A first attempt at this concept was done by Borisov et al. [130], who reported that they could affect changes on the exchange bias field in Cr_2O_3 (111)/$(Co/Pt)_3$ heterostructures by using the magnetoelectric nature of the substrate (Cr_2O_3) and a series of different cooling treatments with applied electric and magnetic fields. A unique aspect of this work was the ability to change the sign of the exchange bias with different field cooling treatments. Dynamic switching of the exchange bias field with an applied electric field, however, remained elusive until a report by Laukhin et al. [131] focusing on $YMnO_3$ at 2 K. Utilizing heterostructures of permalloy and (0001) $YMnO_3$ films, the authors demonstrated that after cooling samples from 300 to 2 K in an applied field of 3 kOe and at various applied electric field biases, significant changes in the magnitude of magnetization was observed (Fig. 13a). Subsequent cycling of the voltage at low temperatures resulted in reversal of the magnetization direction in the heterostructure (Fig. 13b).

In the last few years, significant advancement in the understanding of the interactions present in such heterostructures has occurred. Initial reports noted an inverse relationship between domain size in $BiFeO_3$ film and the exchange bias measured in $CoFeB/BiFeO_3$ heterostructures [132]. This initial report offered little detail on how the domain structures were controlled and the nature of the domain walls present in the films. A study that soon followed found a correlation not only to the density of domain walls, but also to the density of certain types of domain walls [50]. What was observed was the presence of two distinctly different types of magnetic properties for $Co_{0.9}Fe_{0.1}/BiFeO_3$ heterostructures (Fig. 14a and b). Through careful control of the growth process – specifically controlling the growth rate of the $BiFeO_3$ films – the authors were able to create two starkly different types of domains structures: so-called stripe-like (Fig. 14c) and mosaic-like (Fig. 14d) domain structures. These different structures were found to possess vastly different fractions of the different domain walls that can exist in $BiFeO_3$ (Fig. 14e and f). It was observed that not only was there

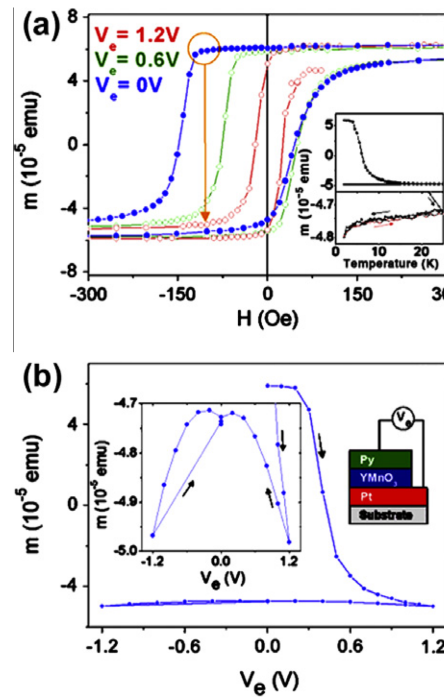

Fig. 13. Low temperature electric field control of ferromagnetism. (a) Magnetization loops for permalloy/$YMnO_3$/Pt, measured at 2 K, after cooling the sample from 300 K in a 3 kOe field, under various biasing-voltage (V_e) values. The circle and arrow illustrate schematically the expected change of magnetization when biasing the sample by an electric field. The inset shows the temperature dependence of the magnetization at $H = 100$ Oe and $V_e = 0$ when heating the sample from 2 K to 25 K (top panel) and subsequent cooling–heating–cooling cycles between 25 K to 2 K (bottom panel). (b) Dependence of the magnetization on V_e measured at 2 K in $H = 100$ Oe field after cooling the sample from 300 K in 3 kOe field. The inset shows (left) a zoom of the −1.2 to 1.2 V portions of the bias excursion and (right) a sketch of the sample structure and electric biasing (adapted from Ref. [131]).

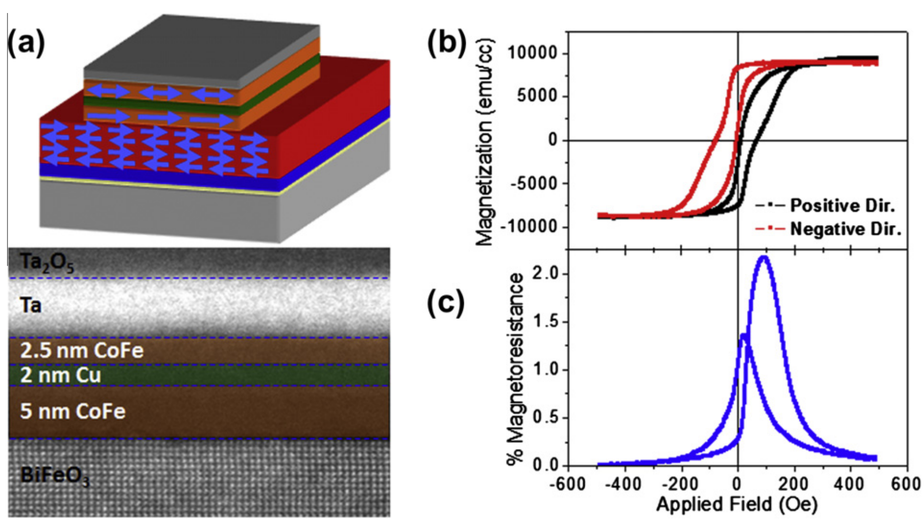

Fig. 12. Spin valve structures based on $Co_{0.9}Fe_{0.1}/Cu/Co_{0.9}Fe_{0.1}/BiFeO_3$ heterostructures. (a) Schematic illustration and scanning transmission electron microscopy image of the actual device. (b) Magnetic hysteresis loops of spin valve structures. (c) Current-in-plane magnetoresistance measurements (adapted from Ref. [129]).