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Observation of logic states of HfO2-based ferroelectric FETs using STEM-DPC

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Background incl. aims

In recent years, ferroelectric field-effect transistors (FeFETs) have become valuable alternatives to the flash technology for nonvolatile memory applications. Not only do they incorporate ultra-fast and energy-efficient switching as well as radiation hardness, but they also provide high thermal stability of their logic states. [1, 2]

The low-VT and high-VT states have been intensively studied and characterized, e.g., as described in [1], yet the understanding of the exact electrostatic field in the polarized ferroelectric (FE) gate stack is still subject of discussion. While various TCAD simulations aim to analyze these from a theoretical perspective [3], utilizing scanning transmission electron microscopy (STEM) can deliver more direct insights. Recent work [4] has shown the observation of the FE polarization in STEM utilizing the differential phase contrast (DPC) method. In addition, STEM-DPC analysis of FE devices would provide the opportunity to conduct failure analysis, not only of structural defects in single devices, but also of imperfections in the crystallographic phase and the resulting electrostatic field itself.

Methods

DPC is a STEM imaging method which can visualize local electrostatic and magnetic fields in specimens at high resolution. The fields are detected as a shift of the transmitted bright-field disk on a segmented annular or a pixelated detector resulting from the interaction of the local fields with the incident electron beam. Since the FE polarization in FE materials creates electrostatic fields, the DPC method is suitable for the investigation of local polarization effects in the thin FE layers of FeFETs.

In this study, HfO_2-based FeFET arrays were programmed in a striped pattern, as described in [2]. The FeFETs consisted of 10 nm FE HfO_2, a 1 nm SiO_2 interfacial layer, TiN and a top electrode made from polycrystalline Si. For investigation with the DPC method, TEM specimens of the programmed array were prepared by in-situ lift-out utilizing the focused ion beam (FIB). A convergent electron beam was employed to achieve high spatial resolution and thus investigate the FE polarization states in the FE material.

Results

The local charge carrier density was calculated from the DPC data and analyzed for the investigated FeFETs, respectively. The FeFETs programmed in low-VT and high-VT states showed opposing gradients of the charge carrier density in the FE layer. The direction of the electrostatic fields indicated by those gradients was found to be in accordance with the theoretical direction of the electrostatic fields due to the FE polarization of the material.

Conclusion

In future investigations, the use of DPC can provide deeper insights into the properties of FeFETs. Combining DPC with other techniques, such as precession electron diffraction (PED), could yield additional information about these devices. Employing PED would help reduce diffraction-related artifacts in DPC data. Furthermore, PED can identify grains of both FE and non-FE phases within the material. In addition, observing the in-situ switching behavior of FE devices would contribute significantly to understanding the electric behavior of FeFETs during operation.

Keywords:

DPC, STEM, FeFET, logic states

Reference:

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