Magneto-Electric Spin-Orbit Logic and Spin-Orbit Memory Building Blocks for Beyond CMOS

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As nanoelectronics approaches the nanometer scale[1-4], a massive effort is underway to identify an energy efficient scalable logic technology beyond Complementary Metal Oxide Semiconductor (CMOS) transistor based computing[5-7]. Such computing technology needs to improve switching energy and delay at reduced dimensions[8], allow improved interconnects[9] and provide a complete logic/memory family. However, a viable beyond-CMOS logic technology has remained elusive. Here, we propose a scalable spintronic logic device which operates via spin-orbit transduction[10-16] combined with magneto-electric switching [17-20]. The Magneto-Electric Spin-Orbit (MESO) logic enables a new paradigm to continue scaling of logic[8,9,21] to switching energies of <10aJ per device at switching delay of < 100 ps.

The MESO devices scale energy strongly and favorably with critical dimensions, showing a cubic dependence of switching energy on size W, $E_{MESO} \propto W^3$, and a square dependence on voltage V, $E_{MESO} \propto V^2$. This excellent scaling is obtained thanks to the properties of the spin-orbit effects (e.g. inverse spin Hall effect (ISHE) and inverse Rashba-Edelstein effect (IREE)) and the dependence of capacitance on size. The operating voltages for these devices are predicted to be < 100 mV allowing a significant jump ahead of historic trends of scaling voltage with size and corresponding reduction of energy[22]. Interconnect resistance is a critical obstacle for scaling below 10nm dimensions. We show that MESO logic is amenable to operating with even highly resistive interconnects (100 μΩ.cm-1 mΩ.cm) which opens up the possibility to use nanometallic (width << bulk electron mean free path) or doped semiconducting wires[23] for short range (< 1 μm) interconnects. A dimensionally scalable, CMOS compatible, non-volatile logic family based on MESO may enable the next energy efficient multi-generational scaling technology for computing devices. In Figure 1A, 1B, we show a schematic a MESO device operating with magneto-electric switching nodes and utilizing spin orbit read out. We utilized vector spin circuit methods [26] to model the magnetization switching (Fig 1C, 1D) with Magneto-electrics and spin orbit coupling for spin to charge conversion. A low voltage interconnect with cascaded MESO devices is shown in Fig.1E.

Towards the magneto-electric (ME) control of devices, we show ME control of exchange bias using a multi-ferroic. We present the electrical control of exchange bias on a laterally scaled ferromagnet that is exchange coupled to the multi-ferroic $BiFeO_3$ at room temperature. We show that the exchange bias in this bilayer is thermally robust, electrically controlled and reversible. We also show indications that magneto-electricity enters a new and exciting paradigm when the spatial dimension of the magnetic order of the ferromagnet and the multi-ferroic order converge. We anticipate that magneto-electricity at such scaled dimensions provides a powerful starting paradigm for computing beyond the modern nanoelectronics transistors by enabling a new class of non-volatile, ultra-low energy computational devices.

On the other hand, spin memory provides an opportunity to significantly enhance the available on-chip embedded memory to boost computing performance. Switching of perpendicular magnetization is a technological priority for the development of high speed, low energy, and high density spintronic memory. Here we study the generation of perpendicular spin torque using spin-orbit effects to switch a perpendicular magnet. In particular, we focus on the exchange-bias/dipole-field induced perpendicular switching of a PMA magnet. We show that, in presence of an external exchange bias or a dipole field, a field-like component of the spin-orbit torque directly generates the perpendicular spin torque necessary to deterministically switch perpendicular magnetization.

In summary, spin-orbit effects show potential for highly integrated nano-electronics beyond the advanced CMOS era. The exploitation of quantum nano-magnetic effects (exchange bias, magneto-electricity, spin-momentum locking) enable a new class of devices with the ability to be integrated into very large scale integrated circuits for energy efficient computing.

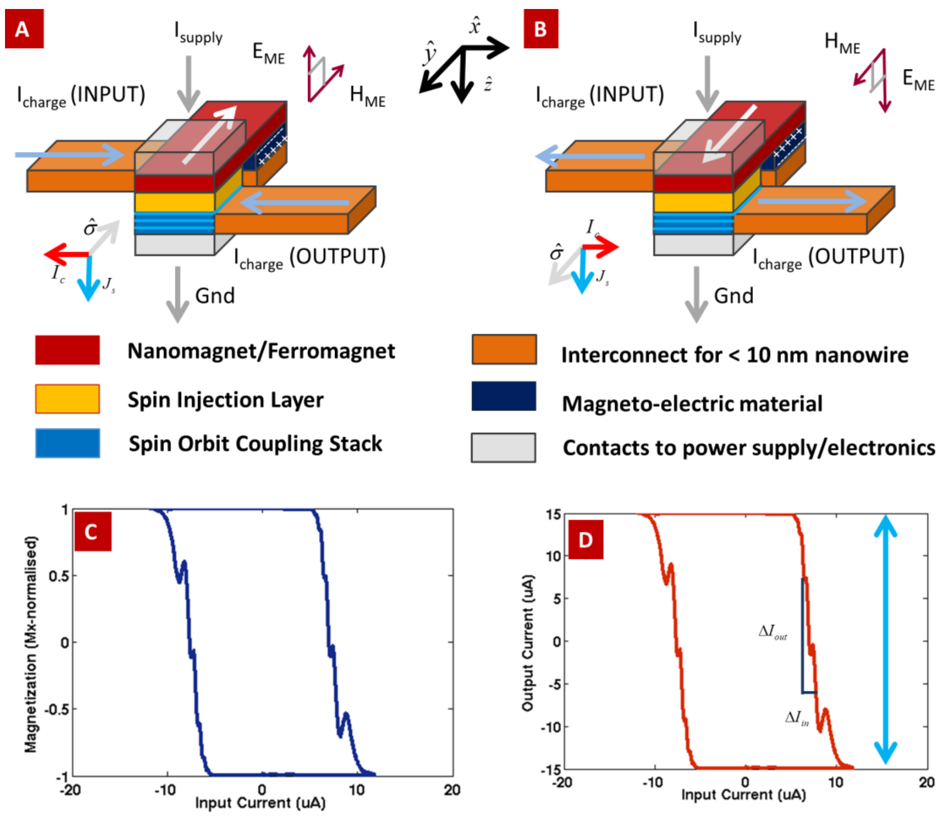

Figure 1. Charge in - charge out inverting logic unit for MESO. A) Positive charge current (1) to negative charge current (0) conversion. B) Negative charge current (0) to positive charge current (1) conversion. C) DC transfer function for magnetic state with input current. D) DC transfer function for output current vs input current modeled using vector spin transport [21]

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