Statistics of Spin-Torque Switching

Bill Butler, Pieter Visscher, Tim Mewes, Claudia Mewes
Center for Materials for Information Technology (MINT)
Department of Physics
University of Alabama
Tuscaloosa, AL, U.S.A.

Spin-Torque switching is a phenomenon in which spin-polarized currents transfer angular momentum between two ferromagnetic layers. This transfer of angular momentum can cause the relative orientation of the magnetization of the two layers to change, hence spin-torque switching. Spin-torque devices usually consist of two thin ferromagnetic films separated by a non-magnetic layer. The thickness each of the layers is typically on the nanometer scale. The lateral size of the devices is in the range of 10-200nm. Recently it has been discovered that a materials set, (100)CoFe ferromagnetic layers with (100) MgO tunnel barrier, that has been known to give high spin polarization and high spin-torque can be made to have a net magnetic anisotropy that is perpendicular to the layers. Perpendicular spin-torque devices, for given damping, spin-torque efficiency and thermal stability have a significantly lower critical current for switching.

In this talk we will first briefly review spin-torque theory and derive the Landau-Lifshitz-Gilbert-Slonczewski (LLGS) equation. We will then use this equation to discuss the statistics of spin-torque switching for both perpendicular and in-plane devices using the macrospin approximation. In the macrospin approximation, the entire free layer of the device is treated as single spin. We treat the statistical nature of the switching using the Fokker-Planck equation. The Fokker-Planck equation allows us to calculate the probability of extremely unlikely events that would be difficult to simulate directly from the LLGS equation. We also obtain approximate analytic solutions for both the high current and low current regimes relevant to the write soft error rate (WSER) and read soft error rate (RSER) respectively.

Both perpendicular and in-plane devices when treated in the macrospin approximation show exponential tails in the switching probability for long times and large currents/voltages (compared to the critical current or voltage for switching). These tails are of the form,

$$\ln P_{ns} \approx -2\left(\frac{\overline{I}}{I_c}-1\right)\alpha\gamma\mu_0 H_K t\,, \qquad (1.1)$$

for perpendicular devices and

$$\ln P_{ns} \approx -2\left(\frac{\overline{I}}{I_c}-1\right)\left(1+\frac{M_S}{2H_K}\right)\alpha\gamma\mu_0 H_K t \qquad (1.2)$$

for in-plane devices. Perpendicular devices are still superior because the in-plane devices have a higher I_c by the factor $\left(1+\frac{M_S}{2H_K}\right)$.

These tails in the write error rate would make it very difficult to achieve target error rates. Recent measurements on relatively large perpendicular spin-torque devices appear not to show the predicted tails. These devices are too large to apply the macrospin theory. Target device sizes for many applications such as DRAM replacement will probably place them in the single domain regime. A critical question that must be answered soon is whether or not macrospin STT-RAM device scaling will return as devices are fabricated in the single domain size regime. We will discuss some reasons to be hopeful that this effect may not appear.