Thermal Spin-Wave Scattering in Hot-Electron Magnetotransport Across a Spin Valve

R. Jansen, P. S. Anil Kumar, O. M. J. van't Erve, R. Vlutters, P. de Haan, and J. C. Lodder

Information Storage Technology Group, MESA$^+$ Research Institute, University of Twente, 7500 AE Enschede, The Netherlands

(Received 16 February 2000)

The role of thermal scattering in spin-dependent transport of hot electrons at 0.9 eV is studied using a spin-valve transistor with a soft $Ni_{80}Fe_{20}$/Au/Co base. Spin-dependent scattering makes the collected electron current depend sensitively on the magnetic state of the base. The magnetocurrent reaches 560% at 100 K, decays with increasing temperature, and a huge effect of 350% still remains at room temperature. The results demonstrate that thermal spin waves produce quasielastic spin-flip scattering of hot electrons, resulting in mixing of the two spin channels.

PACS numbers: 75.30.Ds, 73.40.Vz, 75.70.Pa, 85.70.Kh

Spin-dependent transport of Fermi electrons has been widely studied in ferromagnets in relation to (giant) magnetoresistance. Transport studies of *hot* electrons are comparatively few. Early work on hot-electron scattering at energies of about 5 eV employed spin-polarized photoemission from overlayer structures [1,2]. This and also later experiments [3,4] at energies as low as 1.5 eV showed unambiguously that the inelastic mean free path of hot electrons is spin dependent in ferromagnets. This was confirmed by studies of the transmission through freestanding magnetic thin film foils [5,6], as well as by a time-resolved, two photon photoemission experiment [7] that directly probed the inelastic lifetime for majority and minority spins. Spin-dependent scattering of hot electrons is essential in various spin-polarized electron spectroscopies that are widely used to examine magnetic materials. It also underlies phenomena such as the spin-valve effect for secondary electrons in magnetic multilayers [8], and leads to spin filtering. The latter has recently enabled magnetic imaging with nanometer resolution [9] in the magnetic version of ballistic electron emission microscopy [10]. Moreover, with the introduction of the spin-valve transistor [11,12], hot-electron magnetotransport became relevant for magnetic sensors and magnetoelectronics.

For ferromagnets, experiments carried out thus far have always found that the inelastic mean free path of hot electrons is shorter for the minority spin electrons [13]. A common interpretation is that this originates from the difference in the number of unoccupied states for the hot electron to scatter into, assuming so-called Stoner excitations to be the dominant scattering mechanism. However, recent experimental [14] and theoretical work [15] suggests that scattering by spin-wave excitations may also contribute to the spin dependence of the mean free path. The asymmetry is created by spontaneous spin-wave emission, which due to conservation of angular momentum is allowed only for minority spins. Spontaneous spin-wave emission is not dependent on temperature (T) and occurs even at $T = 0$. It is calculated [15] to dominate at electron energies below $\approx$3 eV, and is found to be the major source of small energy losses [14]. Besides spontaneous emission, there is also a thermal part that gives rise to spin-wave absorption as well as emission. Information on these contributions is obtained most directly by varying T. While spectroscopic measurements have been performed, the T dependence has so far not been explored. This can now be done readily with the spin-valve transistor, as it is a solid-state device. In this Letter we report on the first measurements of spin-dependent hot-electron scattering as a function of temperature, using the spin-valve transistor. We show that scattering by thermal spin waves has a noticeable effect on spin transport of hot electrons, in particular, by introducing spin mixing.

The spin-valve transistor is a three-terminal device with the structure emitter/base/collector. The emitter and collector are semiconductors (Si), while the metallic base comprises a spin valve. Hot electrons, with typical energies of 0.5–1 eV, are injected from the emitter into the spin-valve base, where they undergo spin-dependent scattering. This makes the collected current depend sensitively on the magnetic state of the base. A relative current change of 390% was obtained [11] at 77 K, and a device operating at room temperature demonstrated a 15% effect in fields of a few kOe [12]. To investigate the T dependence, we have used a base with a soft $Ni_{80}Fe_{20}$/Au/Co spin valve with Co and $Ni_{80}Fe_{20}$ layers of well-separated coercivity. Thereby, clear parallel and antiparallel orientation is obtained over a wide temperature range. Also, improvements in the collector properties have eliminated the obscuring effect of collector leakage, facilitating measurements of the true hot-electron spin-valve effect up to room temperature. We note that these two modifications have also led to a drastic improvement of the device performance, i.e., a relative magnetocurrent effect above 300% at room temperature in magnetic fields of only a few Oe was achieved [16].

As previously described [16,17], the spin-valve transistor is prepared by a combination of vacuum evaporation of metal layers onto two precleaned and HF-etched semiconductor substrates, subsequent metal bonding in vacuum, followed by device processing using photolithography and dry and wet etching techniques. The final structure is n-type Si(100)/Pt (20 Å)/$Ni_{80}Fe_{20}$ (60 Å)/Au

(35 Å)/Co (30 Å)/Au (20 + 20 Å)/n-type Si(111). All metal layers are grown in a pressure better than 1×10^{-9} mbar using a molecular beam deposition system, in which also the *in situ* bonding is carried out using the 20 + 20 Å thick Au layer. At the Si/Pt interface a Schottky barrier of 0.86 ± 0.01 eV is formed, while a barrier height of 0.80 ± 0.01 eV is obtained for the Au/Si contact. The Si/Pt diode is used to emit hot electrons into the base at a mean excess energy of about 0.9 eV; the Au/Si diode is used as the collector. This collector Schottky barrier accepts only electrons that have sufficient *energy* to surmount the barrier. It also reflects electrons that impinge on the base/collector interface at *angles* larger than a critical angle [10,12], since these electrons cannot retain a nonzero momentum in the direction of the collector after passing the interface. The energy and momentum selection makes the device extremely sensitive to (spin-dependent) elastic and inelastic scattering in the base. The hot-electron injection is controlled by the emitter current I_E, while the resulting induced collector current I_C is measured under application of a voltage V_{BC} across the collector and the base. The metal base is $700 \times 350\ \mu\text{m}^2$; the Si emitter is $350 \times 350\ \mu\text{m}^2$ and about 30 μm thick.

Figure 1 shows the typical variation of the collector current with applied magnetic field at two temperatures (80 and 290 K), for an injected current $I_E = 2$ mA. At high fields the magnetizations of the Co and $Ni_{80}Fe_{20}$ films in the spin-valve base are parallel (P), and hot electrons scatter relatively little. Hence, the collector current I_C^{P} is largest. When one of the magnetizations is reversed and a clear antiparallel (AP) magnetization alignment is obtained, scattering is much stronger. As a result, the collector current I_C^{AP} is a factor of 6.6 smaller (at 80 K). This means a relative magnetocurrent effect $\text{MC} = (I_C^{\text{P}} - I_C^{\text{AP}})/I_C^{\text{AP}} = 560\%$. Interestingly, a huge effect of 350% still remains at 290 K. Similar results were reproducibly obtained.

In Fig. 2, the temperature variation of I_C^{P} and I_C^{AP} (top panel) and the magnetocurrent MC (bottom panel) are displayed. For the parallel case, the collector current first increases with T, but above 200 K it decreases. In contrast, I_C^{AP} increases over the whole temperature range. The resulting decay of the MC is relatively weak, especially below 200 K. The conventional current-in-plane magnetoresistance (CIP-MR) of an identical spin valve is also included. The CIP-MR is not only orders of magnitude smaller, but also exhibits a stronger thermal decrease that is linear, as also found by others [18].

Let us first discuss a somewhat unexpected feature, the existence of a region where the collector current for P and AP configurations increases with T. This is surprising since any thermally induced scattering enhances the overall scattering in the base of the transistor and is thus expected to reduce the collector current. Hence, the increase of I_C is not related to scattering in the base. Rather, it originates from distribution effects in the following way. We begin by noting that there is always some spatial distribution of Schottky barrier heights, both at the emitter and the collector side. If the Schottky barrier height distribution of the emitter overlaps with that of the collector, then in some parts of the transistor area the emitter barrier is lower than the collector barrier. At low temperature, these regions

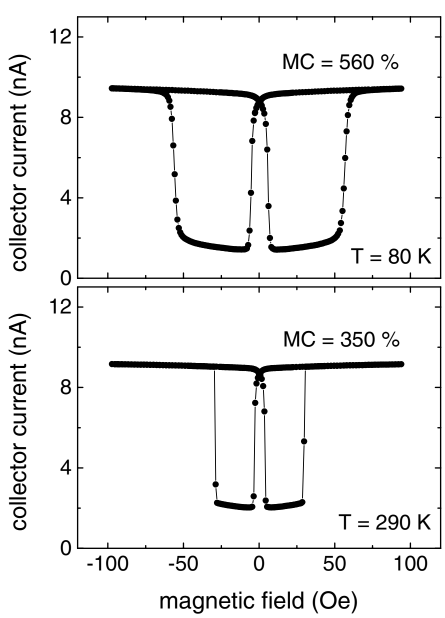

FIG. 1. Collector current versus magnetic field at $T = 80$ K (top) and $T = 290$ K (bottom), for a spin-valve transistor with a soft NiFe/Au/Co spin-valve base. $I_E = 2$ mA; $V_{BC} = 0$.

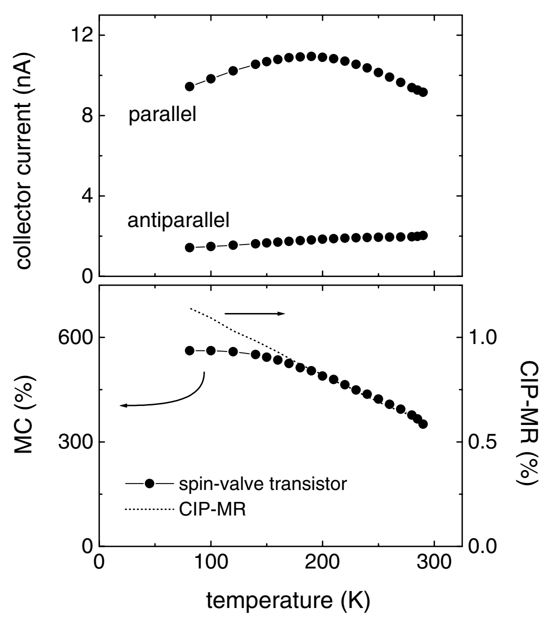

FIG. 2. Temperature variation of collector current I_C for parallel and antiparallel alignment (top panel) and the magnetocurrent (bottom panel, symbols). $I_E = 2$ mA and $V_{BC} = 0$. Also shown is the much smaller CIP-MR of an identical spin valve (dashed line in bottom panel and right vertical scale).

do not contribute to the collector current since all the hot electrons are injected at energies below the collector barrier maximum. However, at finite T, the injected hot electrons have some thermal distribution in energy of about 4 kT wide, with a low energy cutoff determined by the emitter Schottky barrier, and a tail extending up to higher energy. Thus at finite T electrons from the tail of this injection distribution are able to surmount the collector barrier. Since this tail gets more pronounced when T goes up, it causes the collector current to increase. This behavior occurs for P and AP states of the base, as is observed up to 200 K. This interpretation is supported by studies using different emitter/collector height combinations, as well as modeling, to be presented in detail elsewhere. Note that the deviation from this behavior above 200 K is caused by the additional effect of thermal scattering in the base, in particular, spin mixing, as discussed below.

Thermal scattering may change the MC in two ways. First, scattering may attenuate, i.e., remove electrons from the collected current in a spin-dependent fashion. The second possibility is spin mixing, in which electrons are scattered into the other spin channel by a spin-flip process, without being removed from the collected current. We will show that when we neglect possible thermally induced spin mixing, the MC does not decay with T.

We follow Ref. [11] in describing the transmission of spin-up and spin-down hot electrons through the spin valve in terms of spin-dependent attenuation lengths λ. For the sake of the argument, we consider a simple base with the structure $N/F/N/F/N$, where N is a normal metal and F is a ferromagnetic layer, all with thickness d. Within the bulk of each layer, the transmission decays exponentially with d. For N we have $\exp(-d/\lambda_N)$, while for F we have $\exp(-d/\lambda_F^M)$ for majority spins M and $\exp(-d/\lambda_F^m)$ for minority spins m. For each N/F or F/N interface we introduce attenuation factors Γ_{NF}^M and Γ_{NF}^m. The transmission for a given spin is the product of appropriate bulk and interface terms, and depends on whether the magnetizations in the two F layers are parallel or antiparallel. For example, for spin-up and parallel magnetizations we have $[\exp(-d/\lambda_N)]^3[\exp(-d/\lambda_F^M)]^2(\Gamma_{NF}^M)^4$. It is then straightforward [11] to show that the MC is given by

$$\mathrm{MC} = \frac{1}{2}\left[x + \frac{1}{x}\right] - 1\,, \tag{1}$$

$$x = \frac{\exp(-d/\lambda_F^M)}{\exp(-d/\lambda_F^m)}\left[\frac{\Gamma_{NF}^M}{\Gamma_{NF}^m}\right]^2. \tag{2}$$

Note that since the attenuation length λ_N in the normal metal does not depend on spin, the MC does not depend on λ_N, nor on its T variation. Also note that the above derivation is easily generalized to the case of dissimilar layers of different thicknesses.

Using Matthiessen's rule, we can write λ_F^M and λ_F^m in terms of the attenuation lengths for all the distinctive scattering processes:

$$\frac{1}{\lambda_F^M} = \frac{1}{\lambda_{\mathrm{stoner}}^M} + \frac{1}{\lambda_{\mathrm{el}}^M} + \frac{1}{\lambda_{\mathrm{ph}}} + \frac{1}{\lambda_{\mathrm{TSWabs}}^M}\,, \tag{3}$$

$$\frac{1}{\lambda_F^m} = \frac{1}{\lambda_{\mathrm{stoner}}^m} + \frac{1}{\lambda_{\mathrm{el}}^m} + \frac{1}{\lambda_{\mathrm{ph}}} + \frac{1}{\lambda_{\mathrm{TSWemis}}^m} + \frac{1}{\lambda_{\mathrm{SSWemis}}^m}\,, \tag{4}$$

where $\lambda_{\mathrm{stoner}}$, λ_{el}, and λ_{ph} are the attenuation lengths associated with stoner excitations, elastic scattering, and phonon scattering, respectively. Also included are attenuation lengths $\lambda_{\mathrm{TSWabs}}^M$ and $\lambda_{\mathrm{TSWemis}}^m$ due to absorption and emission of *thermal* spin waves, respectively, as well as a term $\lambda_{\mathrm{SSWemis}}^m$ due to *spontaneous* emission of spin waves. Note that due to conservation of angular momentum, absorption is allowed only for majority spin hot electrons, whereas (spontaneous and thermal) emission is allowed only for minority spins [19]. The overall rate of spin-wave scattering has a spin asymmetry due to $\lambda_{\mathrm{SSWemis}}^m$ and its importance for the spin dependence of the hot-electron lifetime has been pointed out recently [14,15].

Only λ_{ph}, $\lambda_{\mathrm{TSWabs}}^M$, and $\lambda_{\mathrm{TSWemis}}^m$ depend on temperature, while stoner excitations, elastic scattering, and spontaneous spin-wave emission do not. Although the phonon terms vary with T, these either do not affect the MC or may even be expected to slightly increase the MC with T (see also Ref. [20]). This being noted, we now retain only $\lambda_{\mathrm{TSWabs}}^M$ and $\lambda_{\mathrm{TSWemis}}^m$ for the T dependence of x and MC. We can write

$$x(T) = \frac{\exp(-d/\lambda_{\mathrm{TSWabs}}^M)}{\exp(-d/\lambda_{\mathrm{TSWemis}}^m)}\,x(T = 0)\,. \tag{5}$$

At very low T, $\lambda_{\mathrm{TSWabs}}^M$ and $\lambda_{\mathrm{TSWemis}}^m$ become very large and x approaches $x(T = 0)$. At finite T, the MC can only become smaller than $\mathrm{MC}(T = 0)$ when $x(T) < x(T = 0)$, which requires $\lambda_{\mathrm{TSWabs}}^M < \lambda_{\mathrm{TSWemis}}^m$ [more generally, $\mathrm{MC}(T)$ can only be smaller than $\mathrm{MC}(T = 0)$ if the thermally induced scattering process has a spin asymmetry of opposite sign to that at $T = 0$. To the best of our knowledge, no such scattering process exists]. Theoretical analysis by Hong and Mills [15] clearly shows that the scattering rates of hot electrons by *thermally* induced spin-wave emission and absorption, respectively, are virtually identical, because of the quasielastic nature of the process [21]. This implies that $\lambda_{\mathrm{TSWabs}}^M = \lambda_{\mathrm{TSWemis}}^m$, which means that $x(T) = x(T = 0)$ at all T. We therefore conclude that if we neglect spin mixing, and only consider the extra attenuation of the hot-electron current by thermal scattering, a decay of MC does not result. This may be quite remarkable, as spin-independent thermal scattering does reduce the ratio λ_F^M/λ_F^m. We can understand this by realizing that the MC does not depend on λ_F^M/λ_F^m, but rather on the ratio of the (exponential) attenuation it produces [see Eqs. (1) and (2)].

Given the above discussion, we attribute the decay of MC to thermally induced spin-flip scattering, causing mixing of the two spin channels. This is consistent with the observation (Fig. 2) that the current for the parallel state goes down above 200 K, while the current for the antiparallel case continues to go up. Since exchange scattering by paramagnetic impurities and spin-orbit scattering have negligible T dependence in our experimental range [22], we consider spin-flip scattering by thermal spin waves. We stress that spin mixing results only for those scattering events in which the energy and/or momentum transferred to the spin wave is such that after scattering, the hot electron is still able to enter the collector (recall that the electron needs a minimum energy to surmount the collector barrier, and has to be incident at an angle smaller than the critical angle of acceptance [10,12]). We therefore consider the Bose-Einstein distribution function $N_q = 1/[\exp(Dq^2/kT) - 1]$, which determines the typical wave vector **q** and energy Dq^2 (D the spin-wave stiffness, typically 400 meV Å^2) of thermal spin waves. We see that even at 300 K virtually all thermal spin waves have low energies that are smaller than the maximum allowed energy loss (≈60 meV) given by the difference between the emitter and the collector barrier. Thus, the change of hot-electron energy will generally not remove the electron from the collected current. The situation is different when one considers the wave vector **q**, which has magnitudes up to roughly 0.3 Å^{-1} at room temperature. For the largest **q**, spin-wave scattering may deflect the hot electron enough to prevent collection, thus causing attenuation. However, for small **q** or when the **q** component perpendicular to the hot-electron direction of motion is small, the deflection is weak. In that case, the process contributes to spin mixing.

In conclusion, a spin-valve transistor was used to study the role of thermal scattering in magnetotransport of hot electrons. We find a thermal decrease of the magnetocurrent, due to mixing of the two spin channels by thermal spin-wave scattering with small energy transfer (quasielastic) and small momentum transfer.

We acknowledge financial support from the Royal Netherlands Academy of Arts and Sciences (KNAW) and the Dutch Technology Foundation (STW).

[1] D. T. Pierce and H. C. Siegmann, Phys. Rev. B **9**, 4035 (1974).

[2] D. P. Pappas, K.-P. Kämper, B. P. Miller, H. Hopster, D. E. Fowler, C. R. Brundle, A. C. Luntz, and Z.-X. Shen, Phys. Rev. Lett. **66**, 504 (1991).

[3] J. C. Gröbli, D. Guarisco, S. Frank, and F. Meier, Phys. Rev. B **51**, 2945 (1995).

[4] J. C. Gröbli, D. Oberli, and F. Meier, Phys. Rev. B **52**, R13 095 (1995).

[5] H.-J. Drouhin, A. J. van der Sluijs, Y. Lassailly, and G. Lampel, J. Appl. Phys. **79**, 4734 (1996).

[6] D. Oberli, R. Burgermeister, S. Riesen, W. Weber, and H. C. Siegmann, Phys. Rev. Lett. **81**, 4228 (1998).

[7] M. Aeschlimann, M. Bauer, S. Pawlik, W. Weber, R. Burgermeister, D. Oberli, and H. C. Siegmann, Phys. Rev. Lett. **79**, 5158 (1997).

[8] R. J. Celotta, J. Unguris, and D. T. Pierce, J. Appl. Phys. **75**, 6452 (1994).

[9] W. H. Rippard and R. A. Buhrman, Appl. Phys. Lett. **75**, 1001 (1999); Phys. Rev. Lett. **84**, 971 (2000).

[10] L. D. Bell and W. J. Kaiser, Phys. Rev. Lett. **61**, 2368 (1988).

[11] D. J. Monsma, J. C. Lodder, Th. J. A. Popma, and B. Dieny, Phys. Rev. Lett. **74**, 5260 (1995).

[12] D. J. Monsma, R. Vlutters, and J. C. Lodder, Science **281**, 407 (1998).

[13] G. Schönhense and H. C. Siegmann, Ann. Phys. (Leipzig) **2**, 465 (1993).

[14] M. Plihal, D. L. Mills, and J. Kirschner, Phys. Rev. Lett. **82**, 2579 (1999).

[15] J. Hong and D. L. Mills, Phys. Rev. B **59**, 13 840 (1999).

[16] P. S. A. Kumar, R. Jansen, O. M. J. van't Erve, R. Vlutters, P. de Haan, and J. C. Lodder, J. Magn. Magn. Mater. **214**, L1 (2000).

[17] J. C. Lodder, D. J. Monsma, R. Vlutters, and T. Shimatsu, J. Magn. Magn. Mater. **198–199**, 119 (1999).

[18] B. Dieny, V. S. Speriosu, and S. Metin, Europhys. Lett. **15**, 227 (1991); B. Dieny, P. Humbert, V. S. Speriosu, S. Metin, B. A. Gurney, P. Baumgart, and H. Lefakis, Phys. Rev. B **45**, 806 (1992).

[19] At finite T, thermally excited spin waves are available for absorption, which strictly speaking, opens up new processes which conserve angular momentum [for instance, the simultaneous emission and absorption of two (different) spin waves, which is possible for hot electrons of either spin]. Such processes are not expected to have any significant spin asymmetry, and are of higher order, giving only a negligible correction to the spin-wave scattering rates.

[20] No spin dependence is expected at large enough hot-electron energy. Yet, at energies of about 0.9 eV the density of states of, for example, Co has a spin asymmetry because the energy is below the top of the minority spin d band. If phonons have a sufficient cross section for scattering hot electrons into these minority d states, a spin-dependent phonon scattering rate may be expected. The asymmetry would be of the same sign as that for, e.g., stoner excitations, implying that it would only *enhance* the MC at higher T. This mechanism is thus not responsible for the observed decay of MC.

[21] We have explicitly confirmed this by calculating the rates of thermal emission and absorption, respectively, using Eqs. (26)–(29) of Ref. [15].

[22] A. Fert, J. L. Duvail, and T. Valet, Phys. Rev. B **52**, 6513 (1995).