# Configuration and temperature dependence of magnetic damping in spin valves

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Using vector-analyzer ferromagnetic resonance, we have studied the microwave susceptibility of a Py/Co/Cu/Co/MnIr spin valve over a large temperature range (5-450 K) and as a function of the magnetic configuration. An effective magnetization and Gilbert damping constant of 1.1 T and 0.021, respectively, are found for the permalloy free layer, with no discernible variation in temperature observed for either quantities. In contrast, the pinned layer magnetization is reduced by heating, and the exchange bias collapses near a temperature of 450 K. The ferromagnetic resonance linewidth of the free layer increases by 500 MHz when the layer magnetizations are aligned in antiparallel, which is attributed to a configuration-dependent contribution to the damping from spin pumping effects. © *2011 American Institute of Physics*. [doi:10.1063/1.3638055]

## I. INTRODUCTION

The optimization of high-speed spintronic devices requires the capacity to engineer the magnetic properties of constituent elements on the nanoscale. An important property for high-frequency applications is magnetic damping, which characterizes the rate at which energy can be transferred between the magnetic system and external degrees of freedom. This parameter underlies the basic function of proposed high-frequency sensors and magnetic memories, as it limits the rate at which the magnetic system can respond to external stimuli. This question is particularly relevant for spin-torque driven magnetic multilayers for which the value of damping is a key figure of merit that determines magnetization switching thresholds and auto-oscillation instabilities.[1,2]

Unlike other important magnetic properties such as the saturation magnetization, shape anisotropy, and interlayer coupling (e.g., exchange bias), tailoring the damping parameter $\alpha$ remains a challenging problem. Some proven methods for modifying the local damping in metallic ferromagnets include doping with rare-earth elements,[3] ion mixing,[4] and ion-induced segregation.[5] However, these methods carry the risk of altering the other magnetic properties[6] and being detrimental to spin-polarized transport properties in multilayers.

One promising scheme that minimizes unwanted side-effects involves the spin-pumping effect,[7] which describes magnetic relaxation through the generation of diffusive spin-currents across a ferromagnet/normal metal interface. This effect is a nonlocal form of magnetic relaxation, as the spin-currents carrying moments away from a precessing magnetization are dissipated in metallic layers that are not immediately adjacent to the magnetic film. For example, it has been shown that appreciable effects can be seen for multilayered structures containing Pt or Pd layers that are well separated from the magnetic film by thick metallic spacers.[8,9]

For small-amplitude precession, dissipation due to spin-pumping can be described as an additional Gilbert-like term on the ferromagnetic resonance (FMR) linewidth.[10] A striking example of the nonlocality can be seen in a trilayer system comprising two ferromagnetic layers separated by a nonmagnetic metallic spacer. In such systems, it has been shown that the contribution from spin-pumping depends on the relative precessional frequencies of the magnetization in the two layers, with a strong suppression of the effect when the frequencies are equal.[11] In a similar fashion, relaxation through spin-pumping can also depend on the *relative* orientation of the magnetizations in a trilayer system. It has been proposed that such a configurational dependence for the additional damping should be more apparent for systems in which the resonance frequencies of the magnetizations are strongly unmatched, such as in a spin-valve structure where the pinned layer experiences a higher effective field than the free layer due to coupling to an antiferromagnet.[12] Under such nonresonant conditions, the role of "spin-sink" played by one ferromagnetic layer for the precessing magnetization in a second layer is greatly enhanced.

In this paper, we present an experimental study of the temperature and configurational dependence of spin-pumping effects in spin valve structures. We have employed vector network analyzer ferromagnetic resonance (VNA-FMR) to measure the high-frequency susceptibility for the free and pinned layer magnetizations, which allows for detailed characterization of the effective magnetization, anisotropy fields, and exchange bias. We find that the resonance linewidth of the free magnetic layer remains largely independent of the temperature, but exhibits a strong dependence on the magnetization orientation of the pinned layer, which suggests a strong contribution from nonlocal damping due to spin-pumping.

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## II. SAMPLES AND METHODS

The spin valve multilayers used in our study were grown by sputtering under an argon working pressure of $5.8 \times 10^{-4}$ mbar and a magnetic field of 100 mT applied in the plane of the layers. The nominal composition of the films is Si (substrate)/$SiO_2$/Ta 3 nm/Cu 3 nm/Py 2.5 nm/Co 1.5 nm/Cu 4 nm/Co 4 nm/IrMn 6 nm/Ta 3 nm. At room temperature, the free layer coercivity is measured to be 1.7 mT and the hysteresis loop indicates 24 mT as the average of the back and forth coercivities of the pinned layer. We will see that this average describes only a part of the exchange bias since the latter incorporates a large amount of rotatable anisotropy.[13] The consequence of this rotatable component is that the pinned layer magnetization partially drags the interfacial spins in some parts of the antiferromagnet, such that the amplitude of the exchange bias field is modified when the pinned layer magnetization is reversed.[14] The current-in-plane giant magnetoresistance of our spin valves is measured to be 2.1%.

The quasi-static magnetic properties of the films were studied and verified using longitudinal and polar magneto-optical Kerr effect (MOKE) magnetometry. The detailed high-frequency characterization was performed using temperature-dependent vector network analyzer ferromagnetic resonance (VNA-FMR (Ref. 15)) in the total reflection configuration.[16] In this method, the spin valve studied is inductively coupled to a microwave coplanar waveguide terminated by an open circuit. The frequency dependence of the impedance of this ensemble is used to extract the microwave magnetic transverse susceptibility spectrum of the sample, including both its real part (in-phase susceptibility $\chi'$) and its imaginary part (in-quadrature susceptibility $\chi''$). For this procedure, a reference spectrum with no magnetic signal[15] is needed in principle. In practice, we have constructed a satisfactory estimate of this reference spectrum by averaging spectra over many various field conditions and orientations. Positive $\chi''$ values indicate susceptibility levels lower than the reference. The Fig. 1 displays the representative measurement of the real and imaginary parts of the susceptibility at 43 mT and 420 K.

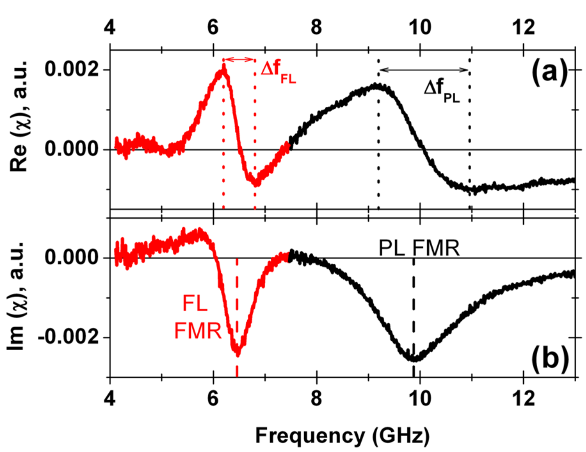


FIG. 1. (Color online) Frequency dependence of the real (a) and imaginary (b) parts of the transverse susceptibility (arbitrary units) of the spin valve at T = 420 K under an applied field of 43 mT.

At each applied field, the imaginary part of the susceptibility (Fig. 1(b)) consists of two absorption (hence negative) peaks located at the ferromagnetic resonance frequencies $f_{FMR}$ of the free and pinned layers. These absorption peaks shift in frequency with the applied field, when swept back and forth from −115 mT to +115 mT, as shown for instance in Fig. 2 for a temperature of 270 K. The strong absorption at the resonance frequency of the free layer (FL) appears as a dark trace on this spectral map, while the lighter trace at higher frequencies corresponds to the weaker absorption at the resonance of the pinned layer (PL). Note that the total susceptibility of the sample is markedly low at high frequencies (zone with bright contrast in Fig. 2) for an antiparallel configuration (AP) of the free and pinned layer magnetizations in comparison with the parallel (P) case.

Such spectra are used to extract the FMR frequencies $f_{FMR}$ at each field and each temperature from 5 K to 450 K, starting from the lowest temperature to minimize the impact of any possible in-field annealing of the exchange bias.[17] In order to extract the effective magnetization $M_{eff}$, anisotropy field $H_k$, and the exchange bias $H_{ex}$ where applicable, we use the Kittel equation to fit the field dependence on the resonance frequency for applied fields at which only one magnetic configuration is stable,

$$f_{FMR} = \frac{\gamma_0}{2\pi}\sqrt{H_{||}(H_{||} + M_{eff})}, \quad (1)$$

where $H_{||} = |H + H_{ex}| + H_k$ and $\gamma_0$ is the gyromagnetic factor. For the pinned layer resonance, we assumed $H_k = 0$ and fitted the curves only for field regions in which the pinned layer magnetization is parallel to the exchange bias (i.e., the central part of Fig. 2), such that the deduced amplitudes of the exchange bias fields incorporate the rotatable anisotropy in totality.

Finally, we use the peak-to-peak linewidth $\Delta f$ (Fig. 1(a)) of the real part of the susceptibility of each resonance

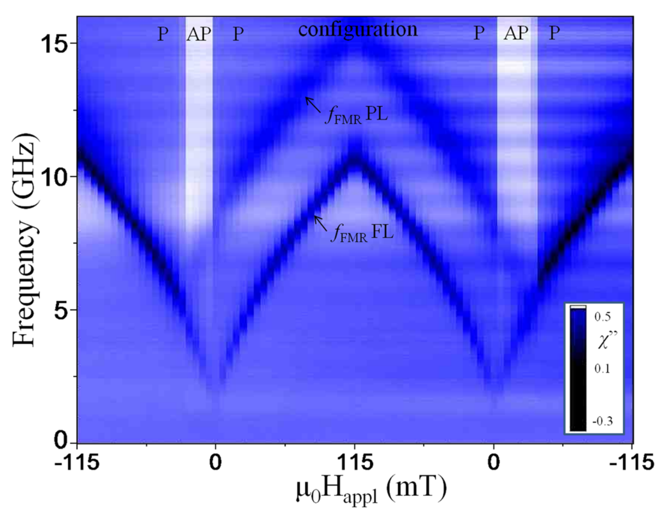


FIG. 2. (Color online) Field and frequency dependence of the out-of-phase susceptibility (arbitrary units) during an hysteresis loop, sweeping back and forth from through parallel (P) and antiparallel (AP, bright zone) orientations at 270 K. The color scale is an indication of the amount of power absorbed by the spin-valve. Note the resonance lines corresponding to the FL FMR and the PL.

mode to obtain an estimate of the effective damping parameter $\alpha_{\mathrm{eff}}$ in the layer subject to resonance. We use the fact that for Gilbert relaxation, the linewidth and damping are linked by the relation

$$\Delta f = \alpha_{\mathrm{eff}} \frac{\gamma_0}{2\pi}\left(2H_{||} + M_{\mathrm{eff}}\right). \quad (2)$$

Note that the measured resonance linewidth generally also includes extrinsic contributions, such as inhomogeneous line broadening and two magnon processes. They contribute significantly to the linewidth at low applied fields (i.e., $\mu_0 H \ll 60$ mT in our case), and lead to a linewidth incorporating a $1/H$ dependence in addition to the abovementioned applied field dependence. In order to obtain an accurate picture of the temperature dependence of the intrinsic Gilbert damping, we have only considered resonances measured for $\mu_0 H > 60$ mT to minimize extrinsic contributions.

## III. RESULTS

We begin by first considering the temperature variations of the magnetization and exchange bias in our spin valves. Over a temperature range of $T = 5$ K to 450 K, we find that the free layer magnetization (Fig. 3) remains almost constant, with a slight decrease of $\mu_0 M_{\mathrm{eff}} = 1.11$ T to 1.07 T observed. This confirms that the free layer has a Curie temperature substantially far above 450 K. On the other hand, the pinned layer exhibits a much stronger temperature dependence, where its effective magnetization is seen to decrease from 1.7 T at 5 K to 1.3 T at 450 K. This reduction is possibly associated with some mixing at the interface with the antiferromagnetic MnIr layer. Spin disorder at the interface is indeed high, which results in an exchange bias field (Fig. 3) that decreases dramatically with increasing temperature from $H_{ex} = 100$ mT at 5 K to only 30 mT at 450 K. This is consistent with the previously reported blocking temperature of ≈ 400 K for CoFe on 6 nm of MnIr (see Ref. 18, with a strong thickness dependence in that range of MnIr thicknesses. For all temperatures, the anisotropy $H_k$ of the free layer was found to be less than 2 mT (not shown).

The variation of the effective damping with temperature, for both the free layer and the pinned layer, is shown in Fig. 4. Within experimental accuracy, the free layer effective damping is temperature independent and is equal to $\alpha_{\mathrm{eff}} = 0.021 \pm 0.002$. This observation is consistent with previous work[19] and can be attributed to the fact that the main channels of carrier scattering[20] (alloy disorder and nonspecular reflection at disordered interfaces) and the spin-orbit coupling are almost temperature independent. However, we would like to highlight the fact that the magnitude of the Gilbert damping constant measured is much larger than that measured in single layer films of similar thickness.[21,22] As we shall discuss in more detail later, this additional contribution is attributed to spin-pumping effects. In contrast, larger variations of the effective damping with temperature are observed for the pinned layer. As the temperature increases, $\alpha_{\mathrm{eff}}$ varies from 0.035 at $T = 100$ K to $0.031 \pm 0.002$ at 450 K, which represents a variation that closely mirrors that for the exchange bias. This behavior is consistent with previous studies where a strong correlation between the pinned layer damping and the exchange bias is seen.[23]

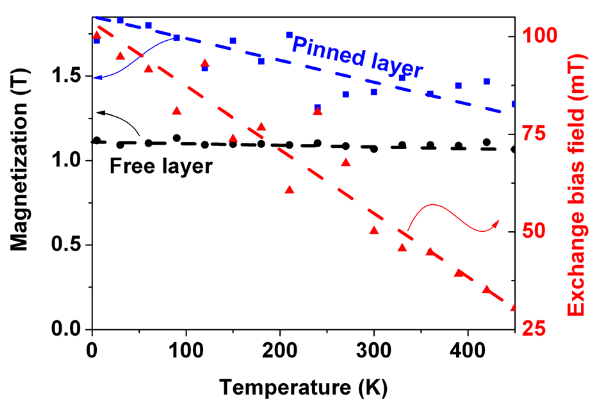


FIG. 3. (Color online) Temperature dependence of the effective magnetization of the free layer (circles) and pinned layer (squares) and exchange bias field (triangles) when the pinned layer magnetization is parallel to the exchange bias field. The dashed lines are guide to the eye.

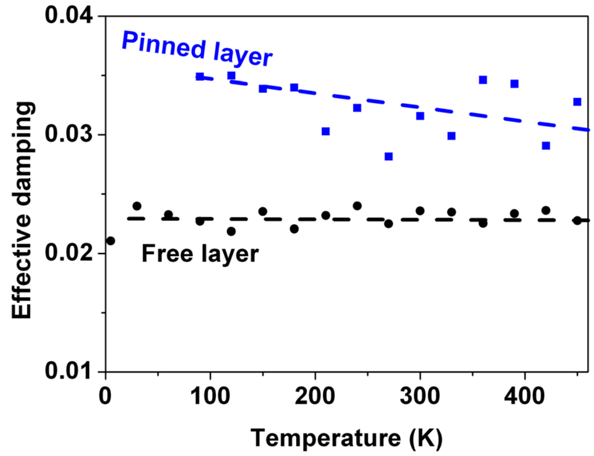


FIG. 4. (Color online) Temperature dependence of the effective damping parameter of the free layer (square symbols) and the pinned layer (circles).

While damping in the free layer is quite insensitive to temperature variations, it strongly depends on the magnetic configuration of the spin valve. An illustration of this behavior can be seen in Fig. 5, where we show a representative FMR linewidth variation of the free layer during a hysteresis loop sweep at 30 K. Since the free layer magnetization switches in near zero field and the pinned layer magnetization switches near the exchange bias field, there is a field interval in which the magnetization of the two layers are aligned in AP. Because of coercivity, this field interval is slightly larger for the decreasing field branch (i.e., from 115 to −115 mT) than for the increasing field branch. A striking observation is that the free layer FMR linewidth is substantially larger in the AP configuration than in the parallel (P) configuration. Indeed from a mean value of 800 MHz in the P state, $\Delta f$ increases to typically 1300 MHz in the AP state. This increase is strongly suggestive of a nonlocal contribution due to spin pumping and is consistent with previous observations where no configurational dependence was seen for magnetic tunnel junctions.[24] Within experimental accuracy, we can conclude that the difference in linewidth between the AP and P states is not temperature dependent

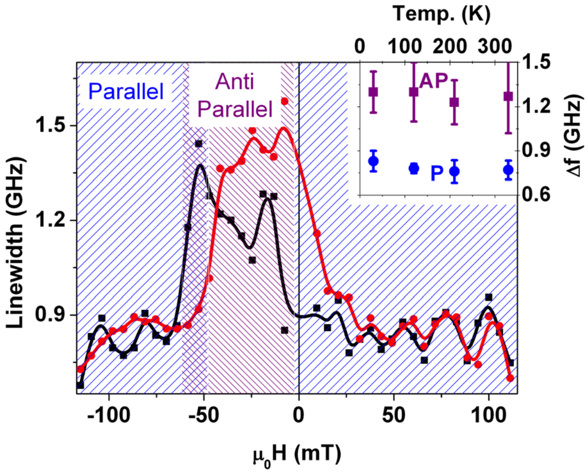


FIG. 5. (Color online) Plot of the FMR linewidth of the free layer vs the applied field at 30 K. The applied field is swept from −115 mT to 115 mT (circles) then back to the negative values (squares). In the range from −65 to 0 mT, the spin-valve is in the antiparallel state. Lines are guide to the eye. Inset: temperature dependence of the average of the linewidth in the parallel state (circles) and in the antiparallel state (squares). The error bars illustrate the standard deviations of data.

between 30 and 330 K (see inset of Figure 5). Above 330 K, the FMR peaks for the free and pinned layers are too close in frequency in the AP configuration to allow the individual linewidths to be extracted in any meaningful way.

## IV. DISCUSSION

We argue that the configuration-dependent linewidth observed cannot arise from the standard form of Gilbert damping. One extrinsic contribution to the FMR linewidth can be attributed to inhomogeneous broadening, which can be seen in the linewidth increase for applied fields under 15 mT in the P state (Fig. 5). However, there are no physical grounds on which we can exclude this contribution in the AP state, so it cannot give rise to a configuration-dependent damping term. In any case, the contribution due to inhomogeneous broadening is too small to explain the difference in linewidth between the P and AP states.

As discussed briefly above, nonlocal damping due to the spin-pumping effect represents a plausible source of the configuration-dependent damping. In this picture,[7] the precessing magnetization in a ferromagnetic emits a diffusive spin current into an adjacent metallic layer. The emitted spin current propagates in a direction perpendicular to the film plane and carries away a spin orientation that is parallel to the dynamic part of the precessing magnetization.[11] The magnetic moment carried away by the spin current is eventually diffused in a "spin-sink," which can consist of normal metal with large spin-orbit coupling (such as Pt), or another ferromagnetic material. This "spin-sink" effect effectively reduces the lifetime of the precessional mode and therefore contributes to an enhancement of the FMR linewidth.

For significant spin current absorption to occur in the metallic spacer, the spacer thickness must exceed the spin diffusion length in that material. Since the thickness of our copper spacer is only 4 nm, i.e., much smaller than the mean free path (typically 15 nm at 290 K),[25] the spin currents traverse the copper spacer almost ballistically; we can suppose therefore that they reach the interface of the other magnetic layer without any significant scattering. In the P and AP states of the spin valve, the dynamic magnetization in each layer is always purely transverse to the magnetization of the other layer. Through spin transfer torque, the spin vector carried by the spin current emitted by one layer is thus perfectly absorbed by the other layer, which results in a dynamic coupling through mutual "spin pumping."[26,27]

To see the effect of spin-pumping on the free layer dynamics, it is necessary to consider the total dynamic spin vector due to both the emitted and absorbed spin current.[11] If the magnetizations of the two layers precess with the same rotation sense (parallel case), the two counter-propagating spin currents carry spin vectors that have a mutual orientation that is *constant* in time. At each time instant, the total spin vector seen by the free layer is the difference of the counter-propagating spin vectors, such that there is partial cancellation. This is sketched in Fig. 6, where we have chosen to plot the dynamic magnetizations for a pumping field of frequency $f_{\mathrm{pump}}$ below the FMR of the two layers. In this specific case, the dynamic magnetizations are in phase with the exciting field. In that very specific condition where $f_{\mathrm{pump}} < f^{\mathrm{PL}}_{\mathrm{FMR}}, f^{\mathrm{FL}}_{\mathrm{FMR}}$, the cancellation of the spin currents would be complete is the layers possessed the same susceptibilities and thicknesses. However, the situation is different for the antiparallel orientation. In this state, the dynamic

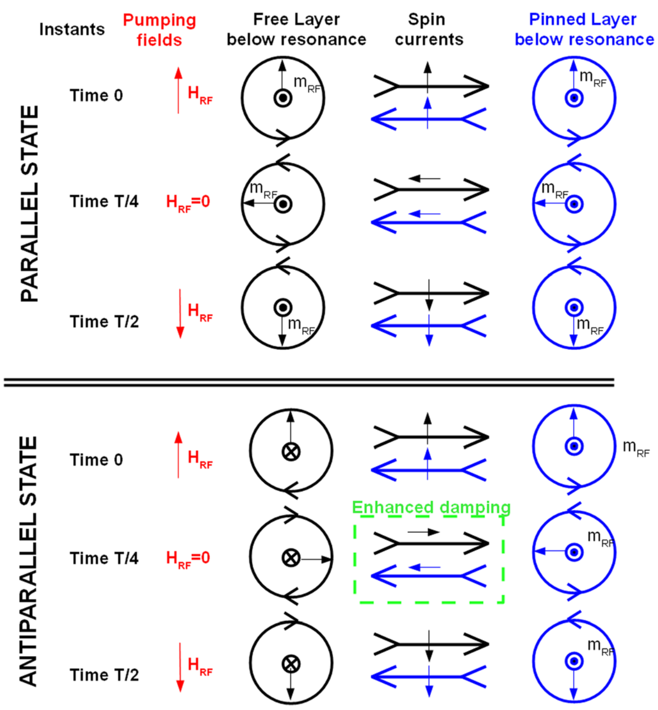


FIG. 6. (Color online) Qualitative description of the influence of the configuration (P or AP) on the spin pumping damping. The free and pinned layers static magnetization are denoted by the ingoing or outgoing arrows. $m_{RF}$ are the dynamic magnetization components induced by the pumping fields $H_{RF}$ of period T. The horizontal arrows with V-shaped ends illustrate the spatial direction of the spin currents emitted as done in Ref. 11, while the little arrow that they carry stems for the transported spin direction, which is parallel to the dynamics magnetization in the emitted layer. Note that in most situations there is a partial cancellation of the two spin currents, except half of the time in the AP state, as emphasized by the rectangle in dashed line.

magnetization of the two layers rotate in *opposite* senses, such that the two counter-propagating spin currents carry spin vectors that rotate in opposite senses; the total spin vector *varies* in time and almost never cancels. It leads to a dynamic coupling between the two layers that damps the magnetization motion, which leads to a broadening of susceptibility peaks (see the highlighted area in Fig. 6 at a fourth of the period of the exciting field).

Let us evaluate numerically whether this phenomenon can quantitatively describe the difference in the susceptibility linewidth between the P and AP configurations. Following Ref. 10, the maximum contribution of spin pumping to the damping can be written as

$$\alpha_{SP} = \frac{1}{4\pi}\frac{g\mu_B}{t_{FL}M_S}\Re(A^{\uparrow\downarrow}), \qquad (3)$$

where $A^{\uparrow\downarrow} \approx 4\times10^{19}\ \mathrm{m}^{-2}$ is the complex spin-pumping conductance per unit area for Co/Cu.[28] $\mu_B$ is the Bohr magneton and $t_{FL}$ =4 nm is the free layer thickness. Application of Eq. (3) yields a maximum increase of damping resulting from spin pumping as $\alpha_{SP} = 0.016$. Converted into a linewidth, this corresponds of a maximum increase of 490 MHz. This figure is compatible with our experimental observations, where the AP linewidth is typically 500 MHz greater than the linewidth in the P state.

Our assertion is also supported by the temperature dependence of the linewidth. According to Eq. (3), any temperature variation in the spin-pumping term would predominantly arise from the saturation magnetization of the free layer, which we have shown to remain almost constant between 5 and 450 K (Fig. 3). As such, the spin-pumping contribution to the linewidth is not expected to strongly depend on the temperature, which is consistent with our measurements.

## V. CONCLUSION

We have measured the temperature dependence of the magnetic properties of a Py/Co/Cu/Co/MnIr spin valve from 5 K to 450 K. The magnetization and the damping of the free layer are almost independent of the temperature, being 1.1 T and 0.021, respectively. The exchange bias decreases by a factor of three in this temperature interval from 100 mT to 30 mT, while the pinned layer magnetization is reduced by a quarter, from 1.7 to 1.3 T. The ferromagnetic resonance linewidth of the free layer when the magnetic layers are antiparallel to each other is greater by 500 MHz than when in the parallel orientation, which can be described as a configuration dependent damping contribution of 0.016. The order of magnitude of this increase is in agreement with an additional relaxation channel due to spin pumping.

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