4-2

Study of Current Induced Magnetic Domain Wall Movement with Extremely Low Energy Consumption by Micromagnetic Simulation

K.Kawabata, M. Tanizawa, K.Ishikawa, Y. Inoue, M.Inuishi, T.Nishimura
Renesas Electronics Corporation, Mizuhara 4-1, Itami, Hyogo 664-0005, Japan
Email: kiyoshi.kawabata.gx@renesas.com

Abstract— **We study the velocity and energy consumption of current induced magnetic domain wall (DW) movement, which is a new paradigm in spintronics devices such as a next generation MRAM and race track memory, by LLG (Landau-Lifshitz-Gilbert) micromagnetic simulation.**

It is found that DW velocity is almost the same in current in magnetic thin film plane(CIP) and current perpendicular to plane (CPP-Perp.). On the other hand, the energy consumption is much lower in CPP-Perp. than CIP. These results show that the CPP-Perp. structure has potential solutions for high speed and low energy consumption applications

Keywords-spin transfer torque, MRAM, domain wall movement

I. INTRODUCTION

MRAM (Magnetic Random Access Memory) is a new nonvolatile memory using ferromagnetic materials[1][2][3]. The data is stored as the direction of magnetization in the materials. The memory elements usually consist of two ferromagnetic layers and a nonmagnetic layer, which is sandwiched by them. Magneto resistance (MR) effect is used for the data reading. The resistance of memory elements depends on the relative magnetization direction of two layers. When the magnetization direction of them is same, which is called parallel (P) state, the resistance is lower. It has higher resistance at opposite direction of each other, anti-parallel (AP) state.

The magnetization direction of ferromagnetic layer is controlled by various method. These are classified into two categories. One category is the driving forces for magnetization direction in the layer. They are magnetic field or spin transfer torque. The latter is induced by the current injection into ferromagnetic layer in multilayer stacks. Another category is the response under the driving force. There are uniform magnetization rotation and magnetic domain wall (DW) movement. These are summarized in Table 1.

We focus on the spin transfer torque magnetic DW movement. The detail is shown in Fig.1. In a magnetic strip the magnetization usually aligns parallel to longer direction. There may be two opposite magnetization direction each other. In this case DW exists at the boundary. The position of DW is changed by magnetic field and electron injection. This is called as DW movement, especially current induced DW movement under current injection. The electron current carries the spin transfer torque into the adjacent region whose spin direction is anti parallel to electrons. Spin transfer torque forces their spins to align parallel to electron spin direction.

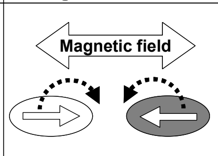
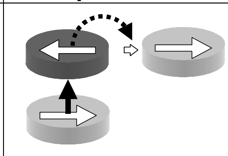
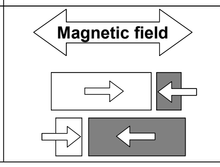
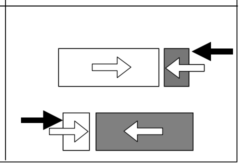
		Driving force	
Magnetic Response		Current induced magnetic field	Spin transfer torque
	Uniform rotation		
	Domain wall movement		

Table. 1 Driving force on magnetization direction and magnetic response. Dotted arrow shows the movement of spin. Real arrow shows the injected electron flow.

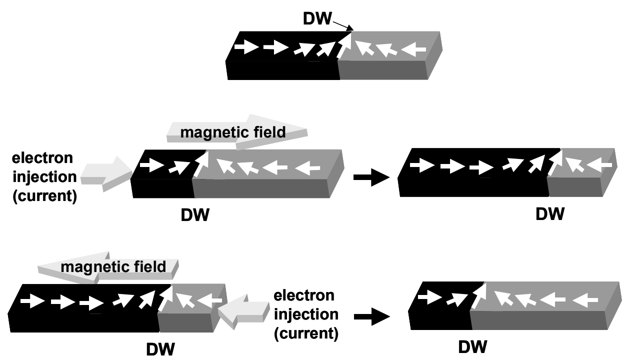


FIG. 1 Magnetic structure of DW and movement.Ferromagnetic strip with one DW at the center. White arrows show the magnetization direction. Magnetic field and current injection move DW.

978-1-61284-418-3/11/$26.00

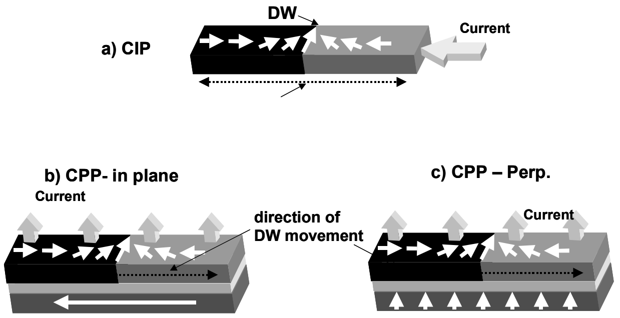


FIG. 2 Test structures for current induced domain wall movement. CIP is one layer, CPP-in plane and CPP-Perp. are three layer stack with bottom layer magnetization is pinned.

From the viewpoint of device applications, DW movement corresponds to data writing because the magnetization is changed after DW passed away. Especially DW velocity is one of the key factors of the device performance, which is related to data writing time, and the energy consumption. They are a critical issue of low energy consumption devices.

In this paper these factors are examined in three test structures using DW movement by current injection as shown in Fig.2. a) Current flows parallel to the magnetic thin film plane (CIP). b) Current flows perpendicular to the magnetic thin film plane from in plane magnetic anisotropy thin film (CPP-in plane). c) Current flows perpendicular to the magnetic thin film plane from perpendicular magnetic anisotropy thin film(CPP-Perp). Both CPP structures consist of tri-layer stack. Top layer is in-plane magnetic anisotropy film with DW, second is nonmagnetic metal film. The bottom layer of "CPP–in plane" has in-plane magnetic anisotropy, in which the magnetization is parallel to the film plane. That of "CPP-Perp." has perpendicular magnetic anisotropy. Their magnetization is pinned.

II. MODELING

Current induced DW movement in CPP and CIP structure is described by LLG equation (1). DW movement is induced by the spin transfer torque term, TCIP/CPP, in (1). TCIP is used for CIP; the detail is shown in (2). TCPP is used for CPP structure (3). The parameters νj and aj are a function of current density, j.[4][5]. M is magnetization vector in magnetic materials.

Three test structures are shown in Fig.2. The whole area is 1000 x 100 nm^2 in size. The magnetic parameters of the top layer are for NiFe : thickness is 2nm, Ms = 800 emu/cm^3, the exchange constant A = 1.05 x 10^{-6} erg/cm, α= 0.02, a spin polarization P = 0.3 for "CPP-in plane" and "CPP-Perp.", 0.5 for "CIP", and non adiabatic spin torque factor β = 0.02 in "CIP". Interlayer between two ferromagnetic layers is non magnetic layer. The bottom layer is ferromagnetic layer whose magnetization is pinned.

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\times\vec{H}_{eff} + \frac{\alpha}{Ms}\left(\vec{M}\times\frac{d\vec{M}}{dt}\right) + T_{CIP/CPP} \qquad (1)$$

$$T_{CIP} = -v_j\frac{\partial\vec{M}}{\partial x} + \beta v_j\vec{M}\times\frac{\partial\vec{M}}{\partial x} \qquad (2)$$

$$T_{CPP} = -\gamma\frac{a_j}{Ms}\eta(\theta)\vec{M}\times\left(\vec{M}\times\vec{M}_p\right) \qquad (3)$$

The simulation consists of a numerical integration of Eq. (1) on a tree-dimensional mesh of 5 x 5 x 2nm^3 using commercial micromagnetic simulator[6]. The DW velocity is extracted from current injection time and the difference of averaged DW positions before and after current injection. The energy consumption for DW movement is estimated by the injected current, resistance of NiFe and current injection times.

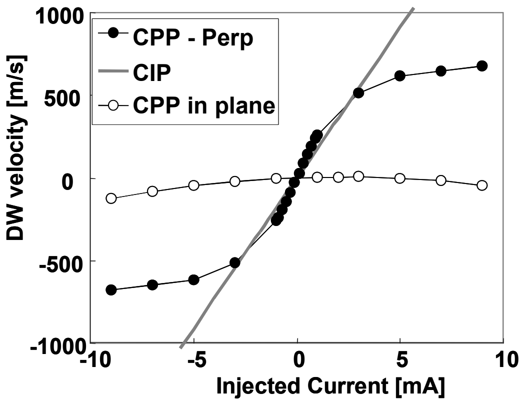


FIG. 3 DW velocity as a function of injection current in CIP (line) , CPP- in plane (open circles), and CPP- Perp. (filled circles) structure.

III. RESULTS AND DISCUSSION

Fig.3 shows the relation between injected current and DW velocity of three test structures. It is found that "CPP-in plane" is much slower than "CIP" and "CPP-Perp."[5][7]. In CPP- in plane the effective field due to spin transfer torque is directed to perpendicular to the film plane, and then it does not move the DW well, compared to CIP and CPP-Perp. in which it is in plane. Moreover it is found that DW movement of "CPP- in plane" is almost one way, and that does not depend on the injected current polarity. This one-way movement is not adequate to device application, and, therefore, it is omitted in the following discussion. At high current it is observed that the DW structural change causes the reduction of DW velocity in "CPP-Perp.".

For device application DW velocity should be converted to data write time. It is defined as appropriate distance

(200nm) divided by DW average velocity. Fig.4 shows the relation between data write time and injected current. Both structures shows nearly same properties, for example, data write time is1ns at 1mA.

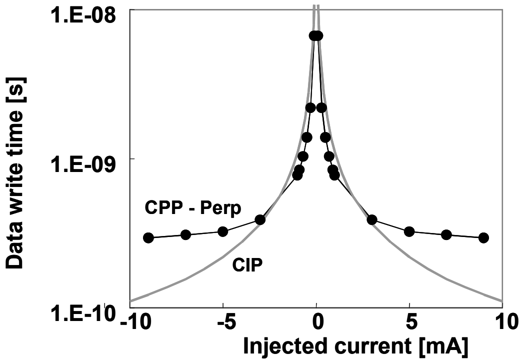


FIG. 4 Data write time of Current induced DW as a function of injection current in CIP (line) and CPP- Perp. (filled circles) structure.

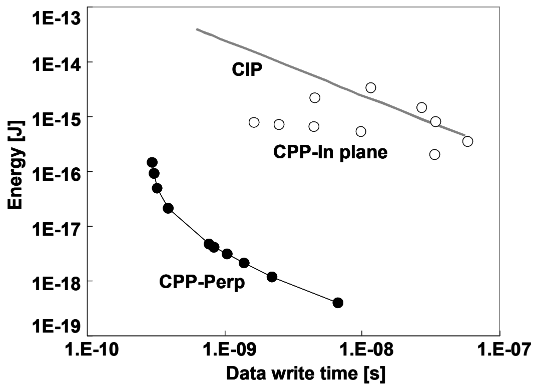


FIG. 5 Energy consumption of Current induced DW as a function of data write time in CIP (line) , CPP- in plane (open circles), and CPP- Perp. (filled circles) structure.

The energy consumption for DW movement of 200nm is estimated as a product of current, resistance, and data write time. The resistance of "CIP" structure is higher than that of "CPP-Perp." due to the geometrical properties, the cross section is smaller and the length is longer than "CPP-Perp.". As a result, the energy consumption of "CPP-Perp." is much lower than "CIP" as shown in Fig.5. These results show that the "CPP-Perp." structure has potential solutions for high speed and low energy consumption applications.

For device application, however, "CPP-Perp." structure is not suitable in spite of quite low energy writing. It is not sufficient for data reading. Data reading ability is measured by the difference of resistance at parallel (P) and anti parallel (AP) spin configuration due to magneto resistance effect. The magneto resistance effect in "CPP-Perp." structure is small, which is called GMR effect.

GMR effect is a typical in the structure consists of ferromagnetic layer/non magnetic metal layer/

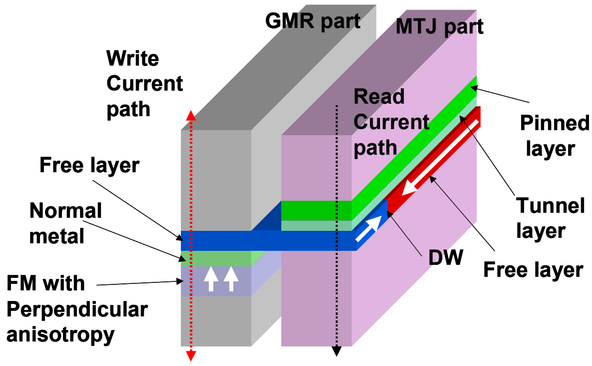


FIG. 6 A hybrid structure of "CIP-Perp." and MTJ.

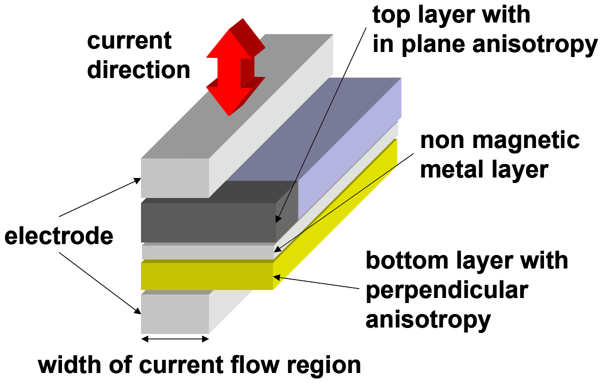


FIG. 7 The structure for partial current flow induced DW motion.

ferromagnetic layer. A larger magneto resistance effect is known as tunnel magneto resistance (TMR) effect in magnetic tunnel junction (MTJ) whose structure consists of ferromagnetic layer/non magnetic tunnel barrier/ ferromagnetic layer.

For practical application of "CPP-Perp." structure it is suggested that a hybrid structure consists of "CPP-Perp." part for data writing and MTJ part for data reading. Fig. 6 shows a suggested structure which enables this. The current flow path is switched at data writing and reading. In this structure, however, write current does not flow in whole area of free layer, and then the spin transfer torque is not fully able to operate on the spin in free layer. Is it possible to write data in this situation? In order to answer these questions, the structure in Fig.7 is used, in which the area under the influence of spin transfer torque effect is limited.

The width of current flow region is varied from 100nm to 20nm. The DW velocity is simulated by the same method described above. Fig.8 shows the relation between injected current and DW velocity. Decreasing the width, DW velocity also decreases, but does not become zero. Therefore the structure in Fig.6 could work at data writing. Even at 20nm, one fifth of whole width, DW moves due to the spin transfer torque. This is explained by the exchange interaction between spins. The interaction tends to align adjacent spin direction at same direction, which is fundamental one in ferromagnetic materials. Due to this interaction spins without spin transfer torque could change direction, result in DW motion.

Dependence of write current on write time and energy consumption are shown in Figs. 9, 10. Even at 20nm width the energy consumption is still lower than CIP structure. Therefore, the structure in Fig.6 is applicative for devices of an extremely low energy consumption.

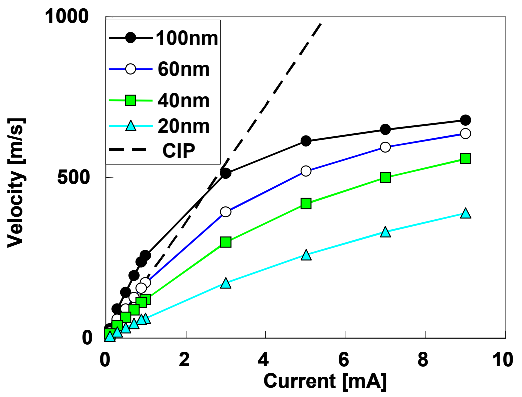


FIG. 8 DW velocity as a function of width of current injection area in CPP- Perp. structure.

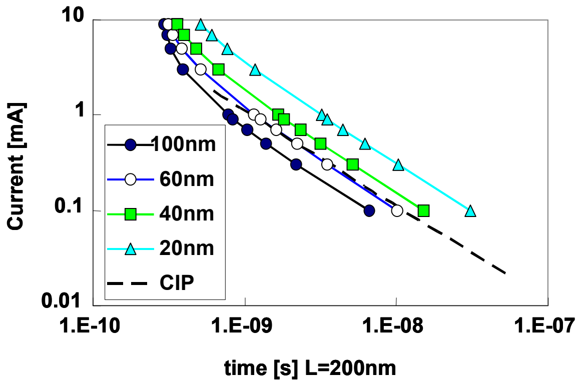


FIG. 9 Dependence of write current and write time on width of current injection area in CPP- Perp. structure.

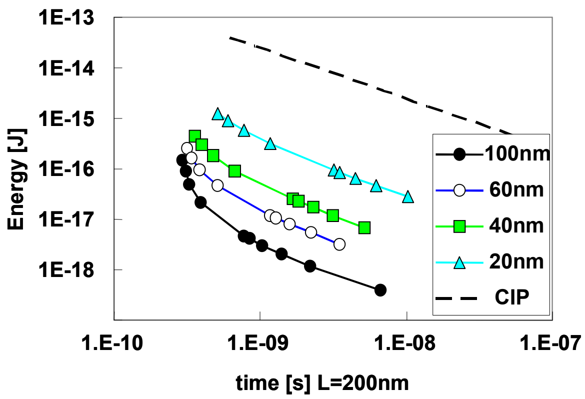


FIG. 10 Energy consumption of DW motion as a function of width of current injection area in CPP- Perp. structure.

IV. CONCLUSION

We study the velocity and energy consumption of current induced magnetic DW movement, which is a new paradigm in spintronics, by LLG micromagnetic simulation. It is found that DW velocity is almost the same in CIP than CPP-Perp.. On the other hand, the energy consumption is much lower in CPP-Perp. than CIP. These results show that the CPP-Perp. structure has potential solutions for high speed and low energy consumption applications.

References

[1] S.Fukami *et al.* , *Appl.Phys.Express*. 3,113002 (2010)

[2] T.Suzuki *et al.* , *IEEE.Trans.Mag*. 45,3776 (2009)

[3] S.S.P. Parkin, USA Patent No.6,834,005 (2003-06-10) (filed)

[4] G.S.D. Beach *et al.* ,*J.Magn.Magn.Mater*. 320,1272 (2008)

[5] A.V.Khvalkovskiy *et al*.,*Phys.Pev.Lett*102,067206 (2009)

[6] M.R.Scheinfein ,*LLG Micromagnetic Simulator*^{TM}

[7] C.T.Boone et al., *Phys.Pev.Lett*104,167205 (2010)