3εFERRO

Energy efficient Embedded Non-volatile Memory Logic based on Ferroelectric Hf(Zr)O2

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INTRODUCTION

This document describes the overall impact of the work carried out in the 3εFERRO project. The detailed experimental, modelling simulation and design work are described in the relevant deliverables, indicated in the text. Here we focus on the teaching modules prepared utilising project results for use in regular graduate courses and indicate the specific contribution of 3εFERRO.

Project scope

3εFERRO is aimed at improving the current status of embedded FeRAM by introducing new ferroelectric materials (HfO_2) and develop a competitive FeRAM which could replace eFlash in MCUs for IoT. A second major ambition is to enrich eFeRAM with novel LiM circuit designs in order to improve the energy efficiency of MCUs and increase their capabilities to process sensory data at the place where they are stored adding flexibility and increasing the range of applications. Thirdly, we have developed FeFET edge logic based on 28 nm CMOS technology from GlobalFoundries. Thus, there are three major ambitions:

- Materials optimization and solutions to specific, device determining materials problems;
- Circuit optimization and logic in memory design for low power IoT applications
- 1T-1C memory arrays and 1T FeFETs, integrated with CMOS providing the conditions for technology transfer for development of industrial products

PROJECT IMPACT

Workpackage 6

The full potential of embedded ferroelectric memory and logic for energy efficient storage and processing developed by the project has to be spread towards the current and future generations of engineers and researchers. Without such actions, the advances proposed within this project could be misused or even not used at all. This task will plan educational and training activities, with the following objectives:

- To raise awareness among the young engineers and researchers and to let them embrace all the possibilities offered by activities such as informative home page, contribution to courses for professionals, contributions to conferences;
- To educate and reinforce knowledge for students in engineering and PhD students through implementation of the project results into relevant PhD or other graduate courses and summer schools. Several specific modules (tutorial and also training in clean room environment) on (i) growth/characterization of ferroelectric films; (ii) ferroelectric capacity fabrication and elaboration; (iii) architecture simulation for LiM application will be prepared that will be made available to project partners for their teaching activities and on line. ECL will integrate project results in lectures for students of engineering courses and PhD students (doctoral and summer schools) on the national and international level.

Deliverables

D6.7 – Teaching module prepared utilising project results for use in regular graduate courses (ECL, M42)

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PROJECT RESULTS

1. FZJ/ University of Konstanz

At Konstanz University, the following modules have been taught using data and knowledge from/on the 3εFERRO project has been used since 2020:

1) Bachelor thesis (analysis of synchrotron HAXPES data).
A HAXPES dataset on La-doped HfO_2 samples (provided by Namlab) was measured by the Juelich/Konstanz team in 2020 at the beamline P22, DESY (Hamburg) and served as data input for a bachelor thesis. The BA candidate learned how to sort the data, how to fit the background and the detailed peaks and how to interprete the data. The parameter varied was the La-doping concentration by which clear spectral relations were revealed. The Bachelor thesis is scheduled for three month, and will be submitted and defended in July 2021. The results will be further discussed by FZJ/Konstanz and lead to a publication in the frame of the 3εFERRO project.

2) Lecture (teaching on spectroscopy methods and ferroelectric HfO_2).
The lecture took place as in a virtual format at University of Konstanz, with 4 hours of lecture per week for 14 weeks in summer term 2021. It was announced as a Master course and was also opened to interested Bachelor student, finally 9 participants registered for the class. The topics of the lecture included synchrotron-based spectroscopy of complex materials, for which HfO_2-based system provided a very good example. The students were introduced to different photon-based photoemission spectroscopy and microscopy techniques, which also were a fundamental basis for the project of FZJ in the 3εFERRO project.

3) Lab course (hand-on course on HfO_2 XPS analysis)
The lab course took place in person at University of Konstanz as a one-day block course. The students were taught how to record an XPS spectrum of HfO_2-based samples, how to identify the different peaks and take detailed scans for further analysis. As a written performance record, the students have to hand in a "minipaper" in which they write a short abstract, describe the experiment, plot the data and briefly discuss the results. In this way, they are introduced to writing a small manuscript in LaTeX for the first time. The samples used for the lab course were provided by Namlab and had been previously studied by FZZ/Konstanz via HAXPES at beamline P22, DESY (Hamburg).

Students performing XPS lab experiments on HfO_2-based samples at University of Konstanz.

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2. NamLab

Data/knowledge from/on the 3εFERRO project has been used for since 2021 in a module on ferroelectric HfO_2 in master course lecture (and practice classes) at TU Dresden: Memory Technology 2. The lecture covers the concept and technology of several alternative memories. While conventional semiconductor memories – like Flash, DRAM or SRAM – use charge to store the data, these innovative memories use other material effects. Especially 3h are dedicated to ferroelectric memories - FRAM (about 30 min lecture, 60 min tutorial, and 90 min practical training). The chapter starts with fundamentals and history, then the memory effect is explained, with examples of results from 3εFERRO project.

3. Ecole centrale de Lyon

ECL proposed during the academic years 2019-2020 and 2020-2021 several specific modules for its students using data and knowledge from/on the 3εFERRO project:

(i) A lab training activities – title: memories for IoT -on growth by sputtering and characterizations (XRD & PUND measurements) of $HfZrO_2$ films in clean environment and the modelisation of a ferroelectric memory cell using Cadence software. The training duration is: 20 hrs on 2 weeks for 10 engineering students (M2 level). The3εFerro project's video is used as introduction for the lab training and following by a lecture for introduction to clean room process.

The goal of the 8 hours of clean room lab session is to realize a ferroelectric $HfZrO_2$ capacitor and to characterize this elementary cell. The first 4h session is dedicated to the deposition on silicon wafer by sputtering at room temperature of a TiN/HZO/TiN structure, following by a rapid thermal annealing. The top TiN electrode is deposited by lift-off process: the students have to pattern a mask in photoresist than to UV photolithography. The top electrodes are disks with diameters varying from 1 µm to 1 mm. This session is organised within the Nanolyon platform. For all the students, this is the first working session in a clean room environment. The next 4h session is dedicated to the characterizations of the HZO samples:

- glancing incident X-ray diffraction (GIXRD) to check if the samples are crystalline and which phases are present, especially if the orthorhombic ferroelectric phase can be observed in the sample.

- positive up negative down (PUND) electrical measurements in order to check if the samples are well ferroelectric and what are their electrical parameters (polarisation, leakage current, etc.). These data will be then used during the next session (CAB lab training).

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ECL's students using the sputtering and the RTA systems. Observation of samples with optical microscope after lift-off process.

The process used by students in clean room is based on the results of the PhD thesis of Jordan Bouaziz within the 3εFERRO project.

The objective of the two 4 hours CAD lab sessions is to enable students to build on the technology and characterization work undertaken in the first part of the course. In the first session, the students are first brought to familiarize themselves with the Cadence design environment (some of the students are using the tool suite for the first time) through the design, performance evaluation and manual optimization of a simple CMOS inverter. They then use the inverter as a building block in the context of a volatile 6T-SRAM cell, measure the main performance metrics (in particular read and write time and energy consumption) and through a relevant simulation bench are brought to understand the volatile nature of information as stored in such a circuit. In the second session, the students adapt the initial 6T-SRAM cell to add non-volatile functionality to achieve a non-volatile flip-flop cell. Specifically, the cell uses a Black&Das circuit topology with FeFETs added in series to the pull-down branch of each inverter (thus acting on the impedance balance of the bistable circuit to systematically force the bistable to one or other state according to the state of the FeFETs) coupled with a short circuit transistor to enable read operations. After a theoretical analysis of the functionality of the circuit, the students employ a Verilog-A compact model of a ferroelectric capacitor gate-coupled to a conventional FET, and after verifying functional agreement between theory and simulation, pursue performance evaluation and optimization. Of particular importance is the verification of state readout after a power-down and wakeup cycle.

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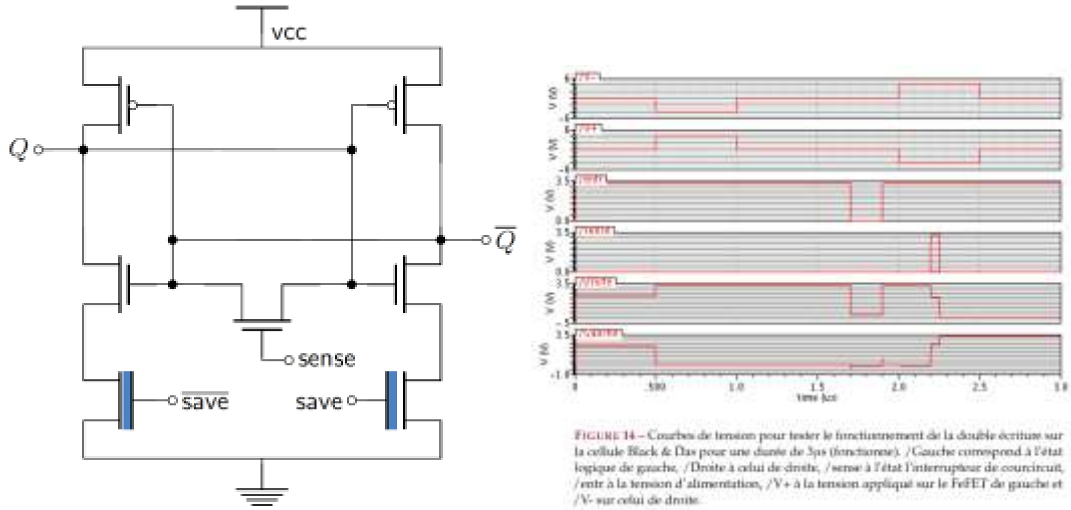

(a) Schematic of FeFET-based Black&Das non-volatile flip-flop cell.
(b) Transient simulation results demonstrating non-volatile operation.

The final evaluation of the training is based on a report and an oral presentation following by questions from professors.

(ii) A series of lectures on Emerging Memory technologies for ICT, including 1T FeFET and 1T-1C FRAM. This lecture includes 15 master students (M2 level) for 10 hrs. Lectures starts by emphasizing the growth and importance of memory market in the worldwide semiconductor industry. Both embedded and standalone markets are then presented together with the main industrial players in these fields. Still being the main non-volatile memory technology, the evolution of Flash memory technology is described together with the main dowscaling issues both for embedded or standalone applications. Finally, emerging memory technologies are presented (RRAM, PCRAM, FRAM, FeFET, MRAM) from the physics of storage mechanism to the most advanced technological demonstrators. Results and knowledge gained during 3eFERRO project are presented during the lecture. The series of lecture concludes on the unique opportunities provided by emerging memory technologies in the field of Low-Power and Logic-in-Memory applications.

The ambition of these graduate courses was to be also adapt for a summer/fall school attended by the PhD students involved in 3εFERRO project. As a result of the Covid-19 crisis, IEEE Ferro School which should be organized at Lyon by ECL partner (with special tutorials and training for PhD students on HfO_2-based ferroelectrics by members of 3εFERRO project) was postponed from November 2020 to November 2021 (then held after the end of the project):

https://ieee-uffc.org/news/2020-ferroelectrics-school-postponed-2021/

It was also considered to also create Massive Open Online courses (MOOC) in order to increase the dissemination of the education activities. However, as ECL's Learning Lab has not been available and accessible since March 2020, it was not possible to carry out this activity.

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4. PhD students

Twelve PhD students were working within the framework of 3eFERRO, although not all are directly funded by the project. In the table below we have compiled the list of PhD students, their institute, the title of their thesis and the expected thesis defense date. Of course the latter can shift, particularly due to Covid-19 induced delays but the table nevertheless gives a good overall view of the new research work being carried out and the level of PhD training leveraged by the project.

Institution	Phd student	PhD thesis subject	Thesis defense
ECL	Jordan Bouaziz	Ferroelectric properties of sputtered (Hf,Zr)O2 thin films	July 15th 2020
CEA	Wassim Hamouda	Characterization of the interface electronic structure of ultra-thin ferroelectric $HfZrO_2$ films for low power, CMOS compatible, non-volatile memories	December 2021
Namlab	Furqan Mehmood	Lanthanum Doped Hafnium Zirconium Oxide based Ferroelectric Capacitors'	September 2021
NCSRD	Christina Zacharaki	Growth of ferroelectric HZO and study of the physical and electrical properties	December 2021
FZJ	Thomas Szyjka	HAXPES study of interface and bulk chemistry of ferroelectric HfO_2 capacitors	December 2021
EPFL	Matteo Cavalieri	Tailoring functionalities in CMOS-compatible ferroelectric oxides	January 2021
ST	Ivane Battala-Gambetta	Elaboration and characterization of ferroelectric films for FeFETs	January 2022
CEA	Terry François	Electrical characterization of ferroelectric non volatile memories for embedded applications	November 2021
EPFL	Carlotta Gastaldi	NC in HfO_2-based heterostructures	February 2022
NIMP	Cosmin Istrate	TEM investigation of doped HfO2 films and related structures	September 2021
NamLab	Evelyn Breyer	Development and Investigation of Novel Logic-in-Memory and Memory-in-Logic Circuits Utilizing Hafnium Oxide Based Ferroelectric Field Effect Transistors	November 2020
ECL	Mayeul Cantan	Energy-efficient edge computing with integrated ferroelectric devices	October 2021

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