Enhanced giant magnetoresistance in spin-valves sandwiched between insulating NiO

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We have investigated the giant magnetoresistance of artificial structures containing metallic Co/Cu/Co and $Ni_{80}Fe_{20}/Cu/Ni_{80}Fe_{20}$ spin-valves confined within insulating antiferromagnetic NiO layers. The observed enhanced magnetoresistance as compared to conventional all-metal spin-valves is interpreted with a semiclassical approach in which specular reflections at the metal/insulator barrier are included.

INTRODUCTION

Since the discovery of the giant magnetoresistance (GMR) effect in layered magnetic structures the majority of investigations[1,2] were focused on the elucidation of the spatial origin of spin-dependent scattering (SDS), in the bulk of the ferromagnetic layers or at the interface with the spacer material, which is still a matter of debate. The discovery of GMR also intensified the search for theoretical models for transport in thin films and multilayers, and in recent years several semiclassical[3,4] and quantum-statistical theories[5] have been proposed. Most of these approximations have in common that they deal with a (nearly) free-electron gas with a constant potential throughout the chemical constituents of the layered structure. In recent literature however it is speculated that electron channeling or reflectivity[6] is expected to show up in magnetoresistance experiments when, generally speaking, one goes beyond the assumption of a flat potential throughout the layers. A transparent manifestation of electron reflectivity should be observed in the GMR when all the electrons in a common spin-valve would be reflected at the outer surfaces, since usually in trilayers the giant magnetoresistance effect is relatively small due to spin-independent boundary scattering. When the trilayer is sandwiched between a high barrier potential facilitated by, e.g., an insulating top and bottom layer, all the electrons are internally reflected or channeled within the barrier and in fact the trilayer then mimics an infinite multilayered system. This should necessarily enhance the GMR, since the reflectivity considerably enhances the lifetime of the electrons, and in fact they may travel back and forth between the two ferromagnetic layers to experience each time the presence of spin-dependent scattering. In this paper we will try to investigate experimentally the possibility of increased reflectivity in a metallic spin-valve incorporated in a metallic/oxidic structure, consisting basically of Co/Cu/Co or $Ni_{80}Fe_{20}/Cu/Ni_{80}Fe_{20}$ metal trilayers sandwiched between the antiferromagnetic insulator NiO. More precisely, the large potential step at the insulator/metal interface is expected to induce an increased reflectivity of the electron wave functions, which in turn would lead to enhanced magnetoresistivity compared to common all-metal spin-valves. Indeed, as we will show, we have found in, e.g., Co/Cu/Co unusually high GMR ratios of 15% at room temperature and almost 25% at low temperatures. Very recently Anthony, Brug, and Zhang[7] and Egelhoff *et al.*[8] also reported large magnetoresistances in structures including NiO layers, and the latter authors suggest that a simple intuitive model would possibly predict that some specular scattering of electrons at the Co/NiO interfaces is present.[8] In this paper the considerable improvement of the GMR ratio in our new spin-engineered structures will be analyzed more systematically by the introduction of specular reflections of the electrons at the potential barrier of the impenetrable NiO in a semiclassical approach for giant magnetoresistance. We will however also discuss alternative possibilities that may lead to improved giant magnetoresistance in this type of spin-valve structure.

EXPERIMENT

The samples are grown on glass substrates by magnetron sputtering in Ar atmosphere at $p=7$ mTorr for Co and Cu and $p=1$ mTorr for the NiO, in the presence of a magnetic field. NiO directly on top of the substrate was deposited at 200 °C to ensure a (111) texture of the layer, whereas the remainder of the stack was grown at ambient temperature to avoid diffusion between the separate chemical constituents. We have used a superconducting quantum interference device (SQUID) and the magneto-optical Kerr effect for magnetic characterization. Resistance measurements were made in standard four-point contact geometry with the current in the plane of the sample. We have basically studied the following spin-valve structures: 500 Å NiO/F1/NM1/F2/NM2/100 Å NiO, with NM1 = 20 Å Cu, and NM2 = 12 Å nonmagnetic Cu; see the schematic representation in the top of Fig. 1. A typical example of magnetoresistance and magnetization for F1 = 20 Å Co and F2 = 40 Å Co is shown in Figs. 1(b/c) and 1(d/e), respectively, and reflects an antiparal-

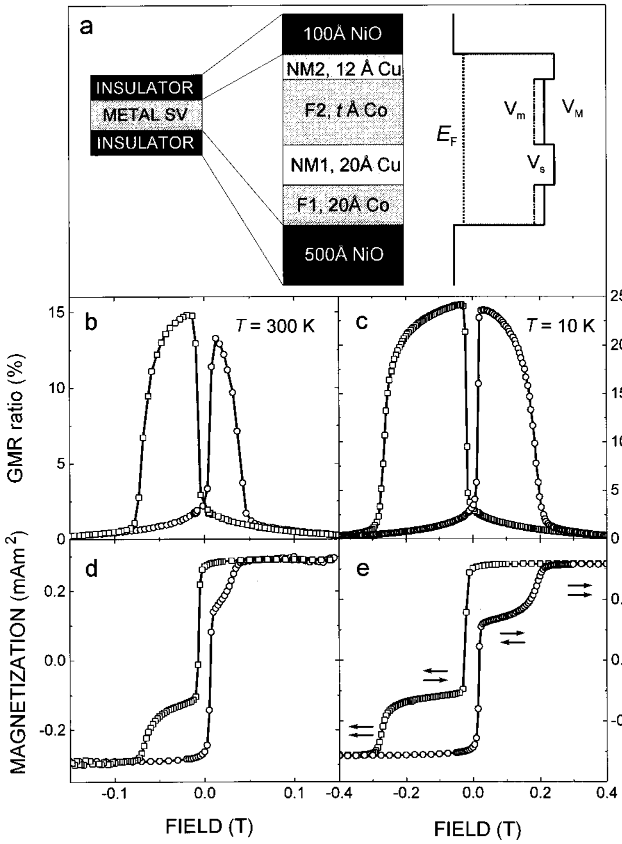

FIG. 1. (a) Illustration of an insulating/metal artificial layered structure consisting basically of 500 Å NiO/F1/NM1/F2/NM2/100 Å NiO, with F1 = 20 Å Co, NM1 = 20 Å Cu, F2 $=t$ Co, and NM2 = 12 Å Cu. At the far right of this panel the potential landscape is schematically depicted, with E_F the Fermi level, and V_s, V_M, and V_m, the potentials for spacer electrons, majority electrons and minority electrons of the ferromagnet, respectively. The room-temperature GMR ratio ($=[G_{\mathrm{P}}-G_{\mathrm{AP}}]/G_{\mathrm{AP}}$) and magnetization of a system with F2 = 40 Å Co is shown in panels (b) and (d), respectively; panels (c) and (e) are data obtained at 10 K. The magnetic field was applied along the bias direction. Arrows in the low-temperature magnetization data (e) visualize the direction of the magnetization F1 and F2.

lel (AP) state of F1 and F2 most clearly visible at negative magnetic fields. This is the key element to our Co/Cu/Co and $Ni_{80}Fe_{20}$/Cu/$Ni_{80}Fe_{20}$ spin-valve structures and, qualitatively, the observed behavior can be understood as follows. The bottom NiO layer imposes an exchange biasing H_{ex} on layer F1, accompanied by a strong increase in coercive field H_c with $|H_c|>|H_{\mathrm{ex}}|$. This is in accordance with separately investigated NiO with a single magnetic layer on top, of which the magnetic behavior is described elsewhere.[9] On the other hand, the top ferromagnetic layer F2 switches its magnetization direction almost at zero field since it is intentionally magnetically isolated from NiO on top by a thin nonmagnetic layer NM2 to circumvent exchange biasing and enhancement of H_c of F2 as well. The reversal of F2 at zero field also reflects the essentially decoupled behavior of this layer in the case of 20 Å spacer NM1. We found that for a smaller Cu interlayer thickness ($t_{\mathrm{Cu}}<20$ Å) the magnetoresistance as well as the exchange biasing is suppressed which may be explained from deterioration of the antiparallel alignment of the magnetization F1 and F2 when interlayer coupling becomes effective. Without coupling, the magnetization of the ferromagnetic layers F1 and F2 are simply additive and this results in the characteristic magnetic and magnetoresistive behavior of the entire spin-valves, as exemplified for Co/Cu/Co in panels (d/e) and (b/c) of Fig. 1, respectively.

Now we will focus on the *magnitude* of the observed GMR which is expected to embody the impact of increased specular reflectivity at the insulating barriers, as we will show later on. To allow for comparison with conventional all-metal spin-valves, mostly exchange biased with metallic FeMn, we applied a common practice in studies on GMR,[1,2] viz. a variation of the thickness of the uncoupled ferromagnetic layer t_F, whereas the exchange-biased layer is kept unchanged since otherwise the switching fields of this layer and therefore the AP alignment of the spin-valve may be affected. Upon variation of t_F, the GMR ratio, defined as $(G_{\mathrm{P}}-G_{\mathrm{AP}})/G_{\mathrm{AP}}$ with G the sheet conductivity, in general displays a maximum at $t_{F,\,\max}=50-100$ Å in all-metal spin-valves.[1,2,10,11] This is brought about by saturation of the differential sheet conductivity $G_{\mathrm{P}}-G_{\mathrm{AP}}$ when t_F is roughly speaking[12] larger than the bulk mean free path and the movement of the (spin-polarized) electrons is not limited by boundary scattering. On the other hand, G_{AP} (and G_{P}) is almost linearly increasing with t_F, since in the lowest order of approximation the current is carried in parallel in the various layers.[10] This characteristic behavior is also observed in our material, see Fig. 2, although the maximal GMR ratio is located at smaller ferromagnetic layer thickness, roughly between 20 and 40 Å. A comment should be made at this point about the possibility that the maximum might appear due to structural degradation of the uncoupled ferromagnetic layer when its thickness becomes very small. In this respect, we could not detect indications for nonuniform or clusterlike behavior of Co from both magnetoresistance and magnetization, down to the smallest thicknesses covered in the experiments ($t_{\mathrm{Co}}=15$ Å), which is in favor of the true spin-valve nature of the observed maximum. In the discussion we will return to this maximum in more detail.

The most prominent feature of the data is the magnitude of both $G_{\mathrm{P}}-G_{\mathrm{AP}}$ and the GMR ratio. In the Co/Cu/Co system an unusually high GMR ratio of 15% at room temperature, increasing at low temperatures to almost 25%, has been measured, whereas the systems containing $Ni_{80}Fe_{20}$/Cu/$Ni_{80}Fe_{20}$ yield more than 5% at room temperature and 15% at low temperatures, which is illustrated in Fig. 2. The Permalloy data cannot be easily compared with reports in literature due to differences in the individual layer thicknesses, although the GMR ratio in FeMn-based $Ni_{80}Fe_{20}$/Cu/$Ni_{80}Fe_{20}$ spin-valves never exceeds 10% at low temperatures,[10,11] which in our case amounts to 15%. To allow for comparison with the Co/Cu/Co materials, Fig. 2 is supplemented with low-temperature data obtained in UHV-sputtered 30 Å Ta/t Co/30 Å Cu/20 Å Co/100 Å FeMn/20 Å Ta all-metal spin-valves[11] in which the thickness of the pinned Co layer is also 20 Å, and this clearly demonstrates enhanced magnetoresistivity in the NiO structures by a factor of 5. In the FeMn structure the Cu thickness is 10 Å more than for the NiO material, of which the effect on the GMR

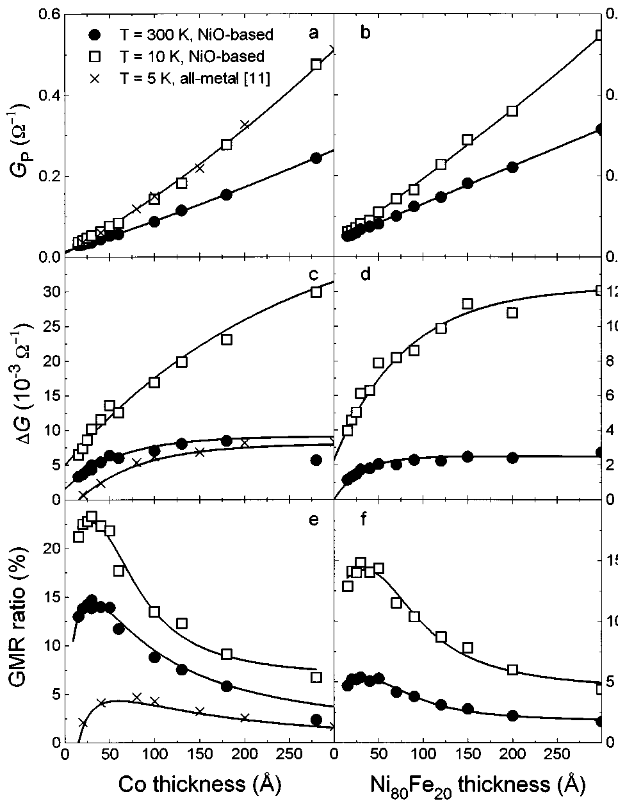

FIG. 2. Parallel sheet conductivity G_P [panels (a) and (b)], differential sheet conductivity $G_P - G_{AP}$ [panels (c) and (d)] and GMR ratio $[G_P - G_{AP}]/G_{AP}$ [panels (e) and (f)] of Co- and $Ni_{80}Fe_{20}$-based structures consisting of 500 Å NiO/F1/NM1/F2/NM2/100 Å NiO, with NM1 = 20 Å Cu, NM2 = 12 Å Cu, the ferromagnetic layer F1 fixed at 20 Å, and a variable thickness of the ferromagnetic layer F2. In the left panels F1 and F2 refer to Co, the right panels refer to $Ni_{80}Fe_{20}$. The data are obtained at $T = 300$ K (●) and $T = 10$ K (□). Low-temperature data (×) of FeMn-exchange biased all-metal spin-valves (Ref. 11) of the type 30 Å Ta/*t* Co/30 Å Cu/20 Å Co/100 Å FeMn/20 Å Ta are included for comparison. All the curves in the figure are guides to the eye only.

ratio will not exceed a factor of 2.[1,2] Furthermore, our data are consistent with the observation by Anthony *et al.* of large GMR ratios in $Ni_{80}Fe_{20}$/Co/Cu/Co/$Ni_{80}Fe_{20}$ spin-valves grown on NiO. Egelhoff *et al.*[8] reported a GMR ratio exceeding 21% at room temperature in symmetric Co/Cu/Co/Cu/Co spin-valves sandwiched between NiO, but in both cases the spin-engineered structures are too much different from our spin-valve design, which complicates a straightforward and meaningful comparison with the present data. In the following we will specifically evaluate the Co/Cu/Co data and focus on the physical mechanism behind unusually large GMR ratios observed in this type of spin-valve. The results of the Permalloy-containing spin-valves will be presented in greater detail in a separate paper.[9]

INTERPRETATION

It is obvious that the description of electron channeling within the metallic part of the spin-valves [see Fig. 1(a) at far right] requires a treatment in which the potential step at the insulating barrier is included. Since we are outside the regime of quantum-size effects ($k_F^{-1} \ll L$, with L the potential width) and quantum-interference effects ($k_F^{-1} \ll \lambda$, with λ the mean free path), we may in this respect safely adapt[13] semiclassical theories based on the extension of the Fuchs-Sondheimer model.[14] Moreover, it was shown recently[15] that an exact quantum-statistical calculation based on the Kubo-Greenwood linear-response formula agrees well with a modified semiclassical theory over all ranges of layer thicknesses and mean free paths in thin films and multilayers, provided that the aforementioned quantum corrections are absent. Therefore, we feel confident to restrict ourselves in this paper to a simplified semiclassical calculation based on the Fuchs-Sondheimer extension of the Boltzmann equation,[14] that was solved initially by Camley and Barnas[3] for the analysis of GMR in magnetic metallic multilayers, and supplemented thereafter with potential scattering at the interfaces by Falicov and Hood.[6] In their view, the spin-dependent potentials V_m, V_M, and the spacer potential V_s, as shown in the top panel of Fig. 1 at far right, may be an important source for giant magnetoresistance in Co/Cu/Co trilayers[6,16] due to the channeling effect within the Cu spacer that is effectuated when V_s is larger than both V_m and V_M. However, our main goal here is to consider most transparently the effect of the *dominant* potential step that is located at the interfaces between insulating NiO and the adjacent metallic spin-valve, and thus we assumed a constant potential within the metal part of the structure, $V_m = V_M = V_s$. The insulating NiO is expected to be the source for electron reflectivity, since it is well known that an electron wave function impinging on such a barrier potential [where $V > E_F$, see Fig. 1(a)] cannot effectively penetrate into the barrier and only tunneling may occur with no net transmission, which, in terms of the reflectivity corresponds to full specular reflection of all electrons. Now the description of our structures is in fact identical as used originally by Camley and Barnas,[3] in which R is the reflectivity and the remainder of the electrons is diffusively scattered at the barrier ($D = 1 - R$), since the transmission T is essentially zero. With this model we have calculated the magnetoresistance of NiO/F1/NM1/F2/NiO with F1 = 20 Å Co and NM1 = 20 Å Cu, as a function of the layer thickness of F2 for three cases of the barrier reflectivity R at NiO/F1 and F2/NiO insulator/metal interfaces: (1) $R = 0$ that represents perfectly diffusive scattering when electrons that strike the barriers lose all memory of their previous velocity, (2) $R = 1$ representing full specular reflectivity ($D = 0$), and (3) an intermediate situation $R = \frac{1}{2}$ where half of the electrons reflect and the remaining part is diffusively scattered ($D = \frac{1}{2}$). With increasing specular reflectivity R the shape of the magnetoresistance curve is significantly changed, and generally speaking, the maximum in the GMR ratio is pushed to a lower ferromagnetic thickness. Most importantly, the reflectivity induces a dramatic enhancement of the GMR ratio, which is a common feature in semiclassical calculations when a trilayer system is compared with an infinite multilayer[1,2,17] that in fact represents a trilayer buried within infinite potentials.

When we focus on the enhancement of the GMR ratio this may be understood easily from the right panel of Fig. 3 in which the trajectory of a spin-up electron is schematically drawn. In sandwiches the differential conductivity

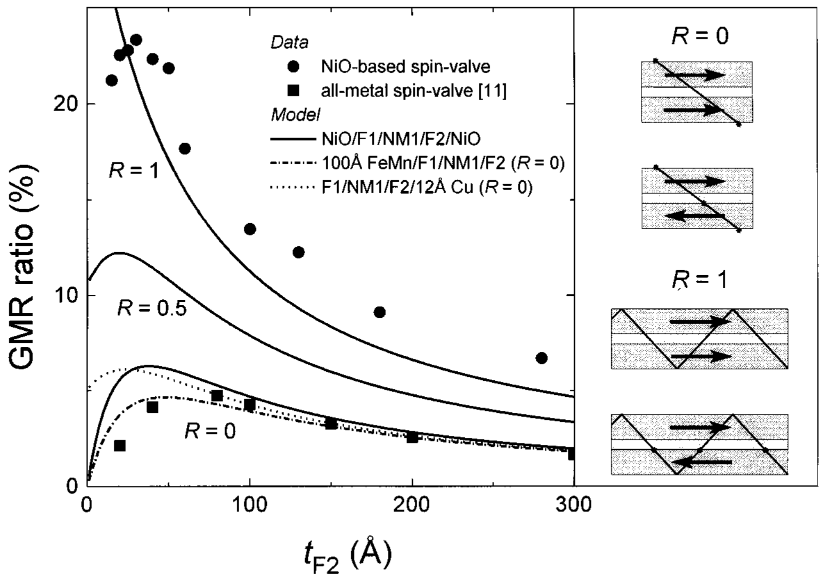

FIG. 3. In the left panel the solid curves represent the calculated GMR ratio of a model system NiO/F1/NM1/F2/NiO with F1 = 20 Å Co, NM1 = 20 Å Cu, as a function of the ferromagnetic layer thickness of F2, for $R=0$, 0.5, and 1, i.e., the reflectivity at the insulator/metal interfaces NiO/F1 and F2/NiO. The dashed-dotted curve represents a model system 100 Å FeMn/F1/NM1/F2 with F1 = 20 Å Co, NM1 = 20 Å Cu, $\lambda=12$ Å estimated from the mean free path in FeMn (Ref. 11), and with diffusive scattering at the outer boundaries $(R=0)$. The dotted curve represents a system F1/NM1/F2/NM2, again with F1 = 20 Å Co, NM1 = 20 Å Cu, and diffusive boundary scattering $(R=0)$, and with NM2 = 20 Å Cu. For comparison the low-temperature data of all-metal Co/Cu/Co spin-valves are included (■, Ref. 11) together with the data obtained in our stacks (●), see also Fig. 2. The parameters used for the semiclassical calculations are $R_M=0$, $T_M=1$, $R_m=0$, $T_m=0.2$ for the Co/Cu interfaces, $\lambda_M=80$ Å, $\lambda_m=20$ Å for the spin-dependent mean free paths in Co, and $\lambda_{Cu}=200$ Å. Note that these parameters are close to those used by Dieny *et al.*, see Ref. 10. In the panel at right the solid lines represent the trajectory of a spin-up electron, stars (⋆) indicate scattering events. It is shown that the conductivity in parallel configuration is dramatically enhanced when diffusive boundary scattering $(R=0)$ is replaced by specular reflectivity $(R=1)$. For a more detailed explanation see the text.

G_P-G_{AP} is considerably reduced by spin-independent boundary scattering, corresponding to $R=0$ (see the top of the sketch). When the reflectivity of the electron is unity $(R=1)$ the spin-up electron in the parallel configuration may experience its full bulk mean free path before being scattered and is thereby able to induce a significant increase of G_P. In contrast, no substantial increase of conductivity is expected in the antiparallel case (G_{AP}) since the "lifetime" of a spin-up electron is still to a great extent limited although now by spin-dependent scattering. This explains the enhanced difference between the conductivity in the parallel and antiparallel states when a spin-valve is confined within reflective barriers. Quantitatively, the actual enhancement of the GMR ratio induced by electron reflectivity at the outer boundaries of the trilayer depends very much on the (spin-dependent) parameters chosen in the calculations. As an example, when the mean free path of the carriers is small compared to the ferromagnetic layer thicknesses the enhancement is only very modest, whereas with increasing scattering lengths it may become arbitrarily large. In the calculations presented in Fig. 3 the maximal attainable GMR ratio is enhanced by at least a factor of 4 when choosing a set of parameters in the range of what has been reported previously in sputtered Co/Co/Co spin-valves.[10] Subsequently, the calculations are compared with the experimental data for Co/Cu/Co spin-valves (see again Fig. 3) obtained at low temperatures, that is the limit to which the semiclassical calculation applies when no spin-mixing terms are taken into account.[3] It is clearly seen that the data for FeMn are fairly close to the situation with no reflectivity at the surfaces, $R=0$, whereas in the present NiO-based material a nonzero reflectivity seems indispensable to predict a considerable higher GMR ratio observed at a smaller ferromagnetic layer thickness. We would like to emphasize that although it is not our aim in this paper to pursue *quantitative* description of the observed magnetoresistive enhancement, the data can be simply understood by the introduction of reflectivity at the insulating barrier. Moreover, it is gratifying that a fair agreement with the data (*with* and *without* the insulating barrier) has been established by using a set of parameters close to reports in literature,[10] see the caption of Fig. 3. We like to mention however that the apparent agreement may be somewhat fortuitous as we will see in the discussion of the specular reflectivity later on.

It should be noted at this point that one may argue that even without reflectivity of electrons $(R=0)$ the impenetrable NiO prevents any shunting of current through subsidiary layers (such as FeMn in the metallic case) and may result in an effective enhancement of the GMR ratio. To calculate the role of current shunting we have applied the semiclassical approach to a model system representative for the aforementioned exchange-biased all-metal spin-valves, viz. 100 Å FeMn/F1/NM1/F2, with F1 = 20 Å, and NM1 = 20 Å, assuming diffusive scattering at the outer boundaries (which in fact corresponds to $R=0$). The low-temperature mean free path of FeMn is estimated as $\lambda=12$ Å.[11] The calculated dashed-dotted curves in Fig. 3(c) represent the GMR ratio of this structure and apparently no great reduction due to shunting via FeMn can be expected. Parenthetically we note that a reduced GMR ratio in FeMn-based spin-valves can also (partially) be understood if spin-flip (magnon) scattering is present in the antiferromagnetic part of the stack, which is obviously absent in the case of the impenetrable NiO. Additionally, one should realize that the nonmagnetic layer at the outer surface of the spin-valve trilayer, NM2 [see Fig. 1(a)], also contributes to $G_{\mathrm{P}}-G_{\mathrm{AP}}$, and hence the GMR ratio. However, we estimated from a calculation of the model system F1/NM1/F2/NM2, again with F1 = 20 Å, NM1 = 20 Å, $R=0$, and with NM2 = 12 Å Cu according to our actual spin-valve design, that this does not affect the maximal attainable GMR ratio, see the dotted line in Fig. 3(c). Only this maximum occurs at a smaller magnetic layer thickness of F2 due to the fact that the outside nonmagnetic layer effectively enlarges the regime that contributes to the differential sheet conductivity $G_{\mathrm{P}}-G_{\mathrm{AP}}$. Summarizing the semiclassical calculations presented here, we find strong indication for the presence of increased reflectivity at an insulating NiO barrier since without specular reflections a description of the data obtained in these spin-valves seems impossible.

DISCUSSION

One of the drawbacks of the application of the semiclassical Boltzmann equation, is the fact that it is not designed to predict *ab initio* the magnitude of the giant magnetoresistance in a specific artificial magnetic structure. It would be much more favorable when straightforward evidence for the presence of enhanced reflectivity of the confined electrons in our structures could be obtained. In this respect, the conductivity of a single thin film, that is limited by diffusive scattering at the outside (rough) surfaces, should inevitably increase when the electrons are channeled by sandwiching the film within reflecting barriers. In view of this, we have measured the sheet resistivity of single Co layers (with thicknesses in between 10 and 100 Å) on top of a 500 Å NiO layer and capped with Cu to avoid oxidation of the Co, as shown by the open squares in the top panel of Fig. 4. A magnetic field was applied during the measurement to obtain a reproducible saturated magnetic state of the ferromagnetic Co. We expect that the outside Cu interfaced to air is nonreflective for the conduction electrons due to contamination and oxidation after growth. When this system is compared with a Co layer capped with a second top NiO layer, which in fact symmetrically confines the Co conduction electrons within insulating barriers, we found an *increase* of the sheet resistance (see again the figure), opposite of what one would expect when reflections at this top NiO interface were important. Although it would be possible to unravel the origin of the apparent lack of reflectivity in these specific structures, it was more obvious to test the role of the top NiO layer also in the actual spin-valve structures, which for this purpose were designed with and without a capping NiO layer in one series of sputter-deposited samples. Again we did not find evidence for specular scattering of electrons at the *top* NiO layer from the observation that the GMR ratio is not significantly affected, see the data in Fig. 4(b).[18]

The absence of specularity of the top NiO layer may be rather confusing in view of the reflectivity proposed in the foregoing paragraphs and one would be tempted to test the role of this bottom NiO as well just by removing the bottom NiO and monitor the impact on the GMR. This layer is however the key element to our spin-valves, and when removed, the AP magnetic state will be absent and no magnetoresistance will be left. Nevertheless, it should be emphasized that the apparent absence of reflectivity at the top barrier cannot be simply extrapolated to the bottom barrier due to several reasons. To start with, from XRD we have observed that NiO grown at room temperature, which in fact is the growth condition of NiO on top, does not yield a well-defined texture [(111) and (200) Bragg reflections were observed] and this may actually lead to a loss of interface quality. Hence, the interface reflectivity may be rather poor and, e.g., semiclassical calculations[19] have predicted that progressive roughening of the interface (beyond a few Å) reduces the GMR ratio irrespective of the details of the potential landscape of the spin-valve or multilayer. In contrast to the top NiO, the bottom NiO layer was grown at 200 °C temperature to obtain a

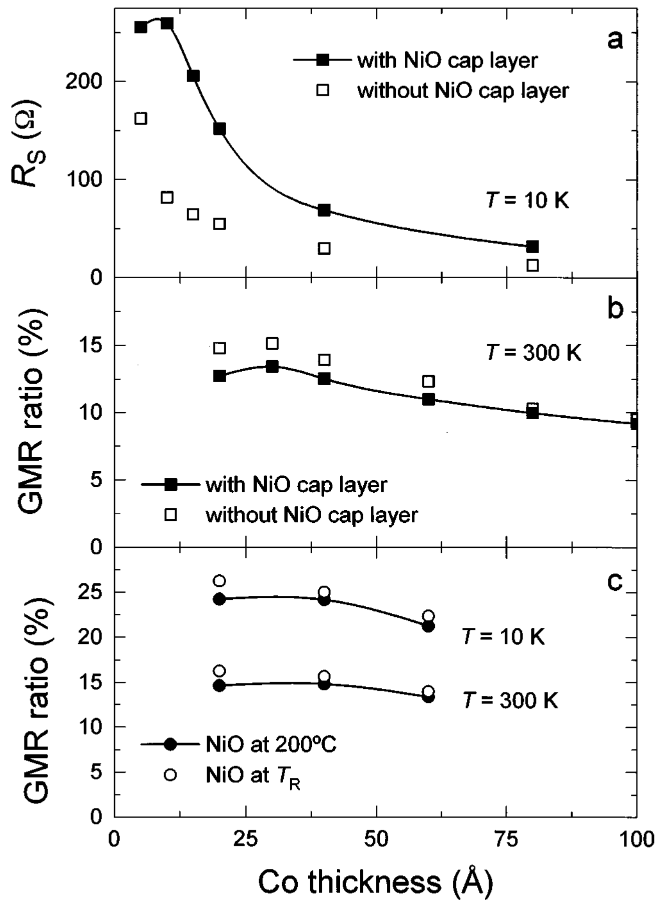

FIG. 4. (a) Low-temperature sheet resistance R_s of 500 Å NiO/t Co/100 Å NiO/30 Å Cu (■) and 500 Å NiO/t Co/30 Å Cu (□). The data do not support reflectivity at the Co/NiO interface. (b) GMR ratio of 500 Å NiO/20 Å Co/20 Å Cu/t Co/12 Å Cu/100 Å NiO, (●) and 500 Å NiO/20 Å Co/20 Å Cu/t Co/12 Å Cu taken at $T=300$ K (□). Reflectivity at the top Cu/NiO interface is also in this case not evidenced. (c) GMR ratio at $T=10$ K and $T=300$ K of 500 Å NiO/20 Å Co/20 Å Cu/t Co/12 Å Cu/100 Å NiO, in which the bottom 500 Å NiO layer is grown at 200 °C (●) and ambient temperature (○), yielding no substantial difference in magnetoresistance.

(111) texture, which might have a positive impact on the interface quality. We tried to affect the structural properties of the interfacial NiO/Co region by growing one series of samples of both 200 °C and room temperature. Although we observed that the (111) texture is present only when the bottom NiO is grown at elevated temperatures this does not change the GMR properties,[18] which is exemplified by the data presented in Fig. 4(c). In the room-temperature grown samples even a slight enhancement of the GMR ratio is observed, which means that the presence of reflectivity may not be concluded from this type of experiment and it is conceivable that diffusion between, e.g., NiO and Co may be a relevant factor for the observed behavior in Fig. 3(c). More detailed experiments are in progress to unravel the relation between the growth parameters of the NiO and the corresponding giant magnetoresistance effect.

Another explanation for the absence of a reflective top NiO layer may be the fact that the top NiO layer is grown on nonmagnetic Cu whereas the bottom NiO is directly interfaced with a ferromagnetic layer. Hypothetically, it might be the magnetic character of the interface between the oxidic antiferromagnetic NiO and the ferromagnetic Co that is most favorable for reflectivity of the electron wave function. In fact, the scattering of electrons impinging on an antiferromagnetic oxide may be profoundly affected by the spin dependence of the electron lifetime in ferromagnetic materials. No experimental data or theoretical models are yet available, and this certainly requires further investigation. We intend to address this experimentally by replacing NiO by CoO, since the Néel temperature of the latter is around room temperature, whereas NiO orders at a much higher temperature ($T_N \approx 250$ °C). This means that with CoO it would be possible to monitor the (spin-dependent) scattering at barriers in the antiferromagnetic state of CoO below room temperature, but also when CoO is paramagnetic at higher temperatures, which might yield some clues about the underlying fundamental mechanism.

In the discussion about possible reflections at insulating NiO we should not forget to mention one final point of interest which also focuses on structural aspects. In all-metal spin-valves[1,2] the trilayer is grown often on a thin metallic buffer layer [e.g., 20 Å Ta (Ref. 11)] to improve the texture, and thicker buffer layers are avoided to prevent considerable shunting of the current that effectively suppresses the GMR ratio. In contrast, the NiO we use as a base layer is in all cases relatively thick (500 Å), which is not disadvantageous in view of shunting due to its insulating behavior, but on the other hand it might improve the structural integrity of the subsequently grown stack. It is however rather difficult to address this experimentally since a thick NiO layer is indispensable for the required exchange biasing of the first ferromagnetic layer. ^{59}Co-NMR experiments will be used to investigate the local structure of Co and possibly also the topology of its interfaces with neighboring Cu and NiO in more detail.

A final comment concerns the ferromagnetic layer thickness at which a maximal GMR ratio is observed ($t_{F,\max}$) in both our structures (see Fig. 2) and the symmetric structures of the type 500 Å NiO/t_2 Co/18 Å Cu/t_1 Co/18 Å Cu/t_2 Co/NiO studied by Egelhoff *et al.*[8] The latter authors argued intuitively that an independent variation of t_1 and t_2 might be a fingerprint for the relevance of specular reflectivity. More precisely, it was suggested that in their case only some fraction of the electrons scatter specularly, since the optimum thickness of the center Co ($t_{1,\max}$) is somewhat less than twice that of the top and bottom Co layers ($t_{2,\max}$). However, our semiclassical transport calculations applied to these symmetric spin-valves do only partially corroborate this intuitive model. It appears that the location of the maxima is determined by a delicate balance between interface and bulk spin-dependent scattering (SDS) and is certainly not simply a factor of 2, although in general it follows from the calculations that $t_{2,\max}$ is *always smaller* than $t_{1,\max}$. But most interestingly, we found that without reflectivity, i.e., diffusive scattering at the outer boundaries of t_2, the situation is completely reversed, viz. $t_{2,\max}$ is *larger* than $t_{1,\max}$, since the thickness of the outside layers t_2 should be at least of the order of the bulk mean free path to avoid the negative effect of boundary scattering on the GMR ratio. The experimental observation by Egelhoff *et al.* ($t_{2,\max} < t_{1,\max}$) may thus be regarded as a straightforward additional proof for the presence of specular reflectivity in NiO-based spin-valves. In our structures with only two ferromagnetic layers such an argument is inappropriate and consequently it appears that $t_{F,\max}$ is not simply indicative for the presence of specular reflectivity. That would require a detailed fitting procedure of solutions by the semiclassical transport equation to the experimental data, which is far outside the scope of the present paper and would certainly not yield unambiguous conclusions on the role of reflections. Nevertheless, we like to mention that calculations for our system with two ferromagnetic layers do predict that when diffusive boundary scattering is replaced by reflective barrier scattering, $t_{F,\max}$ will be located at a *smaller* layer thickness. This is consistent with our observation that $t_{F,\max}$ in the NiO structure is considerably less (20–40 Å) than commonly seen in conventional FeMn-based spin-valves[10,11] where $t_{F,\max}$ is always more than 50 Å.

SUMMARY

To summarize, we have presented experimental evidence for enhanced magnetoresistivity in spin-valve trilayers contained within insulating barriers of antiferromagnetic NiO. From semiclassical transport calculations we have found indications that this enhancement is induced by reflectivity of electron waves at the insulator/metal interface. In particular, the bottom NiO/Co interfaces are expected to play a key role in the observed increased giant magnetoresistance in the NiO-based spin-valves.

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