Memory Technologies for Machine Learning - EITP25
Handin 3 - Spring 2020

Measuring Ferroelectrics

Hicham Mohamad, hi8826mo-s

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1 feedback from Robin

I think your code looks good, what you have done is correct. However it is not complete since you would need to

- define the vector elements of each pulse in the input PUND signal in order to subtract the charge of the U pulse from the P pulse and likewise for the N and D pulses.
- Finally you would need to shift the PE curve around the y-axis (in order to center it around zero) with the assumption that we are only measuring a relative change in the polarization and not an absolute one.

2 Introduction

In this assignment, we will practice on characterizing **ferroelectrics** which are used in **nonvolatile memories** (NVM). At the end, we will benchmark three measured IV-datasets.

The resulting plots and values in this report are obtained by running the implemented Matlab script `lab_FE.m`.

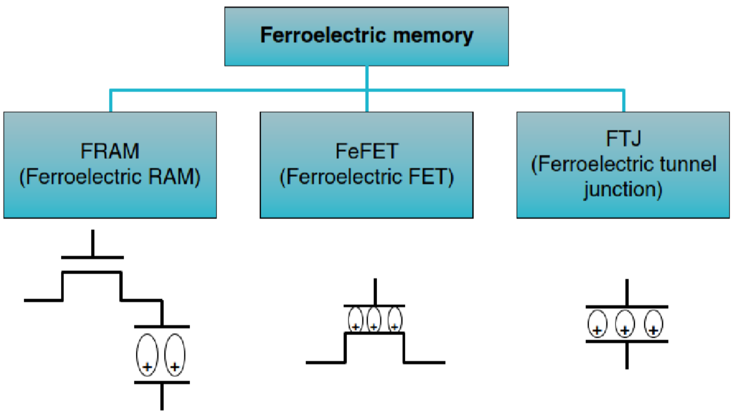

Figure 1: Three types of ferroelectric memories. ***FeRAM****: Ferroelectric capacitor placed in series with MOSFET selector.* ***FeFET****: Integrate ferroelectric gate dielectric in MOSFET.* ***FTJ****: Ferroelectric tunnel junction, two-terminal resistive memory which relies on transport through the ferroelectric layer.*

3 Background

Introduction to Ferroelectrics

Dielectric materials are highly attractive as insulators due to there ability to block charges from passing through them. For polar dielectrics with a **non-centrosymmetric** unit cell structure very interesting properties can arise. In regards to crystalline materials these are divided into crystal classes depending on their properties. One of these crystal classes is ferroelectric materials.

Ferroelectric materials are characterized by two stable **polarization states** that can be switched from one to another by applying an electrical field. A ferroelectric (FE) material is defined by its spontaneous polarization which can be reversed in the presence of an electric field.

This **polarization change** stems from the physical movement of ions in the unit cell structure from one equilibrium to another. Due to the two stable and uniquely defined states of FE materials they are excellent for memory applications storing "1"s and "0"s as the different polarization state of the material. *The states are uniquely defined, non-volatile and has a non-destructive readout.* All of which are big advantages of FE based memories.

As illustrated in Figure 1, we can distinguish between three types of ferroelectric memories.

Ferroelectric switching mechanism

The metric for **benchmarking** FE materials is the Polarization-Electric field (PE) curve, from this the remanent polarization P_r and coercive field E_c can be extracted. As shown in Figure 2

- the **remanent polarization** P_r represents the displaced charge at zero applied electric field
- whereas the **coercive field** E_c provides the minimum electric field required to displace the charge and reverse the polarization direction.

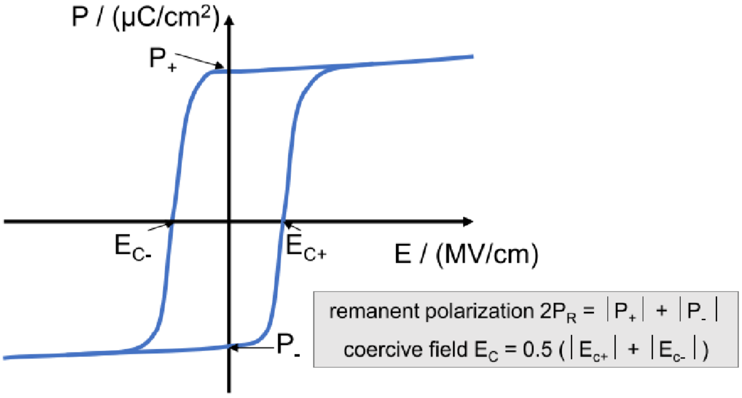

Figure 2: Typical hysteresis P-E curve of a ferroelectric material showing the most important properties remanent polarization and coercive field.

Polarization - PE curve

The polarization and hence the **PE curve** cannot be measured directly, instead it is derived from the **IV characteristics**. From this we can attain the net change in polarization. In the simplest case of a field plate capacitor the stored **surface charge** at any time t is calculated by the integral

$$Q(t) = \int_{t_1}^{t_2} I dt \tag{1}$$

The **dielectric displacement** D is calculated as the surface charge density by

$$D(t) = \frac{Q(t)}{A} \tag{2}$$

where A is the specimen surface area. For high permittivity ferroelectrics, $\chi > 20$, the polarization P is roughly equal to the dielectric displacement D. Note that this approximation is only valid for materials with a large permittivity. The expression for polarization then becomes

$$P(t) = \frac{Q(t)}{A} \tag{3}$$

Characterizing ferroelectrics

When trying to characterize **FE response** there are two different types of measurement schemes used among researchers:

1. The first one is known as the "**PUND**" method which stands for **Positive Up Negative Down**. A typical PUND sequence is shown in figure 3a.
2. The second method is the "**Virtual Ground**" setup where identical pulses of alternating sign is continuously pulsed after each other, depicted in figure 3b.

The two measurement schemes are equally common in literature. Why do you think that is? What are the benefits and drawbacks of the two methods?. Hint: The "Positive" and "Negative" pulses in PUND switch the polarization whereas the "Up" and "Down" pulses do not.

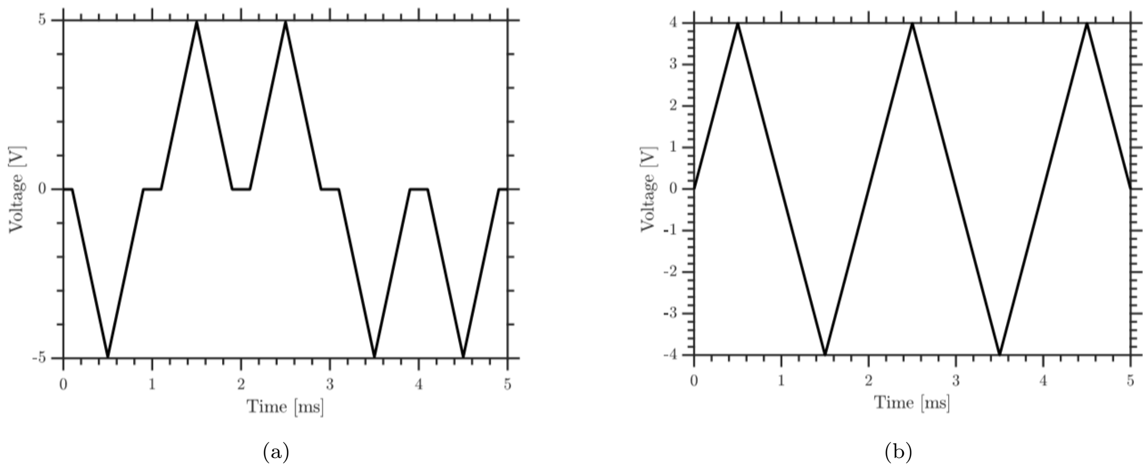

Figure 3: The two pulse sequences used to characterize Ferro Electric (FE) materials. a) Example of Positive Up Negative Down (PUND) implementation. b) Example of Virtual Ground (VG) implementation.

4 Assignments

The goal of this handin assignment is to derive the corresponding PE curves of three materials in order to benchmark them. Using the received three sets of measured IV-data and our task is to implement the PUND data analysis in MATLAB to derive the PE curves.

For more detailed information on the subject please see the lecture slides in [1] related to this topic or in [4]. All three **data sets** are measured on a **circular parallel plate capacitor** with $r = 25\mu m$.

The FE material in all the three structures are **metal organic oxides** with a high permittivity. The **dielectric** measured in files A and B are $15nm$ thick whereas for the third data set, file C the dielectric thickness is 10 nm.

Finally the PE curve displayed in Figure 3 below shows a classical **anti-ferroelectric** (AFE) response, would it be possible to measure this type of response by implementation of the PUND method? If so why or why not?

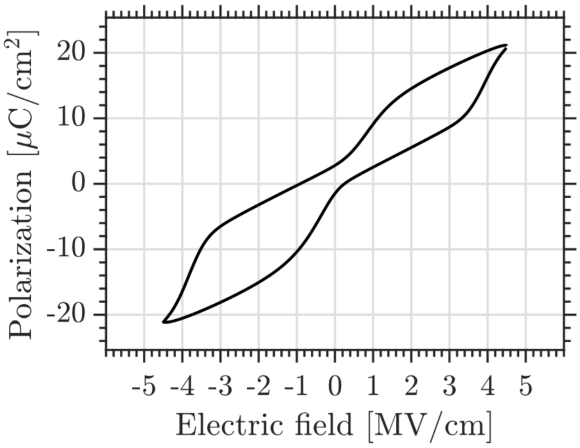

Figure 4: Measured PE curve of anti-ferroelectric response of pure ZrO_2.

5 Appendix

References

[1] Mattias Borg, Memory Technologies For Machine Learning - EITP25, Lectures notes: `https://canvas.education.lu.se/courses/2101`

[2] Chen, Hutchby, Zhirnov and Bourianoff, Emerging Nanoelectronic Devices, Wiley 2015.

[3] Manan Suri: Advances in Neuromorphic Hardware Exploiting Emerging Nanoscale Devices. Springer, 2017, ISBN: 978-81-322-3701-3.

[4] D. Hall, M. Cain, M. Stewart, T. U. K. C. f. M. M. National Physical Lab., and Technology;, "Ferroelectric hysteresis measurement and analysis," in Minutes of the NPL CAM7 IAG Meeting, 1998.

[5] T. Mikolajick, U. Schroeder and S. Slesazeck, The Past, the Present, and the Future of Ferroelectric Memories, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 67, NO. 4, APRIL 2020.

[6] S. Oh, H. Hwang and I. Yoo, Ferroelectric materials for neuromorphic computing, APL Materials 2019.

[7] Matthew Jerry et al., Ferroelectric FET Analog Synapse for Acceleration of Deep Neural Network Training, 2017 IEEE International Electron Devices Meeting (IEDM).

[8] Lin Chen, et al., Ultra-low power $Hf_{0.5}Zr_{0.5}O_2$ based ferroelectric tunnel junction synapses for hardware neural network applications, Nanoscale, The Royal Society of Chemistry 2018.