JOURNAL OF APPLIED PHYSICS VOLUME 91, NUMBER 10 15 MAY 2002

Temperature dependence of tunneling magnetoresistance: Double-barrier versus single-barrier junctions

J. H. Lee, K. I. Lee, W. L. Lee, and K.-H. Shin
Nano Device Research Center, KIST, Seoul 130-650, Korea

J. S. Lee and K. Rhie[a)]
Department of Physics, Korea University, Chochiwon 339-700, Korea

B. C. Lee
Department of Physics, Inha University, Incheon 402-751, Korea

The temperature dependence of tunneling magnetoresistance (TMR) is studied for spin valve type double-barrier tunnel junctions. Normalized TMR values for double-barrier tunnel junctions (DBTJs) and single-barrier junctions (SBTJs) are plotted as functions of temperature and it is found that the DBTJ shows stronger temperature dependence of TMR than the SBTJ. The strong temperature dependence of TMR for the DBTJ is explained in terms of temperature dependence of the spin polarization of the middle magnetic layer and decrease of the spin coherence length with increasing temperature. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1452232]

The tunneling magnetoresistance (TMR) effect has attracted much attention recently. Since significant TMR values were reported,[1,2] the magnetic tunnel junction (MTJ) emerged as a promising component for magnetic sensors[3] and magnetic random access memory.[4] The TMR of MTJ decreases with increasing bias voltage[1] and this is one of the main obstacles to be resolved for the applications in devices. Recent theoretical works[5,6] show that a double-barrier tunnel junction (DBTJ) yields higher magnetoresistance (MR) than a single-barrier tunnel junction (SBTJ). In this case, DBTJ can be considered as a better candidate for device applications. It was also experimentally observed that TMR of DBTJ ($\mathrm{TMR}_{\mathrm{DBTJ}}$) decreases more slowly than that of SBTJ ($\mathrm{TMR}_{\mathrm{SBTJ}}$) as a function of a bias voltage.[3,7] Recently, Lee *et al.*[8] argued that $\mathrm{TMR}_{\mathrm{DBTJ}}$ is expected to be two times larger than $\mathrm{TMR}_{\mathrm{SBTJ}}$ within an extended Jullière model for DBTJ. They experimentally showed that $\mathrm{TMR}_{\mathrm{DBTJ}}$ is larger than that of $\mathrm{TMR}_{\mathrm{SBTJ}}$ at liquid nitrogen temperature, while the TMR values are about the same for both junctions at room temperature. The temperature dependence of $\mathrm{TMR}_{\mathrm{DBTJ}}$, however, is not reported yet to our knowledge, while there exist several works on that of $\mathrm{TMR}_{\mathrm{SBTJ}}$.[9–11] In this article, the temperature dependence of TMR fabricated in various conditions is presented. Strong temperature dependence of $\mathrm{TMR}_{\mathrm{DBTJ}}$ is found, and this result is explained with an extension of Jullière's model and the spin coherence length.

Double-spin valve type DBTJ was fabricated by using a six-gun magnetron sputter machine with a structure of SiO_2/Ta (5 nm)/NiFe (6 nm)/FeMn (8 nm)/CoFe (4 nm)/ Al_2O_3 (1.6 nm)/NiFe(t)/ Al_2O_3 (1.6 nm)/CoFe (2 nm)/NiFe (6 nm)/ FeMn (8 nm)/Ta (5 nm). Each bottom and top ferromagnetic layer is coupled to the corresponding antiferromagnetic FeMn layer. The NiFe layer ($t=3$ and 4 nm) in the middle works as a free layer that valves a spin-dependent current depending on the direction of applied fields. Multilayers were deposited with a base pressure below 4×10^{-8} Torr and the growing pressure was 5×10^{-3} Torr. The 50 μm×50 μm junctions were patterned by a photolithographic lift off and an ion milling process. All processes were done in the clean room (class 100∼1000). During the growth, magnetic field with strength of about 400 Oe was applied to define the uniaxial magnetic anisotropy of the magnetic layer. The Al_2O_3 barrier was formed by oxidizing 1.6 nm Al layer in a separate plasma oxidation chamber. By changing the oxidation time, optimally oxidized (24 s) and less oxidized (18 s) samples were prepared. SBTJs were fabricated in similar conditions. The structure is SiO_2/Ta(5 nm)/NiFe(6 nm)/FeMn(8 nm)/CoFe(4 nm)/Al_2O_3(1.6 nm)/CoFe(2 nm)/NiFe(10 nm)/Ta(5 nm). Some samples were annealed for an hour at 200 °C after measuring TMR at low temperatures.

Lee *et al.*[8] compared expected TMR of DBTJ to that of SBTJ based on Jullière's model.[12] The expected TMR is

$$\mathrm{TMR}_{\mathrm{SBTJ}}=\frac{1/G_{\uparrow\downarrow}-1/G_{\uparrow\uparrow}}{1/G_{\uparrow\uparrow}}=\frac{2P_1P_2}{1-P_1P_2}, \tag{1}$$

and

$$\mathrm{TMR}_{\mathrm{DBTJ}}=\frac{1/G_{\uparrow\downarrow\uparrow}-1/G_{\uparrow\uparrow\uparrow}}{1/G_{\uparrow\uparrow\uparrow}}=\frac{2(P_1P_2+P_2P_3)}{1-P_1P_2-P_2P_3+P_3P_1}, \tag{2}$$

where G is the conductance for different magnetization directions of each layer whose configuration of magnetization direction is denoted with arrows in subscript. P_i ($i=1,2$, and 3) is the spin polarization of each magnetic layer and i stands for the magnetic layer from bottom to top in sequence. They pointed out that the $\mathrm{TMR}_{\mathrm{DBTJ}}$ becomes twice of $\mathrm{TMR}_{\mathrm{SBTJ}}$ when P_i's are the same and the electrons that tunneled the

---

[a)] Author to whom all correspondence should be addressed; electronic mail: krhie@korea.ac.kr

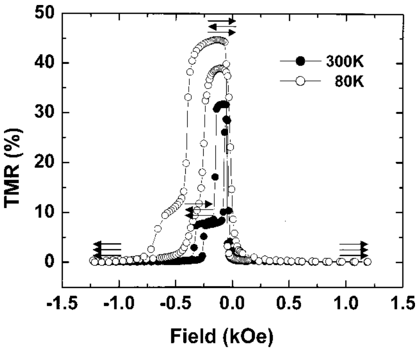

FIG. 1. TMR curve of the annealed double barrier tunnel junction (DBTJ) with the thickness of the middle layer $t=3$ nm. The solid and open circles are MR measured at 300 K and 77 K, respectively. The arrows indicate the magnetization configuration of magnetic layers.

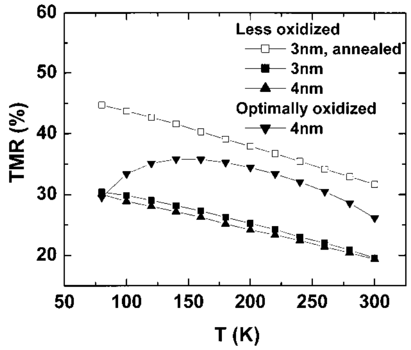

FIG. 2. Temperature dependence of TMR of DBTJs fabricated in various conditions. The thickness of the middle layer is 3 nm (squares) and 4 nm (triangles). Only the sample represented by open squares is annealed and the others are as grown. Note that, for as-grown junctions, TMR for 3 nm thick middle layer has a slightly larger value than that with 4 nm thick middle layer.

first barrier reach the second one without losing spin information. If the electrons lose spin information in the middle layer, the DBTJ becomes simply a series of SBTJ, and $\mathrm{TMR}_{\mathrm{DBTJ}}$ becomes the same as $\mathrm{TMR}_{\mathrm{SBTJ}}$. On this theoretical basis, one may expect that the $\mathrm{TMR}_{\mathrm{DBTJ}}$ should exhibit stronger temperature dependence than $\mathrm{TMR}_{\mathrm{SBTJ}}$, since the spin coherence length of electrons in the middle magnetic layer is longer at low temperature. Since it is difficult to fabricate a pair of DBTJ and SBTJ in the exactly same condition, it will be easier to compare normalized temperature dependence of TMR for DBTJs and SBTJs.

Figure 1 displays a representative TMR curve of the annealed DBTJ with the thickness of the middle layer $t=3$ nm. The solid and open circles are MR observed at 300 K and 77 K, respectively. The top and bottom ferromagnetic layers are pinned by FeMn layers and this seems to make the TMR curve more complicated. The magnetization reversal of each layer is clearly distinguishable, which demonstrates that each magnetic layer is properly separated by the $\mathrm{Al_2O_3}$ layers. The change of TMR for different magnetic states is explained better if we assume that the DBTJ is a series of two SBTJs whose exchange fields are different each other. However, the spin coherence length is comparable to the thickness of the middle layer and some of tunneling electrons conserve the spin through double barriers and the effect of the modified Jullière model may survive. Repeated sample fabrications yielded good reproducibility of TMR, but the shapes of the TMR curves are sample dependent. Especially, two pinned layers are not clearly separated for as-grown samples.

The temperature dependence of TMR is shown in Fig. 2 for various DBTJs. The thickness of the middle layer is $t=3$ and 4 nm for squares and triangles, respectively. The filled symbols are for the as-grown samples and the unfilled are for the annealed ones. Two different oxidation times were used and the meaning of "optimal" oxidation is that the tunnel junction in this condition yields the highest TMR values at room temperature. At room temperature, less oxidized as-grown samples (filled squares and filled upper triangles) show similar TMR values of 19%, and optimally oxidized as-grown one has 26%. After annealing, TMR of the less oxidized sample increased to 32%. The increase of TMR in DBTJ after the annealing process is analogous to that of SBTJ.[13] The resistance area product is 4.9 and 2.5 $\mathrm{M}\Omega\,\mu\mathrm{m}^2$ for less oxidized as-grown samples with the thickness of the middle layer $t=3$ and 4 nm (filled square and triangle in Fig. 2), respectively. It is 13 $\mathrm{M}\Omega\,\mu\mathrm{m}^2$ for the optimally oxidized as-grown one (filled inverse triangle), and 3.68 $\mathrm{M}\Omega\,\mu\mathrm{m}^2$ (empty triangle) for the less oxidized annealed one.

No significant difference is observed between the $t=3$ nm (filled square) and 4 nm (filled triangle) cases for the less-oxidized as-grown DBTJs. In our simple modified Jullière model for the DBTJ, one may expect a higher TMR value at low temperature for the sample with a thinner middle layer because the probability of spin flip in the middle layer is smaller. Indeed, TMR for $t=3$ nm is slightly larger than that of $t=4$ nm. However, there are other factors which effect TMR values and it is hard to tell if the TMR difference is due to that of the middle-layer thickness. For instance, it is expected that less-oxidized tunnel barriers contain abundant voids through which the spin-independent two-step process[9] can occur. In such a case, the effect of DBTJ can not be observed. The optimally oxidized DBTJ (inverse triangle) exhibits rather novel temperature dependence. The TMR value increases with temperature from 80 to 140 K. But, this has nothing to do with the effects of DBTJ. SBTJs grown in similar conditions show the same behavior as shown in Fig. 3. The initial increase of TMR as a function of temperature is interpreted as the effect of spin-dependent scatterings at the oxidized ferromagnetic layer.[14,15]

The TMR of DBTJs is supposed to have a higher value only when the middle layer is thin enough for tunneling electrons to conserve the spin. Dubois *et al.*[16] experimentally estimated the spin coherence length of Py to be about 5 nm at 77 K. Thus, the middle-layer thicknesses of our junctions are considered to be comparable to the spin coherence length at 80 K. Since the spin coherence length decreases with increasing temperature, the middle-layer thickness is expected to be larger than the spin coherence length at room temperature. This change of the spin coherence length will effect TMR of DBTJs significantly in our extended Jullière model for DBTJ. As a result, the temperature dependence of DBTJs is expected to be much stronger than that of SBTJs. For

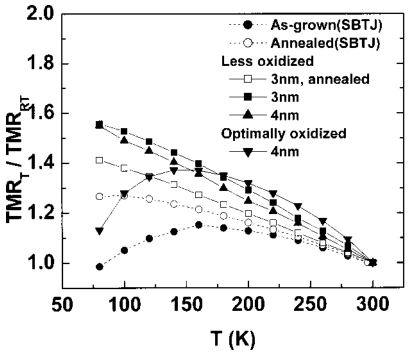

FIG. 3. Temperature dependence of normalized TMR for DBTJs (solid lines, squares, and triangles) and SBTJs (dashed lines, circles). The TMR is normalized with respect to the value measured at room temperature. All the SBTJs shown are optimally oxidized. Filled symbols are for as-grown samples and unfilled symbols are for annealed ones, respectively. The TMR of DBTJ is supposed to be compared with that of SBTJ fabricated in a similar condition. Note that the temperature dependence of DBTJs is stronger than that of SBTJs.

comparison, the normalized TMR of DBTJs and SBTJs is plotted as functions of temperature in Fig. 3. It is assumed that, at room temperature, the spin coherence length is very short and the TMR of DBTJ is about the same as that of corresponding SBTJ. Then, it is natural to normalize the TMR values with respect to the value measured at room temperature. The solid and dotted lines represent normalized $\mathrm{TMR}_{\mathrm{DBTJ}}$ and $\mathrm{TMR}_{\mathrm{SBTJ}}$, respectively. Filled symbols are for as-grown samples, and unfilled ones are for annealed ones. It is evident that the temperature dependence of $\mathrm{TMR}_{\mathrm{DBTJ}}$ for a group of samples is much stronger than that of $\mathrm{TMR}_{\mathrm{SBTJ}}$. For optimally oxidized as-grown samples, both the DBTJ (filled down triangles) and SBTJ (filled circles) show novel temperature dependence due to the oxidized ferromagnetic layer.[15] Still, the temperature dependence for DBTJ is clearly stronger than that for SBTJ. Actually, the temperature dependence of TMR for other SBTJs, which are not included in Fig. 3, was also weaker than that for DBTJs. This stronger temperature dependence of TMR for DBTJ is consistent with the extended Jullière model for DBTJ. On the other hand, Shang *et al.*[10] attributed the decrease of TMR with increasing temperature to that of spin polarization of magnetic electrodes. They also found that TMR for permalloy electrode decreases faster than that for CoFe as a function of temperature. Since the magnetic middle layer for DBTJs in this article is made of permalloy, their argument can also explain the stronger temperature dependence of DBTJ. The bias dependence of TMR was measured, and TMR for DBTJs decreased more slowly than that for SBTJs with increasing bias voltage as reported by Montaigne *et al.*[3]

In summary, it is observed that the temperature dependence of TMR for DBTJs is stronger than that for SBTJs. This result can be explained by the decrease of the spin coherence length and spin polarization with increasing temperature.

This work was supported by the National Program for Tera-level Nanodevices of the Ministry of Science and Technology and the electron Spin Science Center at POSTECH established by KOSEF.

[1] J. S. Moodera, L. R. Kinder, T. M. Wang, and R. Merservey, Phys. Rev. Lett. **74**, 3273 (1995).
[2] T. Miyazaki and N. Tezuka, J. Magn. Magn. Mater. **139**, L231 (1995).
[3] F. Montaigne, J. Nassar, A. Vaurès, F. Nguyen Van Dau, F. Petroff, A. Achuhl, and A. Fert, Appl. Phys. Lett. **73**, 2829 (1998).
[4] S. S. P. Parkin, K. P. Roche, M. G. Samant, P. M. Rice, R. B. Beyers, R. E. Scheurlein, E. J. O'Sullivan, S. L. Brown, J. Bucchigano, D. W. Abraham, Y. Lu, M. Rooks, P. L. Trouilloud, R. A. Wanner, and W. J. Gallagher, J. Appl. Phys. **85**, 5828 (1999).
[5] L. Sheng, Y. Chen, H. Y. Teng, and C. S. Ting, Phys. Rev. B **59**, 480 (1999).
[6] X. Zhang, B. -Z. Li, G. Sun, and F. -C. Pu, Phys. Rev. B **56**, 5484 (1997).
[7] K. Inomata, Y. Saito, K. Nakajima, and M. Sagoi, J. Appl. Phys. **87**, 6064 (2000).
[8] J. H. Lee, I.-W. Chang, S. J. Byun, T. K. Hong, K. Rhie, W. Y. Lee, K.-H. Shin, C. Hwang, S. S. Lee, and B. C. Lee, J. Magn. Magn. Mater. (in press).
[9] J. Zhang and R. M. White, J. Appl. Phys. **83**, 6512 (1998).
[10] C. H. Shang, J. Nowak, R. Jansen, and J. S. Moodera, Phys. Rev. B **58**, 2917 (1998).
[11] X.-F. Han, M. Oogane, H. Kubota, Y. Ando, and T. Miyazaki, Appl. Phys. Lett. **77**, 283 (2000).
[12] M. Jullière, Phys. Lett. A **54**, 225 (1975).
[13] R. C. Sousa, J. J. Sun, V. Soares, P. P. Freitas, A. Kling, M. F. da Silva, and J. C. Soares, Appl. Phys. Lett. **73**, 3288 (1998).
[14] J. H. Lee, I.-W. Chang, S. J. Byun, K. Rhie, K.-H. Shin, K.-I. Lee, J. G. Ha, and B. C. Lee, J. Magn. Magn. Mater. (in press).
[15] K. I. Lee, J. H. Lee, W. Y. Lee, K.-H. Shin, Y. B. Sung, J. G. Ha, K. Rhie, and B. C. Lee, J. Appl. Phys. **91**, 7959 (2002).
[16] S. Dubois, L. Piraux, J. M. George, K. Ounadjela, J. L. Duvail, and A. Fert, Phys. Rev. B **60**, 477 (1999).