Teaching Electro-Ceramics

Radiant Technologies, Inc., Albuquerque, NM USA
radiant@ferrodevices.com
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Abstract

Radiant Technologies has created the Radiant EDU, a simple, low cost laboratory instrument with matching ferroelectric capacitor samples specifically for the purpose of introducing electro-ceramics to science and engineering students. The unit is designed to study ferroelectric devices as well as sensors and memories made from these components.
The EDU

The Radiant EDU consists of an arbitrary waveform generator (AWFG), an electrometer, and an oscilloscope integrated into a single unit controlled by an on-board microprocessor that receives requests from the host computer via USB communications.

The EDU does not have an enclosure in order to avoid the perception by students that it is a “black box”.

Student projects can be operated using the external port.

The EDU measures hysteresis curves on packaged ferroelectric capacitors.
System Functionality

The external port containing the AWFG stimulus signal, the electrometer input, and the oscilloscope input allows students to fabricate their own experiments or design and test their own sensors.

A homemade force sensor for the EDU built at Radiant.
Ferroelectricity

Ferroelectric materials, like Lead Zirconate Titanate (PZT) or Barium Titanate, are complex oxides with highly non-linear properties. They exhibit polarization hysteresis and sensitivity to force, displacement, and temperature changes. They are useful as memory materials and as sensors.

Classic Polarization Hysteresis
(0.25u thick PZT)

With packaged PZT capacitors supplied by Radiant, the student can explore the principles of capacitance, the electrical properties of materials, memory, and sensors.
Radiant Technologies, Inc. is the world’s leading manufacturer of test equipment for electro-ceramics. Our test systems can actuate 10KV devices or measure the hysteresis of a thin ferroelectric film capacitor with dimensions less than a square micrometer.

A submicron PZT capacitor courtesy of the University of Maryland.
Philosophy

Non-linear capacitors are an exciting technology, used in almost every aspect of society today. Civilization would not function without them. Sonar, medical ultrasound, fire detectors, infrared cameras, accelerometers, medical sensors, mechanical actuators, microphones, and intrusion detectors are just a few of the devices using non-linear capacitors as the critical operating element. Yet, these very special capacitors are practically unknown by engineers or even physicists and chemists.

Radiant Technologies created the EDU to make the technology accessible to university students and encourage them to pursue careers studying non-linear capacitors or building useful circuits with these unique devices.
Read More!

For a narrative on the EDU and its applications, click on the link below to jump further into this file.

Primer on the Radiant EDU

You may contact us with questions or recommendations for the EDU and/or new ferroelectric-based components.

– Sales information: Michelle Bell
– Technical assistance: Joe Evans or Bob Howard.
– Shipping instructions: Geri Martinez
– e-mail: radiant@ferrodevices.com
– Telephone: 505-842-8007
– Fax: 505-842-0366
– web site: www.ferrodevices.com
A Primer on the Radiant EDU Educational Tester

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Overview

• Hardware Design
• Circuit Architecture
• Graphical User’s Interface
• Charge Measurement
• Ferroelectric Capacitors and Sensor Chips from Radiant
• External Sensor Projects
• Oscilloscope Operation
• Syllabi
Hardware Design

• The test circuitry in Radiant’s EDU is implemented with modern surface mount technology and components to reduce costs.
• A USB communications port connects the tester to a host computer.
• Standardized ferroelectric capacitor samples connect to the tester through a built-in TO-18 transistor-type socket.

Capacitor under test
Radiant EDU - A Simple Ferroelectric Tester for Education

The EDU has one ±10V output and three synchronously captured 12-bit inputs. Its execution clock is 50µs.
Hardware Design

- Cap A/B Switches
- Charge Measurement
- Power
- OSC Port
- Packaged Sample Socket
- Stimulus Voltage
- Microprocessor
- Digital-to-Analog Converter
- Analog-to-Digital Converter
Simple Graphical Users Interface

- Only one measurement task is necessary: Charge vs Voltage vs Time
  - 100Hz to 1Hz frequency range
  - ±10V range

- A separate waveform task allows recovery, fatigue, and imprint tests to be executed manually.

- All file formats and export formats are in ASCII but plots may be pasted from the GUI directly into other programs.

- Plotting options include derivatives and measurements vs time.
Radiant EDU - A Simple Ferroelectric Tester for Education

Simple GUI

- Four parameters define the test profile. The capacitor values can range from ~10pF to 1nF. Plus, there is an on-board mux to select between Cap A and Cap B in the packaged parts.
Despite its simplicity, the EDU has a powerful set of plotting tools. All of the data displayed on the following pages was taken with an EDU, formatted using EDU plotting tools, and then copied from the EDU GUI directly into the presentation.

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Radiant EDU - A Simple Ferroelectric Tester for Education
Measuring a Linear Capacitor

Plots of the voltage stimulus produced by the EDU (called the Drive) versus the charge generated by a linear capacitor in response to the stimulus shown. The linear capacitor is, well, linear!
Plotting the measured charge against the voltage on the X-axis yields $Q = CV$. The slope of the line is “$C$”, the capacitance. This is “hysteresis” data, albeit with zero hysteresis!
Radiant EDU - A Simple Ferroelectric Tester for Education

This is a lot more interesting! The ferroelectric material translates the stimulus into a completely different set of temporal frequencies.
Hysteresis of the PZT Capacitor

Packaged PZT Capacitor
[ Radiant Type AB White ]

Plotted versus voltage, a real hysteresis emerges.

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Radiant EDU - A Simple Ferroelectric Tester for Education
Why does Hysteresis Happen?

All solid materials are held together by a balance of electrical forces between the atoms in the material lattices. Normally, atoms in a lattice arrange themselves so that all of the electrons and protons cancel each others’ electric fields.

Ferroelectric materials have very complex geometric structures for their atoms. This complexity gives rise to asymmetries in the lattice that prevent all of the electrical fields of the electrons and protons from canceling each other out even though there are an even number of electrons and protons. From these asymmetries arise all of the useful properties of ferroelectric materials.

Click on the link to give a short tutorial on the origin of the ferroelectric hysteresis.

The Origins of Hysteresis
Packaged Ferroelectric Capacitors

Radiant has designed small packaged ferroelectric capacitors specifically to work with the EDU. The packaged capacitors make it possible for a class to study and use ferroelectric properties in the lab.

- Two capacitors to each package
- Capacitor sizes range from 100,000 square microns down to 100 square microns.
The Packaged Die

- 0.26µ 20/80 PZT
- Platinum electrodes
- TiOx/SiOx ILD
- Chrome/Gold metallization
- 5V saturation
- Will withstand unlimited exposure to 9V.

10,000 square micron capacitor

Contact Pad in Gold

PZT

1.4mm
Building Gadgets

• The EDU has a built-in port, accessible with standard 6-line telephone cable and telephone jack plugs, to allow students to build their own projects and operate them using the EDU software.

• The external port on the Radiant EDU has the following signals:
  – ±10V AWFG output
  – ±10nC electrometer input
  – ±10V oscilloscope input
  – ±15V power and system ground

• Using these signals, the student can build his or her own gadget, power it, stimulate it, and measure it from the EDU.
Projects

• Below is short list of interesting projects that can be built and operated with the EDU:
  
  – Traditional Sawyer Tower measurement circuit for ferroelectric capacitors.
  
  – FeRAM emulator.
    
    • FeRAM = Ferroelectric Random Access Memory.
  
  – Air gap metal plate capacitor
  
  – Force sensor.
  
  – Heat sensor.
  
  – Acoustic sensor.
Radiant also manufacturers a large PZT capacitor suitable for building simple force and heat sensors by hand.

- 1.0µ 4/20/80 PNZT
- Platinum electrodes
- TiOx/SiOx ILD
- Chrome/Gold metallization
- 15V saturation
- Will withstand unlimited exposure to 36V.
- Can be soldered to PC board.

4mm x 4mm PZT capacitor with 1µ thick PNZT.

- Piezoelectric Constant ~ 500pC/N
- Pyroelectric Constant ~ 2.2nC/°C
Where do sensor properties come from?

The sensor properties arise directly from the electric dipoles in the material.

Go to the following link for a very short explanation of the sensor properties of ferroelectric materials.

The Origin of Sensor Properties
Sensor Board for EDU

- Radiant supplies a sensor board compatible with the EDU external port that uses the sensor die shown earlier.
  - A charge amplifier, powered from the EDU and connected to the sensor capacitor, converts any piezoelectric or pyroelectric stimuli to a voltage on the oscilloscope input.
The Real Time Oscilloscope

• The real time oscilloscope software supplied with the EDU can capture signals as fast as 2KHz or as slow as 10Hz and display data taken over 10 minutes or more.

The plot shown is the carotid artery pressure wave at the neck captured with the EDU sensor board configured to be a force sensor.

“Down” means compression of the sensor capacitor @ ~1V/1N.
The Real Time Oscilloscope

- By extending the time scale to the human time frame, it is possible to watch the flow and ebb of heat around the sensor.

A sine wave made by nearby cups of coffee and ice water interrupts the serenity of an EDU sensor configured for detecting radiant heat. The room air conditioning caused the wiggles!
Tutorials and Syllabi

- Radiant has created a set of tutorials and guided experiments for the EDU.
  - Eight lessons describe the physics of the dielectric constant, linear capacitors, paraelectric capacitors, and ferroelectric capacitors.
  - The first five experiments familiarize the user with the EDU and its tools.
  - The remaining experiments explain remanent polarization and memory, sensors, test procedures for electro-ceramics, and reliability of electro-ceramics.
  - They are installed automatically with the EDU software.

- Professors are welcome to submit their own contributions to the tutorials or to publish their own syllabi for the unit.
Contact Information

We hope that you have enjoyed our tutorial about the Radiant EDU. You may contact us with questions or recommendations for the EDU and/or new ferroelectric-based components.

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- web site: www.ferrodevices.com
A Short Tutorial on the Origin of Hysteresis in PZT

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Why does Hysteresis Happen?

All solid materials are held together by a balance of electrical forces between the atoms in the material lattices. Normally, atoms in a lattice arrange themselves so that all of the electrons and protons cancel each others’ electric fields.

Ferroelectric materials exist with a very complex geometric structure for their atoms. This complexity gives rise to asymmetries in the lattice that prevent all of the electrical fields of the electrons and protons from canceling each other out even though there are an even number of electrons and protons. From these asymmetries arise all of the useful properties of ferroelectric materials.
The Lattice and its Bonds

Diamond has a trihedral structure with symmetrical covalent bonds between all carbon atoms:

**DIAMOND**

Symmetrical lattice + covalent bonding means no net electric fields.

PZT has a tetragonal structure with asymmetrical, partially ionic bonds between the oxygens and the metals.
The electrons surround each atom equally in time and space. Hence, there are no separated charges for an electric field to act on. Diamond has a low, very linear dielectric constant, ~5.6.

The carbon atoms in diamond are about 1.5Å apart along an edge. Each carbon atom occupies about 1Å. So, as temperature goes down, there is plenty of room for the carbon atoms to move closer without bumping into each other. Diamonds electrical properties are uniform over a wide temperature range!
In the perovskite structure most ferroelectric materials have, no metals are bonded to metals. Every metal is bonded only to nearby oxygens. The bonding diagram looks like this:

The electrons stay near the red oxygens, giving every metal/oxygen pair a net electric dipole. An external electric field will repel the metals and attract the oxygens, severely distorting the lattice as it expands.

Since dielectric constant depends on physical “Displacement” (the “D” in Maxwell’s equations), perovskites can have huge dielectric constants, as high as 30,000!
The Titanium/Oxygen Cage!

An easy way to visualize the distortion is to look at the effect of a field on the Titanium/Oxygen sub-lattice.

The Lead/Oxygen lattice also distorts.
Coefficient of Thermal Expansion

All solids can be treated as a network of balls and springs:

Temperature is simply the motion energy of each atom. The higher the temperature, the faster they move, the harder they bounce off each other, and the further apart they force each other to stay. Hence, physical size of solids changes with temperature. The change in dimensions vs the change in temperature is the Coefficient of Thermal Expansion!

The CTE of PZT is $\sim15$ times that of Diamond.
Remanent Polarization

PZT has a 4Å lattice constant, but many more atoms are squeezed into that volume than with diamond! As the temperature drops and the lattice shrinks, eventually, there is not enough room for all the atoms in the symmetrical format. So, the lattice distorts to squeeze the atoms closer together. A simple model is that the body-centered atom slides up about 0.05Å so it is no longer co-planar with the oxygens.

Since the titanium’s electrons stay mostly around the oxygens, a net vertical dipole is created.

Note: \[ P = Q \times d \sim 100\mu\text{C/cm}^2 \] for PZT unit cell.
Finally: Hysteresis!

On many materials called “electrets”, the lattice is rigid and the internal dipoles are fixed relative to the lattice, never to switch. Ferroelectric materials, on the other hand, have just the right amount of softness so external forces like an external electric field can make the charged atoms shift position to line up with the voltage but the right amount of rigidity so the resultant dipoles stay lined up when the force is removed at zero volts.

The next page shows how dipoles make this “half” hysteresis loop.
The Electrical Measure of Hysteresis!

- **Negative Charge**
- **Positive Charge**

**Current Meter**

(a) Dipole starting at zero volts.

(b) Apply voltage and charge capacitor in opposite direction as dipole. Dielectric and remanent charge both move.

(c) Discharge capacitor.

(d) Dipole at zero volts again and in the opposite direction.

$Q$ vs $V$

(A) $Q$ vs $V$

(B) $Q$ vs $V$

(C) $Q$ vs $V$

(A) $Q$ vs $V$
The ferroelectric capacitor will give a “little bit” of charge or a “lot” of charge depending on the direction of the applied voltage and the direction of the dipoles. This property is used in modern Ferroelectric RAM ICs to make high-speed non-volatile memory chips.
Mysteries of Memory

What is this waveform? It happens millions of times a second to individual data bits in a magnetic disk drive when new data is written to the disk. Disk drives depend on magnetic hysteresis to store data.
Conclusion: Hysteresis!

Electrical hysteresis arises in natural materials much like magnetic hysteresis in magnetite with which many more people are familiar. Materials engineers, tinkering with composition and process, have now created new materials with strong ferroelectric properties and usefulness.

Click on the link below to return to the main narrative.

Return to Narrative
A Very Short Tutorial on the Origin of Environmental Sensing in PZT

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Where do sensor properties come from?

The sensor properties arise directly from the electric dipoles in the material.

- The dipoles are tied directly to the lattice and their strengths are determined by the lattice spacing.
- Force and temperature change the size of the lattice.
- Since the dipoles hold the remanent electrical charge on the plates of the ferroelectric capacitor, force or temperature changes applied to the capacitor cause the dipole strength to change and force electrons to flow onto or off of the capacitor plates to keep the net electric field of the capacitor zero!
Direct Piezoelectricity
(The generation of charge due to the application of force)

The remanent dipoles exist without an external force applied.

An external force stretching the lattice stretches the dipoles. Charge flows onto the capacitor to compensate.

An external force compressing the lattice shrinks the dipole. Charge flows off of the capacitor to compensate.
Pyroelectricity
(The generation of charge due to the change in temperature.)

The remanent dipole exists without an external applied field. A decrease in the temperature makes the lattice shrink more asymmetrically and the dipole strength grows. Charge flows onto the capacitor to compensate. An increase in the temperature makes the lattice expand, allowing more symmetry, and the dipole strength reduces. Charge flows off of the capacitor to compensate.
An environmental stimulus, either force or temperature, on a ferroelectric capacitor causes the capacitor to change the amount of charge stored on its plates. An external sensor circuit should keep track of the total charge to leave or enter the capacitor due to a stimulus. The charge integrator circuit below performs this function.

\[
V_{\text{out}} = \frac{-\Delta Q_{\text{sensor}}}{C_i}
\]
An environmental stimulus forces charge to leave the capacitor. The circuit will act to keep the “-” node of the operational amplifier equal in voltage to the “+” node, i.e. ground. Thus, the output voltage will change to force current to flow through the integrating capacitor $C_i$ from the “-” node so just as much charge leaves the “-” node as enters the node from the sensor capacitor. The voltage on $C_i$, which is also $V_{out}$, is the sum of the charge that left or entered the sensor capacitor since the measurement began. The “-” node always stays at zero volts.

$$V_{out} = -\frac{\Delta Q_{sensor}}{C_i}$$
Conclusion: Sensors!

Force (piezoelectricity) and temperature (pyroelectricity) sensing arise directly from the remanent polarization of ferroelectric capacitors. The capacitors are exquisitely sensitive and rugged. Simple circuits may be used to detect changes in the capacitors originating from environmental changes around the capacitor.

Click on the link below to return to the main narrative.

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