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

Nano Device Research Center, KIST, Seoul 130-650, Korea

J. S. Lee and K. Rhie
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 sensors3 and magnetic random access memory.4 The TMR of MTJ decreases with increasing bias voltage1 and this is one of the main obstacles to be resolved for the applications in devices. Recent theoretical works5,6 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 (TMRDBTJ) decreases more slowly than that of SBTJ (TMRSBTJ) as a function of a bias voltage.3,7 Recently, Lee et al.8 argued that TMRDBTJ is expected to be two times larger than TMRSBTJ within an extended Jullièrre’s model for DBTJ. They experimentally showed that TMRDBTJ is larger than that of TMRSBTJ at liquid nitrogen temperature, while the TMR values are about the same for both junctions at room temperature. The temperature dependence of TMRDBTJ, however, is not reported yet to our knowledge, while there exist several works on that of TMRSBTJ.9–11 In this article, the temperature dependence of TMR fabricated in various conditions is presented. Strong temperature dependence of TMRDBTJ is found, and this result is explained with an extension of Jullièrre’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 SiO2/Ta (5 nm)/NiFe (6 nm)/FeMn (8 nm)/CoFe (4 nm)/Al2O3 (1.6 nm)/NiFe(t)/Al2O3 (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. Multi-layers 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 Al2O3 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 SiO2/Ta(5 nm)/NiFe(6 nm)/FeMn(8 nm)/CoFe(4 nm)/Al2O3(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 Jullièrre’s model.12 The expected TMR is

\[
\text{TMR}_{SBTJ} = \frac{1/G_{11} - 1/G_{\perp \perp}}{1/G_{11}} = \frac{2P_1P_2}{1 - P_1P_2},
\]

and

\[
\text{TMR}_{DBTJ} = \frac{1/G_{11\parallel} - 1/G_{11\perp}}{1/G_{11\parallel}} = \frac{2(P_1P_2 + P_2P_3)}{1 - P_1P_2 + P_2P_3 + P_3P_1},
\]

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 TMRDBTJ becomes twice of TMRSBTJ when \(P_i\)’s are the same and the electrons that tunneled the...
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 SBTJs, and TMR\textsubscript{DBTJ} becomes the same as TMR\textsubscript{SBTJ}. On this theoretical basis, one may expect that the TMR\textsubscript{DBTJ} should exhibit stronger temperature dependence than TMR\textsubscript{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 measured at 300 K and 77 K, respectively. The arrows indicate the magnetization configuration of magnetic layers.

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. The resistance area product is 4.9 and 2.5 M$\Omega \mu$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 M$\Omega \mu$m$^2$ for the optimally oxidized as-grown one (filled inverse triangle), and 3.68 M$\Omega \mu$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 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.

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. 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
For optimally oxidized as-grown samples, both the DBTJ is evident that the temperature dependence of TMRDBTJ for a as-grown samples, and unfilled ones are for annealed ones. It
short and the TMR of DBTJ is about the same as that of SBTJ. This result can be explained by the decrease of the spin co-
herence 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 Tech-
nology and the electron Spin Science Center at POSTECH established by KOSEF.

ham, Y. Lu, M. Reoos, P. L. Trouilloud, R. A. Wanner, and W. J. Gal-