MOLECULAR PHYSICS REPORTS **40** (2004) 192-199

TEMPERATURE DEPENDENCE OF TUNNEL MAGNETORESISTANCE OF IrMn BASED MTJ

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Abstract: The temperature dependence of tunnel magnetoresistance (TMR) is investigated between 30 K and 300 K for annealed junctions with the structure of Ta(5)/Cu(10)/Ta(5)/NiFe(2)/Cu(5) /IrMn(10)/CoFe(2.5)/Al_2O_3(1.5)/CoFe(2.5)/NiFe(***t***)/Ta(5), where t = 10 and 100 nm. For the junction (t = 100 nm) annealed at 270°C we were able to separate the spin-dependent and the spin-independent contributions to the temperature dependence of the TMR. For the junction with t = 10 nm annealed at 300°C the electron spin polarization conductance is small in comparison to high conductance *via* trapped states, which arises from defects and magnetic impurities diffusion. For both junctions anomalous decrease of the TMR with decreasing temperature was observed below 75 K. The anomaly is attributed to the reduced value of the antiparallel conductance, due to not fully antiparallel alignment of magnetizations of FP and FF layers.

1. INTRODUCTION

The temperature dependence of the tunnel magnetoresistance (TMR) in a magnetic tunnel junction (MTJ) was investigated in several papers [1-3]. In the paper [1] theoretical model of the temperature dependence of the TMR, including the spin dependent and the spin independent current contributions to the TMR, was proposed as well as experimental verification of the model was performed on the junctions such as Co/Al_2O_3/$Ni_{80}Fe_{20}$, Co/Al_2O_3/Co/NiO, and Co/Al_2O_3/$Ni_{80}Fe_{20}$/NiO. Similar approach to the temperature dependence of TMR of Co/Fe/Al_2O_3/Co/Cu/Co (where the hard electrode was artificial antiferromagnet) is given in paper [2]. In both studies, authors assumed that the spin dependent contribution to the current, defined as a difference of conductance ($dG = G_P - G_{AP}$) between parallel (G_P) and antiparallel (G_{AP}) alignments of magnetizations, which is proportional to the polarization of top and bottom electrodes, decreases with temperature due thermally excited spin waves in similar way as the interface magnetization does, in the form of the Bloch law $M(T) = M(0)(1-BT^{3/2})$ [4]. However, results presented in paper [3] show that for annealed (between 250°C and 300°C) Spin Valve (SV) MTJs with the structure NiFe(6)/FeMn(8) /CoFe(4)/Al_2O_3(1.6)/CoFe(2)/NiFe(10) (similar electrodes system to ours), spin-polarized tunneling does not follow $P \propto (1 - bT^{3/2})$ proportionality proposed in paper [1]. The authors argued that for annealed junctions the increase of *dG* with increasing temperature is *via* impurity states caused by diffusion of magnetic elements to the barrier [3].

In this work, we analyzed temperature dependence of TMR in annealed $Ir_{25}Mn_{75}$ based SV-MTJ structures in order to verify the model of temperature dependence of TMR proposed in paper [1].

2. EXPERIMENT

The investigated MTJ structures were composed of Si(100)/SiO_x/Ta(5)/Cu(10)/Ta(5)/$Ni_{80}Fe_{20}$(2)/Cu(5)/IrMn(10)/$Co_{80}Fe_{20}$(2.5)/Al_2O_3(1.5)/$Co_{80}Fe_{20}$(2.5)/$Ni_{80}Fe_{20}$(*t*)/Ta(5), where t = 10 and 100 nm. The MTJs were prepared using DC magnetron sputtering technique (for details see [5]). The samples were annealed in vacuum (10^{-6} hPa) at 270°C and 300°C for 1 hour in the external magnetic field of 80 kA/m, followed by field cooling. The size of the junctions was 180×180 μm^2. TMR of the samples was measured as a function of temperature between 30 and 300 K.

3. RESULTS AND DISCUSSION

Junction Magnetoresistance

The annealing of the MTJs at different temperatures for 1 hour (Fig. 1) leads to the maximum of TMR. The increase of the TMR up to a certain temperature and then decrease can be explained by two processes occurring in junction: one is the reducing of defects in the tunneling barrier and its interfaces, the second process is the diffusion of materials to the interface of tunneling barrier, which lowers its effective spin-polarization and decreases the TMR ratio.

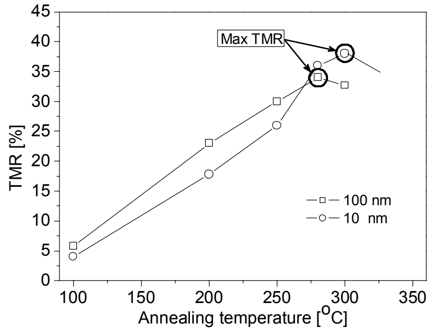

Fig. 1. Annealing effect on TMR of MTJs with *t* = 100 nm and *t* = 10 nm

In Figure 2 the examples of JMR minor loops at different temperatures are shown. The JMR was calculated from the formula given by Julliere [6], JMR* = $(G_P - G_{AP})/G_P$. The minor

*Please note that JMR defined by Julliere as JMR = $(G_P - G_{AP})/G_P$ is lower then as generally assume TMR = $(G_P - G_{AP})/G_{AP}$. The TMR and JMR are called optimistic and pessimistic magnetoresistances, respectively.

loops characterize by small coercivity of the ferromagnetic free (FF) layer (H_{CF}) and low interlayer coupling field (H_S) for thick NiFe electrode (100 nm) (Fig. 2a), and by large H_S and H_{CF} for thin NiFe (t = 10 nm) electrode (Fig. 2b). The bilayer structure of the FF layer (hard – CoFe and soft - NiFe) and thin NiFe layer in the buffer are reason for the not rectangular shape of the loops. The shift of the loops with respect to H = 0 indicates a ferromagnetic coupling between the soft and hard magnetic electrodes and is interpreted as "orange peel coupling" [7]. As shown in Fig. 3 the interlayer coupling field (H_S) is for both samples approximately independent on temperature. However, coercive field decreases stronger with temperature increasing for thinner then for thicker FF layer. The domain structure observation shows that thick (100 nm) NiFe FF layer has large domains separated by 180° Bloch walls, while thin (10 nm) layer shows crossing stripes domains separated by 180° and 360° walls [8, 9].

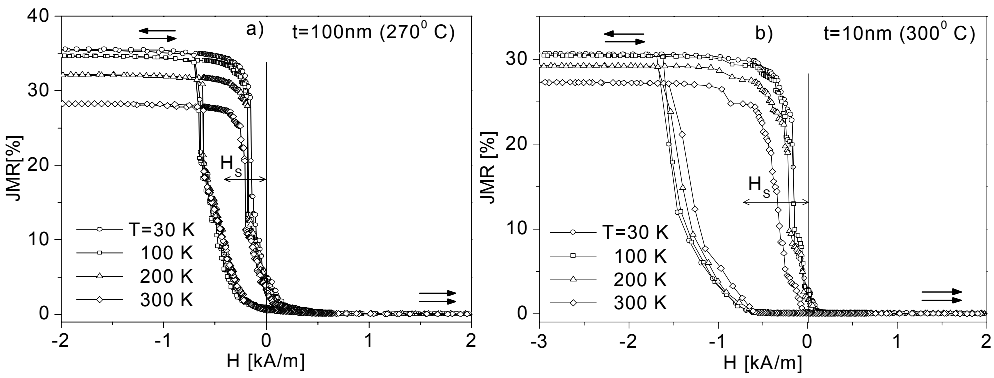

Fig. 2. Examples of minor loops at different temperatures of MTJs with t = 100 nm (a) and t = 10 nm (b)

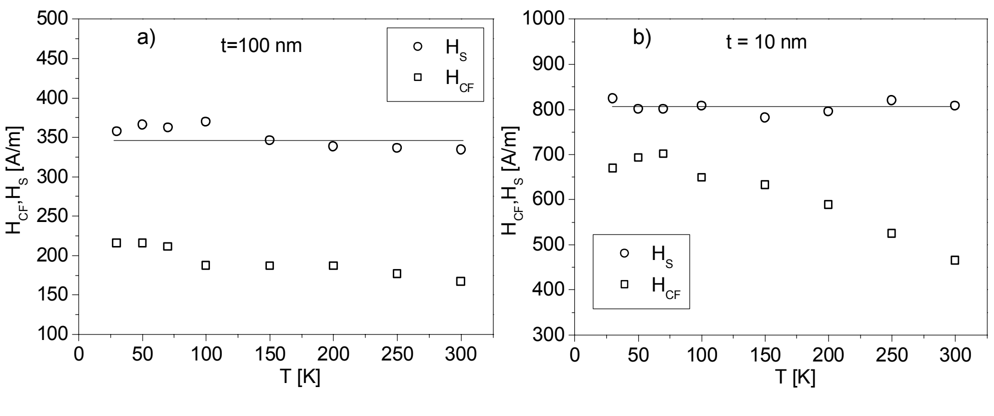

Fig. 3. Coercive and interlayer coupling fields of FF layer of MTJs with t = 100 nm (a) and t = 10 nm (b). The lines are guide for eyes

The decrease of JMR with increasing temperature for the sample with t = 100 nm is stronger than for the sample with t = 10 nm (Fig. 4a). Moreover, in Fig. 4a can be seen decrease of the JMR with decreasing temperature at low temperature range (T < 75 K), which does not predict the discussed model. The anomaly is stronger for the junction with the thin layer (t = 10 nm). To better understand that anomaly we performed low temperature SQUID measurements of magnetizations of the junctions, which are described in the magnetization section.

The model proposed in [1] assumes two current contributions to the total conductance of the junction, namely: spin dependent elastic tunneling current and spin independent current. The total conductance is expressed as

$$G(\theta_1,\theta_2, T) = G_T(T)[1 + P_1(T)\, P_2(T)\cos(\theta_1 - \theta_2)] + G_{SI}(T), \tag{1}$$

where θ_1 and θ_2 are the magnetization directions of the two electrodes ($\theta_1 - \theta_2 = 0°$ or $180°$ for parallel or antiparallel magnetizations, respectively), $P_1(T)$ and $P_2(T)$ are spin polarizations of the electrodes.

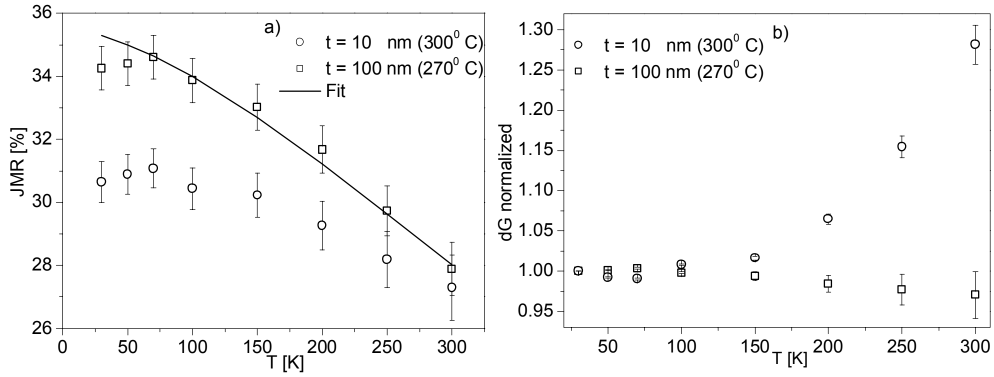

Fig. 4. Temperature dependence of the JMR (a) and normalized dG (b). The solid line is the fit by the model function

The variable $G_T(T)$, accounts for the conductance due to direct elastic tunneling, can be written as

$$G_T(T) = G_0\, CT/\sin(CT), \tag{2}$$

where G_0 is the conductance at T = 0 K, and $C = 1.387 \times 10^{-4} d/\sqrt{\phi}$ is a material constant dependent on a barrier thickness d and the barrier height ϕ. For our samples, d = 15 Å and ϕ = 3.4 eV [1], it gives $C = 1.1 \times 10^{-3}\ \mathrm{K}^{-1}$. Since, for typical barrier parameters, G_T at 300 K is slightly higher than at 0 K its influence on total conductance can be negligible [1].

Considering influence of electrodes polarization $P_1(T)P_2(T)$ on conductance in similar way as magnetization, the effective polarizations can be written as

$$P_1(T)P_2(T) = P_{01}(1 - b_1 T^{3/2})P_{02}(1 - b_2 T^{3/2}), \tag{3}$$

where P_{01}, P_{02} are polarizations of the electrodes at $T = 0$ K, and b_1, b_2 are spin wave material constants.

The term $G_{SI}(T)$ represents the spin independent contribution to total conductance of a junction. According to the model proposed in the paper [1], $G_{SI}(T)$ can be expressed as $G_{SI}(T) = NT^{\alpha}$ where N indicates number of defects in a barrier and α is a electron hopping parameter [1].

In order to describe the results with proposed functions the parameters G_0, P_{01}, P_{02}, b_1, b_2, N, α (where references parameters G_0 and P_0 were determined by extrapolation of $G_P(T)$ and $G_{AP}(T)$ to $T = 0$ K) are found for the junction annealed at 270°C with $t = 100$ nm, because only its conductance difference $dG(T) = G_P(T) - G_{AP}(T)$ decreases with temperature as shown in Fig. 4b. The dG does not contain G_{SI} and is equal to

$$dG = 2G_T P_1 P_2. \tag{4}$$

The normalized conductance $dG(T)/dG(30\text{ K})$ is plotted in Fig. 5a where the solid line is the fit by means of the model function. Next, the spin independent conductance G_{SI} was calculated from

$$G_{SI}(T) = [G_P(T) + G_{AP}(T)]/2 - G_T(T). \tag{5}$$

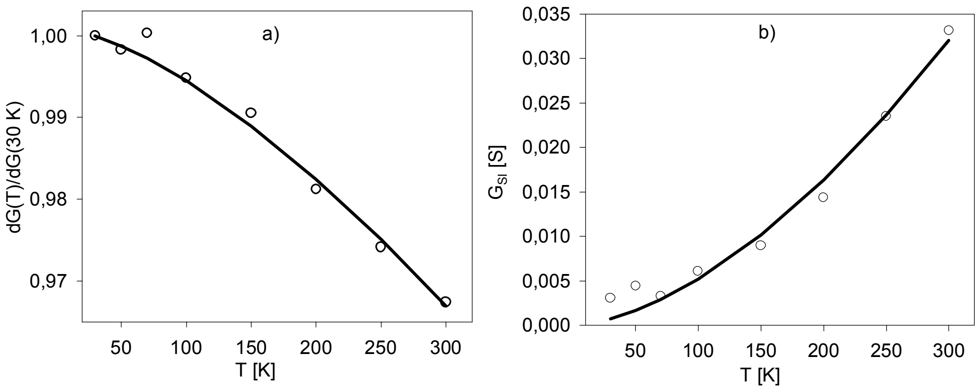

Fig. 5. Temperature dependence of the normalized dG for MTJ annealed at 270°C with t =100 nm (a). Temperature dependence of the spin independent conductance G_{SI} (b). The solid lines represent the theoretical fits

The experimental data of $G_{SI}(T)$ were fitted using the function $G_{SI}(T) = NT^{\alpha}$, as given by the solid line in Fig. 5b. The fitting parameters are summarized in Table 1 together with parameters from papers [1, 2] shown for comparison. Our parameters of polarization and spin wave constants are only comparable in order of magnitude to those from [1, 2] because of different junction structure. The exponent $\alpha = 1.33$ indicates that hopping conductance through localized states in amorphous Al_2O_3 barrier is dominant process while the coefficient N depends on the number of defects and indicates the quality of the barrier [10]. Large values of α and N (Table 1) for our annealed junction are responsible for faster rising $G_{SI}(T)$ with T than decreasing $dG(T)$. In our opinion, annealing in higher temperature than 270°C leads to the increase of trapped states in the barrier due to diffusion of magnetic impurities [11, 12],

Table 1. The model parameters for MTJ with t =100 nm and for comparison parameters from literature (*effective polarization)

	P_{01}(%)	P_{02}(%)	b_1 ($K^{-3/2}$)	b_2 ($K^{-3/32}$)	N ($\Omega^{-1}K^{-\alpha}$)	α
Our	NiFe 48 ± 4	CoFe 45 ± 6	CoFe $(9.2 \pm 0.3) \times 10^{-6}$	CoFe /NiFe $(1 \pm 0.25) \times 10^{-6}$	$(3.21 \pm 1.1) \times 10^{-6}$	1.61 ± 0.22
[1]	NiFe 42 ± 3	Co 34±2	NiFe 3-5 $\times 10^{-5}$	Co 1-6 $\times 10^{-6}$		1.33 ± 0.15
[2]	Co/Fe $32 \pm 1^*$		Co/Fe $(10 \pm 0.8) \times 10^{-6}$		$(2.0 \pm 0.5) \times 10^{-6}$	1.33

thus stronger change of $G_T(T)$ with temperature than theory predicted [10]. In consequence, the deterioration of the barrier can be responsible for increase of dG with temperature, observed for the MTJ with t = 10 nm annealed at 300°C (Fig. 4b) similarly to the results in [3], and nonconformity of thermally spin waves excitation in the form of Bloch law $P \propto (1 - T^{3/2})$.

Magnetization

The low temperature magnetization measurements of the junctions were performed by SQUID magnetometer. The example of the major loops, at low and room temperatures, are shown in Fig. 6. The temperature dependences of the magnetization at low magnetic fields, where the magnetization of FF layer is antiparallel oriented with respect to ferromagnetic pinned (FP) layer, are plotted in Fig. 7.

As can be seen in Fig. 6 the shape of the $M(H)$ major loops at temperature below 75 K (in Fig. 6 are only shown loops at 10 K but similar shape of these loops are observed up to 75 K), indicates that magnetizations of the FP layer continuously change in the field range of the FF layer switching.

Following the model proposed by Tsunoda and Takahashi [13, 14], which assumes a random distribution of the magnetocrystalline anisotropy axes of the antiferromagnet (AF) grains, the AF layer is regarded as an aggregation of the AF grains and the FP layer is regarded as single domain (*i.e.* the magnetization of the FP layer is treated as a single spin). From the fact that, below 75 K spins in the AF layer follow close to the magnetization of the FP layer, which is rotating with applied filed, can be infered that for some AF population grains (note asymmetrical loops of FP layer Fig. 6a and c) the interfacial surface energy (J_{EB}) is larger than the energy of magnetic ordering of AF grains (expressed as effective surface energy $K_{AF} \cdot t_{AF}$) $J_{EB} > K_{AF} \cdot t_{AF}$. Above 75 K, the major hysteresis loops are biased (loops of the FP layer are shifted, Fig. 6 b and d), due to the domination of magnetic ordering energy of AF grains over the J_{EB} energy ($J_{EB} < K_{AF} \cdot t_{AF}$).

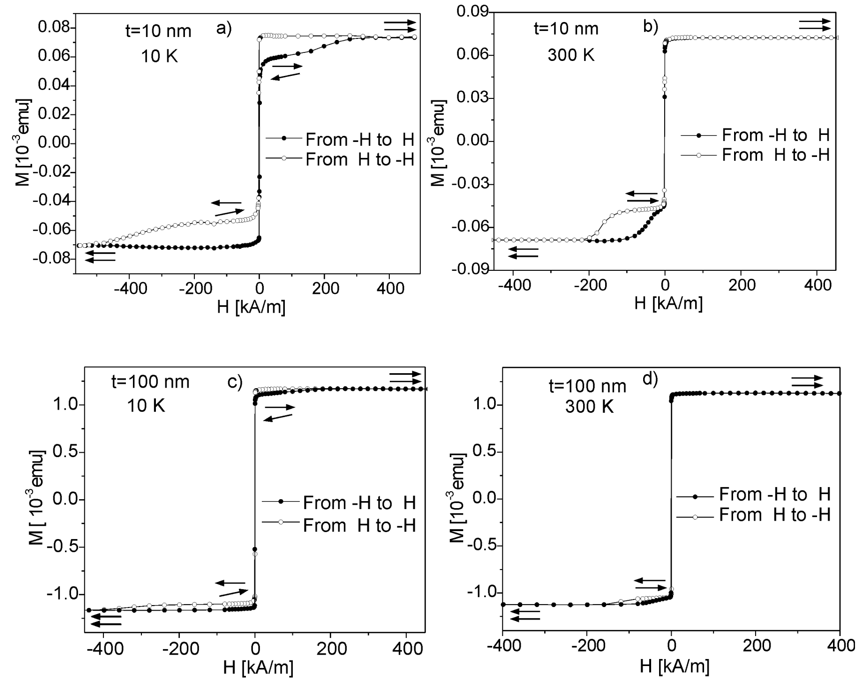

Fig. 6. Exemplary major hysteresis loops of the junctions with t = 10 nm (a, b) and 100 nm (c, d) for selected temperature measured by SQUID

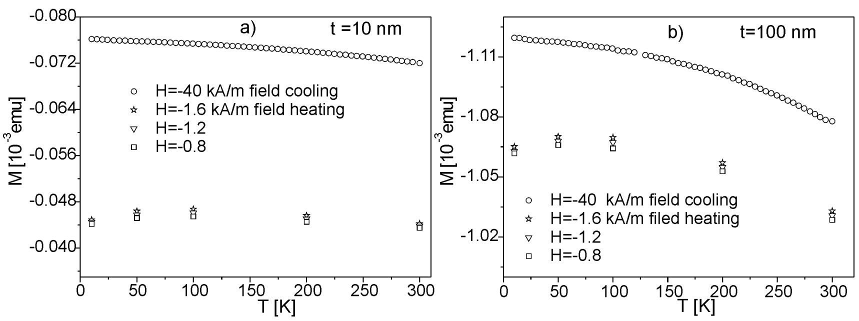

Fig. 7. Temperature dependences of the low field magnetizations of the junctions with t = 10nm (a) and 100nm (b) at antiparallel (AP) state

The change of the magnetization of FP layer in the range of switching field of the FF layer manifests in decreasing of the magnetization with increasing temperature as is shown in Fig. 7. The low field magnetizations anomaly was observed in measurements of the junctions during the heating in the field. When the magnetization was measured at freezing AP alignment of the magnetizations during the field cooling, the anomaly was not observed. The field cooling measurements of the magnetization follow Bloch law, for details see [15].

As is known from the previous section the value of JMR depends on the difference between conductance at the AP and the parallel (P) state. Since the junctions do not show AP state, it means that the antiparallel conductance (G_{AP}) does not reach maximal value at low temperature. The decrease of the JMR (Fig. 4a) at temperature below 75 K is small (about 0.5%) and it resemblances the decrease of the magnetization shown in Fig. 7, which is caused by the not fully antiparallel alignment of the magnetizations of the FF and FP layers.

4. CONCLUSIONS

For the junction (t = 100 nm) annealed at 270°C we were able to separate electron polarization spin-dependent and spin-independent contributions to the temperature dependence of the JMR. For junction with (t = 10 nm) annealed at 300°C the electron spin polarization conductance is small, in comparison to high conductance *via* trapped state arises from defects and magnetic impurities diffusion into the barrier. In order to explain which tunneling current, the spin dependent or spin independent, is dominant in annealed spin valve junctions, control of the barrier parameters is necessary. For both junctions anomalous decrease of the TMR with decreasing temperature was observed below 75 K. The anomaly is attributed to the reduced value of the AP conductance, due to not fully antiparallel alignment of the magnetizations of the FP and FF layers. This is because some population of AF grains, in the low temperature, has interfacial exchange energy larger than magnetic ordering energy, which results in small deviation of AP alignment.

Acknowledgements
This work was partially supported by Polish Ministry of Scientific Research and Information Technology grant 4T11B 020 25.

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