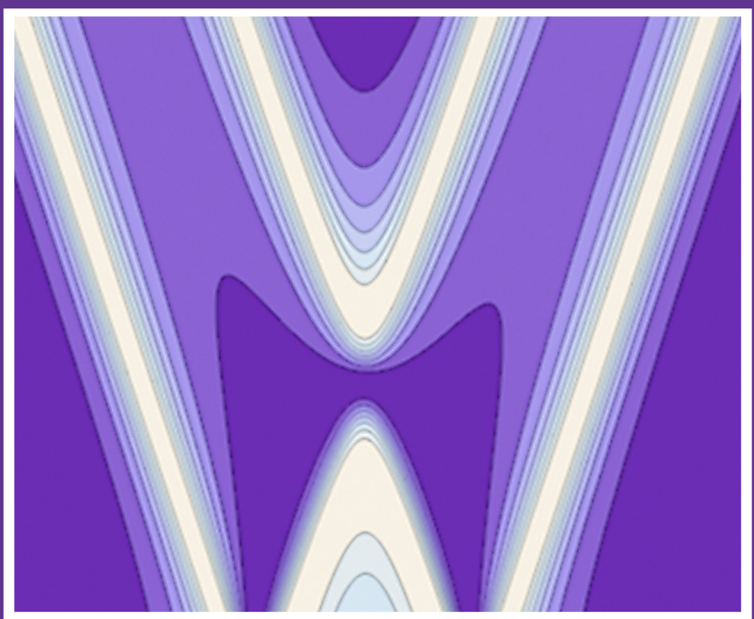
Spintronics in Nanoscale Devices

Edited by Eric R. Hedin | Yong S. Joe



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Preface

Classical electronics exploits the electron charge to designate binary information, whereas spintronics is an emerging field in which the *spin* of the electron is used for switching purposes and to communicate information. Spintronics is one of the most attractive investigation frontiers in condensed matter physics and material science due to its potential application in nanoscale devices. Future spintronic devices hold the promise of faster switching speeds, less electric power consumption, and higher density of circuit elements, made possible by lower heat production per switching element. The generation and detection of spin-polarized electric currents through nanoscale systems are important issues and primary goals for spintronics.

Quantum mechanically, the intrinsic spin of the electron comprises a two-state system. The energy splitting between these two spin states can be manipulated by magnetic fields via the Zeeman effect (with external fields or by means of the magnetic properties of materials), or by electric fields and spin–orbit coupling via the Rashba and Dresselhaus effects. In conjunction with quantum dots (QDs) formed lithographically as part of a semiconductor heterostructure, manipulation and detection of the electron spin has become an experimental reality. Adding to the potential usefulness of semiconductor nanodevices for spintronics applications is the observation that electron spin states show a relatively long decoherence time. This is due to the fact that the spin of the electron can only couple to the environment indirectly through the spin–orbit coupling, which renders the spin state relatively stable against random charge fluctuations. The electron spin is assumed to be conserved as it tunnels in and out of the QD, which is very important for spintronics and quantum computing applications. Since the electron spin automatically comprises a two-level system, it is a natural representation of a quantum bit, or "qubit." The qubit is the fundamental logic element in conceptions of future designs of quantum computers. Semiconductor QDs with two-level electron spin states show particular promise for quantum computing as a natural extension of the vast semiconductor-based computing infrastructure. More recently, much research into the experimental and theoretical studies have shown the possibility of preparing and manipulating spin-polarized electron states in graphene.

This book contains contributions from numerous experts who are active researchers in the developing field of spintronics, and focuses on solid-state semiconductor-based devices for producing and manipulating spin-polarized current. Chapter 1 reviews the study of spin-polarized transport in multiterminal, multi-QDs systems and employs numerical schemes to address several important aspects of spin-dependent transport, such as generating and detecting spin polarization, and the odd–even parity oscillations of spin polarization. The Rashba spin–orbit interaction with QDs located in the arm of an Aharonov–Bohm (AB) ring is analyzed for spin-dependent transport effects. Chapter 2 focuses on optical experiments related to probing and manipulating spins confined in individual coupled QDs. Relevant interactions such as exchange, tunneling, and Pauli blocking are briefly discussed and related to the experimental results. Using InAs samples with excitons in the strong confinement regime, discrete energy levels, analogous to the discrete orbital states for atoms, are produced. Optical emission properties are controlled by varying the size of the QD, which allows practical flexibility. Exchange interactions result in spin-split energy configurations, which can be resolved spectroscopically and addressed with tunable laser pulses. By addressing the excited state spectra through the use of optical polarization signatures and ultrafast coherent laser techniques, progress will continue to be made in coherent manipulations of entangled spins.

Chapter 3 analyzes a unique triple-coupled QD in a triangular structure and shows how a driving magnetic field, composed of crossed dc and ac fields, can operate as a suitable tool for spin qubit manipulation. The dc field applied perpendicular to the plane of the triangular structure causes a non-zero flux through the center of the triangle, which produces a flux-dependent phase shift of the electron wavefunction traversing the structure. A time-dependent ac field induces rotation of the electron spin. Electron spin resonance conditions allow one to consider the triple quantum dot (TQD) as a qubit where Rabi oscillations between two dark states can be controlled. It is demonstrated that a generic property of magnetic ac fields is to induce spin blockade at certain frequencies in both double QDs and TQDs. These and other properties provide new possibilities for designing spintronic devices. In Chapter 4, the focus is on AB rings with a QD embedded in each arm. These structures allow for a fine degree of control over the electron transmission states as a function of electron energy, QD energy levels, and the amount of coupling between the QDs and the leads. In conjunction with these effects, an AB phase shift leads to precise control over transmission resonances by means of an external magnetic field. In addition, spin-polarized transmission and filtering becomes possible *via* the Zeeman effect which induces spin-splitting of the QD energy levels. When combined with the AB and energy-level effects, these devices demonstrate a high potential for producing and manipulating spin-polarized output. The analysis includes the performance of both single and double AB rings in series.

Chapter 5 presents an introduction to atomistic tight-binding simulation of spin–orbit-coupled semiconductor devices, focusing particularly on the spin-filtering effect. A double-barrier resonant structure (DBRS), which models a QD, is taken as an example where the resonant energy levels in the DBRS are spin-split due to two distinct spin–orbit coupling mechanisms. The atomistic calculations include the intra-atomic spin–orbit interactions, which confirm the appearance of spin-filtering behavior. In Chapter 6, the text focuses on the possibility of reducing the heat generation concomitant with charge-based electronic computation. Energy-efficient processors become even more essential in health science applications, where regular recharging of a battery supply is impractical. By encoding a bit of digital information in the spin degree of freedom of electrons (or holes), the energy dissipation associated with the manipulation of the bit (a spin-flip operation) becomes minimal. This concept, in the application of logic gates for

Boolean computation is described as Single Spin Logic. A practical methodology for realizing spin-based logic is Nanomagnetic Logic, where single-domain nanomagnets are employed as the elementary logic switches. Although further development is needed, these devices hold great potential for ultra-low power memory, logic, and information processing at room temperatures.

Chapter 7 reports on the experimental study of magnetic 1D atomic chains and 2D atomic layers fabricated on vicinal substrates using the molecular beam epitaxy (MBE) technique. Such a study is an extension of earlier, highly profitable investigations of novel nanomaterials with tailored electronic and magnetic properties. Low-dimensional (1-D and 2-D) systems at the nanoscale or even the atomic scale show promise for controlling the magnetic properties of matter. Magnetic nanostructures demonstrate a variety of anisotropies which may allow for durable long-range ferromagnetic order at finite temperature, enhancing the potential of these devices for magnetic data storage and spin-based computing. Chapter 8 rounds out the text with an important review of graphene in the context of magnetic nanostructures. The practical attainment of monoatomic layers of graphene has opened up the intensely studied topic of graphene physics. The benefit of graphene for nanoelectronics stems from its properties which facilitate formatting graphene structures with the techniques of nanolithography. In addition, graphene has uniquely desirable electrical and thermal properties. And with regards to possible spintronics applications, graphene has a high spin-decoherence time, facilitating the transport and manipulation of spin states.

This book includes sufficient detail on the methods used for conducting theoretical modeling to provide a starting point for ongoing research in spintronics, or for conducting experimental investigations. Since a goal for the book is that it could be used as a practical handbook or graduate text, it includes plenty of illustrations, case studies, and practical examples of potential spintronics applications in nanoscale devices.

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