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Invited Paper

Cascaded Spintronic Logic Gates based on Graphene Nanoribbon Magnetoresistance: All-Carbon Spin Logic

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ABSTRACT

The extremely large magnetoresistance demonstrated with graphene nanoribbons (GNRs) is highly attractive as a potential spintronic switch. To develop a computing system in which GNRs can be cascaded requires a mechanism for transforming the GNR resistance into a magnetic field that can activate the magnetoresistance of other GNRs. All-carbon spin logic provides this necessary direct cascading by routing the GNR current through carbon nanotubes (CNTs) positioned adjacent to other GNRs. Applying a constant voltage bias across each CNT-GNR-CNT path results in a magnetic field-dependent electrical current that can perform logical functions, providing a scaling path toward large-scale computing systems.

Keywords: graphene nanoribbon, carbon nanotube, all-carbon spin logic, spintronic logic, beyond-CMOS computing, spin-diode logic

1. INTRODUCTION

The development of a computing system that efficiently exploits spintronic devices[1–4] requires a technique for directly cascading[5] the output of one spintronic switch to the input of another spintronic switch[6–10]. In the absence of such a direct cascading mechanism, additional circuitry is necessary to convert the output of one device into a form that can be utilized as the input of another device. This conversion/amplification circuitry must generally be implemented with conventional electronics, thereby reducing the improvement derived from the spintronic devices and preventing the full exploitation of the spintronic devices[11].

All-carbon spin logic[12,13] provides a direct cascading mechanism necessary to efficiently exploit the extremely large magnetoresistance[14–18] demonstrated in zigzag graphene nanoribbons[19–26] (GNRs) without additional cascading circuitry. In all-carbon spin logic, input carbon nanotubes[27–34] (CNTs) are positioned alongside both edges of a zigzag GNR. The currents through the CNTs control the edge magnetization of the GNR, thus controlling the GNR magnetoresistance. Output CNTs are connected to both ends of the GNR in this all-carbon system, with a constant voltage bias applied to each CNT-GNR-CNT path. Therefore, the current through the input CNTs modulates the current through the output CNTs.

Cascading is achieved by using the output CNTs of one all-carbon spin logic gate as the input CNTs that control the GNR magnetoresistance in other all-carbon spin logic gates. Individual GNR gates naturally perform the OR and XOR functions, which can be cascaded to perform any complex logic function. In addition to its compact nature resulting from the use of low-dimensional carbon materials, the dependence of the speed on electromagnetic wave propagation provides the potential for extremely high-speed and energetically efficient computing systems.

2. ALL-CARBON SPIN LOGIC SWITCH

The basic component of all-carbon spin logic is shown in Figure 1, composed of two CNTs adjacent to a GNR. A voltage bias is applied to the GNR and each of the CNTs, and there is therefore always current flow through each of these components. As the system performs logical operations, the magnitude of the current at various points within the system vary, though the current direction is always constant. In this logic family, low currents represent logical ‘0’ and are written here as I_L, while high currents represent logical ‘1’ and are written here as I_H.

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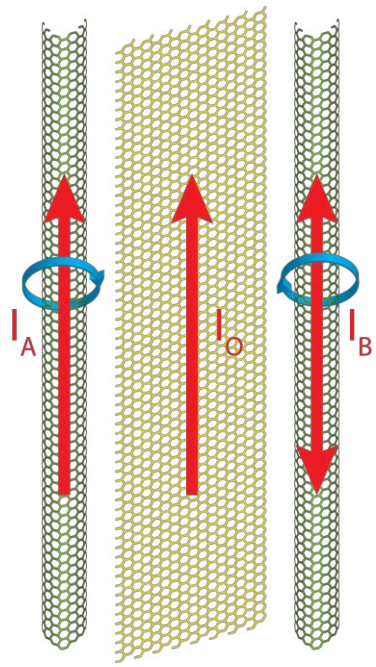

Figure 1. Basis all-carbon spin logic switch with two CNT control wires. The current direction within any CNT or GNR is fixed by a constant voltage bias.

When the magnetic ordering at the two edges of the GNR is aligned in the same direction, the GNR is in a highly conductive state; when the edges have opposite magnetic ordering, the GNR is in a highly resistive state. Therefore, as a constant voltage bias is always applied to the GNR, switching of the relative edge magnetization causes a switch between a high I_H current and a small I_L current.

This switching can be controlled by the application of current through the CNTs adjacent to the GNR edges. The cascading scheme (see section 3) ensures that the currents through the CNTs also represent binary '1' and '0' values with currents of I_H and I_L, respectively. Large '1' currents are sufficient to switch the local GNR edge magnetization, while small '0' currents are not. As shown in Figure 1, these currents flow through the CNTs either in the same direction or in opposite directions, thus determining the interactions between the binary current values and therefore the logical operations. As mentioned previously, it is assumed that these currents result from a fixed voltage bias present in the circuit; it is therefore not possible to change the current direction, which would enable reconfigurable logic.

Table 1 shows the binary logical operations performed by the CNT/GNR logic gate. When the input current through both CNTs flows in the same direction, the GNR output current is large when there is a '1' current in exactly one of the two input CNTs; the GNR output current is small when there is a '1' current in either both or neither CNT. Therefore, when both input currents flow in the same direction, the logic gate performs the XOR function. When the two CNT currents flow in opposite directions, the output GNR current is large whenever at least one input CNT current is large, thereby performing the OR function.

3. CASCADED ALL-CARBON SPIN LOGIC GATES

The logic gates of Figure 1 can be cascaded with the technique of spin-diode logic[35–38], with the GNRs considered as spin-diodes that are controlled by CNT control wires. The currents through the GNR spin-diodes are therefore provided to the CNT control wires of other logic gates. This is shown in Figure 2, where the GNR output currents from XOR1 and OR1 are used as the input currents to XOR2. This logic circuit therefore performs the half-adder function, computing the Sum and Carry values. The cascading mechanism central to this half adder can be extended generally to all-carbon spin logic circuits, as described in previous work[12,13].

Table 1. Logical functionality of the basis all-carbon spin logic switch. Positive current values refer to currents flowing toward the top of the page and negative current values refer to currents flowing toward the bottom of the page.

I_A	I_B	I_O
$+I_L$	$+/- I_L$	$+I_L$
$+I_L$	$+I_H$	$+I_H$
$+I_L$	$-I_H$	$+I_H$
$+I_H$	$+/- I_L$	$+I_H$
$+I_H$	$+I_H$	$+I_L$
$+I_H$	$-I_H$	$+I_H$

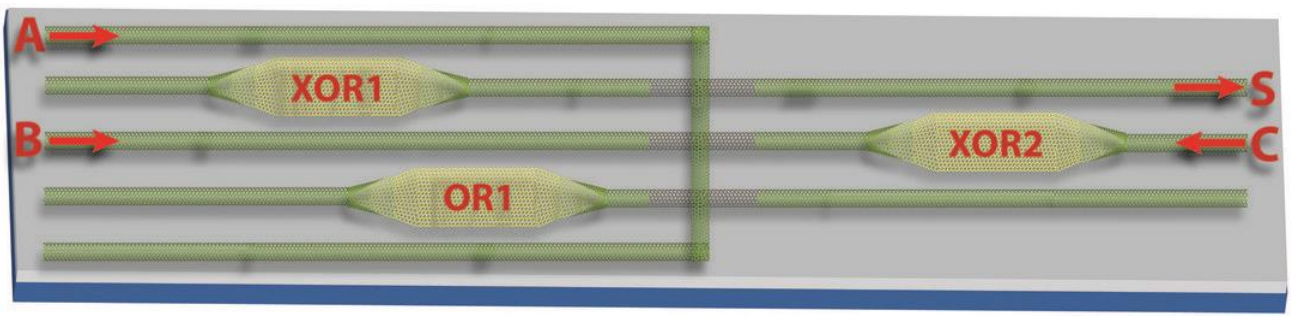

Figure 2. All-carbon spin logic half adder in which inputs A and B control both XOR1 and OR1, with the outputs of XOR1 and OR1 used as the inputs of XOR2. A ground node is connected to the CNT to the left of XOR2 to provide proper electrical behavior.

4. CONCLUSIONS

All-carbon spin logic exploits the magnetoresistance of GNRs and high current density of CNTs to enable a spintronic computing system composed solely of carbon. The current magnitude-based CNT input binary signals enable basis logical OR and XOR functions, with current magnitude binary outputs produced by the GNR. As the inputs and outputs are of the same type and within the same range, direct cascading is achieved by using the GNR output currents as CNT input currents. Furthermore, the use of currents rather than voltages to encode binary information enables extremely high-speed switching, as propagation through the interconnect primarily relies on electromagnetic wave propagation rather than the resistor-capacitor delay present in conventional systems. This all-carbon spin logic paradigm is therefore an exciting technology for the next generation of computing.

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