Probing fast heating in magnetic tunnel junction structures with exchange bias

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Abstract. Heat diffusion in a magnetic tunnel junction (MTJ) having a ferromagnetic/antiferromagnetic free layer is investigated. The MTJ is heated by an electric current pulse of power $P_{HP}$, flowing through the junction in current perpendicular to the plane (CPP) geometry, via Joule heat dissipation in the tunnel barrier. According to a proposed one-dimensional (1D) model of heat diffusion, when an electric voltage is applied to the MTJ, the free layer experiences a transient temperature regime, characterized by an exponential increase of its temperature $T_{AF}$ with a time constant $\tau_{TR}$, followed by a steady temperature regime characterized by $T_{AF} = T_{RT} + \alpha P_{HP}$, where $T_{RT}$ is the room temperature and $\alpha$ is a constant. Magnetic transport measurements of exchange bias $H_{EX}$ acting on the free layer allow the determination of $\alpha$ and $\tau_{TR}$. The experimental values of $\alpha$ and $\tau_{TR}$ are in agreement with those calculated using the 1D model and an estimation of the MTJ thermodynamic parameters based on the Dulong–Petit and Widemann–Franz laws.
1. Introduction

The possibility to control the orientation of the magnetization of a submicron-sized magnetic thin film by using the spin momentum transfer effect [1, 2] of a polarized current pulse applied perpendicular to the film plane, has been extensively investigated during the past few years due to the potential applications in non-volatile magnetic random access memories (MRAM) and for current-tunable microwave generators [3]–[7]. However, the Joule heat dissipation that occurs during the application of current pulses of density \( \sim 5 \times 10^6 \text{ A cm}^{-2} \), as required for switching the magnetization of a free ferromagnetic layer by the spin transfer effect, has not yet been quantitatively evaluated. Particularly important in the case of magnetic tunnel junctions (MTJ) containing electrically insulating layers, the heating effect of a current pulse can reduce the switching current density [8]–[12], enhance the spin transfer-assisted magnetic noise [13] and broaden the linewidth of the spin transfer-induced magnetization excitations [14, 15]. The goal of this paper is to elaborate a model of heat diffusion in an MTJ stack that correlates the thermodynamic parameters of the junction layers, namely the heat capacity and thermal conductivity, to a set of directly measurable quantities such as: (i) the cooling time constant \( \tau_{TR} \) of the junction subsequent to the application of a current pulse and (ii) the proportionality constant \( \alpha \) between the power of the heating pulse and the stationary temperature reached by the junction layers during the application of a current pulse. Comparison between the theoretical and experimental values of \( \tau_{TR} \) and \( \alpha \) allows the ‘calibration’ of the MTJ thermodynamic parameters and enables the calculation of the junction temperature profile due to the application of the current pulse.

The temperature dependence of heat capacity \( C \) for thin films has applications in various research areas, e.g. for establishing the relationship between the melting point of nanoparticles and their size [16, 17], for evidencing the transition between ferromagnetic (F) [18] or antiferromagnetic (AF) [19] and paramagnetic states, or the transition between states of different vorticities in superconducting thin films [20]. The principle of a dc calorimeter [21] usually involves the measurement of the sample temperature decay subsequent to the application of a heating pulse. The characteristic decay time \( \tau \) is related to the sample heat capacity according to the relation \( \tau = C_{TOT}/K_{EFF} \), where \( C_{TOT} \) (J K\(^{-1}\)) is the sum of the sample heat capacity and various addenda contributions, e.g. electrical leads and thermal link between the heater and the sample, and \( K_{EFF} \) (W K\(^{-1}\)) is the thermal conductance of the thermal link. Thermal conductance
Figure 1. MTJ with thermally assisted switching of the F/AF free layer; the tunnel barrier acts as a heater during the application of an electric current pulse of amplitude $I$.

$K_{\text{eff}}$ is measured in the steady temperature regime from the ratio between the heating power and the corresponding variation of the sample temperature, while the sample heat capacity is usually found by a differential method allowing the evaluation of the addenda contribution to $C_{\text{TOT}}$. The method to access the thermodynamic parameters of an MTJ stack proposed in this paper follows closely the principle of a dc calorimeter, enabling the measurement of the heat capacity of a particular thin film inserted in the MTJ stack.

Previous studies of heat dissipation in MTJ aimed to explain the writing mechanism of an MRAM device with thermally assisted switching (TAMRAM) [22]–[24]. Such a device contains an MTJ having a F/AF structure of the free layer. During the application of an electric current pulse of power $P_{\text{HP}}$ and duration $\delta$ perpendicular to the MTJ plane, the tunnel barrier, having the highest electrical resistance in the MTJ stack, experiences the most important heating by the Joule effect. The heat dissipated in the tunnel barrier diffuses throughout the junction and increases the temperature $T_{\text{AF}}$ of the free layer (figure 1). The free layer heating efficiency is increased by inserting on both sides of the MTJ two ancillary layers of low thermal conductivity $k_{\text{TB}}$, playing the role of thermal barriers (TBs). During the application of the heating electric pulse as well as during the subsequent natural cooling of the MTJ layers back to room temperature (RT) $T_{\text{RT}} = 298$ K, the MTJ is submitted to an external magnetic field $H_{\text{SET}}$, high enough to keep the orientation of the free layer F magnetic moment parallel to its direction. As a result, the uncompensated magnetic moments belonging to a fraction of the free layer AF grains are unpinned during the heating stage and pinned in the direction of $H_{\text{SET}}$ during the cooling stage. This process leads to a modification of the exchange bias $H_{\text{EX}}$ acting on the free F layer at the end of the cooling stage, accessible by transport measurements. The orientation of the reference layer magnetic moment is unaffected by the application of the heating and magnetic pulses since the Néel temperature $T_N$ of its own AF pinning layer is much higher than that of the free layer AF. Previous studies on TAMRAM devices have neither established the relationship between the power of the electric current pulse and the temperature of the junction, nor have they discussed the possibility of measuring the thermodynamic parameters of the MTJ, as required for a correct calculation of the junction temperature profile.

In the present work, we use the high temperature sensitivity of the exchange bias acting on the F/AF free layer of an MTJ junction similar to those used in TAMRAMs to probe the temperature evolution during the application of an electric pulse. Based on a proposed
one-dimensional (1D) model of heat diffusion, when a heating electric pulse is applied to the MTJ at RT, the free layer is demonstrated to experience a transient temperature regime, of characteristic time $\tau_{TR}$, followed by a steady temperature regime characterized by a linear relationship between $T_{AF}$ and $P_{HP}$, such as $T_{AF} = T_{RT} + \alpha P_{HP}$. The 1D model of heat diffusion offers analytical expressions relating $\alpha$ and $\tau_{TR}$ to the thermodynamic parameters (heat capacity and thermal conductivity) of the MTJ layers. The exchange bias $H_{EX}$, measured by quasistatic magnetoresistance (MR) hysteresis loops during and subsequent to the application of the heating pulse(s), is used for measuring both $\tau_{TR}$ and $\alpha$. The experimental values of $\tau_{TR}$ and $\alpha$ are in remarkable agreement with those calculated by the 1D model of heat diffusion, confirming the proposed model and validating the values of the MTJ thermodynamic parameters used in the model.

2. 1D model of heat diffusion in the MTJ stack

Let us consider the MTJ structure presented in figure 1, where the TB1 and TB2 layers are assumed to be identical. Since the TB layers have the lowest thermal conductivity in the MTJ stack, they experience the most important temperature gradient during the application of a heating electric pulse. The junction electrodes, placed outside the region delimited by the TB layers, can be assumed to behave as heat sinks at constant temperature $T_{RT}$, due to their high thermal conductivities and large volumes. By assuming that the entire energy of the electric pulse is converted into heat by Joule effect inside the MTJ tunnel barrier, the summation of the heat diffusion equations for all the individual layers of the MTJ leads to:

$$\left(\sum_i c_i \rho_i d_i + c_{TB} \rho_{TB} d_{TB}\right) \frac{\partial T}{\partial t} - 2 \frac{k_{TB} d_{TB}}{S} (T - T_{RT}) = \frac{P_{HP}}{S}, \quad (1)$$

where $i = 1, \ldots, N$ refers to the layers sandwiched between the TB layers (designated by magnetic stack in figure 1), $k_{TB}$ is the thermal conductivity of the TB layers, $\rho_i$ is the mass density, $d_i$ is the thickness and $c_i$ is the specific heat capacity of layer $i$ (the corresponding heat capacity is $C_i = c_i \rho_i d_i S$), $S$ is the in-plane surface of the junction, $T$ designates the temperature and $t$ is the time. All the $i$ layers, including the MTJ free layer, have the same temperature $T$ since they experience negligible temperature gradients with respect to the TB layers. Let us further assume that $c_i$, $c_{TB}$ and $k_{TB}$ in (1) are temperature independent. According to (1), during the application of a heating electric pulse at RT, the temperature of the free layer $T_{AF}$ evolves according to:

$$T_{AF} = T_{RT} + \alpha P_{HP} \left[1 - \exp\left(-\frac{t}{\tau_{TR}}\right)\right], \quad (2)$$

where

$$\alpha = \frac{d_{TB}}{2 k_{TB} S}, \quad (3a)$$

$$\tau_{TR} = \frac{d_{TB}}{2 k_{TB}} \left(\sum_i c_i \rho_i d_i + c_{TB} \rho_{TB} d_{TB}\right). \quad (3b)$$

During the time interval $3 \tau_{TR}$ from the application of the heating electric pulse, the free layer experiences a transient temperature regime. For electric pulse durations longer than $3 \tau_{TR}$, by
the end of the heating pulse the free layer reaches a steady temperature regime characterized by $T_{AF} \approx T_{RT} + \alpha P_{HP}$. If the electric pulse is suppressed at $t = 0$, the solution of (1) becomes:

$$T_{AF} = T_0 + (T - T_0) \left[ 1 - \exp \left( -\frac{t}{\tau_{TR}} \right) \right],$$

(4)

where $T_0 = T(t = 0)$. Equations (2) and (4) imply that the characteristic times of the heating and cooling transient regimes of the free layer are identical. This observation suggests that $\tau_{TR}$ can be determined by investigating the natural cooling process of the free layer.

3. Experiment

3.1. Experimental setup

The MTJ subject of our investigation has the following structure (all thicknesses are in nm): bottom electrode/Ta 50/Pt 36/Mn 80 20/Cu 250 nm and Al 300 nm, respectively. The F/AF free layer includes the F bilayer Co 80 Fe 20 3 exchange biased by a 5 nm thick Ir 20 Mn 80 AF layer. The reference layer comprises a synthetic antiferromagnet Co 80 Fe 20 2.5/Ru 0.8/Co 80 Fe 20 3.0 pinned by a Pt 36 Mn 64 layer, which is a high Néel temperature AF. As will be shown in the following, the bottom bilayer Ta 50/Pt 36/Mn 80 20 and the top Ta 90 layer play the role of TBs due to their lowest thermal conductivities and largest thicknesses in the MTJ stack. The junction was patterned in an elliptical shape of 450 nm long and 250 nm short axes. The saturation magnetization of the free layer is $M_S = 910 \times 10^3$ A m$^{-1}$, leading to a theoretical shape anisotropy $K_D = 1.59 \times 10^3$ J m$^{-3}$.

The experimental setup is presented in figure 2(a). Setting of $H_{EX}$ is performed by connecting the probe pin board PPB to a pulse generator of output impedance $Z_{PG} = 50 \Omega$ (0–2 in figure 2(a)), followed by the simultaneous application of a rectangular heating electric pulse, of nominal amplitude $U$ and width $\delta$ produced by the pulse generator, and of a rectangular magnetic field (oriented along the easy axis of the free layer) pulse, of amplitude $H_{SET} = \pm 39.8$ kA m$^{-1}$, generated by an electromagnet (figure 2(a)). The magnetic field pulse acts as a trigger for the heating electric pulse, its amplitude being strictly constant during the application of the heating electric pulse and during the subsequent cooling time of the junction $3\tau_R \approx 10$ ns. Magnetic properties of the F/AF free layer (coercivity $H_C$ and exchange bias $P_{EX}$) are measured at RT, immediately after switching off the applied field, from quasistatic MR hysteresis cycles performed by connecting the PPB to an MR tester (0–1 in figure 2(a)), applying $U_{BIAS} = 40$ mV to the junction and sweeping the applied field between $\pm 39.8$ kA m$^{-1}$, as illustrated in figure 2(b). The measurement of an MR cycle takes $t_{MEAS} = 50$ ms. In order to minimize the exchange bias training effects, $n = 50$ MR cycles were performed before the actual measurement. The power of the heating electric pulse was evaluated based on $P_{HP} = (U - Z_{PG} I - U_{OSC}) I$, where $I = U_{OSC}/Z_{OSC}$ is measured by an oscilloscope OSC of internal impedance $Z_{OSC} = 50 \Omega$. The high values of $U$ used in this study ($U = 1–3$ V) lead to a negligible variation of the tunnel MR (typically $\leq 5\%$) and current $I$, corresponding to the switching of the free layer, during the application of the heating electric pulse. This observation enables the approximate calculation of $P_{HP}$ by using the average value of $U_{OSC}$ over the duration $\delta$ of the heating electric pulse. Prior to each measurement of $H_{EX}$, the magnetic state of the free layer is reinitialized by saturating $H_{EX}$ to $H_{EX}^{SAT}$ (figure 2(b)). For this purpose, an electric pulse of power $P_{HP}^{SAT} = 2$ mW, width $\delta^{SAT} = 1$ ms, triggered by a
3.2. Temperature regimes of the MTJ free layer

3.2.1. The transient temperature regime. In order to measure the characteristic cooling time \( \tau_{TR} \) of the free layer subsequent to the suppression of a heating electric pulse, we use a pump–probe experiment involving the application of two consecutive electric pulses. The width of the first pulse, denoted hereafter by pump pulse, is \( \delta_{PUMP} = 7 \text{ ns} \), and the width of the second heating pulse, denoted by probe pulse, is \( \delta_{PROB} = 3 \text{ ns} \). The power of the pump pulse \( P_{PUMP} \) was fixed to the threshold value corresponding to an isolated pulse having the width \( \delta = \delta_{PUMP} + \delta_{PROB} = 10 \text{ ns} \), i.e. \( P_{PUMP} = P_{HP}^{WRT}(\delta = 10 \text{ ns}) \) (figures 3(a) and (b)). The probe pulse was applied after a time interval \( \tau \) from the suppression of the pump pulse and it was used for probing the temperature of the F/AF free layer due to the application of the pump pulse, at the instant \( t = \tau \) from the suppression of the pump pulse (figure 3(c)).

Previous to the application of the two consecutive pulses, the exchange bias acting on the free layer, \( H_{EX} \), was initialized to \( H_{EX}^{SAT} \). The pump pulse was applied simultaneously with a magnetic field pulse of amplitude \( H_{SET} = -39.8 \text{ kA m}^{-1} \), is applied to the junction. The value of \( P_{HP}^{SAT} \) was established by monitoring the dependence of \( H_{EX} \) on \( P_{HP} \) for progressively increasing values of the heating power and for both orientations of the applied field \( H_{SET} \) until \( H_{EX}(H_{SET} = -39.8 \text{ kA m}^{-1}) = -H_{EX}(H_{SET} = +39.8 \text{ kA m}^{-1}) = H_{EX}^{SAT} \). It is worthwhile mentioning that \( H_{EX}^{SAT} \) coincides with the value of \( H_{EX} \) obtained by cooling the MTJ from 350 °C to RT in the presence of 397.9 kA m\(^{-1} \) applied field and represents the maximum attainable \( H_{EX} \) for given hysteresis measurement conditions (RT, \( t_{MEAS} = 50 \text{ ms} \), amplitude of the applied field 39.8 kA m\(^{-1} \)). The procedure for setting \( H_{EX} \) to a specific threshold, e.g. \( H_{EX}^{WRT} = 0 \text{ A m}^{-1} \) as shown in figure 2(b), consists of the application of an electric pulse of power \( P_{HP} \), duration \( \delta \), triggered by a field pulse \( H_{SET} = +39.8 \text{ kA m}^{-1} \), the value of \( P_{HP} \) being progressively increased until \( H_{EX} = H_{EX}^{WRT} \). The latter condition is fulfilled for \( P_{HP} = P_{HP}^{WRT}(\delta) \).

**Figure 2.** (a) Experimental setup. (b) Setting of the exchange bias field acting on the free layer \( H_{EX} \) by the simultaneous application of an electric current pulse of power \( P_{HP} \) and of a magnetic field pulse of amplitude \( H_{SET} \); saturation of \( H_{EX} \) to \( H_{EX}^{SAT} \) using \( P_{HP}^{SAT} = 2 \text{ mW} \), \( H_{SET} = -39.8 \text{ kA m}^{-1} (\bigcirc) \), \( H_{EX} \) reversal to \( H_{EX}^{WRT} = 0 \text{ A m}^{-1} \) using \( P_{HP} = 1.1 \text{ mW} \) and \( H_{SET} = +39.8 \text{ kA m}^{-1} \) (solid line) and saturation of \( H_{EX} \) to \( -H_{EX}^{SAT} \) using \( P_{HP}^{SAT} = 2 \text{ mW} \), \( H_{SET} = +39.8 \text{ kA m}^{-1} (\triangle) \); rotation of the F layer moment from parallel to perpendicular with respect to the exchange bias direction takes place during \( t_{C} - t_{S} \approx 0.5 \text{ ms} \) (points C and S are marked by solid circles).
Figure 3. (a) Timing diagram of an experiment involving the application of a single electric pulse ($E_1$) of power $P_{HP}$ and width $\delta$, triggered by a magnetic field pulse ($H$) of amplitude $H_{SET}$. (b) Power $P_{HP}^{WRT}$ of the electric pulse required to set $H_{EX}$ to the threshold value $H_{EX}^{WRT} = 0 \text{ A m}^{-1}$ as a function of the electric pulse duration $\delta$. (c) Timing diagram of a pump–probe experiment involving the application of two consecutive electric pulses ($E_1$, $E_2$), triggered by a magnetic field pulse ($H$) the first pulse ($E_1$) (pump pulse) of width $\delta_{PUMP} = 7 \text{ ns}$ and power $P_{PUMP} = P_{HP}^{WRT}(\delta = 10 \text{ ns})$ (figure 3(b)) is used for heating the junction, whereas the second pulse ($E_2$) (probe pulse) of width $\delta_{PROB} = 3 \text{ ns}$ and power $P_{PROB}$ is used to probe the junction temperature. (d) Power of the probe pulse $P_{PROB}^{WRT}$ required to set $H_{EX}$ to the threshold value $H_{EX}^{WRT} = 0 \text{ A m}^{-1}$ as a function of the time delay $\tau$ between the pump and probe pulses; the solid line is an exponential fit according to $P_{PROB}^{WRT}(\tau) = P_{HP}^{WRT}(\delta_{PUMP} + \delta_{PROB}) + [P_{HP}^{WRT}(\delta_{PROB}) - P_{HP}^{WRT}(\delta_{PUMP} + \delta_{PROB})](1 - \exp(-\tau/\tau_{TR}))$ suggesting a characteristic cooling time $\tau_{TR} = 2.7 \text{ ns}$.

magnetic field pulse, of amplitude $H_{SET} = +39.8 \text{ kA m}^{-1}$, that remained applied during both heating pulses plus 10 ns. The amplitude/power of the probe pulse $P_{PROB}$ was progressively increased until $H_{EX}$, measured after the application of the two pulses, reached the threshold value $H_{EX}^{WRT} = 0 \text{ A m}^{-1}$. This condition was fulfilled for $P_{PROB} = P_{PROB}^{WRT}$. The experiment was repeated for various values of $\tau$ in the range 1 ns–100 ns, the resulting dependence $P_{PROB}^{WRT}(\tau)$ being plotted in figure 3(d). For $\tau$ values higher than the width of the transient temperature regime of the free layer ($\approx 3 \tau_{TR}$), the threshold power of the probe pulse reaches that of an isolated pulse of the same width $\delta = \delta_{PROB}$, i.e. $P_{PROB}^{WRT}(\tau \geq 3 \tau_{TR}) = P_{HP}^{WRT}(\delta_{PROB})$. With

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decreasing $\tau$, the threshold power of the probe pulse approaches that of an isolated pulse of width $\delta = \delta_{\text{pump}} + \delta_{\text{prob}} = 10\,\text{ns}$, i.e. $P_{\text{prob}}(\tau \to 0) = P_{\text{hp}}(\delta = 10\,\text{ns})$. The lowest time interval $\tau$ that can be probed without overlapping the two consecutive electric pulses was limited by the pulse generator rise time to 0.8 ns. As one can notice in figure 3(d), the characteristic time of the transient temperature regime of the free layer is $\tau_{\text{TR}} = 2.7\,\text{ns}$.

3.2.2. The steady temperature regime. Since the time required for the free layer to reach the steady temperature regime ($\approx 10\,\text{ns}$ according to figure 3(d)) is much smaller than the measurement time of a point on the MR hysteresis curve ($50\,\mu\text{s}$), the free layer reaches the steady temperature regime during the MR measurement leading to a linear relationship between the temperature of the free layer $T_{\text{AF}}$ and the bias power $P_{\text{bias}} = U_{\text{bias}}^2 / R$, where $R \approx 2R_{\text{max}}R_{\text{min}} / (R_{\text{max}} + R_{\text{min}})$ is the average value of the junction resistance over the MR hysteresis cycle. Since the MR ratio $R_{\text{max}} - R_{\text{min}} / R_{\text{min}}$ decreases with increasing $U_{\text{bias}}$, the above expression of $P_{\text{bias}}$ represents a good approximation for the electric power consumption of the MTJ. The relationship between $T_{\text{AF}}$ and $P_{\text{bias}}$ could be established in a straight-forward manner by matching the temperature dependence of the exchange bias field $H_{\text{EX}}$ and coercivity $H_{\text{C}}$ of the free layer, measured from the quasistatic MR hysteresis cycles for a small value of the dc bias voltage $U_{\text{bias}} = 40\,\text{mV}$ (leading to a negligible heating of the tunnel barrier by the Joule effect) by using a heating chuck, and the dependencies of $H_{\text{EX}}$ and $H_{\text{C}}$ on $P_{\text{bias}}$, for $U_{\text{bias}} = 200\,\text{mV} - 1\,\text{V}$ (leading to a progressive heating of the tunnel barrier by the Joule effect) by keeping the temperature of the chuck to $T_{\text{RT}}$. In figure 4 are plotted $H_{\text{EX}}(T_{\text{AF}})$ and $H_{\text{C}}(T_{\text{AF}})$ as measured, and also $H_{\text{EX}}$, $H_{\text{C}}$ originally recorded as a function of $P_{\text{bias}}$ and then expressed as a function of temperature using the linear power–temperature relationship

$$T_{\text{AF}} = T_{\text{RT}} + 100 \times 10^3 (\text{K W}^{-1}) \times P_{\text{bias}}.$$ 

By using (2) and (5), one obtains $\alpha = 100 \times 10^3 \text{K W}^{-1}$.

In order to corroborate the above result, an independent determination of $\alpha$ was performed on a similar MTJ junction based on the comparison between the experimental dependence of

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure4}
\caption{Exchange bias $H_{\text{EX}}$ (●) and coercivity $H_{\text{C}}$ (▲) of the free layer measured as a function of the free layer temperature $T_{\text{AF}}$ (solid symbols); empty symbols represent $H_{\text{EX}}$ (○), $H_{\text{C}}$ (△) originally recorded as a function of the dc bias power $P_{\text{bias}}$ and expressed as a function of $T_{\text{AF}} = T_{\text{RT}} + 100 \times 10^3 (\text{K W}^{-1}) \times P_{\text{bias}}$.}
\end{figure}
the exchange bias $H_{\text{EX}}$ and coercivity $H_c$ of the free layer as a function of the heating pulse power $P_{\text{HP}}$ and width $\delta$, and the theoretical dependence of $H_{\text{EX}}$ and $H_c$ on temperature and on heating time calculated by an Arrhenius–Néel (A–N) model described in the appendix. In order to establish the $T_A - P_{\text{HP}}$ relationship, the reversal of $H_{\text{EX}}$ with increasing $P_{\text{HP}}$ was measured for $\delta = 100 \text{ ns}$, $1 \text{ ms}$ and $1 \text{ s}$. Before each measurement, $H_{\text{EX}}$ was saturated to $H_{\text{EX}}^{\text{SAT}}$. In an attempt to reverse the orientation of $H_{\text{EX}}$, a heating pulse of power $P_{\text{HP}}$, width $\delta$, triggered by a magnetic field pulse of amplitude $H_{\text{SET}} = +39.8 \text{ kA m}^{-1}$, was applied to the junction, followed by the measurement of $H_{\text{EX}}$ and $H_c$ once back to RT. The $H_{\text{EX}}(P_{\text{HP}})$ and $H_c(P_{\text{HP}})$ data were recorded for increasing $P_{\text{HP}}$, i.e. higher $T_A$, by keeping $\delta$ constant and reinitializing $H_{\text{EX}}$ to $H_{\text{EX}}^{\text{SAT}}$ after each reversal attempt. The pulse widths $\delta$ were chosen to be much larger than the inverse of the A–N attempt frequency $1/f_0$ $\approx$ $1 \text{ ns}$ to avoid significant stochastic and spin precession effects, and also larger than the time required for the free layer to reach the steady thermal regime $3\tau_{\text{TR}}$. The A–N model was used to calculate the $H_{\text{EX}}(T)$, $H_c(T)$ curves by assuming a rectangular temperature pulse having same width $\delta$ as the electric pulse. For this purpose (A.1), (A.2), (A.3a) and (A.3b) were used, where $T = T_{\text{RT}}$ is the measurement temperature and $P_0 = P_\delta[T = T_A, t = \delta, n = 1, P_\delta = 1 - P_{\infty}(T_B)]$, $T_B$ being the solution of the equation $\tau = \delta^{\text{SAT}}$. The above expression for $P_0$ is the probability for an AF grain magnetic moment to be oriented in the direction of the applied field $H_{\text{SET}} = +39.8 \text{ kA m}^{-1}$ at $T_{\text{RT}}$ after heating the free layer at $T_A$ during the time interval $\delta$ in the presence of $H_{\text{SET}} = +39.8 \text{ kA m}^{-1}$ starting from the initially saturated state $H_{\text{EX}} = H_{\text{EX}}^{\text{SAT}}$. By matching the experimental curves $H_{\text{EX}}(P_{\text{HP}})$ to $H_{\text{EX}}(T_A)$, as shown in figure 5(a), one obtains the following relationship between the heating power and the quasi-equilibrium temperature reached by the free layer

$$T_A = T_{\text{RT}} + 87.1 \times 10^3 (\text{K W}^{-1}) \times P_{\text{HP}},$$

leading to $\alpha = 87.1 \times 10^3 \text{ K W}^{-1}$.

To assess the consistency of (6), thermal stability of the F/AF free layer was also measured in figure 5(b). After setting $H_{\text{EX}}$ to $H_{\text{EX}}^{\text{SAT}}$, an electric pulse of width $\delta \geq 100 \text{ ns}$ was applied

Figure 5. (a) $H_{\text{EX}}$ (solid line) and $H_c$ (dashed line) calculated by the A–N model for $\delta = 1 \text{ s}$ (●), $1 \text{ ms}$ (■) and $100 \text{ ns}$ (▲); the measured $H_{\text{EX}}$ (solid symbols) and $H_c$ (empty symbols) were originally recorded as a function of power $P_{\text{HP}}$ and converted into temperature using $T_A = T_{\text{RT}} + 87.1 \times 10^3 (\text{K W}^{-1}) \times P_{\text{HP}}$. (b) Experimental (symbols) and calculated (solid line) $H_{\text{EX}}(\delta)$ for $P_{\text{HP}} = 0.38$ (●), $0.69$ (■), $0.92$ (▲), $1.24$ (▼), $1.47$ (◀), $1.7$ (●), and $2.24$ (★) mW and the corresponding temperatures according to the above relation.
simultaneously with a magnetic field pulse of amplitude $H_{SET} = 39.8$ kA m$^{-1}$. The exchange bias $H_{EX}$ was recorded after each heating pulse, by keeping $P_{HP}$ constant and progressively increasing the pulse width $\delta$, i.e. longer heating times. The $H_{EX}(\delta)$ data were measured for increasing values of $P_{HP}$, as shown in figure 5(b). The values of $P_{HP}$ were converted into temperatures $T_{AF}$ using (6) and then introduced in the A–N model for calculating $H_{EX}(\delta)$. For this purpose, (A.1), (A.3a) and (A.3b) were used, where $T = T_{RT}$ and $P_0 = P_\infty [T = T_{AF}, t = \delta, n = 1, P_0 = 1 - P_\infty (T_B)]$. The general agreement shown in figure 5(b) validates (6). Equations (5) and (6) indicate a reasonable agreement between the values of $\alpha$ obtained by the two experimental methods for similar MTJs.

### 3.3. Discussion

According to (3a) and (3b), the heating/cooling time of the MTJ junction during/after the application of an electric current pulse is determined by three parameters: the heat capacity of the TBs $C_{TB} = c_{TB} \rho_{TB} d_{TB} S$, the total heat capacity of the MTJ magnetic stack $C = \sum_i c_i \rho_i d_i S$ and the thermal conductivity of the TBs $k_{TB}$. However, since the investigated MTJ structure: bottom electrode/Ta 50/Pt36Mn64 20/C080Fe20 2.5/Ru 0.8/C080Fe20 3.0/AlOx 0.5/C080Fe20 1.5/Ni80Fe20 3/Ir20Mn80 5/Ta 5/Al 20/Ta 90/top electrode, contains a significant number of layers, an estimation of the thermodynamic parameters $k$, $c$ for all the MTJ layers is requisite. These values are listed in table 1.

For the layers made of pure elements (excepting Ta), we have used the RT bulk values for $k$, $c$ and $\rho$ [25]. For Ta as well as for the alloy thin films, thermal conductivities, $k$, were estimated based on the Widemann–Franz law of electronic thermal conduction $k = LT / \rho_c$ where $L = 2.5 \times 10^{-8}$ WΩ K$^{-2}$ is the Lorenz number, $\rho_c$ is the film electrical resistivity and $T = T_{RT}$ is the temperature. Since all the MTJ layers excepting the very thin tunnel barrier are metals, this law is expected to be a reasonable approximation. As one can notice in table 1, the ($\beta$)-Ta layers [26, 27] and the AF layers Pt36Mn64 and Ir20Mn80 have the lowest thermal conductivities in the MTJ stack. Thus, one may assume that the Ta 50/Pt36Mn64 20 bilayer represents the bottom TB1 while Ta 90 represents the top TB2 in figure 1. Specific heat capacities $c$ for Ta and for the alloys were estimated based on the Dulong–Petit law. According to the latter, $c = C_M / (\rho V_M)$ where the molar heat capacity takes similar values for all metals $C_M \approx 26$ J (K mol$^{-1}$), $V_M = (N_A V_U) / Z$ is the molar volume, $V_U$ is the volume of the crystalline.

### Table 1. Estimated values of density $\rho$, thermal conductivity $k$ and specific heat capacity $c$ for all the layers of the investigated MTJ.

| Material | $\rho$(kg m$^{-3}$) | $c$(J (K kg)$^{-1}$) | $k$(W (K m)$^{-1}$) |
|----------|---------------------|---------------------|---------------------|
| Ta ($\beta$) | 16327 | 144 | 4.3 |
| PtMn | 12479 | 247 | 4.9 |
| CoFe | 8658 | 446 | 37 |
| Ru | 12370 | 239 | 120 |
| AlOx | 3900 | 900 | 27 |
| IrMn | 10181 | 316 | 5.7 |
| NiFe | 8694 | 447 | 37 |
| Al | 2700 | 904 | 235 |
| SiO$_2$ | 2200 | 730 | 1.4 |

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lattice unit cell, $Z$ is the number of atoms per lattice unit cell and $\rho = Z \sum_i (n_i A_i) / (N_A V_U)$ is the mass density, $n_i$ and $A_i$ being the atomic concentration and atomic masses of the constituents.

In order to comply with the assumption of the 1D model regarding the similar properties of TB1 and TB2, we assume an average thickness $d_{TB} = 80$ nm for both TBs and we estimate their average thermal conductivity $k_{TB}$ and specific heat capacity $c_{TB}$. In an attempt to identify the bilayer Ta$_{50}$/Pt$_{36}$Mn$_{44}$ 20 with a single TB layer TB1, thermal conductivity and density were averaged over the thicknesses of the two layers leading to $k_{TB1} = 4.47$ W (K m)$^{-1}$, $\rho_{TB1} = 15228$ kg m$^{-3}$ and the specific heat capacity was averaged over the masses of the two layers leading to $c_{TB1} = 168.1$ J (K kg)$^{-1}$. By averaging the values of $k_{TB}$ and $c_{TB}$ over TB1 and TB2, one obtains $k_{TB} = 4.38$ W (K m)$^{-1}$, $c_{TB} = 154.1$ J (K kg)$^{-1}$ and $\rho_{TB} = 15846$ kg m$^{-3}$. By using in (3a) the measured values of $\alpha = 100 \times 10^3$ K W$^{-1}$, $S = 8.84 \times 10^{-14}$ m$^2$ and $d_{TB} = 80$ nm, one obtains $k_{TB} = 4.53$ W (K m)$^{-1}$, value which is in agreement with that estimated above. By introducing in (3b) the measured $\alpha = 100 \times 10^3$ K W$^{-1}$, $\tau_{TR} = 2.7$ ns, $d_{TB} = 80$ nm and $k_{TB} = 4.53$ W (K m)$^{-1}$, one obtains $\sum_i \rho_i d_i + c_{TB} \rho_{TB} d_{TB} = 0.315$ J (K m$^2$)$^{-1}$, value which is in agreement with 0.306 J (K m$^2$)$^{-1}$ calculated based on the estimated values for $c_i$, $\rho_i$, $c_{TB}$ and $\rho_{TB}$.

The application of the 1D model involves a number of approximations that may influence the accuracy of the obtained result, e.g. TBs TB1 and TB2 were assumed to be identical and the lateral heat diffusion, through the SiO$_2$ insulator deposited around the MTJ pillar and between the electrodes, was ignored. The effect of these approximations on the theoretical values of $\alpha$ and $\tau_{TR}$ was checked by a full 3D simulation of heat diffusion in the MTJ using the commercial software COMSOL. A realistic geometry of the MTJ as suggested by a TEM crosssection image, was used in the simulations (figures 6(a) and (b)). Conducting heat transfer was assumed between adjacent layers and constant $T_{RT}$ temperature condition was used for the end surfaces of the electrodes that were assumed to be much longer (10 $\mu$m) than the junction size (~300 nm). The values of the MTJ thermodynamic parameters used in the simulations are those of table 1. The heat applied to each MTJ layer was assumed to be zero except for the tunnel barrier where it was equal to the electric pulse power, equivalent to assuming that the entire power of the electric pulse was dissipated by the Joule effect in the tunnel barrier. A first simulation was performed in order to check the relationship between the power of the electric pulse $P_{HP}$ and the average temperature $T_{AF}$ of the free layer AF in the steady temperature regime ($\partial T/\partial t = 0$), i.e. at the end of a heating electric pulse of width $\delta \gg \tau_{TR}$. According to figure 6(c), $T_{AF} = T_{RT} + 83.6 \times 10^3$ (K W$^{-1}$) $\times$ $P_{HP}$, leading to $\alpha = 83.6 \times 10^3$ K W$^{-1}$. In order to determine $\tau_{TR}$, the temperature profile of the MTJ at the end of a heating pulse of power $P_{HP} = P_{HP}^{WRT}(\delta = 10$ ns) was calculated and used as the initial condition for a subsequent simulation of the cooling process ($P_{HP} = 0$). The calculated evolution of the average temperature of the free layer AF during the cooling, plotted in figure 6(d), was fitted with an exponential decay law of characteristic time $\tau_{TR} \approx 2.3$ ns. Thus, the values of $\alpha$ and $\tau_{TR}$ obtained by 3D simulations are in agreement with those calculated based on the proposed 1D model and they are both close to the experimental values.

4. Summary

Heat diffusion in a MTJ during the application of an electric current pulse was investigated. The F free layer was exchange biased by a low Néel temperature AF layer. This choice

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Figure 6. (a) Device geometry used in the 3D simulations of heat diffusion: ① is the bottom electrode, ② is the top electrode, ③ is the SiO₂ insulating layer and ④ is the MTJ. (b) Enlarged image of the MTJ. (c) Temperature of the free layer AF as a function of the electric pulse power $P_{HP}$ in the steady temperature regime obtained from a 3D simulation of heat diffusion (symbols); solid line is a linear fit using $T_{AF} = T_{RT} + 83.6 \times 10^3 \text{ (K W}^{-1} \text{)} \times P_{HP}$. (d) Evolution of the free layer AF temperature subsequent to the application of an electric current pulse of power $P_{HP} = P_{HP}^{WRT} (\delta = 10 \text{ ns})$ and width $\delta = 7 \text{ ns}$ calculated by a 3D simulation of heat diffusion (symbols); solid line is an exponential fit of characteristic time $\tau_{TR} = 2.3 \text{ ns}$.

led to a sensitive variation of the exchange bias acting on the free layer during the heating of the MTJ by Joule dissipation in the tunnel barrier. The exchange bias, accessible by magnetotransport measurements, was used to probe the temperature of the free layer during and after the application of the electric current pulse. Two TB layers, having a much lower thermal conductivity than the rest of the MTJ layers, were placed on both sides of the MTJ magnetic stack in order to enhance the heat diffusion time constant $\tau_{TR}$ above the time required for the magnetic stack to reach thermal equilibrium. According to a proposed 1D model, two temperature regimes of the magnetic stack can be distinguished: an initial transient regime where the temperature increases according to an exponential law of time constant $\tau_{TR}$, followed
by a steady temperature regime characterized by a linear relationship between the power of the electric pulse and temperature, of proportionality constant $\alpha$. Measurements of exchange bias field acting on the free layer were used to determine both $\tau_{\text{TR}}$ and $\alpha$. Thermal conductivities and heat capacities of the MTJ layers were estimated based on the Widemann–Franz law of electronic thermal conduction and on the Dulong–Petit law, respectively. Their values were used for calculating $\tau_{\text{TR}}$ and $\alpha$ according to the analytical expressions offered by the 1D model. The experimental and theoretical values of $\tau_{\text{TR}}$ and $\alpha$ are in good agreement, validating the conclusions of the proposed 1D model and suggesting the potential application of the temperature dependence of exchange bias for measuring the heat capacity of a thin film layer inserted in an MTJ stack.

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Appendix

Let us consider an F/AF bilayer. The AF layer is assumed to have a granular structure, each grain having thickness $a_{\text{AF}}$, diameter $D$ distributed according to $G(D)$ and uniaxial anisotropy $K_{\text{AF}}$, the easy axes being oriented in the same direction. The F layer is supposed to be a single-domain of thickness $a_{\text{F}}$ and uniaxial anisotropy $K_{\text{F}}$, the easy axis being parallel to those of the AF grains. The temperature dependence of the exchange bias $H_{\text{EX}}$ and coercivity $H_{\text{C}}$ of the F/AF bilayer along the easy axis direction can be expressed based on an Arrhenius–Néel (A–N) model of thermal relaxation [28]–[30]:

$$H_{\text{EX}} = \frac{J_{\text{INT}}}{a_0 M_S a_F} \int_0^\infty \frac{(P_- - P_+)D G(D) dD}{\text{Max}(D_0, D^*)}, \quad (A.1)$$

$$H_{\text{C}} = \frac{2K_F}{M_S} + \frac{J_{\text{INT}}}{a_0 M_S a_F} \int_0^\infty \frac{(P_- - P_+ - 1)D G(D) dD}{D^*}, \quad (A.2)$$

where $I = \int_0^\infty D^2 G(D) dD$, $D_0 = J_{\text{INT}}/(K_{\text{AF}} a_{\text{AF}} a_0)$, $J_{\text{INT}}$ is the exchange interaction energy between a pair of F/AF atoms and $a_0 = 2.5 \text{ Å}$ is the mean AF atomic distance at the F/AF interface. In (A.1), (A.2), $P_+$ and $P_-$ represent the occupation probabilities of an AF grain energy minimum in the direction of the F layer just before switching the F layer in the opposite direction

$$P_+ = 1 - \left[1 - P_\infty (1 - e^{-t/\tau})\right] \sum_{i=0}^{2n-2} \left[(-1)^i e^{it/\tau}\right] + P_0 e^{-(2n-1)t/\tau}, \quad (A.3a)$$

$$P_- = 1 - \left[1 - P_\infty (1 - e^{-t/\tau})\right] \sum_{i=0}^{2n-1} \left[(-1)^i e^{it/\tau}\right] - P_0 e^{-2nt/\tau}, \quad (A.3b)$$
where

$$\tau = \left\{ f_0 \sum_{\pm} \exp \left[ -K_{AF}a_{AF}D^2/(k_B T) \left( 1 \pm \frac{J_{INT}}{2DK_{AF}a_{AF}a_0} \right)^2 \right]\right\}^{-1}$$  \hspace{1cm} (A.4)$$

is the AF grain relaxation time, $f_0 \approx 10^9$ s\(^{-1}\), $t \approx t_{MEAS}/2$ is the time the F layer is oriented in either direction during the measurement of the hysteresis cycle, $n = 50$ is the number of hysteresis cycles performed at the measurement temperature $T$ prior to measuring $H_{EX}$ and $H_C$, $P_\infty = 1/[1 + \exp[-2J_{INT}D/(a_0 k_B T)]]$ and $P_0$ is the initial occupation probability, before the hysteresis measurement. In (A.1), (A.2) the exchange coupling energy per unit F/AF contact area is $J_E = J_{INT}/(a_0 D)$ \([23]\). In \([29]\) it is assumed that the switching of the F layer is an instantaneous event. Under this assumption, all the AF grains having the relaxation time $\tau < t_{MEAS}/2$ contribute to the coercivity. However, experimentally, the rotation of the F layer from parallel to perpendicular to the easy axis occurs over a finite time interval, e.g. $t_{SW} = t_C - t_S \approx 0.5$ ms as shown in figure 2(b), allowing for a fraction of the AF grains to relax during the switching of the F layer \([31]\). This effect can be corrected for in (A.1), (A.2) by introducing a diameter $D^*$, having the meaning of the upper AF grain diameter that reaches thermal equilibrium during the switching of the F layer. The value of $D^*$ can be estimated according to:

$$t_{SW} = (1/f_0) \exp \left\{ \frac{K_{AF}a_{AF}D^2}{k_B T} \left[ 1 - J_{INT}/(2K_{AF}a_{AF}D^* a_0) \right]^2 \right\},$$  \hspace{1cm} (A.5)$$

which is the expression of the AF relaxation time for a perpendicular orientation of the F layer with respect to the easy axis, corresponding to the maximum energy barrier to rotation of the AF grain uncompensated moment during the rotation of the F layer. The temperature dependence of $K_{AF}$ and of $J_{INT}$ are those of \([30]\), i.e. $K_{AF}(T) = K_{AF}^0 (1 - T/T_N)^{0.99}$, $J_{INT}(T) = J_{INT}^0 (1 - T/T_N)^{0.33}$, where $T_N = 350$ °C is $T_N$ for the Ir\(_{20}\)Mn\(_{30}\) AF layer. The above model was used to identify the magnetic parameters of the F/AF free layer for the investigated MTJ junction. For this purpose, $H_{EX}$ and $H_C$ were measured at several temperatures $T$ from MR hysteresis cycles using the described setup and the results were fitted by (A.1) and (A.2).

The MTJ was previously heated up to 350 °C and cooled down to RT in the presence of a 397.9 kA m\(^{-1}\) applied field, in order to initialize $H_{EX}$. The fit, using the AF grain size distribution $G(D)$ measured by electron microscopy (lognormal of median value $D_m = 21$ nm and standard deviation $\sigma = 0.17$), led to the following parameter values: $t_{SW} = 0.6$ ms, $K_F = 1.3 \times 10^4$ erg cm\(^{-3}\), $K_{AF}^0 = 1.3 \times 10^6$ erg cm\(^{-3}\) and $J_{INT}^0 = 1.03 \times 10^{-11}$ erg. The corresponding RT values, $K_{AF} = 7.3 \times 10^5$ erg cm\(^{-3}\) and $J_{INT} = 8.5 \times 10^{-15}$ erg, are in good agreement with those previously reported in the literature \([32]\)--\([34]\).

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