an inverse relationship between domain size and the magnitude of the exchange bias measured (Fig. 14g), but that it was directly related to the density and total length of 109° domain walls present in the sample (Fig. 14h). In addition to identifying the importance of 109° domain walls in creating exchange bias (and in turn suggesting the relationship with enhanced magnetism in $BiFeO_3$ thin films), this report outlined the idea that two distinctly different types of exchange interactions are occurring in these exchange bias heterostructures. The first interaction was called an exchange bias interaction and takes place between pinned, uncompensated spin occurring at 109° domain walls in $BiFeO_3$ and spins in the $Co_{0.9}Fe_{0.1}$ layer. This interaction results in a shift of the magnetic hysteresis loop for the ferromagnetic layer. The second interaction has been called an exchange enhancement interaction and it arises from an interaction of the spins in the ferromagnet and the fully compensated (0 0 1) surface of the G-type antiferromagnetic surface of $BiFeO_3$. This interaction results in an enhancement of the coercive field of the ferromagnetic layer.

4.4. Room temperature electric field control of ferromagnetic domain structures

Utilizing these findings, researchers have moved to create the first room temperature devices designed to enable control of ferromagnetism with an electric field. Initial results point to the ability to utilize the above exchange enhancement interaction to deterministically change the direction of ferromagnetic domains by 90° upon application an applied electric field (Fig. 15) [133]. By creating very high quality $Co_{0.9}Fe_{0.1}/BiFeO_3/SrRuO_3/SrTiO_3$ (0 0 1) heterostructures, the authors were able to demonstrate the first example of a room temperature device structure that utilizes a multiferroic material to access new functionalities in materials. This work also outlined the complexity of such an undertaking. It has become apparent that in order to achieve significant advances with such systems one will need to understand and be able to control (at least at some level) the coupling between the two (in this case dissimilar) materials which requires that one have a perfunctory understanding of the various energies scales at play (including shape anisotropy effects, how processing effects the interfacial coupling strength, magnetostriction effects, and more). This initial work also demonstrated the importance of length scales in this work as the observed ferromagnetic domain structures were typically much more complex than the underlying ferroelectric domain structures, suggesting that diminished feature sizes could give rise to single magnetic domain configurations and therefore a more robust and simple device. In this spirit, current work is focused on making the coupling in such heterostructures more robust in hopes of extending this coupling to high temperatures and producing more deterministic control of electric field switching.

More recently, attention has turned back to one of the earliest studied magnetoelectric materials, Cr_2O_3, and a careful study has given rise to exciting work in electric field control of ferromagnetism. Using a combination of modern thin film growth techniques, magnetometry, spin-polarized photoemission spectroscopy, symmetry arguments,

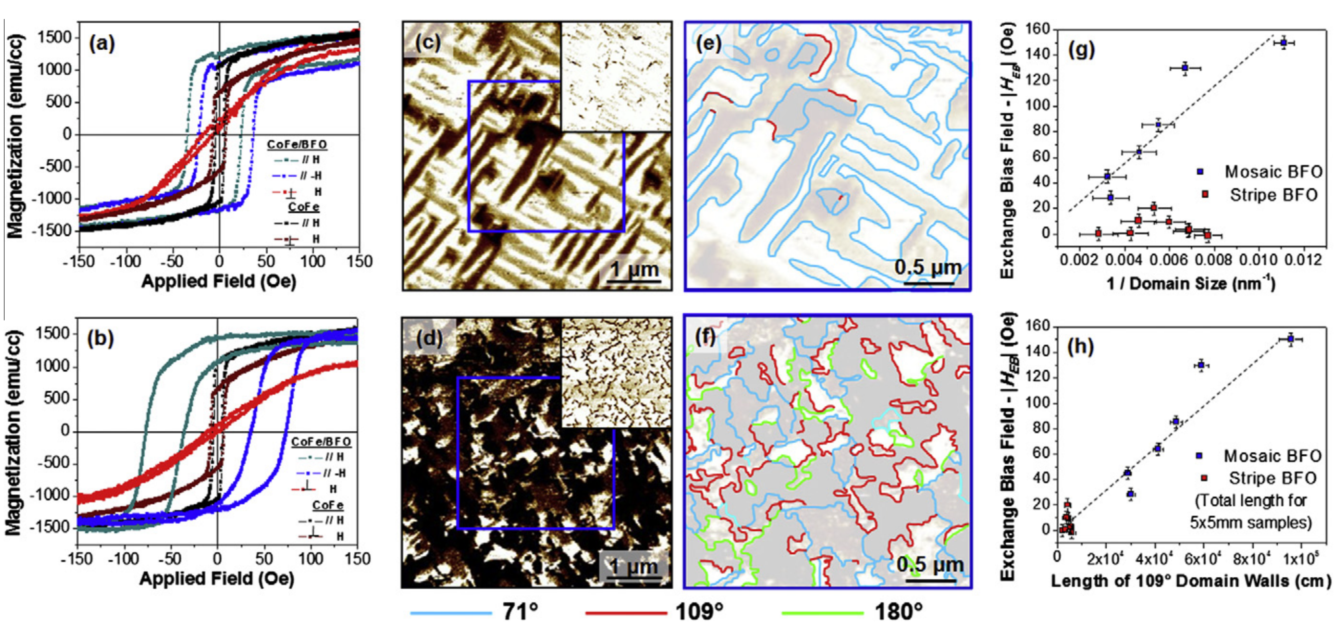

Fig. 14. Domain control of exchange bias. Room temperature magnetic properties for heterostructures exhibiting (a) exchange enhancement and (b) exchange bias properties. In-plane and out-of-plane (inset) PFM contrast for typical $BiFeO_3$ films that exhibit (c) exchange enhancement and (d) exchange bias, respectively. Detailed domain wall analysis for (e) stripe-like and (f) mosaic-like $BiFeO_3$ films. (g) Dependence of exchange bias field on domain size for $Co_{0.9}Fe_{0.1}/BiFeO_3$ heterostructures grown on mosaic-like (blue) and stripe-like (red) $BiFeO_3$ films. (h) Exchange bias field of the same samples here graphed as a function of the total length of 109° domain walls/sample surface area in 5 × 5 mm samples (adapted from Ref. [50]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)