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Emitter-coupled spin-transistor logic

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HIGHLIGHTS

- First logic family with magnetoresistive semiconductor heterojunction transistors.
- Spintronic logic family with cascadable stages.
- High-permeability shielding material concentrates magnetic field.
- First logic family based on ECL to use the spin-degree of freedom.
- Potential to replace CMOS for general-purpose computing.

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ABSTRACT

The recent invention of magnetoresistive bipolar spin-transistors makes possible the creation of new spintronic logic families. Here we propose the first logic family exploiting these devices, extending emitter-coupled logic (ECL) to achieve a greater range of basis logic functions. By placing the wire from the output stage of ECL logic elements near spin-transistors in other logic stages throughout the circuit, additional basis logic elements can be realized. These new logic elements support greater logic minimization, resulting in enhanced speed, area, and power characteristics. A novel magnetic shielding structure provides this logic family with the crucial ability to cascade logic stages. This logic family potentially achieves a power-delay product 10–25 times smaller than conventional ECL, and can therefore be exploited to increase the performance of very high-speed logic circuits while broadening the range of design choices for a variety of electronic applications.

1. Introduction

The ability to switch a logic gate through control of electron spin is the fundamental concept underlying spintronic logic circuits. By using electron spin along with charge, new avenues for manipulating signal flow become available [29]. It is therefore possible to develop logic devices with additional capabilities that are more efficient, leading to logic circuits with improved characteristics [31]. In this paper we present a logic family exploiting a newly developed spintronic switch. The power dissipation of circuits made from this logic family is nearly independent of frequency, providing an advantage over CMOS for very high-speed applications.

The recent invention of the bipolar magnetic junction transistor makes possible a new class of logic families [14,27]. This "spin-transistor" provides large signal amplification, and the ability to exploit spin as an additional control allows for the modification and improvement of existing logic families. Emitter-coupled logic (ECL), a bipolar family used in very high-speed electronics [19], can be modified and improved using spin-transistors. Circuits designed with ECL and potentially our new ECL-based logic family dissipate minimal dynamic power, causing the power dissipation to be nearly frequency-independent. This characteristic is in contrast to CMOS circuits, in which dynamic power dissipation increases proportionally with frequency, as depicted in Fig. 1. The power dissipation of the emitter-coupled spin-transistor logic family is significantly less than ECL across all frequencies. A leftward shift in the frequency at which the two design styles intersect can be noted, making this logic family an effective technology for high-speed applications.

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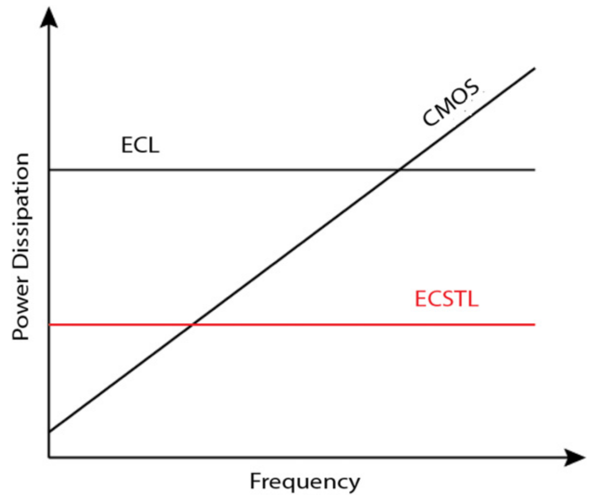

Fig. 1. Power dissipation of emitter-coupled spin-transistor logic (ECSTL) is less than CMOS at high frequencies and ECL at all frequencies.

The improved characteristics of this logic family are derived from exploiting the magnetic properties of the spin-transistors. We have constructed emitter-coupled spin-transistor logic circuits by routing the ECL differential amplifier currents to create magnetic fields that control the state of spin-transistors. This technique reduces current consumption, and allows for the logic stages to be cascaded similarly to conventional ECL circuits. The number of stages and devices required to implement logic functions is decreased, producing logic circuits that are superior in terms of speed, power, and area without any significant tradeoffs. In summary, the contributions of this work are:

- the first logic family based on magnetoresistive semiconductor heterojunction transistors,
- a spintronic logic family with cascadable stages using a high-permeability shielding material to concentrate a magnetic field, and
- the first logic family based on high-speed ECL structures making use of the spin-degree of freedom.

2. Spintronics background

The spin of an electron is a quantity that signifies its magnetic state within an atomic orbital and is related to its angular momentum. The spin of every electron is either positive or negative, and the Pauli exclusion principle prevents two electrons with similarly signed spins from occupying the same quantum state. Therefore, the total net spin of the electrons in most conventional materials is close to zero. In magnetic materials, interestingly, the presence of significant net spin magnetization results in a rich set of physical phenomena. While electron spin has found a ready application for computing in memory structures such as hard drives and magnetoresistive random-access memory (MRAM), the difficulty in cascading these devices has prevented its incorporation in logic structures.

2.1. Datta–Das current modulator

The original spintronic logic device is the field effect transistor proposed by Datta and Das in 1990 [9]. In their proposed switch, a source and drain composed of iron are separated by a semiconductor. The conductivity of electrons through the semiconductor is affected by the relative orientation of the spin in the semiconductor and iron boundaries. A gate voltage controls the spin-precession of electrons moving between the source and drain, thus controlling the flow of current through the transistor. There are many issues with this design, including the requirement that spin-polarized current be efficiently injected into the channel. This requires overhead for cascaded circuits that significantly degrades the utility of the current modulator.

2.2. Current-controlled magnetic tunnel junction

One prominent technique for designing spintronic logic gates uses a current-carrying wire to switch a magnetic tunnel junction (MTJ) between its conductive and resistive states [21,28]. An MTJ is composed of two ferromagnetic metals sandwiching a tunneling barrier. When the two ferromagnetic layers are aligned, there is minimal resistance impeding electron flow across the barrier; when the two magnetic layers are not aligned, there is a larger resistance. Using a current-carrying wire to create a magnetic field through the MTJ, the ferromagnet alignment can be manipulated, thereby switching the logic state. Multiple clock cycles are required to switch the MTJ state, requiring additional devices of another type that increase the delay and also consume area and power.

2.3. Magnetic quantum cellular automata

First proposed by a group at the University of Notre Dame in 1993, much has been achieved toward the use of quantum cellular automata (QCA) for logical computing. The original QCA logic family is based on the use of electric dipoles to define binary states. A circuit is divided into cells, in which there are two possible states, depending on the location of the electrons. Due to electrostatic repulsion between electrons, the state of one cell affects the state of neighboring cells. By setting the input to a QCA circuit, the remainder of the circuit is forced into the lowest energy state to minimize electron repulsion, thus producing the logical output. One of the primary strengths of this logic family is that signals can be propagated over long distances with only local transit of individual electrons. A functional majority gate was constructed in 1997, but operation has been demonstrated only at a temperature of 70 mK [2].

A modified QCA system has been proposed in which the spin of the electron is utilized. In this version of QCA, the spin of the electrons is used to create the repelling force rather than the electron charge. A simple magnetic QCA (MQCA) device was first published in 2000 [8], and an MQCA majority gate was demonstrated in 2006 [17]. Various researchers have also contributed to MQCA circuits [3,22,30]. Further development is challenged by signal integrity and other performance issues.

2.4. Magnetic domain-wall logic

Magnetic domain-wall logic makes unconventional use of the magnetic properties of nanowires. As nanowires can contain multiple regions of differing magnetic alignment called “domains”, the inventors of magnetic domain-wall logic perform logical computing by controlling the motion of domain boundaries [1]. A rotating magnetic field is applied to the spintronic circuit, and the flow of domain walls is affected by the shape of the nanowire junctions as well as the local domain orientations. This logic family performs computation without the motion of any particles, but through localized spin-flipping. This logic family faces several challenges, however, most notably the long period of time required to switch domain orientations through the cycling of the external magnetic field.

2.5. Spin accumulation

The logic family developed by Dery et al. utilizes spin accumulation to perform logical computation [10]. “Magnetologic gates” (MLGs) are the basis elements of this family, and consist of several