Anisotropic Spin-Orbit Scattering of Hot-Electron Spins Injected into Ferromagnetic Thin-Films

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Anisotropic spin-orbit scattering of hot-electron spins in ferromagnets is examined by injecting a hot-electron current into the thin ferromagnetic base of a transistor and measuring the current attenuation as a function of the magnetization orientation. The transmission anisotropy is described by a simple model, from which we extract an effective spin-orbit scattering length of 420 nm for hot-electron spins in $Ni_{80}Fe_{20}$, independent of temperature. The corresponding scattering time (<0.3 ps) is surprisingly short, suggesting efficient spin-lattice relaxation of hot electrons. The results also unambiguously demonstrate the attenuation of a hot-electron current by an elastic scattering process.

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When nonequilibrium, hot-electron spins are injected into a magnetic solid, the transport through the material naturally is spin dependent. Control and manipulation of spins in magnetic heterostructures and semiconductors is at the heart of the flourishing field of magnetoelectronics [1], promising unique electronic devices and new functionality. The spin transport of hot electrons forms the basis of devices such as the spin-valve transistor (SVT) [2–4], while in tunneling magnetoresistance, part of the bias dependence has been attributed to hot-electron effects [5]. Nonequilibrium electrons also dominate ultrafast optical demagnetization experiments [6,7], and more recently, magnetization precession by hot spin injection was reported [8]. Such ultrafast methods for control of magnetization are considered for high-speed magnetic and magneto-optical recording. In addition, hot-electron spin transport is important in several spin-polarized electron spectroscopies and magnetic imaging techniques [9]. In all cases, the basic behavior is governed by the fundamental interactions of the hot-electron spins with the various degrees of freedom in a magnetic solid. These include those with other (spin-polarized) electrons, phonons, spin waves, or with the lattice via the spin-orbit coupling. Detailed information on these interactions is indispensable for a correct interpretation of many hot-electron spin phenomena and characterization techniques, as well as for spin-electronic devices and data storage.

Information on the various scattering mechanisms can be obtained in the time domain [10,11] or by injecting hot-electron spins into a ferromagnetic thin film and measuring the transmission [12,13]. For injected electrons with a typical velocity of a few times 10^6 m/s and thin films of a few nm thick, the relevant processes occur on time scales down to a few femtoseconds. It has long been believed that hot-electron transmission is dominated by electron-electron scattering, producing electron-hole pairs [14]. The transmission is spin dependent due to the spin asymmetry in the inelastic lifetime [10], caused by a difference in the number of final d-hole states for the hot electrons to scatter into. However, evidence for energy loss due to (spontaneous) emission of spin waves has recently been presented [15,16], while scattering by thermal spin waves was shown to be responsible for the thermal decay of magnetocurrent in the SVT [17]. In this Letter, we examine spin-orbit scattering of hot-electron spins injected into a ferromagnetic thin film and show that the transmission is anisotropic, i.e., dependent on the angle between the magnetization vector and the direction of the injected current. The transmission anisotropy is independent of temperature and scales with the thickness of the ferromagnetic layer, as described by a simple phenomenological model that allows extraction of the spin-orbit scattering parameters.

A direct measure of the transmission anisotropy is obtained in a so-called anisotropic magnetotransistor (AMT). The AMT is a three-terminal device with an n-type Si emitter and collector and a metallic base that comprises a single magnetic thin film (see Fig. 1). At the interfaces between the metal base and the semiconductors, Schottky barriers are formed. To avoid contact between the magnetic layer and the Si and to obtain the desired high-quality Schottky barriers with the proper height, thin layers of Pt and Au are inserted at the emitter and collector side, respectively. The

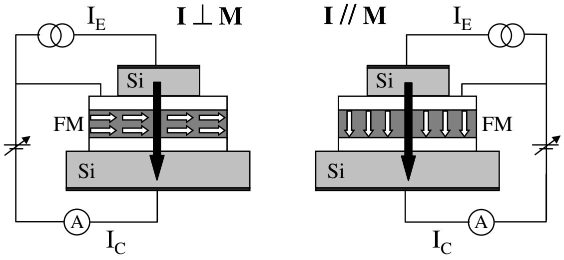

FIG. 1. Measurement geometry for anisotropic spin-orbit scattering of hot-electron spins in a magnetic metal base transistor. The base transmission is different when the hot-electron current **I** and magnetization **M** are perpendicular (left) or aligned (right).

full structure is thus Si/Pt (2 nm)/FM(t)/Au (4 nm)/Si, where FM is either $Ni_{80}Fe_{20}$ or Co with thickness t. A Schottky barrier height of 0.86 ± 0.01 eV was determined for the Si/Pt emitter contact, while the Si/Au collector barrier was 0.80 ± 0.01 eV. As previously described [3,4] for the SVT, the device is fabricated by a combination of vacuum evaporation of metal layers onto two precleaned and HF-etched Si substrates, subsequent vacuum metal bonding [18] in the Au layer, followed by photolithography and dry and wet etching techniques. The emitter area is 350×350 μm^2; the metal base is 700×350 μm^2.

When an emitter current I_E is established between Si emitter and metal base, hot electrons are injected into the base at an energy of about 0.9 eV above the metal Fermi energy. A fraction of the injected electrons arrives at the base/collector interface with enough energy and the correct momentum to overcome the collector Schottky barrier and enter the Si collector. Hence, a collector current I_C between collector and base is produced, with a magnitude that depends sensitively on the scattering conditions in the metal base. Although several scattering processes are active, the spin-orbit scattering is easily separated out because it is the only process that is anisotropic, i.e., dependent on the angle θ between the hot-electron current $\mathbf{I}$ and the magnetization vector $\mathbf{M}$ in the magnetic base film. With the direction of the current fixed and perpendicular to the base layer, a change of I_C is produced when the base magnetization is varied from in plane to out of plane.

The dependence of I_C on the angle between the magnetization and the hot-electron current is illustrated in Fig. 2 for a transistor with a base containing 3 nm of NiFe (left panel) or 3 nm of Co (right panel). In both cases, the magnetization for zero applied magnetic field is in the plane of the films, and thus $\mathbf{M}$ and $\mathbf{I}$ are perpendicular. In this situation the spin-orbit scattering is minimized and hence the collector current is largest. When a sufficiently large magnetic field (>0.7 T) is applied *perpendicular* to the base, the magnetization is rotated out of the film plane and becomes aligned with the hot-electron current. This causes an increase of the spin-orbit scattering and thus a reduction of I_C (as shown by the closed symbols). The reduction is symmetric with respect to the polarity of the applied field, since the spin-orbit interaction scales as $\cos^2(\theta)$. The data in Fig. 2 represent the first direct observation of anisotropic hot-electron attenuation in ferromagnetic thin films.

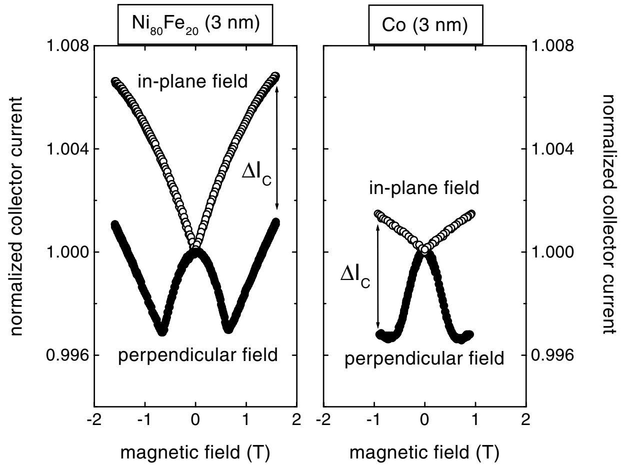

FIG. 2. Left panel: collector current vs magnetic field for a transistor with a Pt/NiFe (3 nm)/Au base, for fields applied in plane of the NiFe film, or perpendicular to it ($T = 300$ K). Right panel: same for a Pt/Co (3 nm)/Au base.

In addition to the reduction of I_C due to the *rotation of the magnetization,* one observes a superimposed second scattering contribution that manifests itself as an approximately linear increase of I_C with increasing magnetic field. This linear term is present irrespective of the direction of the applied field; i.e., it produces the linear part at high perpendicular fields, as well as the increase of I_C for fields applied in the film plane (open symbols). Since the coercivities of the NiFe and Co films are only 5 Oe (0.5 mT) and 25 Oe (2.5 mT), respectively, the magnetization is already aligned with the field direction at small in-plane fields. Thus, the linear rise cannot be due to a change in the magnetization direction. The fact that this contribution is isotropic excludes deflection of hot electrons by the Lorentz force as a possible explanation. The origin of the isotropic term is unclear at present. It may result from a magnetic field induced suppression of collective magnetic excitations (spin waves), which would tend to enhance the transmission, as is observed. As indicated by the arrows in Fig. 2, the true anisotropic contribution is obtained as the difference ΔI_C between the currents for perpendicular and in-plane fields. Note that ΔI_C for NiFe and Co are comparable.

Figure 3 shows results for AMT's with a Pt/NiFe/Au base for various thicknesses of the magnetic layer. Absolute currents are on the order of 10–100 nA for $I_E = 2$ mA. Since I_C is attenuated exponentially with NiFe thickness (with a decay length of 43 Å at 100 K), the curves have been normalized to allow comparison. For perpendicular applied fields, we observe that the transmission anisotropy clearly increases with NiFe thickness, and at $t = 10$ nm, the anisotropic contribution dominates the linear term. The effect of an in-plane field is also enhanced for thicker films. For the control structure with a nonmagnetic base [with zero NiFe thickness, but still having Pt (2 nm)/Au (4 nm)], we observe no magnetic field dependence whatsoever. This proves that the magnetic field dependence is due to the NiFe layer only and not due to magnetic field induced changes of the transport across the Schottky barriers or the nonmagnetic layers.

Below we present a simple model for the anisotropic transmission. Following the approach [19] taken also for the well-known anisotropic magnetoresistance (AMR), the spin-orbit scattering is characterized by a scattering length λ_{so}^{σ} and a scattering anisotropy A_{so}^{σ}. The superscript σ denotes the spin of the hot electron. Note that the spin dependence arises from the spin splitting of the energy bands

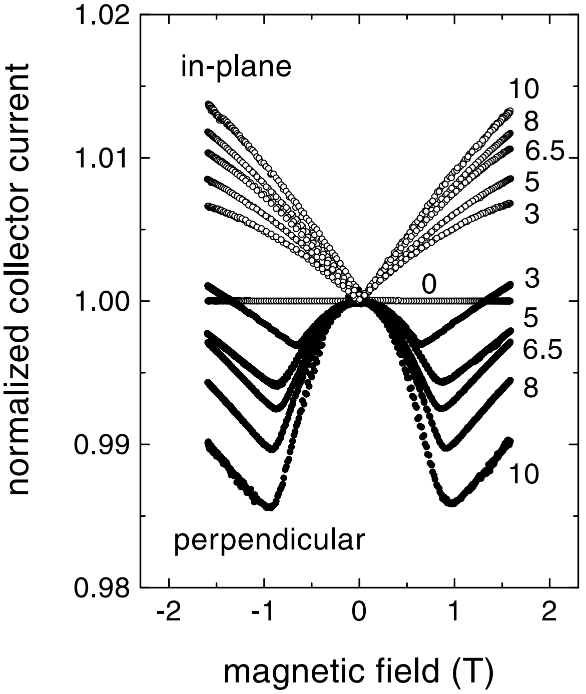

FIG. 3. Collector current vs magnetic field for AMT's with a Pt/NiFe/Au base with the thickness of the NiFe film varying from 0 to 10 nm (labels denote t in nm). $T = 300$ K.

in ferromagnets, such that the majority spin hot electrons scatter from different states with different orbital symmetry than minority spins do. The dependence on the angle θ between the current and the magnetization is given by [19]

$$\lambda_{\mathrm{so}}^{\sigma}(\theta) = \lambda_{\mathrm{so}}^{\sigma}[1 - A_{\mathrm{so}}^{\sigma} \cos^2(\theta)]. \quad (1)$$

The result of the scattering is to reduce I_C exponentially according to

$$I_C(\theta) = F^{\uparrow} \exp[-t/\lambda_{\mathrm{so}}^{\uparrow}(\theta)] + F^{\downarrow} \exp[-t/\lambda_{\mathrm{so}}^{\downarrow}(\theta)], \quad (2)$$

where $F^{\uparrow}$ and $F^{\downarrow}$ are spin-dependent prefactors that, however, do not depend on θ. These prefactors contain all processes other than the spin-orbit scattering. The most important one is the excitation of electron-hole pairs, which is significantly stronger for minority spins in ferromagnets [10,14]. In Co, the attenuation length due to electron-hole pair creation was measured [9] to be 0.7 nm for minority spins and 2.3 nm for majority spins at around 1 eV. We have determined a comparable yet slightly stronger asymmetry for NiFe using the SVT [20]. Because of the exponential attenuation, the transmission of minority spins is thus vanishingly small for large enough film thickness, i.e., $F^{\downarrow} \ll F^{\uparrow}$. For our films between 3 and 10 nm, we therefore neglect the last term in Eq. (2) and use the approximation $I_C(\theta) \approx F^{\uparrow} \exp[-t/\lambda_{\mathrm{so}}^{\uparrow}(\theta)]$. The anisotropic magnetocurrent (AMC) is then given by

$$\mathrm{AMC} = \frac{I_C(\frac{\pi}{2}) - I_C(0)}{I_C(\frac{\pi}{2})} = 1 - \exp(-t/\lambda_{\mathrm{eff}}), \quad (3)$$

where

$$\lambda_{\mathrm{eff}} = \lambda_{\mathrm{so}}^{\uparrow}\left(\frac{1 - A_{\mathrm{so}}^{\uparrow}}{A_{\mathrm{so}}^{\uparrow}}\right). \quad (4)$$

The AMC is thus dominated by the spin-orbit scattering parameters of the *majority* spins. We stress that λ_{eff} is the *effective* length that governs the AMC; it depends on the strength of the spin-orbit interaction as represented by λ_{so}, as well as on the angular asymmetry A_{so} of the scattering. For A_{so} close to 1 or 0, the value of λ_{eff} deviates significantly from λ_{so}. In the limit $\lambda_{\mathrm{eff}} \gg t$, the AMC is linearly proportional to t.

By plotting the AMC as a function of t, we can determine λ_{eff}. This is done in Fig. 4 at two different temperatures of 300 and 100 K. For both temperatures we find a linear increase of AMC with t, which can be described by a straight line through the origin. The latter shows that there is no interface contribution to the AMC; i.e., it is a pure volume effect. The observation that λ_{eff} does not vary with temperature is consistent with pure elastic [21] spin-orbit scattering, since the associated interaction does not contain any temperature dependent factors. Note that scattering by, for instance, phonons or spin waves does not affect the AMC, as these processes do not depend on the angle θ between **M** and **I**. In the AMT, these scattering processes reduce I_C by a factor independent of θ, such that there is no effect on the *relative* transmission anisotropy given by the AMC. This allows us to isolate the spin-orbit scattering. In contrast, for the conventional AMR effect the resistance change due to spin-orbit scattering is divided by a background resistance containing all scattering processes, including those that depend on temperature, causing the AMR to decay towards room temperature.

From a fit of the AMC data to Eq. (3) we extract a value for λ_{eff} of 420 ± 50 nm (at both temperatures). Although the present experiment does not allow us to determine λ_{so} and A_{so}, the value for λ_{eff} defines the possible

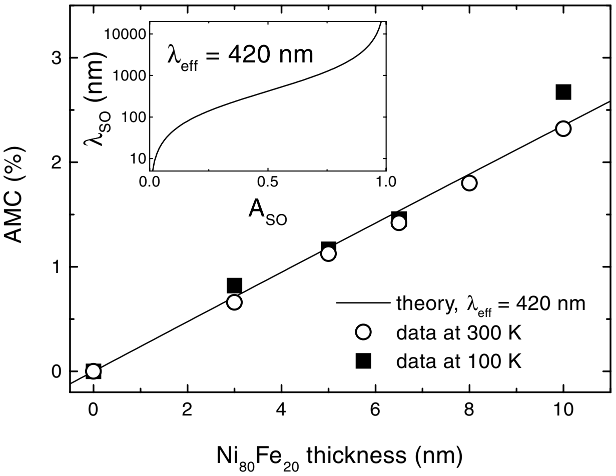

FIG. 4. AMC at 300 K (open circles) and 100 K (closed squares) as a function of the thickness of the NiFe layer. The solid line gives a value of 420 nm for the effective anisotropy length, which defines the λ_{so} vs A_{so} curve shown in the inset.

combinations of λ_{so} and A_{so}. This is illustrated in the inset in Fig. 4. To get an idea of a reasonable value of A_{so}, we look at the AMR for Fermi electrons in Ni-based dilute alloys [19], which is well described by scattering anisotropies between 0.1 and 0.33. It is rather unlikely that A_{so} is much larger, so we use 0.5 as a safe upper limit. This then gives $\lambda_{\mathrm{so}} < 420$ nm. With a typical electron velocity of 1.5×10^6 m/s at 0.9 eV, this corresponds to a surprisingly short spin-orbit scattering time of less than 0.3 ps. Although a direct comparison with experiments on ultrafast spin dynamics is not possible, the time scale determined here is strikingly close to the estimated values of 0.5–1 ps for the optically induced demagnetization in ferromagnetic nickel [7]. This supports the conjecture made in Ref. [7] that indeed an extremely efficient spin-lattice relaxation may underlie the ultrafast magnetic response.

The present work also addresses the question whether attenuation of hot electrons in metals is governed exclusively by inelastic scattering, as is often assumed, or also by elastic scattering [21]. The issue has been heavily debated in the context of ballistic electron emission microscopy of thin metal films on semiconductors, where conflicting results have appeared [22–24]. While some authors [22] describe their data by a combination of elastic and inelastic bulk scattering, others [23] claim that electrons make multiple passes through the metal films and scatter diffusively at the boundaries, while transmission of the metal-semiconductor interface without conservation of parallel momentum has also been invoked [24]. A principal problem is that elastic and inelastic processes are present simultaneously, and clearly separating the two contributions has remained elusive. In the present experiment we have succeeded in separating out a single elastic process, spin-orbit scattering, without resorting to a comparison with models. The observation of anisotropic transmission proves unambiguously that elastic scattering does produce hot-electron attenuation.

In conclusion, spin-orbit scattering of hot-electron spins injected into a ferromagnetic thin film was investigated using a magnetic metal base transistor. The observed anisotropic transmission is described phenomenologically in terms of spin-orbit scattering parameters, and a surprisingly short scattering time (<0.3 ps) was extracted.

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[1] G. A. Prinz, Science **282**, 1660 (1998).
[2] D. J. Monsma, J. C. Lodder, Th. J. A. Popma, and B. Dieny, Phys. Rev. Lett. **74**, 5260 (1995).
[3] D. J. Monsma, R. Vlutters, and J. C. Lodder, Science **281**, 407 (1998).
[4] P. S. Anil 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).
[5] S. Zhang, P. M. Levy, A. C. Marley, and S. S. P. Parkin, Phys. Rev. Lett. **79**, 3744 (1997).
[6] E. Beaurepaire, J.-C. Merle, A. Daunois, and J.-Y. Bigot, Phys. Rev. Lett. **76**, 4250 (1996).
[7] B. Koopmans, M. van Kampen, J. T. Kohlhepp, and W. J. M. de Jonge, Phys. Rev. Lett. **85**, 844 (2000).
[8] W. Weber, S. Riesen, and H. C. Siegmann, Science **291**, 1015 (2001).
[9] W. H. Rippard and R. A. Buhrman, Appl. Phys. Lett. **75**, 1001 (1999); Phys. Rev. Lett. **84**, 971 (2000).
[10] M. Aeschlimann, M. Bauer, S. Pawlik, W. Weber, R. Burgermeister, D. Oberli, and H. C. Siegmann, Phys. Rev. Lett. **79**, 5158 (1997).
[11] A. Scholl, L. Baumgarten, R. Jacquemin, and W. Eberhardt, Phys. Rev. Lett. **79**, 5146 (1997).
[12] H.-J. Drouhin, A. J. van der Sluijs, Y. Lassailly, and G. Lampel, J. Appl. Phys. **79**, 4734 (1996).
[13] D. Oberli, R. Burgermeister, S. Riesen, W. Weber, and H. C. Siegmann, Phys. Rev. Lett. **81**, 4228 (1998).
[14] G. Schönhense and H. C. Siegmann, Ann. Phys. (Leipzig) **2**, 465 (1993).
[15] M. Plihal, D. L. Mills, and J. Kirschner, Phys. Rev. Lett. **82**, 2579 (1999).
[16] J. Hong and D. L. Mills, Phys. Rev. B **59**, 13 840 (1999); Phys. Rev. B **62**, 5589 (2000).
[17] R. Jansen, P. S. Anil Kumar, O. M. J. van't Erve, R. Vlutters, P. de Haan, and J. C. Lodder, Phys. Rev. Lett. **85**, 3277 (2000).
[18] T. Shimatsu, R. H. Mollema, D. J. Monsma, E. G. Keim, and J. C. Lodder, J. Vac. Sci. Technol. A **16**, 2125 (1998).
[19] Th. G. S. M. Rijks, R. Coehoorn, M. J. M. de Jong, and W. J. M. de Jonge, Phys. Rev. B **51**, 283 (1995).
[20] R. Vlutters *et al.* (unpublished).
[21] In transmission experiments where electron energy analyzers are used, the term elastic is usually taken to include all scattering processes with energy transfer within the energy resolution of the analyzer. In our terminology, elastic refers to scattering without *any* energy transfer.
[22] R. Ludeke and A. Bauer, Phys. Rev. Lett. **71**, 1760 (1993).
[23] L. D. Bell, Phys. Rev. Lett. **77**, 3893 (1996).
[24] D. L. Smith, E. Y. Lee, and V. Narayanamurti, Phys. Rev. Lett. **80**, 2433 (1998).