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Introduction

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Research in spintronics exploits both charge and spin degrees of freedom of electrons to provide additional advantages to conventional charge-based microelectronic devices, such as non-volatility and reduced power consumption. The discovery of giant magnetoresistance (GMR) in 1988 kick-started the field of spintronics, a result for which Albert Fert and Peter Grünberg were awarded the Nobel Prize in Physics. After that, many phenomena have been studied, including the magnetotransport properties of nanostructured magnetic systems controlled by electrical current, the interplay of charge and spin transport, and spin dynamics in magnetic and nonmagnetic systems. For large-scale commercial applications, the GMR-based spin valves and magnetic tunnel junctions (MTJs) have been extensively used as magnetic field sensors in the read heads of hard disk drives, position or proximity sensors in automated industrial tools, and data storage like magnetic random access memory (MRAM). However, the magnetization manipulation in MRAM based on GMR/tunneling magnetoresistance (TMR) effects by applying an external magnetic field still restricts practical applications.

Since the proposal of spin-transfer torque (STT) by Slonczewski and Berger in 1996, which tunes the transfer of spin angular momentum between two magnetic layers with noncollinear magnetization, electrical approaches have become a direct and effective method to switch magnetization and act as the main stream for manipulating the bit states in MRAM (STT-MRAM). STT has been widely studied in magnetic sandwich structures, including spin valve and MTJ, where a spacer layer (nonmagnetic metal and oxide tunneling barriers, respectively) is sandwiched by two ferromagnetic electrodes. However, the requirement to write information by passing a high current density directly through a spacer layer impacts upon its stability. Moreover, only minority electrons at fermi levels are involved in the magnetization switching from a parallel state to an anti-parallel state, which also decreases the energy efficiency.

Alternatively, the current-induced spin-orbit torque (SOT), originating from the strong spin-orbit coupling (SOC), can transfer charge current into spin current in nonmagnetic semiconductors, heavy metals or topological materials, which results in sustained magnetic oscillations or switching of magnetic structures. Spintronic devices based on SOT have the advantages of non-volatility, fast speed, large endurance, and low power consumption, which are promising candidates used in energy efficient data storage and information processing,

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as well as unconventional computing schemes like neuromorphic and probabilistic computing. Current-assisted magnetization switching by SOT was first observed in dilute magnetic semiconductor (Ga,Mn)As in 2009. Thereafter, manipulation of magnetization via SOT has been extended to ferromagnetic metal multilayers. Recent developments contain the generation and interconversion of charge and spin based on non-equilibrium spin-orbit interaction effects, such as spin Hall and Rashba-Edestein effects. Importantly, SOT has been demonstrated to manipulate the magnetism of most magnetic materials, including ferromagnetic (ferrimagnetic or antiferromagnetic) metals, semiconductors and insulators. In particular, taking advantage of a lateral wedge oxide, a ferroelectric substrate, interlayer exchange coupling by a ferromagnetic layer, or antiferromagnetic layer, current-induced magnetization switching has been achieved without an external magnetic field. Furthermore, SOT can also be used to drive non-uniform magnetization states, including domain walls and skyrmions. However, it should be noted that numerous problems remain to be overcome in SOT spintronics, such as the three-terminal configuration, new materials and mechanisms for high efficient SOT switching.

In addition, using an electrical field instead of an electrical current to manipulate the electronic properties of magnetic materials is promising for realizing ultralow-energy-consuming memory devices due to the suppression of Joule heating, especially when the devices are scaled down to the nanoscale. Spintronic devices based on magnetoelectric and multiferroic materials (such as Cr_2O_3 and $BiFeO_3$) have become an active area and numerous emergent phenomena have been reported over the past decades. However, the practical application of voltage-controlled MRAM is still challenging. For example, the use of moderate voltages (of around 1 V) cannot obtain a sufficient voltage-induced change of magnetic anisotropy (VCMA) to produce magnetization switching, while guaranteeing the magnetic thermal stability of the devices in standby; moreover, the write time window in these devices is small and size-dependent, leading to reliability issues.

In this book, we describe recent progress on materials, devices, and applications of spintronics. Chapters 2 and 3 focus on GMR and TMR materials and devices for magnetic sensors. We introduce the underlying mechanisms of GMR and TMR effects and several industrial and biomedical applications of the GMR and TMR devices, as well as the GMR and TMR sensors' surface modifications, sensors combined with different auxiliary tools, such as microfluidic channels and magnetic flux concentrators (MFCs), and methods of improving the signal-to-noise ratio. Two recently crucial methods for electrical manipulation of magnetization switching (STT and SOT) are described in Chapters 4 and 5, which include the fundamental physics and the progress of STT and SOT on materials and devices, as well as the challenges and opportunities for future development of the related materials and devices. Then the STT- and SOT- based spintronic devices (like MTJ), used in spin oscillators and artificial neural networks, are discussed in detail in Chapters 6 and 7. More fundamental research about skyrmions is described in Chapter 8. In addition to conventional ferromagnetic materials, multiferroelectric materials, typical dilute magnetic semiconductor (Ga,Mn)As, and antiferromagnetic materials, which are viewed as the active materials for future spintronic devices, are also introduced. This book contains spintronic materials ranging from metals, semiconductors and insulators, with ferromagnetic, ferrimagnetic or antiferromagnetic behaviors. It also introduces representative spintronic devices, such as GMR spin valves, STT- and SOT-MTJs, which have great potential applications in information storage and processing. This book will provide a comprehensive and deep understanding of spintronics.