Enabling Ferroelectric Memories in BEoL - towards advanced neuromorphic computing architectures

David Lehninger*, Maximilian Lederer *, Tarek Ali* Thomas Kämpfe*, Konstantin Mertens*, Konrad Seidel*
*Fraunhofer IPMS, Center Nanoelectronic Technologies (CNT), An der Bartlake 5, Dresden 01099, Germany
Email: David.Lehninger@ipms.fraunhofer.de

***Abstract*—Advanced non-volatile memory concepts such as the 1T1C ferroelectric (FE) random-access memory (FeRAM) and the 1T1C FE field-effect transistor (FeFET) can be realized by connecting a metal-ferroelectric-metal (MFM) capacitor placed in the back end of line (BEoL) of a microchip to the drain and gate contacts of a standard logic device, respectively. With the vertical distributed select devices in the front-end of line (FEoL) and the storage elements in the BEoL, both concepts increase the effective memory density of a microchip without introducing major changes in the FEoL fabrication technology. However, for advanced neuromorphic computing architectures, the 1T1C FeFET is the device of choice, since it provides non-destructive readout. The most promising material for the integration of FE non-volatile memory functionalities into the BEoL is Zr doped HfO_2 (HZO). It crystallizes at low temperatures in the orthorhombic phase (the one with FE properties) and with a polycrystalline structure. The latter is important to enable analogue like switching in synaptic devices. Herein, the above-mentioned memory concepts are introduced and key steps to optimize the HZO films for the BEoL integration and for the neuromorphic computing use case are described.**

***Index Terms*—**

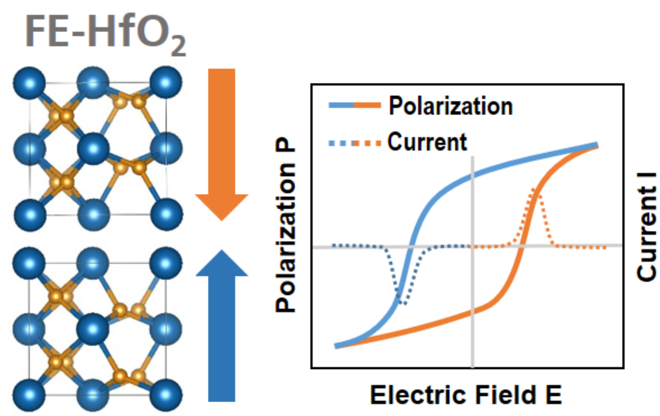

Fig. 1. Displacement of ions in a ferroelectric (FE) HfO_2 crystal (left) and associated electrical measurable polarization- and current versus electric field characteristics (right). Very little self-limited energy is expended to change the polarization state, as seen from the small displacement current peak.

I. Introduction

Data storage is an integral part of today's microelectronic systems. A high diversity of memory concepts is available, starting from very fast volatile static random access memories (SRAMs) with low storage density to high-density non-volatile flash memories with large data volume and long access time. However, new applications like smart and low-power sensors for intelligent internet of things devices at the edge require new memories that combine the properties of high-speed, non-volatility and low power together with good reliability in one concept. [1]

Ferroelectric (FE) non-volatile memory (NVM) concepts show promise in meeting these requirements. [2] The non-volatility is caused by the two remanent polarization states (P_r^+, P_r^-) instigated by the displacement of ions in a FE crystal lattice. Near the coercive field ($|E_c|$), the polarization switches between both stable states [3], which can be detected via electrical measurements (Fig. 1).

FE memory concepts based on perovskites were already introduced more than 70 years ago [4]. Nevertheless, due to their challenging integration into standard microelectronic production lines, their use is still limited to microcontrollers for niche applications. [5]

However, the discovery of ferroelectricity in HfO_2 [6], a material already successfully integrated into standard high-k metal gate technologies, has the potential to disrupt the FE memory market. The ferroelectricity in HfO_2 is attributed to the formation of the non-centrosymmetric, orthorhombic phase of space group $Pca2_1$. [7] This thermodynamically unstable phase can be stabilized by introducing various dopants into the crystal lattice, such as Si, Zr, Gd, Y, and Al.

Zr is the most promising dopant for the integration of FE memory concepts into the back-end of line (BEoL). Zr doped HfO_2 (HZO) crystallizes in the FE phase at comparatively low temperatures [8]–[10] and over a wide range of compositions [11]. Furthermore, the morphology is usually polycrystalline with small grain sizes [12], which is important to implement analogue like switching in synaptic devices for artificial intelligence.

Herein, two FE memory concepts for the BEoL are presented: The 1T1C FE random-access memory (FeRAM) and the 1T1C FE field-effect transistor (FeFET). In addition, the key steps to optimize HZO films for BEoL and neuromorphic computing requirements are described.

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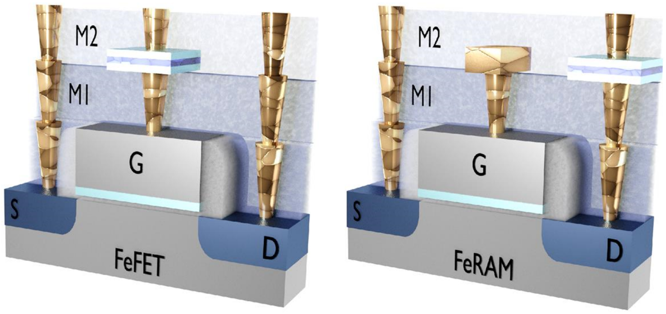

Fig. 2. MFM capacitors placed in the BEoL of a microchip can be connected to the gate contact and to the drain contact of a standard logic device to realize a 1T1C FeFET or a 1T1C FeRAMs, respectively.

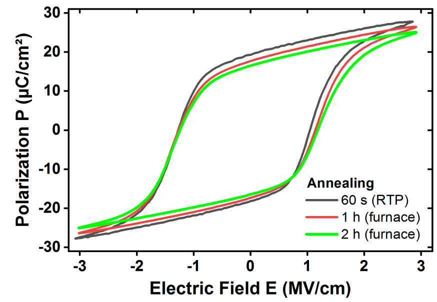

Fig. 3. Polarization versus electric field (P-E) measurements of MFM capacitors with a HZO film optimized to meet the BEoL requirements. The test structures were annealed at 400°C either within an RTA for 60 s or within a furnace-type oven for 1 h or 2 h.

II. Ferroelectric BEoL Memory Concepts

An important building block for embedded FE NVMs are metal-FE-metal (MFM) capacitors. Placed in the BEoL of microchips, they can be connected either to the gate or drain contact of a standard logic device to realize a 1T1C FE FeFET and a 1T1C FeRAM, respectively (Fig. 2).

The concept of the 1T1C FeRAM is similar to that of a dynamic random access memory (DRAM). However, unlike the latter, which stores information (volatile) in the form of charges, the FeRAM uses the (remanent) polarization state of the FE material. The FeRAM is hence a NVM. For readout, the FE polarization is switched and the resulting displacement current is sensed. The readout is thus destructive.

In case of the 1T1C FeFET, the polarization state of the FE material modulates the surface potential (i.e. the conductivity) of the channel, which impacts the threshold voltage of the transistor. Readout is conducted by sensing the drain current at small gate voltages (significantly below $|E_c|$). The readout is thus non-destructive.

III. Requirements of HZO BEoL Integration

The following requirements/wishes must/should be fulfilled for a successful BEoL integration of the HZO films: (i) The HZO must be crystallized in the FE phase at BEoL compatible temperatures, which are usually limited to 400°C. (ii) Crystallization into the FE phase via furnace treatments that are part of the BEoL process flow would be beneficial, instead of using a dedicated rapid thermal annealing (RTA). (iii) The periodically occurring high-temperature steps should not trigger phase transformation processes from the metastable FE to a non-FE phase after crystallization, which would reduce the FE properties and/or promote further grain growth, which would degrade the linear switching properties.

To optimize the HZO accordingly, the effect of the film thickness and composition on the crystallization process was investigated [8]–[10]. Fig. 3 shows the polarization versus electric field (P-E) characteristics of the most promising HZO film embedded in MFM capacitors [8]. Annealing was done at 400°C for different durations: 60 s within an RTP tool (best known method to form the FE phase) as well as 1 h and 2 h within a furnace-type oven to simulate the thermal conditions of BEoL processing. All devices show promising hysteresis loops with a large remanent polarization ($2P_r$) of about 38 $\mu C/cm^2$. A significant degradation of the FE film properties with increasing annealing time can not be observed.

Other important characteristics, such as leakage currents, endurance, and the grain size are also not negatively impacted by the long-term thermal treatment. [8]

Just recently, the successful BEoL integration of HZO films was reported and used to fabricate 1T1C FeRAMs [13] and pyroelectric energy harvesters. [14]

IV. The 1T1C FeFET for Neuromorphic Computing

The BEoL integration of FE memory concepts is considered as a key enabler for neuromorphic computing, which requires NVMs in close proximity to the logic devices. Although both above presented concepts have the potential to significantly increase the effective memory density of a chip without introducing major changes in front-end-of-line (FEoL) technology, the 1T1C FeFET is the concept of choice for neuromorphic computing due to its non-destructive readout.

For the 1T FeFET (FEoL approach), the ideal suitability for hardware accelerated neural networks, due to the low-power write and read operation [15] and the excellent peak performance exceeding 13700 TOPS/W [16], was already shown. In addition, high dynamic range, multi-bit operation, and good linearity as well as symmetry was reported [15].

To show good linearity characteristics, an analogue like switching of the FE material, which is directly linked to the polycrystalline grain distribution and associated crystallographic orientation is important. The latter can be examined by analytical methods like transmission Kikuchi diffraction (TKD).

Recent studies showed that the 1T1C BEoL FeFET could further improve the analog like switching characteristics. This is due to the use of the MFM structure instead of the metal-FE-insulator-semiconductor (MFIS) gate stack and HZO instead of silicon doped HfO_2 (HSO). As Fig. 4 shows, significantly smaller grain sizes were detected for MFM structures with HZO (1T1C approach) compared to MFIS stacks with HSO (1T approach). [12], [17]

Recently, the existence of multi-state sub-loops (due to the linear switching of the FE material) was directly observed from P–E measurements of HZO based MFM capacitors

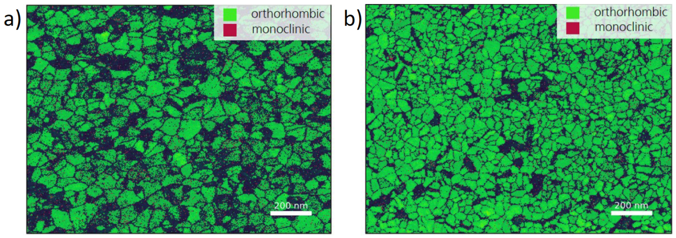

Fig. 4. Phase-maps of a) a HSO film and b) a HZO film measured by transmission Kikuchi diffraction (TKD). After thermal treatment at identical conditions, HZO films have significant smaller grain sizes than HSO films. The figure was reprinted from [12].

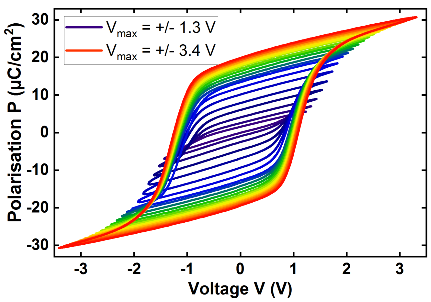

Fig. 5. P-E measurements of HZO based MFM capacitors annealed at 350°C for 1 h in a furnace-type oven showing multi-state sub-loop behavior for programming voltages below the saturated polarization switching. (Reprinted with permission from [10].)

(Fig. 5). [10] The well controllable sub-loops range from approximately zero $2P_r$ to the full loop and show promising retention characteristics. [10]

Furthermore, the 1T1C FeFET is expected to improve the endurance compared to the 1T FeFET due to the absence of a HZO/Si interface.

V. Conclusion

BEoL FE memories like the 1T1C FeRAM and the 1T1C FeFET have been introduced. Both concepts are realized by connecting a MFM capacitor placed in the BEoL to the drain and gate contact of a standard logic device, respectively. HZO films are well suited for this application. The thermal budget present during the interconnect formation can be used to crystallize the HZO in the desired FE phase without using a dedicated RTA anneal, which minimizes the number of involved fabrication steps. The BEoL integration of FE memories is attractive for neuromorphic computing. Due to the non-distructive readout, the FeFET is the device of choice for this application. Compared to 1T FeFETs, which already showed suitability for neuromorphic hardware accelerators, the 1T1C BEoL device is expected to further improve the analog like switching characteristics.

Nevertheless, additional integration related challenges have to be solved. For example, the metal electrode used for the MFM capacitors is crucial to achieve a maximum $2P_r$ and reliability. BEoL TiN optimized to be a highly conductive diffusion barrier is not well suited for this application.

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