Data storage takes an electric turn

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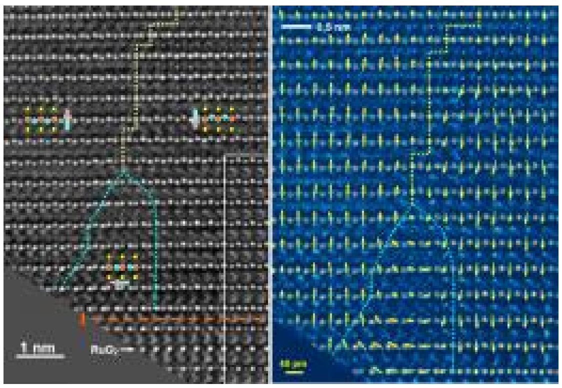


Domains in a ferroelectric memory: The image from the aberration-corrected transmission electron microscope shows the positions of both the positively charged titanium and zirconium atoms and the negatively charged oxygen in a cross-section sample of the ferroelectric PZT. The extent to which the zirconium and titanium atoms have been displaced in the depolarised PZT (yellow arrows in the image on the right) indicates the orientation of the dipole moments. The yellow dotted line marks the boundary between the two domains with a polarisation which has rotated 180 degrees. The domain demarcated by the blue dotted line was observed for the first time. It represents a dipole flux closure. The red dashed line shows where the strontium ruthenate layer begins. © C.-L. Jia/FZ Jülich

(PhysOrg.com) -- German scientists from the Forschungszentrum Julich and the Max Planck Institute of Microstructure Physics in Halle have discovered the basis for the next generation of memory devices. In a ferroelectric material, they have, for the first time, been able to observe directly how dipoles, which store the information in this material, continuously rotate and therefore may be organised in circular structures. The report was published in the journal *Science*. The findings were obtained using a type of high-resolution transmission electron microscopy with especially sharp contrast, developed by the Julich scientists. Arranging the dipoles in a circular structure could allow for significantly denser data storage than previously possible, while still ensuring fast writing and reading processes.

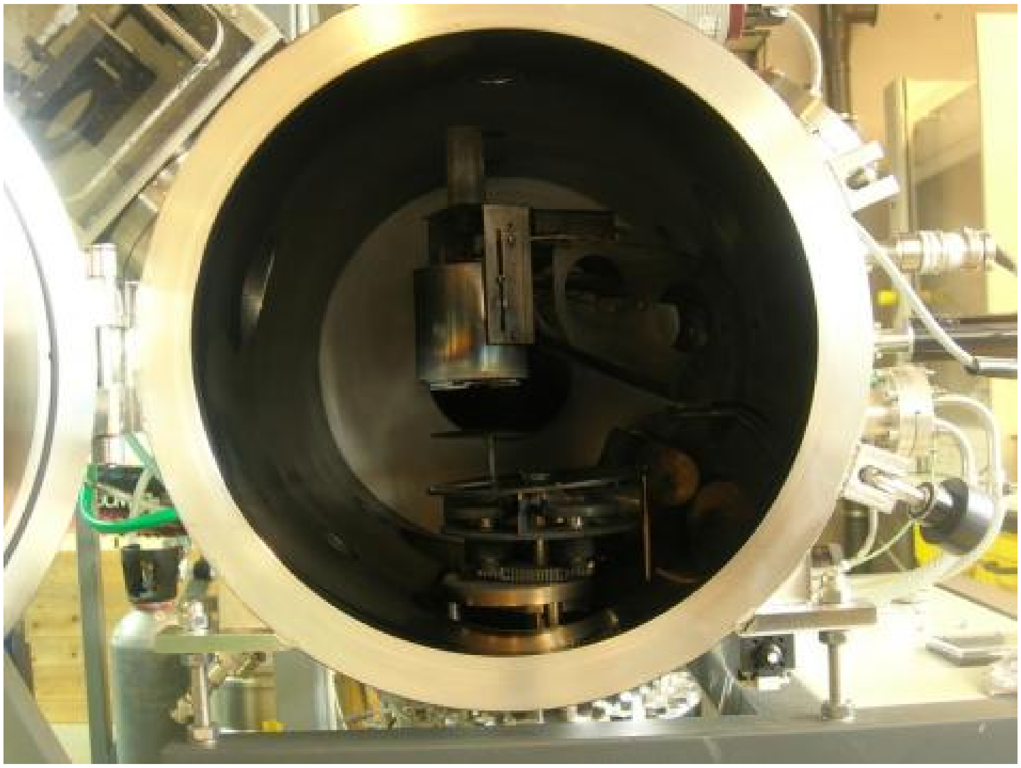
Ferroelectrics could be the way out of a dilemma troubling the chip industry. They provide durable storage and yet can be written and read quickly. Magnetic materials, on the other hand, which are used to produce hard disks and which provide permanent data storage, are sluggish. Semiconductors, for their part, are efficient in handling data, but quick to forget - which means that the electrical charges of their capacitors require constant renewal. Ferroelectrics combine the benefits of both materials. In addition, it may be possible to achieve greater data density in them than previously assumed. They could therefore soon become the material of choice for working memories with a density of several terabits per square inch.

Ferroelectric materials store bits in which their unit cells, their smallest structural units, are polarised. In other words, an electric field displaces the positively and negatively charged atoms slightly in relation to each other, so that the unit cells are somewhat distorted and a dipole is created. The dipole is maintained until a field of inverse polarisation switches the dipole or causes depolarisation. Each bit is assigned to an area – a so-called domain in physics – of the ferroelectric memory, where all the dipoles have the same orientation. “We have now discovered that under certain conditions the polarisation is maintained even in very small domains”, says Chun-Lin Jia, a scientist at the Forschungszentrum Julich.

The results were obtained through the use of a ferroelectric material produced at the Max Planck Institute of Microstructure Physics in Halle. The material, which goes by the designation of lead zirconate titanate (PZT), contains lead, zirconium, titanium and oxygen. Chun-Lin Jia and Knut Urban, Director of the Ernst Ruska Center for Microscopy and Spectroscopy with Electrons (based in Aachen and Jülich) have studied the sample of PZT using a particularly sensitive atomic-resolution transmission electron microscope. This aberration-corrected device delivers particularly sharp and contrast-rich images of very small details. It can even measure the positions of atoms with a precision of a few picometres (one picometre is a 10^{-12} metres). In contrast to conventional transmission electron microscopes, this method permits the localisation of the oxygen atoms in the PZT, where they are otherwise almost impossible to detect due to their weak scattering yield.

By determining the exact positions in the PZT sample of the oxygen atoms on the one hand, and the zirconium and titanium atoms on the other hand, the scientists identified the dipole orientation in each and every one of more than 250 unit cells. The sample consists of a cross-section of a PZT layer, which is approximately twenty unit cells thick, i.e. a good forty atomic layers. The ferroelectric material was deposited very accurately on a monocrystalline strontium titanate substrate by Ionela Vrejoiu from the Max Planck Institute of Microstructure Physics. This was additionally equipped with a thin marker layer of ruthenium oxide, in order to better distinguish the interface between the ferroelectric film and the substrate. Even the boundaries between two domains with inverse polarisation could be detected accurately in the transmission electron microscopic image of the sample cross-section.

There, where the domain boundary meets the ruthenium oxide marker layer, the scientists from Jülich observed something unexpected: an additional domain measuring only a few square nanometres, in which the orientation of the dipole system continuously rotates 180 degrees; the scientists call this a flux-closure domain. "Such domains are known from magnetic materials and had been predicted in theory for ferroelectric materials", says Knut Urban. "However, we are the first to have observed them directly".



This chamber is used by scientists at the Max Planck Institute for Microstructure Physics to produce the ferroelectric material PZT using pulsed laser deposition (PLD). The method permits extremely accurate control of the material formation. © MPI of Microstructure Physics

"I didn't think that they existed", confesses Marin Alexe, who researches ferroelectrics at the Max Planck Institute in Halle. For good reason: magnetisation is caused by electrons and can be reoriented using a small amount of energy. To reorient dipoles in ferroelectrics, however, a distortion or a rearrangement of the unit cells is required. Such changes cost much more energy than a magnetic reorientation, since they disturb the symmetry of the crystal. A 180 degree rotation is still conceivable, but many scientists considered a gradual distortion of the unit cells simply too energy-consuming.

Circular dipole structures allow for dense data storage

"That we have been able to demonstrate the dipole flux closure and the continuous rotation of the dipoles should be of practical use", says Dietrich Hesse, one of the participating scientists at the Max Planck Institute in Halle. "Apparently, nature has found a way to maintain polarisation even in structures as small as ten by ten nanometres." Previously, physicists assumed that the polarisation in such structures would collapse, as they contain too few dipoles.

Ferroelectricity is a collective phenomenon, where the dipoles support each other to a certain extent. If their number falls below a certain limit, small electric charges, which are constantly occurring on the surfaces, will break up the order of the dipoles. This effect is also what caused the polarisation on the upper side of the PZT film to disappear, which the team of scientists studied. "Until now, we therefore had to assume that domains could not be reduced to less than 20 by 20 nanometres, due to depolarisation", explains Marin Alexe. However, it would now seem that it is possible.

"We will now examine the exact conditions under which the structures with circular polarisation form", says Alexe. The zero and one of a bit can be coded by orienting the dipoles clockwise and anticlockwise, alternatively. "We already have ideas for new research along those lines", says Dietrich Hesse. "However, it will be a few years before we see data storage that can store several billion data points per square inch and that can write and read them as quickly as the currently available memory devices."

More information: Chun-Lin Jia, Knut W. Urban, Marin Alexe, Dietrich Hesse, Ionela Vrejoiu, Direct Observation of Continuous Electric Dipole Rotation in Flux-Closure Domains in Ferroelectric Pb(Zr,Ti)O3, *Science*, 18 March 2011; DOI: 10.1126/science.1200605

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