High-Performance Computing Based on Spin-Diode Logic

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ABSTRACT

The cascading of logic gates is one of the primary challenges for spintronic computing, as there is a need to dynamically create magnetic fields. Spin-diode logic provides this essential cascading, as the current through each spin-diode is modulated by a magnetic field created by the current through other spin-diodes. This logic family can potentially be applied to any device exhibiting strong positive or negative magnetoresistance, and allows for the creation of circuits with exceptionally high performance. These novel circuit structures provide an opportunity for spintronics to replace CMOS in general-purpose computing.

Keywords: Spintronic logic, spin-diode, spin-diode logic, beyond-CMOS, spintronics, emerging technology, next-generation computing, giant magnetoresistance

1. INTRODUCTION

Much work has been dedicated to the identification and development of magnetoresistive materials and devices[1–6]. Numerous two-terminal devices have been found to exhibit a resistance change in response to an applied magnetic field; this magnetoresistance occurs due to a variety of phenomena and with varying magnitudes and directions. Whereas conventional electric diodes are two-terminal devices with the electric current between the two terminals modulated by an electric field, these two-terminal magnetoresistive devices can be generally referred to as "spin-diodes" in which the electric current between the two terminals is modulated by a magnetic field.

Potential applications of "spin-diodes" are vast, and significant interest has been dedicated to the development of a logical computation system based on magnetoresistive switching. In order to create such a system, it is necessary to utilize the magnetoresistance of one spin-diode to create a magnetic field that affects other spin-diodes. The identification of an efficient mechanism for dynamically creating the required magnetic fields, however, has been a significant challenge, preventing the cascading of spin-diodes and impeding the progress of this research.

Spin-diode logic (SDL) is the only logic family in which two-terminal volatile magnetoresistive devices can be directly cascaded[7,8]. This logic family uses the current passing through the spin-diodes as the source of the magnetic field to switch other spin-diodes. Positive and negative magnetoresistance devices can be cascaded in this manner to create a functional logic family, allowing large-scale computing systems. Several types of spin-diode devices are discussed here, and each has intriguing prospects for replacing Si CMOS in general-purpose computing.

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2. SPIN-DIODE CHARACTERISTICS

A “spin-diode” is the spintronic analog of an electrical diode: the application of an external magnetic field greater than the spin-diode threshold B_T switches the spin-diode between an insulating state and a conducting state. Numerous phenomena have been demonstrated experimentally to produce this behavior, and the exact nature of the physics is not relevant to the logic structure. This SDL family can be applied to various types of magnetoresistance devices, with only minor differences in circuit topology. However, while the logic circuit structure is not significantly affected by the device behavior, the particular physical characteristics of the spin-diodes determine the computing system efficiency.

2.1. Positive vs. Negative Magnetoresistance

The sign of the polarity of the magnetoresistance signifies whether an externally applied magnetic field increases or decreases the resistance between the device's two terminals:

- Positive magnetoresistance: the resistance increases with increasing magnetic field, with an insulating state resulting from a large magnetic field. The device is in a conductive state when no field is applied. This characteristic is shown in Figure 1.
- Negative magnetoresistance: the resistance decreases with increasing magnetic field, with a conductive state resulting from a large magnetic field. The device is in an insulating state when no field is applied. This characteristic is shown in Figure 2.

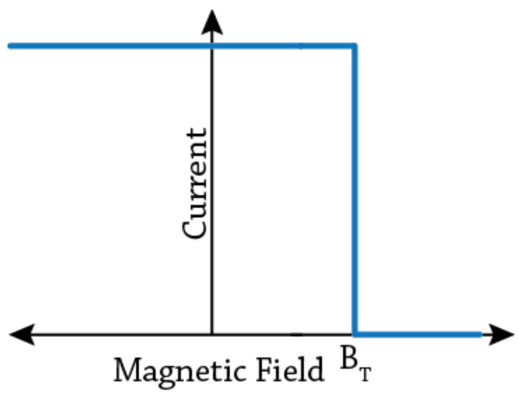

Figure 1. Ideal I-B characteristic for a spin-diode exhibiting unipolar positive magnetoresistance. The spin-diode switches from a highly conductive state to an open circuit for applied magnetic field greater than B_T.

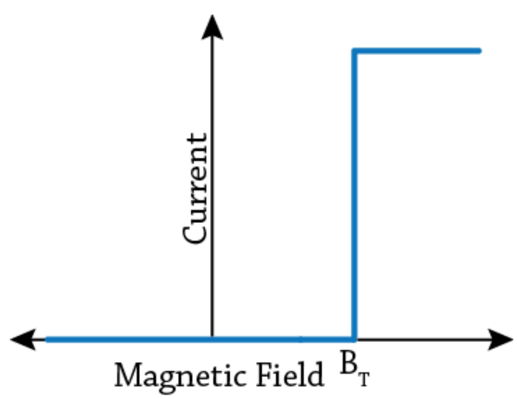

Figure 2. Ideal I-B characteristic for a spin-diode exhibiting unipolar negative magnetoresistance. The spin-diode switches from an open circuit to a highly conductive state for applied magnetic field greater than B_T.

Figures 1 and 2 are I-B (electric current vs. magnetic field) curves for the ideal unipolar case, in which a constant bias voltage is applied across the spin-diode. These figures show infinite resistance in the resistive state, and a constant low resistance in the conductive state, with an infinitely sharp transition at the threshold magnetic field B_T.

2.2. Magnetoresistance Symmetry

In many spintronic systems, magnetoresistive effects can be observed in response only to magnetic fields in particular directions. In the figures above, the resistance changes in response to a magnetic field in only one direction. While this is the case for some spintronic devices, other devices respond to magnetic fields in multiple directions.

As SDL does not involve the movement of the magnetoresistive devices or the magnetic field sources, magnetic fields can be created only along a single axis. There are therefore two relevant types of magnetoresistance symmetry:

- Unipolar: the resistance changes in response to a large magnetic field in only one direction, and not the opposite direction. This asymmetric case is shown in Figures 1 and 2.
- Bipolar: the resistance changes in response to a large magnetic field in both directions. In the ideal case of perfect symmetry, as shown in Figures 3 and 4, the response to a magnetic field is identical and of the same magnitude in both directions.

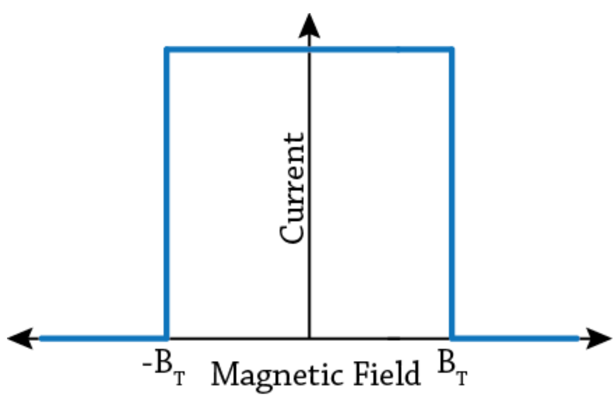

Figure 3. Ideal I-B characteristic for a spin-diode exhibiting bipolar positive magnetoresistance. The spin-diode is highly conductive in the absence of a magnetic field, and is insulating in the presence of a magnetic field in either direction along the magnetoresistive axis.

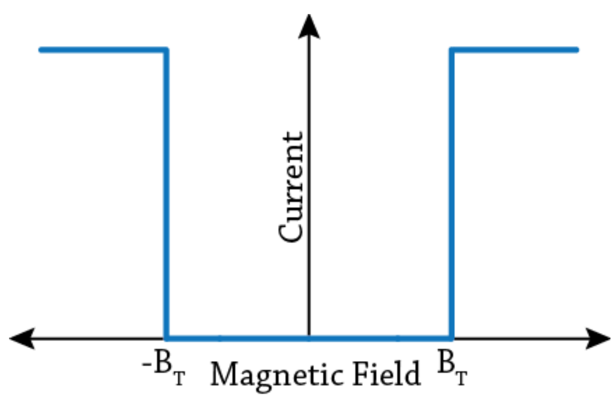

Figure 4. Ideal I-B characteristic for a spin-diode exhibiting bipolar negative magnetoresistance. The spin-diode is insulating in the absence of a magnetic field, and is conductive in the presence of a magnetic field in either direction along the magnetoresistive axis.

Figures 3 and 4 are I-B (electric current vs. magnetic field) curves for the ideal bipolar case. These figures show infinite resistance in the resistive state, and a constant low resistance in the conductive state, with an infinitely sharp transition at the threshold magnetic fields $-B_T$ and B_T.

2.3. Magnetoresistance Curve Non-Ideality

In a feasible physical system, the vertical line step functions in Figures 1-4 are not realistic; there is likely to be a smooth curve through which the resistance changes gradually with magnetic field. Additionally, it is unlikely that the two-terminal spin-diode can actually be completely insulating. In this realistic case, illustrated in Figures 5-7, there are intermediate states between the ideal and conducting states. The shapes of these curves determine the availability of various circuit designs and the suitability of these devices for the SDL structure.

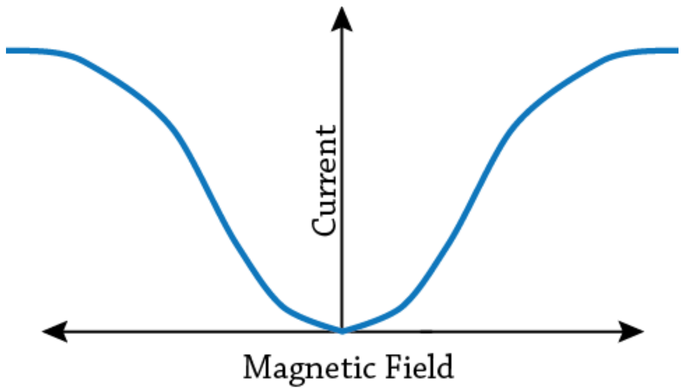

Figure 5. Realistic non-ideal I-B characteristic for a spin-diode exhibiting a symmetric bipolar negative magnetoresistance with a gradually increasing field-dependent current. There is no clear high- or low-current state, resulting in the lack of a magnetic threshold field B_T.

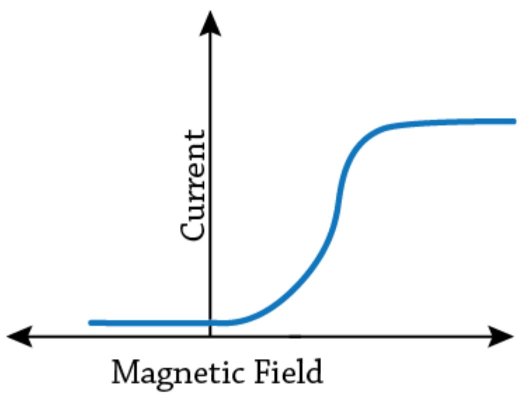

Figure 6. Realistic non-ideal I-B characteristic for a spin-diode exhibiting bipolar negative magnetoresistance with a gradually increasing field-dependent current, and a non-zero current in the low-current state.

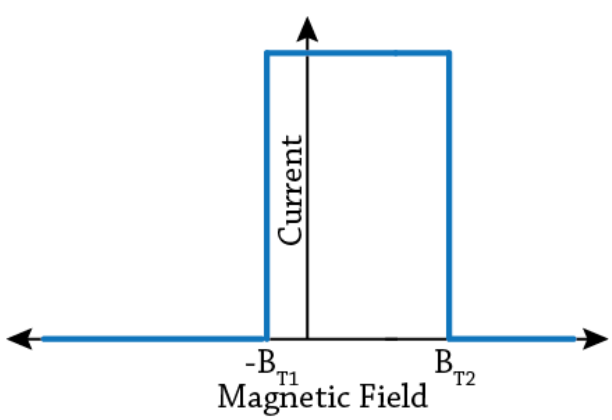

Figure 7. Non-ideal I-B characteristic for a spin-diode exhibiting bipolar negative magnetoresistance with asymmetric magnetic field thresholds.

The non-idealities in these I-B characteristics impact the circuit design and the availability of various basis logic functions. While such non-idealities limit the design space, such devices may still function as the basis elements of an SDL computer.

3. SPIN-DIODE LOGIC

3.1. Logic Family Structure

In SDL, a constant bias voltage is applied to all spin-diodes, and the current through each spin-diode is modulated by magnetic fields created by control wires. One terminal of the spin-diode is always connected to the circuit high voltage, while the other terminal is connected to the low voltage. For spin-diodes with behavior dependent on the polarity of the applied voltage, the constant voltage bias is applied with the proper orientation to ensure the correct mode of operation. The currents through the spin-diodes are routed through the control wires of other spin-diodes to create a magnetic field. This magnetic field through a spin-diode activates the magnetoresistance, switching the resistance state of the spin-diode.

Binary logic states are represented by the spin-diode currents as state variables. Large currents resulting from magnetic fields that impose the conductive state are a logical ‘1’, and small currents resulting from magnetic fields that impose the resistive state are a logical ‘0’. Multiple control wires can be used for each spin-diode, resulting in a total magnetic field equal to the superposition of the fields created by the control wires. Depending on the directions of the control currents, the magnetic fields created by the multiple control wires add or counteract. This cascading technique allows for the creation of complex circuits necessary for computing.

3.2. Spin-Diode Technologies

The SDL structure can potentially be implemented with a wide variety of spin-diode technologies. Initially, SDL was developed for InMnAs magnetoresistive semiconductor heterojunction diodes[9]. These devices, which exhibit bipolar positive magnetoresistance, have been studied previously, and basis logic gates and complex circuits can be found in [7, 8]. More recently, graphene nanoribbons and InSb diodes have been investigated, and preliminary results are promising. It is likely that many other technologies are candidates for the SDL structure, and the development of large-scale spintronic computing systems[10,11].

4. CONCLUSION

The purpose of this paper is to discuss the characteristics necessary for a spintronic device to form the basis of a SDL computer. The magnetoresistive properties discussed here may be achieved by a wide variety of technologies, inspiring an exciting application for devices that so far have remained of a purely scientific interest. By contributing a mechanism for cascading two-terminal magnetoresistive spintronic devices in a structure exhibiting exceptional speed and power efficiency, SDL provides an opportunity for a new generation of high-performance spintronic computers.

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