Spintronics: Recent developments on ultra-low-energy, area-efficient, and fast spin-devices and spin-circuits

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ABSTRACT

Unlike charge-based devices, spin-devices are switched by flipping spins without moving charge in space. Here we review the recent developments on ultra-low-energy, area-efficient, and fast spin-devices based on electric field-induced magnetization switching in multiferroic magnetoelectric composites. We also review the spin-circuit representation of spin pumping by considering spin potential and spin current similar to the charge-based counterparts using Kirchhoffs voltage/current laws. Such representation, apart from being necessary for large-scale circuits, is useful for understanding and proposing experiments.

Keywords: Spintronics, ultra-low-energy, area-efficient, fast switching, spin-circuits

1 Introduction

The invention and development of transistor-based electronics has been a story of great success [1]. However, the proven concept of enhancing the performance metrics by miniaturization [2] of devices is approaching its fundamental limits [3]; while there are issues due to process variation, basically the excessive energy dissipation in the devices limits the further improvement of transistor-based electronics [4]. Electron's spin-based counterpart, so-called spintronics [5, 6] has profound potential to be the replacement of current technology, particularly in quest of energy-efficient computing [7, 8, 9, 10, 11, 12] in our future information processing systems.

2 Ultra-low-energy, area-efficient, and fast spin-devices

Spintronics has been widely studied in the context of nanomagnets [13]. Although some energy is still dissipated in flipping spins due to magnetization damping [14, 15], it can be considerably less than the energy associated with current flow in charge-based devices. Unfortunately, this advantage is squandered if the method adopted to switch the spin is so energy-inefficient that the energy dissipated far exceeds the energy dissipated inside the system. Regrettably, this has often be the case particularly while using magnetic field to switch the magnetization of a nanomagnet. It has been shown that electric field-induced magnetization switching in strain-mediated piezoelectric- magnetostrictive multiferroic composites [16, 17, 18, 19], with a suitable choice of materials and dimensions, dissipates a miniscule amount of energy of 1 attojoule (aJ) in sub-nanosecond switching delay at room-temperature [7, 8, 9, 10, 11, 12, 20, 21, 22] and the experimental efforts are emerging [23, 24, 25, 26, 27, 28, 29]. It eliminates the need to use spin-polarized current [30, 31, 32, 33, 34] for writing bits although new method of utilizing giant spin-Hall effect is promising [35]. Using multiferroic devices, digital computing [10, 36, 37], analog signal processing capability with transistor-like high-gain region [38, 39], scaling trends [40], separating read and write units [41], and Landauer limit of energy dissipation [42] have been studied. Also, interface-coupled multiferroic heterostructures [43] and dynamics in single-phase multiferroic materials [44] have been studied. For technological suitability, antiferromagnetically exchange-coupled nanomagnets can be employed to harness area-efficiency and faster switching speed (see Fig. 1).

3 Spin-circuits

Although there has been enormous progress in the field of spintronics and nanomagnetics in recent years with the advent of new materials and phenomena, it remained a formidable challenge to integrate them into functional devices and evaluate their potential. Circuit theory has been tremendously successful in translating physical equations into circuit elements in organized form for further analysis and proposing creative designs for applications. Different components can be represented as 4-component (one for charge and 3 for spin-vector) circuit elements in general and we can utilize the traditional circuit theory considering spin relaxation [45, 46]. Complex multilayers can be solved programmatically by simply writing a netlist. Spin pumping [47] injects a *pure* spin current into surrounding conductors and it can be detected by the inverse spin Hall effect [48, 49] (see Fig. 2a). The spin-circuit in Fig. 2b can be utilized to benchmark the results in literature and propose experiments [47, 50, 51] (see Fig. 2).

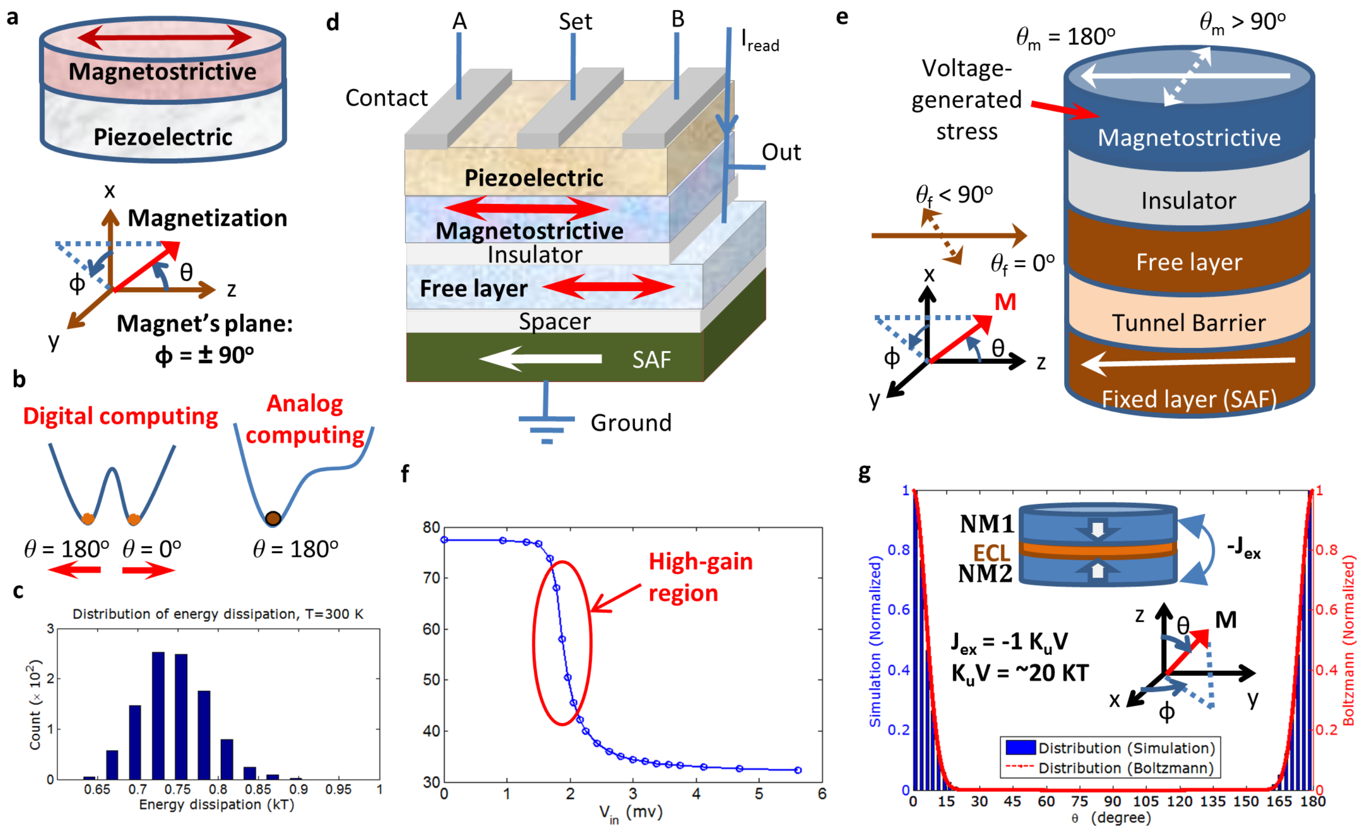

Figure 1: **(a)** Schematic diagram of a strain-mediated multiferroic composite (piezoelectric-magnetostrictive heterostructure), and axis assignment. **(b)** A shape-anisotropic single-domain nanomagnet with two 180° symmetry equivalent states has two stable easy axes and switching between them allows us to store a non-volatile binary bit of digital information. To harness the analog computing capability and facilitate a continuous rotation of magnetization, we propose to make the potential landscape of a nanomagnet monostable to avoid any abrupt switching of magnetization [39]. **(c)** Simulation results for Landauer limit of energy dissipation in a magnetostrictive nanomagnet. It is important to note that for a few cases, the Landauer bound (kT ln(2) = 0.6932 kT) is violated but the mean of the energy dissipation (0.74 kT) exceeds the Landauer bound safeguarding the Landauer's principle and the second law of thermodynamics [42]. **(d)** Logic design using read-write units. The read unit is an MTJ, which reads the free layer's magnetization direction with respect to the fixed layer. The magnetostrictive layer and the free layer are dipole coupled (anti-parallel orientation), hence the magnetostrictive nanomagnet's direction can be read. Such read-write units can be concatenated to devise complex circuits. Two inputs can be incorporated to design single-element straintronic universal logic gates (e.g., NAND, NOR). By applying voltages at the terminals A and B, the magnetization of the magnetostrictive nanomagnet can be switched and depending on the design of the nanomagnets, the respective logic operation can be performed [36]. **(e)** A magnetostrictive nanomagnet dipole coupled with a free layer of an MTJ with an effective field exerted from a fixed layer. The fixed layer of the MTJ is exerting an effective field $H_{fixed,f}$ on the free layer. When a sufficient stress is active on the magnetostrictive layer, free layer's magnetization also comes towards $\theta_f = 90°$ (note $\theta_m > 90°$ and $\theta_f < 90°$ due to $H_{fixed,f}$) [39]. **(f)** Input voltage V_{in} versus output voltage V_{out} characteristics showing a high gain transition region where we can bias an ac input voltage and can achieve an amplified version of the input voltage at the output, harnessing the analog computing capability [39]. Such voltage gain is also necessary for error resiliency in digital integrated circuits. **(g)** Distributions of two antiferromagnetically exchange-coupled magnetizations' fluctuations achieved by solving stochastic Landau-Lifshitz-Gilbert equation of magnetization dynamics at room-temperature (300 K). For technological suitability, apart from being energy-efficient, spin-devices must be area-efficient (~10 nm lateral dimensions) and possess fast switching speed. This composite structure with antiferromagnetically exchange-coupled nanomagnets can be employed to harness area-efficiency and faster switching speed. For even faster switching speed (fs to ps), optical magnetization switching is a promising candidate.

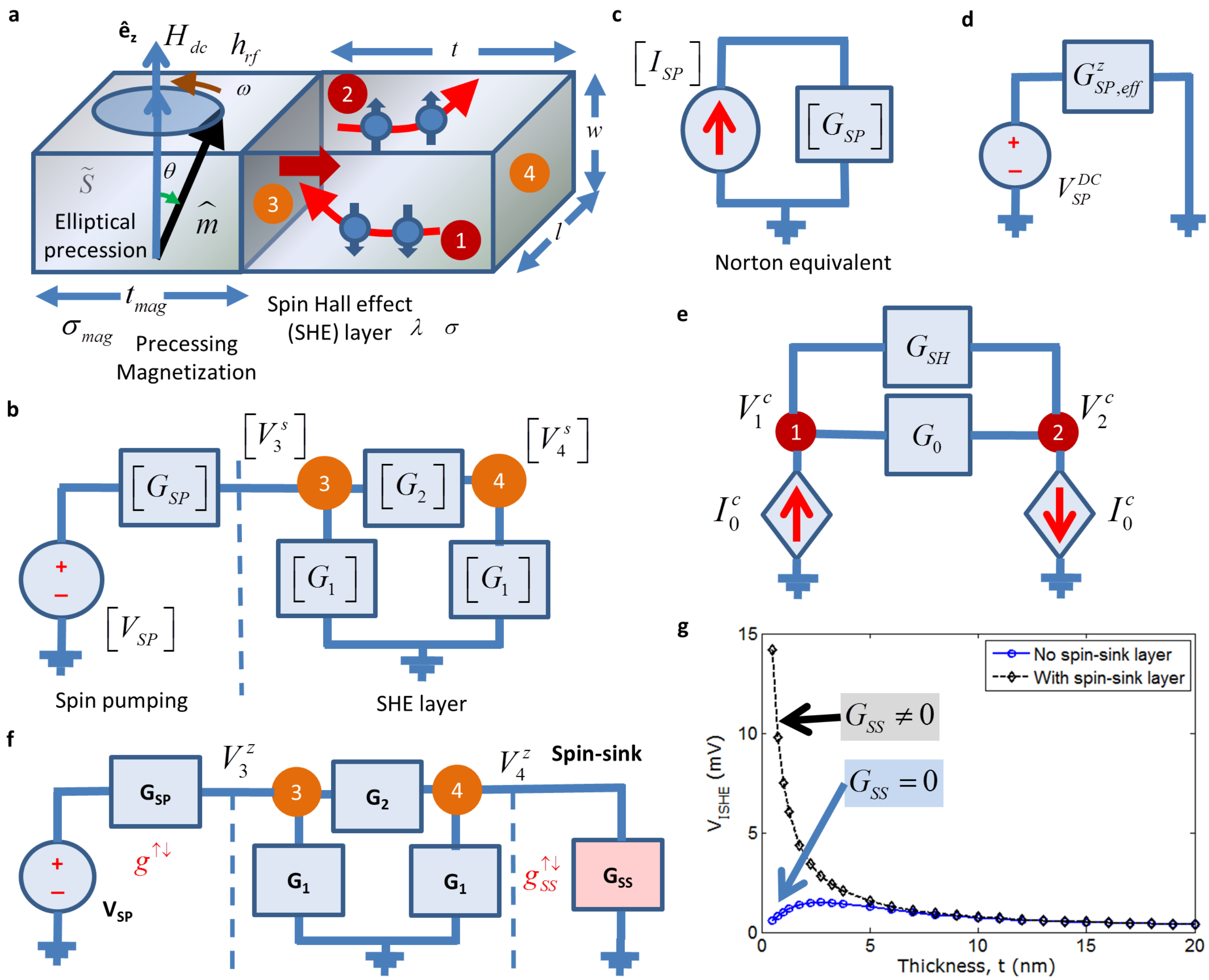

Figure 2: **(a)** A precessing magnetization is pumping pure spin current to an adjacent layer possessing a high spin orbit coupling and it generates a considerable amount of charge current due to inverse spin Hall effect (ISHE). Charge potentials are developed at the surfaces marked by 1 and 2, while spin potentials are developed at the surfaces marked by 3 and 4. **(b)** Instantaneous 3-component spin circuit with the voltage source $[V_{SP}]$ acts as a spin battery, $[G_{SP}]$ is the interfacial spin mixing conductance between the magnetic layer and the SHE layer. **(c)** The spin circuit for the spin pumping can be represented by Norton-equivalent with a spin current source, compared to Thevenin-equivalent with a spin battery as shown in part (b). **(d)** Reduced dc spin-circuit with average spin polarization acting in the z-direction representing the effective spin mixing conductance with the SHE layer conductance included in it. This effective spin mixing conductance can be determined experimentally from the enhancement of damping in ferromagnetic resonance experiments and it matches the mathematical expression derived in literature [47]. **(e)** The charge circuit for the spin-to-charge conversion by ISHE with the current sources I_0^c dependent on the spin circuit in the part (c), G_0 and G_{SH} are the conductances for the SHE and FM layers, respectively. The expression of inverse spin Hall voltage ($V_{ISHE} = V_2^c - V_1^c$) can be determined by applying the Kirchhoffs circuit laws and it matches the mathematical expression derived in literature [50]. **(f)** The spin-circuit representation of a precessing magnetization injecting pure spin current to the adjacent SHE layer with a spin-sink layer (a magnetic layer) attached. We propose how spin pumping efficiency can be enhanced in giant spin Hall materials and also in topological insulators [51]. **(g)** Results showing that the inverse spin Hall voltage can be significantly enhanced through the addition of the spin-sink layer.

ACKNOWLEDGMENT

This work was supported in part by FAME (Function Accelerated nanoMaterial Engineering), one of six centers of STARnet, a Semiconductor Research Corporation program sponsored by MARCO and DARPA.

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