Competition between Thickness and Electrical Conditioning Influence in Enhancing Giant Magnetoresistance Ratio for NiCoFe/Alq3/NiCoFe Spin Valve

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Abstract
Spacer thickness and electrical conditioning have their own influence in enhancing giant magnetoresistance (GMR) ratio. At some condition one factor can override the other as reported by experiment results. An empiric model about competition about these two factors is discussed in this work. Comparison from experiment results to validate the model are also shown and explained. A formulation is proposed to extend the existing one that now accommodates both spacer thickness and electrical conditioning in one form.

Keywords: giant magnetoresistance, thickness, electrical conditioning, model

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Introduction
As tunneling magnetoresistance (TMR) [1] and giant magnetoresistance (GMR) [2] are discovered in metallic spin valves (SVs) and magnetic tunnel junctions (MTJ), widespread applications in magnetic recording and memory have been rapidly enhanced. And as sensor materials, GMR material promises some important applications, which has many attractive features, for example: low price as compared to other magnetic sensors, its electric and magnetic properties can be varied in very wide range, low-power consumption, and reduction size [3, 4]. Many factors have play important roles in enhancing GMR ratio such as impurities in spacer layer [5], electrical conditioning [6], spin-transfer torque [7], interparticle interaction [8], and spacer thickness [9-12]. Influence of the latest factor is shown in Figure 1.

Modification of model proposed by Xiong et al. [9] accompanied by electrical conditioning result reported by Niedermeier et al. [6] will be the focus in this work, in order to explain our previous results [12].

NiCoFe/Alq3/NiCoFe thin film
Thin film of NiCoFe/Alq3/NiCoFe, which later acts as spin valve, has been growth at the Laboratory for Electronic Material Physics, Department of Physics, Institut Teknologi Bandung using dc-Opposed Target Magnetron Sputtering (dc-OTMS) method [12]. NiCoFe as ferromagnetic material and Alq3 {[(tris-(8-hydroxyquinoline) aluminum] as an organic material. are the sputtering target. Both targets are made using solid reaction. The first target is reacted with a molar ratio Ni:Co:Fe = 60:30:10, while the second is from Alq3 powder. The NiCoFe/Alq3/NiCoFe thin film was grown onto Si (100) substrate.

Figure 1. Spacer thickness has influence on GMR ratio as measured by: Morley et al. (Δ), Xiong et al. (□), Dediu et al. (◊), Djamal et al. (○).

Figure 2. Schematic of NiCoFe/Alq3/NiCoFe thin film and its configuration for GMR measurement.

The NiCoFe/Alq3/NiCoFe sample were deposited in several different time of growth in order to get different...
spacer layer thickness. Other deposition parameters are fixed. These parameters are: flow rate of Argon gas is 100 sccm, the growth pressure is 0.52 torr, dc Voltage is 600 volt, and the temperature is 1000 °C. The samples were characterized by using SEM (Scanning Electron Microscope) type JEOL JSM-6360 LA and magnetoresistance measurements were made by using a linear four-point probe method with current-perpendicular to-plane (CPP).

Table 1. Growth time, applied voltage, layers thickness, and GMR ratio for NiCoFe/Alq3/NiCoFe thin film.

| Growth time (minutes) | Applied voltage (mV) | Layer thickness NiCoFe / Alq3 / NiCoFe (nm) | GMR ratio (%) |
|-----------------------|----------------------|---------------------------------------------|---------------|
| 10                    | 78.4                 | 100 / 48 / 100                              | 10.5          |
| 15                    | 154.1                | 137 / 72 /137                               | 35.0          |
| 20                    | 95.2                 | 175 / 96 /175                               | 12.0          |

Overall parameters in producing the thin film and measurement results (layer thickness and GMR ratio) are as given in Table 1.

**Thickness and electrical conditioning influence**

As explain in [9] the GMR ratio \( \Delta R / R \) can be formulated using spin polarization \( p \) as in

\[
\frac{\Delta R}{R} = \frac{R_{AP} - R_P}{R_{AP}} = \frac{2p_1p_2e^{-\frac{(d-d_0)}{\lambda_S}}}{1 + p_1p_2e^{-\frac{(d-d_0)}{\lambda_S}}},
\]

where \( R_{AP} \) and \( R_P \) stand for \( R \) in the anti-parallel and parallel magnetization configurations, respectively. The spin polarization itself is defined as

\[
p_i = \frac{N_i(E_i) - N_{\bar{i}}(E_i)}{N_i(E_i) + N_{\bar{i}}(E_i)},
\]

with \( N_i \) is carrier density in the majority spin state and \( N_{\bar{i}} \) is in the minority spin state. Index \( i \) has value of 1 or 2 for the first and second ferromagnetic (FM) contact, respectively. The parameter \( \lambda_S \) is the spin diffusion length, while \( d_0 \) is the thickness of an ‘ill-defined’ layer between the conducting (FM) and spacer layer (nonmagnetic, NM). Thickness of the spacer layer is \( d \). There is also extension of Equation (1), that includes temperature \( T \) influence in spin polarization \( p \), spin diffusion length \( \lambda_S \), and new term called spin injection efficiency \( \eta \), which is [13]

\[
\frac{\Delta R}{R}(T) = \frac{R_{AP}(T) - R_P(T)}{R_{AP}(T)} = \frac{2p_1(T)\eta_1(T)p_2(T)e^{-\frac{(d-d_0)}{\lambda_S(T)}}}{1 + p_1(T)\eta_1(T)p_2(T)e^{-\frac{(d-d_0)}{\lambda_S(T)}}},
\]

It has been observed that spin diffusion length \( \lambda_S(T) \) of organic semiconductor Alq3 layer increases as temperature \( T \) decreasing [13] and spin polarization \( p \) is also decreasing at higher temperature \( T \) [9]. The value of GMR ratio itself decreases as temperature \( T \) increasing [14]. The influence of temperature to GMR ratio is out of scope of this work.

From the work of Niedermeier et al. [6] following information through a digitizing process can be found.

Table 2. Electrical conditioning results reported by Niedermeier et al. [6].

| \( I_{\text{cond}} \) (mA/cm\(^2\)) | Figure 2 in [6] | Pixels |
|-----------------------------------|-----------------|--------|
| 10.5                              | -               | 94 42  |
| 35.0                              | - 10            | 537 404|
| 12.5                              | 0               | 276 44 |
| 26.6                              | 6               | 276 88 |
| 44.6                              | 19              | 276 146|
| 66.6                              | 75              | 276 266|
| 125                               | 125             | 276 266|
| 347                               | 347             | 276 266|
| 346                               | 346             | 276 266|
| 369                               | 369             | 276 266|

Two first rows are the reference points, which are used to get the information from Figure 2 in [6]. Using this information following fitting equation can be found

\[
\frac{\Delta R}{R} \approx -0.1281I_{\text{cond}} - 1.7168, \quad (4)
\]

\[
\frac{\Delta R}{R} \approx -14165\ln(I_{\text{cond}}) - 14.831, \quad (5)
\]

where Equation (4) and (5) gives \( r^2 = 0.9605 \) and \( r^2 = 0.9992 \), respectively. These two equations are drawn in solid line in Figure 3.

Equation (4) suggests a rough approximation about influence of conditioning current \( I_{\text{cond}} \), which is related to applied voltage \( V_{\text{app}} \), to the GMR ratio.
\[
\frac{\Delta R}{R} \approx c_1 V_{\text{app}} + c_2,
\]
with \(c_1\) and \(c_2\) is constant to be determined.

By merging Equation (6) with Equation (1) will produced a formulation

\[
\frac{\Delta R}{R} = \frac{R_{21} - R_s}{R_{21}} = \frac{2(c_1 V_{\text{app}} + c_2)}{1 + p_1 p_2 e^{-(d-d_s)/\lambda_s}},
\]

that accommodates the influence of both spacer or NM layer thickness and applied voltage during growth of spin valve thin film to the GMR ratio.

**Results and discussion**

Following parameters are used in Equation (7) to fit the measured result in Table 1: \(c_1 = 0.96 \text{ V}^{-1}\), \(c_2 = -51\), \(p_1 p_2 = 0.35\), \(d_s = 11\ \text{nm}\), and \(\lambda_s = 90\ \text{nm}\). The fitting result is shown in Figure 4, which gives \(r^2 = 0.9959\). As it can be seen there are three different lines that correspond to each \(V_{\text{app}}\), which are 78.4 V, 154.1 mV, and 95.2 mV. Then it can be explained why the measured data does not have a curve as in Figure 1 that GMR ratio is in general decreasing as spacer thickness \(d\) increasing. We propose that the electrical conditioning occurred 'accidentally' in thin film growth process has enhancing the GMR ratio, which its role is dominant to the role of spacer thickness. As it can be seen, Equation (7) will be reduced to Equation (1) if the \(V_{\text{app}}\) is taken to be constant in thin film growth process.
Figure 8. GMR ratio for $d_0$ with value: 11 nm (top curve) and 0 nm (bottom curve).

Figure 9. GMR ratio for $\lambda_1$ with value: 90 nm (top curve) and 30 nm (bottom curve).

In Figure 5 – 9, all parameters used are the same as in Figure 4 and the preceded text. Only one parameter in each figure is changed to show its influence to the curve of GMR ratio $\Delta R / R$ to spacer thickness $d$.

Conclusion

A formulation that can accommodate both influence of spacer thickness and electrical conditioning to GMR ratio has been presented. It can explain measured result with $r^2=0.9959$. The influences of each parameter are also shown.

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References

[1] J. S. Moodera, L. R. Kinder, T. M. Wong, and R. Meservey, "Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junction", Physical Review Letters 74 (x), 3273-3276 (1995)

[2] M. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and Chazelas, "Giant Magnetoresistance of (001) Fe/(001) Cr Magnetic Superlattices", Physical Review Letters 61 (x), 2472-x (1988)

[3] W. Robert Kelsall., Lan W. Hamley, and Mark Geoghegan, "Nanoscale Science and Technology", John Wiley & Sons, Ltd., x Edition, 2005, pp. xx-yy

[4] Bellason and Ed Grochowski, "The era of Giant Magnetoresistive head", URI http://www.storage.ibm.com/hdd/tecnologoi/gmr/grmr [2011.10.xx.xx.xx+07]

[5] Sayani Majumdar, Himadri S Majumdar, Reino Laiho, and Ronald Österbacka, "Organic Spin Valves: Effect of Magnetic Impurities on the Spin Transport Properties of Polymer Spacer", New Journal of Physics 11 (x), 013022 (2009)

[6] U. Niedermeier, M. Vieth, R. Pätzold, W. Sarfert, and H. von Seggern, "Enhancement of Organic Magnetoresistance by Electrical Conditioning", Applied Physics Letters 92 (x), 193309 (2008)

[7] M. Gmitra and J. Barnáš, "Correlation of the Angular Dependence of Spin-Transfer Torque and Giant Magnetoresistance in the Limit of Diffuse Transport in Spin Valves", Physical Review B 79 (x), 012403 (2009)

[8] J. A. De Toro, J. P Andrés, J. A. González, J. P. Goff, A. J. Barbero, and J. M. Riveiro, "Improved Giant Magnetoresistance in Nanogranular Co / Ag: The Role of Interparticle RKKY Interaction", Physical Review B 70 (x), 224412 (2004)

[9] Z. H. Xiong, Di Wu, Z. Valy Vardeny, and Jing Shi, "Giant Magnetoresistance in Organic Spin-Valves", Nature 427 (6977), 821-824 (2004)

[10] N. A. Morley, A. Rao, D. Dhandapani, M. R. J. Gibbs, M. Grell, and T. Richardson, "Room Temperature Organic Spintronics", Journal of Applied Physics 103 (x), 07F306 (2008)

[11] V. Dediu, L. E. Hueso, I. Bergenti, A. Rimmunucci, F. Borgatti, P. Grazioski, C. Newby, F. Casoly, M. P. De Jong, C. Taliani, and Y. Zhan, "Room-Temperature Spintronic Effects in Alq3-based Hybrid Devices", Physical Review B 78 (x), 115203 (2008)

[12] Mitra Djamal, Ramli, Sparisoma Viridi, and Khairurrijal, "Giant Magnetoresistance Effect in Organic Material and Its Potential for Magnetic Sensor", ICIC*BME 2011 (submitted); arXiv:1110.1123v1 [cond-mat.me-sol] 6 Oct 2011

[13] Pang Zhi-Yong, Chen Yan-Xue, Liu Tian-Tian, Zhang Yun-Pang, Xie Shi-Jie, Yan Shi-Shen, and Han Sheng-Hao, "Giant Magnetoresistance in $La_{0.67}Ca_{0.33}MnO_3 / Alq3 / Co$ Sandwiched-Structure Organic Spin Valves", Chinese Physics Letters 23 (6) 1566-1569 (2006)

[14] F. J. Wang, Z. H. Xiong, D. Wu, J. Shi, and Z. H. Vardeny, "Organics Spintronics: The Case of Fe/Alq3/Co Spin-Valve Devices", Synthetic Metals 155 (x), 172-175 (2005)