to encode quaternary information by both ferromagnetic and ferroelectric order parameters, and to read it non-destructively by a resistance measurement. This work represented the starting point for future studies on the interplay between ferroelectricity and spin-dependent tunneling using multiferroic barrier layers and in a wider perspective, suggested a new pathway toward novel reconfigurable logic spintronic architectures.

Yang et al. [140] proposed that eight different logic states could be achieved by combining spin-filter effects and the screening of polarization charges between two electrodes through a multiferroic tunnel barrier (Fig. 18b). In this work, the conductance ratio was found to be dependent on the magnitude of the ferroelectric polarization, exchange splitting, barrier width, and bias voltage. In 2009, Jia and Berakdar [141] proposed a modified spin-field-effect transistor fabricated in a two-dimensional electron gas (2DEG) formed at the surface of multiferroic oxides with a transverse helical magnetic order. The local magnetic moments in the oxide are said to induce a resonant momentum-dependent effective spin–orbit interaction acting on the 2DEG and thus the carrier spin precession is dependent on the magnetic spin helicity that can be electrically controlled in the multiferroic. Such a device could, in turn, be used as a nanometer-scale, decoherence-suppressed spin field-effect transistor and as a nanometer flash-memory device.

5. Future directions and conclusions

We hope that this review has captured some of the exciting new developments in the field of complex oxides, multiferroics and magnetoelectrics, especially from a thin film perspective. New developments are occurring at a rapid pace, throwing further light onto the complexities inherent to these materials. The dramatic progress in thin film heterostructure and nanostructure growth has been a key enabler fueling these discoveries. Since the advent of the superconducting cuprates, complex oxides have emerged as wonderful tools to probe the role of complexity induced by the interactions between the spin, charge, orbital, and lattice degrees of freedom that are pervasive in transition metal oxides. Soon after the cuprates, work on ferroelectric oxides emerged, followed by the colossal magnetoresistance effect in the doped manganites. Transitioning fundamental materials discoveries into real products involves many steps, including pathways to design and create device structures that can then be inserted into systems architectures and the understanding of how these new technologies impact existing markets. A continued limitation of investment into manufacturing may remain a concern for the oxide field for years to come.

In turn, one of the biggest challenges facing the field of multiferroics today is the need for room temperature function. Thus, it is essential that the field works to include both thin film heterostructure and bulk synthesis methods and broadens the search for new candidate multiferroics. The interplay between ab initio, density functional theoretical approaches and controlled synthetic approaches (be it single crystal growth or MBE-like heteroepitaxial thin film growth) is critical. Thin film heterostructures further provide an additional degree of freedom through the mismatch strain; here again, the intimate interplay between theoretical predictions [142] and film growth is imperative. If deterministic control and manipulation of ferromagnetism are desired, then interactions across heterointerfaces will become important as we attempt to design systems capable of these functionalities. Domains, domain walls, and defects will undoubtedly play a critical role in unraveling the coupling phenomena. Further, in such heterostructure-based coupling, differences between interactions with classical itinerant ferromagnets and double exchange ferromagnets (such as the manganite) need to be explored in depth as well. In thin films, heteroepitaxial constraints (such as strain, clamping, and possibly surface termination) are important variables. This is truly a challenge for interdisciplinary condensed matter research.

At a more fundamental science level, complex oxides provide a versatile class of materials for the exploration of coupling and interplay amongst charge, spin, orbital, and lattice degrees of freedom. These interactions lead to novel (and exotic) ground states for the system that can be manipulated by external perturbations. The ability to engineer artificial heterostructures down to the unit cell level through MBE and related techniques provides unprecedented access to quantum phenomena in oxides. At the crystal chemistry level, the interplay between cationic sizes and oxygen coordination chemistry leads to tilts and rotations of the oxygen octahedra. Control and manipulation of these degrees of freedom, especially at heterointerfaces where symmetry breaking is easily achieved, has captured the interest of researchers in the field and is likely to be an active area of research. The orbital degree of freedom, however, is still a relatively less explored aspect. An ideal manifestation would be room temperature electric field control of the orbital order in perovskites such as the manganites. Another area that presents both scientific challenges and opportunities relates to the properties of domain walls, especially conduction at domain walls in otherwise insulating ferroelectrics. A critical question is this: can we possibly create an insulator–metal transition at the wall, i.e. can the walls exhibit metallic conduction? If this is possible through careful control of the electronic structure at the wall as well as through external constraints (epitaxy, defect chemistry, etc.), this is likely to be a major breakthrough, since the domain walls in ferroelectrics are truly "nano-objects" (width of the order of a few nm) and they can be manipulated (written, erased and relocated) using electric fields.

In the end, as we look back at the development of complex oxide research we see that a series of exciting discoveries, from high T_C superconductivity to multiferroism, has propelled the greater field of oxides to the forefront of condensed matter physics. The diverse functionality of