Giant magnetic broadening of ferromagnetic resonance in a GMR Co/Ag/Co/Gd quadlayer.

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Both magnetic-resonance damping and the giant magnetoresistance effect have been predicted to be strongly affected by the local density of states in thin ferromagnetic films. We employ the antiferromagnetic coupling between Co and Gd to provide a spontaneous change from parallel to antiparallel alignment of two Co films. A sharp increase in magnetic damping accompanies the change from parallel to antiparallel alignment, analogous to resistivity changes in giant magnetoresistance.

The discovery of giant magnetoresistance (GMR) by Baibich et al. has led to important applications in magnetic recording and data storage. Nonetheless, a fundamental understanding of the microscopic mechanism remains a subject of continuing research. Early work considered spin-dependent scattering to be the primary mechanism for GMR effects, and indeed such scattering can considerably enhance them. However, Schep, et al. were the first to demonstrate that significant GMR (for currents perpendicular to the magnetic layers (CPP) at least) is possible in a perfect magnetic superlattice, a consequence of s-d hybridization and resultant differential localization of electronic states between parallel (P) and antiparallel (AP) alignment. The same quantum-well states strongly modify the effectiveness of scatterers at the interface, thereby contributing to GMR for in-plane currents (CIP) as well. The aim of this paper is to provide independent evidence for substantial changes in the local density of states accompanying a transition from P to AP alignment. Exploiting the strong antiferromagnetic coupling between Co and Gd, we fabricated a GMR structure that spontaneously reverses the relative orientation of two Co layers as the temperature is reduced. Upon reversal from P to AP alignment, the width of the ferromagnetic resonance line of the free Co layer sharply changes its temperature dependence. We interpret these results in the context of the so-called torque-correlation model of ferromagnetic damping, applicable to Co, in which the linewidth is directly related to the local density of states; by analogy, we term the increased broadening Giant Magneto-Broadening (GMB).

We have prepared a trilayer structure of Co/Ag/Co with an underlying Gd layer; the Ag layer is sufficiently thick that there is no exchange coupling of the two Co layers. Co and Gd are strongly coupled antiferromagnetically. Above, and somewhat below, the Curie temperature of Gd, the two Co layers are ferromagnetically aligned in a modest magnetic field. As the temperature is reduced, the magnetic moment of Gd increases. Below the compensation temperature $T_{\text{comp}}$, the Gd moment exceeds that of its adjacent Co layer, causing it to align with the magnetic field, producing AP alignment of the two Co layers. In Fig. 1, we show the low-field magnetization of a Ag(10 nm)/Co(4 nm) bilayer on Gd(10 nm). The minimum in net magnetization at $T_{\text{comp}} = 170$ K reflects the point at which the magnetization of the underlying Gd and its adjacent Co layer are equal and opposite, oriented perpendicular to the applied field. The small paramagnetic moment at $T_{\text{comp}}$ results from the canting of the opposing moments toward the applied field direction.

Multilayer samples were created at room temperature using a dc magnetron sputtering system. The base pressure of the deposition chamber was $10^{-9}$ Torr. Ultra high purity argon gas was used and the deposition pres-
sure was 3 mTorr. An in situ quartz thickness monitor, calibrated by a stylus profilometer, measures the deposition thicknesses. Samples were sputtered from pure Gd, Co and Ag targets on Si (100) substrates. Ag layers 200 Angstrom (Å) thick were used as buffer layers in all samples. The Co(1)/Ag/Co(2)/Gd multilayer was created with a 100 Å nonmagnetic Ag spacer between the two 4 nm-Co layers, thick enough to suppress any long range exchange interactions. A 100-Å Ag cap layer completed the deposition. The Curie temperature $T_C$ of the Gd thin film is 240 K, somewhat below the bulk value.

The absorption spectrum as a function of applied magnetic field for the Co(1)/Ag/Co(2)/Gd multilayer is shown in Fig. 2 at room temperature. The microwave frequency is 10 GHz and the applied field is in the plane of the sample. Two Lorentzian derivative fits are also shown in Fig. 2 to identify two different resonances. Separation of the adjacent absorption peaks can be made because, as shown previously,[12] a proximate layer of Gd reduces the field for resonance and significantly increases the linewidth of Co thin films. This leads to the conclusion that the broader resonance is associated with the Co(2) layer. Fig 3 shows the temperature dependence of the linewidth associated with Co(1) and Co(2) resonances. Above the Curie temperature of Gd ($T_C = 240$ K), both resonance lines broaden slightly with decreasing temperature. Below $T_C$, the Co(2) resonance is no longer seen while the Co(1) resonance first broadens abruptly and then continues to increase with decreasing temperature to the compensation point, $T_{comp} = 170$ K. Below $T_{comp}$, the linewidth increases much more strongly with decreasing temperature, exceeding the resonant field below 100 K.

Ferromagnetic resonance is generally treated phenomenologically via the Landau-Lifshitz-Gilbert (LLG) equation of motion,[13]

$$\frac{d\vec{m}}{dt} = -\gamma \vec{m} \times \vec{H} + \alpha \vec{m} \times \frac{d\vec{m}}{dt}. \tag{1}$$

where $\vec{m}$ is the reduced magnetization vector, $\gamma$, the gyromagnetic ratio and $\alpha$, the Gilbert damping parameter. Relaxation in metallic ferromagnet films has conventionally been attributed to the transfer of angular momentum from the precessing magnetization to the spin of the conduction electrons via s-d exchange and the subsequent relaxation of the conduction electron polarization via spin-dependent scattering.[14] More recently, attention has been focused on the so-called torque-correlation model first introduced by Kambersky.[15] In this process, the time-dependent magnetization induces charge-currents in the conduction electrons via the spin-orbit interaction. These, in turn, exert torque on the magnetization, transferring angular momentum to the lattice via the relaxation of charge currents. The longer the relaxation time $\tau$ of these currents, the greater the torque and the broader the line. For intraband transitions, Gilmore, et al.[10] have shown that

$$\alpha(T) = \frac{\gamma \tau(T)}{2\mu_0 m} \sum_{nk} |\Gamma_n(k)|^2 \left( -\frac{\partial f}{\partial \varepsilon} \right), \tag{2}$$

where $\tau$ is the orbital relaxation time of the conduction electron, $\Gamma_n(k)$ is the torque matrix element from the spin-orbit interaction, and $(-\partial f/\partial \varepsilon)$ is the negative derivative of the Fermi function. The sum is over band indices. The interplay between the two mechanisms has been discussed by several authors.[1, 16] By artificially changing the Fermi energy in their band calculations, Gilmore et al. demonstrate specifically that the summation in Eq. (2) follows the density of states for Co and other ferromagnetic metals. Note that the linewidth is related to the Gilbert parameter by $\Delta H = 1.16\omega\alpha/\gamma$, where $\omega/2\pi = 10$ GHz is the applied microwave frequency.

As seen in Fig. 3, the Co(1) linewidth gradually increases with decreasing temperature from $T_C$ to $T_{comp}$ and then increases more rapidly below; this is the GMB effect. A linewidth that increases with decreasing temperature is indicative [2] that the torque-correlation process dominates over spin damping, evidently becoming even more dominant below $T_{comp}$. In the absence of torque-correlation processes, spin-damping, which varies $\tau(T)^{-1}$, would require a mechanism that, upon reversal of the Co(2) magnetization, increases with decreasing temperature at a rate that overcomes the increase in $\tau(T)$. The band structure of the Co(1) layer, on the other hand, will change dramatically upon the transition from P to AP alignment,[7] thereby changing the den-
sity of states in the Co(1) layer. Further, Binder et al.\[3\] showed that impurities located within a Co layer in GMR structures exhibit dramatically larger relaxation rates in AP vs P alignment, again reflecting an increase in the local density of states. Impurities located at the interface between Co and Cu, in their calculation, are seven times more effective as scatterers in the AP configuration; the effect is even larger for impurities in the center of the Co layer. Similarly, the torque matrix element $\Gamma_{\alpha}(k)$, which tracks with the density of states, \[10\] should reflect the same increase in local density of states in the AP configuration. We attribute the seven-fold increase in the slope of $\Delta H(T)$ shown in Fig. 3, therefore, to an increase in the summation in Eq. (2) and consequently, to a stronger dependence on $\tau(T)$. Further, Steiauf and Fähnle\[17\] have shown, in the context of the torque-correlation approach, that band-structure effects in lower-dimensional structures dramatically increase the Gilbert parameter of Co relative to the bulk metal. We suggest that, in the single layer considered by Steiauf and Fähnle, both spin sub-bands are localized, much as in the case of AP alignment, while only one sub-band is localized in the P configuration. We conclude that the large enhancement of the temperature dependence of the linewidth that occurs at the transition between P and AP alignment, provides independent confirmation of the role of quantum confinement in GMR structures. At the same time, it provides further evidence that the torque-correlation model plays a substantial role in spin relaxation in metallic ferromagnets, especially in Co, which is nearly a half-metal. Clearly, similar experiments using Fe and permalloy, where the torque-correlation model may be less dominant, are clearly in order.

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