Spintronic Circuits

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Preface

For over a decade, the PI has played an active role in the proposal and evaluation of a number of different approaches to "re-inventing the transistor" in anticipation of the upcoming roadblocks to the continuation of Moore's law at least in its traditional form [1]. Some of these approaches were based on charge-based devices like negative capacitance transistors, whose circuit performance could be evaluated using a relatively straightforward extension of the existing framework for standard MOS transistors. But our early work (2007-2012) also indicated that a large number of viable alternatives could involve spins and magnets described by non-traditional variables like spin currents, spin voltages and magnetization, making their circuit performance difficult to evaluate within the standard SPICE-style circuit simulation framework that has emerged over many decades in the context of CMOS technology.

Even in 2012 new phenomena involving spin voltages and spin currents were being continually discovered which were used to write and read information to and from magnets, with significant potential for a transformative effect on the field of memory devices. It was clear to us that we needed a framework for evaluating the potential use of these new phenomena as the basis for a transistor-like building block with gain and input-output isolation, that could be used to construct large scale circuits providing new and unprecedented functionality. Such devices could enable the continuation of a broader Moore's law characterized not by a regular doubling of the number of transistors, but by a regular doubling of "user value" [2], and this has been the motivating vision behind our work within NEEDS.

What were the goals?

In this work, we had two broad goals:

(1) The initial goal was to develop a modular framework for modleing functional circuits that utilize novel spintronic materials and phenomena.

(2) The second goal and the focus ofour current work makes use of the modular framework to investigate the possibility of probabilistic transistors (p-transistors) as the building block for a new class of probabilistic circuits (p-circuits) designed to provide a totally new kind of functionality.

What was accomplished: Modular Approach to Spintronics:

The Modular Approach [3] is based on the notion that composite devices can be broken up into "elemental" modules while preserving the essential physics. Figure 1a shows the elemental circuit modules in this approach, in the two broad categories of "magnetics" and "transport" that couple magnetization dynamics of magnets with the spin transport equations that are driving them. Figure 1b shows an example spin-circuit built out of these modules to reproduce a non-local spin-valve experiment performed at Purdue by the Chen group [9]. Using only experimentally measured quantities as input parameters, the spin-circuit quantitatively reproduced non-trivial features of this experiment. Indeed, all of the modules in this "library" are either rigorously benchmarked with established theoretical models or take direct input from experimentally measured quantities.

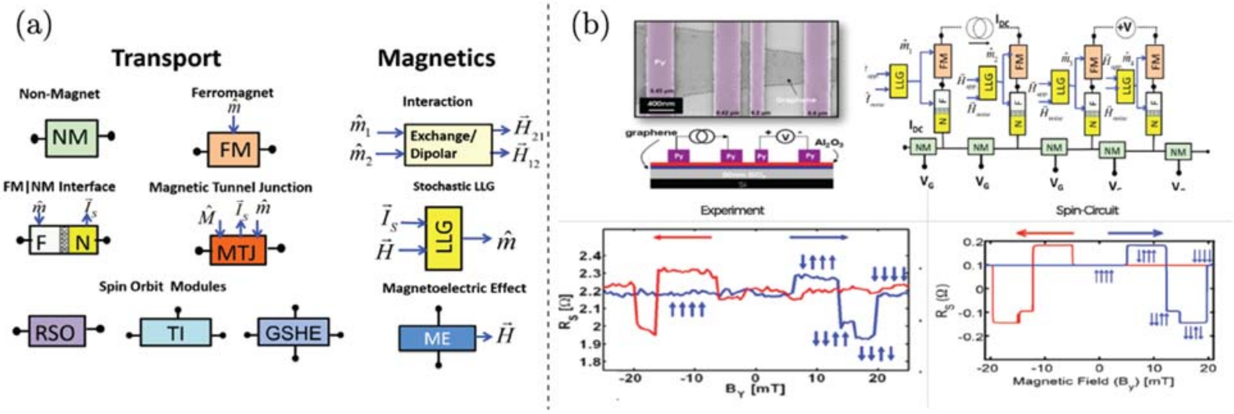

Figure 1. (a) Elemental circuit modules in the Modular Approach are comprised of transport and magnetics blocks. As illustrated above, NM=Normal Metal, FM=Ferromagnetic Metal, F|N: FM-NM Interface, MTJ=Magnetic Tunnel Junction, LLG=Landau-Lifshitz-Gilbert equation solver, RSO=Rashba spin-orbit module, TI=Topological Insulator, GSHE=Giant Spin Hall Effect, ME=Magnetoelectric Effect. (b) An example experimental structure and a spin-circuit built out of the elemental modules is shown. Spin-circuit modeling shows excellent quantitative agreement with the experimental data, while using only measured parameters.

It is important to stress that the notion of "modularity" is not at all obvious. After all, we would not expect to be able to easily express the I-V characteristics of a p-n junction as a series combination of an ordinary p-type resistor and an n-type resistor. What allows the equivalent separation of a spin-valve into two individual ferromagnetic (FM) circuits is the concept of a *generalized* circuit, where each node of the circuit carries a 3-component spin voltage (chemical potential) in addition to the usual charge voltage. This makes the conductances in these circuits 4x4 matrices that couple charge and spin components, making each branch current a 4x1 vector with 3-components for spin currents and 1 for charge.

The modules have been continuously updated by adding new phenomena (e.g, Topological Insulators, voltage-control of magnetism) and improving existing ones (e.g, extending LLG to stochastic LLG for modeling superparamagnets). It has been the primary backbone of the models used in research papers within the Datta group. Specifically, it was used to evaluate the performance metrics of emerging classes of spin-logic devices [10], to propose novel structures to improve the spin-Hall efficiency of heavy metals [11], to understand the physics of exchange coupled ferrimagnets for faster switching [12], to help understand experiments on circular nanomagnets [13], to design structures that can efficiently solve combinatorial optimization problems, and to design a new kind of transistor for p-bits used in probabilistic spin logic [7]. It was also used outside the Datta group by experimental and theoretical groups alike [14, 15, 16].

What was accomplished: P- transistors as building blocks for P-circuits:
Over the last year we have used the Modular Approach to propose a vision for a fundamentally different device that we call a "p-transistor" (Fig.2a) which can be used as a building block for "brain-like" logic based on probabilistic computation [5-8]. Each p-transistor is a 3-terminal device which outputs a sequence of random 1's and 0's whose mean value can be tuned with an input signal (Fig.2b). We have argued that these "p-bits" can be interconnected to create robust correlations that can be used to solve a wide range of problems, including probabilistic inference [5], combinatorial optimization [6] and precise but invertible Boolean logic [7-8].

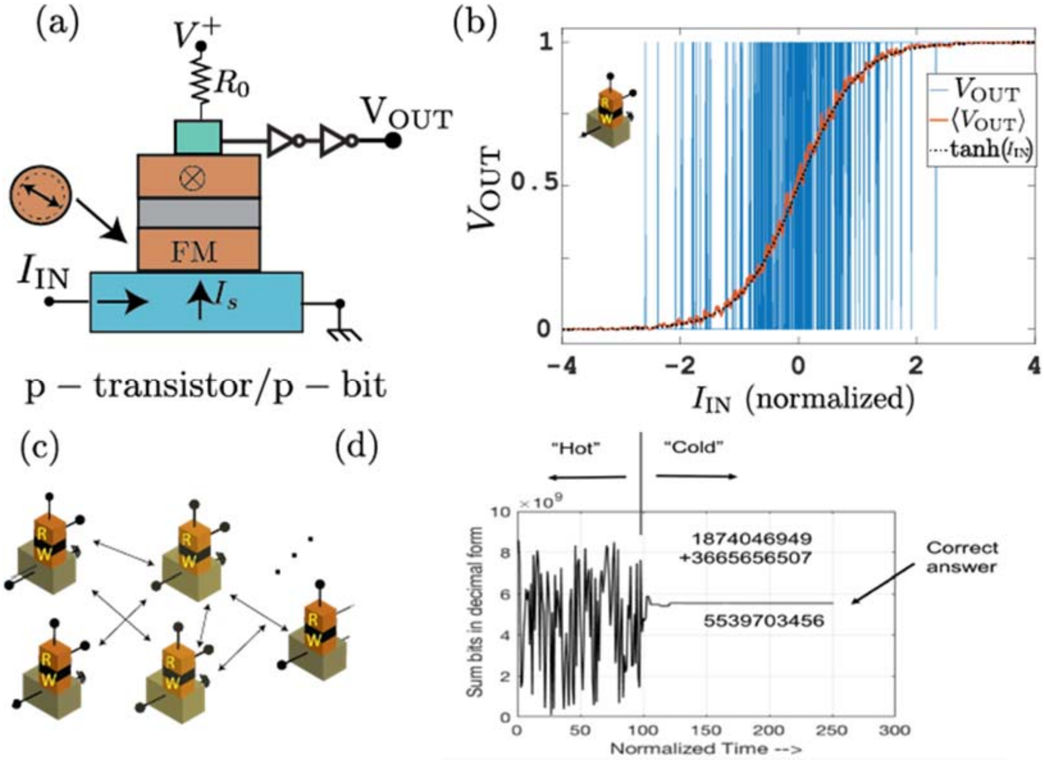

Figure 2. (a) One possible implementation of a p-transistor to generate the required input-output characteristics for a p-bit. (b) The input-output characteristics of the idealized p-bit based on the generic model. The blue line shows the real-time response of the p-bit, the red line is the RC averaged p-bit value that follows a sigmoidal behavior. (c) A network of correlated p-bits operating as a p-circuit. (d) An example illustrating a p-circuit used to implement precise Boolean logic: 32-bit adder implemented using a network of p-bits. Remarkably the operation is invertible as discussed in the text.

As an example of what could be done with a network of correlated p-bits (Figure 2c), we show a network with approximately 500 p-bits connected to act as a 32-bit Adder (Figure 2d). Initially, the connections between the p-bits are weak ("Hot") and the sum bits fluctuate in a weakly correlated manner going over many of different possibilities. Once the connections are switched on ("Cold"), they unerringly converge on THE one correct answer out of 2^33 (~8 billion) possibilities!

Remarkably, the 32-bit adder also performs the inverse function. When the sum bits (S) and one of the input bits (A) are clamped to a fixed number, the system gets correlated to make A+B=S, forcing the bits of the other input (B) to float to the *precise* difference (S-A). The ability of a system to implement the inverse function is a unique feature with far-reaching possibilities. For example, we have also shown that a 4-bit multiplier acting in reverse performs integer factorization [7], suggesting probabilistic computers based on robust, room temperature p-bits could provide practically useful functionalities to many challenging problems.

Why was it important?

In less than two years since its formulation, the Modular Approach to Spintronics [3] has been widely used not only within the Datta group but also by other research groups as a robust, sound framework both for understanding and designing experiments and for proposing and evaluating novel devices and circuits. The main paper [3] already has 24 citations on Google Scholar, and the thesis that serves as a user's manual for the open-source codes available on nanoHUB [4] has been downloaded by hundreds of users. Within our group this approach has enabled us to explore a very exciting concept based on the use of stochastic nanomagnets as p-bits to implement "brain-like" invertible logic based on p-circuits that are very different from standard digital circuits based on stable deterministic bits.

Fig. 2 shows an illustrative example of the operation of the proposed p-circuits: two features are particularly noteworthy about this simulation:

- Firstly, the proposed p-transistor (Fig. 2a) combines diverse spintronic phenomena like the spin-Hall effect in heavy metals, magnetic tunnel junctions and stochastic superparamagnets with 14 nm state-of-the-art FinFET's.

- Secondly, the 32-bit adder is a fairly large functional circuit involving a interconnected network of ~ 500 p-transistors.

This seamless integration of diverse physical phenomena and bridging all the way from microscopic physics to a functional circuit are made possible by our unique modular approach.

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