Temperature dependence of tunnel magnetoresistance

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Electric transport through magnetic tunnel junctions (MTJs) has been studied at various temperatures to gain understanding of the transport mechanisms in such devices. Between 15 and 400 K, MTJs with Al$_2$O$_3$ barriers have been tested at low voltage (barrier height: 2.0–2.1 eV, barrier width: 1.5 nm). For the soft-magnetic electrode a sputtered 1 nm Co/6 nm Fe double layer was used. The hard-magnetic electrode is realized with a 1.5 nm Co/1.0 nm Cu/1.0 nm Co system. Antiferromagnetic coupling between the two Co layers leads to a high saturation field. The 1.5 nm Co layer is used as the second electrode of the MTJ. The conductance increases with growing temperature while the tunnel magnetoresistance (TMR) shows a slight decrease. For interpretation of the results, the temperature dependence of direct tunneling, of the hopping conductance via trapped states, and of the interface magnetization have to be taken into consideration. The dominant factor for the TMR is proportional to $1 - BT^{3/2}$ and follows the temperature dependence of the interface magnetization. The experimental data allow us to separate transport mechanisms and characterize the junction quality. At room temperature the spin-independent hopping conductance of our junctions is calculated to be less than 10% of the total conductance. Concerning the magnetic properties, a ferromagnetic orange-peel coupling corresponding to a field of about 4 Oe (0.3 kA/m) was found at 15 K, which decays exponentially with increasing temperature to less than 0.6 Oe (0.05 kA/m) at 300 K. The coercive field of the soft layer also shows an exponential decay. © 2001 American Institute of Physics. [DOI: 10.1063/1.1359229]

I. INTRODUCTION

The tunneling magnetoresistance (TMR) of magnetic tunnel junctions (MTJs) is reduced significantly with increasing temperature. This phenomenon is quite relevant for most potential applications, but cannot be understood within an early model of the effect given by Jullière$^1$ because it did not consider any explicit temperature dependence at all. The present work describes temperature-dependent transport experiments and explains the results using a theoretical model proposed recently.$^2$

II. EXPERIMENTS

Tunnel junctions investigated in the present study were prepared by sputter deposition on an oxidized Si wafer and lithographic structuring to different sizes. The hard-magnetic electrode of each MTJ is realized with a 1.5 nm Co/1.0 nm Cu/1.0 nm Co system, called an artificial antiferromagnet (AAF) because of the antiferromagnetic coupling between the two Co layers that leads to a high saturation field. Using the AAF instead of a single, thick ferromagnetic layer allows the magnetic stray field to be kept very small. A sputtered (1 nm Co/6 nm Fe) double layer is used as a soft-magnetic electrode. A field of about 20 Oe (3.2 kA/m) is necessary to switch the magnetization of this electrode at room temperature, which increases to about 30 Oe at 15 K. The insulating barrier consists of Al$_2$O$_3$, prepared from a sputtered 1 nm Al layer which was oxidized in an Ar/O$_2$ plasma (80% Ar+ 20% O$_2$). This results in an effective barrier thickness of about 1.5 nm. The barrier height is between 2.0 and 2.1 eV, determined by fitting the $I$–$V$ curve, according to Ref. 3.

The electric and magnetotransport through the MTJs have been studied at various temperatures between 15 and 400 K. The voltage drop across the devices was measured with a constant current of 1 mA, while sweeping an external homogeneous magnetic field parallel to the layers from $-10$ kOe (−800 kA/m) to $+10$ kOe (+800 kA/m) and back. The high fields used for these major-loop measurements ensure that all magnetic layers of the device are magnetized parallel at the beginning and at the end of the measurement. Although the full TMR effect can be detected with these major-loop measurements, so-called minor-loops are more interesting for practical applications, where only the magnetization of the soft-magnetic layer is switched while the hard-magnetic electrode remains nearly unaffected. These minor-loop measurements were made after saturation with a magnetic field of $-10$ kOe by sweeping from $-125$ Oe (−10 kA/m) to $+10$ kOe (+10 kA/m) and back.
kA/m) to +125 Oe (+10 kA/m) and back. Both types of measurements were performed at different temperatures and with junctions of different sizes. The junction resistance varied between 3 Ω for a tunneling area of about \((100 \times 100) \mu \text{m}^2\) and 20 Ω for \((50 \times 50) \mu \text{m}^2\).

III. RESULTS AND DISCUSSION

To discuss the results of the temperature-dependent measurements, we choose one typical series of minor-loop measurements of a sample with \((50 \times 50) \mu \text{m}^2\) junction area \(\text{MTJ1}\), as shown in Fig. 1. It can be seen that the minimum and maximum resistance both decrease with increasing temperature.

In recent years, different mechanisms have been proposed as being responsible for the temperature dependence of MTJs.4–7 The model proposed by Shang, Nowak, Jansen and Moodera2 combines several important factors; it is used as the main model to interpret the present results. According to this model, the maximum of the conductance at parallel magnetization of the two magnetic electrodes can be described by

\[
G_{\text{max}}(T) = G_T(T)[1 + P(T)^2] + G_S(T),
\]

while the minimum of the conductance, which is measured when both electrodes are magnetized antiparallel to each other, can be written as

\[
G_{\text{min}}(T) = G_T(T)[1 - P(T)^2] + G_S(T).
\]

Equations (3.1) and (3.2) include the three temperature-dependent variables \(G_T(T)\), \(P(T)\), and \(G_S(T)\). The term \(G_T(T)\) represents the conductance due to direct elastic tunneling through the junction. In a good approximation, it can be written as

\[
G_T = G_0 \frac{C T}{\sin(C T)},
\]

where \(G_0\) is the conductance at \(T=0\) K and \(C\) is a material constant depending on the effective barrier thickness \(d\) and the barrier height \(\phi\) according to

\[
C = 1.387 \frac{d}{\sqrt{\phi}} \times 10^6 \text{eV}/(\mu \text{K}).
\]

Using \(d=1.5\) nm and \(\phi=2\) eV, we obtain \(C = 1.5 \times 10^{-3}\) K\(^{-1}\).

![FIG. 1. Series of minor-loop measurements showing the magnetoresistance of MTJ1 at different temperatures. The system was saturated in the direction of negative external field before measurements.](image1)

![FIG. 2. Maximum and minimum conductance of MTJ1 vs temperature. Dotted lines: model curves, fitted to experimental data, to obtain parameter \(S\).](image2)

![FIG. 3. Change of conductance of MTJ1 vs temperature. Dotted curve: model curve, fitted to experimental data, to obtain parameter \(B\).](image3)

![FIG. 4. Temperature dependence of the relative change of conductance \(\Delta G/G = \text{TMR}\) of MTJ1. Dotted line: model curve with parameters obtained by the calculations.](image4)
From theoretical work, we know that the spin polarization $P(T)$ of the electrodes is firmly bound to the magnetization of the electrode at the interface with the insulating barrier. The polarization thus can be written as

$$P(T) = P_0 (1 - BT^{3/2}), \quad (3.5)$$

with $P_0$ being the spin polarization at $T=0$ K and the spin-wave parameter $B$ as a material constant, primarily depending on the materials and thickness used for the electrodes. Although we used two different electrodes, it is possible to use one effective spin polarization for the model description, as long as the specific polarization of each electrode is not known. This effective value is used for the present discussion. The term $G_s(T)$ represents the additional spin-independent conductance of the MTJ, which increases the total conductance, but reduces the magnetoresistance ratio. It is suggested that the hopping conductance via trapped states in the barrier is the primary mechanism for this contribution. In general, $G_s(T)$ can be written as

$$G_s(T) = ST^\gamma. \quad (3.6)$$

Theory suggests that we can assume $\gamma = 4/3$ if the spin-independent transport is indeed dominated by a hopping process over one intermediate trapped state, while the constant $S$ mainly depends on the number of defects in the barrier.

To describe the results with these model functions, the parameters $G_0$, $P_0$, $B$, and $S$ must be determined. As can be seen in Fig. 2, where maximum and minimum conductance are plotted versus temperature, the low-temperature measurements allow us to extrapolate both the minimum and maximum conductance to $T=0$ K with high accuracy. Consequently, as a first step, the two ground-state parameters $G_0$ and $P_0$ can be calculated from the resulting ground state equations $G_{\text{max}}(0) = G_0 (1 + P_0^2)$ and $G_{\text{min}}(0) = G_0 (1 - P_0^2)$. Next, $B$ is obtained from a fit of the function $\Delta G(T) = G_{\text{max}}(T) - G_{\text{min}}(T)$ to our experimental data, as shown in Fig. 3. As spin-independent transport does not contribute to the change of conductance, $B$ is the only parameter to be fitted in this step. Finally, $S$ is deduced from a fit of the model function (3.1) or (3.2) to our experimental data, as shown in Fig. 2. Both $G_{\text{max}}(T)$ and $G_{\text{min}}(T)$ gave consistent values for this parameter.

The TMR, defined as the relative change of conductance, $\Delta G/G_{\text{max}}$, is shown in Fig. 4, where experimental data (crosses) and the model function curve (dots) are plotted. Clearly, the model allows us to describe the experiment quite well. The calculated parameters for MTJ1 are summarized in Table I. From those parameters, some conclusions about the transport mechanisms and the quality of the MTJ can be made. First, the ground-state conductance $G_0$ can be compared to theoretical values, corresponding to the assumed barrier parameters. Pinholes or inhomogeneities of the barrier thickness would lead to a much higher conductance than expected theoretically for a uniform barrier of the same thickness. Oxidized or rough ferromagnetic interfaces would result in a decreased $P_0$ compared to the expected values for the used material. In our case, both values meet the expectations and, consequently, we assume a homogenous barrier and clean ferromagnetic interfaces.

The spin-wave parameter $B$ of the interface is increased by a factor 2–10, compared to the bulk value of the same material, as we expected from earlier work. Consequently, the predominant factor for the temperature dependence of the TMR is proportional to $1 - BT^{3/2}$ and follows the temperature dependence of the interface magnetization.

Finally, $S$ indicates the quality of the barrier itself, as a large number of trapped states in the barrier would lead to a high-spin-independent conductance. For the junction discussed in this article, at room temperature, still less than 10% of the total conductance is due to spin-independent hopping processes. This is expected for high-quality Al$_2$O$_3$ barriers.

In addition, the temperature-dependent minor-loop measurements give further information concerning the magnetic properties of the samples. A shift of the minor loops with respect to $H=0$ is observed, which indicates a ferromagnetic coupling between the soft- and hard-magnetic layers. It corresponds to a bias field of 3.7 Oe (0.3 kA/m) at 15 K and is interpreted as due to orange-peel coupling. The coupling strength decays exponentially with increasing temperature to less than 0.7 Oe (0.05 kA/m) at 300 K. Furthermore, the coercive field of the soft layer also shows an exponential decay with increasing temperature. The origin of the temperature dependence of the coupling strength is not clear at present.

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<th>Table I. Resulting model parameters for MTJ1. Transport mechanisms and junction quality are characterized by these values.</th>
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<tr>
<td>$G_0 = (0.045 \pm 0.001) \Omega^{-1}$</td>
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<td>$P_0 = (32 \pm 1) %$</td>
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References: