

# Reversible switching of in-plane polarized ferroelectric domains in BaTiO<sub>3</sub>(001) with very low energy electrons

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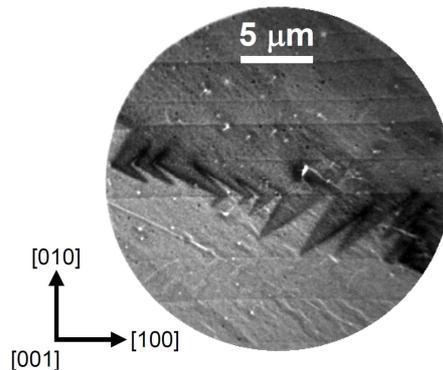
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Polarization switching by an applied field depends on the initial domain ordering, defect concentration, electrical boundary conditions and charge screening. In Merz's original theory of domain formation and switching, the application of an electric field gives rise to a transient current due to displacement of the polarization charge<sup>1</sup>. Therefore the injection of free charge might also switch the polarization. Electron beams can lead to specimen charging, setting up a potential difference and generating an internal electric field large enough to switch polarization<sup>2</sup> However, high energy e-beam switching is generally irreversible because of radiation damage.

We use a low energy electron microscope (LEEM) to simultaneously switch and observe in-plane polarized FE domains of a BaTiO<sub>3</sub> single crystal<sup>3</sup>. At very low electron kinetic energy (KE), called mirror electron microscopy (MEM), electrons are reflected without penetrating the sample surface<sup>4</sup>. At higher KE, the electrons penetrate the surface. In between, the reflectivity gives measure of the local work function or surface potential<sup>5</sup>.

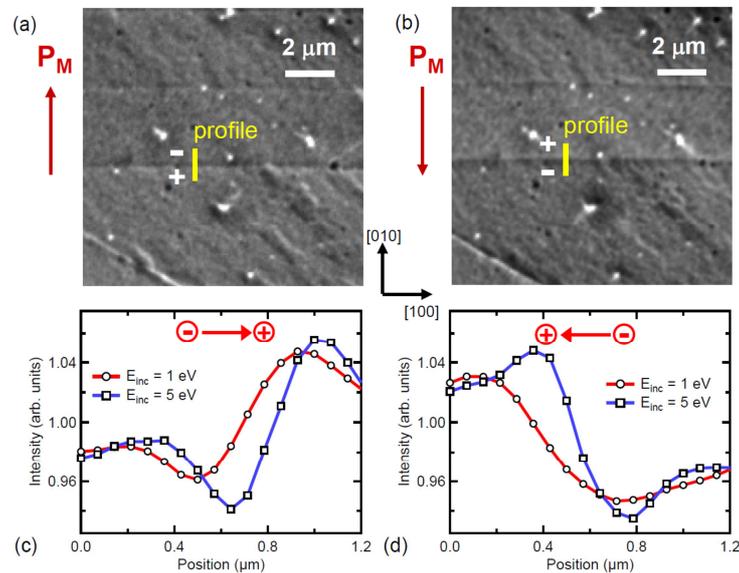


**Figure 1** Electron image of the surface 1.3 seconds after the start voltage has been switched from 1 to 5 eV.

Figure 1 shows the electron image of the surface during switching in a 30 μm field of view (FoV). Nine domain boundaries (thin horizontal lines) are visible. At  $t = 0$  the SV is increased from 1 to 5 eV and the polarization switches. The switching proceeds in a zig-zag around the direction [0-10]. It starts from discrete points at an upper domain wall and propagates as rather broad needles until reaching the opposite domain wall. Then, the needles expand until the polarization is switched in the entire domain. In a fourth step, switching then continues in the next domain but at an angle of 90° with respect to the previous one and so on, until the polarization in the entire FoV has been switched.

Figure 2c shows the normalized intensity profile across the domain wall before switching. The profile obtained across each domain wall is the same. The intensity asymmetry results from the electrons being deflected by the electric field due to the domain wall dipole along [0-10]. Figure 2d shows the intensity profiles across the same wall after polarization switching. The intensity asymmetry across the domain

wall is reversed, showing that the dipole is now along [010]. The profiles across successive domain walls have the same shape, showing that the overall macroscopic polarization is indeed along [010] before and [0-10] after switching.



**Figure 2** LEEM images of sample surface before (a) and after (b) switching, the field of view is  $30\ \mu\text{m}$ . Intensity profiles extracted from LEEM images acquired using 1 eV (round, red symbols) and 5 eV (square, black symbols) along [0-10] across a domain wall before (c) and after (d) switching. The dipole across the wall is shown by the plus/minus signs.

The switched state is therefore a steady state resulting from the balance between the equilibrium domain pattern and the injection of negative charge. The current density required to switch the in-plane polarization is  $0.26\ \text{mA}/\text{cm}^2$ . This scales to 1 pA for a  $10\ \mu\text{m}$  long domain of the same width ( $3\ \mu\text{m}$ ) as in our experiment. Tuning the electron energy allows to increase the switching speed by orders of magnitude. Low energy electrons switch the polarization without the collateral radiation damage which occurs with high energy electrons. Switching by charge injection adds a new dimension to the multifunctionality of ferroic oxides.

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## References

- <sup>1</sup>W.J. Merz, *Phys. Rev.* **95** (1954).
- <sup>2</sup>D.B. Li, D.R. Strachan, J.H. Ferris and D.A. Bonnell, *J. Mat. Res.* **21**, 935–940 (2006).
- <sup>3</sup>J. E. Rault, T. O. Menteş, A. Locatelli, N. Barrett *Scientific Reports* **4**, 6792 (2014)
- <sup>4</sup>N. Barrett et al., *J. Appl. Phys.* **113**, 187217 (2013).
- <sup>5</sup>J. Rault et al. *Phys. Rev. Lett.* **109**, 267601 (2012).