Testing Thermodynamic States

Joe T. Evans,
Radiant Technologies, Inc.
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www.ferrodevices.com

Presentation Outline

- Introduction
- A charge model for electrical materials
- Instrumentation theory based on the charge model
- Simple components in the charge model
- A component model for non-linear capacitors
- Coupled properties
- History, testing, and automation
- Conclusion

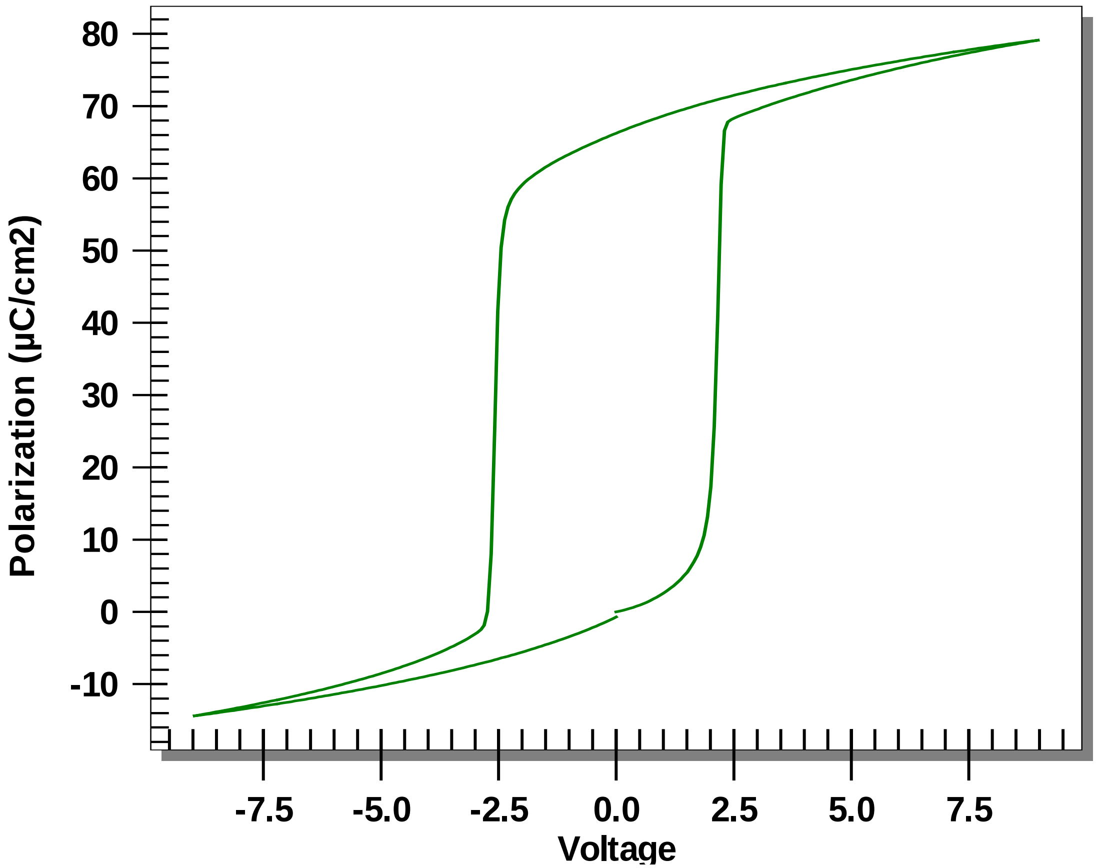
Radiant Technologies, Inc.

- Radiant Technologies pursues the development and implementation of thin ferroelectric film technology.
  - Test Equipment: Radiant supplies ferroelectric materials test equipment world-wide.
  - Thin Films: Radiant fabricates integrated-scale ferroelectric capacitors for use as test references and in commercial products.

The Presenter

- Joe T. Evans, Jr.
- BSEE – US Air Force Academy in 1976
- MSEE – Stanford University in1982
- Founded Krysalis Corporation and built the first fully functional CMOS FeRAM in 1987
  - Holds the fundamental patent for FeRAM architecture
- Founded Radiant Technologies, Inc in 1988.

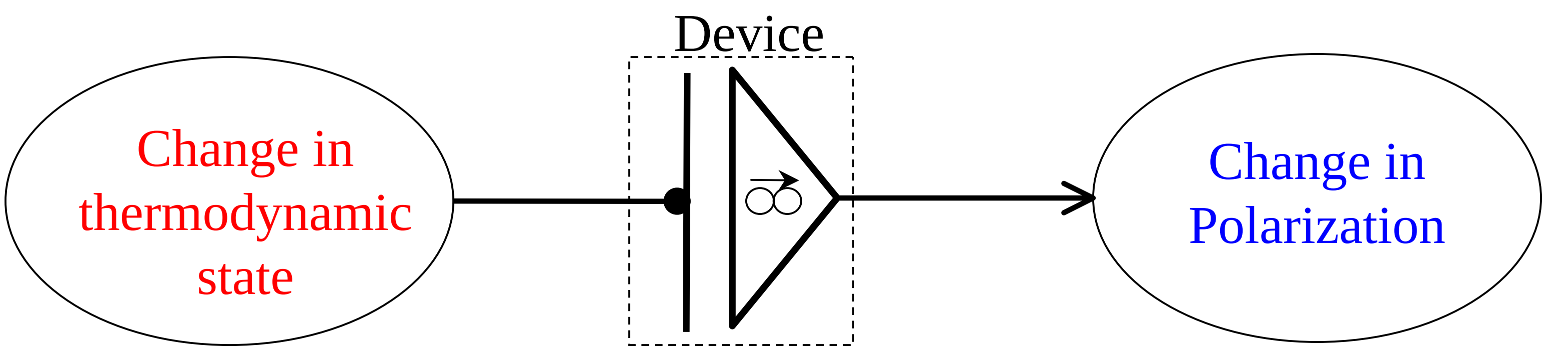
An Excellent Hysteresis Loop



- This loop is nearly “perfect”. How to perceive this device and measure all of its properties is the subject of this presentation!

The Charge Model of Electronics

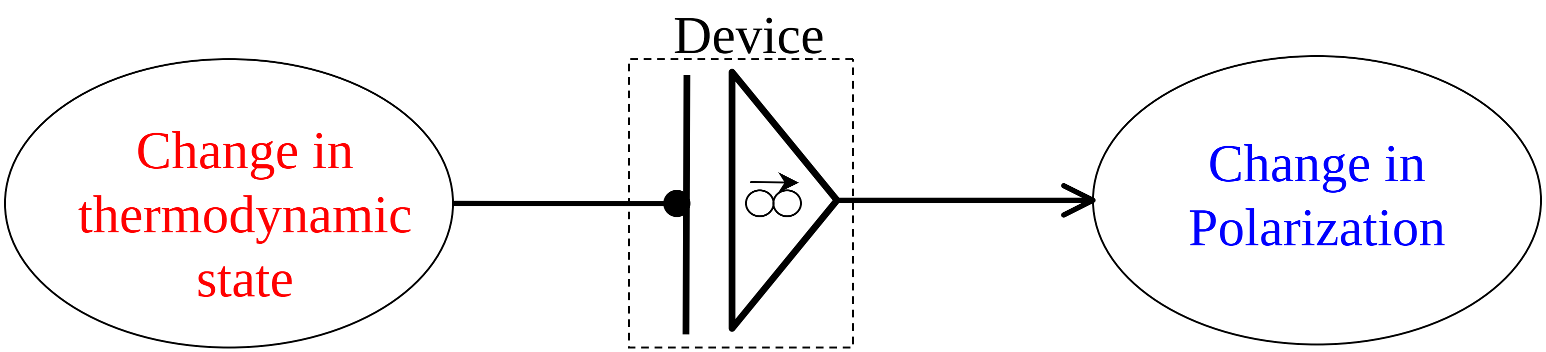
- Every electronic device consists of electrons and protons powerfully attracted into self-cancelling, self-organized structures.
- Every electrical device, when stimulated by one of six changes in thermodynamic state, changes its charge state.



- Every device may be modeled as a *charge source* controlled by an *external factor* separated by *infinite impedance*.

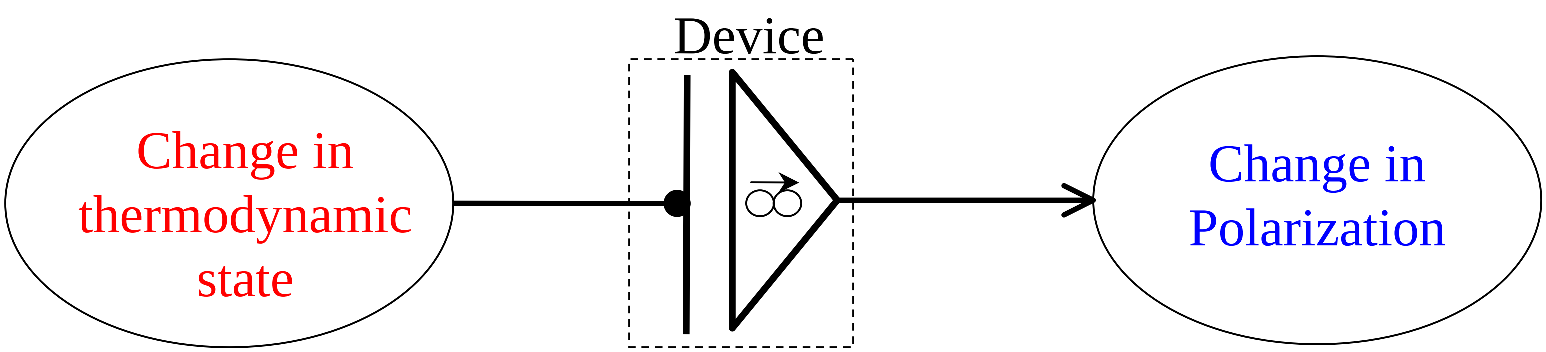
The Charge Model of Electronics

- The ***infinite input impedance*** of the model means that the input and output are *independent* of each other, coupled only by the *equation* describing the model.
- Consequently, the input circuitry from the tester to the Device Under Test (DUT) and the circuitry of the tester that measures the output of the DUT *do not have to be related*.
  - They only need a *common reference* for energy potential.



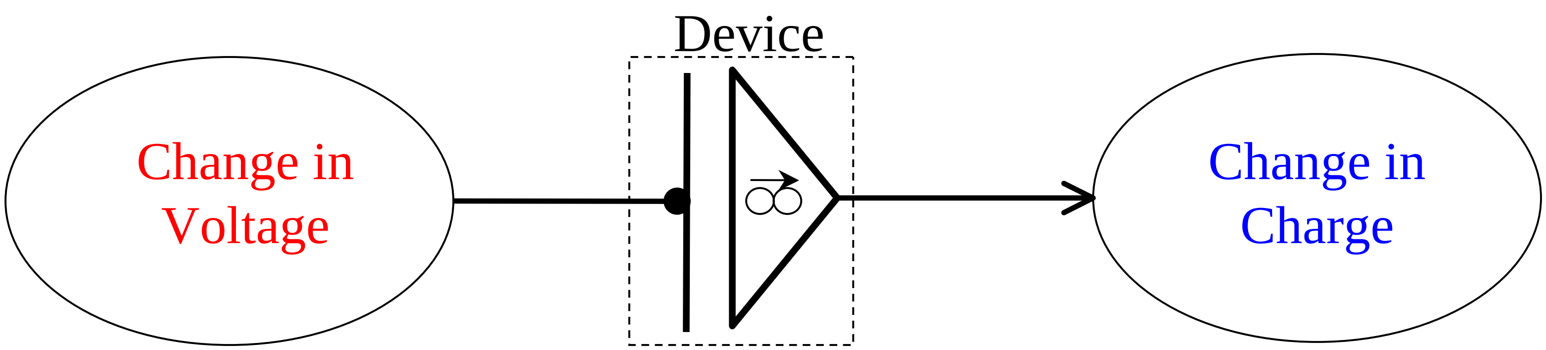
The Charge Model of Electronics

- The six thermodynamic state variables are
  - Stress (T)
  - Strain (S)
  - Electric Field (E)
  - Polarization (P or D)
  - Temperature (θ)
  - Entropy (s)



The Charge Model of Electronics

- A traditional *Loop Tracer* varies only one state variable, *Electric Field*, and measures the change in one other state variable, *Polarization*.

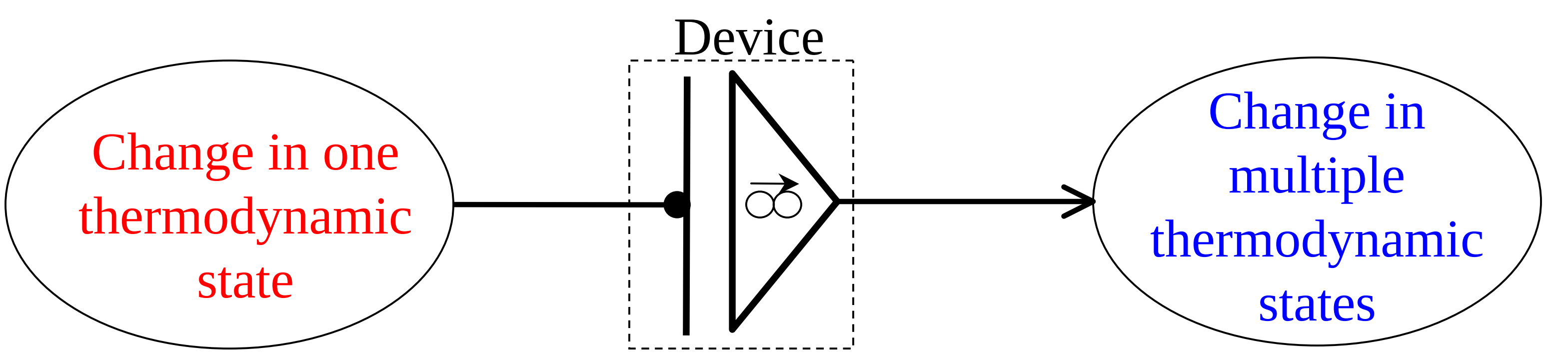


- Absolute units uncorrected for geometry drive the real world, hence the use of Voltage in place of Electric Field and Charge in place of Polarization in the figure above.

The Charge Model of Electronics

- Modern "Polarization" testers measure *charge* and *voltage* simultaneously so the change in *more than one thermodynamic state* may be measured during a test.

- The voltage input can be used to capture the output of sensors that convert a thermodynamic state to a voltage:
  - Displacement sensor
  - Thermocouple
  - Force sensor

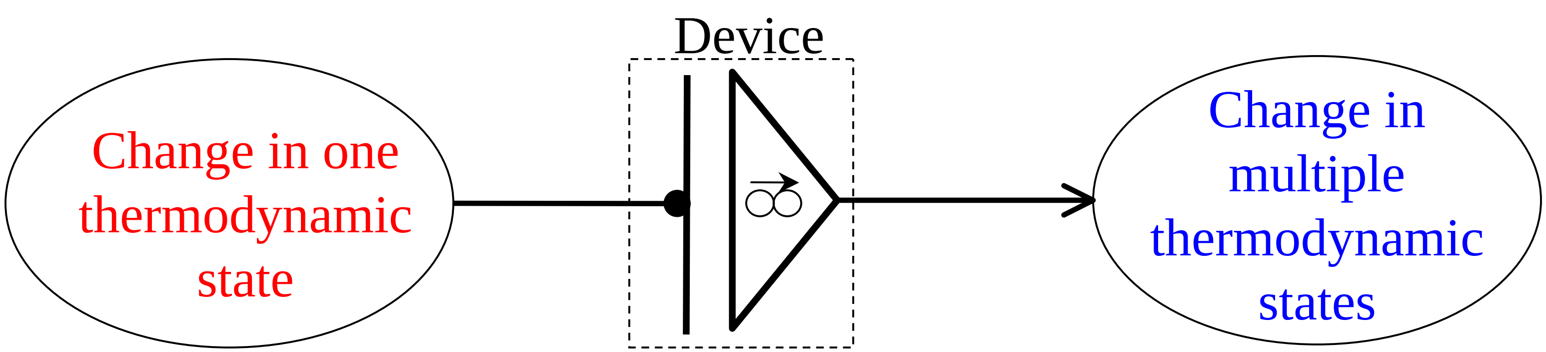


The Charge Model of Electronics

- Modern ferroelectric testers are no longer *Loop Tracers* but instead are *Thermodynamic State Testers!*

- The Precision Premier II measures charge and two input voltages on *every* test.

- ***In keeping with this model, all Radiant testers have an open architecture in electronics and software to allow the user to configure any stimulus/response configuration***



Absolute vs Indirect

- An *absolute* measurement counts or quantifies a material property *directly* in absolute physical units:
  - Number of electrons
  - Amplitude of a force

- An *indirect* measurement measures a *defined* property of a material and then uses a model to *translate* the results into an *absolute* property.

Absolute vs Indirect: Example

- An ***impedance meter***, of which tens or hundreds of thousands have been sold, measures *phase delay* and *amplitude change* of a signal fed through the DUT and then uses *impedance equations* to convert the results into *absolute values* of *capacitance* and *loss*.

- A ***polarization tester*** stimulates a device with a fundamental quantity of nature -> *voltage* -> and *counts* another fundamental quantity of nature -> *electrons* -> before, during, and after the stimulus.

Absolute vs Indirect: Example

- An ***impedance meter*** measures ***averages***.
  - An ***impedance meter*** appears to have low noise in its measurements but this is the result of **measuring averages**.
- A ***polarization tester*** measures ***single events***.
  - A ***polarization tester*** does have high noise in its measurement but multiple single-event measurements can be **averaged**

Linear vs Non-linear

- For a linear DUT, no matter how a parameter is measured, the same result is obtained.
    - *A linear capacitor measured by any tester and test technique will result in the same answer.*
- For a non-linear DUT, a different starting point results in a different end point.
    - *A non-linear capacitor will give different values to different testers attempting to measure the same parameter.*
    - *Both answers are correct!*

Tester Circuits

- In order for a proper thermodynamic state tester to adhere to the model described above:
  - The tester must *stimulate* the DUT directly with one of the *fundamental* quantities of physics.
  - The tester must *directly count* or *quantify* the thermodynamic response of the DUT in *absolute* units.
  - The tester should take advantage of the *independence* of the output from the input.
  - The tester must create a 1:1 time correlation between the *stimulus* and the *response*.
    - *NO IMPEDANCE ALLOWED!*

Stimulus

- The stimulus can be any *one* of the six thermodynamic variables applied in a manner so as to minimize any contributions from other variables.

Stimulus

- Voltage
  - ±10V created from operational amplifiers
  - ±200V created from low solid-state amplifiers
  - ±10kV created from external amplifiers
    - 10kV is the limit due to expense and low demand.
  - Voltage is created directly from software using Digital –to-Analog Converters (DACs).

- Charge
  - Charge source forces the charge state.

Stimulus

- Temperature
  - Voltage or software controlled furnace
  - Voltage or software controlled hot plate
  - The temperature may be generated *directly* by command from the controller by voltage-to-temperature converter or by software communications.
  - The temperature may not be controlled but instead may be *measured* as a parameter in an *open-loop* system.

Stimulus

- Force
  - Any number of actuator types may be used, either voltage or software controlled.
  - The force may be *commanded* or, like temperature, may be *measured* in an open-loop system.

- Strain
  - A strain stimulus requires
    - Force application (See above) plus
    - A strain measurement to capture that state during the test.

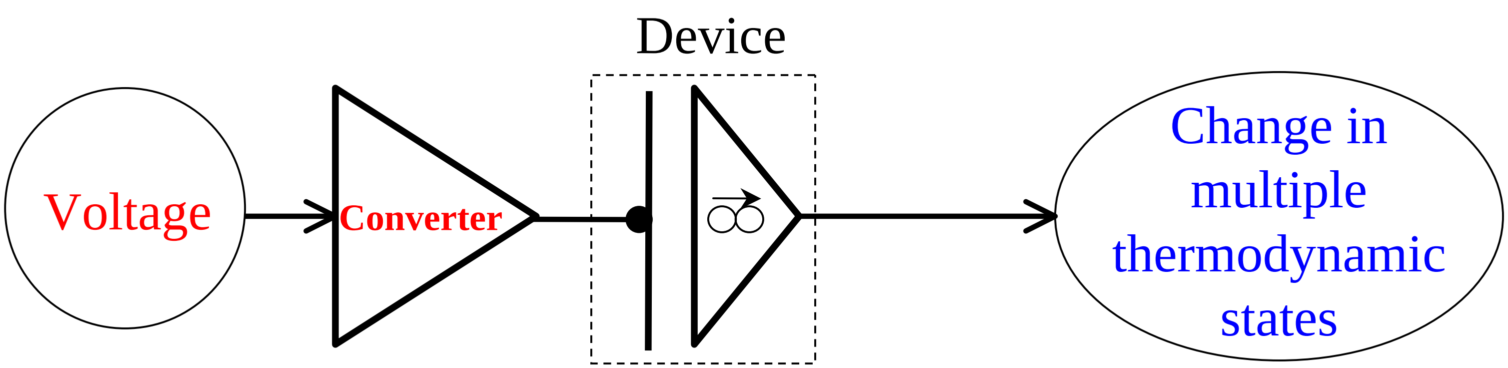
Stimulus

- A independent change in *entropy* is not contemplated today as a stimulus.

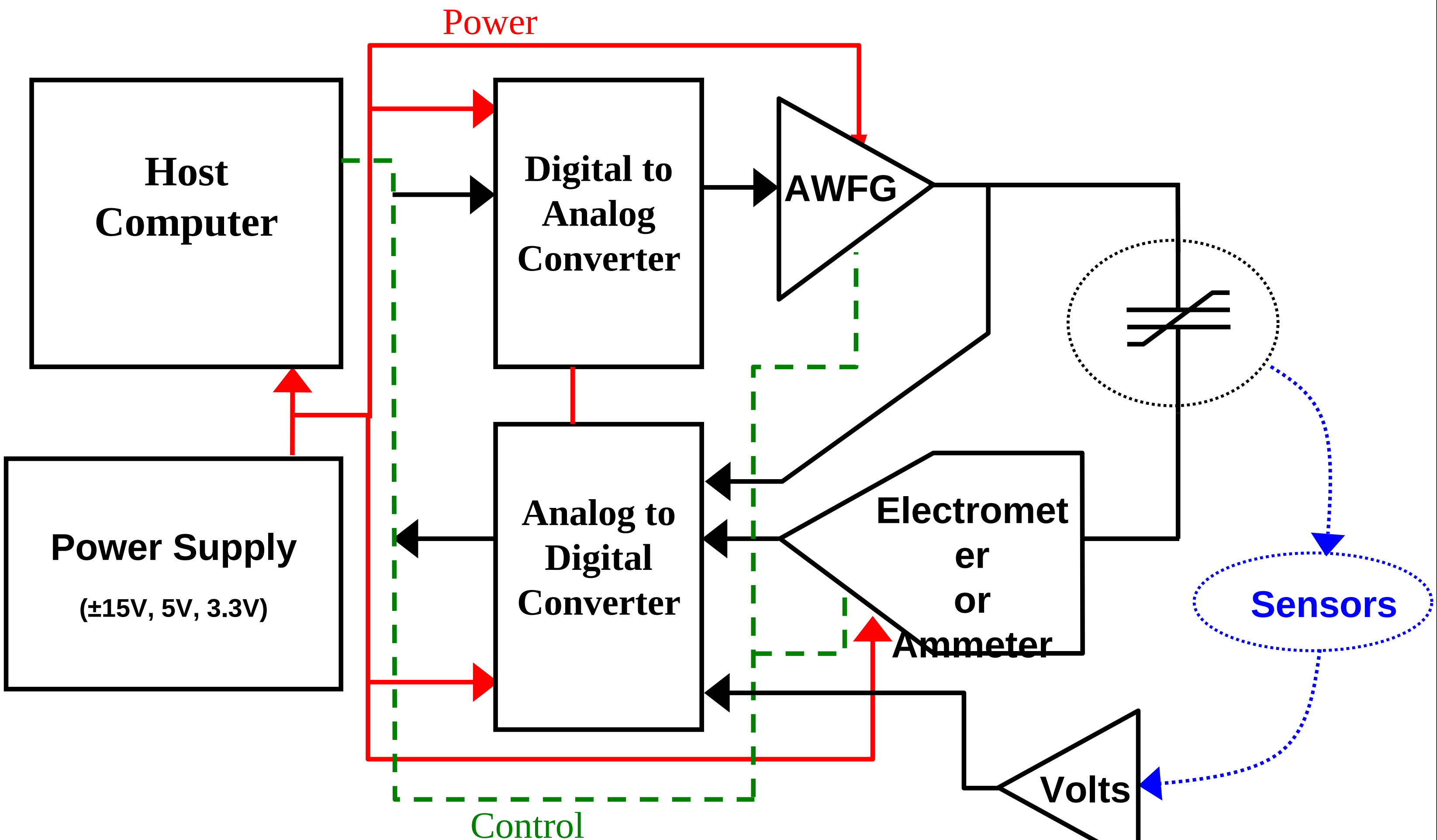
- Theoretically, a *magnetic field* is not a separate thermodynamic stimulus because it was unified with electric fields by James Maxwell in 1861.
    - Magneto-electric testing is coming from Radiant in the near future.

Stimulus

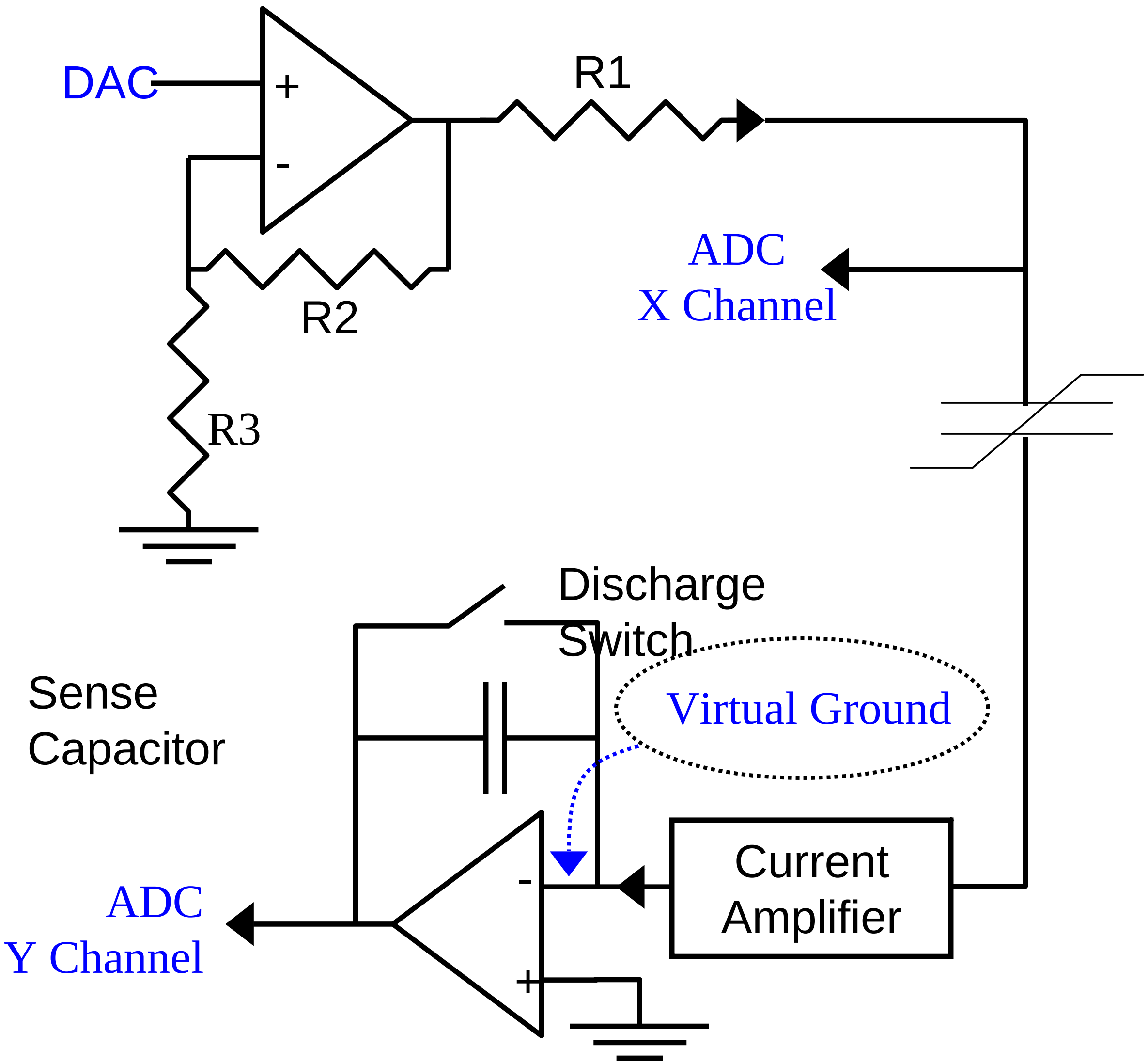
- NOTE: For the four possible stimuli besides voltage (*temperature, strain, stress, and charge*), the best and easiest implementation is a stimulus system that is *voltage controlled* so that a standard *hysteresis* test can be executed.



Test System Diagram

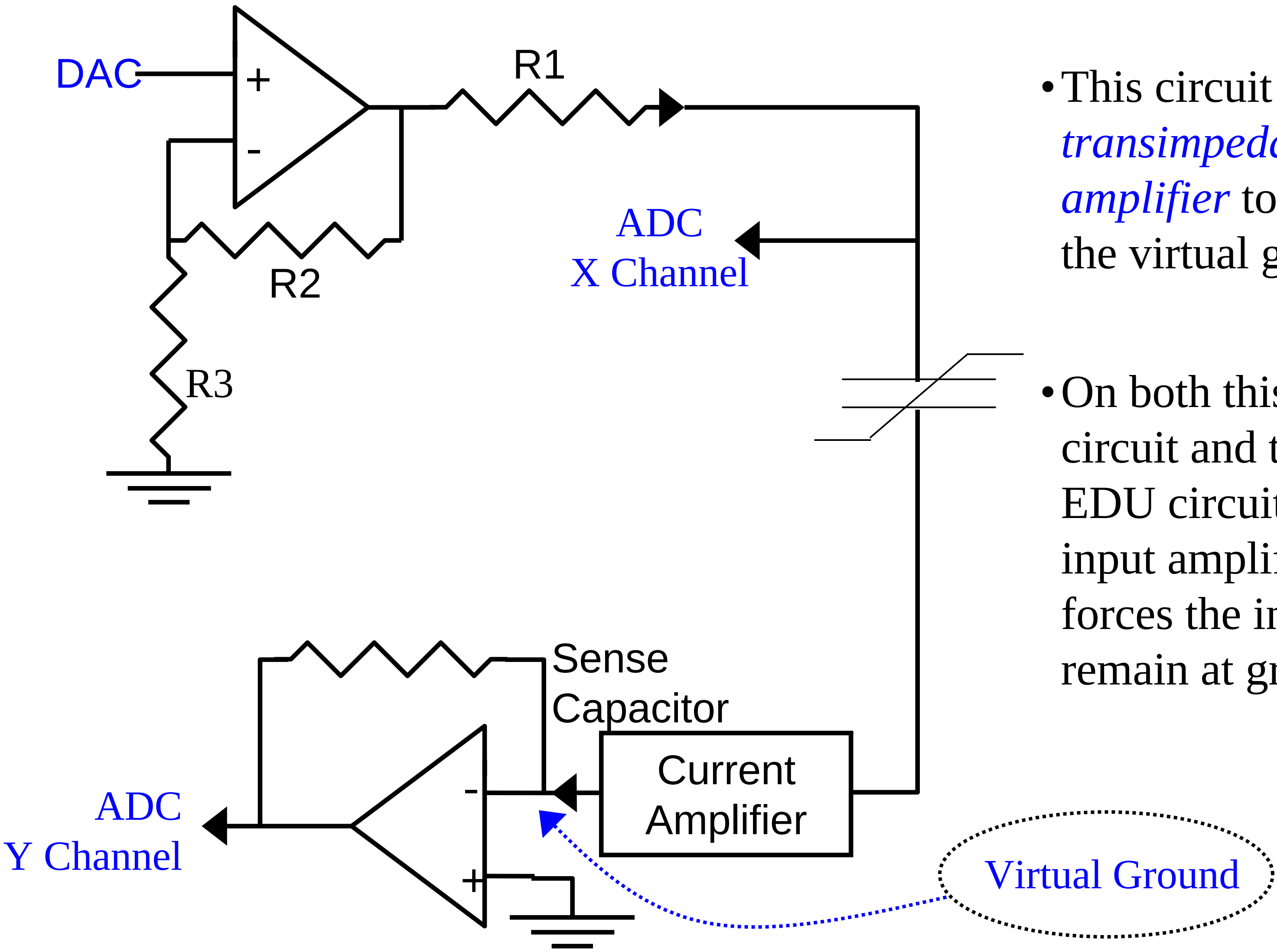


The Test Circuit



- To the left is one example of a test path for a ferroelectric tester.
- This is the circuit for the Radiant EDU, a very simple tester.
- The EDU uses an *integrator circuit* to collect charge.

A Different Test Circuit



- This circuit uses a *transimpedance amplifier* to create the virtual ground.
- On both this circuit and the EDU circuit the input amplifier forces the input to remain at ground.

Mathematics

- Transimpedance amplifier: [aixACCT]
  - Measures "I"
  - Integrate "I" to get charge: $P = \int I \, \delta t \, / \, Area$
  - Plotted value P is *calculated*.

- Integrator: [Radiant]
  - Measures charge directly
  - Divide by area to get polarization
  - Plotted value P is *measured*.
  - Derivative yields current: $J = [\, \delta Q / \delta t \,] \, / \, Area$

The Virtual Ground

- Electrons in the wire connected to the virtual ground input move freely into or out of that node in response to outside forces.

- Since the virtual ground input has no blocking force to that movement, it has *zero impedance*.

- The integrator, or charge amp, *counts electrons* moving into or out of its input node *independent* of the voltage stimulus.

  ∴ Piezoelectric and pyroelectric response.

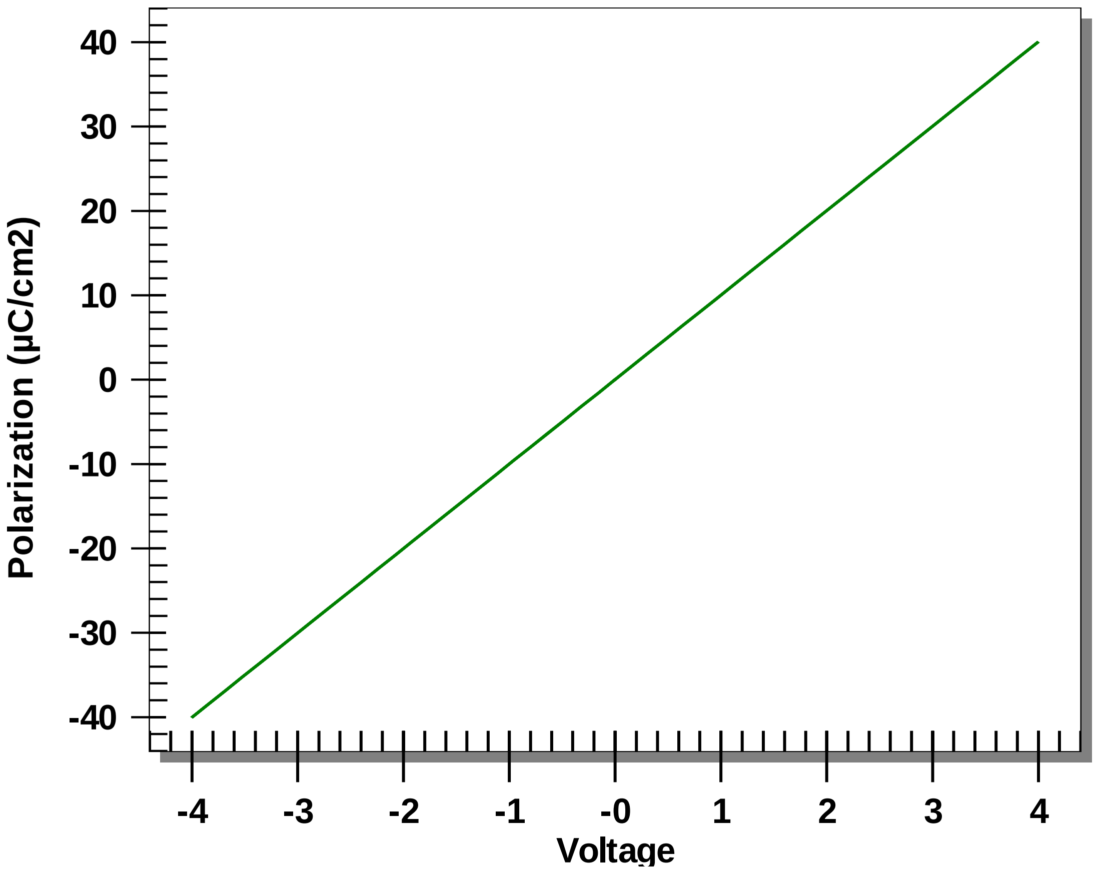
Simple Components in Charge Space

- All electrical components can be measured in "Charge Space": Charge vs Volts.

- Time is not a parameter in the plot but does affects the results.

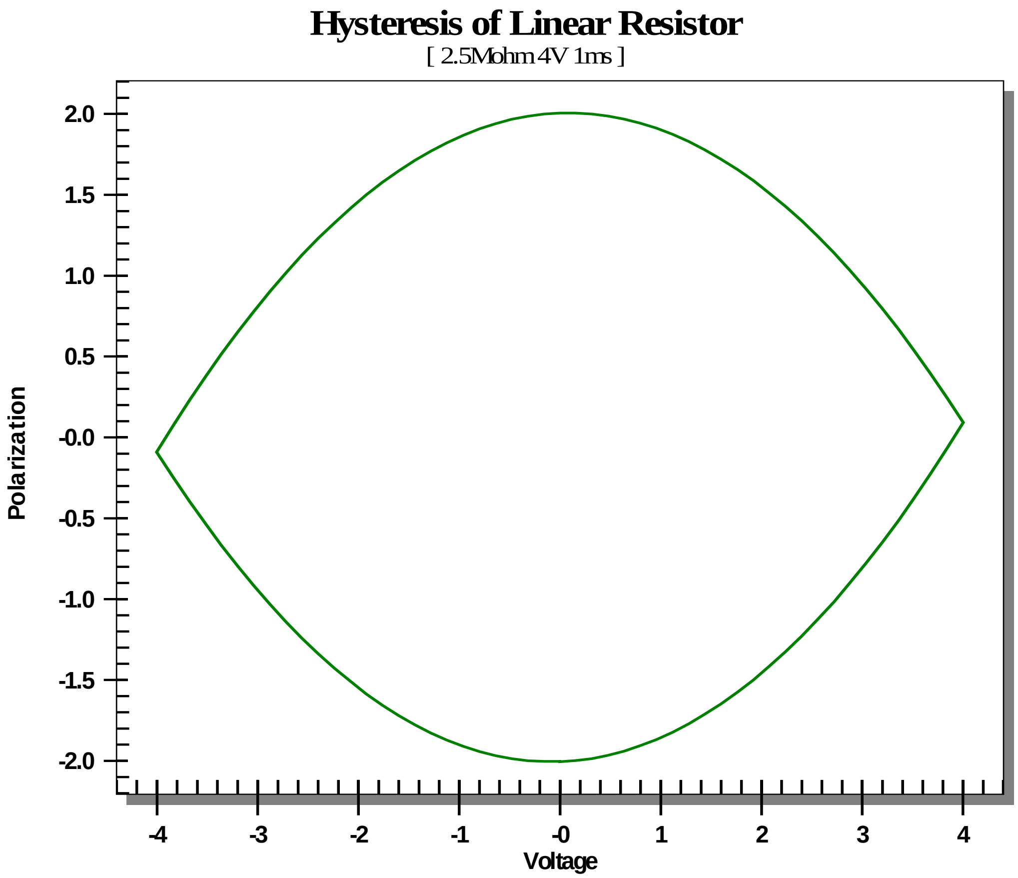
- Each component produces a particular shape in the Hysteresis Test.

Simple Components in Charge Space



- Linear Capacitance

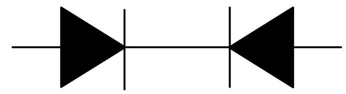
Simple Components in Charge Space

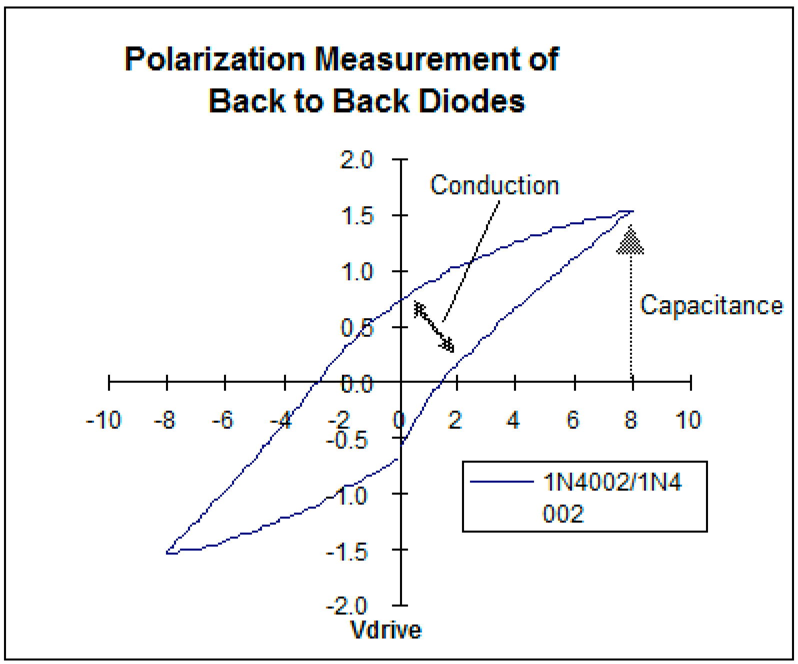


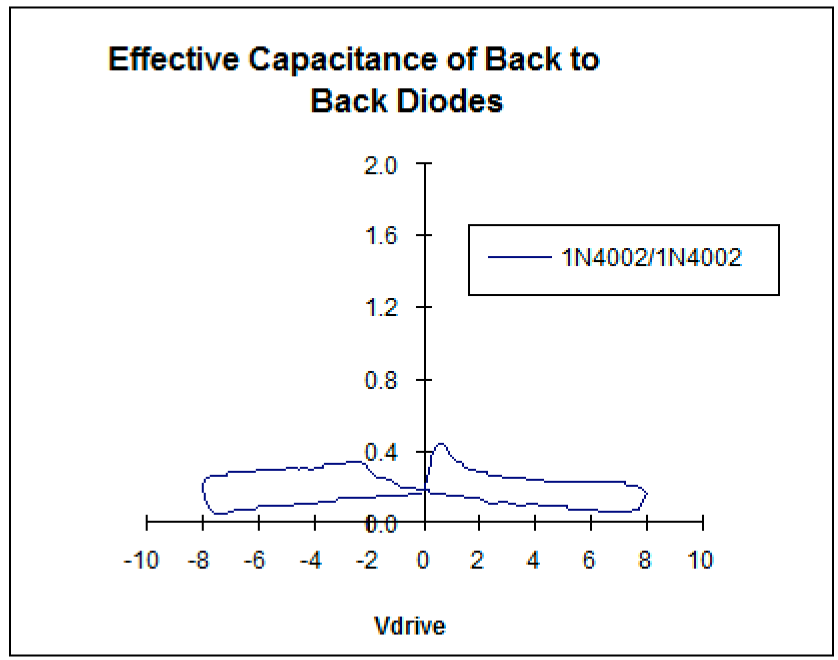
- Linear Resistance

Simple Components in Charge Space

- A pair of Back-to-Back Diodes.







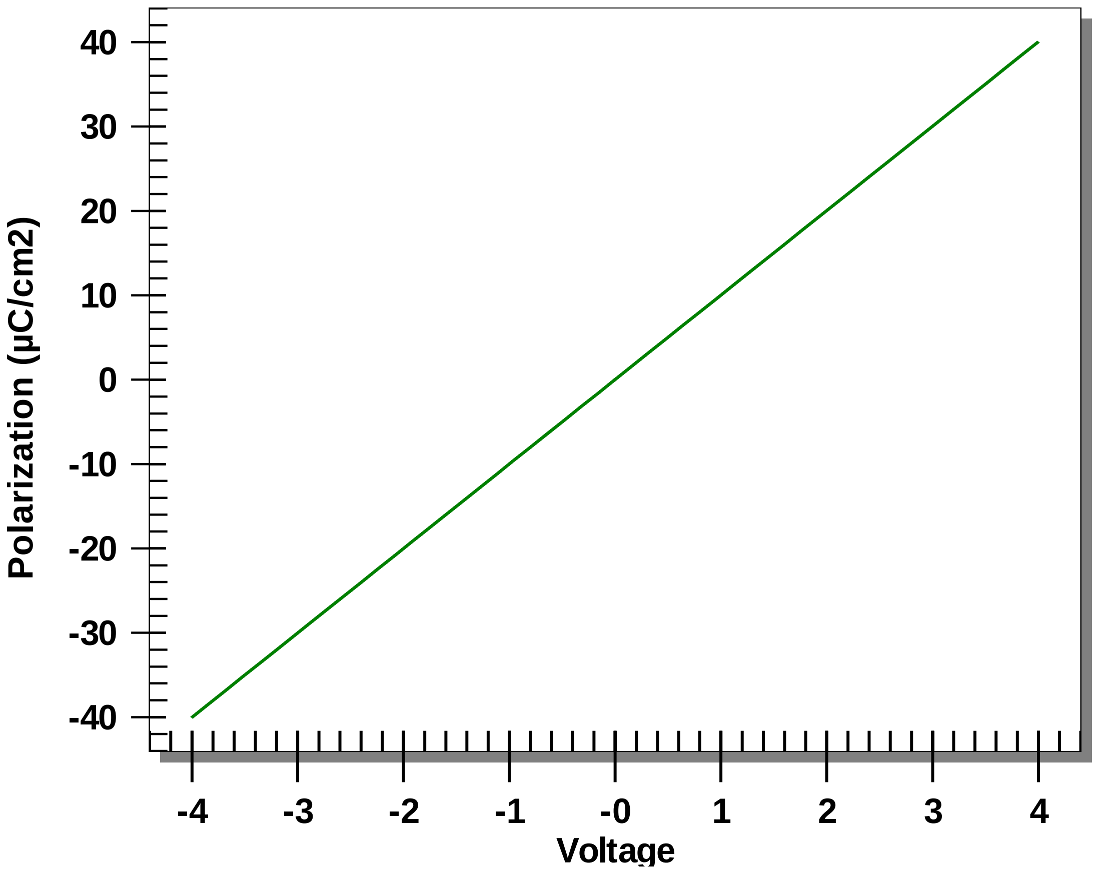
Modeling Nonlinear Capacitance

- 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

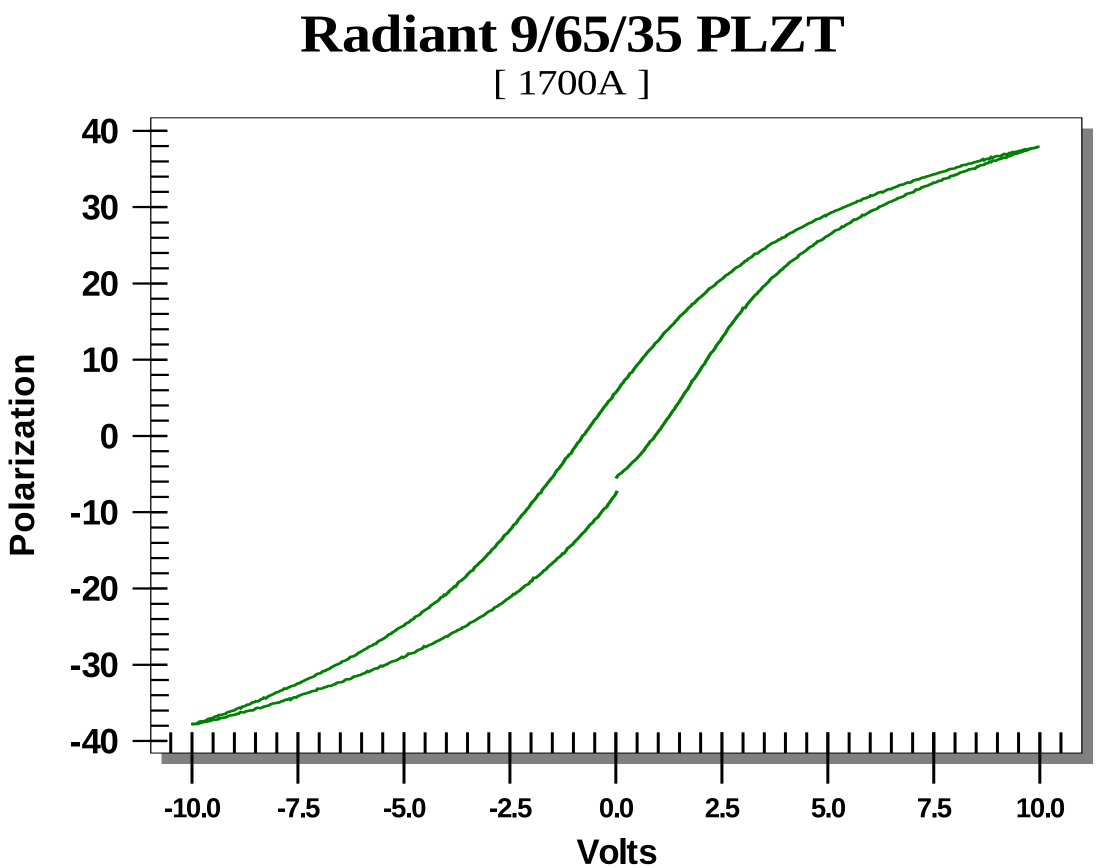
- Remanent polarization
- Linear small signal capacitance (dielectric constant)
- Nonlinear small signal capacitance (dielectric constant)
- Hysteretic small signal capacitance (remanent polarization modulation)
- Linear resistive leakage
- Hysteretic resistive leakage
- Electrode diode reverse-biased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

Linear Capacitance



- Q = CxV where C is a constant

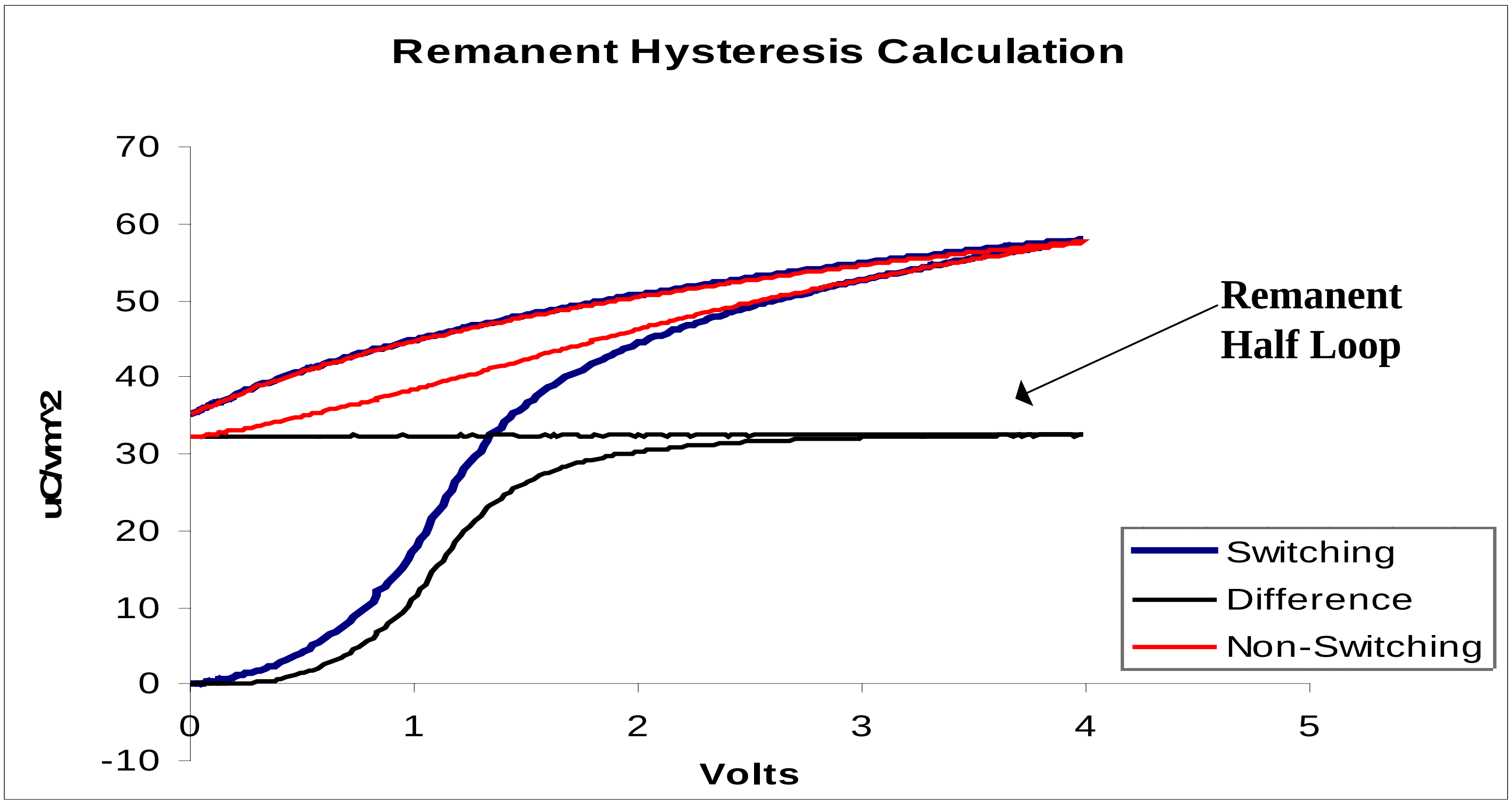
Non-linear Capacitance



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

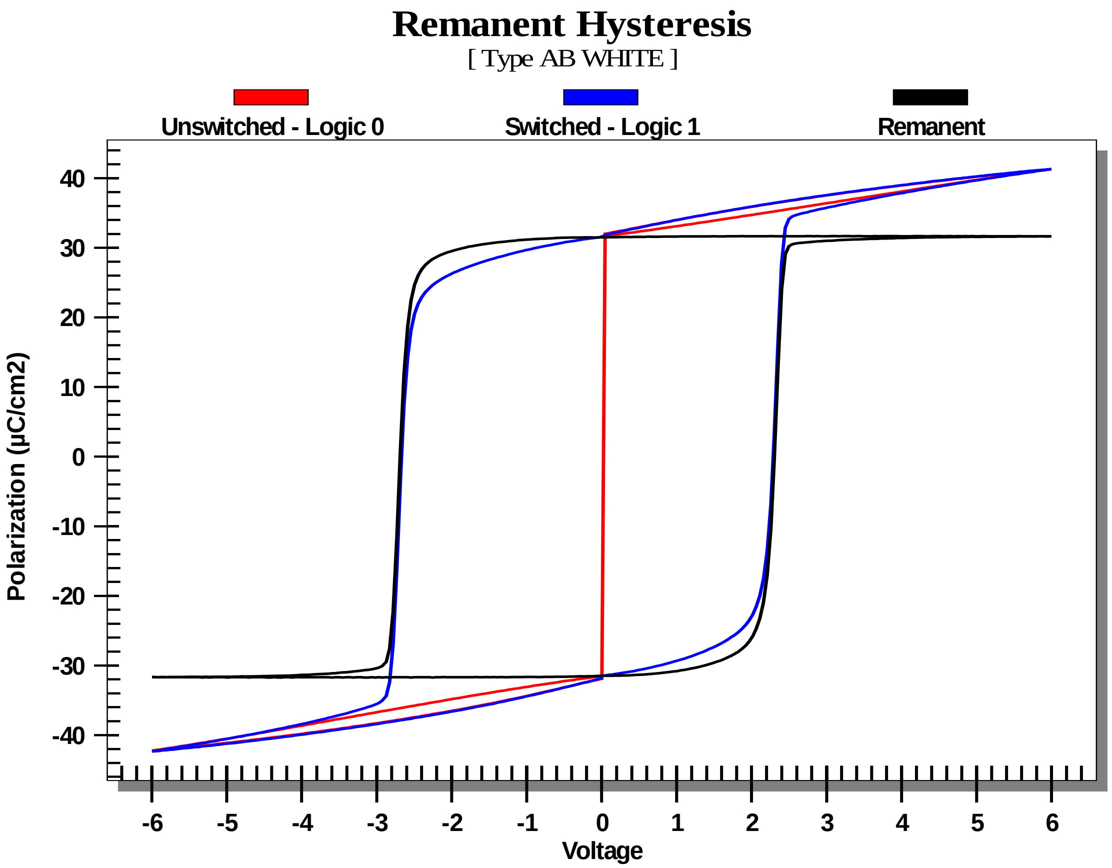
Remanent Hysteresis

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



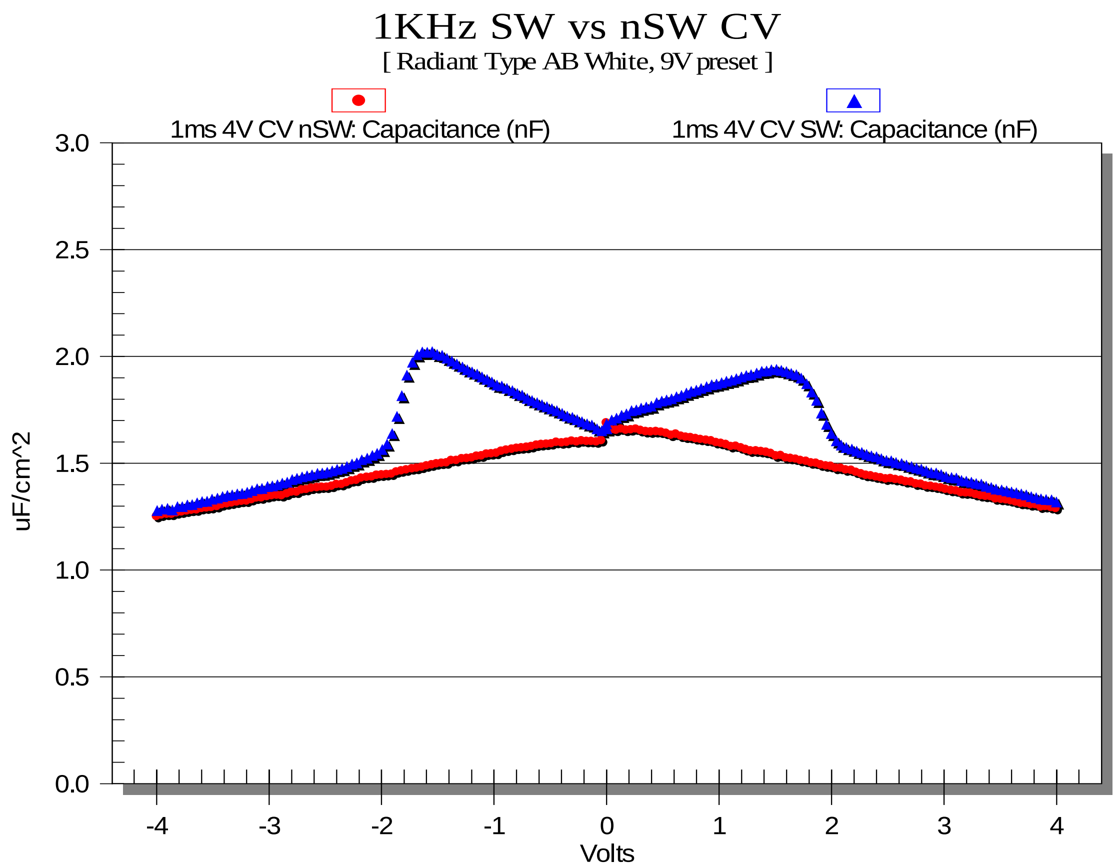
Remanent Hysteresis

- 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.

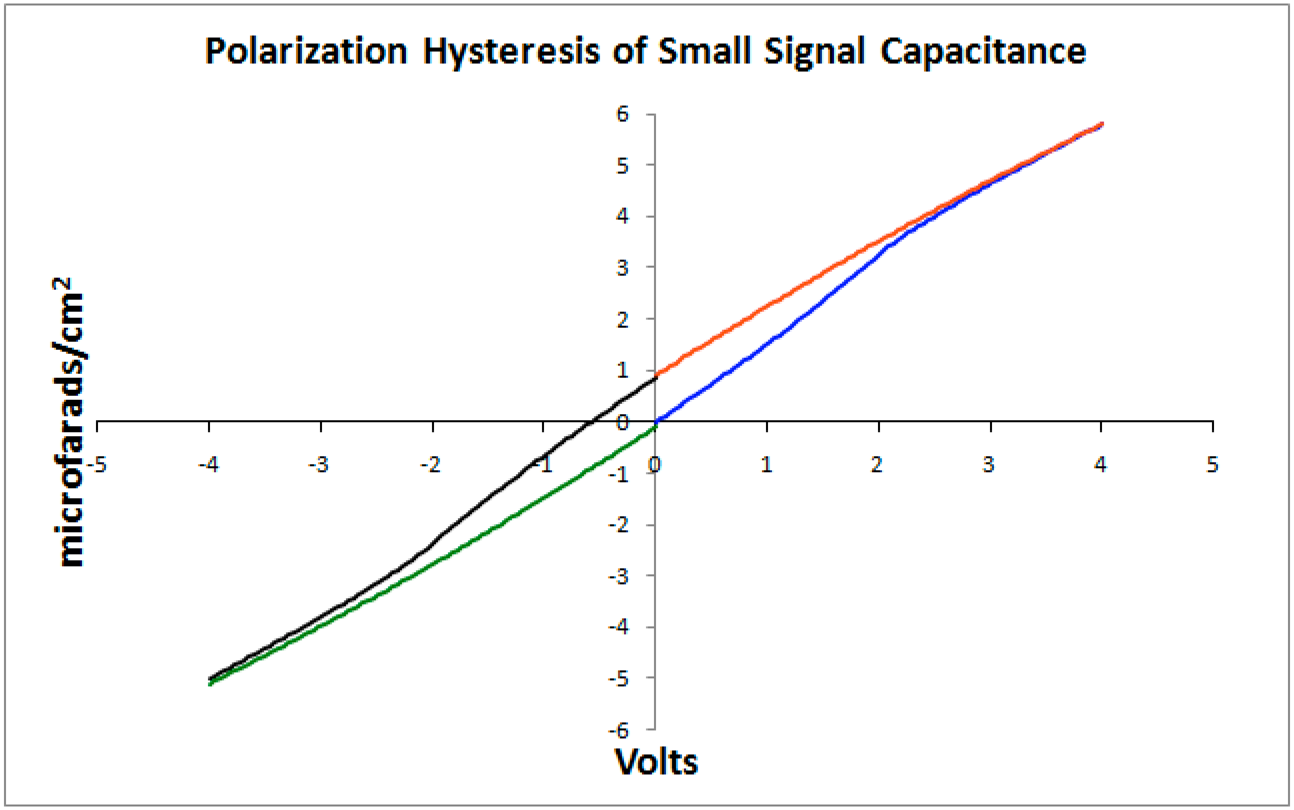


Non-switching vs Switching CV

- 1KHz 0.2V test with 182 points

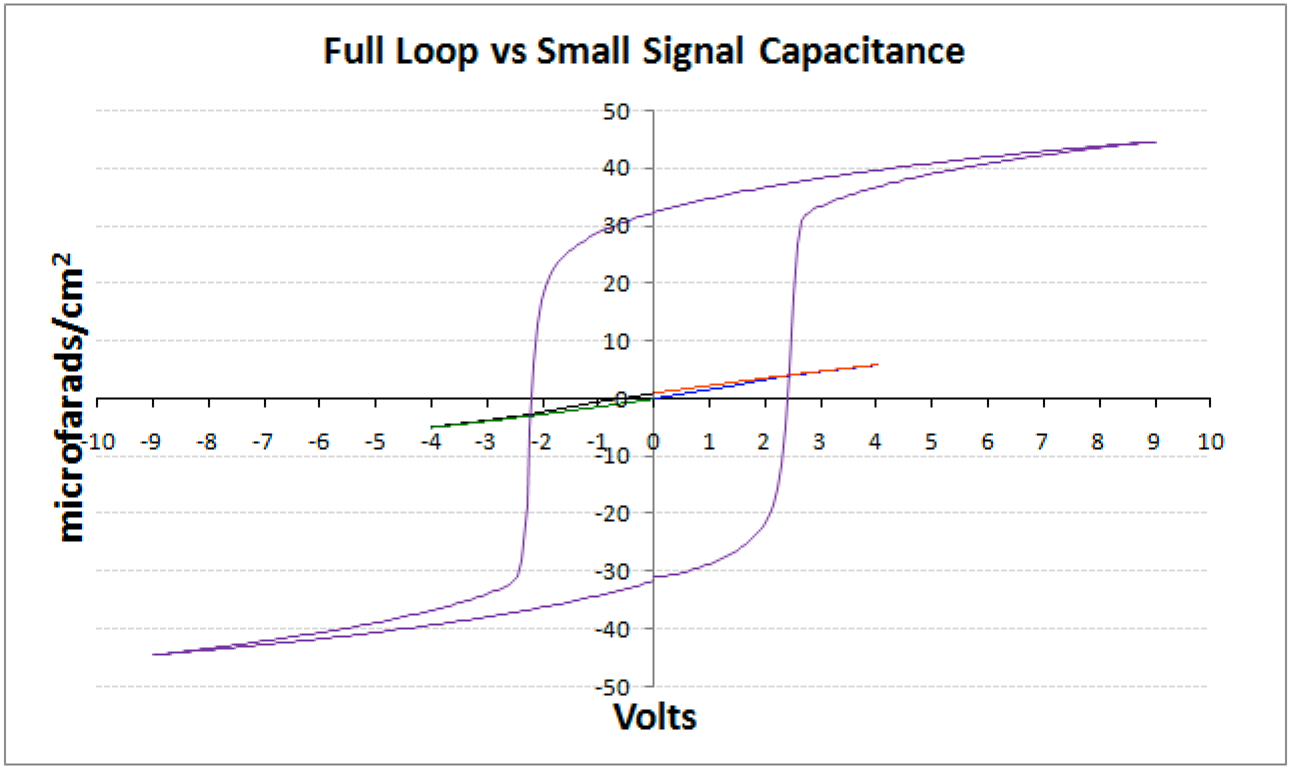


Small Signal Capacitance Polarization



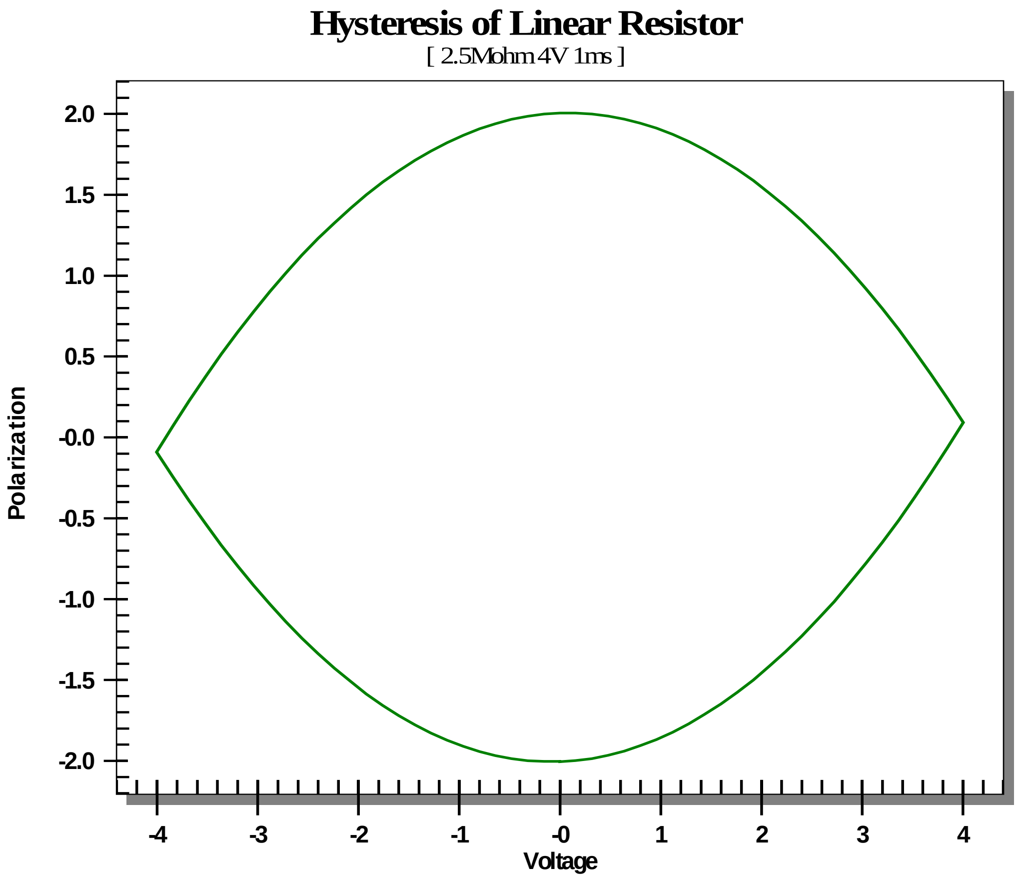
- Small signal capacitance forms a hysteresis of its own.

Small Signal Capacitance Polarization



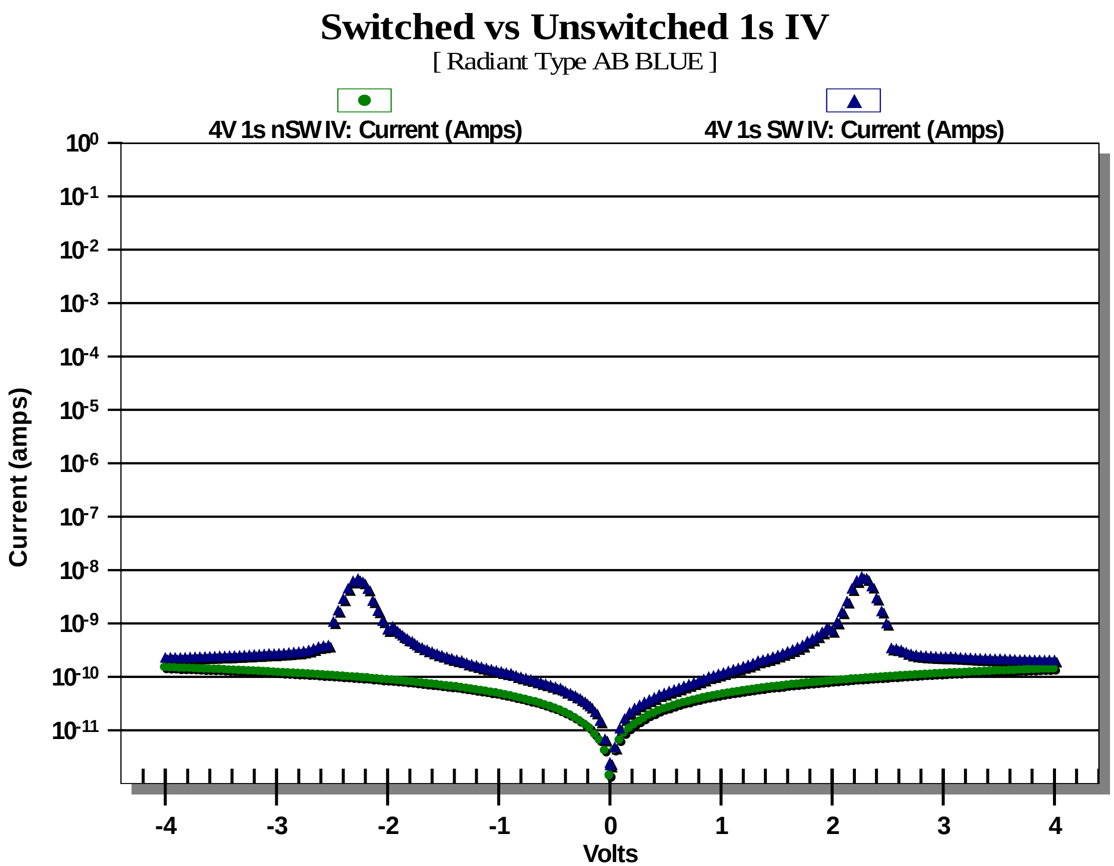
- The contribution of small signal capacitance hysteresis to the overall loop is small in this case.

Linear Resistance



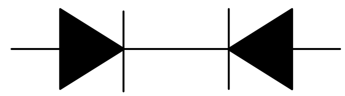
Hysteresis in Leakage

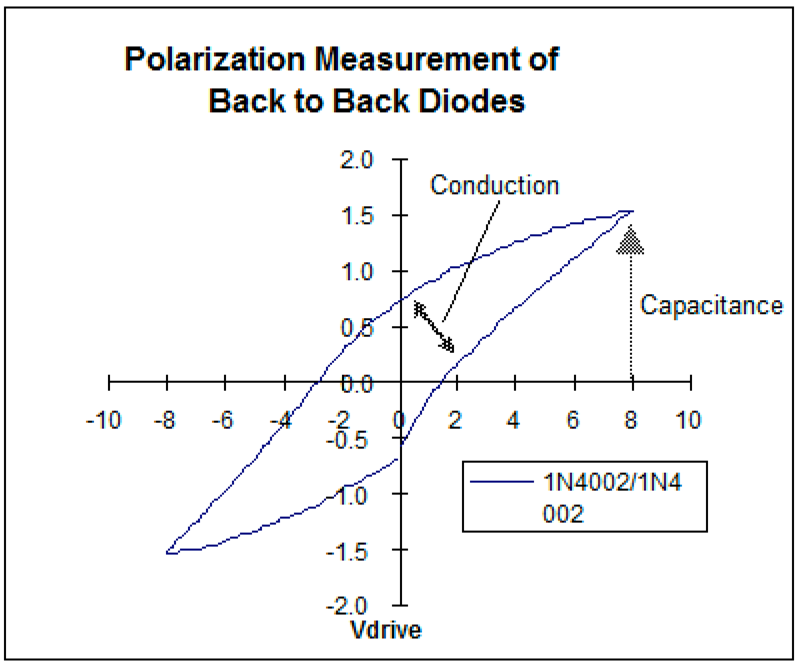
- Leakage in ferroelectric materials does not have to be linear.
- Leakage can have its own hysteresis modulated by remanent polarization.

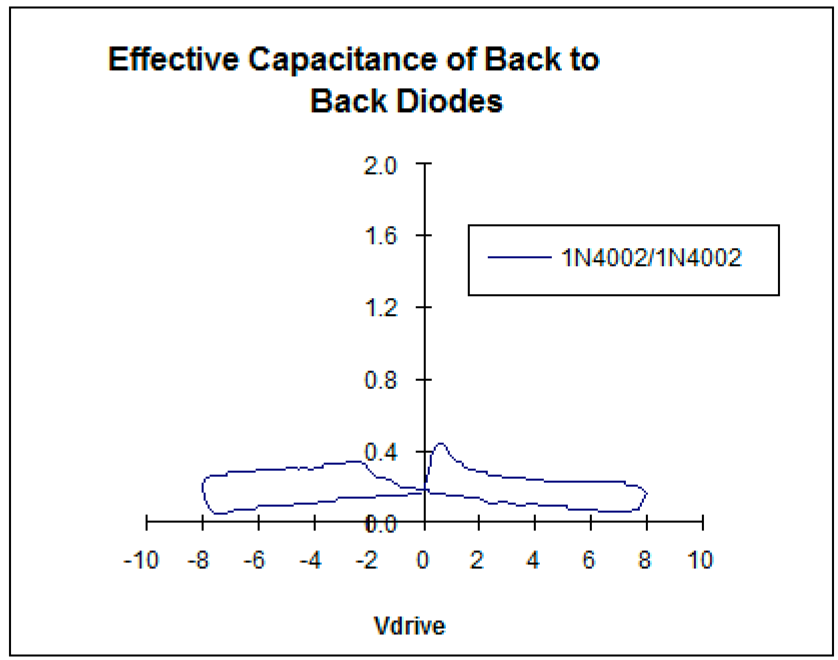


Simple Components in Charge Space

- A pair of Back-to-Back Diodes.







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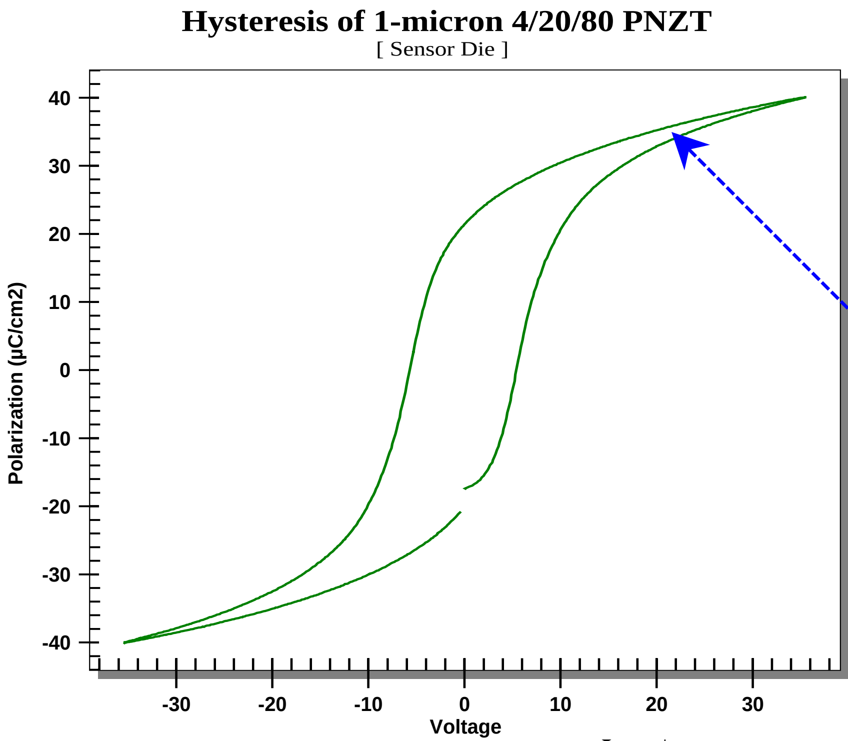
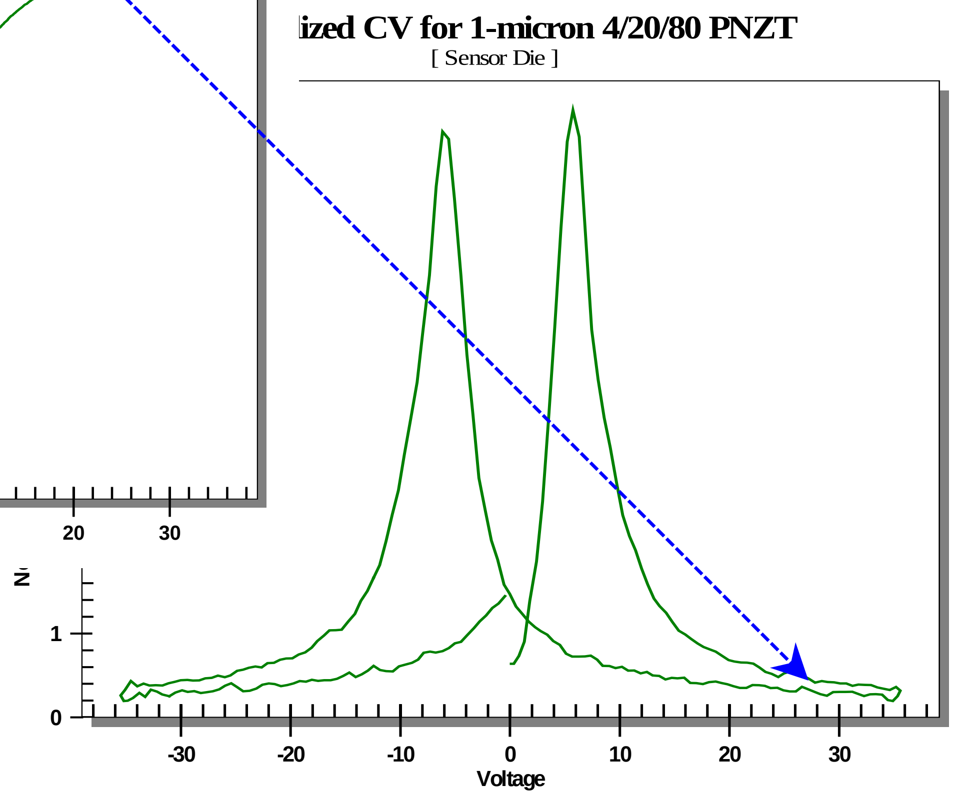
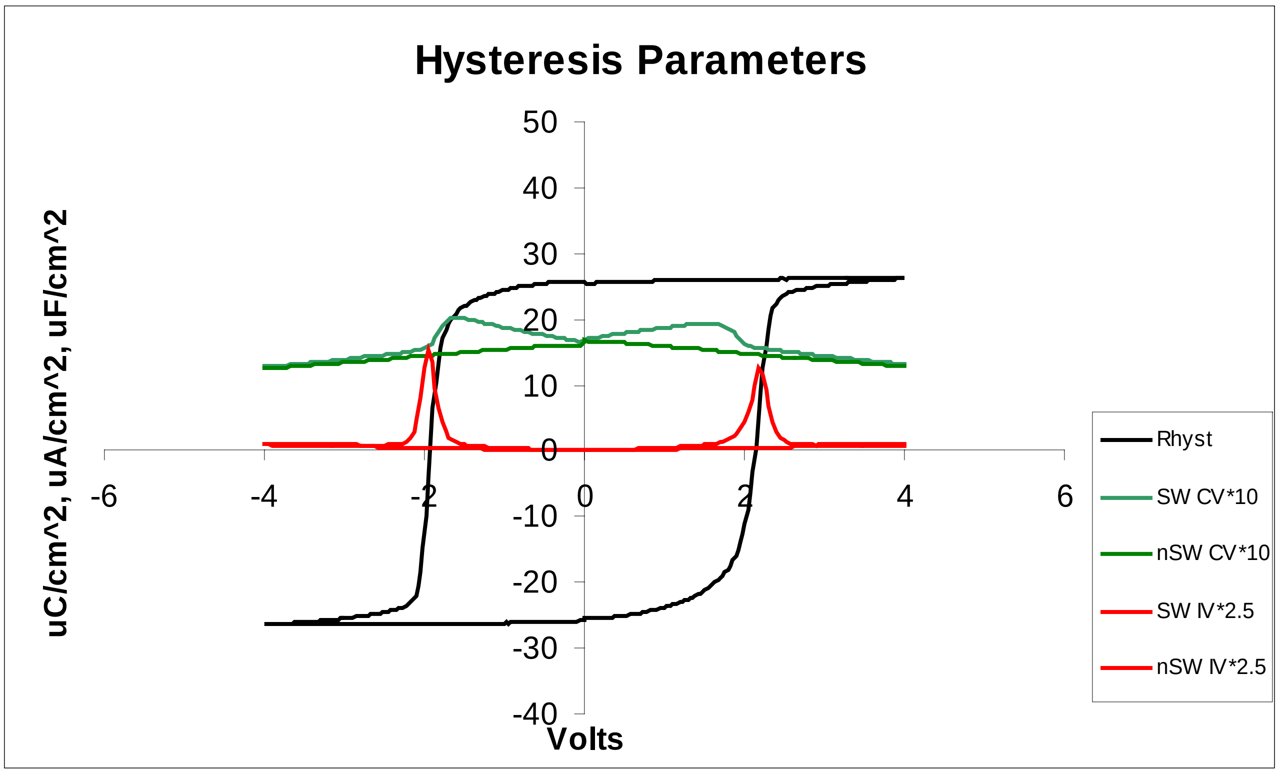




- The back-to-back diode effect is easily seen in every hysteresis loop.

Leakage vs CV vs Remanent Polarization



The Components

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- Electrode diode reverse-biased exponential breakdown

See the Radiant presentation "Ferroelectric Components - A Tutorial" for more detail.

Bulk Ceramics

- Bulk Ceramic capacitors and thin film capacitors have long been treated as completely different from each other.

- We have found that there is no difference so the same tests and the same models can be used for both.

- The results differ in appearance:
  - The greater *thickness* of the bulk ceramics lowers the contribution of *dielectric constant* charge while *remanent polarization* remains *constant* independent of thickness. Therefore, bulk ceramics have a lower slope and *look* more square even though they have the *same properties* as thin films.

Test Definitions

- **Hysteresis** – the polarization curve due to a continuous stimulus signal. The signal can have any shape.
- **Pulse** – the polarization change resulting from a single step up and step down in voltage. Essentially a 2-point hysteresis loop.
- **Leakage** – the current continuing to pass from or through the sample after the polarization has quit switching.
- **IV** – Individual leakage tests conducted over a voltage profile.

Tests

- **Small Signal Capacitance** – The polarization response of the sample when stimulated by a voltage change smaller than that required to move remanent polarization.

- **CV** – small signal capacitance measured over a voltage profile.

- **Piezoelectric Displacement** – the change in dimensions of the capacitor during voltage actuation. Each test listed above has its counterpart measurement of piezoelectric displacement.

Tests

- **Pyroelectricity**– the change in *charge* with a change in temperature.
  - Remanent polarization changes or
  - Dielectric constant changes.

- Three types of **pyroelectric** tests:
  - **Static**: measure dielectric constant or remanent polarization at different temperatures. Calculate slope.
  - **Roundy-Byers**: ramp temperature and measure current.
  - **Photonic**: Hit sample with infrared pulse and measure polarization change.

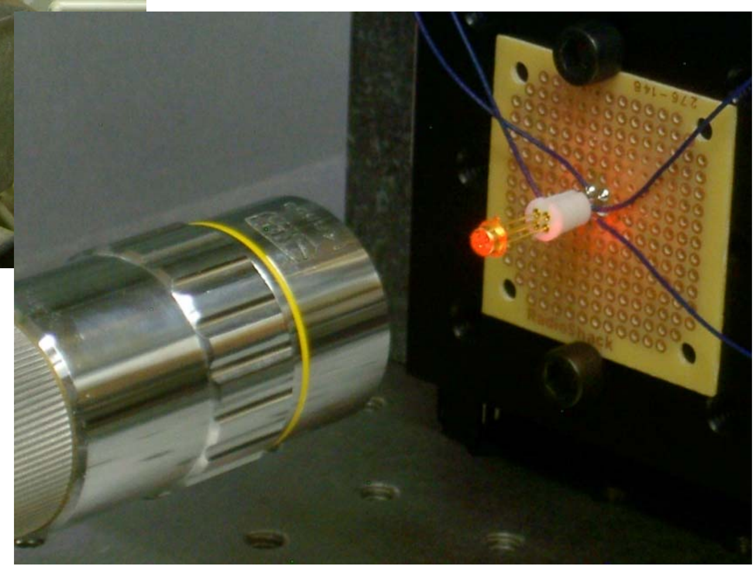
Tests

- **Magneto-electric -** expose sample to changing magnetic field while measuring polarization change.

- **Ferroelectric Gate Transistor -**
  - **Pulse** the gate of the transistor and then measure channel conductivity with the gate set to zero volts.
  - Measure traditional $\mathbf{I_{ds}}$ **versus** $\mathbf{V_{ds}}$.
  - New measurement unique to memory transistors:

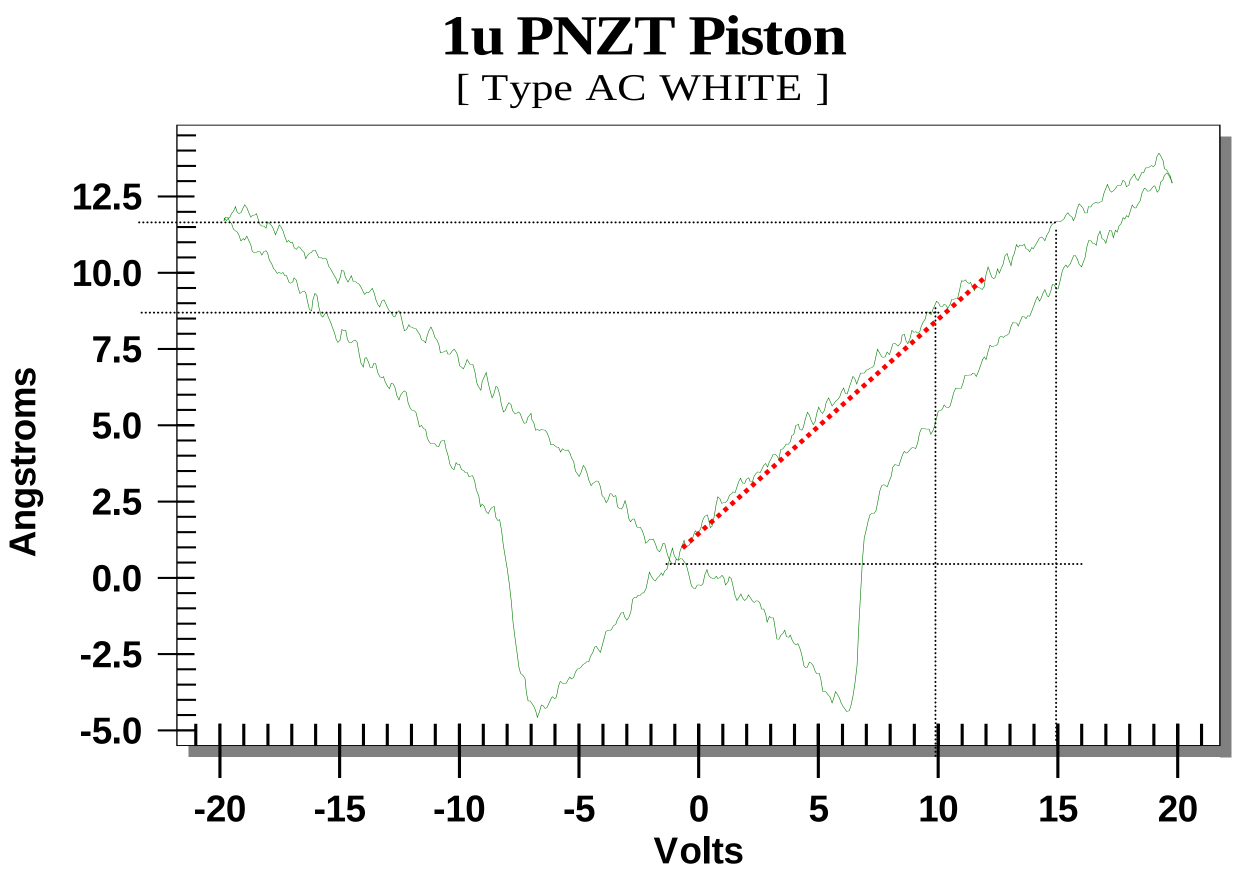
    $\mathbf{I_{ds}}$ **versus** $\mathbf{V_{gs}}$.

Piezoelectric Displacement



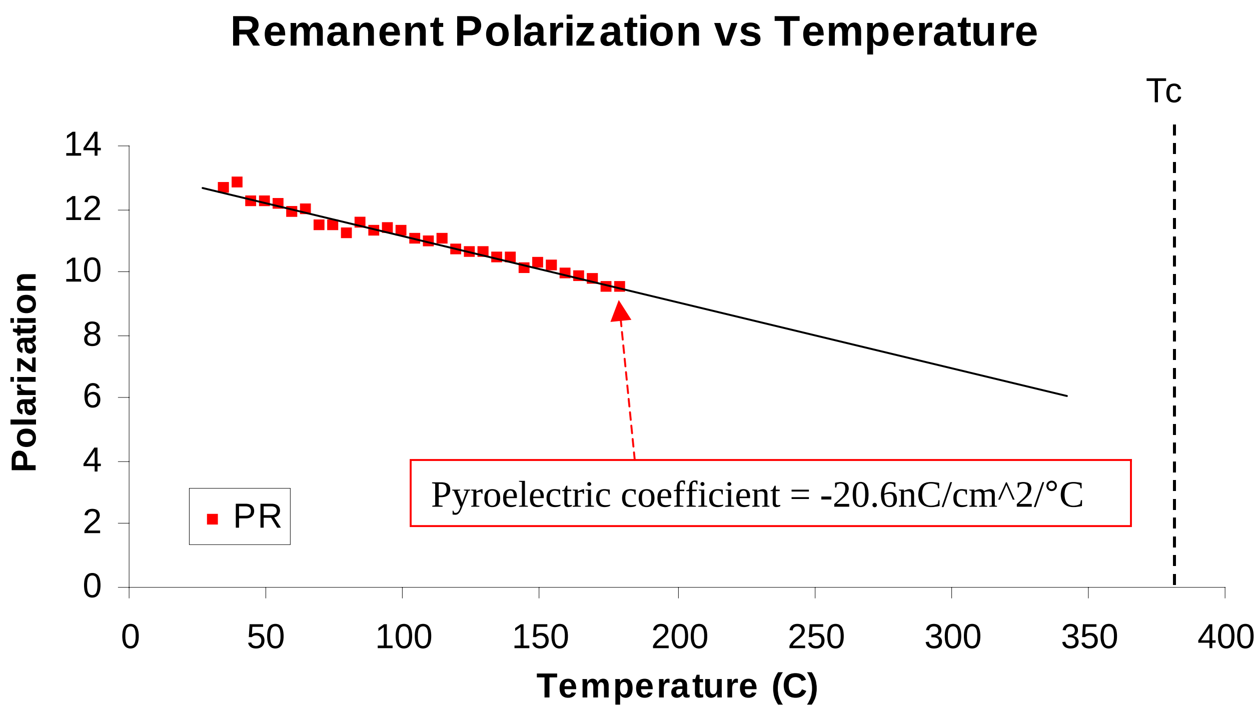
- A Polytec Laser Vibrometer measuring a 1μ-thick Radiant PNZT film.

Piezoelectric Displacement



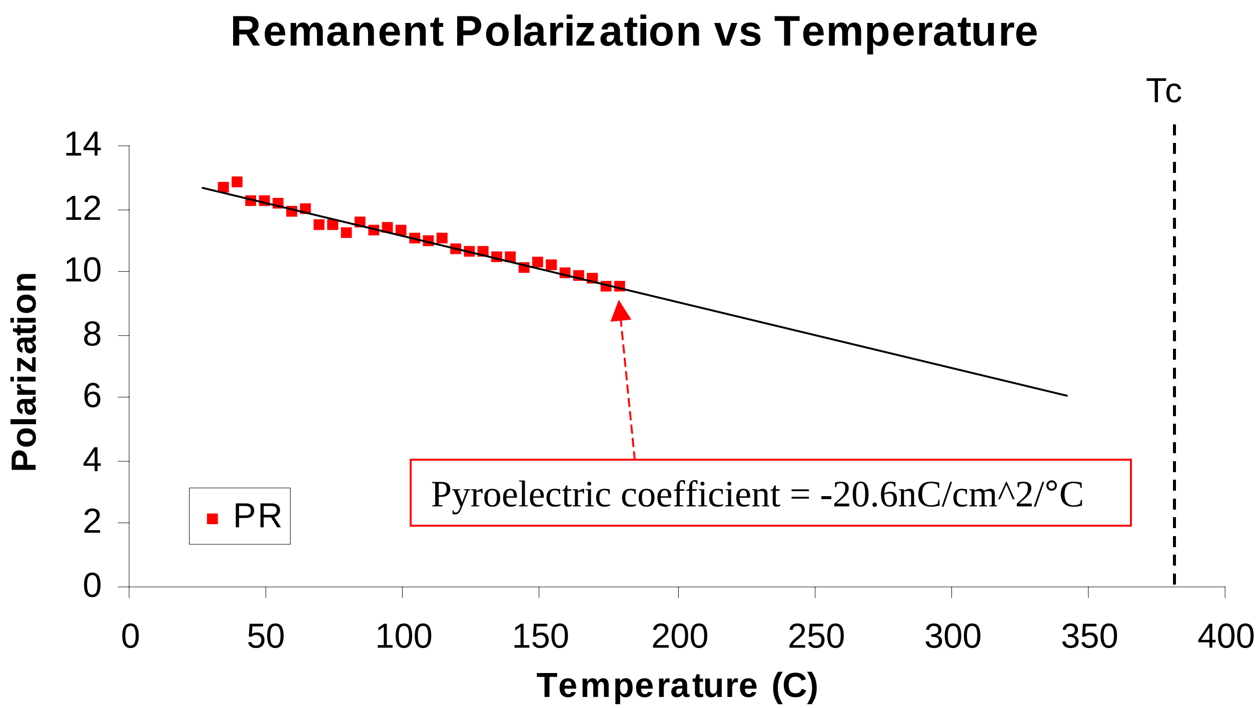
- The d_{33} for Radiant's 1μ 4/20/80 PNZT ranges from approximately 60pm/V to 80pm/V.

Static Pyroelectric



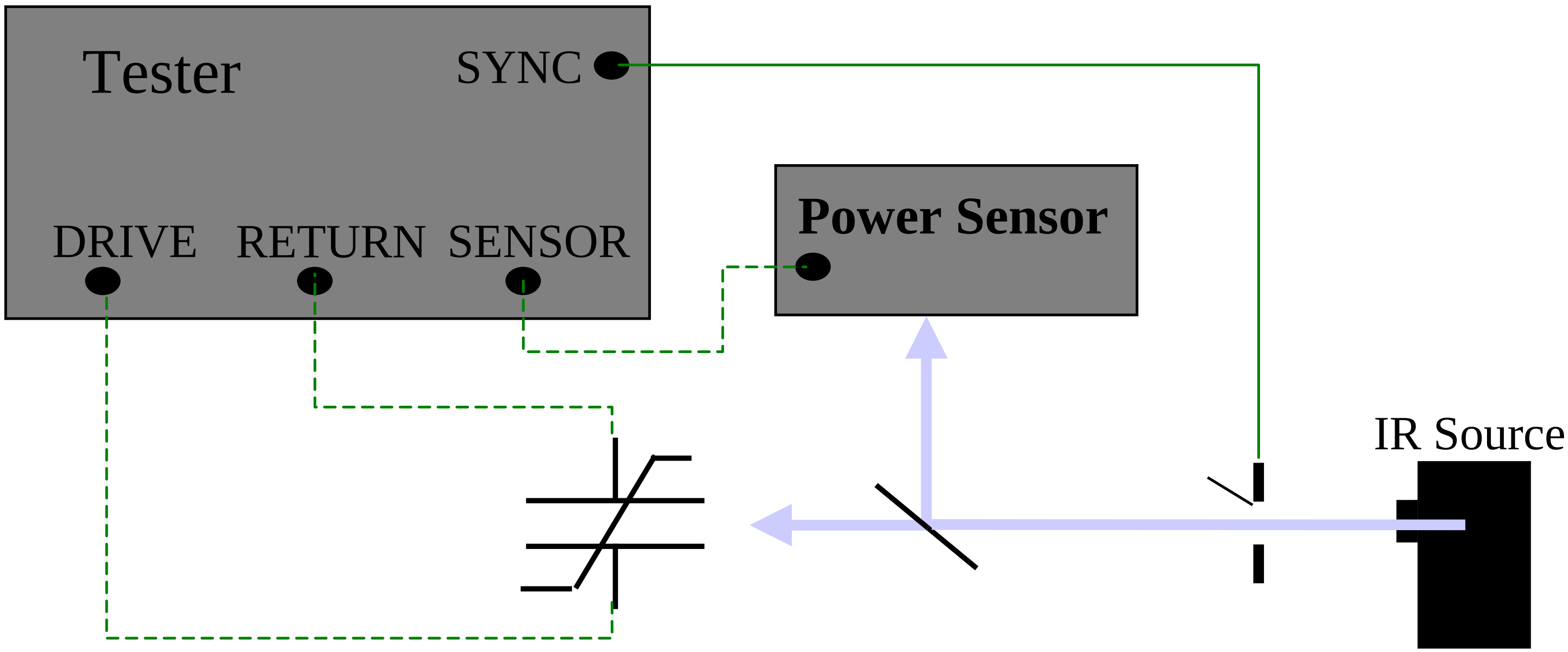
- Execute steps in temperature, measuring remanent polarization at each step.

Static Pyroelectric



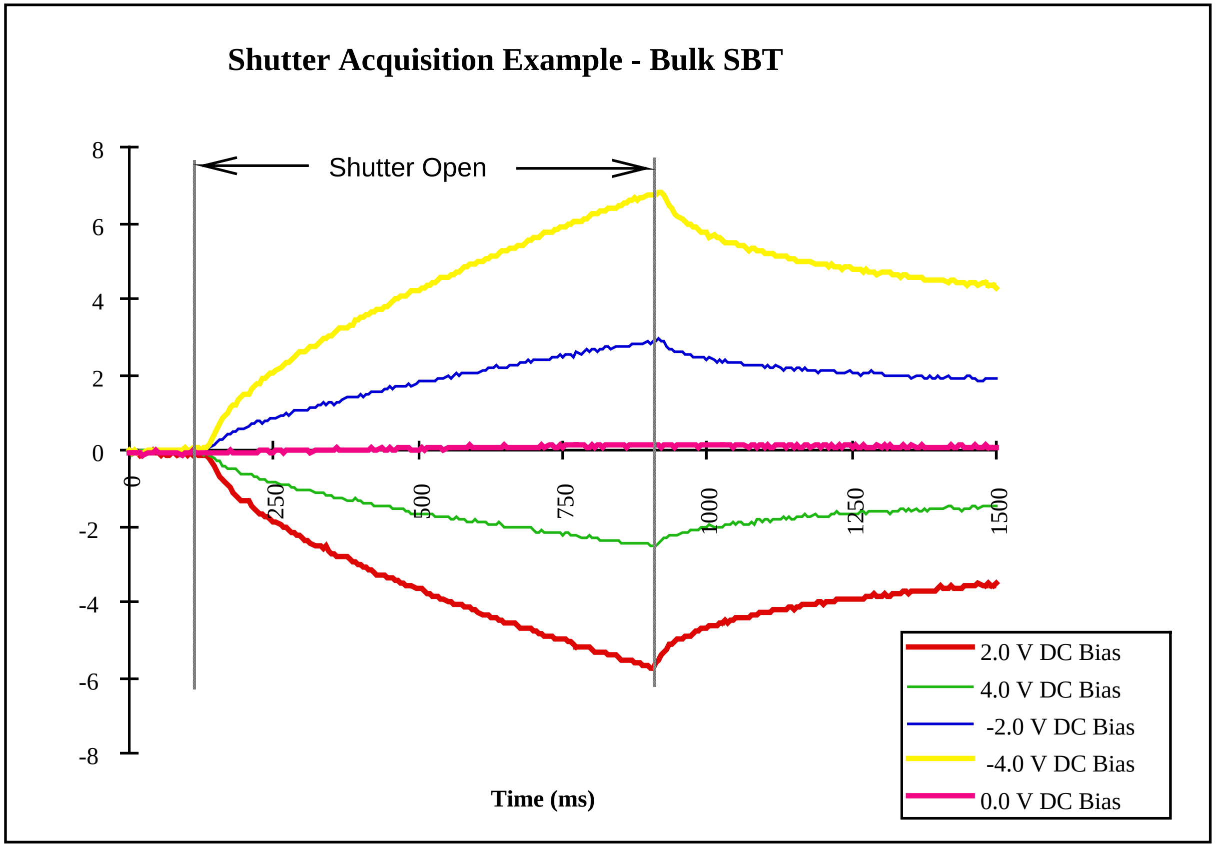
- Execute steps in temperature, measuring remanent polarization at each step.

Photonic Pyroelectric



Use the SYNC signal on the rear panel of the tester to open a shutter and expose the sample to IR signal.

Photonic Pyroelectric



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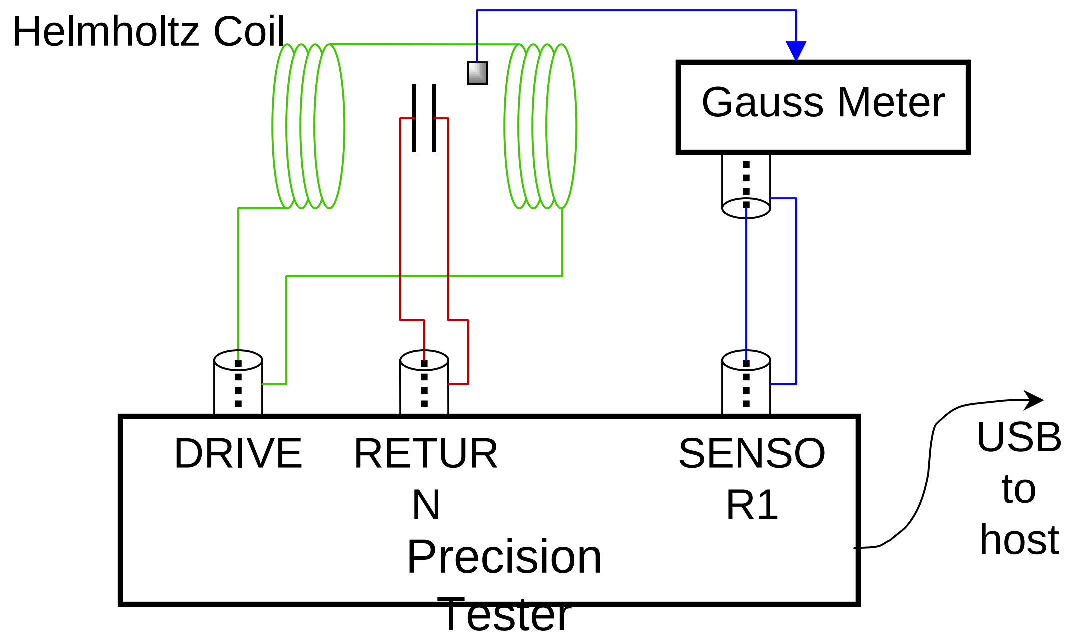
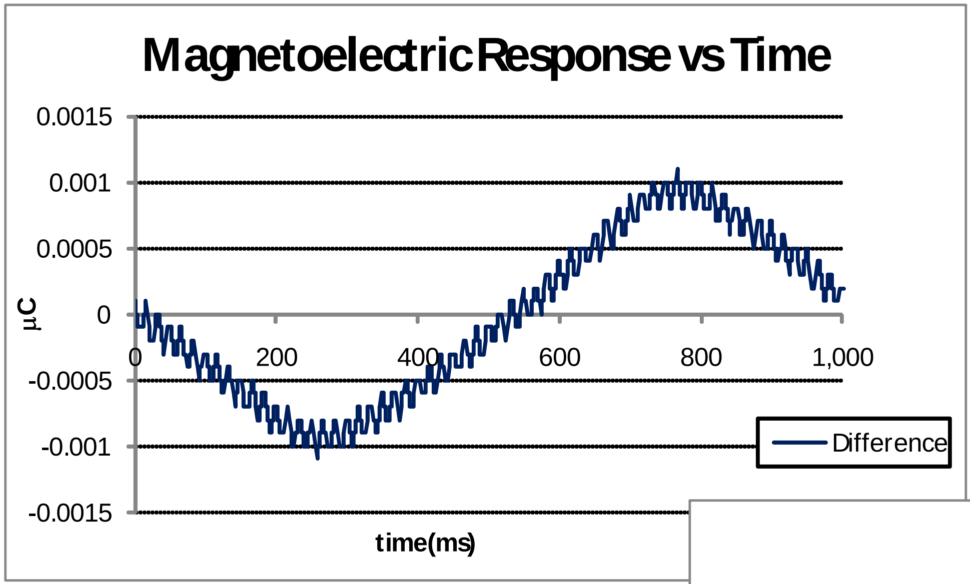
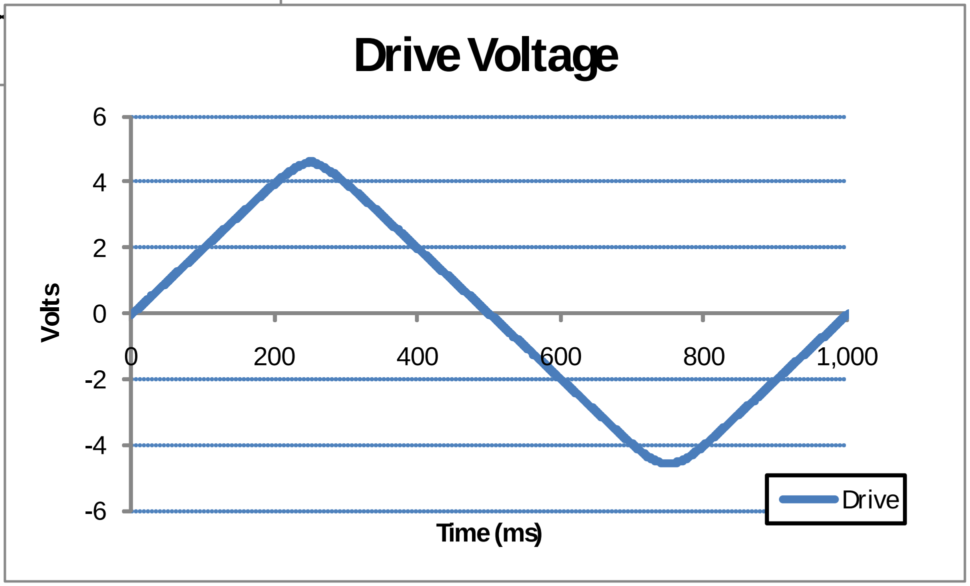
Magneto-Electric



Magneto-Electric

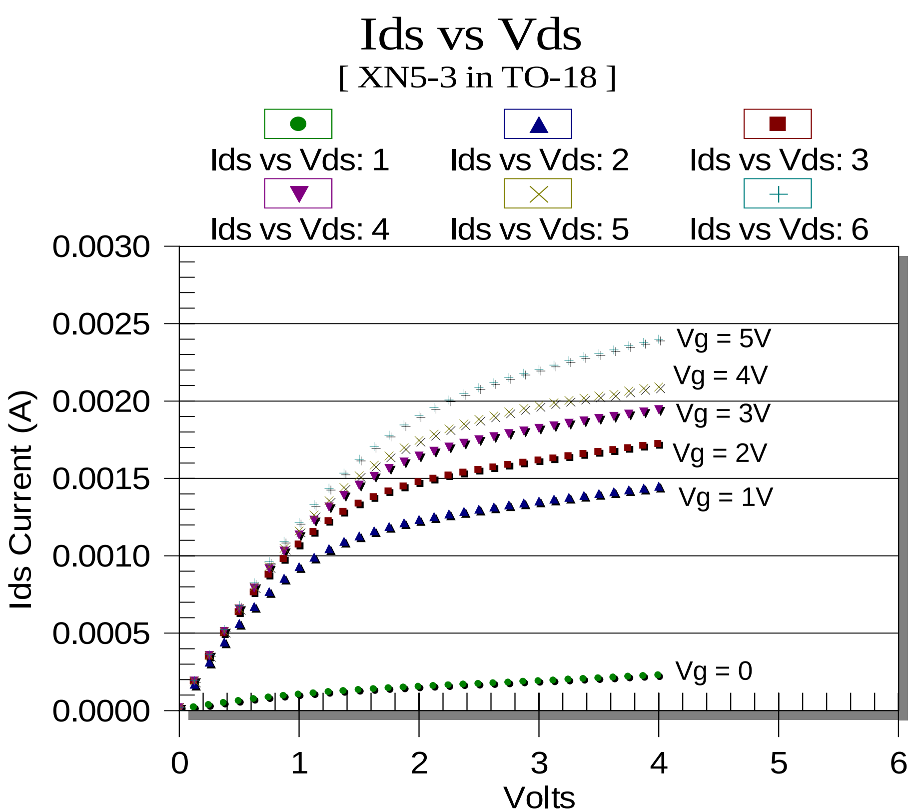


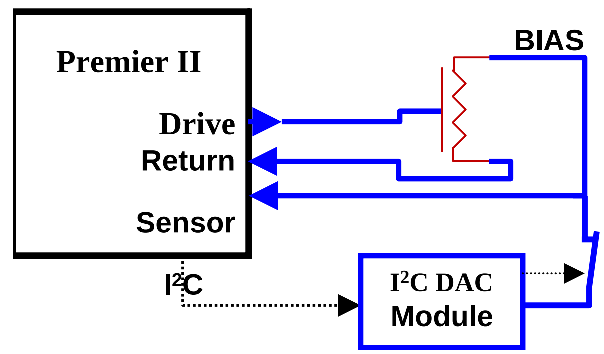


Radiant's very first results working with Virginia Tech University. See upcoming paper.

Ferroelectric Gate Transistor

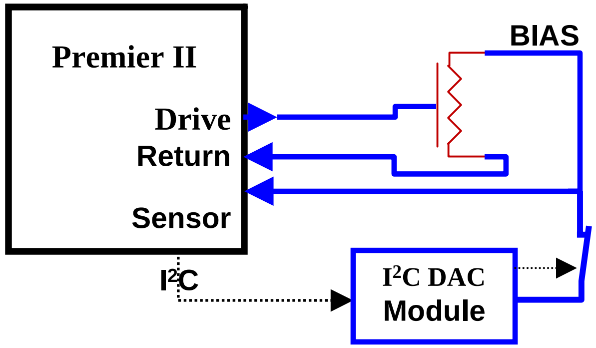
Radiant builds transistors with thin ferroelectric film gates and developed the software to test them.

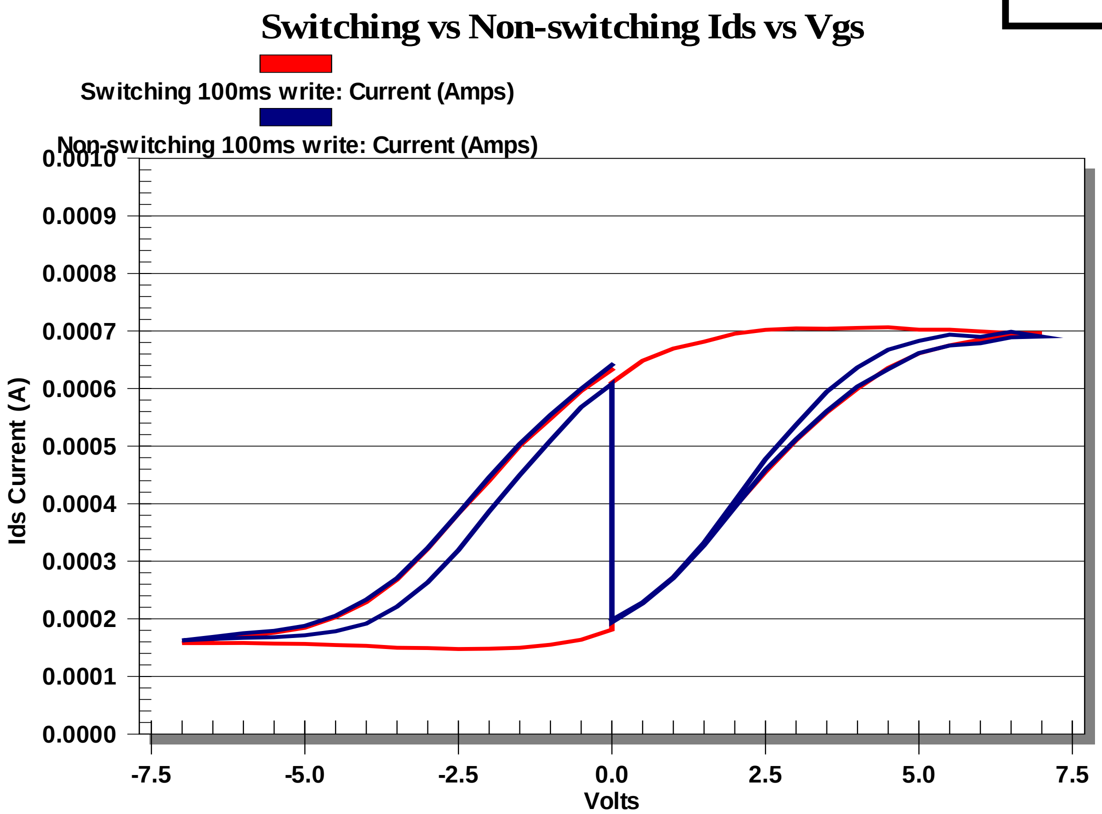




Ferroelectric Gate Transistor

TFF transistors require some tests that are different.





Memory

- The properties of ferroelectrics all derive from its remanent polarization, its *memory*.
- Ferroelectric materials *remember everything that is done to them even during manufacturing.*
- For any particular test, the preset condition is all tests and rest periods that preceded!
- Because of memory, every sample continues to change every *millisecond*, every *second*, every *day*, every *year*.
- To truly understand you're a sample, you *must record its history.*

Vision

- Because of the memory and aging effects in ferroelectric materials, Radiant created the **Vision** test program.
  - Vision uses a database, called a *dataset*, to allow you to record the complete *history* of *every test* on a sample or *every sample* in a lot.
  - Vision can create *programs* of *test tasks* that will execute the same way every time they are called to create uniformity in *timing and execution*.
- You are not using the full power of a Radiant tester unless you create *test definitions* in the Vision Editor and store the results in *datasets* in the Vision Archive!

Summary

- Radiant's testers
  - Are thermodynamic state testers.
  - Vary one thermodynamic state variable and measure the change in one or more other state variables.
  - Measure absolute physical parameters directly.
  - Report the measured parameter, not a model fit.
  - Are constructed so that the measurement channel has no knowledge of the stimulus.

Summary

- Radiant's testers
  - ➢ Use a triangle wave so that the individual components of a hysteresis loop can be recognized
  - ➢ Measure the following components:
    - Linear and non-linear capacitance
    - Remanent polarization
    - Small signal capacitance
    - Leakage
    - Hysteresis in small signal capacitor vs voltage
    - Hysteresis in leakage vs voltage
    - Electrode contact diode function
    - Coupled properties: piezoelectricity, pyroelectricity, magneto-electricity, and ferroelectric transistor function.

Summary

- Non-linear materials remember their history, even the pattern of their test procedures.

  - Inconsistent sample histories make measurement precision fuzzy.

- To make precise measurements, control the history of the sample and its test procedures!

Summary

- The Vision operating system that controls the Radiant testers is designed to record and analyze sample history.
  - Datasets record the execution of programs constructed by the user.
  - Programs ensure reproducible consistency in test execution.
- Vision is the tester!
  - The hardware was designed to support Vision.