Ferroelectric HfO_2-based Materials and Devices: Assessment of Current Status and Future Prospects

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Some dielectrics possess the capacity for remembering their electric, magnetic or caloric history. For the extensively investigated ferroelectrics this ability to memorize manifests in atomic dipoles switchable in an external electric field. With this unique ability at hand it came as no surprise that only a few years after the realization of a working transistor the introduction of ferroelectrics to microelectronics was proposed [1]. It seemed obvious: ferroelectrics are the perfect switch for semiconductor memories.

More than 60 years and several iterations later it is now clear that the success or failure of ferroelectric random access memory is mainly determined by the proper choice and engineering of the ferroelectric material. Perovskite ferroelectrics and related electrode systems underwent an extensive optimization process to meet the requirements of CMOS integration and are now considered the front up solution in FRAM manufacturing [2]. However, those perovskite systems pose scaling limitations on 1T and 1T/1C FRAM that until now remain unsolved.

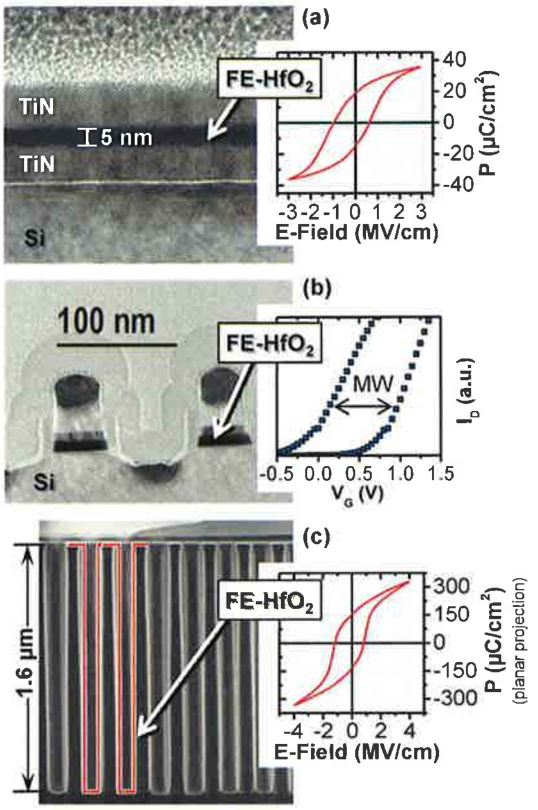

Figure 1 (a) HfO_2-ZrO_2 based MFM capacitor scaled to a ferroelectric film thickness of 5 nm and related P-E characteristics. (b) Ferroelectric Si:HfO_2-based MFIS-FET scaled to the 2X nm technology node and related I_D-V_G memory window demonstration. (c) Al:HfO_2-based deep trench MFM capacitors demonstrating a remanent polarization of 152 $\mu C/cm^2$ in planar projection.

With the recent demonstration of ferroelectricity in HfO_2-based systems (FE-HfO_2) a CMOS-compatible, highly scalable and manufacturable contender has emerged that significantly expands the material choice for 1T and 1T/1C ferroelectric memory solutions [3 and references therein]. As depicted in Fig. 1, HfO_2 thin films provide ferroelectricity down to the single digit nanometer range, allow for a fabrication of ferroelectric field effect transistor at the 2X nm node and provide access to the third dimension for the scaling of capacitor based ferroelectric memories. Additionally, temperature stable ferroelectric properties as well as a high flexibility in terms of thermal treatments have been observed in FE-HfO_2 thin films. However, at the current stage of development the cycling endurance of these new HfO_2-based ferroelectrics remains limited to $\sim 10^{10}$ switching cycles in metal-ferroelectric-metal (MFM) capacitors and $\sim 10^5$ in metal-ferroelectric-insulator-semiconductor FETs (MFIS-FETs).

In this paper we will review and expand the current understanding of ferroelectricity in HfO_2, as well as discuss future prospects of ferroelectric HfO_2-based devices with respect to scaling, reliability and manufacturability. The following key aspects will be covered:

- A generalized stabilization mechanism of ferroelectricity in HfO_2 to predict the suitability of several new dopants as well as ferroelectricity in undoped HfO_2
- Thickness scaling and intrinsic properties of the ferroelectric phase in HfO_2 compared to model systems and conventional ferroelectrics
- Assessment of potential pathways to optimize the material properties and gate stack design towards an improved reliability of FE-HfO_2-based memory devices
- Scaling of voltage, feature size and memory window in 1T and 1T/1C FRAM with respect to the new FE-HfO_2-based approach.
- Prospects of FE-HfO_2 based devices as a cost effective embedded memory solution in HKMG technologies
- Identification of suitable memory architectures and operating regimes for a 1T or 1T/1C cell concept.
- Beyond memory: possible applications of FE-HfO_2 thin films in semiconductor devices.

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References

[1] D. A. Buck, Report R-212, MIT, (1952)

[2] N. Setter, D. Damjanovic, L. Eng, G. Fox, S. Gevorgian, S. Hong, A. Kingon, H. Kohlstedt, N. Y. Park, G. B. Stephenson, I. Stolitchnov, A. K. Taganstev, D. V. Taylor, T. Yamada, S. Streiffer, J. Appl. Phys. 100, 051606 (2006)

[3] J. Müller, T.S. Böscke, S. Müller, E. Yurchuk, P. Polakowski, J. Paul, D. Martin, T. Schenk, K. Khullar, A. Kersch, W. Weinreich, S. Riedel, K. Seidel, A. Kumar, T.M. Arruda, S.V. Kalinin, T. Schlösser, R. Boschke, R. van Bentum, U. Schröder, T. Mikolajick, IEDM Technical Digest: pp. 10.8.1 - 10.8.4, (2013)