Study demonstrates the potential of ferroelectric hafnia for developing low-power logic devices

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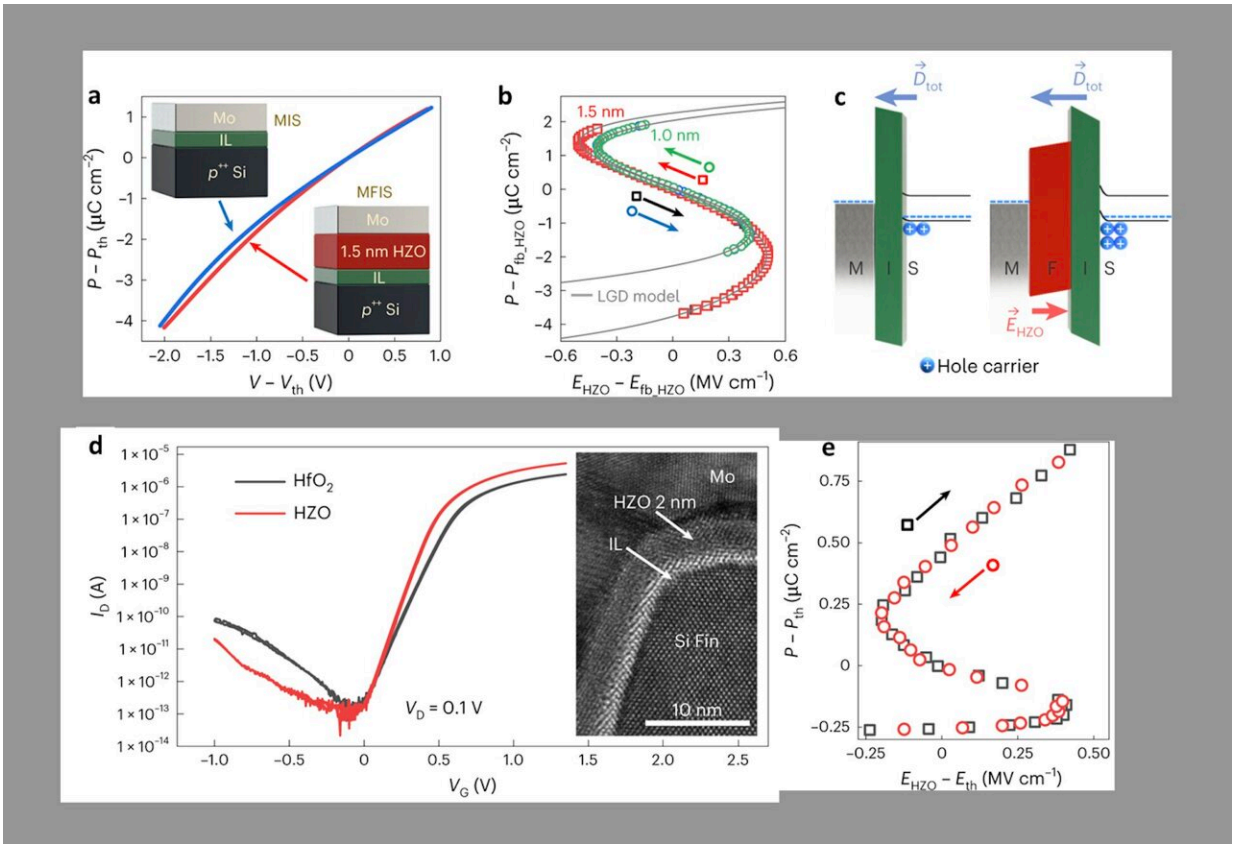

The negative differential capacitance (NDC) of ultrathin ferroelectric hafnia (HZO) with a thickness of ≤2 nm was validated in MOSCAPs and FET, (a) leading to capacitance enhancement in MFIS structures. (b) The P-E curve exhibited an S-shaped characteristic, attributed to the NDC effect. (c) Schematic band diagrams depicting the MIS structure (left) and MFIS structure (right) were illustrated. (d) The FinFET based on HZO exhibited significantly improved

performance in the ID-VG curve compared to the FinFET based on HfO_2. (e) The gate stack displayed an S-shaped P-E curve, indicating that the enhanced performance was attributed to the NDC effect. Credit: Jo et al, *Nature Electronics* (2023). DOI: 10.1038/s41928-023-00959-3

Transistors, semiconducting devices that regulate, amplify and generate the flow of electrical current, are central components of most electronics. Electronics engineers have been trying to develop increasingly smaller transistors, as this could support the fabrication of more compact devices.

Shrinking transistors, however, can adversely impact their energy consumption, as certain challenges can arise, such as short-channel effects and the leakage of current caused by a quantum mechanical phenomenon known as quantum tunneling. The energy consumption of smaller transistors could potentially be decreased by leveraging the negative differential capacitance (NDC) of ferroelectric materials.

NDC is a phenomenon that occurs in ferroelectrics, where a change in charge causes the net voltage across a material to shift to the opposite direction, so that an increase in charge prompts a decrease in voltage. One ferroelectric material that could be used to realize this is ferroelectric hafnium dioxide (HfO_2) or hafnia.

Researchers at the Samsung Advanced Institute of Technology, Samsung Electronics, Sungkyunkwan University and Jeonbuk National University recently demonstrated the promise of using ferroelectric hafnia for creating low-power transistors. Their paper, published in *Nature Electronics*, could open new possibilities for the creation of small logic devices that consume a limited amount of energy.

"By incorporating a ferroelectric layer in the gate stack instead of a high-κ dielectric, a significant reduction in the operating voltage of transistors can be achieved," Sanghyun Jo, one of the researchers who carried out the study, told Tech Xplore. "This is because the inclusion of a ferroelectric layer with NDC in the gate stack can result in an increased total capacitance compared to the case where the ferroelectric layer is not present. This stands in contrast to the conventional gate stack, where the addition of any layers in the stack always decreases the total capacitance."

The recent advancement of hafnia-based ferroelectrics prompted a growing number of research teams to try leveraging the NDC effect in transistors using strategies that can be easily integrated with existing semiconductor fabrication processes. However, very few studies have been able to demonstrate that integrating ultrathin ferroelectric hafnia into the gate stack could lower the energy consumption of transistors.

"So far, there is limited evidence of the electrical benefits of NDC on scaled silicon-based transistors," Jo said. "Our primary objective was to demonstrate the observability of NDC in scaled silicon-based structures and investigate its potential for effective utilization in the development of advanced low-power logic devices."

To conduct their experiments, Jo and his colleagues first developed ferroelectric hafnia (i.e., Zr-doped HfO_2) films with a thickness comparable to that of films used to create gate stacks in commercial logic devices. Ultimately, they were able to produce ultrathin ferroelectric hafnia films with a thickness below 2nm.

"The presence of ferroelectricity in these films was verified through various analyses," Jo explained. "Subsequently, prior to incorporating the ferroelectric layer into the gate stack of FETs, we investigated the NDC phenomenon in Metal-Oxide-Semiconductor Capacitors (MOSCAPs)

that included the ultrathin ferroelectrics with thicknesses reaching as low as 1 nm. The unambiguous proof of NDC was achieved by directly observing NDC through the S-shaped polarization-electric field relation."

The researchers also carried out tests to assess the tunability of the NDC they produced and how well the NDC effect endured when devices were operating for a prolonged time. Finally, they demonstrated that the NDC of their ferroelectric films could enhance the performance of field effect transistors (FETs). To do this, they incorporated one of their 2nm films into the gate stack of a FinFET.

"This integration successfully generated NDC, as confirmed by the S-shaped polarization-electric field relation, within a voltage range suitable for FET operation, leading to a substantial enhancement in performance," Jo said. "Therefore, our sequential approach involved the development of ultrathin ferroelectric hafnia films, verification of their ferroelectric properties, assessment of NDC observability, exploration of NDC tunability and endurance for long-term operation, and final application to FETs."

Overall, the findings gathered by Jo and his colleagues highlight the potential of creating low-power logic devices by leveraging the NDC of ferroelectric materials. They specifically offer experimental proof of this potential using ultrathin ferroelectric hafnia, yet the same advantages could soon also be demonstrated using other ferroelectric materials.

"The validation was achieved by directly observing NDC in scaled Si-based structures, and its confirmation was further supported by the observation of enhanced total capacitance," Jo said. "These electrical measurements were further complemented by simulations. To ensure the robustness of our observations, we conducted in-depth analyses of the

layers within the gate stack. This involved measuring their thicknesses and determining their precise atomic compositions, which was essential for verifying the electrical measurements and ruling out any potential high-k effects."

In their paper, Jo and his colleagues also introduced a reliable method to tune the NDC region in ferroelectric hafnia, which is based on the control of interface charges via doping techniques. This method, along with the robust NDC phenomenon they observed over 10^{15} cycles of voltage pulses, could facilitate the successful implementation of NDC in advanced logic devices.

Notably, the team's approach for leveraging NDC in compact transistors does not require any structural modifications to the devices and is also compatible with 3D architectures. This makes it easier to implement on a large-scale.

"In our recent study, we successfully demonstrated the potential of ferroelectric hafnia as a promising material for implementing NDC FETs," Jo added. "Moving forward, our next objective will be to identify and optimize specific parameters or factors that can maximize the performance enhancement of NDC. This involves uncovering the precise mechanism of NDC in polycrystalline ferroelectrics, including ferroelectric hafnia, as the current NDC model is designed for single crystal ferroelectrics."

More information: Sanghyun Jo et al, Negative differential capacitance in ultrathin ferroelectric hafnia, *Nature Electronics* (2023). DOI: 10.1038/s41928-023-00959-3