PHYSICAL REVIEW B **76**, 140407(R) (2007)

Origin of the spin-asymmetry of hot-electron transmission in Fe

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(Received 30 July 2007; published 24 October 2007)

Using the technique of ballistic electron magnetic microscopy, we have studied the spin-asymmetry of transmission of hot electrons in Fe, for which a recent *ab initio* calculation has shown that the inelastic lifetime is similar for majority and minority spin. Nevertheless, using a spin-valve structure of $Ni_{81}Fe_{19}$/Au/Fe, we find that the attenuation length of hot electrons in Fe at 1.2–1.6 eV is a factor of 4 larger for the majority spin. We argue that this large spin-asymmetry arises from the spin dependence of the group velocity, rather than the lifetime.

DOI: 10.1103/PhysRevB.76.140407 PACS number(s): 75.70.−i, 85.75.−d, 72.25.Rb, 73.40.Vz

When nonequilibrium electrons are injected into a ferromagnetic thin film their energy relaxation is spin dependent, a direct consequence of the exchange splitting of the energy bands. Typically, the phase space of unoccupied states available for nonequilibrium electrons to decay into is largest for the minority spin electrons (due to the presence of partially empty *d* bands) and much smaller for the majority spin. The spin-asymmetry is manifested in a larger inelastic lifetime, τ, for the majority spin, as observed in time and spin-resolved two-photon photoemission experiments, for instance, on Co.[1–3] The spin-asymmetry of the lifetime also produces a spin-dependent transmission in transport experiments with hot electrons, such as those using ballistic electron magnetic microscopy (BEMM),[4] the spin-valve transistor,[5,6] or the magnetic tunnel transistor.[7,8] The spin-dependent attenuation lengths, λ, determined from such measurements are also found to be greater for the majority-spin electrons.

Yet, recent experiment and theory suggests that this is barely the whole story. First of all, even in the absence of any energy relaxation processes, the conductivity at energies up to a few eV above the Fermi level E_F is different for majority and minority spin.[9] Such spin-dependent conductivity arises from the different character of the states. While highly delocalized states dominate for the majority spin, the presence of empty *d* bands for the minority spin hot electrons greatly reduces their group velocity, v_g, and conductivity. Second, the *inelastic* scattering length is a product of the inelastic lifetime and v_g. Hence a spin-dependent group velocity can also contribute to the spin-asymmetry of the hot-electron attenuation length measured in transport. This was recently proposed to account for the unexpectedly large spin-asymmetry of transmission of hot holes with energy below E_F.[10] Most recently, *ab initio* calculations have highlighted Fe as a particularly striking case, as it was found that the calculated inelastic lifetimes for majority and minority spin are quite similar,[11] consistent with time and spin-resolved two-photon photoemission experiments.[3] With a similar inelastic lifetime for majority and minority spin, Fe presents a unique opportunity to investigate the spin dependence of v_g.

Here we show, using the technique of BEMM,[4,12] that a large spin-asymmetry in the attenuation length of hot electrons in Fe exists, despite the absence of a significantly spin-dependent inelastic lifetime.[3,11] In the energy range between 1.2 and 1.6 eV, the majority-spin attenuation length in Fe is found to be 1.5±0.2 nm while the minority-spin attenuation length is only 0.4±0.2 nm. This presents clear evidence of a spin-dependent group velocity, producing a spin-dependent inelastic scattering length and hot-electron conductivity in Fe.

The principle of the BEMM technique was described elsewhere.[13] Briefly, hot electrons are injected from the tip of a scanning tunneling microscope (STM) into a thin (magnetic) metal overlayer on a semiconductor substrate. Depending on the scattering in the metals, a fraction of the hot electrons is transmitted across the metal-semiconductor Schottky barrier, producing a collector current I_C. The samples used here consist of metal layers evaporated onto a hydrogen fluoride etched, *n*-type Si(100) substrate, with a predefined contact area. The configuration is *n*-Si/Au(8 nm)/FM/Au(3 nm), where FM is either a single Fe layer or a $Ni_{81}Fe_{19}$/Au/Fe trilayer with varying Fe thickness *d*. Whereas the top Au layer provides a chemically inert surface for *ex situ* sample transfer, the bottom Au layer forms a high quality Schottky barrier of 0.8±0.02 V with the *n*-Si substrate. All measurements are performed at 150 K in an ultrahigh vacuum STM using PtIr metal tips. An in-plane magnetic field was applied to the trilayer structures during growth, as well as during BEMM measurements.

The hot-electron transmission of single Fe layers of varying thickness was recorded as a function of tip bias, V_T, at a constant hot-electron injection current. We averaged over 100 individual spectra and then normalized the spectrum with the help of an electron current distribution obtained from an area of 1 μm^2 at a fixed bias of −1.7 V. In Fig. 1 (top panel) the transmitted electron current is plotted as a function of Fe thickness at V_T=−1.4 V. From the slope of the curve we extract the attenuation length λ, using an exponential decay $\propto \exp[-d/\lambda(E)]$. The attenuation length is found to be 1.6±0.2 nm at −1.4 V. The values of λ extracted similarly at various energies are plotted in Fig. 1 (bottom panel). The attenuation length decreases from 1.7±0.2 to 1.6±0.2 nm between −1.1 and −1.5 V. Such a weak dependence of λ with energy is not consistent with the increasing number of states available for the hot electrons to decay into, suggesting the influence of other factors.

In order to study the spin-dependence of transmission in Fe and to establish its origin we consider a spin-valve structure. The top panel of Fig. 2 shows representative BEMM spectra for a $Ni_{81}Fe_{19}$ (2.5 nm)/Au/Fe (1 nm) trilayer as a

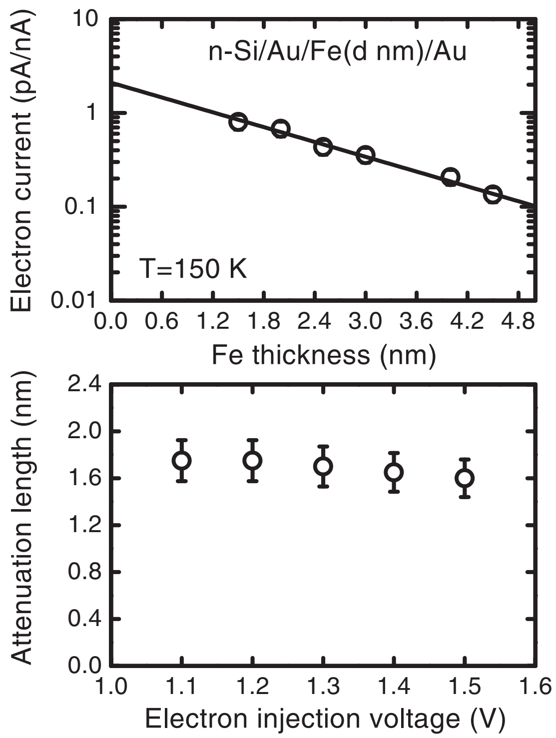

FIG. 1. (Top panel) Transmitted electron current (per nA of injected tunnel current) versus Fe thickness in n-Si/Au/Fe(d nm)/Au structures at V_T=−1.4 V. (Bottom panel) Variation of the attenuation length as a function of V_T. T=150 K.

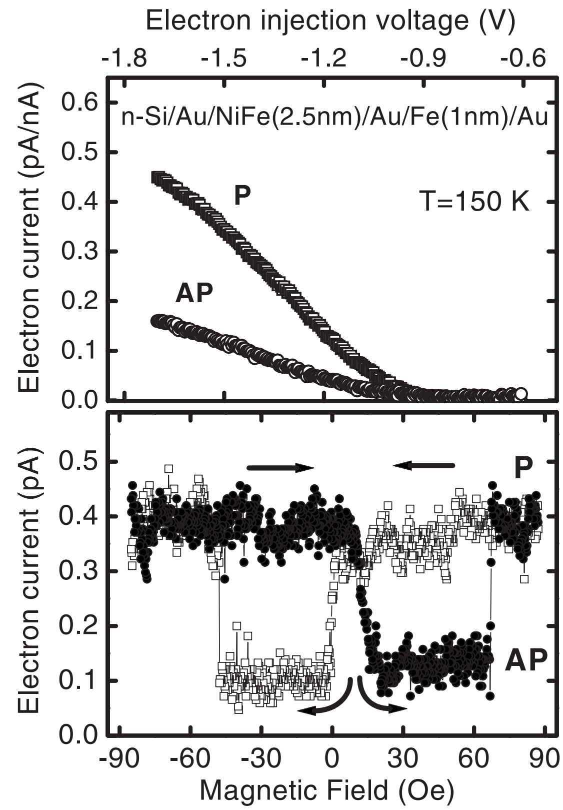

FIG. 2. (Top panel) Transmitted electron current versus tip voltage of a n-Si/Au/$Ni_{81}Fe_{19}$(2.5 nm)/Au/Fe(1 nm)/Au structure for P and AP magnetic state. (Bottom panel) Electron current vs magnetic field at V_T=−1.7 V and an injection current of 1 nA. All data are at 150 K.

function of V_T and for a constant injection tunnel current of 1 nA. Each spectrum is an average of over 100 individual spectra recorded at several locations at a constant magnetic field of +100 Oe or −12 Oe, respectively, corresponding to the parallel (P) and antiparallel (AP) relative magnetization of the $Ni_{81}Fe_{19}$ and Fe layers. Above a tip bias of −0.8 V, corresponding to the Schottky barrier height of the n-Si/Au interface, the electron transmission sharply increases with V_T. The current is larger when both the ferromagnetic layers are aligned parallel and almost a factor of 4 smaller when the layers are aligned antiparallel. In the bottom panel of Fig. 2, we plot the electron current at V_T=−1.7 V and an injection current of 1 nA, obtained while sweeping the magnetic field from +100 Oe to −100 Oe and back. We observe a larger current when both the layers are in the P state, sharp transitions to an AP state with a smaller current, and the expected magnetic hysteresis. Note that the data is not exactly symmetric around zero magnetic field, which we often observe in these samples depending on the tip location, indicating local variations in the magnetic switching behavior. From this hysteresis loop we derive a magnetocurrent $\mathrm{MC}=(I_C^P-I_C^{AP})/I_C^{AP}$ of 300±50%. Note that the current values, obtained from a randomly chosen location of the sample, differ slightly from the average values shown in the top panel, which is due to local variations in the transmitted current. Since these are always present, below we present data obtained from spectra such as those in the top panel of Fig. 2, which represent spatially averaged values.

Figure 3 shows I_C^P and I_C^{AP} (top panel) and MC (bottom panel) at T=150 K versus Fe thickness, while keeping the thickness of the $Ni_{81}Fe_{19}$ constant at 2.5 nm. From these curves and using an exponential decay for each spin,[7] we extract the spin-majority attenuation length λ^M to be 1.5±0.2 nm and the spin-minority attenuation length λ^m to be 0.4±0.2 nm at −1.4 V. The spin-asymmetry of the attenuation length λ^M/λ^m=3.8, which is large indeed. From the data in Fig. 3 we also find the attenuation factor for Au/Fe interfaces to be 0.8, as determined by extrapolating the I_C^P data to zero Fe thickness and comparing it with the I_C value of a structure with no Fe. Such an interfacial attenuation is associated with a mismatch of the band structure on both sides of the interface, in addition to elastic scattering due to interface disorder, defects, etc.

The bottom panel of Fig. 3 shows the variation of the MC with increasing Fe thickness at an energy of −1.4 V. Within the limits of experimental accuracy, it is seen that the MC first increases with Fe thickness and then saturates at a value of 400±50% for a 3 nm Fe layer. The solid line is a fit to the data using the attenuation lengths for Fe as given above, and spin-dependent attenuation lengths for the $Ni_{81}Fe_{19}$ layer taken from Ref. 6. The increase of the MC with Fe thickness indicates that the spin-asymmetry is dominated primarily by the volume attenuation lengths and not by interface scattering, which was found to be rather weak as discussed above. The saturation of the MC at larger Fe thickness is because minority spins are completely filtered out by the Fe layer, leaving the MC limited only by the spin-filtering in the $Ni_{81}Fe_{19}$ layer.

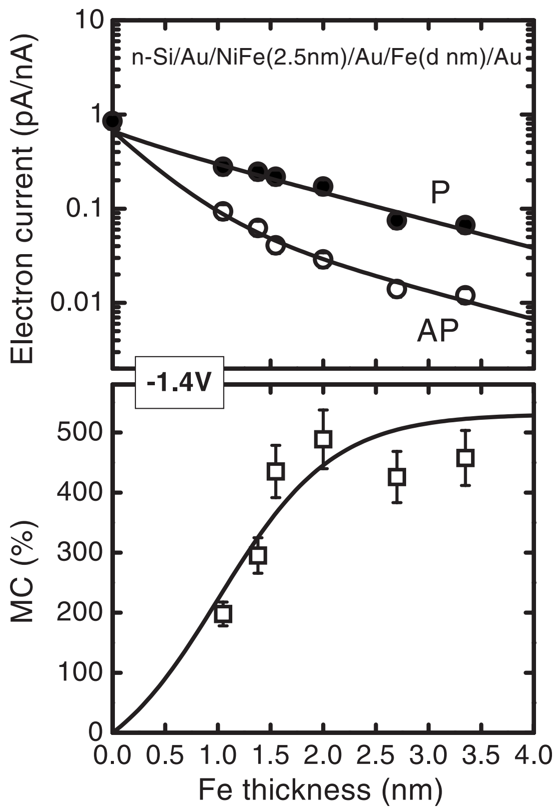

FIG. 3. Variation of I_C^P and I_C^{AP} (top panel) and MC (bottom panel) as a function of Fe thickness at $V_T=-1.4$ V in a n-Si/Au/$Ni_{81}Fe_{19}$/Au/Fe/Au structure. The solid lines represent fits as described in the text.

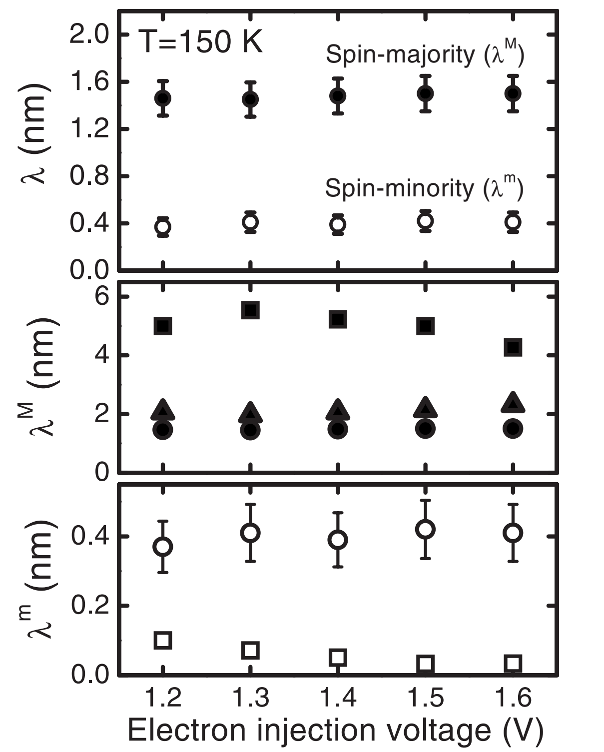

FIG. 4. (Top panel) Variation of λ^M and λ^m (closed and open circles, respectively) with electron injection voltage V_T. (Middle panel) Experimental λ^M (closed circles), calculated inelastic mean free path (closed squares, taken from Ref. 11), and extracted elastic scattering length (closed triangles), all for majority spin electrons in Fe. (Bottom panel) Experimental λ^m (open circles) and calculated inelastic mean free path (open squares, taken from Ref. 11) for minority spin electrons in Fe.

We extracted the spin-majority and spin-minority attenuation lengths in Fe at various energies in a similar way as described above. The results are plotted in the top panel of Fig. 4. We see that λ^M has an almost constant value of 1.5 ± 0.2 nm in the 1.2–1.6 eV energy range. The spin-minority length, λ^m, is significantly smaller and also has an almost constant value of 0.40 ± 0.2 nm. Thus, over the full energy range studied, the majority spin attenuation length is about a factor of 4 larger than the minority spin length. This is much larger than the ratio of the inelastic lifetimes from *ab initio* calculations,[11] which give ratios between 1 and 1.7 in this energy range. Therefore the measured spin-asymmetry of the hot-electron attenuation lengths in Fe cannot be due to the inelastic lifetime.

In the middle panel of Fig. 4 we compare the measured λ^M with the results from *ab initio* calculations.[11] The experimental values show rather weak energy variation, consistent with the calculations. The latter show that the reduction of the lifetime at larger energy is partially compensated by an increase of v_g as the energy increases beyond and away from the top of the d bands.[9,11] This deviates from the Fermi liquid theory for free electrons, from which we know that the inelastic lifetime $\tau\propto E^{-2}$ and the attenuation length as the product of τ and v_g is expected to vary as $(E+E_F)^{0.5}/E^2$. Comparing the magnitude next, we find that the calculated values of λ^{inel} are at least a factor of 3 larger than the experimentally measured values λ^{exp}. To account for this, we note that the experimental transmission is also sensitive to elastic scattering,[12] which can make the measured length shorter than the inelastic mean free path calculated. Using Matthiessen's rule $(1/\lambda^{exp}=1/\lambda^{inel}+1/\lambda^{el})$ we extract the attenuation length due to elastic scattering λ^{el} for the majority-spin electrons (triangles in Fig. 4, middle panel). We find that λ^{el} is comparable to the measured length and thus much shorter than λ^{inel}. Therefore we conclude that the majority spin attenuation length in Fe is limited by elastic (momentum) scattering of the hot electrons, rather than by inelastic scattering as intuitively expected.

A similar comparison for the minority spin (Fig. 4, bottom panel) reveals an essential difference, namely that the measured attenuation length is *larger* than the calculated λ^{inel}, the difference being as much as a factor of 8. This discrepancy cannot be explained by elastic scattering, as done for the majority spin above. Most likely, the explanation lies in the way v_g is calculated, as it represents a momentum averaged value.[11] The weighting of the different states contributing to the transport is particularly critical for hot electrons of minority spin, where in the energy region of interest (1.2–1.6 eV above E_F) the Fe density of states is dominated by an empty d band, intersecting a broader band with predominantly s,p character but much smaller density. It is the large density of d states with small v_g that produces the small value of the calculated λ^{inel}. Since states exist with significantly different v_g, the averaging becomes crucial. Possibly, in experiment the hot electrons injected into the Fe layer are not distributed homogeneously over the available states at that particular energy, but preferentially populate states with higher v_g. Thus, also for minority spin the group velocity appears to play a pivotal role in the hot-electron transmission.

In conclusion, we have examined the spin-asymmetry of transmission of hot electrons in Fe, for which a recent *ab initio* calculation has shown that the inelastic lifetime is similar for majority and minority spin. Despite this, the hot-electron attenuation length at 1.2–1.6 eV is found to be a factor of 4 larger for the majority spin. We interpret this large spin-asymmetry to arise from the spin dependence of the group velocity, rather than the inelastic lifetime which may intuitively be expected to control hot-electron transmission and its spin asymmetry.

The authors thank V. P. Zhukov, E. V. Chulkov, and P. M. Echenique for providing the results of the theoretical calculations and for stimulating discussions. We also thank M. H. Siekman and J. G. M. Sanderink for technical support. We acknowledge financial support from the NWO-VIDI program and the NanoNed program coordinated by the Dutch Ministry of Economic Affairs.

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