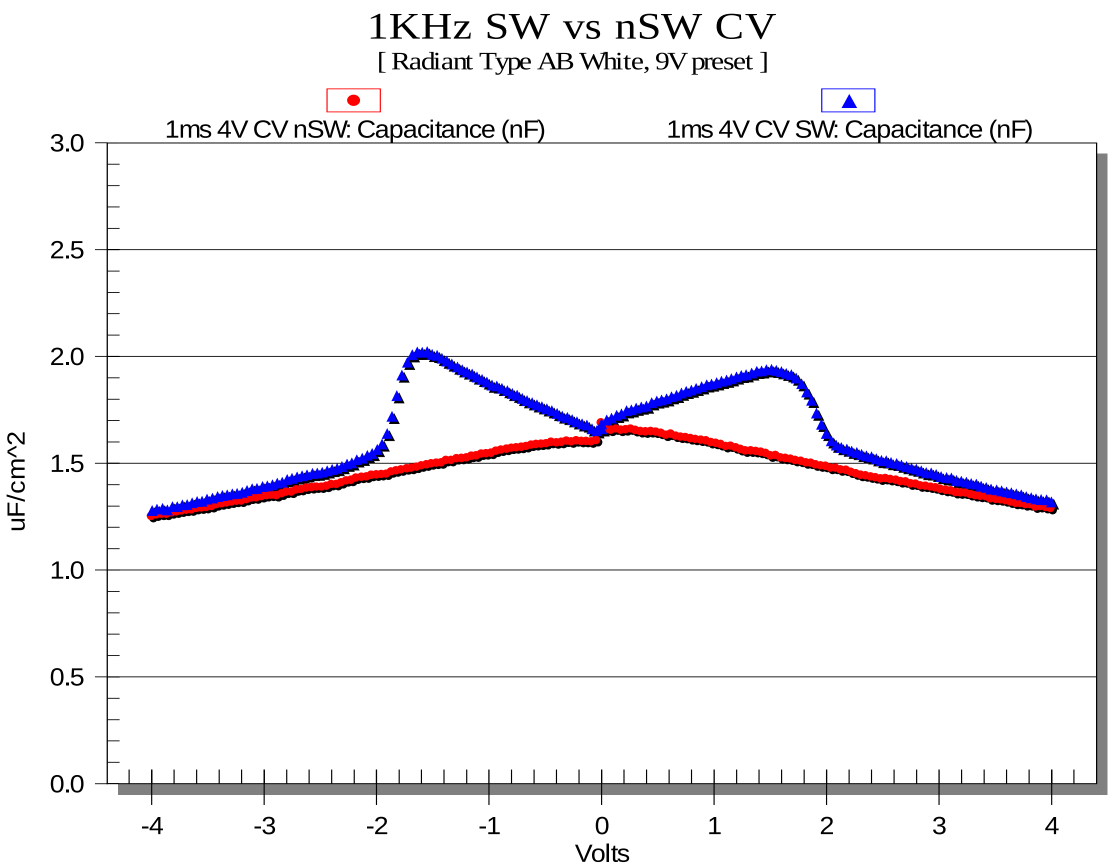
Switching CV for the Sample under Test

- 1KHz 0.2V test with 182 points



Non-switching vs Switching CV

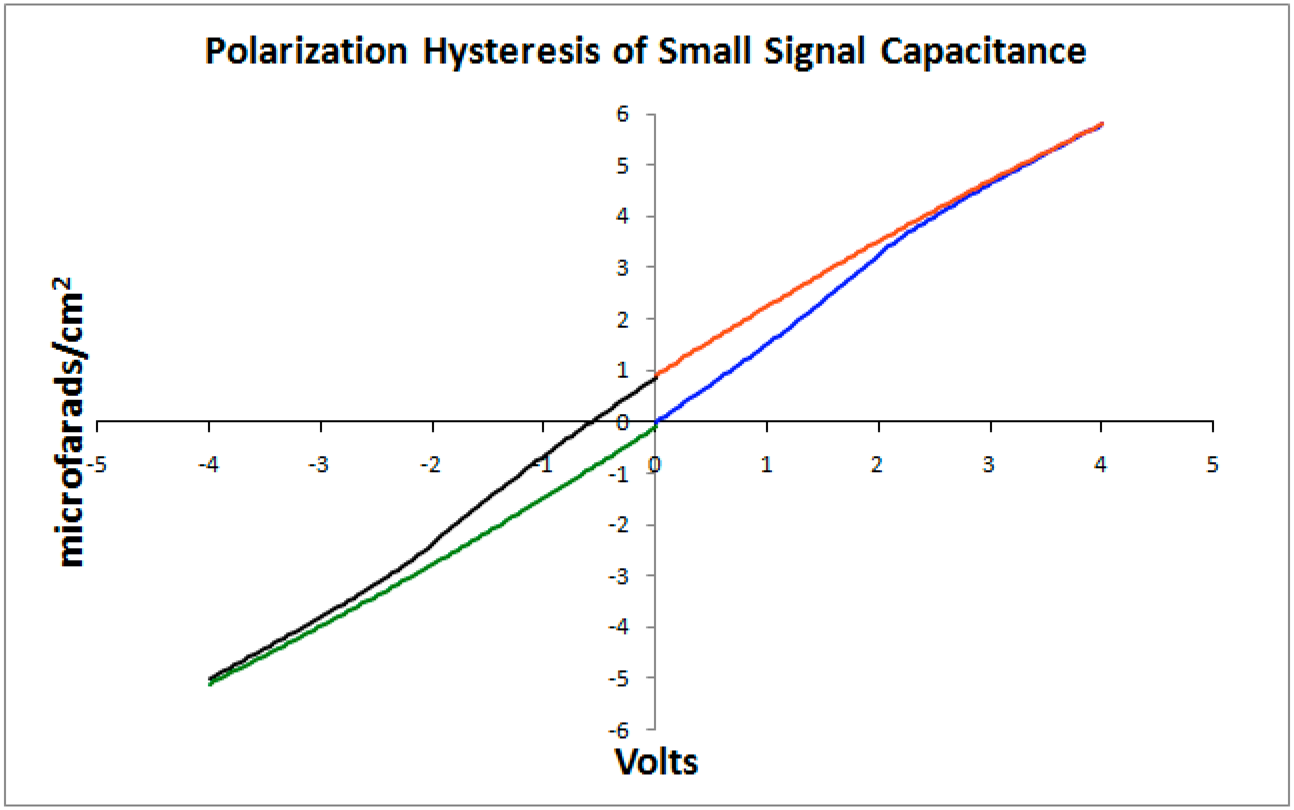
- 1KHz 0.2V test with 182 points



Q vs V from Small Signal Capacitance

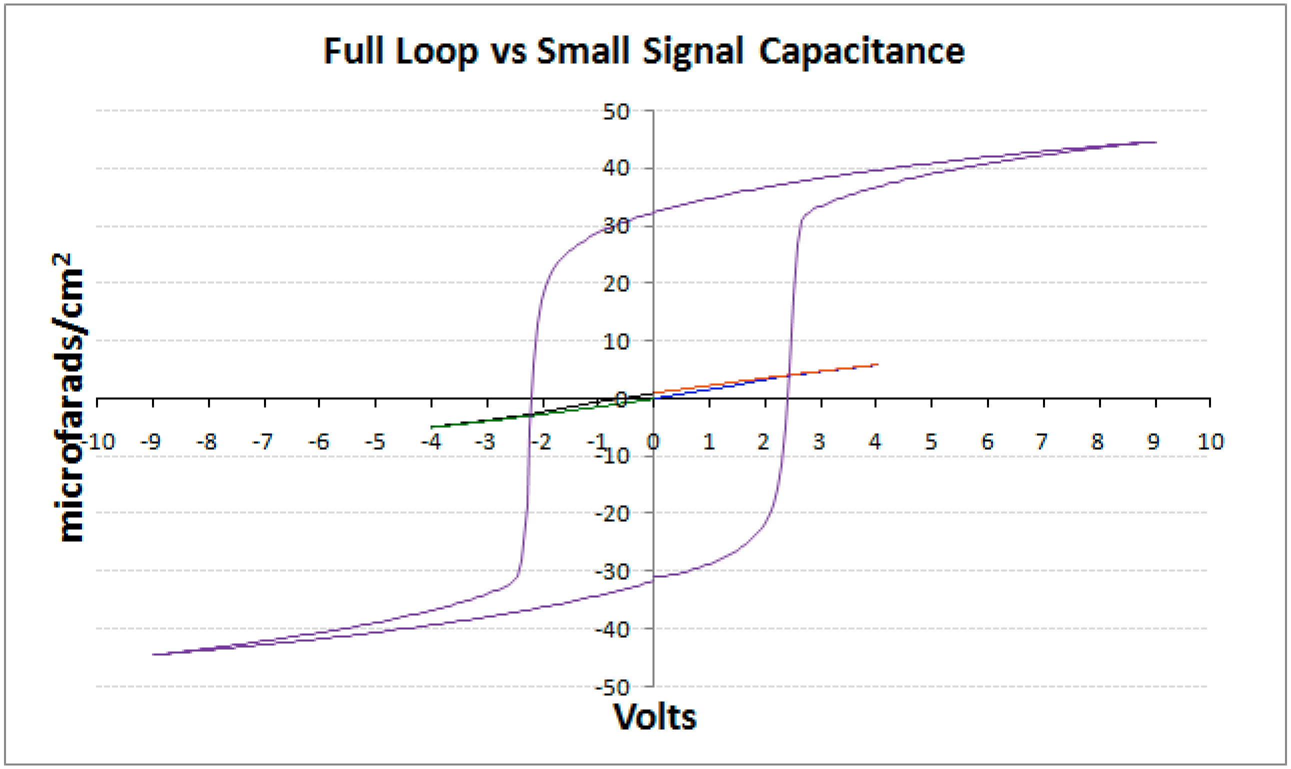
- The small signal capacitance can be multiplied by the dV to get the dQ per test step.
- The dQs may be integrated to see the polarization hysteresis contributed by the modulation of small signal capacitance by remanent polarization!

Small Signal Capacitance Polarization



- Small signal capacitance forms a hysteresis of its own.

Small Signal Capacitance Polarization



- The contribution of small signal capacitance hysteresis to the overall loop is small in this case.

Resistive Leakage in a Hysteresis Loop

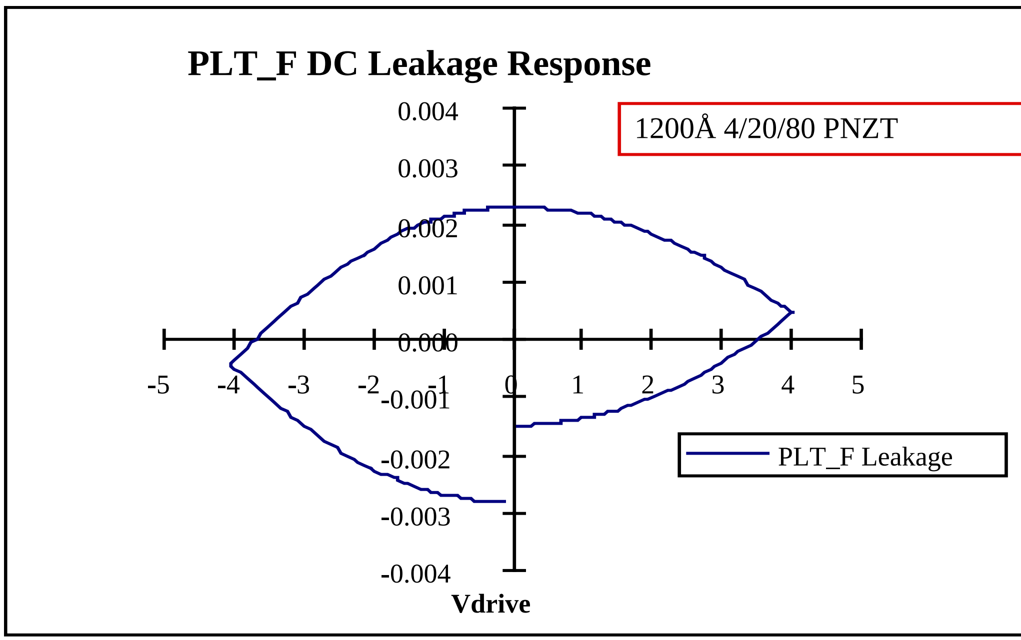
A common problem in ferroelectric ceramics is a linear resistance function. Usually, it appears due to leakage along grain boundaries although it can occur from dopants or defects in the grains themselves.

Resistive Leakage in a Hysteresis Loop

Linear resistance is easy for a triangle wave:

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

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



time=time step per point

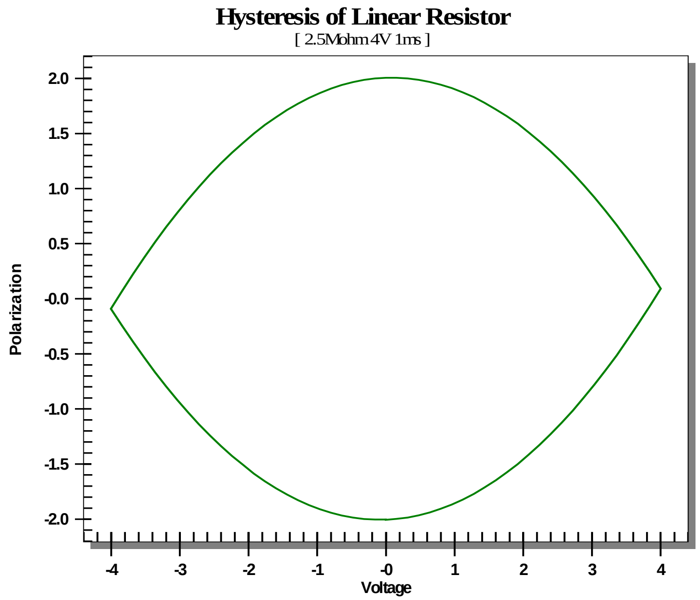
V=fixed voltage step of

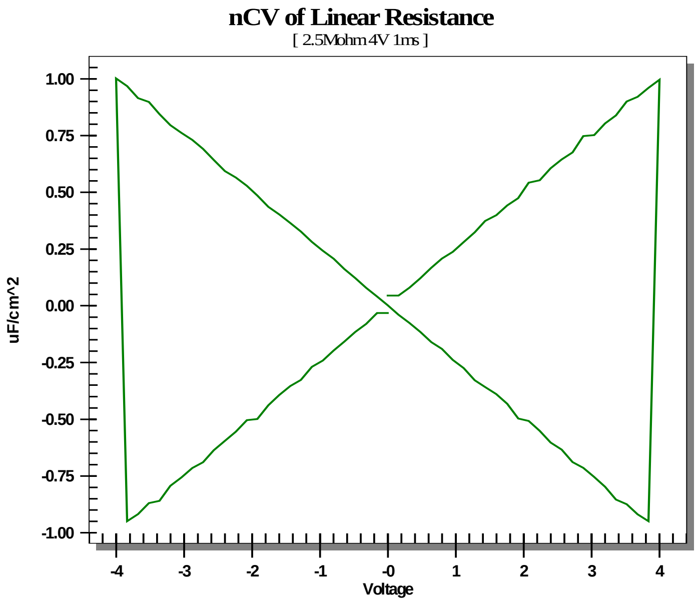
= point number of
gitized triangle wave

esult = "Football"

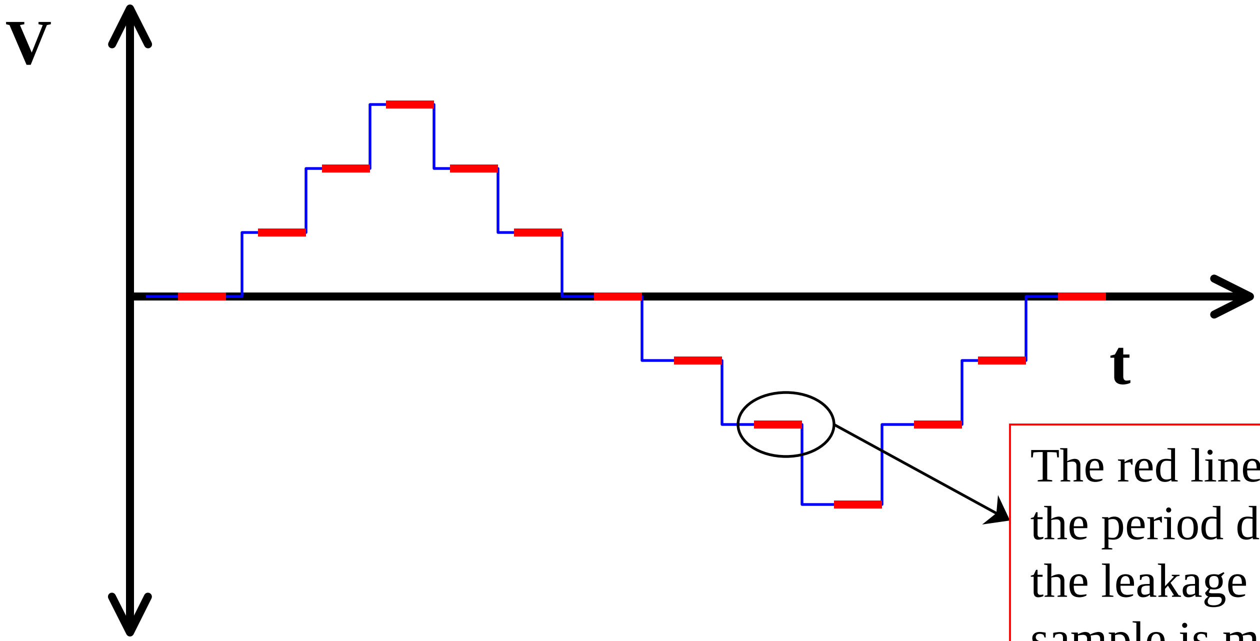
Resistive Leakage in a Hysteresis Loop

The derivative of pure resistive leakage is an “X”.





IV Test

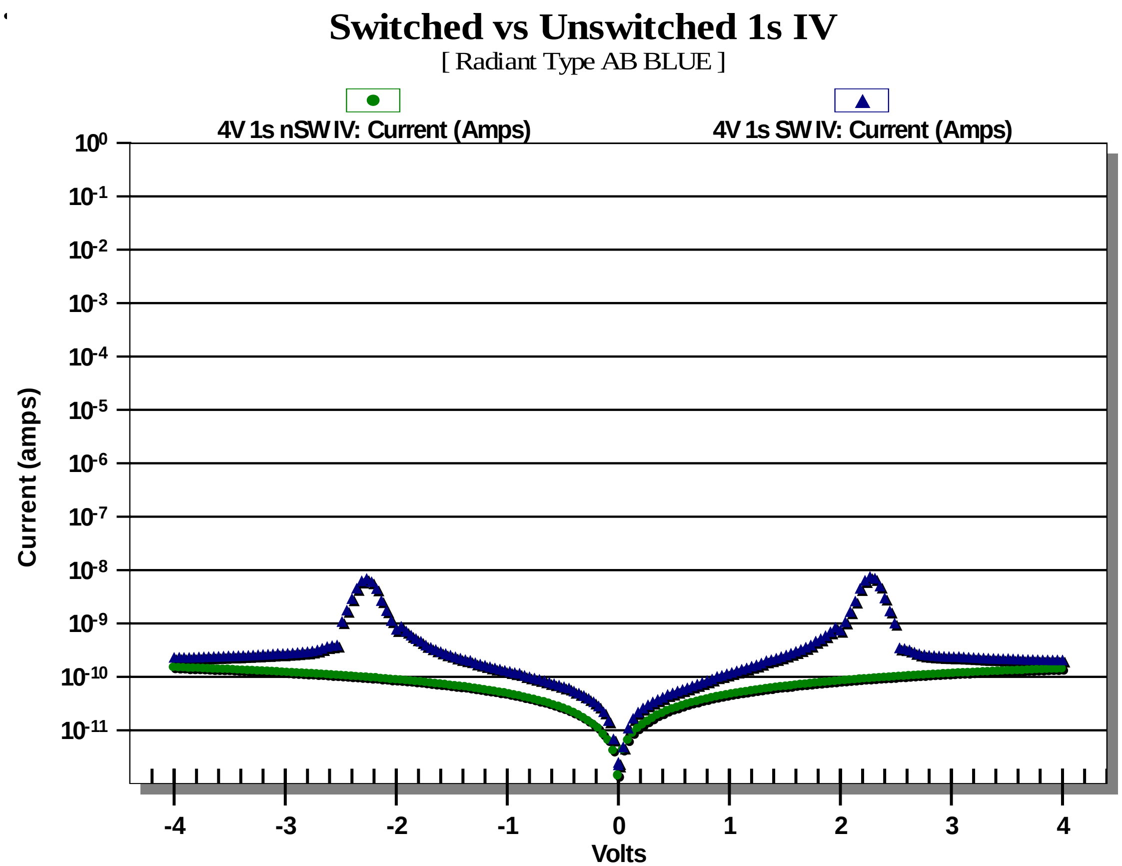


The red line indicates the period during which the leakage through the sample is measured after a soak period.

- The IV, or Current vs Voltage, test is a series of leakage tests executed over the voltage profile used for the traditional hysteresis loop.
- It is necessary because resistive leakage is not always linear!

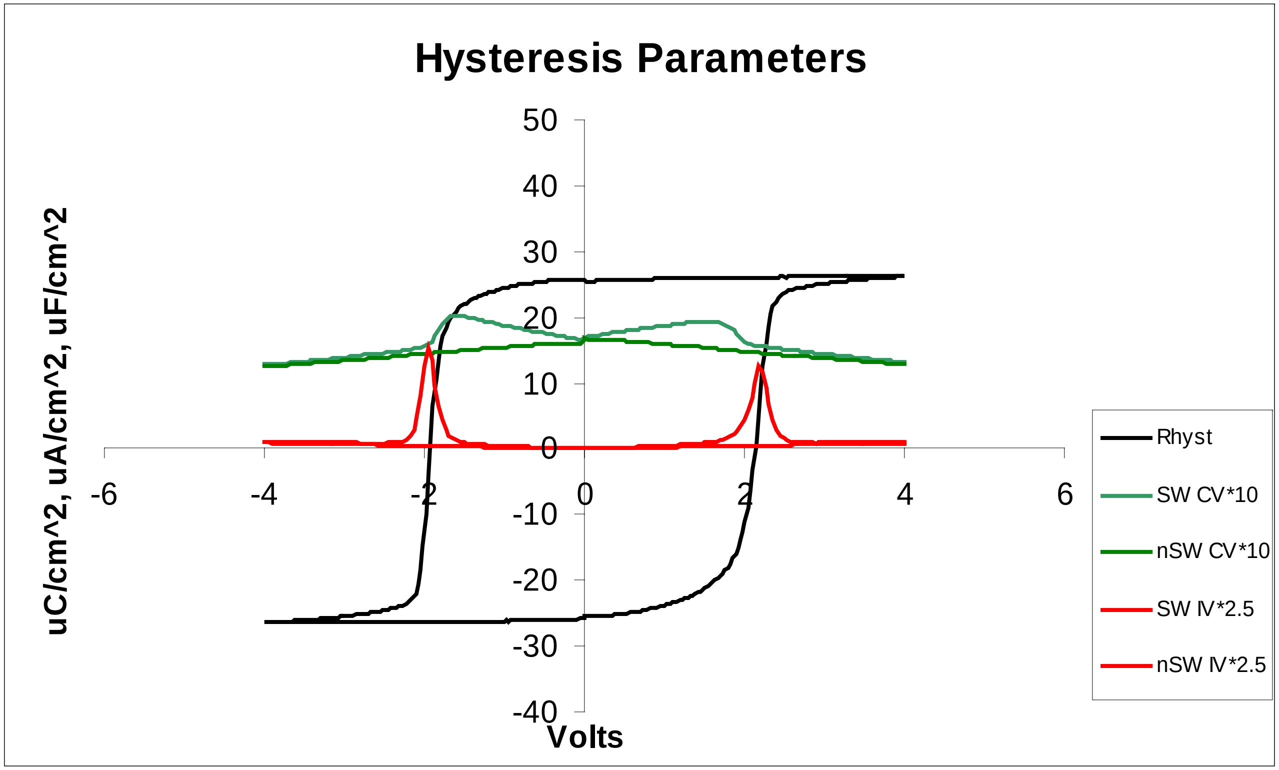
Hysteresis in Leakage

- Leakage in ferroelectric materials does not have to be linear.
- Leakage can have its own hysteresis modulated by remanent polarization.



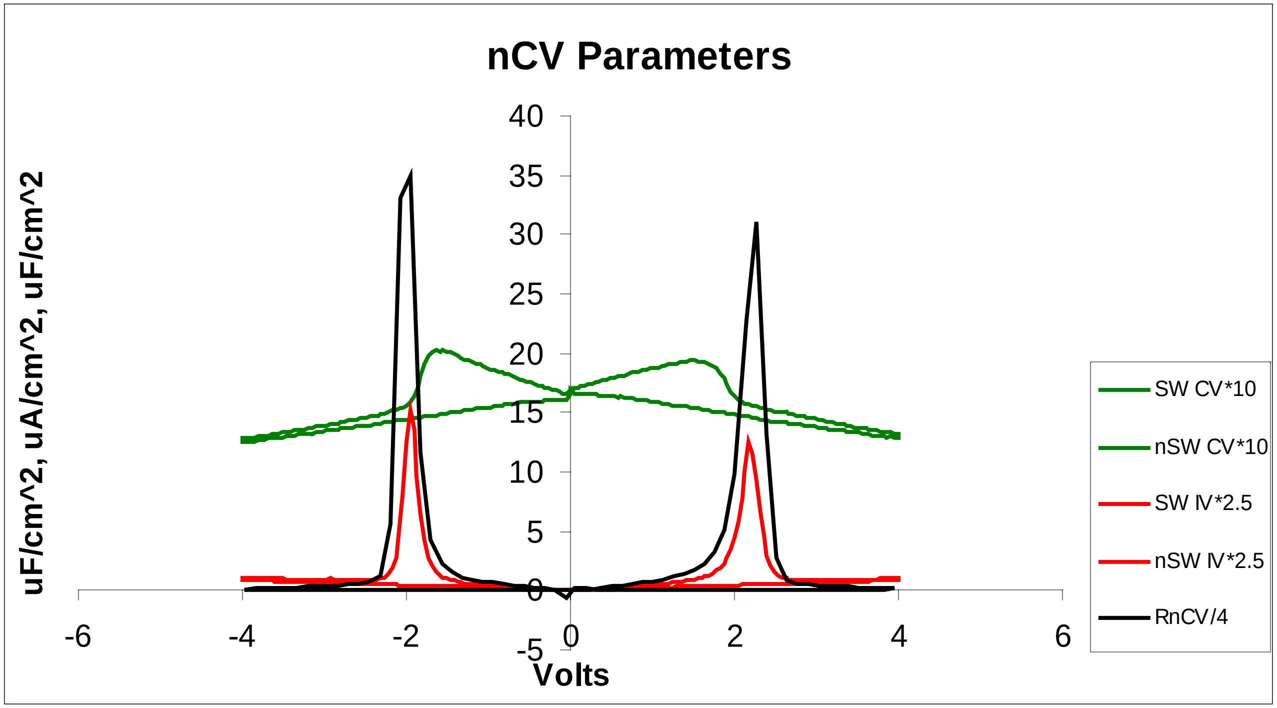
Leakage vs CV vs Remanent Polarization

- Are the remanent polarization, IV, and CV related? YES!



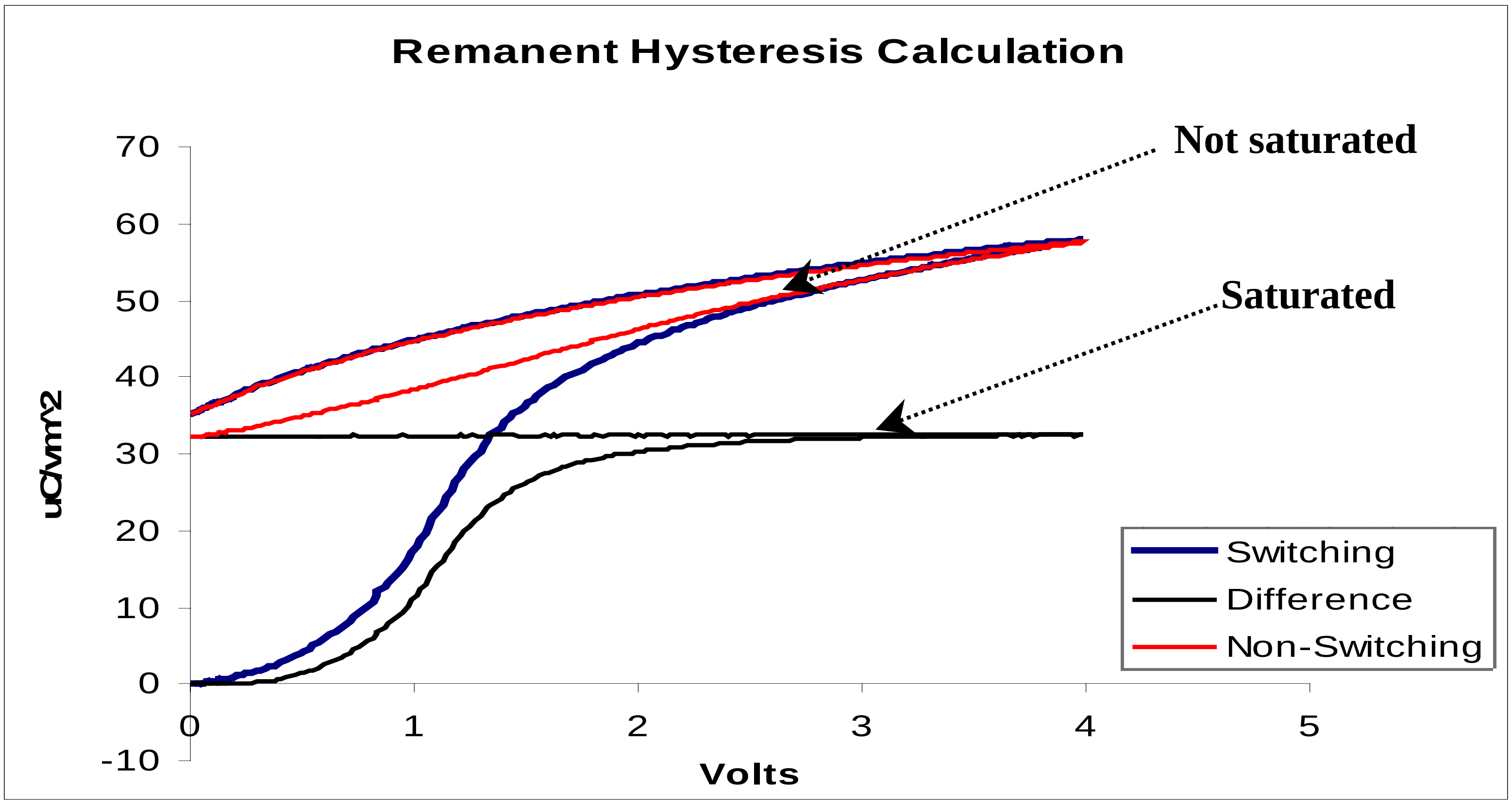
Leakage vs CV vs Remanent Polarization

- The derivative of the remanent polarization makes the relationships clear.



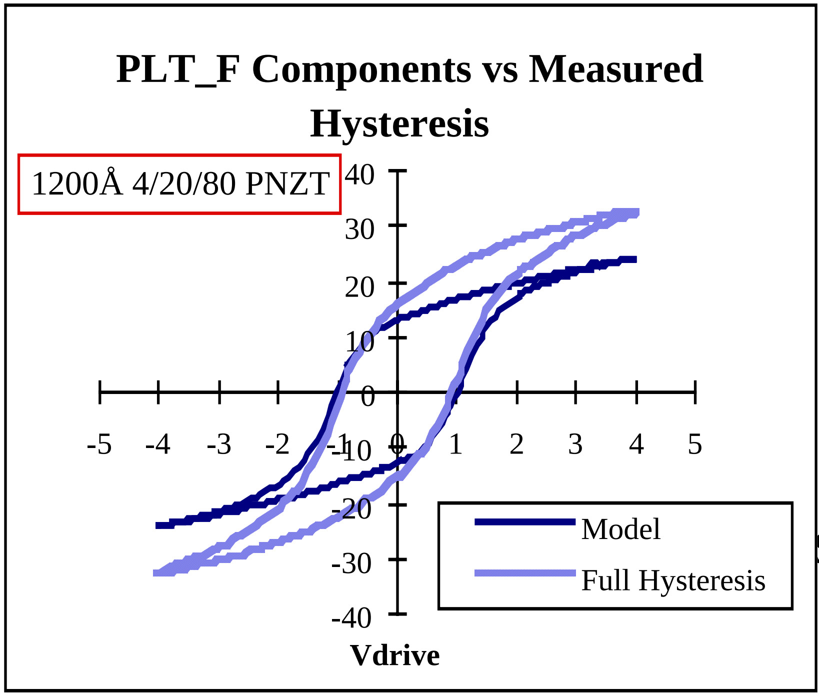
The Gap

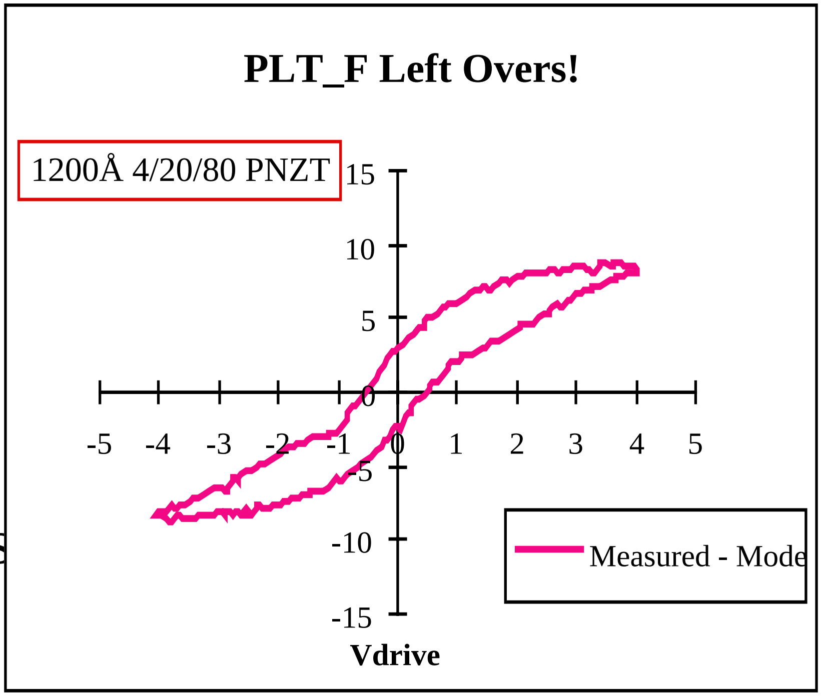
- If remanent polarization saturates nicely, why is the full loop (both switching and non-switching) open at the end?



Something Left Over

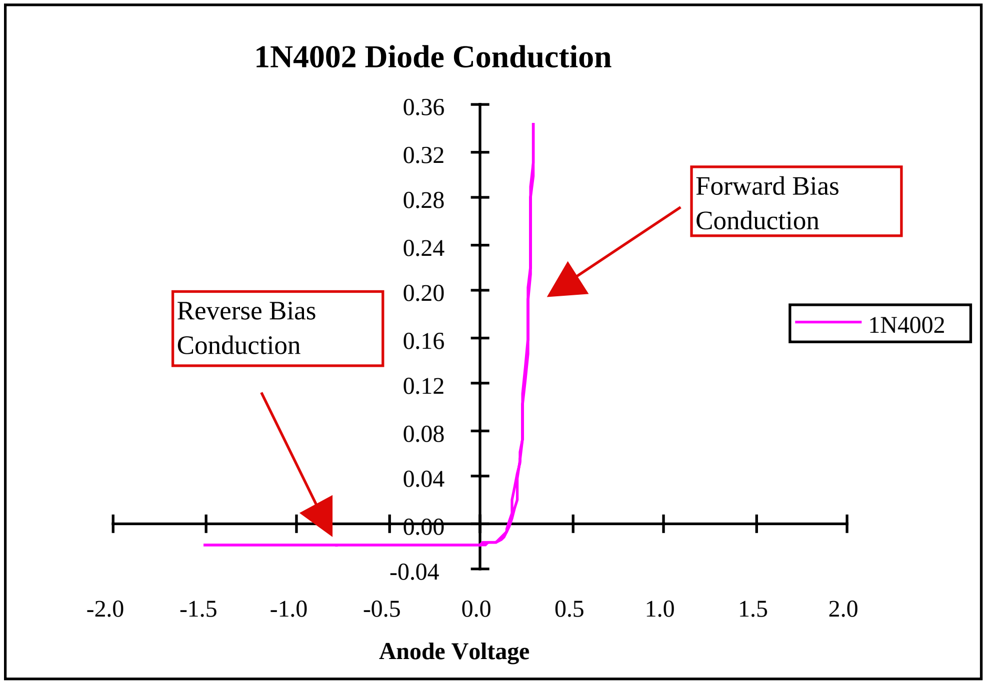
If we measure the remanent polarization, small signal capacitance, and leakage and then subtract them from the full loop, something is left over:

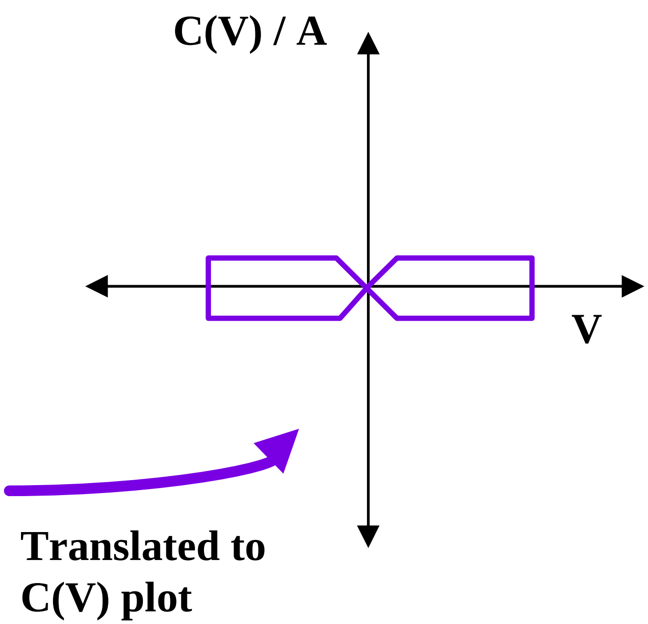




Reversed Bias Diodes

- A platinum electrode based capacitor has two opposing diodes at the ferroelectric/platinum interface, one of which is always turned off.

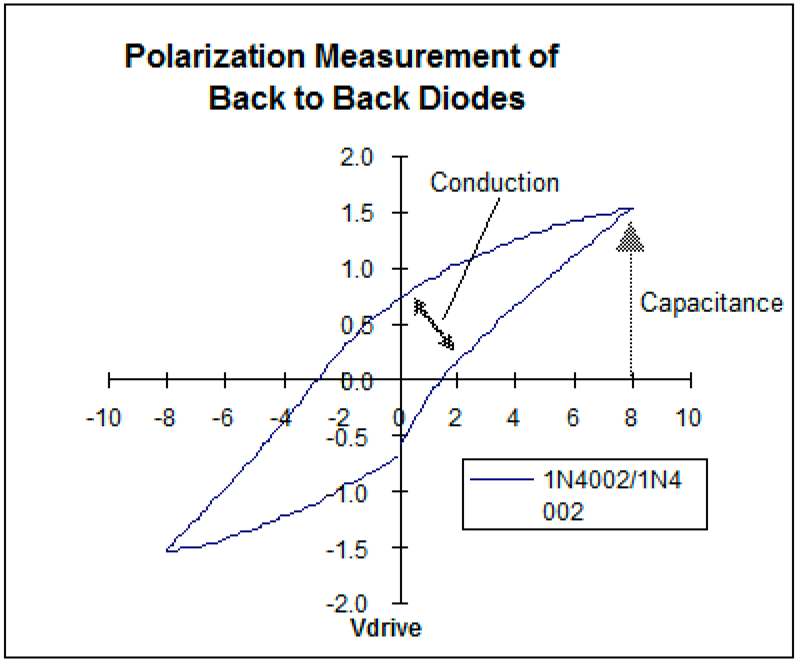


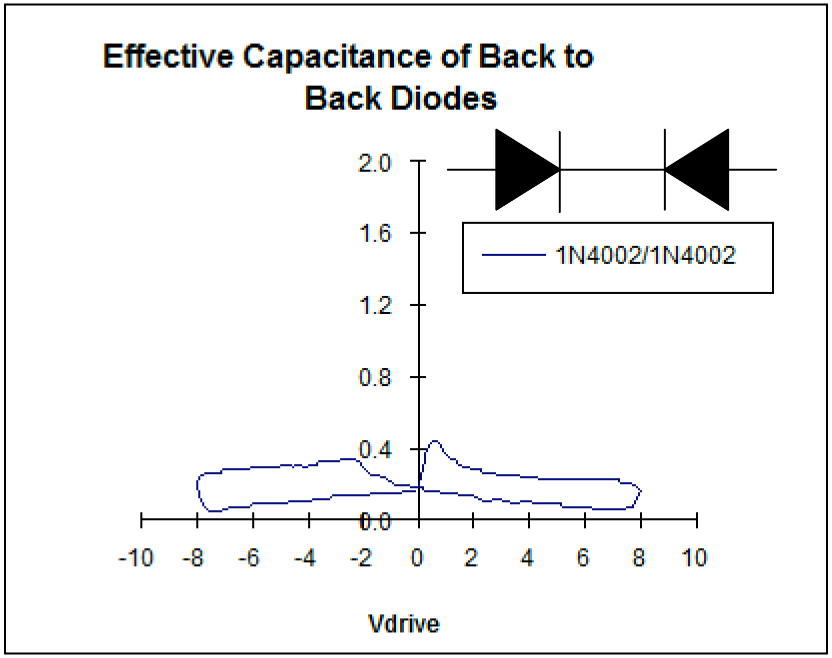


- In reverse bias, a diode has a constant current independent of voltage. *This makes a "bow tie" on the nCV plot.*

Reversed Bias Diodes

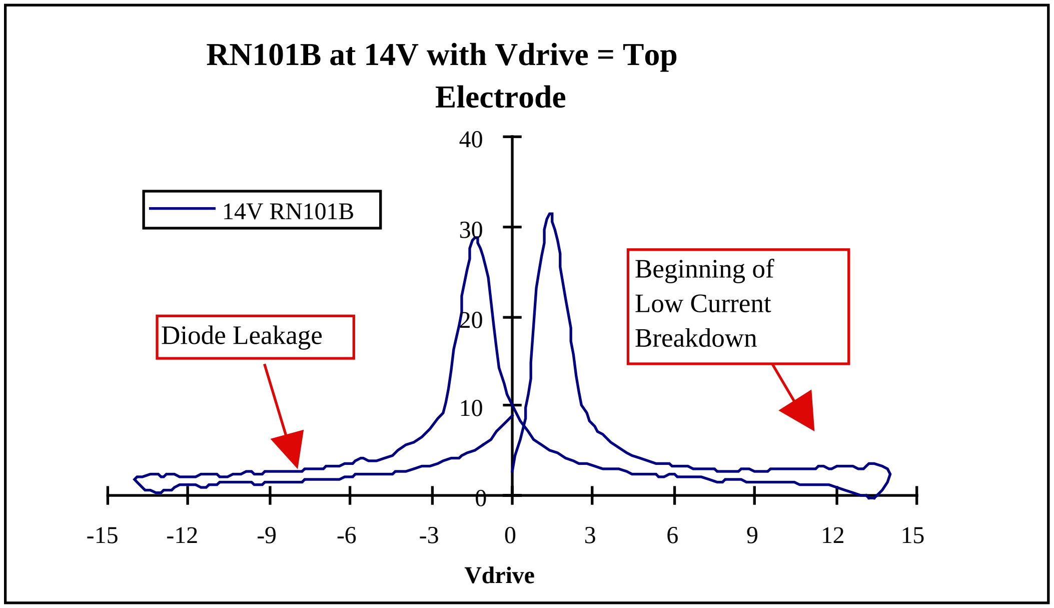
- A pair of back to back diodes have a unique signature on a virtual ground test system which uses a triangular drive voltage.





Reversed Bias Diode Breakdown

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



- The leakage of diode reverse-biased breakdown is marked by exponentially increasing current. This produces a “trumpet flare” instead of the “X” of linear leakage.

The Components

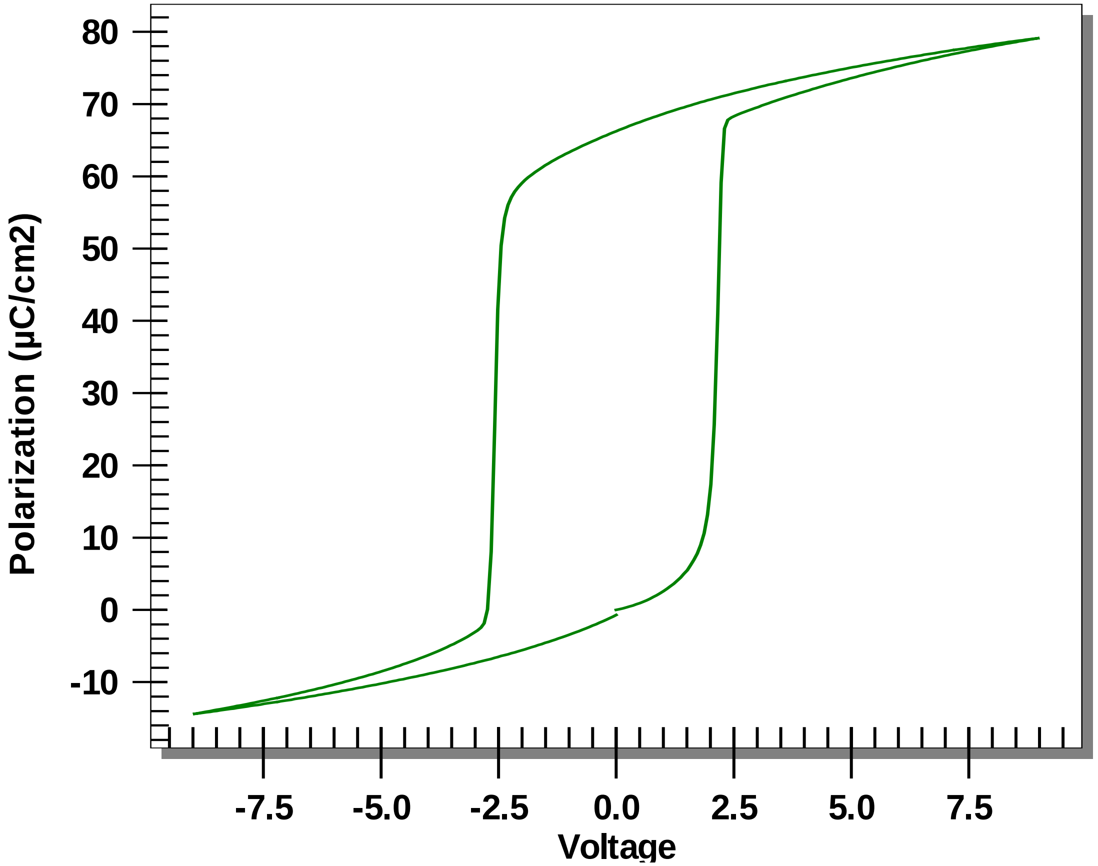
- Remanent polarization
- Linear small signal capacitance (dielectric constant)
- Nonlinear small signal capacitance (dielectric constant)
- Hysteretic small signal capacitance (remanent polarization modulation)
- Linear resistive leakage
- Hysteretic resistive leakage
- Electrode diode reverse-biased leakage
- Electrode diode reverse-biased exponential breakdown

All of these components are visible in the derivative of the polarization hysteresis loop!

What is this?

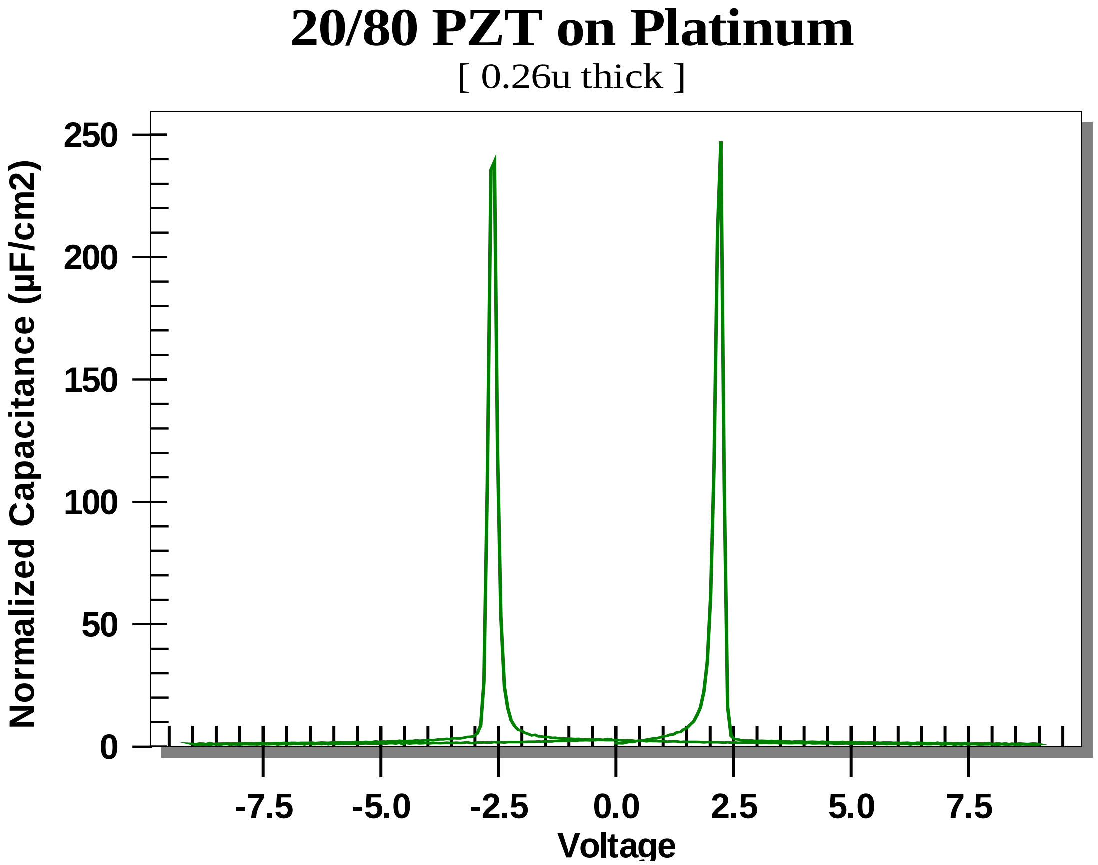
Let’s analyze some capacitors!

An Excellent Hysteresis Loop



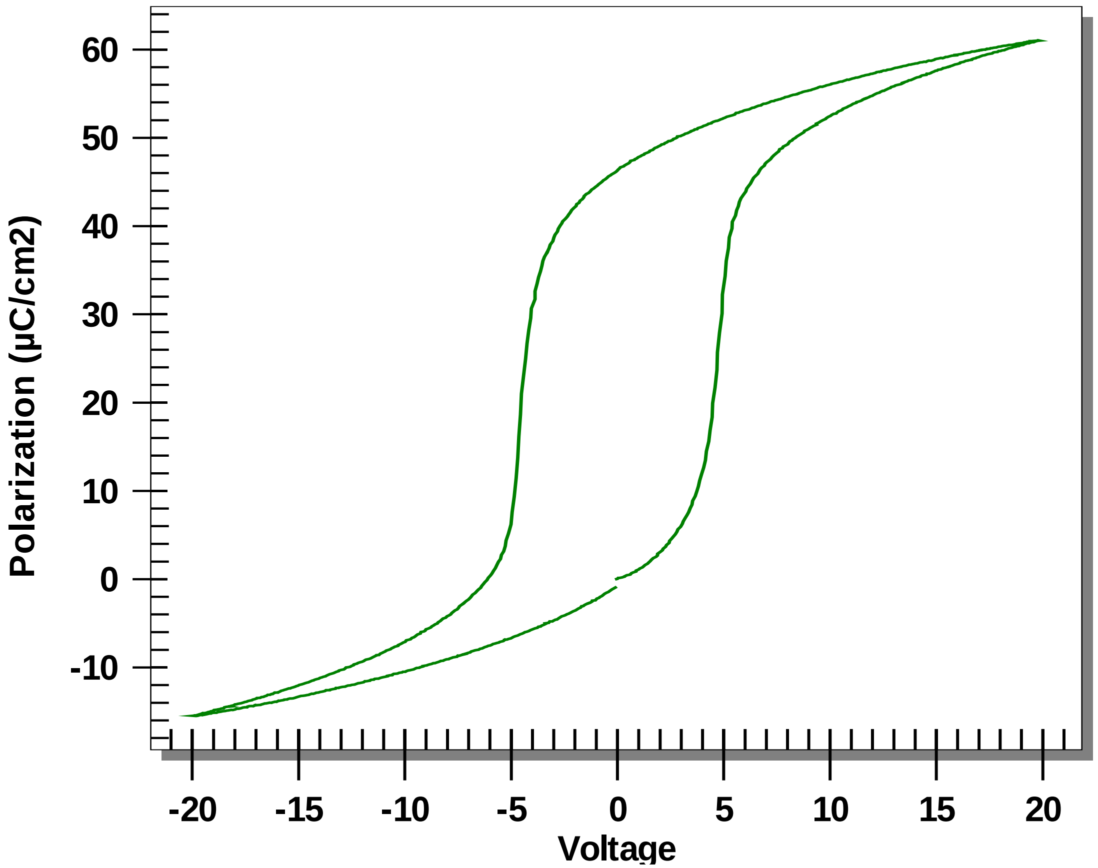
- The nearly “perfect” loop. 20/80 PZT on platinum.

An Excellent Hysteresis Loop



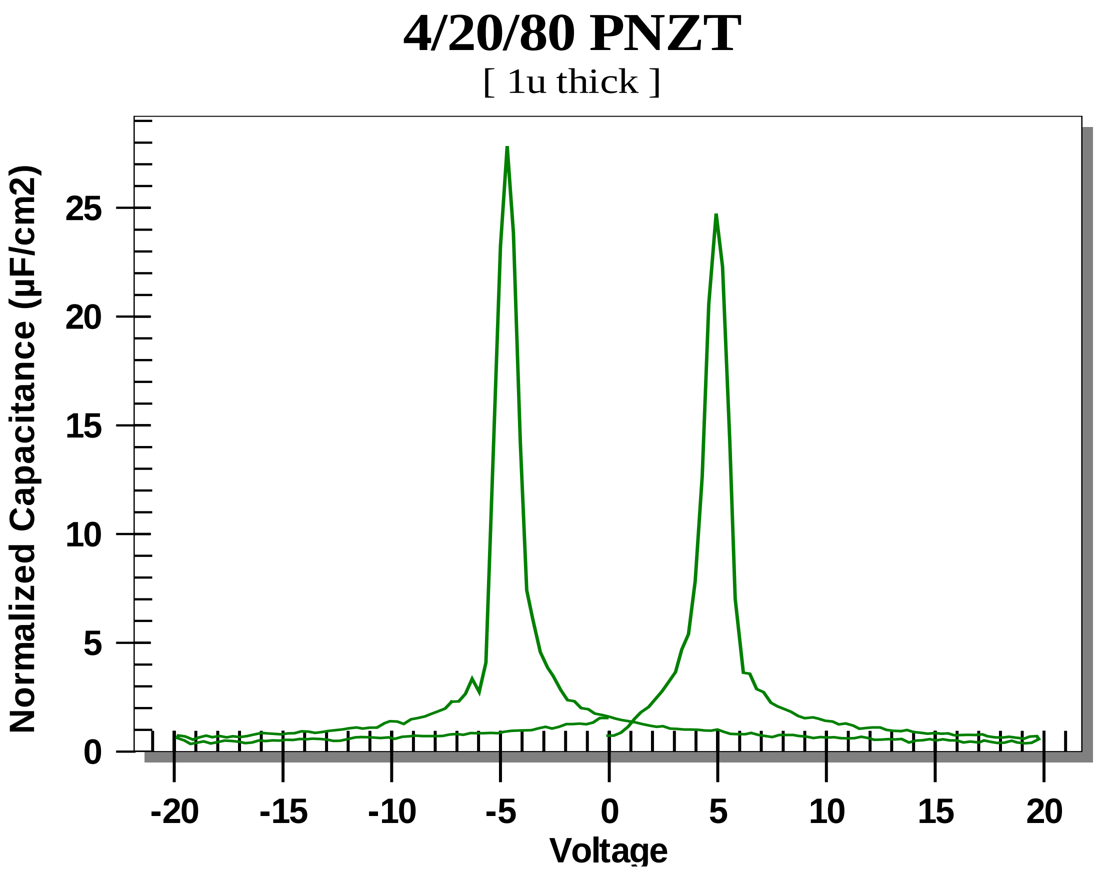
- The 20/80 PZT on platinum is so square that the instantaneous capacitance increases by x250 or more during switching.

What is this?



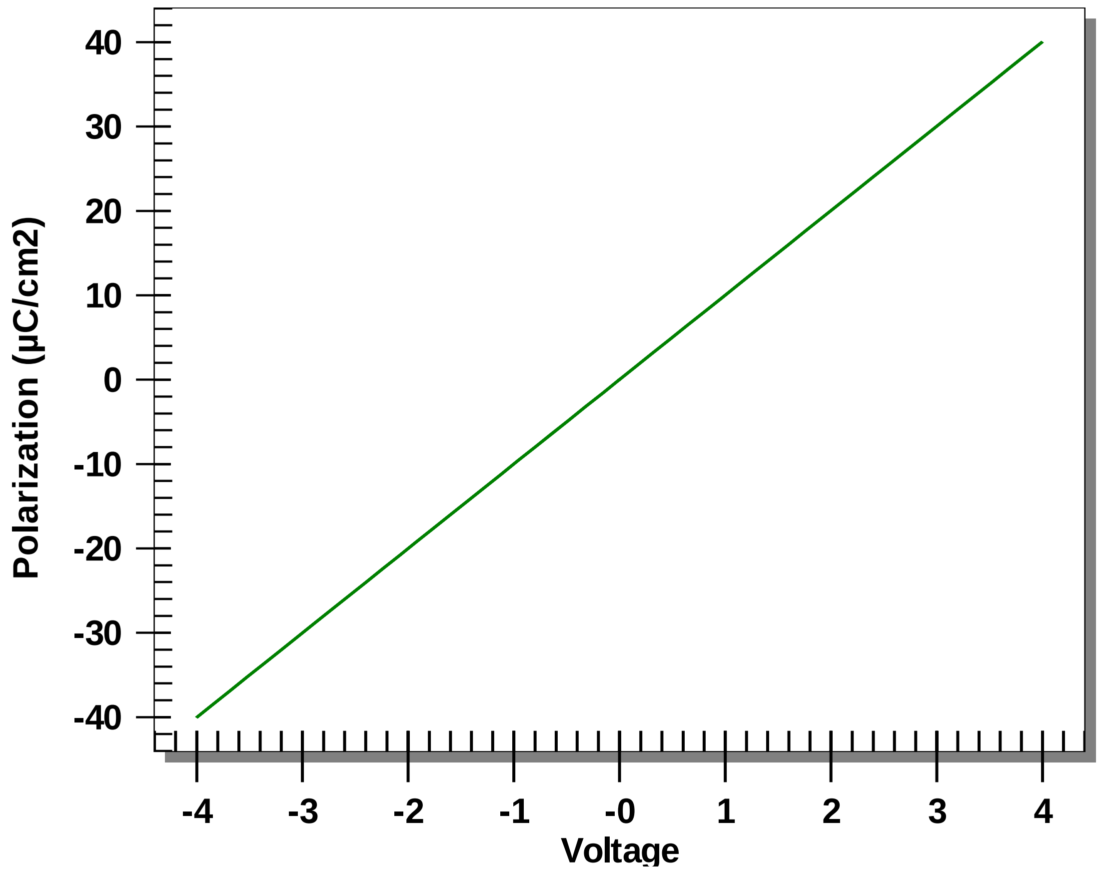
- Is this loop as good as the previous loop? Yes! It is 4/20/80 PNZT, a different composition from 20/80 PZT. So, it has a different shape.

What is this?



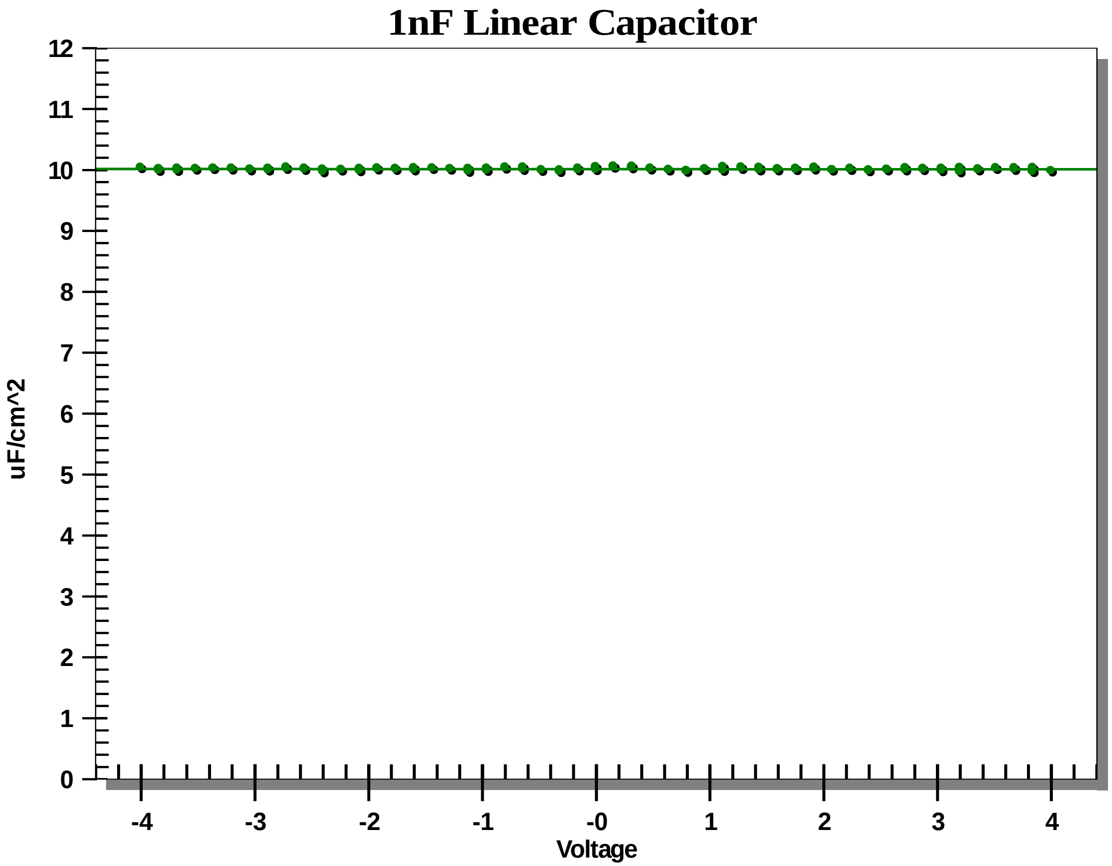
- This loop is good for 4/20/80 PNZT. Note the extra "diode" leakage in the tails that make the saturated tips of the loop open up.

What is this?



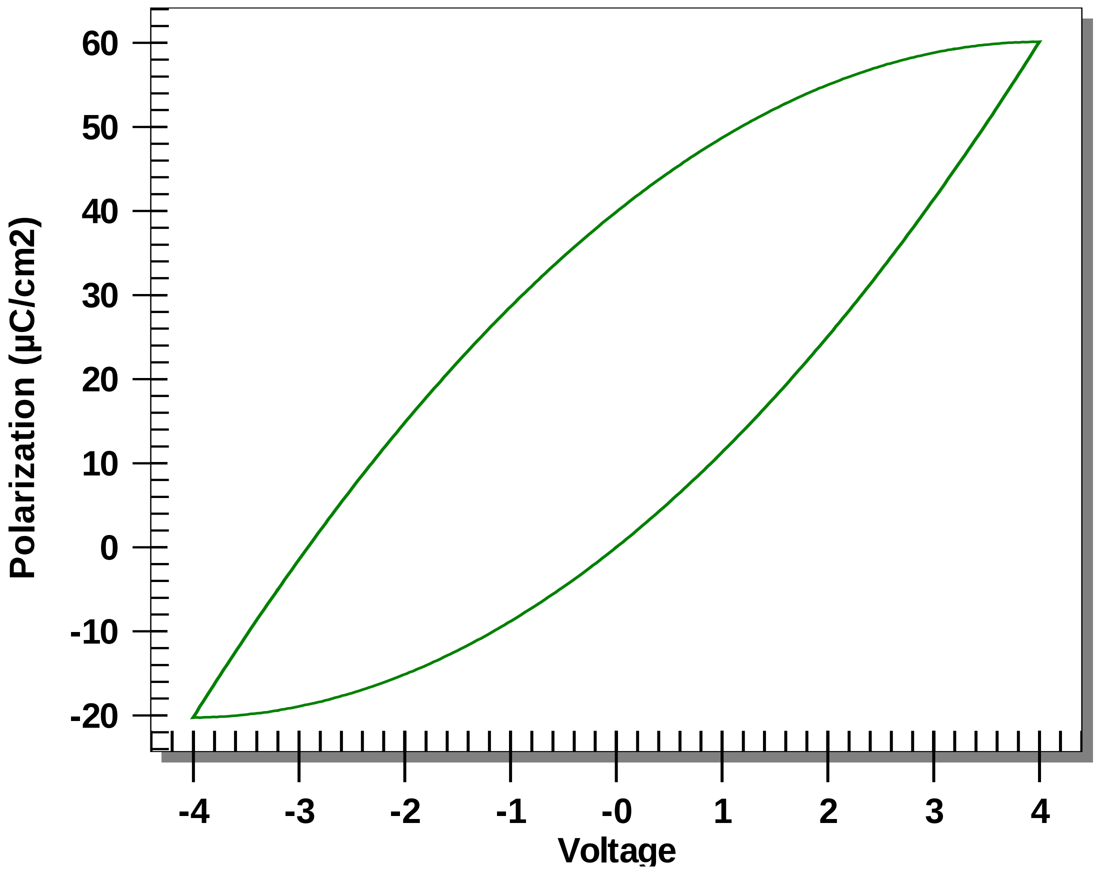
- A linear capacitor.

What is this?



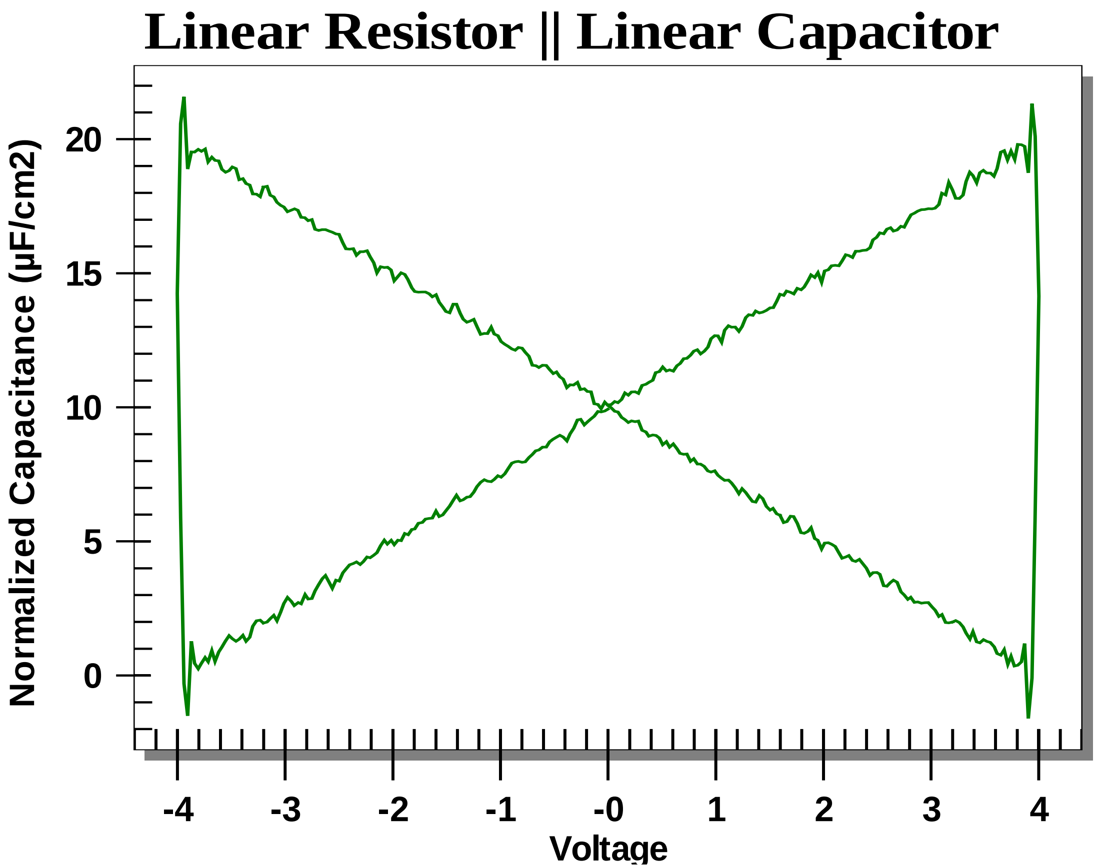
- A linear capacitor. In this measurement, it has a capacitance density of 10μF/cm^2.

A Harder One



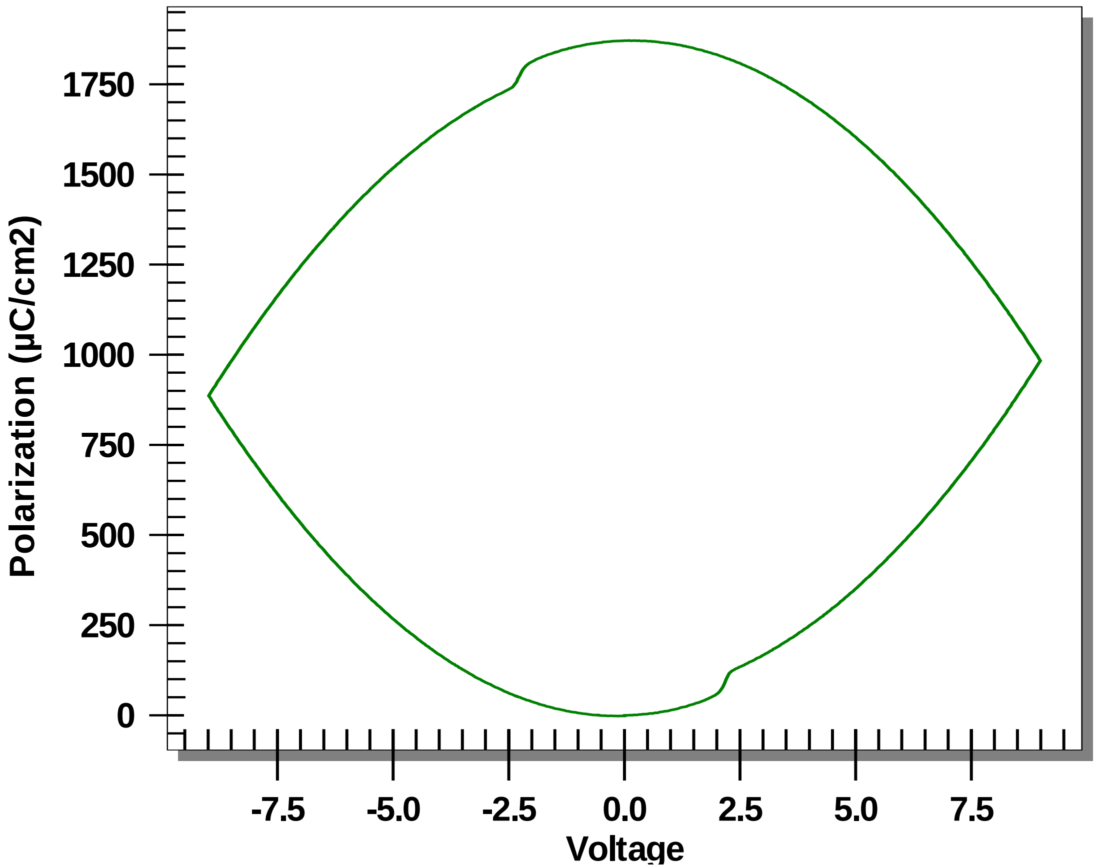
- Quite a few papers include loops that look like this.

A Harder One

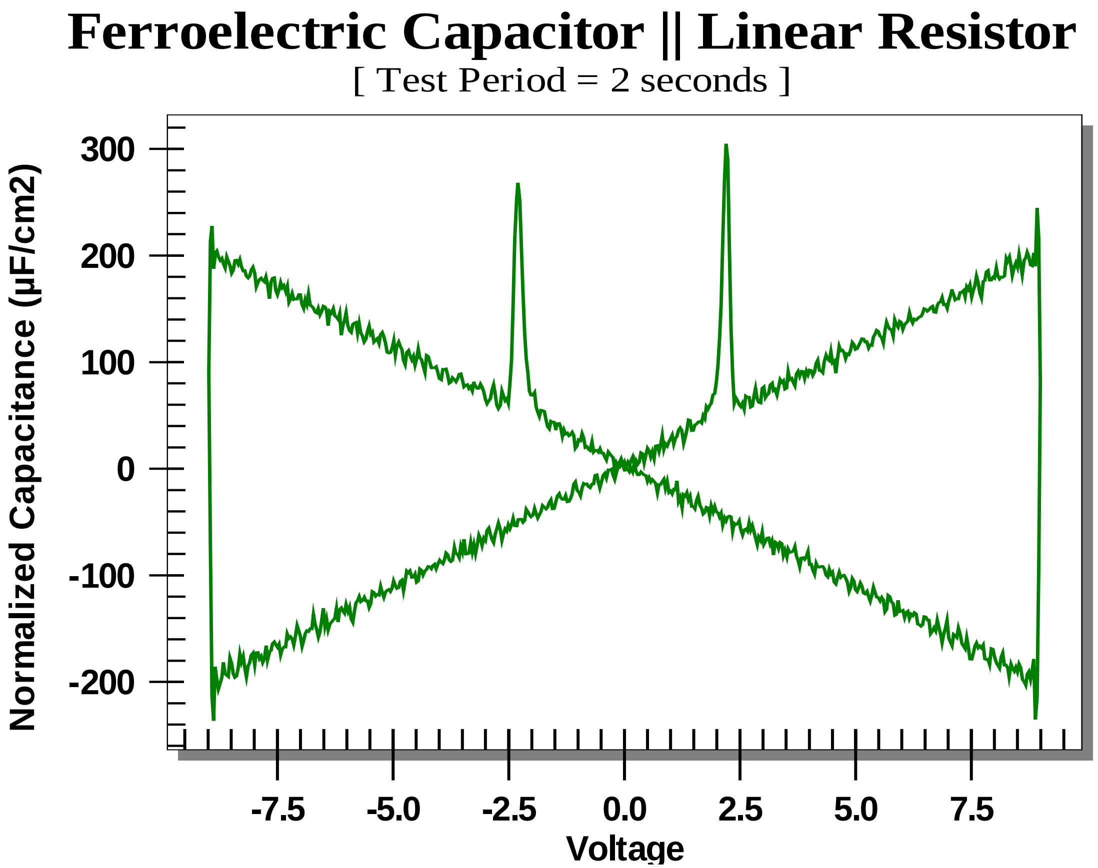


- It is *only* a resistor and a linear capacitor in parallel.

Is this Ferroelectric?

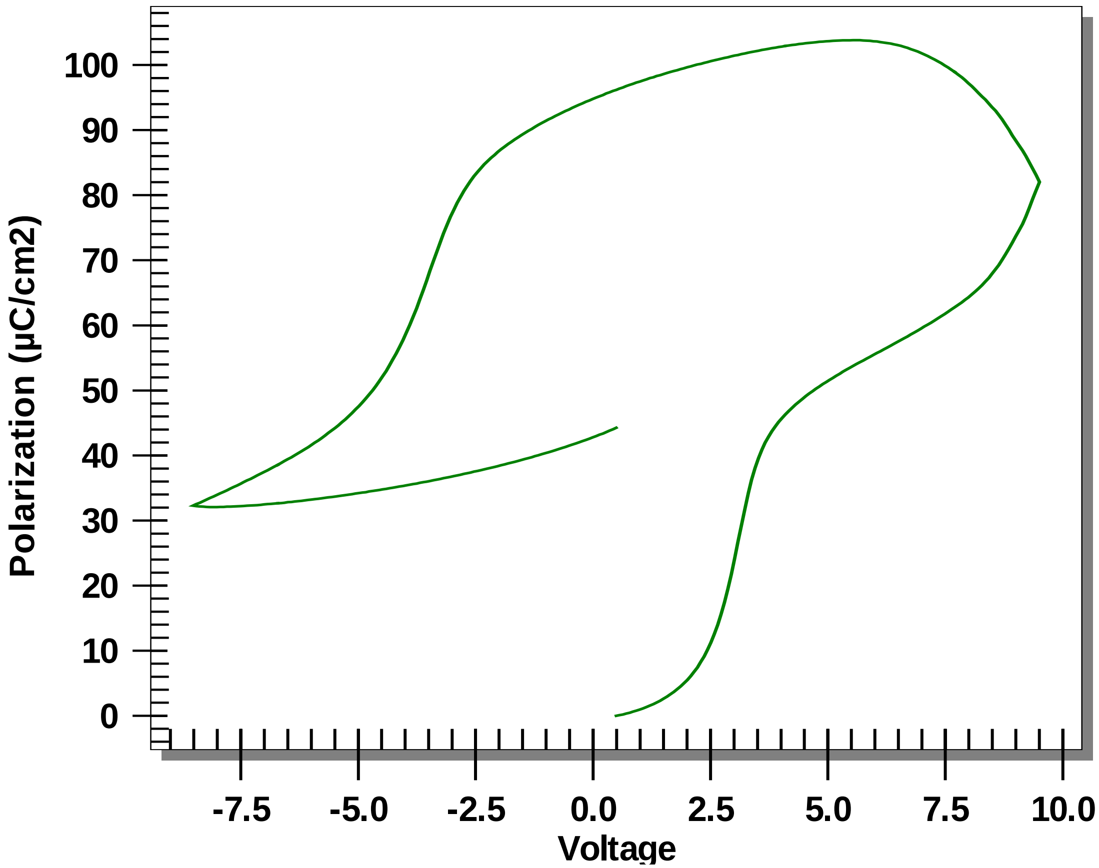


Is this Ferroelectric?



- Yes, it is! See the ferroelectric switching peaks sticking out of the resistor “X”.

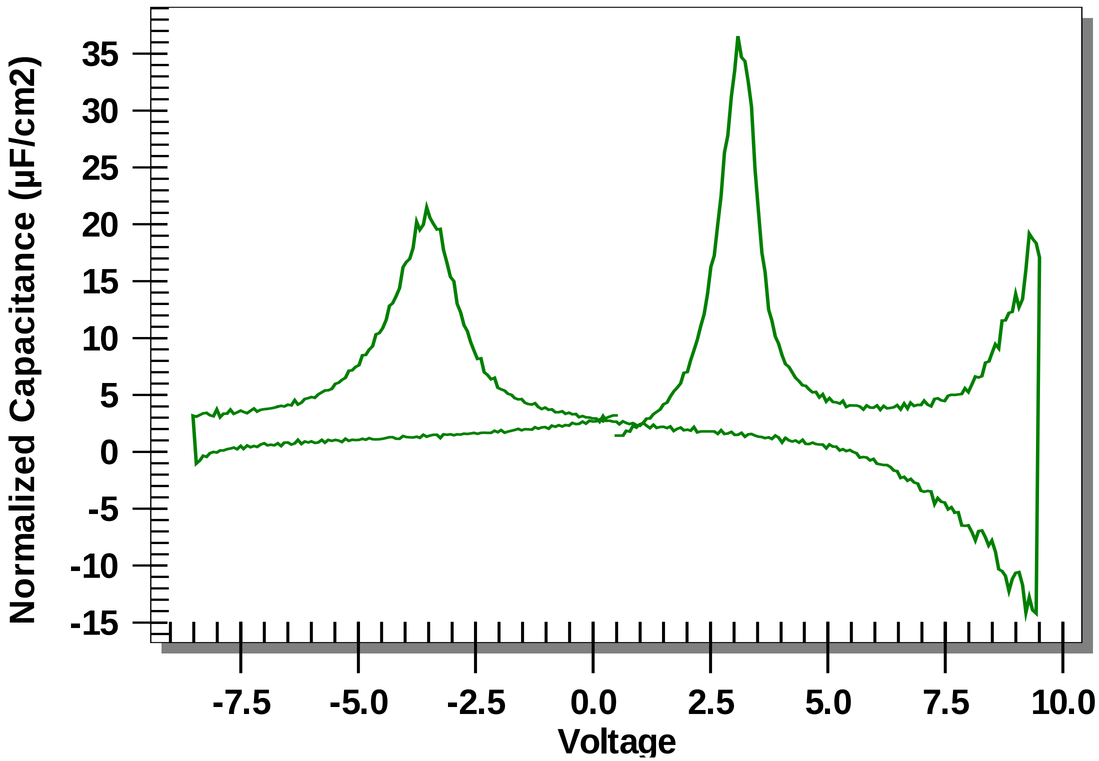
What Happened Here?



What Happened Here?

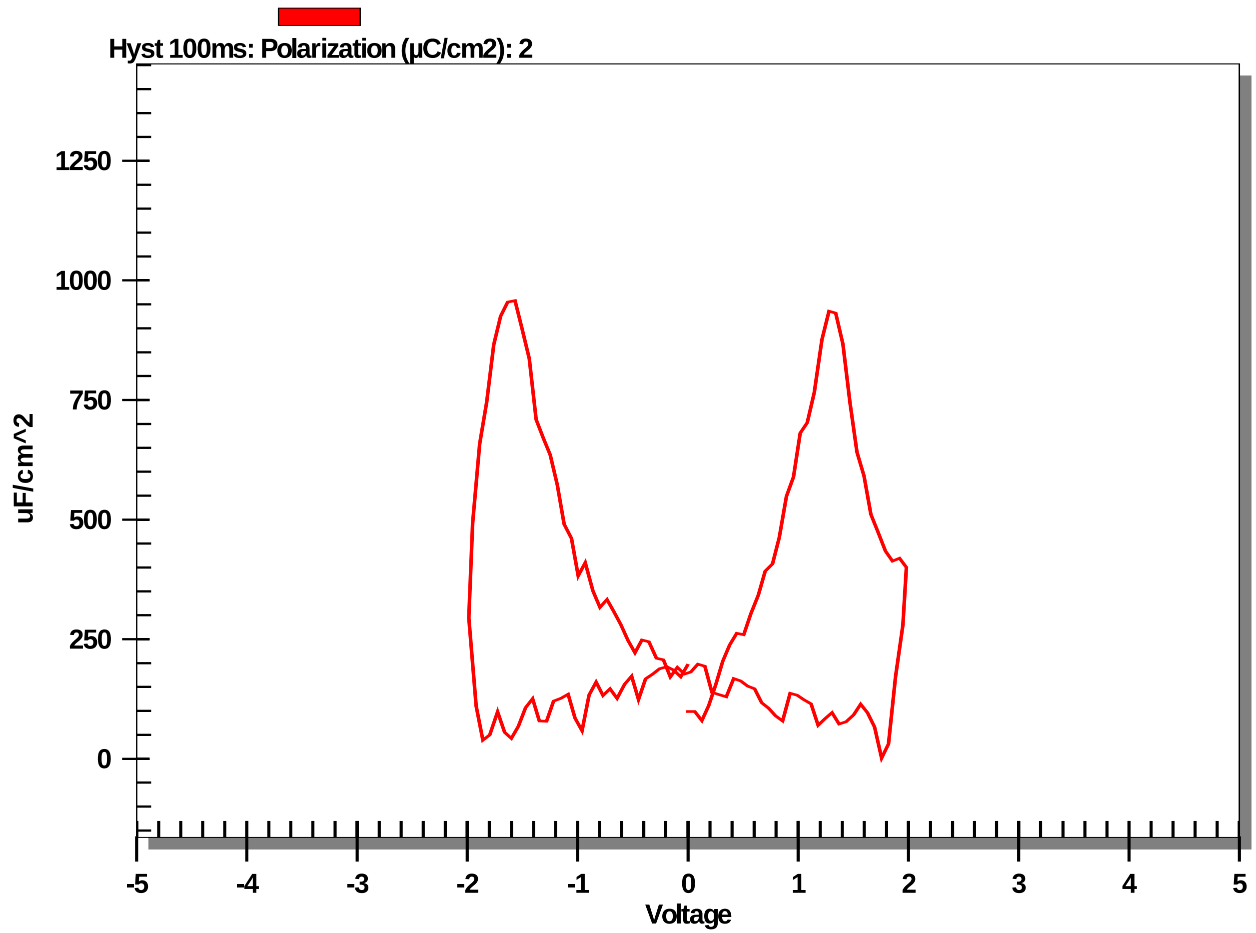
PZT on Nickel Lanthanate - 300ms Period

[EXP09BQ Rev A]



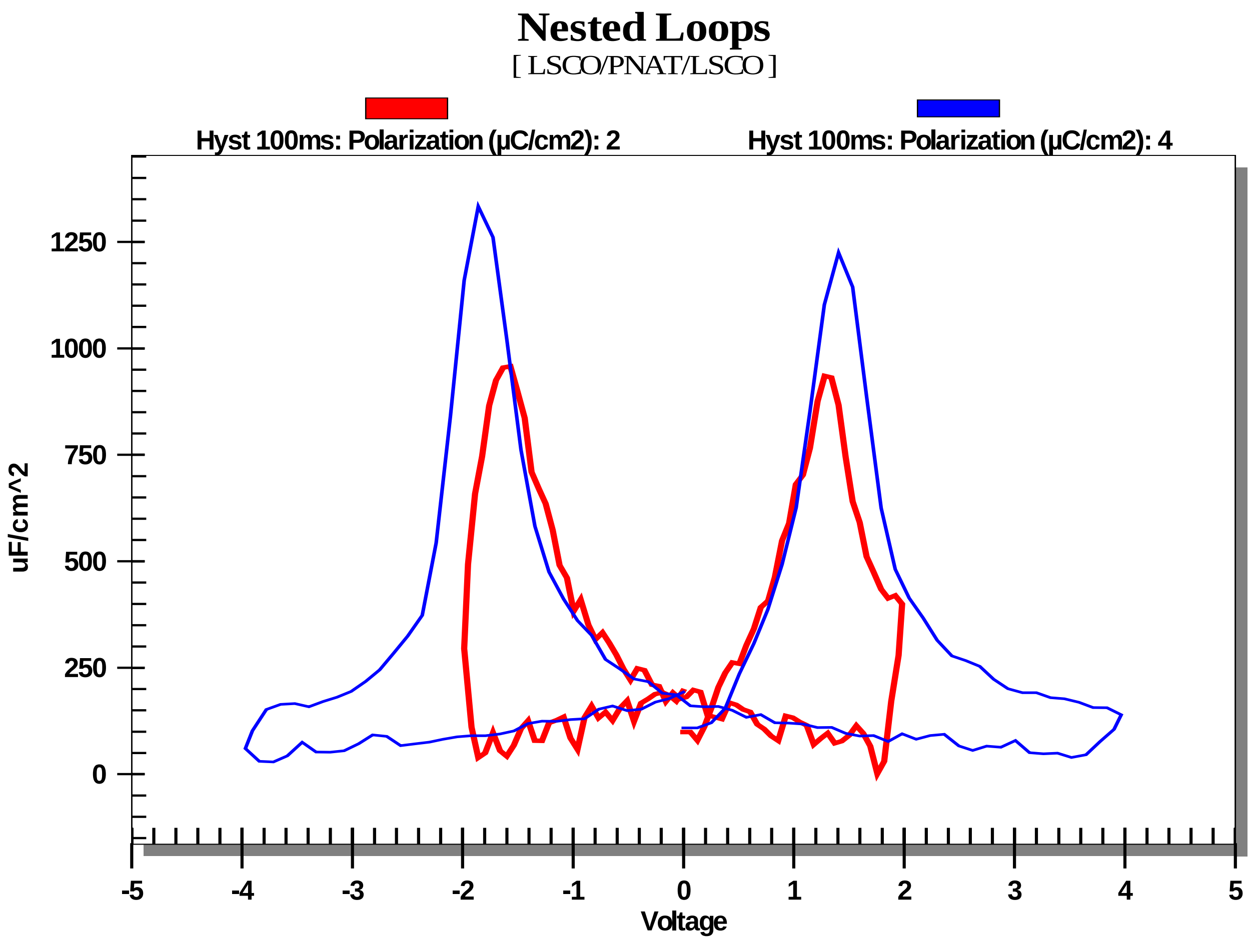
- Different electrodes on each interface means a different switching characteristic with direction. No linear leakage but classic back-to-back diode leakage. Surface diode breakdown at one of the electrode/ferroelectric interfaces.

Gotcha!



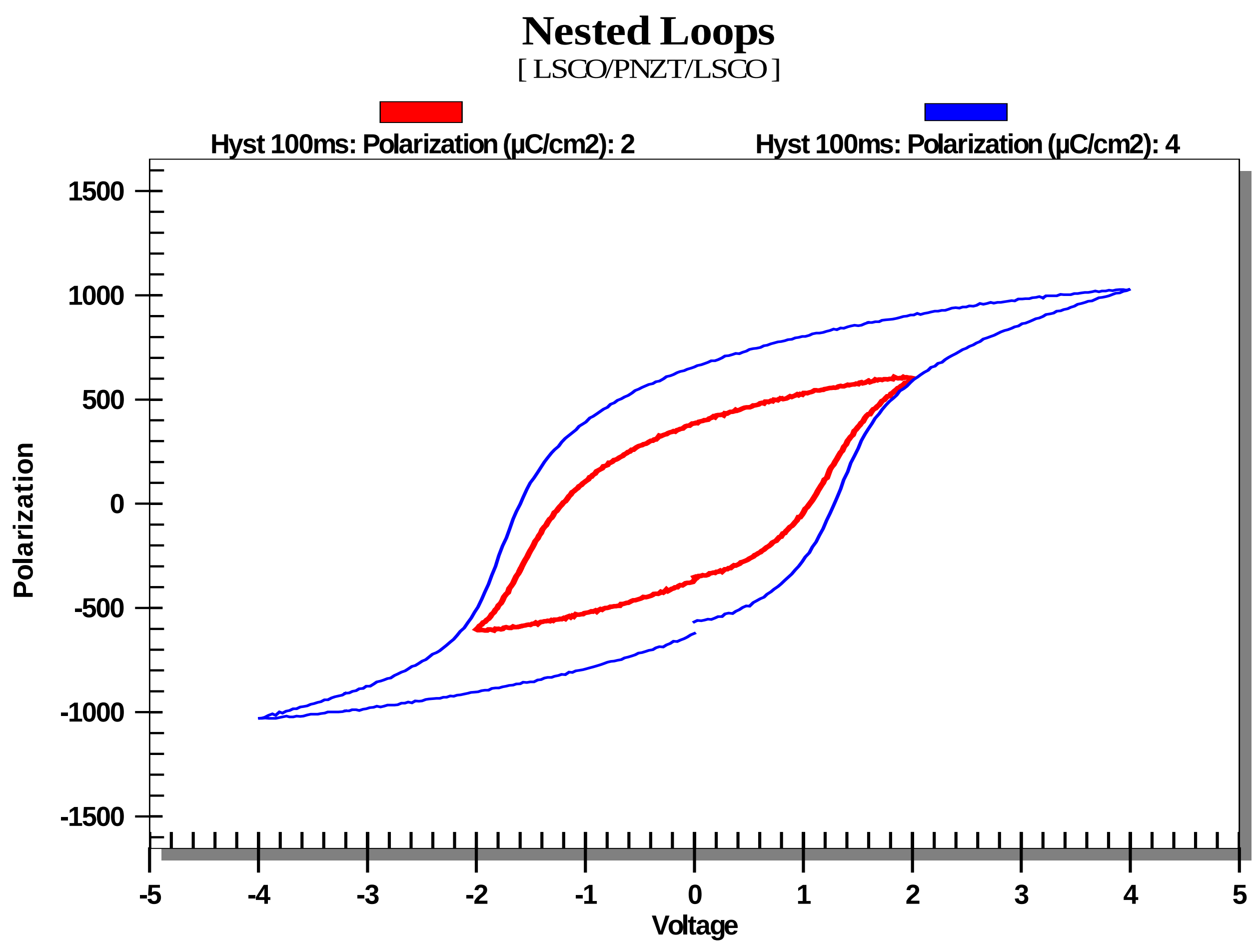
- What is this??? Is it some kind of breakdown???

Partial Switching!



- It is a sub-saturated loop which can sometimes look like breakdown.

Partial Switching!



- Here are the hysteresis loops.

Triangle Wave

- All of the modeling described above is dependent upon using a triangle wave to stimulate the sample.

- $\Delta V / \Delta t$ is constant.

  - nCV = $\Delta Q / \Delta V$

  - $I = \Delta Q / \Delta t \approx \Delta Q / k \Delta V = k \times nCV$

Conclusion of Components

- Geometry is everything, well almost.
- The ferroelectric hysteresis loop may be broken down into independent components.
- The mathematical derivative of the PE loop is a tool that allows identification by inspection of the components contributing to the response of the sample.
- Practice makes perfect.