≪연구논문≫ Journal of the Korean Magnetics Society, Volume 21, Number 2, April 2011 DOI: 10.4283/JKMS.2011.21.2.052

비대칭 자기터널접합에서의 수직 스핀 전달 토크: 물질 변수에 대한 의존성

한재호 · 이현우*
포스텍 물리학과, 경북 포항시 남구 효자동 산31번지, 790-784

(2011년 4월 4일 받음, 2011년 4월 7일 최종수정본 받음, 2011년 4월 8일 게재확정)

스핀전달토크는 나노구조에서 자성상태를 제어하는데 유용한 수단이다. 자기터널접합에서 스핀전달토크는 자성물질층의 자화가 이루는 평면에 평행한 성분과 수직인 성분으로 나눌 수 있다. 이중 평행한 성분의 스핀전달토크의 성질은 상당히 잘 알려져 있으나, 수직인 성분의 스핀전달토크의 성질에 대해서는 여전히 이견이 많다. 비대칭 자기터널접합에서의 최근 실험에서, 수직전달토크의 전압 의존성이 전압의 이차항 성분뿐만 아니라 일차항 성분도 가짐을 보고하였다. 하지만 물질 변수에 대한 의존성은 여전히 잘 알려지지 않았다. 이 논문에서는 비대칭 자기터널접합에서의 스핀전달토크의 전압 의존성을, 강자성층의 스핀 갈라짐 에너지와 일함수의 차이, 그리고 페르미 에너지를 변화시켜 가면서 체계적인 조사를 하였다.

주제어 : 스핀전달토크, 자기터널접합, 비대칭, 전압 의존성

Perpendicular Spin-transfer Torque in Asymmetric Magnetic Tunnel Junctions: Material Parameter Dependence

Jae-Ho Han and Hyun-Woo Lee*
Department of Physics and PCTP, Pohang University of Science and Technology, Pohang, Gyungbuk 790-784, Korea

(Received 4 April 2011, Received in final form 7 April 2011, Accepted 8 April 2011)

Spin-transfer torque is a useful tool to control the magnetic state in nanostructures. In magnetic tunnel junctions, the spin-transfer torque has two components, the in-plane spin torque and the perpendicular spin torque. While properties of the in-plane spin-transfer torque are relatively well understood, properties of the perpendicular spin-transfer torque still remain controversial. A recent experiment demonstrated that in asymmetric magnetic tunnel junctions, the bias voltage dependence of the perpendicular spin-transfer torque contains both linear and quadratic terms in the bias. However it still remains unexplored how the bias voltage dependence changes as a function of material parameters. In this paper, we systematically investigate the perpendicular spin-transfer torque in asymmetric magnetic tunnel junction by varying spin splitting energy, work function difference, and Fermi energy of the ferromagnetic metal leads.

Keywords : spin-transfer torque, magnetic tunnel junction, asymmetry, bias dependence

I. Introduction

The magnetic tunnel junction (MTJ) has large interest because it has many applications such as non-volatile memories and radio frequency generators [1, 2]. These applications are due to the dynamics of magnetization in the ferromagnetic layers, and this dynamics can be controlled not only by a magnetic field but also by a current. Current flowing in a ferromagnetic metal is spin polarized. This polarized current tunnels to the other ferromagnetic metal and interacts with its magnetization. This gives a torque to the magnetization called spin-transfer torque [3, 4].

There are many theories to calculate a spin-transfer torque and many experiments to measure the torque in MTJ, but the controversy still remains especially for the perpendicular torque [5-16]. The bias dependence of the perpendicular

*Tel: (054) 279-2092, E-mail: hwl@postech.ac.kr

torque is unclear even the sign of it. Also most calculations are done for symmetric junctions and not for asymmetric ones.

In this paper, we calculate the perpendicular spin-transfer torque in an asymmetric junction. The voltage dependence of the perpendicular spin-transfer torque is examined systematically by varying the spin splitting energies, work functions, and Fermi energies of two ferromagnetic metals.

II. Method

Consider a conventional MTJ structure, as shown in Fig. 1, which has two ferromagnetic metal leads connected by a nonmagnetic insulator of width d. The angle between the two magnetization directions $\vec{M}_L$ and $\vec{M}_R$ of the leads is θ. We introduce two local coordinate; z (z') axis is along the magnetization $\vec{M}_L$ ($\vec{M}_R$).

We applied the free-electron model [17], and an electron wave function is determined by single electron Schrödinger equation. Considering the exchange energy in the ferromagnetic leads, the difference of work functions of two leads, and the fact that most of applied bias voltage drops in the non-magnetic insulator, the Schrödinger equation is written as follows:

$$-\frac{\hbar^2}{2m}\nabla^2\Psi_\sigma + U_\sigma\Psi_\sigma = E\Psi_\sigma \tag{1}$$

Here $\sigma = \uparrow,\downarrow$ for each spin, and U_σ is spin and spatial dependent potential given by

$$U_\sigma = \begin{cases} -\sigma B_L & (y<0) \\ U_0 - (eV+\Delta W)\dfrac{y}{d} & (0<y<d) \\ -\sigma B_R - (eV+\Delta W) & (y>d) \end{cases} \tag{2}$$

(σ in the formula equals to 1 (−1) for $\sigma = \uparrow$ ($\downarrow$) in the subscript). The magnitude of $\vec{B}$ is half of the exchange energy, and the direction of it is parallel to that of the

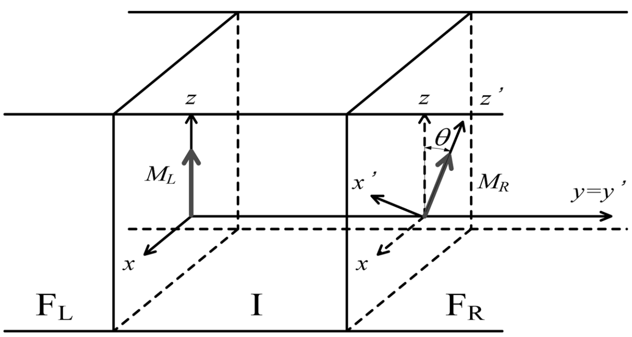

Fig. 1. Schematic diagram of a magnetic tunnel junction.

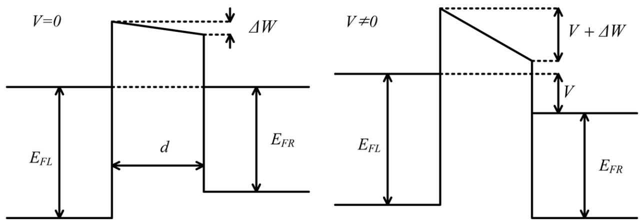

Fig. 2. Potential profile of the MTJ. In the diagram, the energy bottoms of the leads are averaged values of energy bottoms of spin up and down electrons. $-\vec{\sigma}\cdot\vec{B}$ has to be added for each spin.

magnetization of each lead. ΔW is the difference of the work functions ($\Delta W = W_L - W_R$), V is applied bias voltage, and U_0 is the potential barrier height when ΔW and V vanish (Fig. 2).

If we write $\Psi_\sigma(x, y, z) = e^{ik_x x}e^{ik_y y}\psi_\sigma(y)$, the Schrödinger equation is reduced to

$$-\frac{\hbar^2}{2m}\frac{d^2}{dy^2}\psi_\sigma + U_\sigma\psi_\sigma = \varepsilon\psi_\sigma \tag{3}$$

where, $\varepsilon = E - \frac{\hbar^2}{2m}(k_x^2 + k_y^2)$. The solutions of these equations are well known in each region and the wave functions can be written as

$$\begin{aligned} &\psi_{L\sigma} = A_{L\sigma}e^{ik_{L\sigma}y} + B_{L\sigma}e^{-ik_{L\sigma}y}, \quad \hbar k_{L\sigma} = \sqrt{2m(\varepsilon + \sigma B_L)} \\ &\psi_{B\sigma} = C_{B\sigma}Ai(Z) + D_{B\sigma}Bi(Z), \\ &Z(y) = \left(\frac{d\sqrt{2m}}{\hbar eV}\right)^{\frac{2}{3}}\left(U_0 - (eV+\Delta W)\frac{y}{d} - \varepsilon\right) \\ &\psi_{R\sigma} = A_{R\sigma}e^{ik_{R\sigma}(y-d)} + B_{R\sigma}e^{-ik_{R\sigma}(y-d)}, \\ &\hbar k_{R\sigma} = \sqrt{2m(\varepsilon + \sigma B_R + eV + \Delta W)} \end{aligned} \tag{4}$$

Here, Ai, Bi is Airy function of the first and second kind respectively, and $A_{L\sigma}$, $B_{L\sigma}$, $C_{B\sigma}$, $D_{B\sigma}$, $A_{R\sigma}$, $B_{R\sigma}$ are unknown coefficients to be determined by initial and boundary conditions.

After these coefficients are determined, the spin currents can be calculated by the following formula.

$$j_s^i = \frac{\hbar^2}{2m}Im\left(\Sigma_{\sigma\sigma'}\psi_\sigma^*\sigma_{\sigma\sigma'}^i\frac{d}{dy}\psi_{\sigma'}\right) \tag{5}$$

This is a spin current for particular energy ε, and to find the total spin current, we have to integrate up to the Fermi energy E_F in each lead.

$$J_s^i = \int_{-\sigma B_L}^{E_{FL}} j_s^i d\varepsilon - \int_{-\sigma B_R-(eV+\Delta W)}^{E_{FR}-(eV+\Delta W)} j_s^i d\varepsilon \tag{6}$$

In the first integral, j_s^i is determined from the wave function with the initial conditions that the electron flows out from the left lead (for example, if the spin-up electrons flow out from the left lead, $A_{L\uparrow} = 1$, $A_{L\downarrow} = 0$, $B_{R\uparrow} = 0$, $B_{R\downarrow} = 0$). In the second integral, j_s^i is determined in a similar way but electrons flow out from the right lead.

From this total spin current, the spin transfer torque acting on the leads can be calculated by using the angular momentum conservation. The spin transfer torque acting on the left lead is

$$T_L^{in} = -J_s^x,\ \ T_L^{perp} = -J_s^y \tag{7}$$

and for right lead,

$$T_R^{in} = -J_s^{x'},\ \ T_R^{perp} = -J_s^{y'} \tag{8}$$

where,

$$J_s^{x'} = J_s^x\cos\theta + J_s^y\sin\theta$$
$$J_s^{y'} = J_s^x\sin\theta + J_s^y\cos\theta \tag{9}$$

III. Results and Discussion

We investigate the bias dependence of the perpendicular spin-transfer torque acting on the right lead for asymmetric MTJs. As sources of the asymmetry, we consider the following factor; difference of the spin splitting energies, Fermi energies, and work functions of the ferromagnetic metal leads. The effect of each factor is considered independently.

To obtain the numerical results, we set the Fermi energy of the left lead to 2.62 eV, and the spin splitting energy to 1.96 eV. The potential barrier height is 1.5 eV from the Fermi energy of the left lead, and the width of the barrier is 0.7 nm. The angle between two magnetizations of the leads is $\pi/2$.

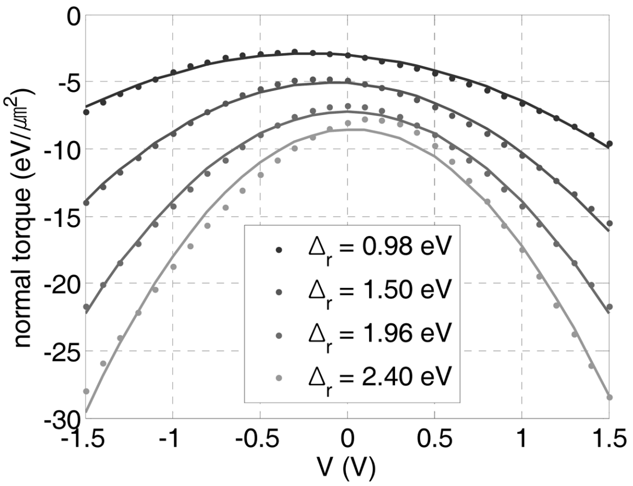

Fig. 3. Perpendicular torque versus bias voltage for various spin splitting energies (Δ_r) of the right lead. The value of Δ_r (= B_R) is 0.98 eV for the top curve and 2.40 eV for the bottom curve.

Table I. Fitting parameters and norm of residuals for the data shown in Fig. 3. Fitting equation is $T = p_1V^2 + p_2V + p_3$.

Δ_r (= B_R) (eV)	p_1 (eV/μm^{2}V^2)	p_2 (eV/μm^{2}V^2)	p_3 (eV/μm^{2}V^2)	Norm of residuals (eV^2/μm^4)
0.98	−2.3964	−1.02040	−3.0293	1.0892
1.50	−4.3867	−0.75111	−5.1036	1.4024
1.96	−6.6625	1.2022e-13	−7.2212	1.7326
2.40	−9.0794	0.42652	−8.5377	4.0145

In Fig. 3, the perpendicular spin torque is calculated for various spin splitting energy of the right lead. The difference of work functions is set to be 0, and Fermi energy of the right lead is the same as that of the left lead. Dots are the results and fitting parameters are in Table I. In the Table, norm of residuals is the sum of squared differences of the data and fitting values.

In the symmetric case (bottom curve with $E_{FR} = 2.62$ eV), the linear term is almost vanishing as expected. But out of the symmetric case, the linear term appears with comparable magnitude to the quadratic term. If the spin splitting energy has larger energy, the maximum of the torque occurs at more negative bias.

Fig. 4 shows the effect of the difference of work functions of the two leads. The Fermi energy and the spin splitting energy of right lead are the same as that of left lead. The fitting parameters are given in Table II. As before, out of the symmetric case, the linear term appears.

The Fermi energy dependence of the torque is shown in Fig. 5. The spin splitting energy of the right lead is the

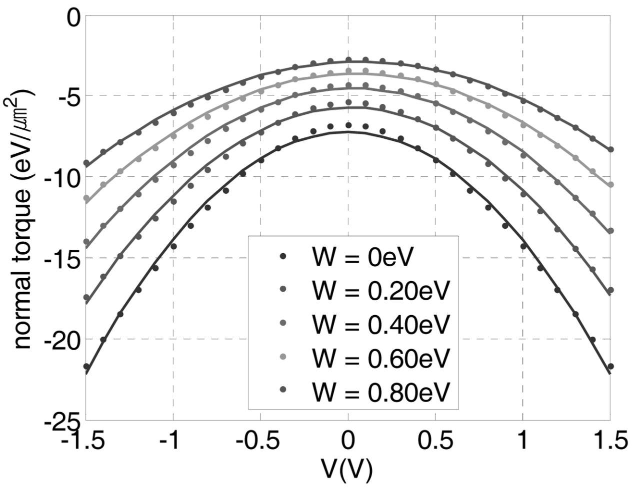

Fig. 4. Perpendicular torque versus bias voltage for various work function differences. The value of W (= ΔW) is 0.80 eV for the top curve and 0 eV for the bottom curve.

Table II. Fitting parameters and norm of residuals for the data shown in Fig. 4. Fitting equation is $T = p_1V^2 + p_2V + p_3$.

$W\,(=\Delta W)$ (eV)	p_1 (eV/μm^{2}V^2)	p_2 (eV/μm^{2}V^2)	p_3 (eV/μm^{2}V^2)	Norm of residuals (eV^2/μm^4)
0	−6.6625	1.2022e-13	−7.2212	1.7326
0.20	−5.2735	0.19066	−5.7219	1.3010
0.40	−4.1790	0.29167	−4.5501	1.0041
0.60	−3.3187	0.33658	−3.6312	0.78941
0.80	−2.6427	0.34713	−2.9079	0.62815

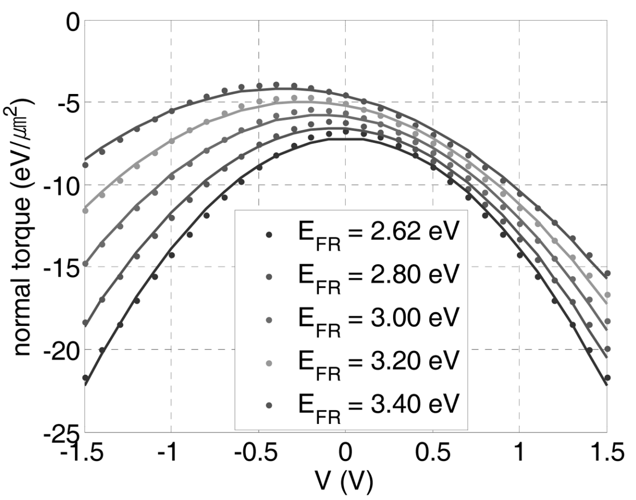

Fig. 5. Perpendicular torque versus bias voltage for various Fermi energies of the right lead. The value of E_{FR} is 3.40 eV for the top curve and 2.62 eV for the bottom curve.

Table III. Fitting parameters and norm of residuals for the data shown in Fig. 5. Fitting equation is $T = p_1V^2 + p_2V + p_3$.

E_{FR} (eV)	p_1 (eV/μm^{2}V^2)	p_2 (eV/μm^{2}V^2)	p_3 (eV/μm^{2}V^2)	Norm of residuals (eV^2/μm^4)
2.62	−6.6625	1.2022e-13	−7.2212	1.7326
2.80	−5.7712	−0.65281	−6.5840	1.3010
3.00	−4.8619	−1.33580	−5.8679	1.3868
3.20	−4.0489	−1.93000	−5.2023	1.3123
3.40	−3.3358	−2.41500	−4.6144	1.1918

same as that of the left lead, and the difference of the work function is set to zero. The fitting parameters are given in Table III.

IV. Summary

We investigate the bias dependence of the perpendicular spin-transfer torque in MTJ. In the symmetric case, the dependence is only quadratic and no linear term. But if the symmetry is broken by varying the spin splitting energy, work functions and Fermi energy of the two leads, the dependence has linear term of which the magnitude is comparable to the quadratic term.

Acknowledgment

This work was financially supported by the KRF (2009-013-C00019) and BK21 Program.

References

[1] Gary A. Prinz, Science **282**, 5394 (1998).

[2] J. A. Katine and E. E. Fullerton, J. Magn. Magn. Mater. **320**, 1217 (2008).

[3] J. C. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).

[4] L. Berger, Phys. Rev. B **54**, 9359 (1996).

[5] A. A. Tulapurkar, Y. Suzuki, A. Fukushima, H. Kubota, H. Maehara, K. Tsunekawa, D. D. Djayaprawira, N. Watanabe, and S. Yuasa, Nature **438**, 339 (2005).

[6] J. C. Sankey, P. M. Braganca, A. G. F. Garcia, I. N. Krivorotov, R. A. Buhrman, and D. C. Ralph, Phys. Rev. Lett. **96**, 227601 (2006).

[7] Jack C. Sankey, Yong-Tao Cui, Jonathan Z. Sun, John C. Slonczewski, Robert A. Buhrman, and Daniel C. Ralph, Nature Phys. **4**, 67 (2008).

[8] Hitoshi Kubota, Akio Fukushima, Kay Yakushiji, Taro Nagahama, Shinji Yuasa, Koji Ando, Hiroki Maehara, Yoshinori Nagamine, Koji Tsunekawa, David D. Djayaprawira *et al.*, Nature Phys. **4**, 37 (2008).

[9] Z. Li, S. Zhang, Z. Diao, Y. Ding, X. Tang, D. M. Apalkov, Z. Yang, K. Kawabata, and Y. Huai, Phys. Rev. Lett. **100**, 246602 (2008).

[10] T. Devolder, Joo-Von Kim, C. Chappert, J. Hayakawa, K. Ito, H. Takahashi, S. Ikeda, and H. Ohno, J. Appl. Phys. **105**, 113924 (2009).

[11] S. Petit, N. de Mestier, C. Baraduc, C. Thirion, Y. Liu, M. Li, P. Wang, and B. Dieny, Phys. Rev. B **78**, 184420 (2008).

[12] Alina M. Deac, Akio Fukushima, Hitoshi Kubota, Hiroki Maehara, Yoshishige Suzuki, Shinji Yuasa, Yoshinori Nagamine, Koji Tsunekawa, David D. Djayaprawira, and Naoki Watanabe, Nature Phys. **4**, 803 (2008).

[13] S.-C. Oh, S.-Y. Park, A. Manchon, M. Chshiev, J.-H. Han, H.-W. Lee, J.-E. Lee, K.-T. Nam, Y. Jo, Y.-C. Kong *et al.*, Nature Phys. **5**, 898 (2009).

[14] C. Wang, Y.-T. Cui, J. Z. Sun, J. A. Katine, R. A. Buhrman, and D. C. Ralph, Phys. Rev. B **79**, 224416 (2009).

[15] M. H. Jung, S. Park, C.-Y. You, and S. Yuasa, Phys. Rev. B **81**, 134419 (2010).

[16] O. G. Heinonen, S. W. Stokes, and J. Y. Yiet, Phys. Rev. Lett. **105**, 066602 (2010).

[17] M. Wilczyński, J. Barnaś, and R. Świrkowicz, Phys. Rev. B **77**, 054434 (2008).