Raman measurements [106]. Finally there are reports of a concomitant structural and ferroelectric transformation at ~85 °C. Based on the study of phonon excitations, as investigated by using Raman scattering as a function of temperature, the low-energy phonon modes related to the FeO_6 octahedron tilting show anomalous behaviors upon cooling through this temperature – including an increase of intensity by one order of magnitude and the appearance of a dozen new modes [107]. Other recent reports have investigated the emergence of an enhanced spontaneous magnetization in the so-called mixed phase structures [108] and that the magnetic Néel temperature of the strained $BiFeO_3$ is suppressed to around room temperature and that the ferroelectric state undergoes a first-order transition to another ferroelectric state simultaneously with the magnetic transition [109]. This has strong implications for room temperature magnetoelectric applications. Finally, other reports have investigated the driving force for the formation of these so-called mixed-phase structures and have revealed that the complex mixed-phase structure likely occurs as the consequence of a strain-induced spinodal instability [110]. Truly this is an exciting and fast-moving field of study today. Such electric-field- and temperature-induced changes of the phase admixture is also reminiscent of the CMR manganites or the relaxor ferroelectrics and is accompanied by large piezoelectric strains, but there appears to be much more to these mixed-phase structures that are a worthy field of further study.

4. Engineering new functionalities with multiferroics

One of the major questions in the study of multiferroics today is how and when will multiferroics make their way into a room-temperature device and what will these devices look like? In early 2005, a number of so-called magnetoelectronic devices based on magnetoelectric materials were proposed [111]. The idea was a simple one, namely to use the net magnetic moment created by an electric field in a magnetoelectric thin film to change the magnetization of a neighboring ferromagnetic layer through exchange coupling. The authors went on to propose a number of electrically tunable giant magnetoresistance (GMR) spin valves (Fig. 10a) and tunnel magnetoresistance (TMR) (Fig. 10b) elements that could be made possible if such structures could be achieved. One additional field that could be greatly affected by this research is the burgeoning field of spintronics. Spin-based electronics, or spintronics, has already found successful application in magnetic read-heads and sensors that take advantage of GMR and TMR effects [112–114]. The future of spintronics is partially focused on evolving beyond passive magnetoelectronic components, like those used today, to devices which combine memory and logic functions in one [115]. There has been growing interest in studying a direct method for magnetization reversal involving spin transfer from a spin-polarized current injected into the device. This effect has been theoretically predicted by Slonczewski [116,117] and Berger [118], and has been experimentally confirmed by several groups [119–122].

4.1. Electric field vs. current control of magnetism

From these initial experiments and theoretical treatments, it was found that significant current densities (larger than 10^7 A cm^{-2}) were required for switching the orientation of a magnetic nanowire [120]. One option is to further

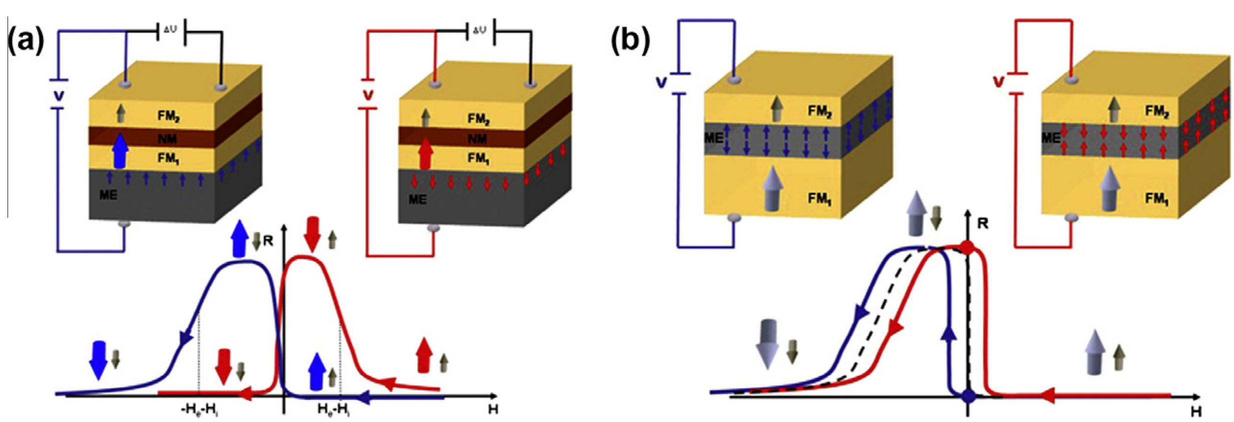

Fig. 10. Multiferroic-based magnetoelectronics. (a) Schematic of the magnetoresistance curve of a GMR device involving a magnetoelectric, multiferroic film as a pinning layer. Half-hysteresis curves are shown, after saturation at positive field values. The change of polarity of the magnetoelectric, multiferroic layer upon application of an electric field changes the direction of the net magnetization of the pinning field. The pinned layer (FM1) switches first at large positive field (red), or second at large negative field (blue). The low field magnetic configuration is therefore either antiparallel (red) or parallel (blue), controlled by the magnetoelectric, multiferroic film. (b) Schematic of the magnetoresistance curve of a TMR device involving a magnetoelectric, multiferroic film as a tunnel barrier. Half-hysteresis curves are shown, after saturation at positive field values. The arrows denote the magnetization directions, with the bottom layer FM1 being harder (or pinned) than the top one FM2. The dashed curve is the expected TMR behavior. The change of voltage polarity changes the direction of the net magnetization of the magnetoelectric, multiferroic layer, adding an exchange bias magnetic field to the resistance curve. The two colors indicate shifting of half-hysteresis curves towards positive or negative fields, depending on the polarity of the applied voltage. At zero magnetic field, the change of voltage polarity changes the resistance value of the device (dashed) (adapted from Ref. [111]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)