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Introduction to Spintronic and Nanomagnetic Computing Devices

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This book focuses on recent developments in two important and interrelated information processing device concepts and related phenomena: "spintronic devices" and "nanomagnetic devices." In the former, individual electron spins are coherently manipulated as they flow through the active region of a device to elicit device functionality. In the latter, an ensemble of spins in a nanostructure acts collectively as a giant classical spin (a single domain nanomagnet) owing to mutual exchange coupling, and the giant spin polarization (or the magnetization of the nanomagnet) is switched between stable orientations to store and/or process binary data. These information processing paradigms have attracted attention because of their low energy dissipation, nonvolatility and relatively fast speed of operation.

1.1 Spintronic Devices

An iconic device in the field of spintronics is the Datta-Das [1] *Spin Field Effect Transistor* (SPINFET) in which the current flowing between two of the terminals (source and drain) is modulated with a gate potential that does not change the carrier concentration in the channel of the transistor, but instead changes the *spin polarization* of the carriers. The source and drain contacts are ferromagnets that act as spin polarizers and analyzers. The source injects spin polarized electrons, the gate voltage precesses the spins in the channel owing to Rashba spin–orbit interaction [2] and the drain selectively transmits electrons depending on the degree

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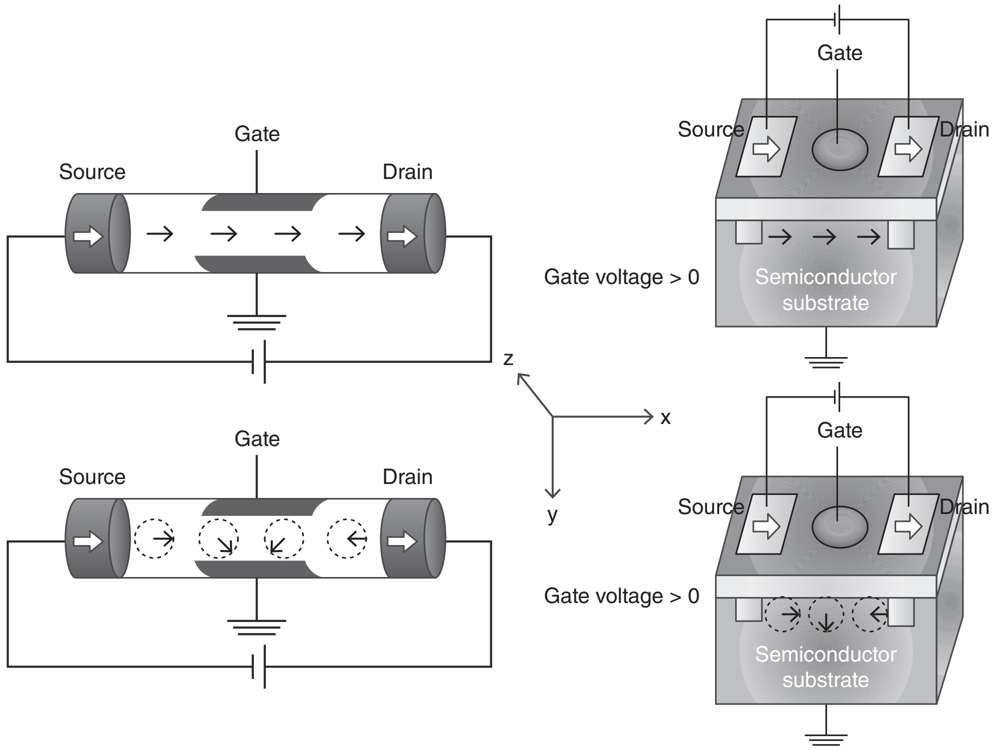

Figure 1.1 Operation of a Datta-Das SPINFET. The source injects spin polarized electrons, polarized in the direction of source-to-drain current (x-direction). When the gate voltage is zero, the spins do not precess and are fully transmitted by the drain resulting in maximum (on) current. When the gate voltage is turned on, it produces an electric field E_y in the y-direction due to Rashba spin-orbit interaction that results in an effective magnetic field of flux density B_z in the z-direction. This field causes the electrons to precess about itself. The left panel shows a one-dimensional SPINFET and the right panel a two-dimensional SPINFET.

of precession they have undergone in the channel. Thus, by varying the gate voltage, one can vary the source-to-drain current and realize transistor action. The operation of the transistor is briefly explained in Figure 1.1.

There are several impediments to practical room temperature implementation of the Datta-Das SPINFET. Foremost among them is the inefficiency of the spin polarizer and analyzer. The inability of ferromagnet/semiconductor interfaces to inject and detect spins with high efficiency results in low on–off ratios of the drain current [3]. The on–off ratio is also reduced significantly if the channel of the SPINFET is not strictly one-dimensional [4], that is, if it is not a quantum wire with only the lowest carrier subband occupied. Finally, coherent transportation and manipulation of spins over the length of the channel at room temperature is challenging. The channel has to be sufficiently long to allow at least one-half period of spin precession and retaining spin coherence over that length is difficult at room temperature. Recently, coherent spin transport was demonstrated in a strictly one-dimensional InSb nanowire at room temperature [5], raising hopes for the Datta-Das transistor. That, together with the vast improvement in spin injection and detection efficiencies made possible by the use of quantum point contacts [6] as source and drain, has made a significant advance toward the demonstration of the Datta-Das device. Very significant steps in that direction have been reported recently involving spin injection, detection and manipulation with quantum point contacts as well as spin manipulation using spin orbit coupling to realize all-electric and all-semiconductor spin field effect transistors [7].

Chapter 2 discusses the use of quantum point contacts (QPC) with lateral spin–orbit coupling (LSOC) to create a strongly spin-polarized current by tuning the asymmetric bias voltages on the side gates *in the absence of any applied magnetic field*. By injecting this strongly spin-polarized current into the channel of a SPINFET, high injection efficiency can be obtained. This chapter also explores the different regimes of operation of all-electric spin valves made of quantum point contact and quantum dots, with spin–orbit coupling, and the ramification of an all-electric spin valve for future spin-based devices, circuits, and architectures.

Chapter 3 explores and surveys interesting variations of the Datta-Das spin transistor by proposing devices that do not rely on the gate voltage controlled precession of spins in the channel. Instead it surveys two other devices:

(i) "Spin MOSFET," comprising a regular MOSFET with ferromagnetic contacts whose magnetizations can be switched from parallel or antiparallel configuration, thereby turning the transistor on and off.
(ii) "Pseudo-spin-MOSFET," which is essentially a MOSFET with a magneto-tunneling junction, or MTJ connected to either the source or the drain.

This chapter further discusses the use of these two devices for energy-efficient (low power) nonvolatile logic circuits. Since the gating action and the parallel/antiparallel orientation of the magnetizations of two ferromagnetic contacts (in case of Spin-MOSFET) or the MTJ's magnetic layers (in case of Pseudo spin-MOSFET) can be independently controlled, these devices are well suited for nonvolatile bistable circuits. Finally, implementation of nonvolatile memory elements based on these devices is also discussed. In some sense, these devices are closer to "nanomagnetic devices" as the magnetic states of the MTJ/ferromagnetic contacts (nanomagnets) encode information.

1.2 Nanomagnetic Devices

Inherent advantages: Nanomagnets have two inherent advantages over transistors as binary switches: nonvolatility (or the ability to store information without any standby power dissipation) and the potential to switch from one stable state to another with extremely small energy dissipation. These are explained below:

1. Consider an elliptical Terfenol-D nanomagnet as shown in Figure 1.2 (rightmost figures) with major axis, minor axis and thickness respectively 110 nm, 90 nm and 6 nm. These dimensions ensure that the nanomagnet has a single domain [11] and that the shape anisotropy energy barrier (E_b), which separates the two degenerate minima in the potential

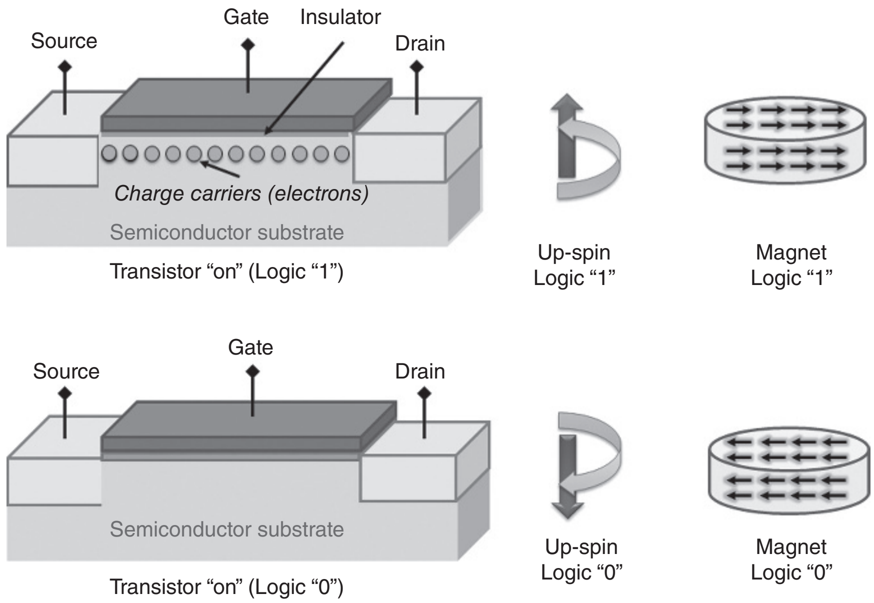

Figure 1.2 Transistor, single-spin and single-domain nanomagnet encoding logical “0” and “1” states.

energy profile of the nanomagnet (these minima correspond to the two stable magnetization orientations that are mutually antiparallel and aligned along the long axis), is 2.2 eV (85.12 kT at room temperature). That makes the probability of spontaneous magnetization flipping between the two stable orientations due to thermal agitations equal to $e^{-E_b/kT} = e^{-85}$ per attempt [8]. Therefore, if binary bit information has been written into the magnetization orientation of the nanomagnet, then that information is retained for a time of $(1/f_0)\, e^{85} = 2.6 \times 10^{17}$ years, if we assume the attempt frequency f_0 to be 1 THz [9]. In other words, the nanomagnet is *nonvolatile*. If we “write” binary information in the nanomagnet by orienting the magnetization along one of the two stable states, that information stays uncorrupted almost in perpetuity, even when no energy is supplied to the nanomagnet to retain the information.

2. The nanomagnet can not only retain information but also process it in a very energy-efficient way. The *minimum* energy dissipated in switching a charge-based device like a transistor at a temperature *T* is *NkTln(1/p)* independent of the switching speed [10] where *N* is the number of information carriers (electrons) in the transistor, *k* is the Boltzmann constant, and *p* is the bit error probability. This happens because the charges act independently of each other and there is no collective dynamics when switching takes place, resulting in *N* degrees of freedom for the charge ensemble. In contrast, the minimum energy dissipated to switch a *single-domain* nanomagnet’s magnetization is only ∼ *kTln(1/p)*, since the *exchange interaction* between the many spins comprising a single domain nanomagnet makes all of them behave collectively like a giant single spin and rotate in unison [10, 11], resulting in a single degree of freedom. The collective dynamics of spins – absent among charges – make the nanomagnet a far more energy-efficient switch than a transistor. If we assume the same number of information carriers in a transistor and in a single domain nanomagnet in Figure 1.2, then for the same bit error probability, the ratio of the minimum

energy dissipated to switch a nanomagnet to that dissipated to switch a transistor will be $\sim 1/N \ll 1$.

Potential impact of nanomagnet based computing devices: The two inherent advantages of nanomagnetic devices discussed above bring within reach two longstanding goals of computer technology:

1. To embed both logic and memory functions in the *same* processing unit or device in order to eliminate the weak communication link between processor and memory that typifies von-Neumann architectures. This requires *nonvolatile logic* that performs Boolean logic operations with bistable switches and then stores the output data in the switches themselves. The inherent nonvolatility of shape anisotropic nanomagnets whose magnetization states are bistable makes this possible. Since program data are stored in situ in the processors, there is no need to fetch instruction sets from a remote memory to execute operations. This improves system reliability and execution speed, eliminates any boot delay (thus producing "instant-on" computers), and reduces overall energy consumption since a significant fraction of the power consumed in a computer is due to processor–memory communication.
2. To pack as many processing units (logic gates, memory cells) as possible into a given area or volume to increase computational prowess. This requires reducing energy dissipation in a device per logic operation so as not to overwhelm thermal management in a chip. Consider a state-of-the-art nanotransistor (in 22 nm node CMOS technology) that dissipates over 1000 kT (4 aJ) of energy to switch in *isolation* [12] and perhaps 10^4–10^5 kT (40–400 aJ) to switch in a circuit. Assuming that a future miniature chip will have 10^{10} transistors/cm^2, and an activity level of 10% (i.e., 10% of the devices are switching at any given time), the energy dissipated per unit area will be 40–400 nJ/cm^2 and the power dissipation will be ∼40–400 W/cm^2 for a clock rate of 1 GHz. Such a high dissipation level is not only an unacceptable for portable electronics, but it also burdens thermal management in the chip.

Potential applications for nanomagnetic devices: Now consider a processor built with nanomagnetic device technology that dissipates ∼1 aJ/bit-flip (as discussed in some of the later chapters) on an active area of ∼1 mm^2 that could accommodate $\sim 10^8$ computing elements and operates at 10% activity level at 1 GHz. This will dissipate a mere 10 mW of power. Therefore, it can be powered by energy harvesting devices [13] without the need for a battery! This opens up unique applications that were hitherto unimaginable. These include monitoring and processing spatio-temporal brain signal patterns to warn of impending epileptic seizures [14,15] while being powered only by the motion of the patient's head. Such processors mounted on unmanned aerial vehicles (UAVs) and powered solely by engine or structural vibrations can recognize targets from aerial images [16], while buoy-mounted processors, powered by energy harvested from vibrations due to sea waves, could detect ships and submarines using inputs from a network of acoustic sensors. Further, they could be used to monitor the structural health of bridges [17] and buildings with inputs from a network of sensors while being powered by vibrations due to wind or passing traffic. All of these "no-battery" applications can be made possible because of two features: (1) the unique information processing capability and (2) the unprecedented low energy requirement of nanomagnets.

The nanomagnet's characteristic advantage led to increasing interest in various nanomagnet-based memory and logic architectures.

In nanomagnetic memory technology, the advances in magneto-resistive read heads using spin valve and magnetic tunnel junctions [18–20] enabled energy-efficient reading of the magnetization state of nanomagnets, while writing into a magnetic memory cell (MRAM) with current generated magnetic fields was not energy-efficient (large I^2R losses) and struggled with issues of fringing write fields. This spurred rapid developments in spin-transfer torque (STT) based write technology [21–25] that ameliorated the problem with fringing fields, but still could not completely overcome high I^2R losses.

This has led to the quest for more energy-efficient paradigms based on different physical phenomena to switch nanomagnets for both memory and logic applications. They are covered extensively in Chapters 4–9 of this book. The coverage is of course not exhaustive since this field moves rapidly and new methodologies are being demonstrated with increasing frequency. Nevertheless, Chapters 4–9 provide a bird's eye view of the mainstream technologies.

1.2.1 Use of Spin Torque to Switch Nanomagnets

Different ways of using spin torque to switch nanomagnet for memory and logic applications are covered in Chapters 4–6. Again, this coverage is not exhaustive since a popular paradigm termed "all-spin-logic" [26] is not included. The interested reader can find a discussion of this concept in the cited reference.

Chapter 4 presents a comprehensive picture of traditional spin transfer torque (STT) devices spanning multiple scales: from the atomic and bandstucture level to the modeling of magnetization dynamics in the presence of thermal noise to estimating the switching error in STT memory devices.

Chapter 5 goes beyond memory and discusses the implementation of MTJ based logic devices including the use of spin transfer torque in switching MTJ based logic devices.

Chapter 6 discusses an interesting alternative to passing spin polarized current through the nanomagnet to provide spin torque. It describes schemes to utilize current flowing through a heavy metal to switch the magnetization (or move domain walls) of nanomagnets (magnetic nanostrips) deposited on top of the heavy metal due to spin orbit torques created by both the Rashba and Spin Hall effects. Since the current in this case flows through a low resistance path, the energy dissipated to clock nanomagnets becomes extremely small.

1.2.2 Other Methodologies for Switching Nanomagnets

There are other switching paradigms for nanomagnets that implement memory and logic functions in an energy-efficient manner. These include use of spin waves and mechanical strain that are covered in Chapters 7–9.

Chapter 7 discusses the use of spin waves to implement magnonic logic devices. Specifically, it looks at spin wave interference to implement Boolean logic gates and carry out non-Boolean information processing.

Chapters 8 and 9 discuss strain-based switching of the magnetization orientation in nanomagnets. A voltage applied across a piezoelectric layer generates a strain in it, which is transferred almost entirely to the magnetostrictive layer by elastic coupling if the latter layer is much thinner than the former. This strain/stress can cause the magnetization of the magnetostrictive layer to rotate by a large angle (via the Villari effect). Chapter 8 focuses on strain-mediated magnetoelectric memory schemes while Chapter 9 builds on some of the memory schemes in Chapter 8 and additionally addresses strain clocked nanomagnetic logic that is not addressed in Chapter 8.

1.3 Thinking beyond Traditional Boolean Logic

Chapter 10 presents an overview of Boolean and non-Boolean computing architectures and approaches that exploit the special features of spin wave interference to elicit powerful data representation and computation. It presents unconventional implementations of multivalued circuits culminating in microprocessors.

The editors hope that this collection of ten chapters will provide a compendium of spintronic and nanomagnetic device technologies to equip the reader with a broad understanding of the field. Questions and comments can be addressed to J. Atulasimha (jatulasimha@vcu.edu) and S. Bandyopadhyay (sbandy@vcu.edu).

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