New Materials and Structures for Spin Logic and Memory Applications

The increase in energy dissipation with device density is a major obstacle for further miniaturization of electronic devices. Spin-based devices offer a transformative advantage over charge-based devices. Spin-based systems are inherently non-volatile, meaning they require zero quiescent power. This promises significant energy savings over purely charge-based electronics, allowing the limits of device density to be increased beyond limits imposed by manipulating charge alone. Spin-based devices already under intense investigation include non-volatile spin torque transfer logic (NV-LOGIC), spin torque transfer random access memory (STT-RAM), and spin torque transfer oscillators (STTO). The non-volatility of spin-based devices offers an additional important advantage over the current charge-based paradigm by allowing one to combine logic and memory functions in the same element, acting as programmable switches, flip-flops, or elements in a memory or look-up table.

To augment - or eventually replace - traditional semiconductor devices, there are crucial areas in which spin-based devices must meet or substantially exceed current performance criteria: speed, switching time, output signal, and energy per switching event. All of these are interrelated aspects of energy dissipation. Analogous to the gate voltage in a semiconductor transistor, is spin-torque switching efficiency, which implies a critical switching current I_C and a device resistance-area product *RA*. Further, analogous to the channel current is the resistance change due to magnetization variation ΔR, the output signal. Finally, specific to spin-based devices is the switching time t_{sw}, which - in addition to I_C - is controlled by magnetization M_S of the material and its anisotropy *K*. Both *RA* and I_C contribute to characteristic I^2R power dissipation, and the switching time t_{sw} thus (roughly) controls the total energy budget for a given power.

Contemporary devices operate at frequencies of tens of GHz or greater, implying that switching times in the sub-100 ps range are required. Optically-driven magnetization switching has been demonstrated in the sub-ps regime, making this one area of potential advantage for spin-based devices. By balancing the currents required for spin-torque switching with switching times, both of which can be manipulated through interdependence with *K* and M_S, the total energy dissipation can be considerably reduced. Though non-volatility is a key advantage of spin-based devices, the relative signal change ($\Delta R/R$), analogous to the "on/off ratio") currently available (~10) is well below those of traditional semiconductor devices. If MR ratios in the 10^5-10^6 range can be realized, this will allow the creation of 'spin switches' that can be used for generic reprogrammable logic with essentially zero quiescent power.

We propose to develop new materials and device concepts for spin-based nonvolatile logic and memory devices. Research and development objectives include magnetic materials for low energy fast switching, low symmetry barrier materials for tunnel junction structures with high magnetoresistance (MR), and oxide-based materials for spintronics.

Magnetic Materials for Low Energy Fast Switching

For spin-based devices, both switching energy and switching time are of critical importance. A reasonable estimate of the minimal switching energy is provided by the barrier for switching a thermally stable bit, $40k_B\text{T} \sim 1\text{eV}$. This is a very small energy, corresponding to performing a logic or storage operation with one volt using 1 electron. The minimum practical time for switching is a few times the ferromagnetic resonance (FMR) period, traditionally thought to be several nanoseconds. This is not a short time by the standards of current devices, emphasizing the need for faster switching. Further, it is difficult to activate an ultrafast switching process commensurate with minimal energy dissipation. Operations on magnetic bits are usually performed with magnetic fields, requiring currents which (at room temperature) imply significant dissipation. Our goal is to switch magnetic systems using energies of order 1eV in sub-nanosecond time frames. This can be accomplished using the angular momentum carried by spin-polarized currents using a properly designed materials set. The material set requires very low magnetization of the switching element and highly spin-polarized currents. Every electron carries a quantum of angular momentum. If we minimize the total amount of angular momentum in the bit, we reduce the number of electrons necessary for switching. The requirement for a thermally stable bit puts a minimum on the product of the magnetization and anisotropy. Thus, a lower magnetization requires a higher anisotropy field, which yields a higher FMR frequency and faster switching. Switching energies close to 1eV and deep sub nanosecond switching are feasible using this approach. Possible materials for the switched layer include Gd compensated CoFe.

Low Symmetry Barrier Materials for Tunnel Junction Structures with High MR

Currently, the most commonly used materials set for spin-torque-based devices is based on CoFeB/MgO magnetic tunnel junctions (MTJs), producing tunnel magnetoresistance values as high as 600% at room temperature. The high symmetry (bcc) CoFe electrode, necessitated by the spin filtering properties of MgO, lead to a low (cubic) anisotropy and a large M_S. We propose to investigate novel hcp barrier and hcp (fcc) electrode combinations. Using a different family of electrode materials gives access to a broader range of desirable properties (K, M_S) while maintaining very high MR. Hexagonal boron nitride (hBN) is one of the most promising candidate material we have identified. Our preliminary band structure calculations indicate that epitaxial MTJs with hBN barriers show symmetry-based spin filter effects similar to MgO-based MTJs. Furthermore, hBN appears to be one of the few dielectric materials with a hexagonal structure and good lattice matching with hcp Co. Two types of electrode-barrier combinations that enable different functionalities will be considered, including a PMA reference layer in hCo/hBN/hCoPt and an in-plane free layer in hCoPt/hBN/NiFe.

Oxide-Based Materials for Spin Logic Devices

In contrast to conventional magnetic tunnel devices that use ferromagnetic metal electrodes for providing spin-polarized carriers, a ferromagnetic insulating or semiconducting barrier can be used as a spin filter to generate a polarized tunneling current. Theoretically, one expects spin filtering with magnetic insulating tunnel barriers to be more robust against structural disorder than the symmetry-based spin filtering in CoFe-MgO. The spin-filter effect may potentially enable fabrication of spin-electronic devices with very high MR that act as a ‘switch’, allowing spin logic and other novel applications. While there have been some recent encouraging results in oxide-based spin filters that perform at room temperature, understanding and controlling their structure, stoichiometry and magnetic properties - particularly in ultrathin films - remains challenging. Our work in oxide spintronics will combine state-of-the-art growth using with advanced interface characterization techniques including magnetic x-ray reflectivity, polarized neutron reflectivity, spin-polarized tunneling measurements and *ab initio* density functional theory techniques. Spinel ferrites with higher T_C, such as $NiFe_2O_4$ (T_C= 850 K) and $CoFe_2O_4$ (T_C=790 K), are of particular interest for applications. Recent reports have confirmed spin filtering effects,**Error! Bookmark not defined.** although much work remains both in terms of fundamental understanding and heterostructure growth control.