From FRAM to FeFET: Ferroelectric HfO_2 based devices and their reliability

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Abstract

With the discovery of ferroelectricity in doped HfO_2 the introduction into scaled non-volatile memory devices based on a one-transistor one-capacitor (1T-1C FRAM) or a one-transistor (1T FeFET) cell became possible. HfO_2 shows ferroelectric properties when doped with a variety of different dopants in ~5-20 nm thin thickness range which enables further scaling of current memory devices. This paper reviews the current status of hafnium oxide based memory devices and their reliability performance, compares their properties to products on the market and describes a possible roadmap for the future.

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1. Introduction

New computer generations require micro-processors in close proximity to non-volatile memories (NVM), both working with low power consumption and high write speed. Since current FLASH technology cannot perform at these specifications, new memory solutions are necessary. Novel HfO_2 based NVM cells could offer the required properties and have the advantage that HfO_2 is already known for its compatibility with CMOS processing as shown in standard state-of-the-art logic nodes. In contrast, current FRAM products on the market are limited by the properties of the ferroelectric $PbZrTiO_3$ material resulting in scaling limitations. NVM devices based on both materials are briefly compared before HfO_2 or ZrO_2 based memory cells are discussed in detail and their possible future roadmaps are reviewed.

2. Experimental

Metal-insulator-metal (MIM) capacitor structures are fabricated on Si substrates consisting of 10 nm thick HfO_2 or ZrO_2 based dielectric layers in between TiN electrodes. Further process details can be found elsewhere [1]. These capacitor structures are compared to FeFET devices in literature [2][3] by structural and electrical characterization.

3. Results and Discussion

In the 1T/1C concept, information is stored in a memory cell as two different polarization states in a ferroelectric capacitor (FeCap) which can be read out via an access transistor. To verify endurance performance, the device is cycled between two different polarization states and a list of characteristic parameters is recorded during field cycling. Fig. 1 shows the remanent polarization and cycles to breakdown as a function of field cycling. The cycling behavior of a ferroelectric HfO_2 based FeCap is determined by a wake-up and fatigue phase resulting in a breakdown of the dielectric material. Recently, an AFE device is described [4], which is operated by switching between a polarized and a non-polarized state. Here, less wake-up and fatigue behavior and longer field cycling performance are reported (Fig.1). As a main reason for this behavior a reduced charge injection during polarization state switching is assumed. Accordingly, a lower imprint behavior can be expected. Evolution of leakage current (Fig.2) and internal bias field (Fig.3) further strengthen that assumption. In addition to endurance behavior, retention of the polarization state and imprint of the hysteresis after retention can be verified. Due to a lower activation barrier between polarization states in the AFE compared to the FE case, a reduced retention behavior is visible (Fig. 4). FeFET device cycling performance is rather limited by charge trapping causing a closure of the memory window, than by dielectric breakdown. Here, a gate last approach is more beneficial compared to the gate first case due to the lower thermal budget during fabrication resulting in a lower amount of trap sites (Fig.5). Good retention behavior could be verified for FeFET approaches, but so far, advantages are present for gate first devices due to the larger memory window (Fig.6).

4. Conclusion

Overall, ferroelectric HfO_2 and ZrO_2 based NVM devices are showing a similar field cycling performance. Degradation behavior is mainly limited by charge injection into defect sites generated during the fabrication process and device operation. Due to the ferroelectric properties of HfO_2 which can be realized even in doped HfO_2 films below 5 nm thickness, the material is a good candidate for future scaled NVM devices.

References

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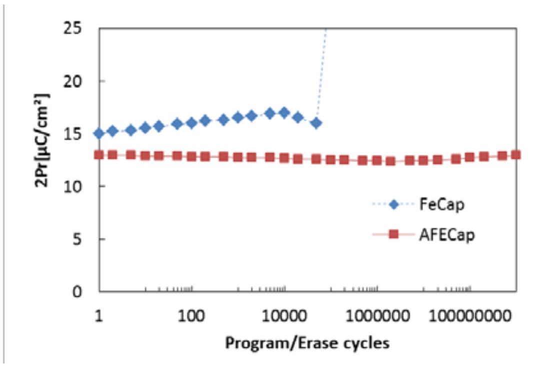

Fig.1: Remanent polarization evolution for field cycling behavior of a Si:HfO$_2$ FERAM vs. ZrO$_2$ AFERAM capacitor.

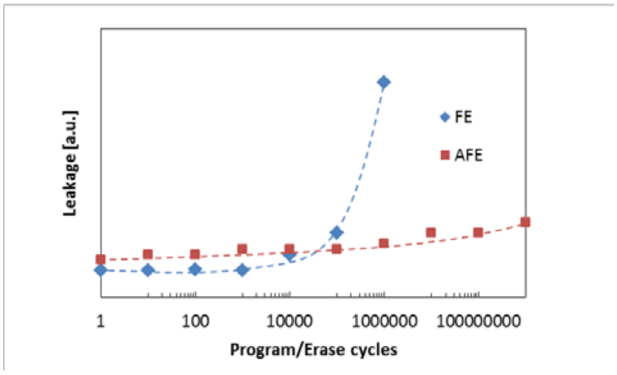

Fig.2: Leakage current evolution for field cycling behavior of a Si:HfO$_2$ FERAM vs. ZrO$_2$ AFERAM capacitor.

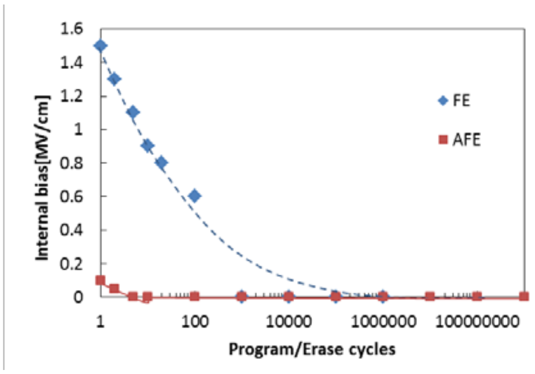

Fig.3: Internal bias field evolution for field cycling behavior of a Si:HfO$_2$ FERAM vs. ZrO$_2$ AFERAM capacitor.

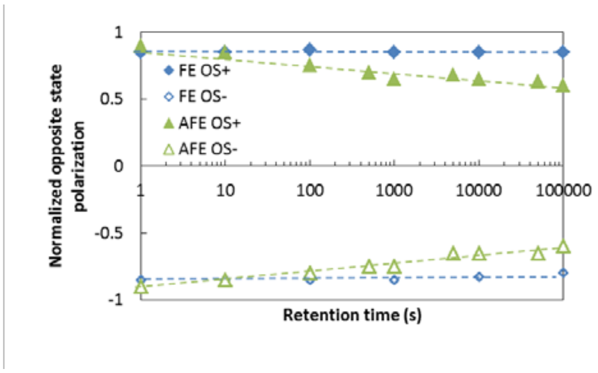

Fig.4: Retention behavior of the most critical case of opposite state switching for a FERAM vs. AFERAM capacitor.

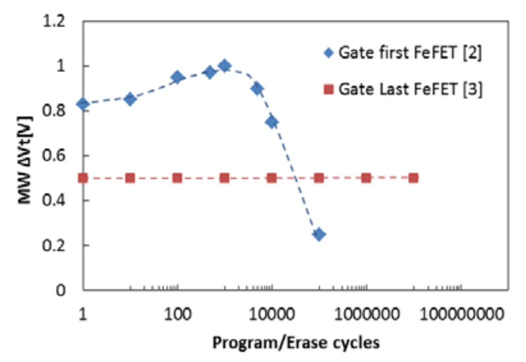

Fig.5: Memory window as threshold voltage difference evolution for field cycling behavior of single gate first vs. gate last device [2][3][5][6].

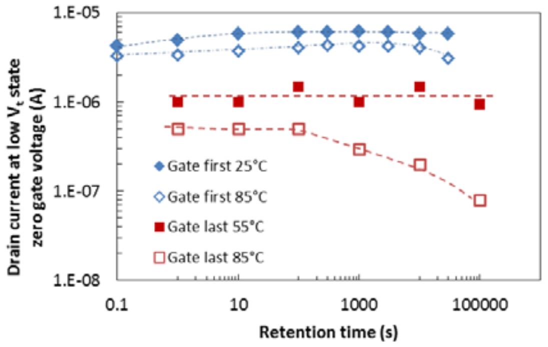

Fig.6: Retention behavior of a single gate first vs. gate last FeFET device: comparison of drain current for low V_t state. Drain current for high V_t state typically at compliance limit of $1{\cdot}10^{12}$A/µm [2][3][5][6].