FERROELECTRICS

Negative capacitance found

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Over the past ten years, negative capacitance in ferroelectric materials has been intensely investigated, both theoretically and experimentally. Researchers have, in particular, used Landau's theory of phase transitions to predict that an unstable negative capacitance region can arise in a ferroelectric material in the form of an S-shape polarization–electric field characteristic, which originates from the double-well polarization–energy landscape of the ferroelectric. The addition of a conventional positive dielectric in series with the ferroelectric is expected to stabilize the negative capacitance state, leading to an enhanced total capacitance that, when used in a transistor gate, can generate more charge in the channel for a given voltage.

It has been hoped that using negative capacitance in this way could overcome the limitations imposed by the Boltzmann distribution of electrons — often termed the Boltzmann tyranny — which restricts how sharply transistors can be switched on and off, and, in turn, how much power they must dissipate and how small they can be made. Recent experiments have indirectly imaged negative capacitance, and shown enhanced transistor performance. However, a lack of experimental evidence confirming the S-shape polarization–electric field characteristics, or direct physical imaging of stable negative capacitance in ferroelectric–dielectric heterostructures, has led to serious doubts as to the origin of previous observations of negative capacitance. Two research groups have now tackled these issues, providing new insight into the theory and origin of negative capacitance.

Michael Hoffmann and colleagues successfully measured the transient S-shape

polarization–electric field characteristics in a $\text{Hf}_{0.5}\text{Zr}_{0.5}\text{O}_2/\text{Ta}_2\text{O}_5$ ferroelectric–insulator heterostructure capacitor. The researchers — who are based in NaMLab and TU Dresden in Germany, and the National Institute of Materials Physics in Romania — used a pulsed voltage measurement technique to measure the charge stored on the capacitor. By assuming the capacitance of the Ta_2O_5 dielectric remains constant, they were able to calculate the electric field in the ferroelectric and plot the S-shaped polarization–electric field characteristics. Importantly, their chosen materials are compatible with semiconductor device manufacturing.

Alternatively, Sayeef Salahuddin and colleagues directly measured steady-state negative capacitance in a $\text{PbTiO}_3/\text{SrTiO}_3$ ferroelectric–dielectric superlattice. The researchers — who are based at institutes in the US, Spain, the UK and Luxembourg — used scanning transmission electron microscopy and an electron microscopy pixel array detector to spatially map the polarization and the electric field simultaneously. They observed that steady-state negative capacitance emerges in the domain walls that result from competition between elastic and electrostatic energies in the PbTiO_3 . Their findings were also confirmed using second-principles and phase-field simulations. While these measurements were not made under the application of an external field, they do offer valuable new insights into the origin of negative capacitance.

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