scale down materials so that spin-transfer becomes a more attractive alternative to stray magnetic field techniques. In the end, integration of such effects into actual devices has been limited because there are a number of technical difficulties involved in reliably making such small structures, applying such large currents – while avoiding heating of the samples, and based on the fact that the intrinsic sample resistance (on the order of a few ohms) further limits the practical use for GMR devices. Similar issues are found in TMR devices, which are hindered by fact that a large current density must pass through a very thin insulator and the few reports on TMR systems to date have been inconclusive [123,124].

4.2. Electric field control of ferromagnetism

The overall motivating question for this section is a simple one: can we deterministically control ferromagnetism at room temperature with an electric field? One possible solution to this question is to utilize heterostructures of existing multiferroic materials, such as $BiFeO_3$, to create new pathways to functionalities not presented in nature. Such a concept is illustrated in Fig. 11. The idea is to take advantage of two different types of coupling in materials – intrinsic magnetoelectric coupling like that in multiferroic materials such as $BiFeO_3$, which will allow for electrical control of antiferromagnetism, and the extrinsic exchange coupling between ferromagnetic and antiferromagnetic materials – to create new functionalities in materials (Fig. 11a). By utilizing these different types of coupling we can then effectively couple ferroelectric and ferromagnetic order at room temperature and create an alternative pathway to electrical control of ferromagnetism (Fig. 11b). But what exactly are the opportunities for using multiferroics to gain electrical control over interactions like exchange bias anisotropy? Until recently the materials and the understanding of the appropriate materials did not exist to make this a plausible undertaking. Let us investigate, in detail, the work done in this field of study.

4.3. Exchange bias with multiferroic antiferromagnets

In the time since the proposal of these magnetoelectronics, studies have been done on a number of multiferroic materials. Among the earliest work was a study of heterostructures of the soft ferromagnet permalloy on $YMnO_3$ [125]. This report found that, indeed, the multiferroic layer could be used as an antiferromagnetic pinning layer that gives rise to exchange bias and enhanced coercivity, but suggested that $YMnO_3$ would likely be an inappropriate choice for continued study as these values varied greatly with crystal orientation and rendered actual device generation unlikely. Soon after this initial result, Marti et al. [126] reported the observation of exchange bias in all-oxide heterostructure of the ferromagnet $SrRuO_3$ and the antiferromagnetic, multiferroic $YMnO_3$. In both of these studies, the exchange bias existed only at very low temperatures due to the low magnetic ordering temperature of the $YMnO_3$. Around the same time, the first studies using $BiFeO_3$ as the multiferroic, antiferromagnetic layer were appearing with hopes that these intriguing properties could be extended to high temperatures. Dho et al. [127] showed the existence of exchange bias in spin-valve structures based on permalloy and $BiFeO_3$ at room temperature and Béa et al. [128] extended this idea to demonstrate how $BiFeO_3$ films could be used in first-generation spintronics devices. This work included the use of ultrathin $BiFeO_3$ tunnel barriers in magnetic tunnel junctions with $La_{0.7}Sr_{0.3}MnO_3$ and Co electrodes where positive TMR up to ~30% was observed at 3 K and also demonstrated that room temperature exchange bias could be generated using $CoFeB/BiFeO_3$ heterostructures. Finally, Martin et al. [129] reported the growth and characterization of exchange bias and spin valve heterostructures based on $Co_{0.9}Fe_{0.1}/BiFeO_3$ heterostructures on Si substrates. In this work large negative exchange bias values (typically 150–200 Oe in magnitude) were observed along with the absence of a training effect – or a systematic decrease in the magnitude of the exchange bias with repeated magnetic cycling (confirming the results of Bea et al. [128]) – even with over 14,000 magnetization reversal cycles. This work also demonstrated room temperature magnetoresistance of ~2.25% for spin valve structures of 2.5 nm $Co_{0.9}Fe_{0.1}$/2 nm Cu/5 nm $Co_{0.9}Fe_{0.1}$/100 nm $BiFeO_3$ (Fig. 12). What these initial studies established was that exchange bias with antiferromagnetic multiferroics was possible in a static manner, but these studies had not yet demonstrated dynamic control of exchange coupling in these systems.

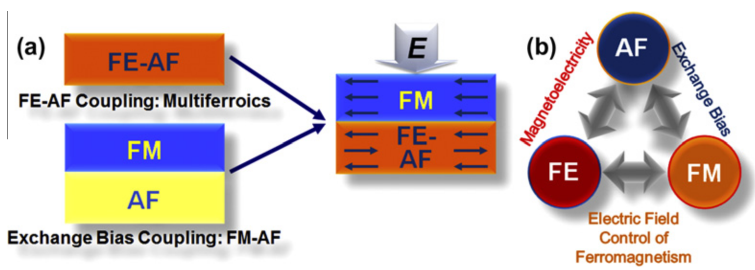

Fig. 11. Schematics illustrating the design algorithm for gaining electrical control of ferromagnetism. (a) By combining multiferroics together with traditional ferromagnets, we can create heterostructures that might have new functionalities. (b) These structures rely on two types of coupling – magnetoelectric and exchange bias – to gain electrical control of ferromagnetism (adapted from Ref. [47]).