New Jersey Institute of Technology, Department of Physics

Measuring the Physical & Electrical Properties of the Ruddlesden-Popper Compound: $(Ca,Sr)_3Ti_2O_7$

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Abstract

The study being presented displays how experimental processes were utilized to identify the characteristics of the sample: $(Ca,Sr)_3Ti_2O_7$. The sample that was synthesized is a bulk crystal which has its own capacitance [1]. The experiments conducted during this sample synthesis were done to measure the electric property of capacitance—a material's ability to store electric charge—based on two different variables: voltage and frequency. The data gathered was organized into a set of two graphs: Capacitance vs. Voltage and Capacitance vs. Frequency. The purpose of the experiment is to examine the capacitance while controlling it by varying the range of the voltage and frequency being provided to the sample.

Introduction

A sample synthesis can have numerous different meanings depending on the context used. In this experiment, four different compounds were synthesized and created into a new sample: a bulk crystal. The four compounds—calcium, strontium, titanium, and oxygen—together form a ferroelectric material. A ferroelectric material is one in which the electric polarization, measured in coulombs per square meter (Cm^{-2}), of the sample remains stagnant and can be reversed/reorientated. In specific, any altercation in the surrounding/external electric field will not affect the polarization [2].

The quantity measured was capacitance: the measurement of how much electrical charge a material can successfully store and use, usually at a later time [3]. The prime example of this is when capacitors, objects with a higher capacitance, are used as voltage producers in generators. Capacitors help store electrical charge so, for example, in the case of a power outage, there is a source of electricity with the use of high-capacitance capacitors.

Capacitors come in a large variety of shapes and sizes, as seen in Figure 1. Depending on multiple different factors, each capacitor has its own capacitance and uses. The capacitance

Figure 1.

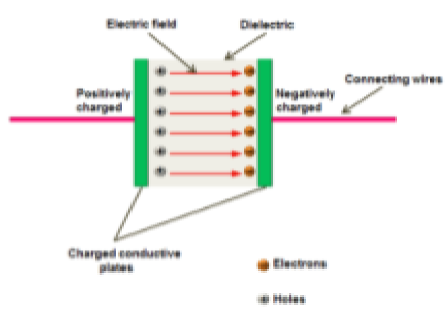


Figure 2.

https://en.wikipedia.org/wiki/Electrolytic_capacitor

https://www.physics-and-radio-electronics.com/electronic-devices-and-circuits/passive-components/capacitors/capacitorconsutructionandworking.html of a material is based on two equations: $C = \frac{q}{V}$ or $C = \frac{Ke_0A}{d}$. The equations used are chosen based on the information provided in the situation. Below is a key for what each variable represents in the two equations:

q = charge
V = voltage
K = dielectric constant of material
e_0 = vacuum permittivity of free space (8.854 x 10^{-12} F/m)
A = area of each plate
d = distance between two plates

Presented in Figure 2 is the process of how a capacitor functions. In between the charged plates of the parallel plate, an electric field is created by positive charges from the positive plate moving to the negative charges of the negative plate. This electric field created between two plates charges the capacitor when there is current flowing through the wires on both ends. When the capacitor becomes fully charged, the current flowing through the system exponentially declines to zero because the electric charge has now been stored in the capacitor.

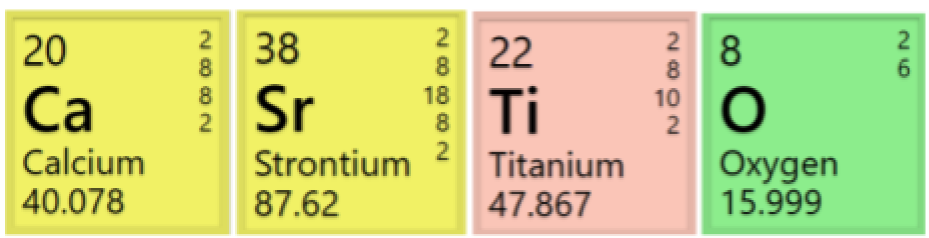
The purpose of this experiment is to outline the quantitative and qualitative effects of voltage and frequency on the capacitance of the material $(Ca,Sr)_3Ti_2O_7$. In the equations of capacitance, voltage V is shown as a variable; thus, it is clear that voltage has an inverse impact on the capacitance. On the other hand, frequency f is nowhere to be found in either equation. This is because the frequency provided alters the vacuum permittivity of free space e_0 [4]. The permittivity of the free space we live in is roughly 8.854 x 10-12 F/m because there is a regulated frequency in the atmosphere of Earth. When that frequency is changed, the permittivity constant changes due to an inverse relationship between the two [5].

Materials & Methods

The materials utilized in this set of experiments revolve around the four elements: calcium, strontium, titanium, and oxygen. In Figure 3, the properties for each element have been derived from the periodic table. Using different concentrations of these four elements, the new sample was synthesized and, ultimately, experimented on; Figure 4 presents the crystallographic structure of $(Ca,Sr)_3Ti_2O_7$.

The initial steps of this experimental process were using LabView, a system-design platform that uses visual programming language, to develop a program to aid with the

Figure 3.

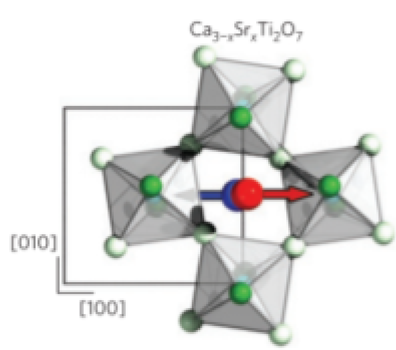


A. B. C. D.

https://ptable.com/?lang=en#Properties

measurements/data. Using a LCR meter—which measures inductance, capacitance, and

Figure 4.



https://www.nature.com/articles/nmat4168 resistance—called Agilent E4980a, the program was refined so that one could control the machine from a computer. Besides physically attaching the sample to alligator clips, the rest of the experiment, including gathering data, was accomplished through a computer because of the LabView program that was developed.

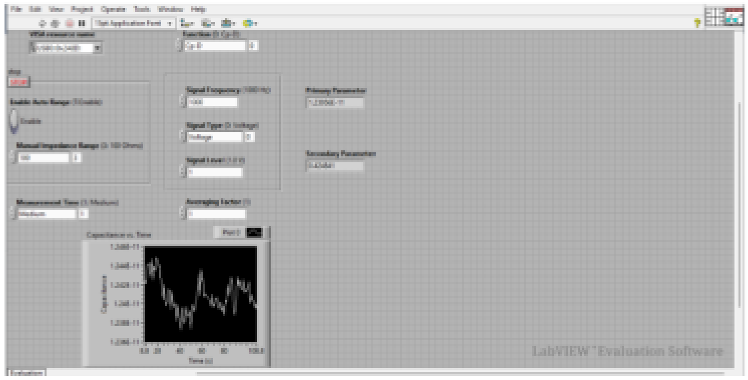
Knowing that our code and program was successful, the next step was to bring the sample to a state in which it could be tested accurately and successfully. The sample $(Ca,Sr)_3Ti_2O_7$ was given in a powder form, but that form of a sample cannot be tested. Using a hydraulic pellet press, the powder was turned into a pellet. This process of going from powder to pellet and then crushing it back into a powder was repeated several times to ensure the accuracy of tests and results.

Figure 5.

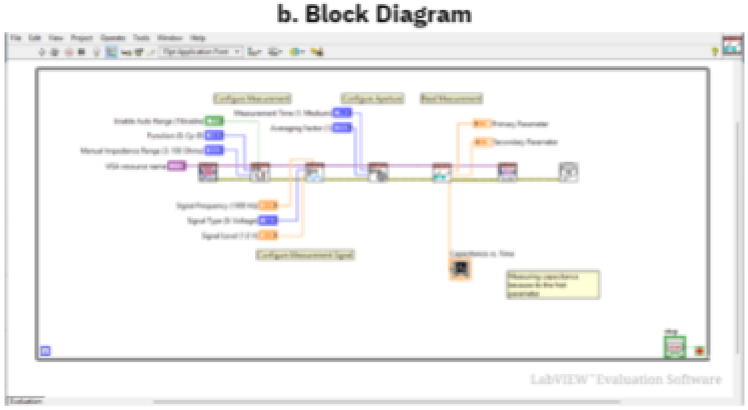
In order to measure the capacitance of this sample, the material has to be in the form of a parallel plate capacitor, as it is shown in Figure 2. To do this, the alligator clips of the LCR meter cannot simply be placed on the physical pellet. Using conductive silver paint, we were able to attach a wire to each side of the pellet to create a provisional parallel plate capacitor; this can be seen above in Figure 5. With an established LabView program—like the example shown in Figure 6—and a sample that was ready to be experimented on, the next step was to gather data through multiple sets of trials.

Figure 6.

a. Front Panel



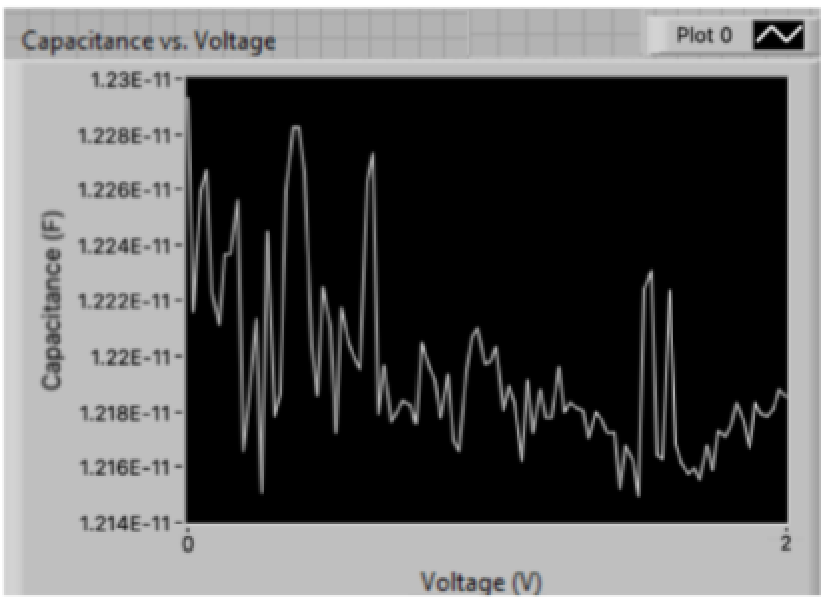
b. Block Diagram



Results

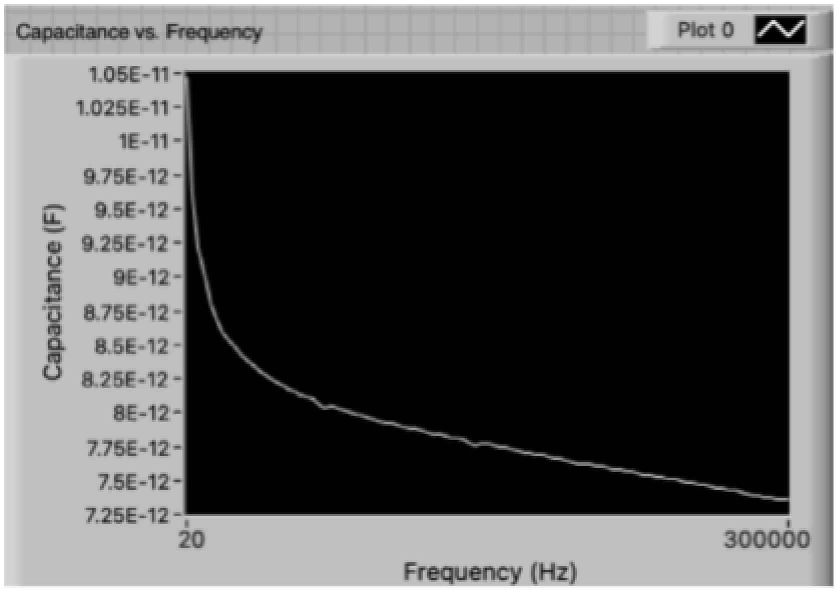
As mentioned before, this experiment's data was split into two graphs: Capacitance vs. Voltage and Capacitance vs. Frequency. In these graphs, we can see the effect of varying these two variables and analyzing its quantitative/qualitative impact on the capacitance of the sample. The first graph is the Capacitance vs. Voltage which is seen in Figure 7.

Figure 7.



The capacitance of the sample begins at 1.23 x 10^{-11} farads (F), which is also 12.3 picofarads (pF) for a simpler conversion. Looking at the trend of the graph, it can be concluded that as voltage increases, the capacitance decreases. This data proves the equation for capacitance: $C = \frac{q}{V}$. At the point when the voltage is measured at 2 volts (V), the capacitance is at 12.2 pF. Although it may not seem like a large difference (0.1 picofarads or pF), this was the effect after an increase of merely 2 V.

Figure 8.



In Figure 8, the graph is showing capacitance as a function of frequency. Compared to the graph in Figure 7, the data in Figure 8 portrays a clearer image of the variable's impact [6]. The graph shows an exponential decay, ensuring that capacitance and frequency have an inverse relationship. At a frequency of 20 hertz (Hz), the capacitance of the sample is 10.5 pF. As the frequency increases slightly, the capacitance decreases at a high rate by looking at the slope (steepness) of the graph at the preliminary interval. Subsequent to the initial decline, the data flattens out and the decrease in capacitance becomes insubstantial comparatively. At a maximum frequency of 300,000 Hz, or 300 kilohertz (kHz), the capacitance of $(Ca,Sr)_3Ti_2O_7$ is approximately 7.35 pF. Generally speaking, over the interval of 0.02 to 300 kHz, the capacitance of the sample decreased by roughly 30%.

The alternate capacitance equation that was presented was $C = \frac{Ke_0A}{d}$. e_0, which is the vacuum permittivity of free space, is the variable in the capacitance equation that is related to the frequency. When the frequency provided is increased, the permittivity constant decreases [7]. This is supported by the graph as we see capacitance decreasing as frequency increases.

Discussion

The research conducted holds a great amount of value because of its applicability to real life and its utilization in a multitude of different electronic concepts. The knowledge that can be apprehended from the research provided is especially impactful in the world of optimization and designing, in electronic devices, to ensure the most efficient performance across diverse operating conditions. Moreover, this study has significant implications for devices that focus on signal frequency such as radio and communication systems. By characterizing capacitance as a function of frequency, researchers can develop efficient signal processing technologies that optimize the energy usage.

Specifically, the study of capacitance variations contributes to material science. This work could potentially stimulate the discovery of novel materials with tailored capacitance responses for applications in flexible electronics and photonics. As all the above points have demonstrated, capacitance's dependence on voltage and frequency unveils opportunities for innovation across a diverse set of fields. This research enriches our understanding of electronic systems, aids in device optimization, fosters technological advancements, and extends its impact to diagnostic and material science realms.

Acknowledgements

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