Ultrafast, high-contrast, high-fidelity 4-state 3-bit ferroelectric control

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Abstract Ferroelectric memory and logic devices typically operate with two stable states, representing the binary 0 and 1 used in digital electronics. Here we demonstrate a ferroelectric device that can be programmed into four stable states, enabling 2 bits of information to be stored in a single memory cell. Unlike conventional approaches that rely on analog tuning of the polarization, our four states are digital and robust, and can be switched with high speed and low energy. We fabricate the devices from a 10-nm-thick film of hafnium zirconium oxide integrated directly on silicon, and characterize their switching dynamics and endurance. Finally, we show that the 4-state cell can be used to perform in-memory computing operations, potentially doubling the density of memory and logic circuits.

Ferroelectric materials have a spontaneous electric polarization that can be switched between two stable states by an applied electric field. This property has been exploited in a range of memory and logic devices, including ferroelectric random-access memory (FeRAM), ferroelectric field-effect transistors (FeFETs) and ferroelectric tunnel junctions (FTJs)[1–3]. In these devices, the two polarization states are used to represent the binary digits 0 and 1, which are the basis of digital electronics.

Recently, there has been growing interest in storing more than one bit of information in a single memory cell, to increase the density of memory and logic circuits[4–6]. This can be achieved by using multiple stable states of the polarization, or by using analog tuning of the polarization between two states. However, both approaches have drawbacks. Multi-state operation can be slow and energy-inefficient, and analog tuning can be sensitive to noise and variability[7,8].

Here we demonstrate a ferroelectric device that can be programmed into four stable states, enabling 2 bits of information to be stored in a single memory cell. Our four states are digital and robust, and can be switched with high speed and low energy. We fabricate the devices from a 10-nm-thick film of hafnium zirconium oxide integrated directly on silicon, and characterize their switching dynamics and endurance. Finally, we show that the 4-state cell can be used to perform in-memory computing operations, potentially doubling the density of memory and logic circuits.

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Here we demonstrate a ferroelectric device that can be programmed into four stable states, enabling 2 bits of information to be stored in a single memory cell. Our four states are digital and robust, and can be switched with high speed and low energy. We fabricate the devices from a 10-nm-thick film of hafnium zirconium oxide integrated directly on silicon, and characterize their switching dynamics and endurance. Finally, we show that the 4-state cell can be used to perform in-memory computing operations, potentially doubling the density of memory and logic circuits.

Device fabrication. The devices were fabricated on a 300-mm silicon wafer using a standard complementary metal–oxide–semiconductor (CMOS) process flow. The ferroelectric layer was deposited by atomic layer deposition (ALD) and crystallized by a rapid thermal anneal. The top and bottom electrodes were titanium nitride. The devices were then patterned by lithography and etching.