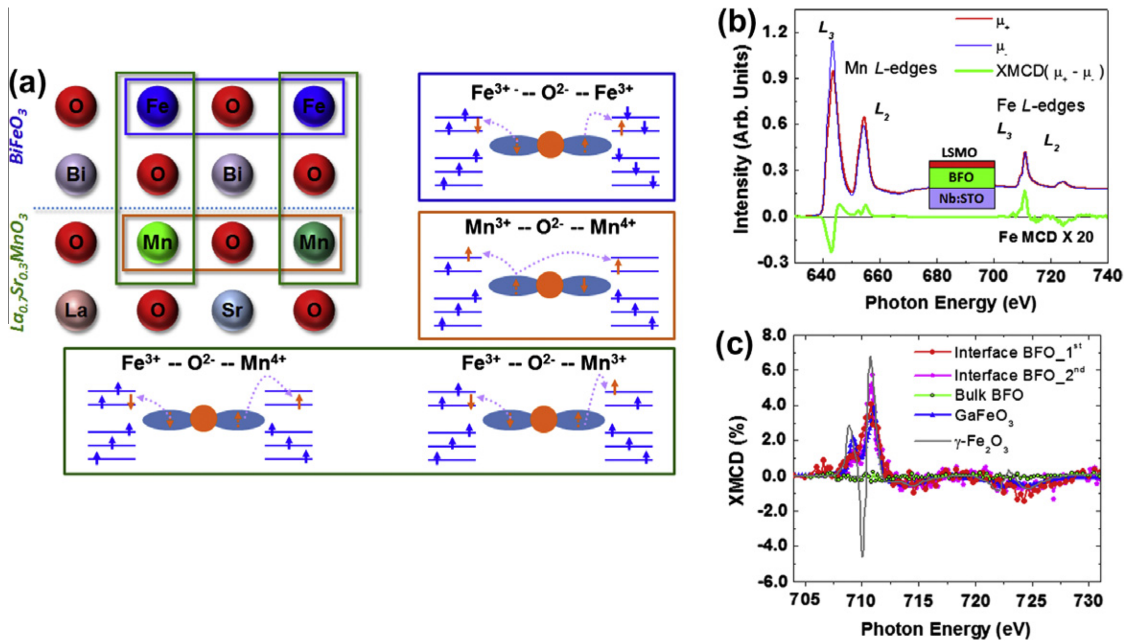

Fig. 17. Magnetic coupling across all-oxide interfaces. (a) Schematic illustrating the complexity of all-oxide interfaces in multiferroic-based heterostructures. In all-oxide heterostructures there is competition between different types of indirect coupling: antiferromagnetic superexchange in $BiFeO_3$ (blue box), ferromagnetic double exchange in $La_{0.7}Sr_{0.3}MnO_3$ (orange box), and cross-interface coupling between Fe^{3+}–Mn^{3+} and Fe^{3+}–Mn^{4+} (green box). (b) X-ray absorption spectroscopy and magnetic circular dichroism (XMCD) spectra of Mn and Fe $L_{2,3}$ edges taken at 10 K. The XMCD signal of Fe is multiplied by a factor of 20. (c) Comparison of the interface Fe XMCD with bulk $BiFeO_3$, $GaFeO_3$ and γ-Fe_2O_3. The spectra of $GaFeO_3$ and γ-Fe_2O_3 are normalized to the same scale as that of interface $BiFeO_3$ state (adapted from Ref. [135]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

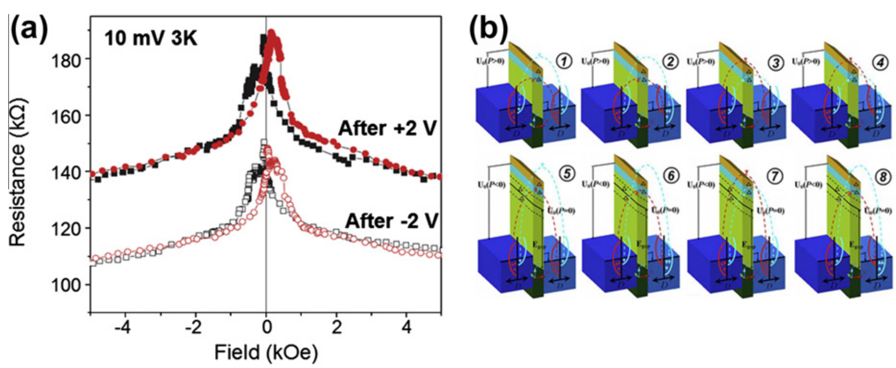

Fig. 18. Multiferroic-based devices. (a) Tunnel magnetoresistance curves at 4 K at $V_{dc} = 10$ mV in an $La_{2/3}Sr_{1/3}MnO_3/La_{0.1}Bi_{0.9}MnO_3$ (2 nm)/Au junction, after applying a voltage of +2 V (filled symbols) and −2 V (open symbols). The combination of the electroresistance effect and the tunnel magnetoresistance produces a four-resistance-state system (adapted from Ref. [139]). (b) The sketch of the potential profiles for each of the eight configurations of a multiferroic-based tunnel junction. Here, the red and light blue arrows denote majority- and minority-spin carriers, and D displays the electronic density of states (adapted from Ref. [140]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

on possible applications is still in its infancy and the field would benefit significantly with strong device-related research.

Over the last few years, a number of new devices based on multiferroic materials and heterostructures have been demonstrated and proposed. In early 2007, Ju et al. [138] presented a theoretical investigation of an electrically controllable spin filter based on a multiferroic tunnel junction that could be switched between multiple resistance states. Soon after this, Gajek et al. [139] demonstrated the production of four logic states based on ultrathin multiferroic films used as barriers in spin-filter-type tunnel junctions. The junctions were made of $La_{0.1}Bi_{0.9}MnO_3$, which was proven to be both ferroelectric and magnetic down to film thickness of only 2 nm and the devices exploited the magnetic and ferroelectric degrees of freedom of that layer. The ferromagnetism permitted read operations reminiscent of MRAM and the electrical switching evoked FeRAM write operations without the need for destructive ferroelectric readout. The results (Fig. 18a) suggest that it is possible