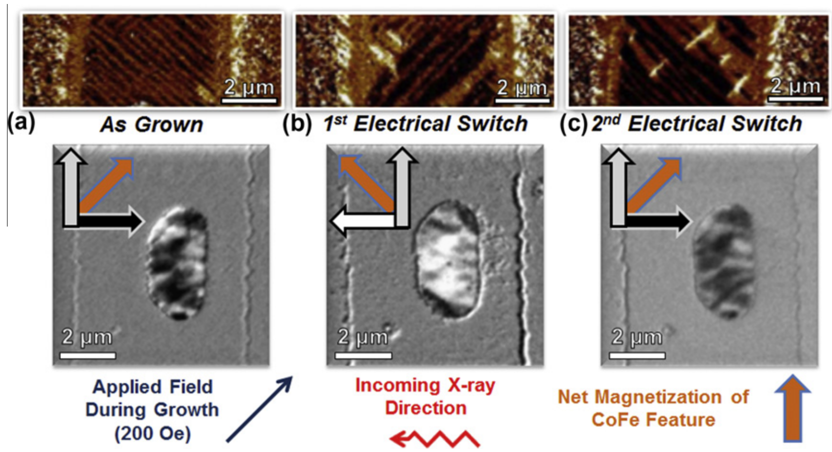

Fig. 15. Electric field control of ferromagnetic domain structures at room temperature. In-plane piezoresponse force microscopy images of ferroelectric domain structure (top) and corresponding photoemission electron microscopy image of ferromagnetic domain structure (bottom) of $Co_{0.9}Fe_{0.1}$ features on $BiFeO_3$ as a function of applied electric field in the (a) as-grown state, (b) after application of an electric field, and (c) following application of the opposite electric field. This represents the first demonstration of reversible electric field control of ferromagnetic domain structures at room temperature (adapted from Ref. [133]).

and first-principles, He et al. [134] studied Pd/Co multilayers deposited on (0001) surface of the antiferromagnet Cr_2O_3 and demonstrated reversible, room temperature isothermal switching of the exchange bias field from positive to negative values by reversing the electric field under a constant magnetic field. The study revealed that the (0001) surface of Cr_2O_3 can be controlled to exhibit a single spin type (Fig. 16a) that gives rise to a strong exchange bias. Magnetic hysteresis loops as a function of various magnetoelectric annealing processes at non-zero electric and magnetic fields reveal the development of exchange bias (Fig. 16b and c), and eventual application of alternating electric fields ($+2.6\ kV\ mm^{-1}$ and $-2\ kV\ mm^{-1}$) at a constant magnetic field (-154 mT) resulted in electric field control of the sign of exchange bias (Fig. 16d).

4.5. Electronic reconstruction and coupling at oxide interfaces

In contrast to the metallic ferromagnet–multiferroic heterostructure described above, one can envision a much broader range of interactions at all-oxide interfaces. The $La_{0.7}Sr_{0.3}MnO_3$–$BiFeO_3$ epitaxial heterostructure presents a good model system to explore such interactions. While exchange coupling at such interfaces typically focuses on the spin degrees of freedom and how they interact at the interface, in oxide systems, especially those with transition metal ions, the orbital and lattice degrees of freedom can be equally active. Recent studies focusing on 20–75 nm $BiFeO_3$/5 nm $La_{0.7}Sr_{0.3}MnO_3$/$SrTiO_3$ (001) heterostructures suggest that by changing the coupling from being direct in nature to indirect across an interface possessing a continuous chemical structure (i.e. Mn–O–Fe bonds that extend across the interface), complex interactions can occur (Fig. 17a) [135]. Through the use of detailed magnetometry, and synchrotron-based X-ray magnetic dichroism studies, the authors reported the formation of a novel ferromagnetic state in the antiferromagnet $BiFeO_3$ at the interface. Using X-ray magnetic circular dichroism at Mn and Fe $L_{2,3}$ edges (Fig. 17b and c), it was observed that the development of this ferromagnetic spin structure was strongly associated with the onset of a significant exchange bias. The results demonstrate that the magnetic state is directly related to an electronic orbital reconstruction at the interface, which is supported by linearly polarized X-ray absorption measurement at the oxygen K edge. In the end, it is such structures, however, that might represent the ultimate manifestation of new functionality if one can engineer and control these different degrees of freedom to some effect.

4.6. Multiferroic and magnetoelectric devices

Applications of coupled behavior can be broadly classified into the following three groups:

(i) High-frequency applications – the coupling between the spin and charge lattice (ferroelectromagnons), which typically occurs around 500–1000 GHz, is then modulated with an electric or magnetic field, akin to FMR devices. A related manifestation is a ferromagnet–multiferroic heterostructure in which resonance in the ferromagnetic layer is controlled by an electric field applied to the multiferroic.
(ii) A second class of applications relates to the control of spin transport with electric fields, in either a tunnel junction or spin valve geometry.
(iii) A third manifestation would be the use of such multiferroics in information storage elements, similar to a nonvolatile ferroelectric memory (FRAM), but one in which both the magnetic and ferroelectric state are used, either independently or in unision.

The potential applications of multiferroics and magnetoelectrics were reviewed by Scott [136]. It is important