

Comparative study of magnetoresistance and magnetization in nano-oxide specular and nonspecular MnIr/CoFe/Cu/CoFe spin valves from 10 to 300 K

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The temperature and magnetic field dependences of the magnetoresistance (MR), superconducting quantum interference device magnetization M , its electrical resistance R and temperature derivative dR/dT (10–300 K) are reported for nonspecular CoFe/Cu/CoFe spin valves and specular spin valves formed by nano-oxidation of the pinned and free CoFe layers. The $MR(T)$ increases linearly with decreasing temperature on both spin valves, and data extrapolation converges to zero MR practically at the same Curie temperature. At temperatures below ~ 175 K the specular spin valve $MR(H)$ curves present two anomalous bumps not seen in the nonspecular curves. Also, for the nonspecular spin valve a clear relation is visible between M and MR curves, which is not the case for the specular spin-valve curves. In the specular spin valve, dR/dT presents an anomalous enhancement after $T \sim 150$ K, which is discussed in terms of electron scattering in the nano-oxide layers. The application of a saturating magnetic field suppresses most of the anomaly, indicating its magnetic origin. © 2002 American Institute of Physics. [DOI: 10.1063/1.1459617]

I. INTRODUCTION

Giant magnetoresistance in layered nanostructures arises from spin dependent scattering at the internal and outer interfaces and in the bulk of the ferromagnetic (FM) and nonmagnetic (NM) layers of the structure. The first semiclassical treatments only considered diffuse scattering,^{1,2} but when a spin valve (SV) is between two insulating smooth layers, producing a high potential barrier, electrons can be specularly scattered at the corresponding interfaces, as first shown on a Co/Cu structure bounded by NiO surfaces.³ The resulting longer electron mean free path leads to higher magnetoresistance (MR). Specular spin valves formed by partial nano-oxidation of free and pinned magnetic layers are receiving great attention to maximize MR.^{4–6}

The MR of a FM–NM–FM spin valve with fully specular boundaries should mimic that of a $(2\text{FM–NM})_{n=\infty}$ multilayer, as long as the structural characteristics in both samples remain the same, with the advantage of a much lower saturation field.² However, $MR \leq 20\%$ for specular SVs (so far) and $\sim 100\%$ in some multilayers, which still gives considerable room for development.

In particular, information on the effect of temperature T is rather scarce.⁵ The simultaneous knowledge of the T dependence of the MR ratio, absolute ΔR and $R(T)$ for zero and applied magnetic field, is important to understand the different roles played by magnetic/nonmagnetic electron scattering processes, and the specific effects arising from the nano-oxide layers (NOLs). The $MR(T)$ dependence in

simple SV⁷ and NOL–SV's,⁵ and the underlying physical factors, need further investigation. From $MR(T)$ data extrapolation to high temperatures we can infer the effective Curie temperature T_C of the FM layers, checking whether it is affected by the presence of the nano-oxide layers.

Another open question is the shape of the $MR(H)$ curve in SV and NOL–SV, and its evolution with temperature: in particular the ΔH width of maximum resistance, SV switch sharpness, and specific effects related to the nano-oxide layers.

We present a comparative study of the temperature dependence (10–300 K) of the MR ratio for a nonspecular glass/Ta/NiFe/MnIr/CoFe/Cu/CoFe/Ta spin valve and for the corresponding specular SV version obtained by controlled nano-oxidation of the CoFe layers. The specular SV has more than twice the GMR value of the nonspecular SV, but the $MR(T)$ dependence is quasilinear in both cases.

We performed superconducting quantum interference device (SQUID) magnetization measurements (20–300 K) both for the specular and nonspecular SV, revealing the magnetization changes in the free and pinned CoFe layers, and also in the NiFe deep layer. A separation of the corresponding individual hysteric loops enabled us to understand specific features due to the NOL, and to extract the coercive and coupling fields as a function of temperature. Direct comparison of $MR(H)$ and $M(H)$, including their temperature dependence, shows a drastic break in the usual connection between transport and magnetic processes, in the case of the specular SV.

We conclude with a study of the electrical resistance $R(T)$ and dR/dT for both types of spin valves from 20 K to room temperature, under $H=0$ Oe and under a saturating

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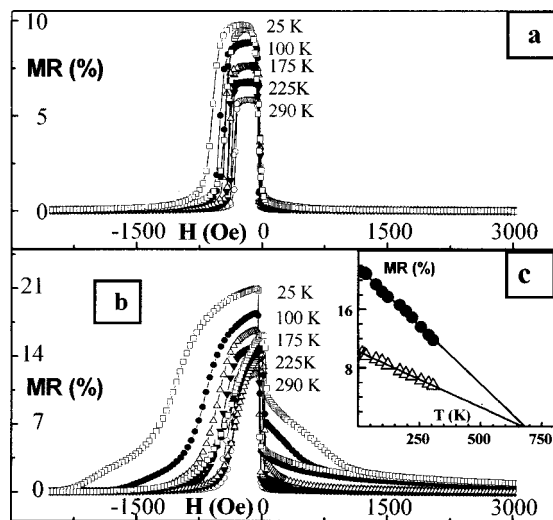


FIG. 1. MR(H) curves for the nonspecular (a) and specular (b) spin valves at several temperatures. (c) Temperature dependence of the maximum of MR for the nonspecular (open triangles) and specular (solid circles) spin valves.

magnetic field. For the specular SV a significant dR/dT enhancement occurs above 150 K, which is discussed in terms of electron scattering processes in the NOL.^{7,8} Our work shows that such effect is of magnetic origin.

II. SAMPLE PREPARATION AND TECHNIQUES

Specular SV structures were fabricated using a standard SV inserted between two nano-oxide layers of CoFe. A NOL-SV with the structure Ta(67 Å)/Ni₈₁Fe₁₉(42 Å)/Mn₈₃Ir₁₇(90 Å)/CoFe(14 Å)/oxidation/Co₉₀Fe₁₀(15 Å)/Cu(22 Å)/Co₉₀Fe₁₀(40 Å)/oxidation/Ta(30 Å) was grown on a glass substrate using ion beam deposition, postannealed in vacuum (10^{-6} Torr) at 270 °C for 10 min, and then cooled in a 3 kOe applied field. The CoFe oxidation was done with the remote plasma method⁶ for 3 min. To compare results, a standard (nonspecular) spin valve was also fabricated, with the same composition, nominal thickness, and growth conditions, except for the missing NOL.

The electrical resistivity and magnetoresistance were measured with a standard four-point dc method, with a current stable to $1:10^6$ and applied fields up to 7 kOe. An automatic data acquisition system provided $R(T)$ values every 80 mK, enabling the direct measurement of dR/dT . SQUID magnetization was measured at several temperatures between room temperature (RT) and 25 K, for which independent MR(H) measurements were also done.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Magnetoresistance

MR curves for both the nonspecular and specular SV at several temperatures between 25 and 300 K are presented in Figs. 1(a)–1(b) with $MR(H) = (R(H) - R_{\text{parallel}}) / R_{\text{parallel}}$. The measurements always started with the sample saturated at positive fields, where both CoFe FM layers (free and pinned) are spin aligned ($\uparrow\uparrow$), providing the low resistance state. Striking differences are observed between the MR(H) curves

of the two spin valves as temperature decreases. For the nonspecular spin valve, MR abruptly rises near $H=0^-$ (at a negative field of a few tens of Oe) when the free layer magnetization suddenly reverses ($\downarrow\uparrow$ alignment), following a ΔH region of maximum resistance due to the persistence of the antiparallel alignment in the active FM layers. Finally an abrupt decrease in resistance occurs when the magnetization reverses in the pinned FM layer ($\downarrow\downarrow$ alignment). These usual features are observed over the whole temperature range.

In contrast, the NOL spin valve exhibits only an incipient ΔH region of maximum resistance near $H=0$, and then MR slowly decreases towards zero at high negative fields. These features rapidly grow below ~ 175 K, when two anomalous bumps also emerge in MR(H), one at each side of the curve. Since these effects are absent in the nonspecular SV [Fig. 1(a)], they are due to the presence of the NOL. A peculiar MR(H) asymmetry also arises in the NOL-SV below ~ 175 K: whereas at moderate negative field we always reach zero MR, indicating perfect $\downarrow\downarrow$ alignment under positive field we are unable to achieve full $\uparrow\uparrow$ alignment in fields up to 8 kOe. This is associated with the two bottom CoFe layers separated by a NOL in the specular SV, the lower one becoming strongly (magnetically) pinned by the underlying MnIr layer.

Figure 1(c) shows the temperature dependence of the maximum of MR for both spin valves. For the nonspecular SV (lower curve), the maximum MR is 5.9% at RT and rises quasilinearly with decreasing temperature, reaching 10% at 17 K. A similar behavior has been observed in other nonspecular SV.⁷ For the specular SV (upper curve), MR_{max} is again linear in T , rising from 12.5% at RT to 21.1% at 17 K. Such linear variation has been recently observed in a particular specular SV, but large deviations have also been reported.⁵ The large MR value is associated with specular reflection (even if only partial) at the NOL/FM interfaces. The MR(T) extrapolation to high temperature for both spin valves (SV and NOL SV), gives zero at a common $T_C \sim 675$ K [Fig. 1(c)], the effective Curie temperature for the FM layers. This is much lower than in bulk CoFe (~ 980 K). Dieny *et al.*⁷ showed that T_C in SVs depends essentially on the FM materials and on the nature of the FM/NM and NM/FM interfaces. Our work shows that the nature of the SV outer boundaries (metallic or nano-oxide), and even possible interdiffusion at these interfaces, has no major effect on T_C for the system under investigation.

B. Magnetization versus magnetoresistance

Figure 2 compares MR(H) with $M(H)$ at different temperatures, both for the nonspecular (upper curves) and specular (lower curves) spin valves. The hysteretic loops can be analyzed in terms of magnetization changes in the free and pinned CoFe layers, and in the NiFe deep layer.

For the nonspecular SV, one observes the usual good correlation between $M(H)$ and MR(H) curves at all temperatures. However the NOL spin valve behaves quite differently, with MR(H) still fairly large when magnetization enters its saturation regime. This effect is more pronounced under negative applied field and greatly increases with re-

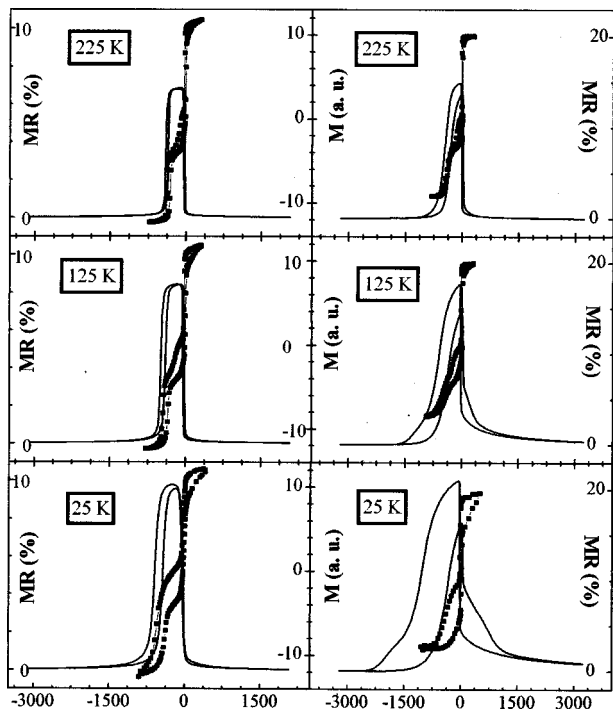


FIG. 2. Comparative plots of the MR(H) (lines) and M(H) (squares) curves of the nonspecular (left side) and specular (right side) spin valves at three different temperatures.

ducing temperature. Therefore, important resistive mechanisms are still operative at (long range) magnetic saturation in the NOL spin valve, associated with the persistence of short-range disorder effects.

We may assume that the lower CoFe layer (the part of the first deposited CoFe layer that was not oxidized), though contributing little to the total magnetic moment of the specular SV due to its small thickness, plays a non-negligible role in electron scattering. In fact, local disorder and anisotropy are expected to increase the rigidity of the magnetic domain structure⁹ of this layer against its reversal by the application of a magnetic field. Thus, increasing the magnetic field from -6 kOe (↓↓ alignment) to zero induces only a partial reversal of the magnetic moment of the lower CoFe layer, producing lower values for MR as compared to those obtained when the system comes from positive fields. The full magnetic reversal is reached only asymptotically for positive magnetic fields, producing the right-hand side bump of the MR(H) curve.

The free layer coercive H_{cf} and coupling H_{coup} fields were obtained from our $M(H)$ data with RT values of $H_{cf} = 10$ Oe (7 Oe) and $H_{coup} = 3$ Oe (22 Oe) for the specular (nonspecular) SV. These results suggest that in the specular SV the local disorder and anisotropy introduced by the NOL are the main factors for the reduction of the net coupling of the CoFe free layer and the simultaneous enhancement of its coercive field, with respect to the nonspecular SV.

C. Electrical resistance and dR/dT

Figure 3 shows the temperature dependence of the electrical resistance (inset) and of its derivative dR/dT , for the

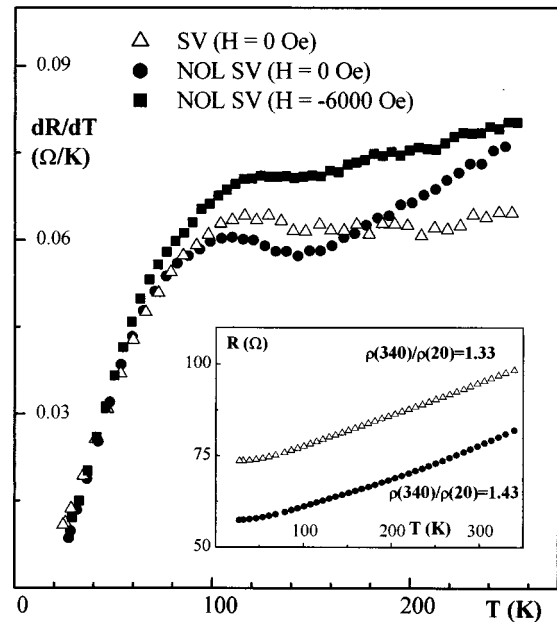


FIG. 3. R and dR/dT curves for the nonspecular (under zero applied field) and specular (under 0 and -6 Oe applied field) spin valves.

two spin valves. The specular SV exhibits systematically lower R values. The corresponding $\rho(340)/\rho(20)$ ratio is also higher, showing a lower density of electron scattering centers, thus suggesting enhanced specular reflection at the NOL surfaces (longer electron mean free path). In the nonspecular SV the temperature dependence of dR/dT strongly resembles the Bloch–Gruneisen (BG) behavior associated with electron–phonon scattering.

In contrast, in the specular SV, dR/dT shows a temperature dependence quite different from the BG type, with a great enhancement above ~150 K, rising almost linearly in T. This means a T^2 resistance contribution, which can hardly be attributed to electron–phonon scattering at high temperatures. In principle, one could consider the possible excitation of phonon surface-modes⁸ in the nano-oxide layers giving extra electron scattering (“equivalent” to surface roughening), or magnon scattering.⁷ To further investigate these possibilities R(T) was measured under a saturating applied field and dR/dT obtained. The application of a saturating magnetic field increases dR/dT globally but decreases its slope above 150 K. No such effect was observed in the nonspecular SV. Therefore, in the specular SV the large dR/dT increase in zero field above 150 K is basically of magnetic origin. Further work on this phenomenon is in progress and will be published elsewhere.

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