Spin Transfer Torque Driven Magnetic QCA Cells

Nilanjana Pradhan and Debashis De

Abstract In this paper we have proposed spin transfer torque current (STT) driven Magnetic QCA cells. The switching energies dissipated gets significantly reduced when the single domain ferromagnet changes their states ("spin up-logic 0" and "spin down-logic 1") in Magnetic QCA. Spin transfer torque generates spin induced current which manipulates the magnetic moment of the electron and it reaches a value such that the overall energy is larger than the energy loss due to damping. This principal is applied in Magnetic QCA for reducing switching energy dissipation.

Keywords Spintronics · Spin transfer torque (STT) · Magnetic QCA

1 Introduction

Spintronics means "spin electronics". The electrons are spin polarized in spintronic device. As a result of this spin polarization ("spin up" or "spin down") spin current is generated. The spin is manipulated to obtain different states. Some of the things which should be explored are spin polarization, spin dynamics and spin polarized transport [1]. There is a difference between spin transport and charge transport. The term spin stands for either the spin of a single electron switch can be

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obtained from its magnetic moment $-g\mu_B s$ (μ_B is the Bohr magnetron and g is the electron g factor, in a solid) or an average spin obtained from an assembly of electrons). The spin polarization can be obtained in several ways. Bohr magnetron μ_B is a physical constant and the natural unit for expressing an electron dipole moment.

In addition to their mass and electric charge, electrons have an intrinsic quantity of angular momentum called spin. A magnetic field is associated with the spin which lines up with the spin axis. Spin is a vector quantity. In a magnetic field electronics with "spin up" and "spin down" have different energies. Spintronic devices create spin polarized currents and use the spin to manipulate the magnetization of ferro-magnets. STT rotates the magnetization axis of a nanomagnet by exerting a torque on it [1]. STT driven MQCA cells suffers from low switching energy dissipation by reducing the saturation magnetization of a magnet (M_s).STT (Is) $\propto M_s$.

$$\boldsymbol{\mu}_B = e\hbar/2m_e c$$

e elementary charge
ħ reduced planck constant
m_e electron rest mass
c speed of light

Elementary charge means electric charge carried by a single proton. Plank constant is the physical constant reflecting the sizes of quanta in quantum mechanics.

Spintronics actively manipulates the spin degrees of freedom. Spin means the spin of a single electron s, which is detected by its magnetic moment. The goal of spintronics is to understand the interaction between the particle spin. Spintronics include investigation of spin transport in electronics materials, as well as understanding spin dynamics and spin relaxation. Spin polarization means creating a non equilibrium spin population. Spin relaxation mechanisms involves in the process of bringing accumulated spin population back in equilibrium. Spin detection is also a part of spintronics which senses the changes in the signals caused by the presence of non equilibrium spin in the system [1]. The common goal in many spintronic devices is to maximize the spin detection sensitivity to the point it detects not the spin itself but changes in the spin states. Electrons with spin which has magnetic moment opposite to the magnetization of a ferromagnetic layer are scattered more than electrons with parallel magnetic moments, resulting in a spin filtering effect. Spin transport devices are based on the effect that the magnetic spin of electrons can be manipulated in optoelectronic devices by magnetic fields or applied voltage [2]. The domain of spin-transport devices is commonly referred to as magneto electronics or Spintronics. The spin transport effects are most widely used today in magnetic metallic devices such as read heads for Hard Disks Drives and in Magnetic Random Access Memories (MRAM) [3].These device structures comprise magnetic thin films, the magnetic orientation of which can be changed with applied magnetic fields. In case of non-volatile MRAM the orientation will be preserved until the bit is switched again [4]. Hence a locally generated field performs the writing of a magnetic bit, by currents in the vicinity of the magnetic structure. The reading principle of magnetic bits is based on the discrimination between two distinct magnetic devices.

The magnetic field or the presence of magnetic materials not necessarily essential for manipulating spins. GMR-based memory devices and spin valves are elementary spintronic applications where the role of spin, however is passive in dictating the size of the resistance depending on the spin direction controlled by local magnetic fields. In spintronics active control of spin dynamics is envisioned to lead to novel quantum-mechanical enabling technologies such as spin transistors, spin filters and modulators, new memory devices [5]. The inherent quantum mechanical nature of spin as dynamical variable and the inherently long relaxation or coherence time associated with spin states are two important characteristics of spintronics.

2 Generation of Spin Transfer Torque

Landau-Lifshitz-Gilbert equation defines the movement of the magnetic moment. There are three terms of the equation. The first term describes the fact that the magnetic moment will rotate around the applied field and is a procession term. The second term denotes the damping torque. The damping torque aligns the magnetic moment to the applied field. The last term is called the spin transfer torque [6]. This torque acts along with the damping torque or against it depending on the direction of the current. The damping and the spin transfer torque if works together the magnetic moment will align with the applied field. The spin transfer torque and damping can work against each other such that the magnetic moment reaches a steady state.

$$\frac{\mathrm{d}\vec{M}_{free}}{\mathrm{d}t} = -\gamma\vec{M}_{free} \times \vec{H} + \alpha\vec{M}_{free} \times \frac{\mathrm{d}M}{\mathrm{d}t} - I\gamma ST\vec{M}_{free} \times \left(\vec{M}_{free} \times \vec{M}_{spin}\right) \quad (1)$$

The Hamiltonian of conduction band electron with momentum $\vec{p}$ and effective mass m is

$$H = \frac{p^2}{2m} + s_\alpha Q_{\alpha\beta} p_\beta \quad (2)$$

$Q_{\alpha\beta}$ characterizes the spin-orbit interaction, s_α is the αth component of electron spin.

The effective magnetic field is given by $B_p = Qp/\mu_B g$ (μ_B is the Bohr magneton, g is the electron g-factor)

The value and direction of the magnetic field is determined by electron momentum $\vec{p}$.

The frequency of the electron spin is given by $\Omega = Qp/\hbar$. The spin orbit interaction is qs[p × n]. The spin density is determined by the following continuity equation: $J_{\alpha\beta}$ is the α component of the flow of electrons along β axis

$$\frac{\partial S_\beta}{\partial x} + \frac{\partial J_{\alpha\beta}}{\partial x_\alpha} = \frac{m}{\hbar}\varepsilon_{\beta j\gamma} Q_{ji} J_{i\gamma} + (\frac{\partial S_\beta}{\partial t})others \tag{3}$$

The spin current operator is given by:

$$\widehat{J}_\alpha = \left(\widehat{\mathrm{V}_{\alpha\beta}}\widehat{\mathrm{S}}_\beta + \widehat{\mathrm{S}}_\beta\widehat{\mathrm{V}}_\alpha\right)/2 \tag{4}$$

$$\widehat{\mathrm{V}}_\alpha = \frac{\partial y}{\partial x} = \frac{\mathrm{p}_\alpha}{\mathrm{m}} + \mathrm{Q}_{\beta\alpha} + \widehat{\mathrm{S}}_\beta \tag{5}$$

The above equation gives the spin velocity operator.

In magnetic multilayer when current flows the electron becomes spin polarized and the angular momentum which causes reversal of magnetization in the thin magnetic layers. An electron spin carried by the current interacts with magnetic layer the interaction causes torques between the spin and the magnetization. The current when flows through a ferromagnet it becomes spin polarized and hence carried angular momentum. The current remains polarized in neighboring non-magnetic layers so that the angular momentum carried by the current can interact with the magnetization. The spin current exerts a spin transfer torque on the magnetizations in the device. The spin transfer induced magnetization and the generation of spin transfer torque is demonstrated by certain devices which have multiple layers like copper layer(non magnetic), an insulating layer and a cobalt layer(magnetic layer). As current passes have uniform density, uniform magnetization the spin transfer torque is also uniform.

3 Spin Current Derivation

Pure spin current is deprived of any kind of association with electric current. In electric current the spins of charge carriers are random. The electrons have two polarizations spin up and spin down.

$$\mathrm{J}\uparrow(\mathrm{spinup}) = -\mathrm{j}\downarrow(\mathrm{spindown})$$

$$\mathrm{J_c} = -\mathrm{e}(\mathrm{j}\uparrow + \mathrm{j}\downarrow) = 0$$

The spin current $\mathrm{J_S} = \;/2\,(\,\mathrm{j} * - * \varphi)\gtrless$

Vector potential for spin current

$$\mathrm{H} = \sum\nolimits_{\mathrm{t},\sigma} = \frac{1}{2\mathrm{m}}\left(\mathrm{p_t} - \frac{\mathrm{e}}{\mathrm{c}}\mathrm{A}\right)^2 + \mathrm{V} \tag{6}$$

The Dirac equation of an electron in electromagnetic field is

$$\left(\beta mc^2\varphi(x,t) + \sum_{k=1}^{3}\alpha pc\right)\varphi(x,t) = i\hbar\frac{\partial\varphi(x,t)}{\partial t} \tag{7}$$

m rest mass of an electron
c speed of light
p momentum
x, t space and time constant
ħ reduced Planck constant
Ψ wave function

4×4 matrices α_k and β. $\alpha_{i=}$ $\beta^2 = I_4$.

Schrondinger equation:

$$\frac{-\hbar^2}{2m}\nabla^2\phi = i\hbar\frac{\partial}{\partial t}\phi \tag{8}$$

The vector potential for the electron spin is

$$H = \sum_{i,\sigma}\frac{1}{2m}\left(P_i - \frac{e}{c}A_\sigma\right)^2 + V \tag{9}$$

$$v_{i,\sigma} = \frac{p_i - \frac{e}{c}A_\sigma}{m} = -\frac{c}{e}\frac{\partial H}{\partial A_\sigma}$$

Spin Velocity =

$$j_\uparrow = -\frac{c}{e}\frac{\partial E(A_\uparrow, A_\downarrow)}{\partial A_\uparrow};$$
$$j_\downarrow = -\frac{c}{e}\frac{\partial E(A_\uparrow, A_\downarrow)}{\partial A_\downarrow}.$$

Spin dependent current:

$$J_s = \frac{\hbar}{2}(j_\uparrow - j_\downarrow) \neq 0 \tag{10}$$

The read–write operation in Magnetic QCA cells using Spin Transfer Torque (STT) reduces the switching energies dissipated during the change of state of electron spins [1]. Hence our proposed scheme is a new approach which aims at reducing the switching energy dissipation in magnetic QCA cells.

$$A_\uparrow = -A_\downarrow \Rightarrow j_\downarrow = -j_\uparrow$$

Pauli found that the data can be recovered from the Zeeman's experiment if an extra spin term $\frac{e\hbar\sigma}{2m}$B is appended.

$$i\hbar\partial_t\psi = \left[-\frac{\hbar^2\nabla^2}{2m} - \frac{e\hbar}{2m}\sigma B\right]\varphi \tag{11}$$

Dirac equation was able to derive spin from information contained within fundamental wave equation.

Dirac equation for particles with spin is:

$$\left[(\alpha, p)c + \left(\beta mc^2\right)\right]\varphi = E\varphi \tag{12}$$

$$\left[-\frac{\hbar^2\nabla^2}{2m} - \frac{e\hbar}{2m}\sigma B\right]\varphi = i\hbar\partial_t\varphi$$

Multiplying both sides by $\varphi^\dagger$

$$\left[-\frac{\hbar^2\nabla^2}{2m} - \frac{e\hbar}{2m}\sigma B\right]\varphi\varphi^\dagger = i\hbar\partial_t\varphi^\dagger \tag{13}$$

Since

$$\varphi^\dagger = \begin{pmatrix}\varphi_1\\ \varphi_2\end{pmatrix}^\dagger = \left(\varphi_1^*\varphi_2^*\right)$$

Spin operator are Hamiltonian

$$\sigma^\dagger = \sigma$$

Solving the above equations and comparing it with the continuity equation we get

$$J_{pauli} = \frac{i\hbar}{2m}\left[\left(\varphi^\dagger\right) - \varphi^\dagger\,\varphi\right]$$

Wave function for spin up is

$$\uparrow\varphi_n = (array{*}20c\varphi_n 0)$$

Wave function for spin down is

$$\downarrow\varphi_n = \begin{pmatrix}0\\ \varphi_n\end{pmatrix}$$

4 Magnetic QCA Cell

In early 1993, the Quantum dot cellular Automata was introduced by Lent [7]. The prime contribution on QCA based logic circuits are developed and different types of defect analysis is reported in [8–13]. Magnetic QCA is nanometer scale magnetic particles (nano-magnets) which exhibits bi-stable states ("0" or "1") on application of magnetic field presenting binary information [14]. In magnetic QCA cell there are mainly five nanomagnets. There is a central nanomagnet surrounded by four others as shown in Fig. 1.

Three of the neighbors can be used as inputs driven by additional driver nanomagnets oriented along the direction so the clock-field. The nanomagnet to the right of the central magnet is the output. The majority gate is simulated by applications of horizontal clock-field. The three-input majority gate acts as a programmable two input NAND or NOR gate depending upon the state of any one of the three input magnets. Boolean logic functions can be built by a network of majority gates. The input is set by external clock field. The driver magnet helps in realizing the different combinations of input. The intersection of horizontal and vertical wires are common to all structures. Figure 2 shows the switching of MQCA wire by an external input and clocking field [15]. The clocking field H_{ext} is applied in the direction of the hard axis. Before the application of magnetic field the nanomagnets are in metastable states as shown in Fig. 2.

As soon as a horizontal magnetic field is applied the nanomagnets are aligns themselves along their hard axes as shown in Fig. 2. The nanomagnets returns to their ground state and arrange themselves in alternating "up" and "down" direction as the magnetic field is reduced slowly as shown in Fig. 2. The "up" and "down" state is equivalent to logic "0" and "1" respectively (Fig. 3).

If we fabricate the Majority gate by Magnetic Tunnel Junction structure which consists of Cu (Antiferromagnet or nonmaget), Cobalt (Ferromagnet) and Insulator and allow current pass through it, it will create spin polarized current which gives rise to Spin torque [5]. The polarity of the voltage applied to each of the input of the majority gate may be a positive voltage "plus" or logic 1 and a negative voltage or "minus" which indicates logic 0 [16]. The "minus" input voltage drives the current from bottom to top and aligns the magnetization of the free layer to align opposite to the fixed layer. The magnetic tunnel junction logic which we are using over here to construct the majority gate consists of free layer and a fixed layer. The free layer which responds to the current induced torques and the fixed layers which is susceptible to Spin Transfer Torque (STT) [16]. The resistance of

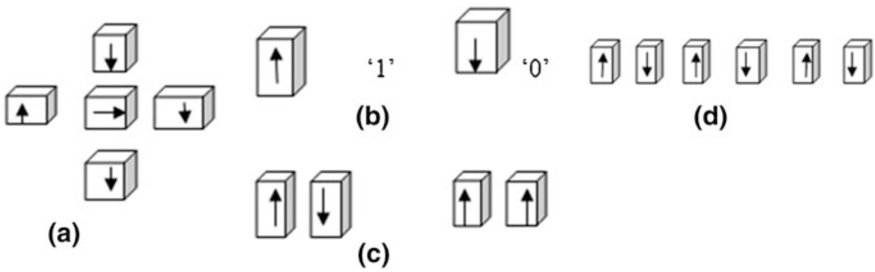


Fig. 1 MQCA Circuits. **a** Majority gate. **b** Logic '1' and '0' for nanomagnets. **c** Ground state, metastable state. **d** MQCA wire

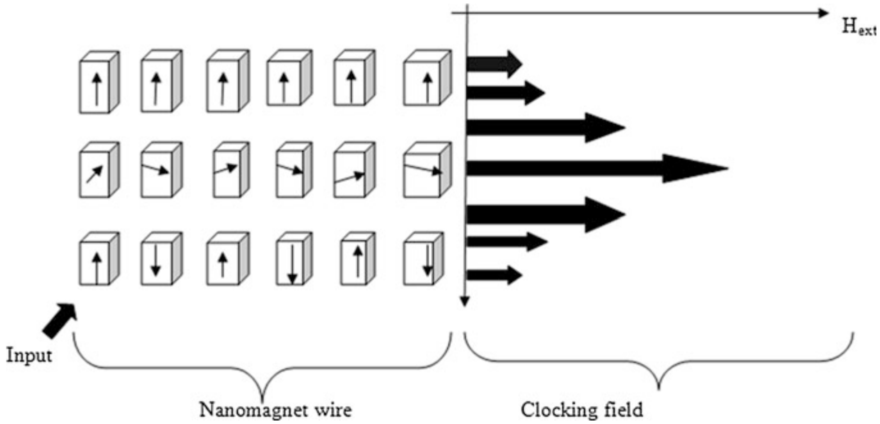
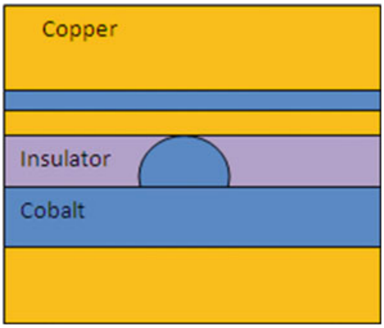


Fig. 2 Clocking of magnetic QCA devices

Fig. 3 Lithographically defined point contact which acts as the majority voter input in magnetic QCA



the structure depends on its magnetic state especially their GMR effect. The spin transfer effect changes the resistance of the device when the current is non-uniform. Spin transfer torque is also non-uniform (asymmetric). The device must have a small cross-sectional area because the heat generated by the current may destroy the device if it is not concentrated into a small area. Spin transfer torque effect decreased as the cross sectional area decreases spin transfer torque is uniform when current density and magnetization is uniform.

5 Conclusion

In this paper we have discussed some of the interesting property of nanomagnets. Spin transfer torque (STT) is one of the interesting property. STT is utilized to drive MQCA majority gates. Special layered structure using the concept of Magnetic Tunnel Junction (MTJ) is used over here. This structure actually generates the spin transfer torque which operates the MQCA cells. Nanomagnet QCA is easier to design and operate with proper usage of its magnetic properties. Hence in future we can utilize this property to bring about a versatile change in the field of Quantum mechanics and Nanotechnology.

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