Oxide Spintronics

edited by Tamalika Banerjee

Oxide materials have been used in mainstream semiconductor technology for several decades and served as important components, such as gate insulators or capacitors, in integrated circuits. However, in recent years, this material class has emerged in its own right as a potential contender for alternative technologies, generally designated as Beyond Moore.

The 2004 discovery by Ohtomo and Hwang was a global trendsetter in this context and involved observing a two-dimensional, high-mobility electron gas at the heterointerface between two insulating oxides, LaAlO3 and SrTiO3. This investigation was supported by the rise of nascent deposition and growth-monitoring techniques, which was an important direction in materials science research. The quest to understand the origin of this unparalleled physical property and find other emergent properties has been an active field of research in condensed matter physics that has united researchers with expertise in diverse fields such as thin-film growth, defect control, advanced microscopy, semiconductor technology, computation, magnetism and electricity, spintronics, nanoscience, and nanotechnology. This book showcases the important scientific advances that have been made in this direction with new oxide materials interfaces or techniques.

The book discusses complex oxide materials, mainly perovskites comprising two different cations. It reviews new structural magnetic or electronic phases created by elastic strain developed at heterointerfaces that can be designed by choosing different cations. Using quantum mechanical calculations within density functional theory, it captures advances that have been made in the theoretical understanding of material properties on the atomic scale. It is an important handbook for oxide spintronics researchers and graduates and covers in great depth the recent research contributions in the field of complex oxides.

Tamalika Banerjee is professor at the Zernike Institute for Advanced Materials (ZIAM), University of Groningen, the Netherlands, since 2013. She studied physics at Presidency University, Kolkata, India, and received her PhD from the University of Madras, India. She subsequently joined the Francis Bitter Magnet Laboratory, MIT, USA, as a visiting scientist, and then the Tata Institute of Fundamental Research, Mumbai, India, as a postdoctoral fellow. In 2002, she was a postdoctoral researcher at MESA+ Institute for Nanotechnology, University of Twente, the Netherlands, where she developed a new technique to study spintronic devices on the nanometer scale that has been applied to different materials systems and their devices. In 2009, she joined ZIAM as a Rosalind Franklin fellow, tenure track, and has her own research group focusing on new approaches of fabricating spintronic materials and devices for Beyond-Moore technology and the Internet of things. Prof. Banerjee has published over 60 refereed articles and participated in 47 invited talks on spintronics. Her research focuses on spintronic materials and devices for Beyond-Moore applications such as spin logic, reconfigurable spintronics architecture, and bioinspired computing.
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Oxide materials have been used in mainstream semiconductor technology for several decades, serving as important components such as gate insulators or capacitors in integrated circuits. However, in recent years this material class has emerged in its own right as a potential contender for alternative technologies, generally designated as ‘beyond Moore’. The 2004 discovery by Ohtomo and Hwang was a global trendsetter in this context—the observation of a two-dimensional high-mobility electron gas at the heterointerface between two insulating oxides (LaAlO$_3$ and SrTiO$_3$), supported by the rise of nascent deposition and growth monitoring techniques, was an important direction in materials science research. The quest to understand the origin of this unparalleled physical property and for finding other emergent properties has been an active field of research in condensed matter, uniting researchers with diverse expertise from thin film growth, defect control, advanced microscopy, semiconductor technology, computational experts, magnetism and electricity, spintronics, nanoscience, and nanotechnology. This book is an attempt to showcase the important scientific advances that have been made in this direction with new oxide materials interfaces or with new techniques.

Complex oxide materials discussed in this book are commonly perovskites with the general formula ABO$_3$, where A and B represent the two different cations. Heterointerfaces designed by choosing different cations causes elastic strain at the interface as discussed in Chapter 1 and leads to new structural magnetic or electronic phases. This is triggered not only by the mismatch in the in-plane lattice parameter but also by a mismatch of the oxygen octahedral rotation and of the polar interface charge. This chapter considers coherently strained films of SrRuO$_3$, manganites, and nickelates and shows how elastic strain can be used as a design tool for tuning their electronic and magnetic properties.

The significance of interface engineering at the interface between the half-metal La$_{0.67}$Sr$_{0.33}$MnO$_3$ on SrTiO$_3$ is discussed extensively in Chapter 2. The formation of a magnetic dead layer at this interface
has been reported earlier in several studies and is deleterious for device applications. The authors have systematically performed compositional engineering at the interface to investigate the different mechanisms that are responsible for its occurrence. They conclude that the tunability of the oxygen octahedral rotation is an important parameter that influences the magnetic dead layer at such interfaces.

Electronic transport (both charge and spin) are strongly influenced by defects, orbital reconfiguration, interdiffusion, and local inhomogeneities at the interface and govern device performance. The field of complex oxide devices gained momentum in recent years by the inclusion of a unique technique that has the ability to probe, at the nanometer scale, and with a high lateral resolution sub-surface features and buried interfaces that are fundamental to the analysis of electronic transport at (non-)engineered interfaces. Chapter 3 discusses one such probe, known as the ballistic electron emission microscope, and demonstrates its first application to the study of complex oxide heterointerfaces on SrTiO$_3$. Using a current-perpendicular-to-plane device geometry, transport parameters such as the mean free path across and close to the magnetic phase transition in ferromagnetic LaSrMnO$_3$ and SrRuO$_3$ are determined.

The advances that have been made in the theoretical understanding of material properties on the atomic scale have been captured in Chapter 4 by means of quantum mechanical calculations within density functional theory (DFT). Several important technological material interfaces are considered such as SrRuO$_3$/SrTiO$_3$, YMnO$_3$/LaMnO$_3$ and Fe/BaTiO$_3$ and experimental findings related to the unusual magnetic and electronic transport are analyzed using DFT-based ab initio electronic structure calculations.

Chapter 5 introduces ferroic and multiferroic materials, in particular, BiFeO$_3$. Displaying magnetism and ferroelectricity in the same material phase, such materials are of tremendous technological importance since they allow control of magnetization (polarization) of devices with an electric (magnetic) field. Demonstrations of domain wall conductivity in thin films of such multiferroics and others have ignited intense research with these materials. The broadly accepted phenomena responsible for the conductivity at the domain walls are the reduction of the band gap at the walls and the electrostatic potential changes due to structural variations. The
chapter also discusses the different mechanisms such as octahedral rotations, increased carrier density, and role of oxygen vacancies that are responsible for the observed conductivity at the domain wall in these material systems.

Spintronic functionalities such as magnetoresistance, anisotropic magnetoresistance, and giant or tunnel magnetoresistances are interesting to investigate in heterostructures based on multiferroics and have been discussed in Chapter 6. After describing the most commonly used phenomena in spintronics, the chapter discusses these effects as exhibited in different types of multiferroic tunnel junctions using the external control knobs of magnetic and electric field and suggests research directions for electrical control of spintronic functionalities.

Electronic and orbital reconstructions at oxide heterointerfaces provide an opportunity to trigger magnetic interactions that can be tailored by strain engineering. Chapter 7 reviews such interfacially induced magnetism in different spintronic devices. Spin reconstruction at the interfaces drives them into a novel magnetic state that acts as a spin filter and can lead to an increase in the tunneling magnetoresistance in tunnel junction devices. The chapter discusses different combinations of cuprate/manganite interfaces and observes a magnetoelectric effect that can be used to electrically switch the magnetization of the magnetic layers without an applied magnetic field. This alternative route of electric field control of magnetism is a functionality that is being actively pursued for the development of low-dissipation spintronics.

Finally, Chapter 8 reviews recent advances that have been made in the exploration of the most archetypal two-dimensional electron system (2DES) of LaAlO$_3$/SrTiO$_3$. This review focuses on the electronic properties of 2DESs such as 2D superconductivity and Rashba spin–orbit coupling at such heterointerfaces. The combined coexistence of 2D-superconductivity with a sizable spin–orbit coupling of the Rashba type, which is tunable by large electric fields, opens up new avenues in oxide electronics and oxide spintronics that utilize such engineered oxide heterointerfaces. The chapter also provides an outlook for future developments in the study of 2D superconductivity and spin–orbit fields using such oxide heterointerfaces.

In summary, the book provides a modest perspective on the vast scientific advances realized using complex oxide heterointerfaces
and demonstrates their recognition as a potential material class for defining new technologies. To drive complex oxides as the next frontier materials in electronics, combined efforts in different directions are needed such as (i) the availability of high-quality large-area substrates for integration with the existing semiconductor technology as well as compatible fabrication methods, (ii) tools for quantifying defects and their control, (iii) analytical tools that are non-destructive and nanoprobe that can non-destructively probe the device interface, (iv) predictive modeling and design of heterostructures, thereby establishing a strong link between experiments and theory, and last but not least (v) continuation of our exploration of new emerging properties across such heterointerfaces that can host new topological phases such as skyrmions and design novel methods to probe them.

The authors of this book expect that this fascinating class of materials will soon define future technologies of its own and play a prominent role in current research and technological programs involving quantum and neuromorphic computing. They also believe that the book will be of interest to researchers, engineers, and technologists working in academia or in industries and will propel many scientific explorations utilizing together the complex oxide materials and their devices. I would like to acknowledge the authors for their extensive contributions and patience and the Jenny Stanford Publishing team for their interest and support in this field.

Tamalika Banerjee
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