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Magneto-reprogrammable semiconductor logic at room temperature

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Abstract

Chameleon processor provides novel functions such as programmable logic operation and non-volatile built-in memory. We introduce a new semiconductor magneto-electronic device that could be a good candidate of chameleon process. It can offer excellent fan-out if combined with low power spintronic devices. Impact ionization is responsible for device operation in which magnetoconductance depends on Lorentz force deflection of carriers and subsequent recombination. Our device can be characterized as a current switch with ON and OFF states. In this work, we fabricated this prototype device, which have demonstrated magnetoconductance ratios of more than 500% in a magnetic field of 1,000 Oe at room temperature. Various Boolean logic gates were tested for a circuit composed of this device, demonstrating elementary functions of the chameleon processor.

Modern digital electronics technology is facing the demand to process larger amounts of data in shorter periods of time, using chips that are compatible with low power handheld and portable devices. Today's information technology is dominated by silicon-based Field Effect Transistors. They offer excellent device performance, but suffer from high operating power and quiescent power. It would be desirable if we could combine the low power characteristics of spintronics with the good scalability of the conventional semiconductor technology. In addition to this need, more radical ideas, so called chameleon processor, have been suggested: logic gates and arrays of gates having functions that can be reconfigured on time scales as short as nanoseconds. In this new concept, there is no distinction between software and hardware. Data applied as part of an input stream (software) can be used to modify the function of the hardware. The result of this functional flexibility can be a dramatic increase in computational speed, along with a decrease in the size and operating power of the microprocessing chip.

Several efforts have been paid for realization of the chameleon processor in spintronic field such as magnetoelectronic Boolean logic devices based on spin valve [1], MTJ [2], magnetic domain walls [3], patterned nanomagnets [4], Hall voltage [5] and magneto-optic readout [6]. However, they have suffered from a low signal-to-noise ratio and other intrinsic weaknesses that are not adequate for integrated operation. Here, we have redesigned the magnetoelectronic logic operation at the lowest level and introduced magnetic field as a digital input in a way that is uniquely different from the previous approaches. Our device is made of non-magnetic semiconductors and works as an electrical switch in which the switching operation is determined by the direction of an external magnetic field. We fabricated several circuits with this device and demonstrated magnetic-field-controlled reconfigurable Boolean logic gates at room temperature [7].

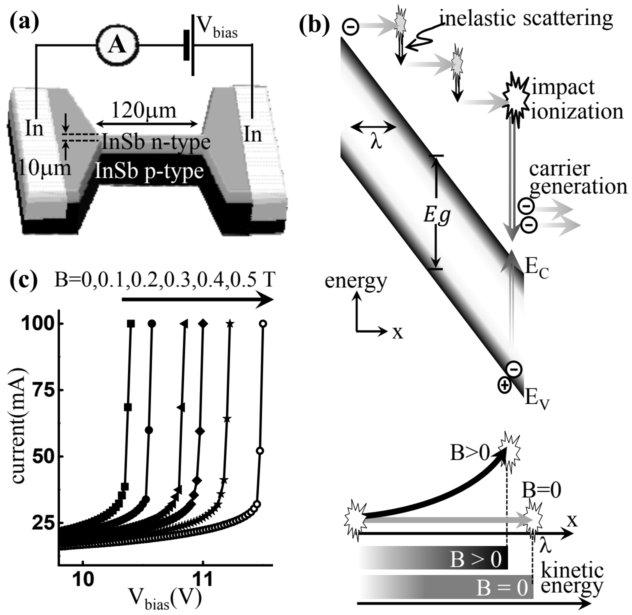

Fig. 1 (a) A p-n bilayer impact ionization device. (b) Top panel: Schematic diagram illustrating carrier generation. An energetic electron ionizes a valence electron and generates new carriers. Bottom panel: The deflection of the electron trajectory by magnetic field. For a given mean-free-path (λ), an electron having the trajectory at non-zero magnetic field (B>0) gains less kinetic energy than that with zero magnetic field (B=0) and carrier generation is suppressed. (c) Current-voltage curves for a variety of values of magnetic field (B). The current abruptly increases at the threshold voltage which depends on the applied magnetic field [7].

We fabricated a magnetic-field-controlled electrical switch using indium antimonide (InSb). The device has a 0.2-μm-thick n-type InSb top layer and a 6-μm-thick p-type InSb bottom layer (Fig. 1 (a)). The core of working principle in our device is impact ionization phenomenon [8]. When a high bias voltage is applied, electrons accelerate to a high speed. If the kinetic energy acquired from the electric field equals the ionization energy, impact ionization occurs. Upon impact with the lattice, the electron expends its kinetic energy on ionizing a valence electron (top panel in Fig. 1 (b)). This process produces carrier electrons and abruptly increases the electric current in the device. Because the device shows such an abrupt change in current, two electrical conducting state can be defined: high-current state (ON, digital '1') and low-current state (OFF, digital '0'). To achieve impact ionization, the electron should accumulate kinetic energy despite the inelastic scatterings. Magnetic field affects this carrier generation process. When magnetic field is applied, the Lorentz force deflects the electronic trajectory, and the net gain of kinetic energy for a given path length is reduced (bottom panel in Fig. 1 (b)) [9]. Thus, the deflection of the electronic trajectory caused by magnetic field affects ON/OFF operation of our device, which leads to the magnetic-field-controlled electrical switch.

New functionalities for information processing are demonstrated by our device [7]. With Boolean logic circuits fabricated with this devices, we have demonstrated the following logic functions: COPY, NOT, AND, OR, NAND, NOR, XOR and XNOR. These circuits show reconfigurable functionality where various logics can be performed with a single circuit and this logic operation is changed by external inputs such as a magnetic or electric signal.

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