Titre: Title:	The tunneling magnetoresistance current dependence on cross sectional area, angle and temperature
Auteurs: Authors:	Z. H. Zhang, Lihui Bai, C. M. Hu, S. Hemour, Ke Wu, X. L. Fan, D. S. Xue et D. Houssameddine
Date:	2015
Type:	Article de revue / Journal article
Référence: Citation:	Zhang, Z. H., Bai, L., Hu, C. M., Hemour, S., Wu, K., Fan, X. L., ... Houssameddine, D. (2015). The tunneling magnetoresistance current dependence on cross sectional area, angle and temperature. *AIP Advances*, *5*(3). doi:10.1063/1.4916584

URL de PolyPublie: PolyPublie URL:	https://publications.polymtl.ca/3623/
Version:	Version officielle de l'éditeur / Published version Révisé par les pairs / Refereed
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Titre de la revue: Journal Title:	AIP Advances (vol. 5, no 3)
Maison d'édition: Publisher:	American Institute of Physics
URL officiel: Official URL:	https://doi.org/10.1063/1.4916584
Mention légale: Legal notice:	

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Citation: AIP Advances **5**, 037134 (2015); doi: 10.1063/1.4916584
View online: https://doi.org/10.1063/1.4916584
View Table of Contents: http://aip.scitation.org/toc/adv/5/3
Published by the American Institute of Physics

AIP ADVANCES **5**, 037134 (2015)

The tunneling magnetoresistance current dependence on cross sectional area, angle and temperature

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(Received 5 January 2015; accepted 19 March 2015; published online 26 March 2015)

The magnetoresistance of a MgO-based magnetic tunnel junction (MTJ) was studied experimentally. The magnetoresistance as a function of current was measured systematically on MTJs for various MgO cross sectional areas and at various temperatures from 7.5 to 290.1 K. The resistance current dependence of the MTJ was also measured for different angles between the two ferromagnetic layers. By considering particle and angular momentum conservation of transport electrons, the current dependence of magnetoresistance can be explained by the changing of spin polarization in the free magnetic layer of the MTJ. The changing of spin polarization is related to the magnetoresistance, its angular dependence and the threshold current where TMR ratio equals zero. A phenomenological model is used which avoid the complicated barrier details and also describes the data. [http://dx.doi.org/10.1063/1.4916584]

An MTJ with uniaxial anisotropy has two resistance states, the parallel state (PS) and anti-parallel state (APS), corresponding to two magnetization configurations which can be controlled by the application of a current through the magnetic stack.[1–12] MTJs have attracted a lot of attention recently and are seen as the next generation of non-volatile memories.[13–19] The threshold current for switching the magnetization in the free FM layer of an MTJ was evaluated by J. Z. Sun by calculating the cone angle of precession.[8]

The fact that the resistance and the TMR of an MTJ decreases as applied current increases has been reported in many works.[9–12] The decreases are always described as the bias dependence and are explained by mechanisms such as interface spin excitation,[20] a reduced polarization for hot electron states and spin dependent wave-vector mismatch[21] or the defects in the tunnel barrier.[22] Due to the difficulty of measuring the physical characteristics of the barrier and interfaces, there is still no mechanism which can explain the TMR bias dependence with clarifying all the details buried. We avoid the complicated details, by linking the TMR decrease with increasing applied current to the change of spin polarization. The critical current I_c, where TMR is equal to zero, is also related to the spin polarization. Similar resistance decreases can be observed as a function of a temperature increase since the spin polarization will be changed by changing the temperature.[23] Both an applied current and a temperature change result in a change of the spin polarization of the FM layer in the MTJ. Therefore it would be worthwhile to find a model that uses the changing spin polarization to describe both current and temperature effects.

As shown in Fig. 1(a), a spin polarized current carries some spins into and some spins out of an FM layer. The net number of spins, which is the difference between the majority and minority spins in the FM layer, is changed under an applied current. We are able to calculate the change in the total

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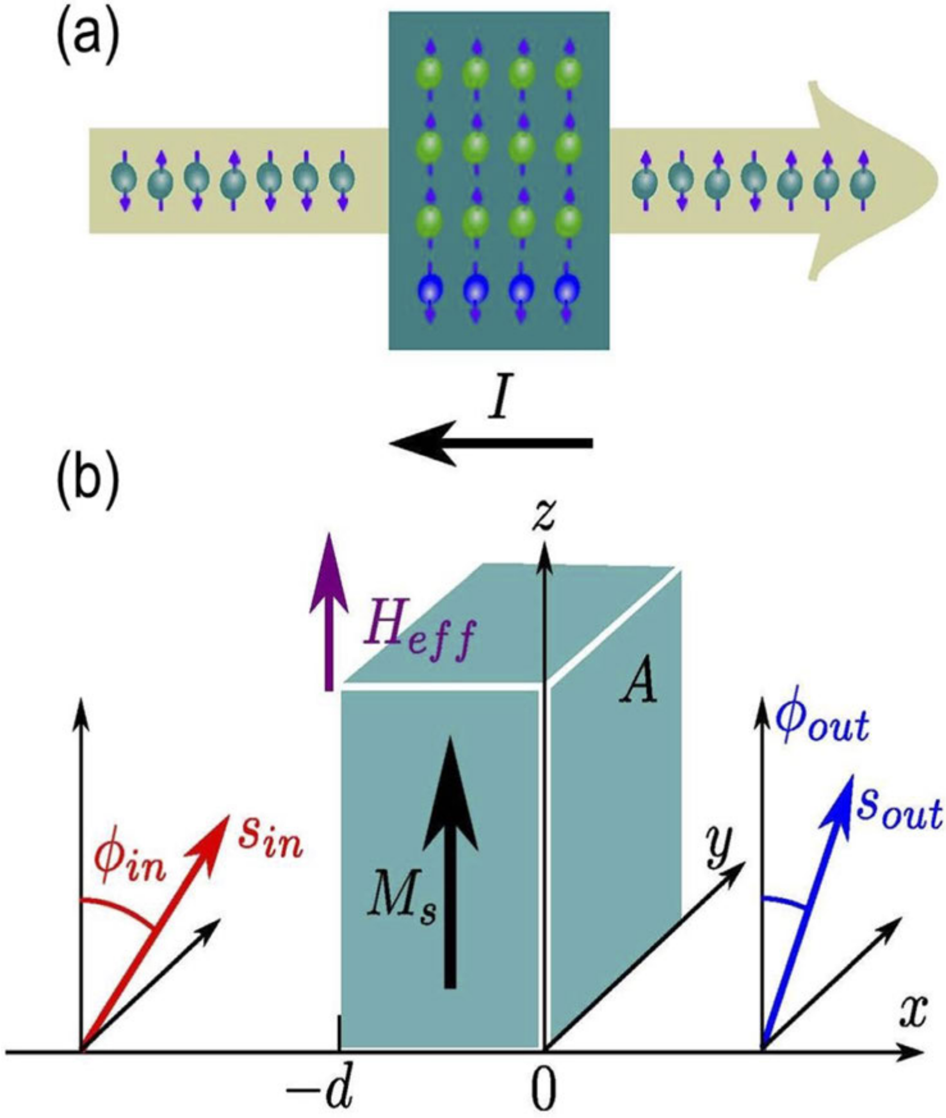

FIG. 1. (a) A sketch of the spins localized in a FM layer replaced partially by the spins carried by a spin-polarized current flow. (b) Coordinates of the spin-polarized current flowing through an FM layer.

number of spins according to the conservation of spin angular momentum. Following this principle, we calculated the spin polarization of the FM layer and the threshold current for switching.

The coordinates we used here are shown in Fig. 1(b). Suppose that a normal current is spin-polarized after it has passed through the fixed FM layer and the direction of polarization is along s_{in} at an angle ϕ_{in} with respect to the z axis. When it passes the free FM layer, the polarization will be changed to the direction s_{out} at an angle ϕ_{out} with respect to the z axis. The reason for the change of polarization of the current is the exchange interaction between the spins carried by the current and localized in the free FM layer. Thus the spin polarization of the free FM layer is changed as well.

The MTJ structures we used were fabricated by Everspin. The multilayer structures include PtMn(20)/CoFe(2.27)/Ru(0.8)/CoFeB(2.2)/CoFe(0.525)/MgO(1.2)/CoFeB(2.5) (with units of nm).

The typical resistance decrease with a current is shown in Fig. 2(a). The red and blue dots are the experimental data of the APS and the PS resistances as a function of current, respectively. The resistance at parallel configuration R_{PS} does not change as much as the resistance at

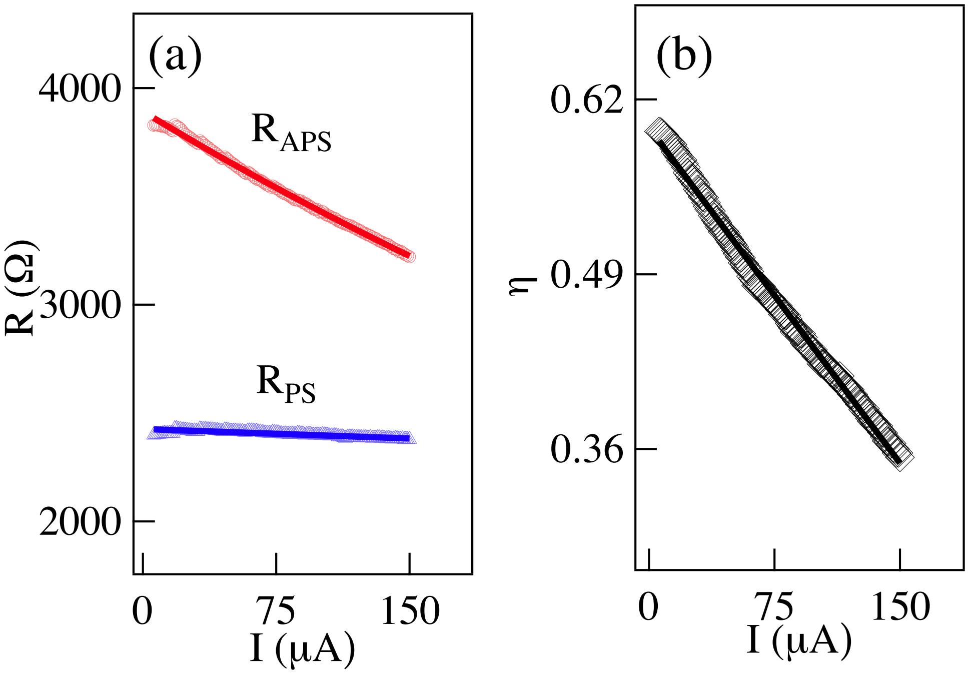

FIG. 2. (a) The resistances of the APS and PS in an MTJ decrease as a function of the current. (b) The TMR ratio η decreases as a function of the current. Solid lines are fitting curves using Eq. (5a).

anti-parallel configuration R_{APS} does when increasing the current. This is because the change of the free FM layer polarization is related to the relative differences of the spin polarization between the spin-polarized current and that of the free FM layer itself. In the PS this difference is much smaller than in the APS. The TMR ratio η is defined as $\eta = (R_{APS} - R_{PS})/R_{PS}$. η as a function of I is plotted in Fig. 2(b). We can see that the TMR ratio η decreases with increasing I as well.

Next, we performed current dependent experiments on samples with various barrier cross sectional area A. In each measurement, the sample was placed in an external magnetic field directed along the easy axis of the sample. The magnetization configurations for the APS or the PS were achieved by setting the external magnetic field at -20 or 20 mT, respectively. In both APS and PS, a current with an amplitude from 0 to 100 μA was sent into the sample and at the same time, the resistance of the sample was detected by a multimeter. Thus, for a certain sample with cross sectional area A, the resistance current dependence at both APS and PS was measured. Then η for various currents was calculated. The η current dependence for samples with various A of 0.040, 0.028, 0.023, 0.015 and 0.014 μm^2 are plotted in Fig. 3(a). η decreases with increasing current for all measurements.

The angle ϕ_{in} which describes the angle between the spin polarization of the current and the magnetization of the layer the current is passing through is related to the magnetization of the fixed FM layer of the MTJ, which can be adjusted by an external field. From Jullière's two current model,[24] we can calculate the angle between the magnetizations in the two FM layers as long as we know the resistance of the MTJ at each configuration. Then ϕ_{in} at each configuration can be calculated. The resistance of the MTJ, R, as a function of an applied current under various ϕ_{in} was measured and is plotted in Fig. 4(a). R decreases as a function of the current for various ϕ_{in}. The values of the angles ϕ_{in} were 178, 152, 133, 112, 98, 72, 62 and 50 ° respectively, which were calculated by reading off the resistance at zero current and using Jullière's two current model.

Finally, we performed the temperature dependence experiments from 7.5 to 290.1 K. Fig. 5(a) shows η as a function of I at 7.5, 140.4, 230.1 and 290.1 K. A resistance decrease with increasing current was observed at various temperatures.

A well known way to explain the TMR current dependence has been established by several groups.[25–29] The basic idea is that a spin-transfer torque was introduced by a spin-polarized current

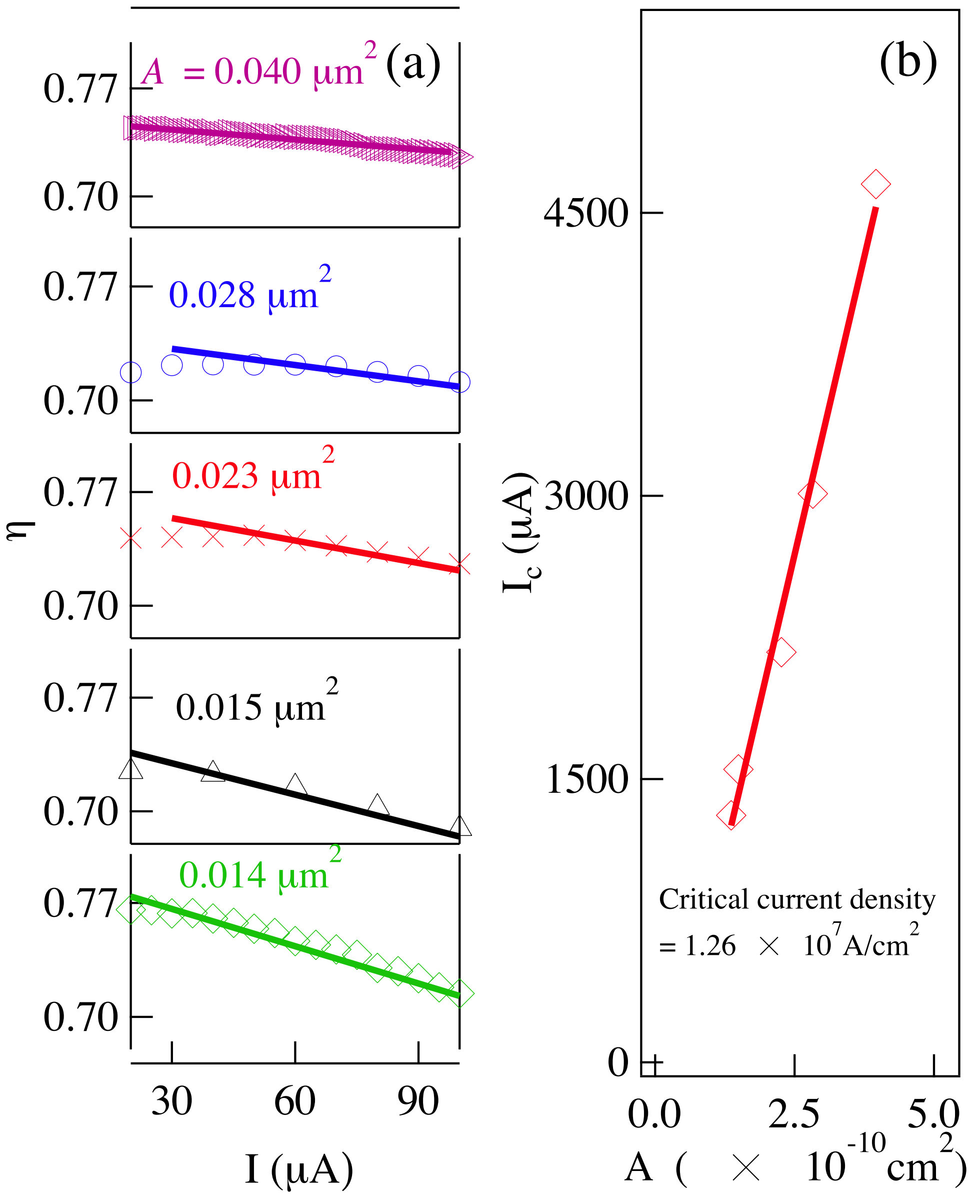

FIG. 3. (a) For different junction area A, all TMR ratios decrease as current I increases, which can be well fitted using Eq. (5a). (b) The critical current I_c is proportional to A as shown by the solid line. The slope of this line indicates the threshold current density of $1.26 \times 10^7 \mathrm{A/cm}^2$ for switching.

applied on the FM layer. Slonczewski showed that there was a close relationship between TMR and voltage-driven pseudo torque, and this torque is proportional to a well defined polarization factor, indicating that the TMR voltage-dependence is directly related to the spin-polarization of the FM layer.[26] Later, Slonczewski and Sun studied the voltage-driven torque in MgO based MTJ and showed that the TMR greatly depends on extrinsic conditions including annealing, dislocations, added element at interfaces and sputtering conditions.[27] Heiliger and Stiles claimed that the torque due to the current in an MTJ is interfacial. Also the de-phasing of the electrons is greatly reduced in typical MTJs because the current and spin current are carried by just a small fraction of the Fermi surface.[28] To avoid the complicated details concealed in the barrier and interfaces, we use a simple model to study the TMR current dependence by considering the conservation of angular momentum and particles. We just consider the beginning and the end points of the whole procedure, i.e. the

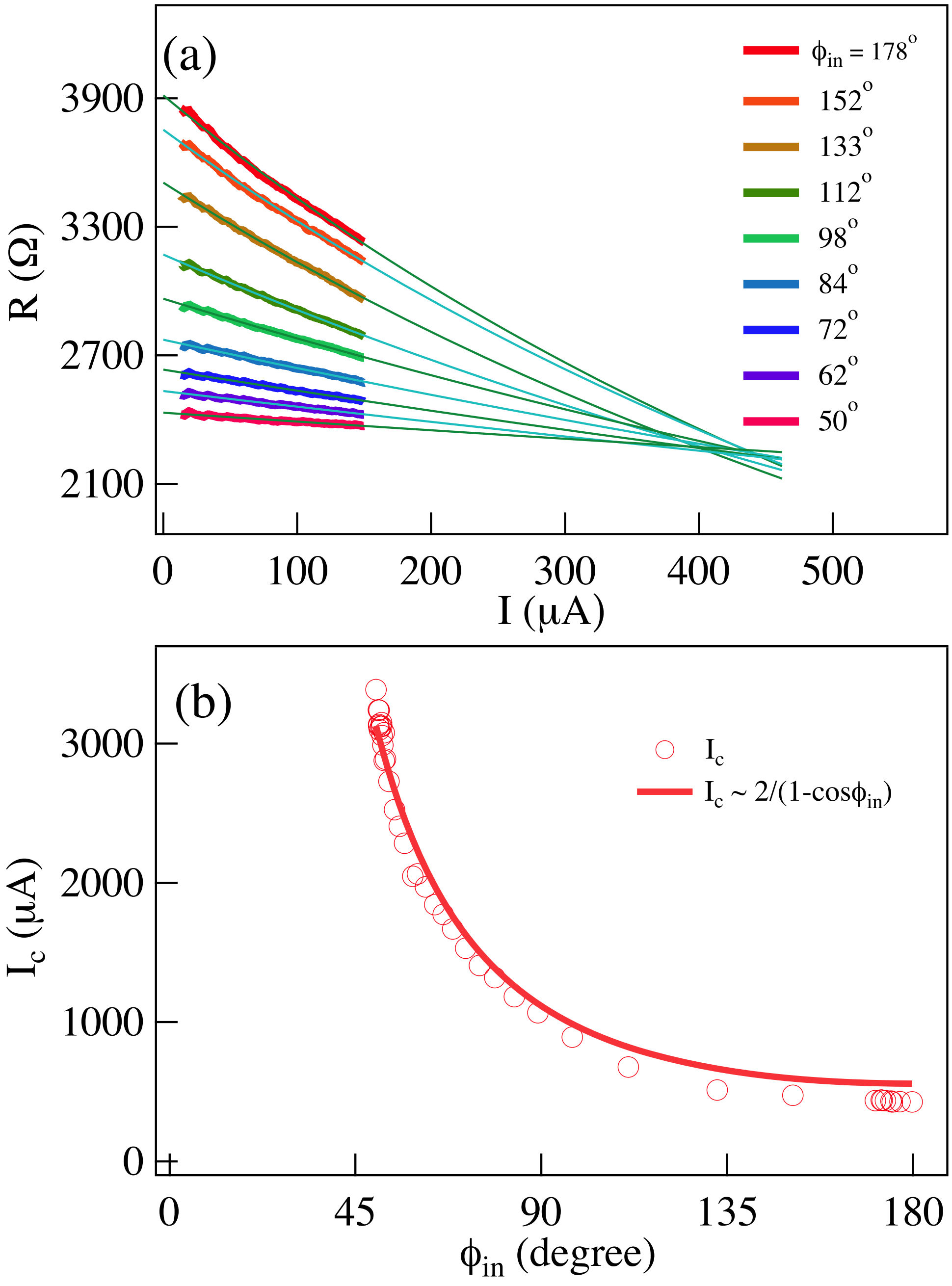

FIG. 4. (a) For different ϕ_{in} , the resistance decreases as a function of current, and is well fitted by using Eq. (5b). All lines intersect around 2217 Ω at the current of 430 $\pm 20\mu A$. (b) Angle ϕ_{in} dependence of I_c, which agrees well with Eq. (4) shown in the solid line.

moment the spin-polarized current arrives and the moment it is leaving. Then we can relate the spin polarization, the threshold current where TMR goes zero and the TMR ratio together. Furthermore, Slonczewski's work also showed that the torque due to the current had a $\sin\phi$ or a $\cos\phi$ behavior, where ϕ is the angle made by the magnetization of the two FM layers.[26,29] We find a $(1-\cos\phi)^{-1}$ relation for the I_c angle dependence, which is in agreement with the experimental data.

We consider the transport as shown in Fig. 1 again. The free FM layer has a cross sectional area A, a thickness d and a magnetization M_s before any current is applied, as shown in Fig. 1(b). M_s is aligned along the direction of the effective field H_{eff} (z axis). The number of net spins in the free

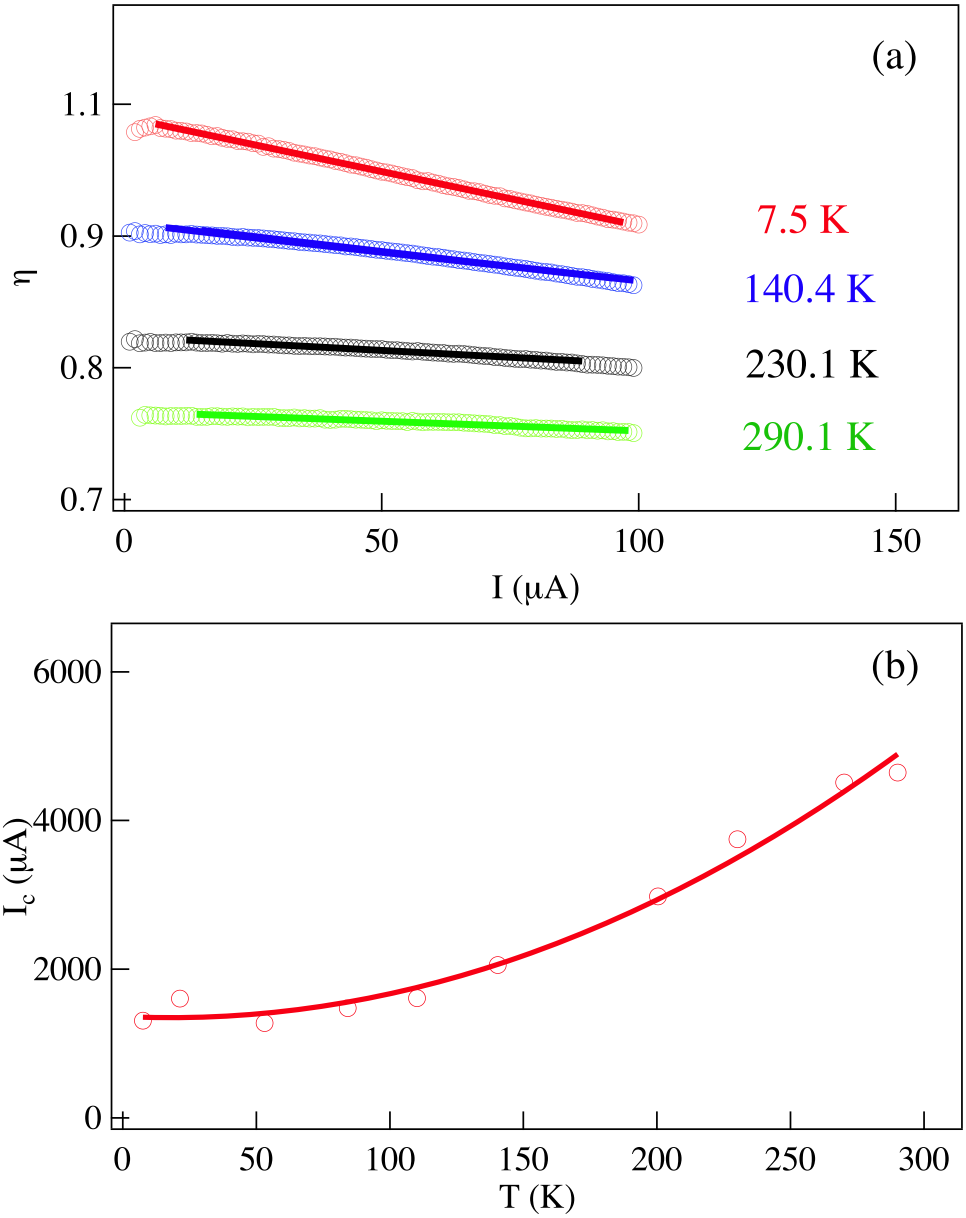

FIG. 5. (a) η as a function of I at 7.5, 140.4, 230.1 and 290.1 K. (b) I_c as a function of temperature T.

layer at a certain temperature N_{free} is

$$N_{free} = M_s Ad/\mu_B \tag{1}$$

where μ_B is Bohr magneton. When there is a spin polarized current with amplitude I passing through the FM layer, within the spin relaxation time τ_r, $I\tau_r$ is the electric charge flowing through the free layer. Because of the exchange interaction between the spins carried by the current and localized in the FM layer, the change of the number of majority spins N_r in the FM layer can be calculated as

$$N_r(I) = -\frac{I\tau_r}{2e}\left[P_{in}(\cos\phi_{in} - 1) - (\cos\phi_{out} - 1)P_{out}\right]. \tag{2}$$

Here, $e = 1.6 \times 10^{-19}$ C, and P_{in} and P_{out} are the polarization of the current before and after going through the FM layer, respectively. Thus, the number of net spins in the free FM layer N_{free}

is a function of the current I when there is a spin-polarized current passing through and can be calculated as $N_{free}(I) = N_{free} - N_r(I)$. The spin polarization of the free FM layer P_{free}, defined as the ratio of the net spin to the number of electrons in the conduction band of the free FM layer, N_{free}^{total}, is a function of the current as well and can be written as $P_{free}(I) = N_{free}(I)/N_{free}^{total}$.

It is a good approximation to assume that the electrons flowing out the free layer have the same polarization and spin orientation as those in the free FM layer because the thickness of the free FM layer is larger than the spin relaxation length.[30,31] Thus, $\phi_{out} = 0$ and $P_{out} = P_{free}(I)$. Then the polarization of the free layer can be written as,

$$P_{free}(I) = P_{free}(0)(1 - I/I_c). \tag{3}$$

Here, we have made the substitutions $\tau_r = 1/\alpha\gamma H_{eff}$ and $\gamma = 2\mu_B/\hbar$, where α is the damping and γ is the gyromagnetic ratio. Also, we assumed that $N_{free}^{total} \gg I\tau_r/e$ and define I_c as,

$$I_c \equiv \frac{2e}{\hbar}\frac{2}{1-\cos\phi_{in}}\frac{\alpha}{P_{in}}M_s A d H_{eff} \tag{4}$$

Combining Eq. (3) and Jullière's two current model, the TMR ratio η and R_{APS} can be represented as

$$\eta = \frac{2P_{fix}P_{free}(1 - I/I_c)}{1 - P_{fix}P_{free}(1 - I/I_c)} \tag{5a}$$

$$R_{APS} = R_{PS}\frac{1 + P_{fix}P_{free}(1 - I/I_c)}{1 - P_{fix}P_{free}(1 - I/I_c)} \tag{5b}$$

where P_{fix} is the spin polarization of the fixed FM layer defined as the ratio between the number of net spins and the total number of conduction electrons in the fixed FM layer. In Eq. (5a), the spin polarization of both FM layers P_{fix} and P_{free} refers to the original spin polarizations with no applied current.

By fitting all the curves in Fig. 3(a) using Eq. (5a), I_c for samples with various A is determined and is plotted in Fig. 3(b). The linear dependence of I_c on A is as expected from Eq. (4). The linear dependence also means that the threshold current density which can be calculated as I_c/A is all the same for MTJs with various A. In our case, it is $1.26 \times 10^7 \mathrm{A/cm^2}$.

For the current dependence at various A, each curve in Fig. 4(a) was fitted by using Eq. (5b). All fitting curves intersect near $430 \pm 20\ \mu$A and the resistance at the intersection is 2217 Ω which is as the same as the PS resistance. Also, from the fitting, the I_c can be determined for various ϕ_{in}. I_c as a function of ϕ_{in} is plotted in Fig. 4(b), and the curve can be fit using Eq. (4) very well.

For the current dependence at various temperatures, the curves in Fig. 5(a) can be fit using Eq. (5a) as well. Since parameters such as P_{in} , M_s and H_{eff} in Eq. (4) are related to T, determined by the sample itself, the relationship between I_c and T is also sample dependent and may be complicated. As showed in Fig. 5(b), I_c does not have a simple linear T dependence.

In conclusion, we performed TMR current dependence measurements on MTJs with various cross sectional area and under various temperatures. The threshold current I_c as a function of the angle between the magnetization of two FM layers was studied as well, which showed a $(1 - \cos\phi_{in})^{-1}$ dependence. Our systematic data is useful for further study of the mechanism of the current dependence in MTJ. To explain the current dependence of an MTJ, based upon spin angular momentum and particle conservation, a simple model was established. Experimental data of the resistance change due to a current is well explained and the I_c can be also determined from our model.

We thank the helpful discussion with Y.S. Gui and M. Harder. This work was funded by NSERC, CFI, and URGP grants (C.-M.Hu). One of the authors (Z. H. Zhang) was supported by the China Scholarship Council (CSC).

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