Spin Transfer Torque in Ferromagnetic Materials

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Spin transfer torque is a mechanism that could greatly reduce the switching time in magnetic multi-layer structures. This technique involves putting current through the magnetic structure, where the current will be polarized from one layer and the free layer will be affected. The polarized will transfer angular momentum to the free layer, resulting on a torque on the magnet. Magnetic multilayers utilize the giant magnetoresistance effect in order to store data. Devices utilizing spin transfer torque can be faster, smaller, and require less power to switch. Simulations show that a permalloy nano-layer device could switch in as little as 0.15ns with a current as small as 0.98 mA. Similarly, cobalt multi-layers would switch in 0.11ns with 1.96mA of current.

INTRODUCTON

The concept of spin transfer torque has recently garnered much attention do to its promise in the electronics industry. The ability to use spin transfer torque to switch magnetic layers could greatly improve magnetic random access memory (MRAM). [1] Not only will the magnetic switching occur faster than current devices, but also could have a much greater device density. The electronics industry in constantly looking for ways to make devices smaller and faster, and if spin transfer torque can be utilized; it was the potential to improve on both of those problems.

THEORY

The devices that are used in spin transfer torque devices are constructed of a pinned magnetic layer, a non-magnetic spacer, and a free magnetic layer. The free layer is generally made up of a magnetic material, in this case either permalloy ($Ni_{80}Fe_{20}$) or Cobalt about 5 nm thick. [2] The spacer is made up of a conducting but non-magnetic material, typically MgO. The pinned layer is another magnetic layer. It can be pinned either by being constructed on top of a anti-ferromagnetic layer, or by having it be considerably larger than the free layer, so it is effectively fixed in regard to the free layer. The device is approximately 10 micrometers wide by 20 micrometers in length.

The devices can than be subdivided into nanopillar devices or point contact devices. A nanopillar is designed such that the free, spacer and pinned layers and constructed with the desired dimensions, and are sandwiched between conducting materials wider than the layers. The current is then easily applied to the larger layers. In the point contact geometry, the current is directed only through a small contact that was created using lithography techniques. The spacer is thin enough that no significant diffusion of the electrons will occur, and therefore the current will be directed only to the area directly under the point contact. [2]

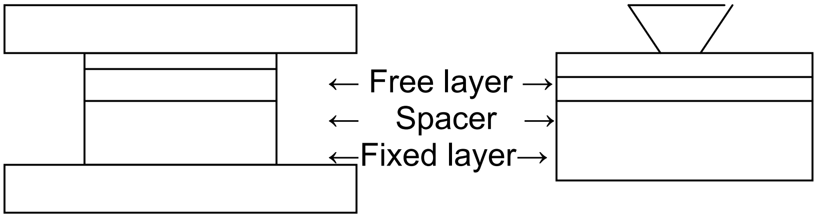


Fig. 1 shows the nanopillar structure (left) and the point contact structure (right)

It is necessary to use one of these methods to direct the current to a small area. Spin transfer torque is only seen in high current density structures, on the order of 10^12 A/m^2. However, when the current is only passing through an area of 100nm or less, this high current density corresponds to a few milliamps, a reasonable number.

The giant magnetoresistance effect governs the different states associated with magnetic layers. [1] When the layers line up with a parallel alignment, there is a low resistance in comparison to the anti-parallel state. Electrons of different spins at the Fermi energy level have different band structures which lead to a different density of states. This density of states is proportional to the scattering rate through magnetic layers. Therefore the two different magnetic states of the anti-parallel alignment will lead to higher scattering of all the incoming electrons, and thus a greater resistance. The giant magnetoresistance effect has the ability to alter the resistance of the device by about ten percent. This phenomenon is what determines the logic state, 1 or 0 of the multilayer. Spin transfer torque can be seen in magnetic multilayers. The torque relies on the fact that the magnetic layers will polarize a current that is applied the structure. As the current passes through the first layer, the spin of the electrons become orientated in the direction of that layer. This polarized current then passes through the second layer and again, the electrons align to the direction of the magnetic moment. However, because angular momentum needs to be conserved, the difference in the orientation of the electrons caused from passing through the magnetic layers is seen as a torque. If the current was first passed through the fixed layer, the torque is absorbed into the free layer. [1] If the current was first passed through the free layer, the fixed layer only allows the portion of the magnetic moment that both layers have in common through, and reflects back upon the free layer the remaining portion and a torque again acts on the free layer. These situations lead to the torque being applied to the free layer in different directions. Therefore, the torque can either force the magnetization of the free layer to the direction of the fixed layer magnetization, or can pull it away from the fixed layer. If in this case the torque is large enough, it can lead to switching of the magnetic moment.

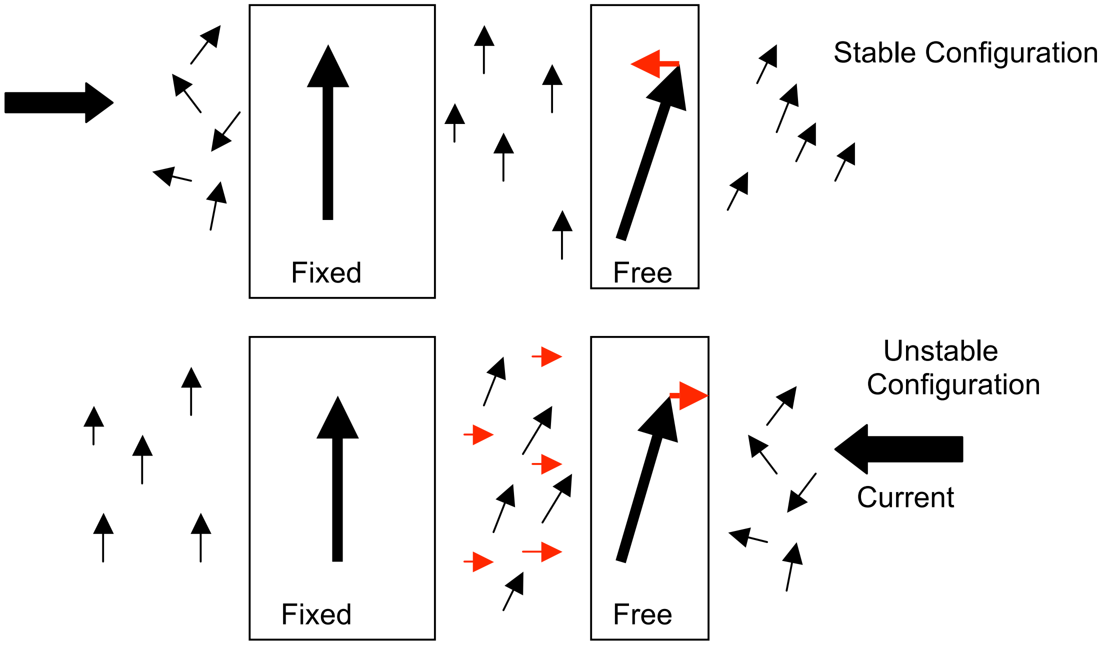
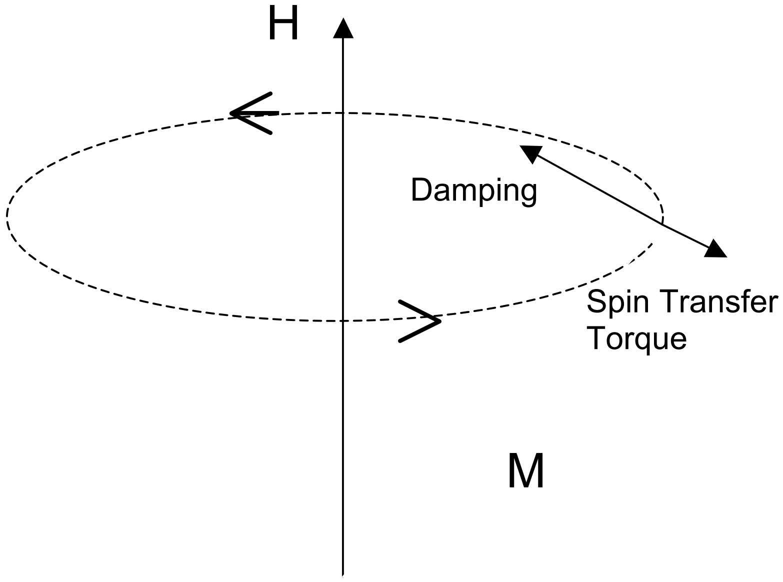


Fig. 2 shows the torque seen on the free layer when it is subjected to current in opposite directions. When the current was incident from the right, the free layer returned to the parallel state. Conversely, when the current was placed from the right, the torque pushed the free layer magnetization away from that of the fixed layer.

The movement of the magnetic moment is defined by the Landau-Lifshitz-Gilbert equation. [1] This equation is seen to have three terms. The first term is a procession term that describes the fact that the magnetic moment will rotate around the applied field. The second term shows the damping torque. This torque will act to align the magnetic moment to the applied field. The last torque is the spin transfer torque. This torque can either act with the damping torque or against it depending of the direction the current in applied from.

$$\frac{d\vec{M}_{free}}{dt} = -\gamma\, \vec{M}_{free} \times \vec{H} + \alpha\, \vec{M}_{free} \times \frac{d\vec{M}_{free}}{dt} - I\,\gamma\, ST\, \vec{M}_{free} \times (\vec{M}_{free} \times \vec{M}_{pin})$$



Where γ is the gyrometric ratio, H is the local magnetic field, α is the damping coefficient, M is the magnetic moment of the respective layers, and ST is the torque origination from spin transfer. [5]

Depending on the direction and strength of the current, the magnetic moment can end in any one of three states. If the damping and the spin transfer torque work together, the magnetic moment will align with the applied field. If the current is applied in the other direction, the spin transfer torque and damping could equally work against each other such that the magnetic moment reaches as steady state and continually precesses around the applied field. [2] This usually occurs when the damping increases with increasing angle, and eventually equals the torque caused by the spin transfer. Another end state is complete switching of the magnetic moment. The moment will move away from the applied field until a critical angle is reached, in which case it will drastically switch directions and spiral into the other direction. This is the case that is necessary for magnetic layer switching.

METHOD

Simulations provide much information about the dynamics of magnetic switching in spin torque devices. Simulations occur on a timescale that allows for the dynamics to be witnessed. It also allows for more ease in altering the parameters of the device to notice how they impact the performance.

Simulations were carried out using the Object Orientated MicroMagnetic Framework (OOMMF). Using this program, the device was specified. The dimensions of the device specified were a 1024nm by 2048nm structure with a 20nm thick fixed layer, a 5nm spacer layer, and a 5nm free layer. Current was directed through a 128nm diameter circle in the center of the structure. Exchange energy was set at 13E-12 J/m for permalloy or 30E-12 J/m for cobalt. [4] The exchange energy between the spacer and the other layers was zero. For permalloy, a value of 860E3 A/m was used for the saturation magnetization, with 1400E3 being used for cobalt. The spin current polarization was set to 0.37 and the torque asymmetry parameter was 2.

It was found that the smaller dimensions of the simulated structure was resulting in waves that were emitted and were being reflected back toward the center of the structure, affecting the results. [3] Therefore the demagnetization was varied such that it remained constant, 0.014, within 300nm from the center of the structure. After this, the demagnetization coefficient was slowly increased using a hyperbolic tangent function. This allowed the simulation to more accurately mimic a larger magnet.

Initially, the layers were in a parallel configuration. A 3kOe external field was applied in order to hold them in this configuration. Current was applied such that the free layer would switch. The current applied was varied, and the time for magnetic switching was observed to see how increased current would affect the switching time. In order to obtain a hysteresis loop, the current was increased in increments, and was reversed after switching occurred in order to bring the magnets back to a parallel arrangement.

RESULTS

For permalloy, parallel to anti-parallel switching occurred when 0.89mA of current was applied. Anti-parallel to parallel switching occurred at 0.22mA. For cobalt, the switching occurred at 1.8mA and 0.43mA respectively.

As different amounts of current were applied, the time in order to switch the field from parallel to anti-parallel was recorded. 0.98mA switched permalloy in 0.148ns. It took 0.104ns to switch the cobalt with 1.96mA. Currents less than these values led to incomplete switching. The graphs took on an exponential curve. As the current continued to increase, the switching time can be seen to level off.

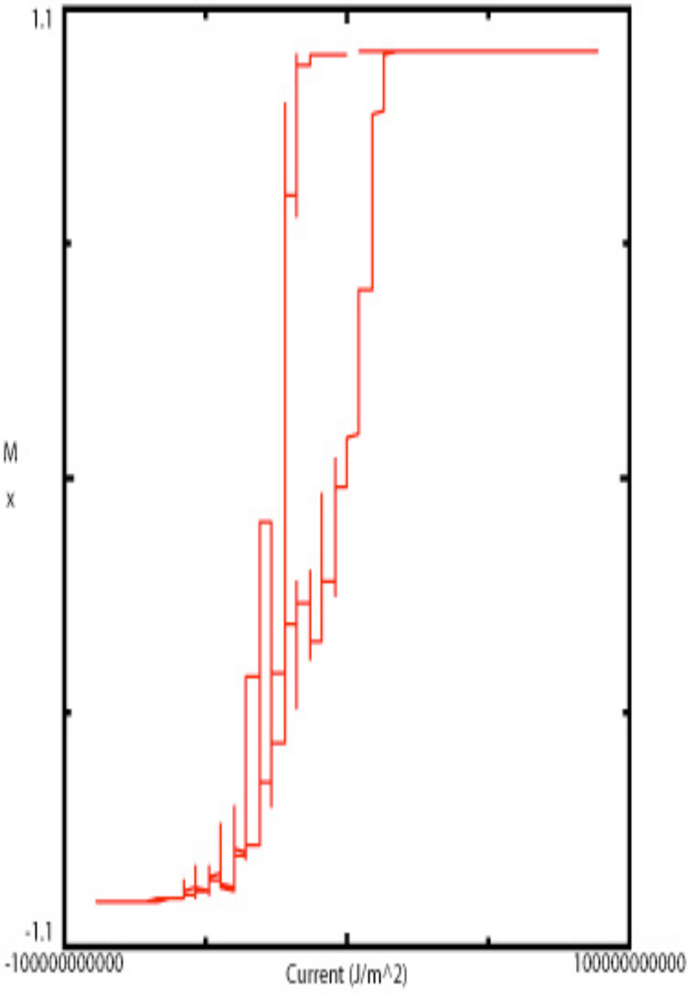


Fig. 3 Shows the hysteresis loop for the permalloy device. Parallel to anti-parallel switching occurred at 0.89mA where anti-parallel to parallel switching could be seen at 0.22mA.

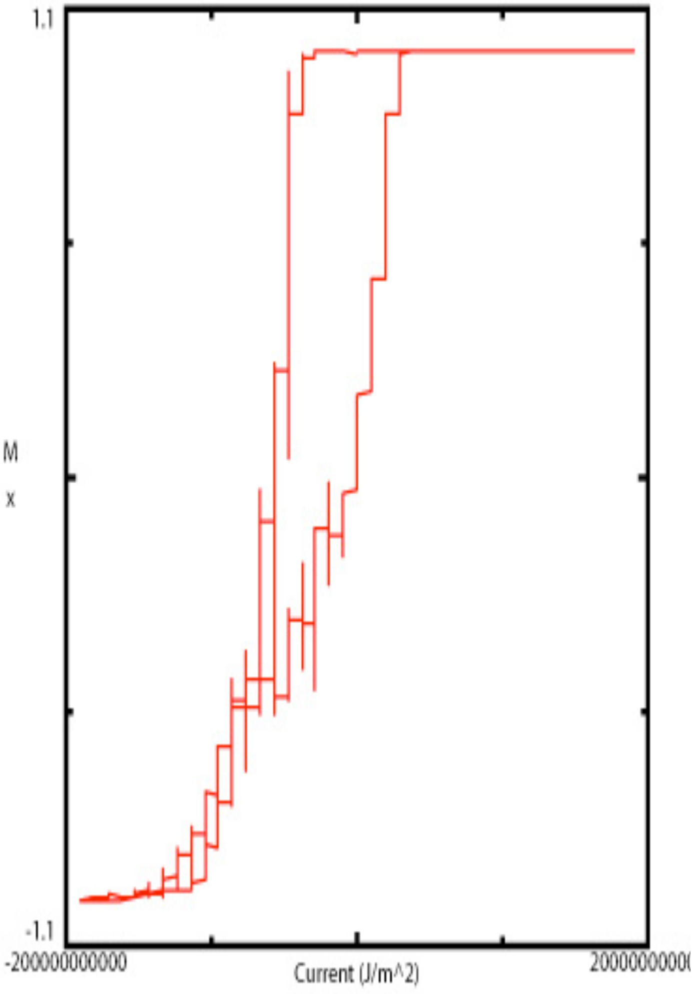


Fig. 4 consists of the hysteresis loop for the cobalt structure. In this case, parallel to anti-parallel switching occurred at 1.8mA, where anti-parallel to parallel switching occurred at 0.43mA.

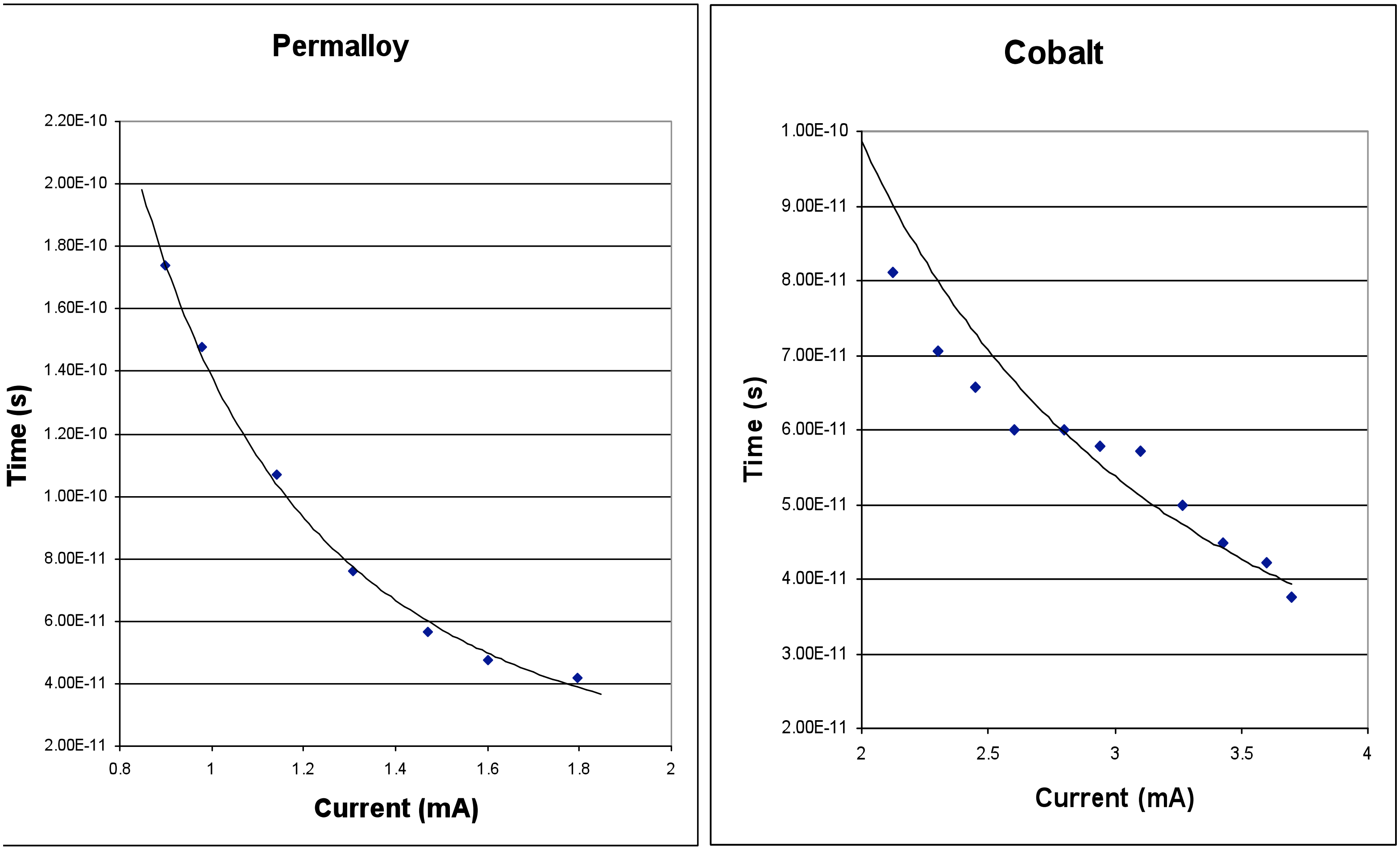


Fig. 5 shows the switching times as a function of the applied current for the two different materials.

CONCLUSION

The devices that were simulated have the ability to switch magnetization in a short time interval. By utilizing the torque created when a current is spin polarized, the free magnetic layers of materials such as permalloy and cobalt can switch in as little as 0.148ns and 0.104ns respectively. The current necessary to produce such magnetic switching is extremely large in terms of current density, but due to the small size of the devices, this current corresponds to only a few milliamps.

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REFERENCES

[1] V. Cros, O. Boulle, J. Grollier, A. Hamzic, M. Munoz, L.G. Pereira, F. Petroff; C.R. Physique 6 (2005) 956-965

[2] D.C. Ralph, M.D. Stiles; Journal of Magnetism and Magnetic Materials, 320 (2008) 1190 – 1216.

[3] D.V. Berkov, J. Miltat; Journal of Magnetism and Magnetic Materials, 320 (2008) 1238 – 1259

[4] O. Ozatay, N.C. Emley, P.M. Braganca, A.G.F. Garcia, G.D. Fuchs, I.N. Krivotov, R.A. Buhrman, D.C. Ralph; Applied Physics Letters, 88 (2006) 202502

[5] G. Hrkac, J. Dean, A. Goncharov, S. Bance, D. Allwood, T. Schrefl, D. Suess, J. Fidler, Micromagnetics of Single and Double Point Contact Spin Torque Oscillators (2008)