Interface, Volume, and Thermal Attenuation of Hot-Electron Spins in $Ni_{80}Fe_{20}$ and Co

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The relative importance of interface, volume, and thermal scattering in spin-dependent hot-electron transmission of magnetic trilayers is quantified. While interfaces produce significant attenuation (factor 2.2 per interface), the spin asymmetry is dominated by volume scattering. Extracted thermal attenuation lengths (130 Å at 300 K for $Ni_{80}Fe_{20}$) show that thermal spin-wave scattering is stronger than hitherto assumed. This suggests that spontaneous spin-wave emission, rather than the details of the spin-dependent band structure, may cause the strong filtering of minority hot-electron spins.

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When hot electrons with typical energies of a few eV above the Fermi energy are injected into a ferromagnetic thin film, the transmission depends on the electron spin. Experiments have thus far always found that the attenuation for minority spin hot electrons is significantly stronger than for majority spins [1–6], a spin-filter effect that is attributed to the spin asymmetry of the inelastic lifetime. The asymmetry is considered to be a consequence of the exchange splitting of the energy bands in a ferromagnet, such that the number of unoccupied electronic states for the hot electron to scatter into is larger for the minority spin. Although the rough trend, a reduced lifetime at higher excess energy, is observed, experiments have not shown spectroscopic features that would be expected on the basis of the band structure. For example, measurements of the inelastic lifetime of Fe using time-resolved two-photon photoemission [6] do not show inversion of the spin asymmetry at low energy, while this is expected from the electronic structure. Also, a strong peak in the minority density of states of Fe at 1.5 eV is not reflected in spectroscopic magnetotransport data obtained with a tunnel spin-valve transistor [7].

Interestingly, theory by Hong and Mills [8] identified an additional source of spin asymmetry, i.e., the emission of spin waves. While the absorption of spin waves is determined by temperature (T) via the distribution of thermal spin waves, the emission rate has two different contributions. Besides a thermal emission part (also determined by T), there is a second, larger contribution due to spin-wave emission that is independent of T and persists even at $T = 0$. The latter, nonthermal contribution, is referred to as spontaneous spin-wave emission, in analogy with light emission in optics. Spontaneous emission is allowed only for minority spins due to angular momentum conservation, thus providing a source of spin asymmetry. It was calculated to dominate the spin-asymmetry at low excitation energy (below 1–3 eV). Experimentally, the emission of spin waves by hot electrons in Fe has recently been observed by spin-polarized electron energy loss spectroscopy [9]. Moreover, spin mixing due to thermal spin-wave scattering of hot electrons was shown to be responsible for the thermal decay of the magnetic response of the spin-valve transistor [10].

Another question is whether interfaces in magnetic layered structures contribute to hot-electron attenuation and its spin dependence. This issue is particularly relevant for magnetoelectronic devices based on heterostructures of magnetic metals, semiconductors, and insulators, where interface and volume scattering plays a role. Quantifying the relative importance of interface, volume as well as thermal scattering is indispensable for a correct interpretation of spin-dependent transport and related phenomena, such as the recently observed excitations of the magnetization (precession and reversal) by injection of a spin-polarized current [5]. Unfortunately, data on hot-electron attenuation at low energies are scarce. Most notably, Rippard and Buhrman [11] have determined the spin-dependent attenuation lengths in Co thin films as a function of electron energy, yielding typical values of 21 and 8 Å around 1.5 eV for majority and minority spins, respectively. Information on the interfaces was also obtained, although the contribution of spin-polarized tunneling at the hot-electron injection surface could not be separated out. Moreover, only room temperature data were reported.

In this Letter, we report on the first quantitative study of the relative importance of interface, volume, and thermal scattering of hot-electron spins in $Ni_{80}Fe_{20}$ and Co based trilayers. While interfaces produce significant attenuation of hot electrons, we find that the spin dependence is dominated by volume scattering. Moreover, we show for the first time that the attenuation is clearly dependent on temperature, and extract the thermal spin-wave scattering length as a function of T.

Experiments are performed using a spin-valve transistor (SVT), a three-terminal device based on the spin-dependent transmission of hot electrons across the spin-valve base of a Si/metal/Si transistor [12]. The operation as well as the fabrication by vacuum metal bonding and dry and wet etching has been previously described [13]. A series of transistors were made with the same base structure Pt(30 Å)/$Ni_{80}Fe_{20}(x)$/Au(44 Å)/Co(y)/Au(44 Å), but with varying thickness x and y of the

$Ni_{80}Fe_{20}$ and Co layer, respectively. When an emitter current I_E is established between emitter and base, hot electrons are injected across the Si/Pt Schottky barrier, entering the base at an energy of ≈ 0.9 eV above the metal Fermi energy. This induces a collector current I_C between collector and base, where I_C is different for parallel (P) or antiparallel (AP) alignment of the magnetizations of the $Ni_{80}Fe_{20}$ and Co layers. The difference arises from spin-dependent scattering in the base, and the energy and momentum selection at the collector Schottky barrier (Au/Si with height 0.80 ± 0.02 eV). The magnetocurrent is defined as $MC = (I_C^P - I_C^{\mathrm{AP}})/I_C^{\mathrm{AP}}$. All data are obtained with zero bias voltage across the base-collector diode, and with a constant emitter current of 2 mA. The latter requires the emitter voltage to be adjusted when T is varied, but this has a negligible effect on the energy of the injected hot electrons.

Figure 1 shows I_C^P and I_C^{AP} (top panel) and MC (bottom panel) at $T = 100$ K, as a function of the thickness x of the $Ni_{80}Fe_{20}$ layer, keeping the Co layer thickness constant at 30 Å. For a parallel magnetic state of the spin valve, minority spins are strongly attenuated in both magnetic layers, and only majority spins contribute to I_C^P. From the exponential decay of I_C^P with thickness we thus deduce a volume attenuation length of 43 ± 3 Å for majority hot spins in $Ni_{80}Fe_{20}$. The interface attenuation for majority spins is extracted by comparing the I_C value of 169 nA for the device with $x = 0$, to the value of 78 nA obtained by extrapolation of the I_C^P data to zero thickness. The latter value is a factor of 2.2 lower, which is due to attenuation by the extra interface that is created when a $Ni_{80}Fe_{20}$ layer is inserted between the Pt and the Au layer of the base (more precisely, the factor of 2.2 represents the difference between the original Pt/Au interface, and the two new Pt/$Ni_{80}Fe_{20}$ and $Ni_{80}Fe_{20}$/Au interfaces). Note that this is the attenuation for the majority spins, as the minority spins are filtered out by the 30 Å Co layer, irrespective of their scattering at the $Ni_{80}Fe_{20}$ interfaces. The interfacial attenuation is a combination of the mismatch of the electronic states at both sides of the interface, and elastic scattering due to interface disorder, defects, etc.

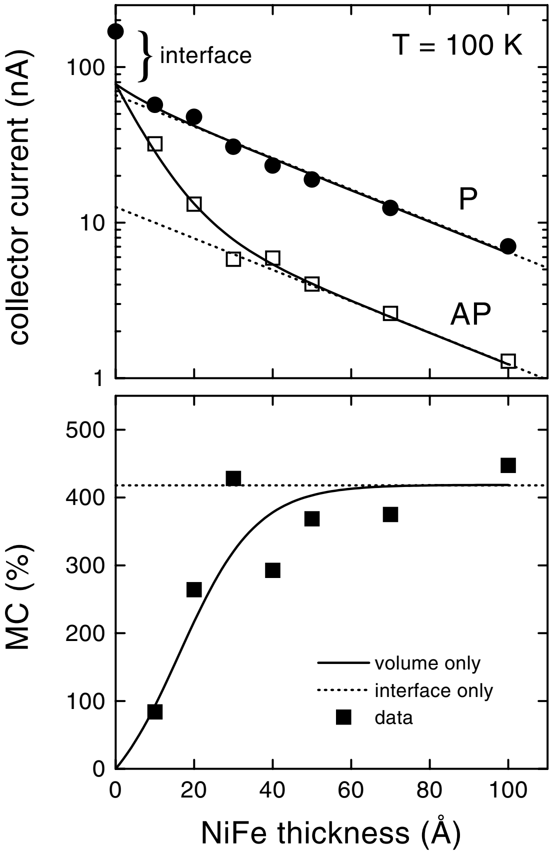

FIG. 1. I_C^P and I_C^{AP} (top panel, labels P and AP) and MC (bottom panel) at 100 K, for SVT's with various $Ni_{80}Fe_{20}$ thickness. Solid and dashed lines, respectively, represent the extreme cases with only spin-dependent volume scattering or only spin-dependent interface scattering (see text).

Information on the spin dependence of the volume and interface attenuation is contained in the difference between I_C^P and I_C^{AP}. Let us first compare the data with what is expected for two extreme cases, using similar expressions for the collector current as in Refs. [10,12]. In the first case, represented by the dashed lines in Fig. 1, all the spin dependence is assumed to arise from the interfacial scattering, while identical volume attenuation lengths are used for both spins. In that case the MC would be independent of $Ni_{80}Fe_{20}$ thickness, and I_C^P and I_C^{AP} decay with x with the same slope. The experimental data clearly deviate from this behavior at small thickness. In contrast, the data agree very well with the other extreme case (solid lines), in which the interface scattering is not spin dependent, and the only spin asymmetry is that of the volume attenuation lengths. In this situation we expect that I_C^P and I_C^{AP} approach each other as x goes to zero, such that the MC tends to zero. Note that for large x, filtering of minority spins is complete and the decay of both I_C^P and I_C^{AP} is determined by the majority spin attenuation length.

More precise analysis, taking into account the experimental error margins, shows that some weak spin dependence of the interface scattering cannot be excluded. For the ratio of the interface attenuation factor Γ for minority and majority spin we obtain $\Gamma^{\downarrow}/\Gamma^{\uparrow} = 0.8 \pm 0.2$, while volume attenuation lengths are $\lambda_{\mathrm{NiFe}}^{\downarrow} = 10 \pm 2$ Å for minority spin and $\lambda_{\mathrm{NiFe}}^{\uparrow} = 43 \pm 3$ Å for the majority spin (as determined above). With these parameters, a 30 Å thick $Ni_{80}Fe_{20}$ film attenuates minority spins a factor of 10 more strongly than the majority spins. Volume scattering is thus by far the dominant contribution to the spin dependence of the hot-electron attenuation. The most important reason is that the attenuation depends exponentially on the layer thickness. Note that we can now quantify the spin polarization of the hot electrons after filtering by the $Ni_{80}Fe_{20}$ film, yielding values of 82% for $x = 30$ Å, and 98% for $x = 60$ Å. Hot-electron spin filtering is thus an excellent candidate to achieve highly polarized spin injection into semiconductors, especially if one considers that traditional ferromagnets with small coercivity and Curie temperatures far above 300 K can be used.

Having determined the relative importance of interface and volume attenuation, we next examine the variation with temperature. Since the parallel magnetic state is defined best, we use the I_C^P data, and divide out all temperature independent attenuation factors by plotting the normalized collector current $I_C^N = I_C^P(T)/I_C^P(100\text{ K})$ (see Fig. 2). The top panel shows data for transistors with different $\text{Ni}_{80}\text{Fe}_{20}$ thickness and constant Co thickness. Starting at 100 K the collector current first goes up slightly, and then is reduced significantly towards room temperature [14]. Moreover, the variation with T is more pronounced at higher $\text{Ni}_{80}\text{Fe}_{20}$ thickness, implying that the additional attenuation at higher T is due to a thermal volume scattering process. The same behavior is observed when the thickness of the Co layer is varied (bottom panel of Fig. 2). However, the T variation for Co has weaker dependence on layer thickness than for $\text{Ni}_{80}\text{Fe}_{20}$, which shows that the thermal attenuation is stronger in $\text{Ni}_{80}\text{Fe}_{20}$ than it is in Co. This is consistent with attenuation due to scattering on thermal spin waves [15], as the Curie temperature of Co (1388 K) is larger than that of $\text{Ni}_{80}\text{Fe}_{20}$ (873 K). Although a hot electron loses only little energy in scattering with a thermal spin wave, attenuation occurs due to the transfer of momentum. This is important because momentum selection at the base-collector interface results in reflection of electrons that impinge on the interface at angles larger than a critical angle [16] (typically <10°).

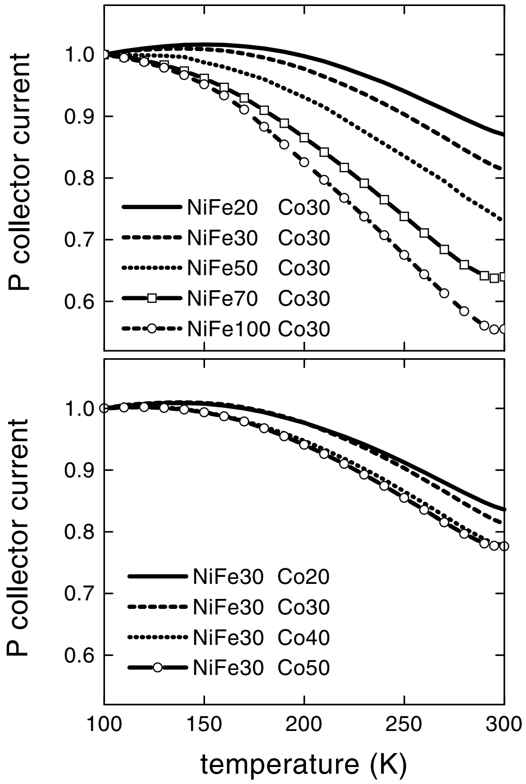

FIG. 2. Top panel: Normalized I_C^P versus T for SVT's with a $\text{Ni}_{80}\text{Fe}_{20}$/Au/Co spin valve with different $\text{Ni}_{80}\text{Fe}_{20}$ thickness and a constant Co thickness of 30 Å. Labels indicate the thicknesses in Å. Bottom panel: similar for varying Co thickness and a constant $\text{Ni}_{80}\text{Fe}_{20}$ thickness of 30 Å.

In order to extract the attenuation length $\lambda_{\text{TSW}}(T)$ due to thermal spin waves, we first use Matthiessen's rule to write the total attenuation $\lambda(T)$ at a given T as $1/\lambda(T) = 1/\lambda(0) + 1/\lambda_{\text{TSW}}(T)$. The collector current I_C^P can then be expressed as a product of T-dependent and T-independent attenuation factors:

$$\frac{I_C^P(T)}{I_C^P(0)} = \zeta_{nm}(T)\Gamma_{\text{tot}}(T)\exp\left[\frac{-x}{\lambda_{\text{TSW}}^{\text{NiFe}}(T)}\right]\exp\left[\frac{-y}{\lambda_{\text{TSW}}^{\text{Co}}(T)}\right], \tag{1}$$

where $\zeta_{nm}(T)$ denotes all T-dependent scattering factors of nonmagnetic origin and $\Gamma_{\text{tot}}(T)$ represents the total T-dependent attenuation of all the magnetic interfaces. We obtain $\lambda_{\text{TSW}}(T)$ by dividing data for two transistors that differ only in the thickness of one magnetic layer, but are identical with regard to the other layers and the interfaces. For the normalized I_C^N data of Fig. 2, the following relation applies:

$$\frac{1}{\lambda_{\text{TSW}}(T)} - \frac{1}{\lambda_{\text{TSW}}(100\text{ K})} = \frac{\ln[I_C^N(x_1)/I_C^N(x_2)]}{x_2 - x_1}, \tag{2}$$

if the thickness x_1 and x_2 are both nonzero. Although $\lambda_{\text{TSW}}(100\text{ K})$ is not known, we obtain $\lambda_{\text{TSW}}(T)$ by plotting the right-hand side of Eq. (2) versus T, and noting that it can be fitted using a power law $\lambda_{\text{TSW}}(T) = a_0 T^{\beta}$ (the exponent β is 2.2 ± 0.2). The result is then averaged over all available pairs of x_1 and x_2 (10 for $\text{Ni}_{80}\text{Fe}_{20}$ and 6 for Co).

The extracted thermal attenuation lengths for $\text{Ni}_{80}\text{Fe}_{20}$ and Co versus T are shown in Fig. 3. For $\text{Ni}_{80}\text{Fe}_{20}$ two sets of data are shown, one for the SVT, the other labeled AMT is extracted from another set of transistors with Pt(20 Å)/$\text{Ni}_{80}\text{Fe}_{20}$/Au(44 Å) base. As noted before, $\lambda_{\text{TSW}}(T)$ is shorter for $\text{Ni}_{80}\text{Fe}_{20}$ than for Co. Interestingly, $\lambda_{\text{TSW}}(T)$ is much shorter than hitherto assumed, with room temperature values of 130 ± 20 Å for $\text{Ni}_{80}\text{Fe}_{20}$ and 270 ± 40 Å for Co. Especially for $\text{Ni}_{80}\text{Fe}_{20}$ this is only three times larger than the majority spin attenuation length at low T. Hence, we conclude that hot-electron attenuation lengths are clearly dependent on T. For instance, the addition of thermal spin wave scattering with a length scale of 130 Å reduces the attenuation length from 43 Å at 100 K, to a significantly lower value of $(1/43 + 1/130)^{-1} = 32$ Å at room temperature.

The inset of Fig. 3 shows the thermal variation of the interface attenuation $\Gamma(T)$ for $\text{Ni}_{80}\text{Fe}_{20}$. Data are obtained by dividing the I_C^N curve for certain $\text{Ni}_{80}\text{Fe}_{20}$ thickness by the curve for $x = 0$, and using the attenuation lengths of Fig. 3 to remove the volume scattering part. We find only a slight change of about 5% in the interface attenuation between 100 and 300 K. This shows that thermal spin-wave scattering is primarily a volume scattering process.

We next address the importance of spin waves for the spin asymmetry of hot-electron transmission. As shown in

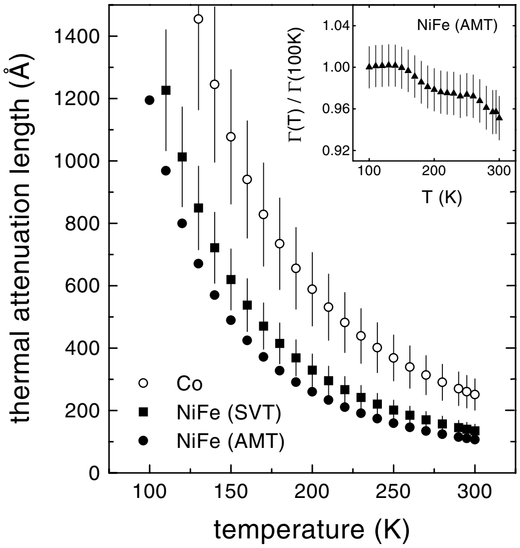

FIG. 3. Thermal spin-wave attenuation lengths versus T for Co and $Ni_{80}Fe_{20}$ (two data sets). The inset shows the thermal variation of the interface attenuation for $Ni_{80}Fe_{20}$.

Ref. [8], the asymmetry is created by the T-independent contribution of *spontaneous* spin wave emission, which is allowed only for minority spins. It is not possible to isolate spontaneous spin wave emission and measure the corresponding scattering length. However, the quantification of the thermal spin wave contribution allows us to estimate the attenuation due to spontaneous emission as the latter is expected to be significantly stronger than the thermal scattering rate. This is because thermal spin waves occupy only a small fraction of the spin-wave phase space up to energies on the order of kT, while for spontaneous spin-wave emission, the complete phase space up to the hot-electron energy (≈ 0.9 eV $\gg kT$) is available at all temperatures. The strength of the observed attenuation due to thermal spin waves is thus indirect evidence for the importance of *spontaneous* spin-wave emission. If we crudely estimate the spontaneous emission rate to be about an order of magnitude larger than the thermal emission rate, we obtain an attenuation length for spontaneous emission that is close to the measured minority-spin attenuation length (10 Å for $Ni_{80}Fe_{20}$). This strongly suggests that the minority spin attenuation is dominated by spontaneous spin-wave emission, as theory predicts [8]. Since the process cannot contribute to attenuation of majority hot spins, we conclude that the spin asymmetry of the attenuation length may well be due to spontaneous spin-wave emission, instead of the spin-dependent rate of electron-hole pair generation that arises from the exchange split band structure.

The notion of spontaneous spin-wave emission as the dominant source of spin asymmetry explains the absence of band structure features in spectroscopic data. In particular, it explains the puzzling observation [6] by time-resolved two-photon photoemission, that the inelastic lifetime for minority spins is shorter than the majority spin lifetime, not only in Co and Ni, but also in Fe. For Fe, a reversed spin-asymmetry at low energy (<1 eV) is expected from the band structure [6]. However, spontaneous spin-wave emission would, as it is forbidden for majority spins, always result in a larger lifetime for majority spins, as observed in the experiment.

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