Excitation and spin-transport of hot holes in ballistic hole magnetic microscopy

E. Haq, T. Banerjee, M. H. Siekman, J. C. Lodder, and R. Jansen[a)]
MESA+ Institute for Nanotechnology, University of Twente, 7500 AE Enschede, The Netherlands

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A hybrid structure of a ferromagnetic $Co/Au/Ni_{81}Fe_{19}$ trilayer on *p*-type silicon is used to probe the excitation of electron-hole pairs in a ferromagnet during inelastic decay of hot electrons and the subsequent spin-dependent transport of the excited holes into the valence band of the *p*-type Si collector. The hole current is remarkably sensitive to magnetic fields, with a magnetocurrent of up to 250% and, unexpectedly, with a positive sign. We determine effective attenuation lengths and their magnetic field and bias voltage dependence. © *2006 American Institute of Physics*.
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Ballistic electron emission microscopy[1] (BEEM) is widely used to study nanoscale properties of metal-semiconductor interfaces, ultrathin gate and tunnel oxides, and metallic and silicide thin films.[2–6] Its spin-sensitive counterpart, ballistic electron magnetic microscopy[7] (BEMM), can be used for nanoscale magnetic imaging employing spin-dependent transmission of hot electrons in ferromagnetic thin films. Recently, spin-dependent transmission of hot holes, rather than electrons, was also demonstrated[8] in ballistic hole magnetic microscopy (BHMM). In BHMM, nonequilibrium holes emitted from the tip of a scanning tunneling microscope (STM) are injected locally into a ferromagnetic metal overlayer on a *p*-type semiconductor. It was shown that also for holes a thin ferromagnetic film acts as an efficient spin-filter.[8] As a result, the transmitted hole current into the valence band of the *p*-type semiconductor is magnetic field dependent.

The origin of spin filtering in ferromagnetic films can be traced to the asymmetry in the available density of states for majority and minority spins. For hot electrons this causes a spin-dependent inelastic lifetime.[9–12] Using various methods, spin dependent attenuation lengths of several ferromagnetic materials, the role of interfaces and scattering from thermal spin waves have been studied.[13–16] However, most of these studies are based on the measurement of the (ballistically) transmitted carriers, which gives only partial information about the scattering processes. Supplementary information can be obtained by investigating the scattering products, for example, the excited electron-hole (e-h) pairs.[17]

Indeed, large spin-dependent effects were recently observed[18] in the scattering or reverse mode of ballistic hole magnetic microscopy (R-BHMM). As described in Ref. 18, in reverse mode the tip voltage is negative, such that hot *electrons* are injected from the STM tip into the ferromagnetic metal stack. Inelastic decay via e-h pair excitation creates holes that can be collected in the valence band of the underlying *p*-type semiconductor. Although magnetic imaging with nanoscale resolution was demonstrated, increased understanding of the origin of the magnetic field dependence is required for further development and assessment of the ultimate resolution. Here we report on a systematic study of R-BHMM, showing that a magnetocurrent of up to 250% can be obtained. We determine the effective length scales for the transmission as a function of ferromagnetic layer thickness, and investigate the magnetic field and bias voltage dependence.

The p-Si/Au(7 nm)/$Ni_{81}Fe_{19}$/Au(7 nm)/Co/Au(3 nm) structures studied here were deposited by thermal evaporation in a molecular beam epitaxy system with a base pressure of 10^{-10} mbar. Substrates consist of HF-etched *p*-type Si(100) with a lithographically defined area of 150 μm diameter, surrounded by a thick SiO_2 insulator. First, a 70 Å Au layer is grown to form a high quality Schottky barrier of 0.3 ± 0.03 eV with a smooth surface onto which the rest of the metal layer stack is grown. Samples contain different thickness of the ferromagnetic layers and have a 30 Å Au cap layer to provide a chemically inert surface for *ex situ* sample transfer. R-BHMM measurements are performed at 150 K in a modified variable temperature ultrahigh vacuum STM, with a base pressure of 10^{-10} mbar. Current coils provide a homogeneous in-plane magnetic field. For all measurements, the metal surface is grounded and negative voltage (V_T) is applied to the PtIr tip with the tunnel current I_T kept constant using feedback. A contact to the back of the *p*-type Si is used to detect the hole current I_{hole} with a two-stage amplifier (10^{11} V/A) and a 300 Hz low-pass filter.

Figure 1 shows a series of local magnetic hysteresis loops measured with the STM tip at the same location of a $Ni_{81}Fe_{19}$(1.8 nm)/Au(7 nm)/Co(1.8 nm) trilayer on *p*-Si. Loops at a given V_T are obtained by sweeping the magnetic field between −100 and +100 Oe and back, while recording the transmitted hole current for a fixed tunnel current of I_T =4 nA. For negative V_T hot electrons are injected by tunneling from the STM tip, while the observed I_{hole} is positive, corresponding to holes flowing from the magnetic metal stack into the valence band of the *p*-type Si. The hole current is clearly magnetic field dependent and larger when the $Ni_{81}Fe_{19}$ and Co layers have their magnetization aligned parallel (P). We observe a strongly reduced I_{hole} for fields between about 10 and 50 Oe of either sign, for which the magnetic trilayer is in a state with antiparallel (AP) magnetization of the $Ni_{81}Fe_{19}$ and Co. At larger V_T the hole current increases, while the magnetocurrent (MC), defined as $MC=(I^P_{hole}-I^{AP}_{hole})/I^{AP}_{hole}$, decreases from 190% at −1.0 V to 135% at −1.6 V. Note that the MC is positive, with $I^P_{hole} > I^{AP}_{hole}$.

a)Electronic mail: ron.jansen@el.utwente.nl

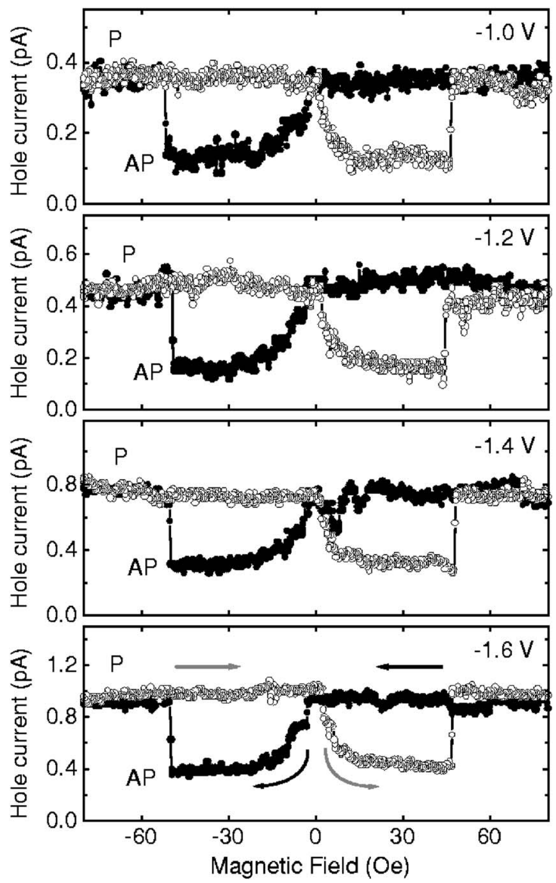

FIG. 1. Hole current vs magnetic field for the structure *p*-Si/Au/$Ni_{81}Fe_{19}$(1.8 nm)/Au/Co(1.8 nm)/Au at different electron injection voltage. States of parallel (P) and antiparallel (AP) alignment of the $Ni_{81}Fe_{19}$ and Co magnetizations are indicated, as are the field sweep directions (arrows). I_T=4 nA and T=150 K.

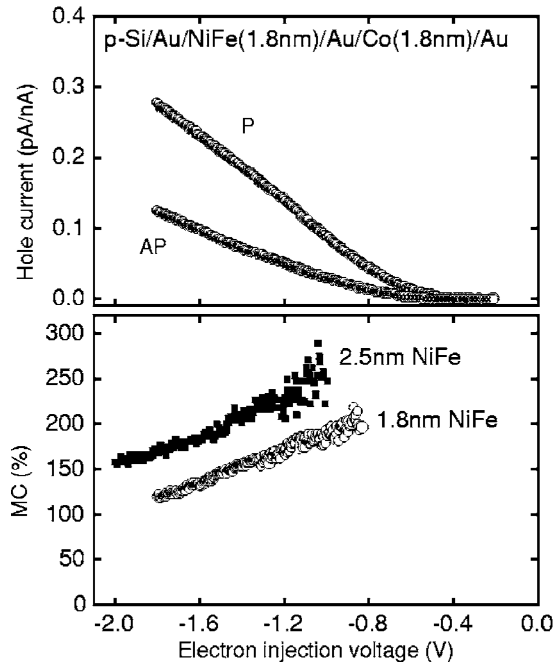

FIG. 2. Top panel: hole current per nanoamperes of injected tunnel current versus electron injection voltage for P and AP magnetic states of a structure with 1.8 nm of $Ni_{81}Fe_{19}$. Bottom panel: magnetocurrent vs electron injection voltage for two structures with 1.8 and 2.5 nm of $Ni_{81}Fe_{19}$. T=150 K.

The top panel of Fig. 2 shows typical R-BHMM spectra for the same $Ni_{81}Fe_{19}$(1.8 nm)/Au(7 nm)/Co(1.8 nm) trilayer as in Fig. 1. The spectra are obtained by recording the hole current as a function of V_T while maintaining a fixed injection tunnel current, in a constant magnetic field of +100 or −23 Oe for the P and AP state, respectively. Each spectrum is an average over 30 curves, and is normalized to the center value of the hole current distribution obtained from images of at least 1 μm^2 at a fixed tip bias of −1.6 V. For low injection voltage no hole current is detected since the injected hot electrons do not have the energy to excite e-h pairs with holes of sufficient energy to overcome the 0.3 eV Schottky barrier at the Au/*p*-Si interface. The hole current becomes detectable for tip bias larger than about −0.5 V and is always larger for the P state. At −1.8 V the hole current per injected nanoamperes of tunnel current reaches values of 0.275 and 0.125 pA for P and AP states, respectively. The resulting MC vs V_T is shown in the bottom panel of Fig. 2, also including data from another sample with a thicker $Ni_{81}Fe_{19}$ layer of 2.5 nm. The latter shows a larger MC of up to 250%, but a similar bias dependence with a decay of MC at larger V_T.

To examine the origin of the large MC we prepared a series of structures with varying thickness of the $Ni_{81}Fe_{19}$ layer from 1.0 to 2.8 nm, keeping the Co layer thickness fixed at 1.8 nm. The results are shown in Fig. 3, where each data point represents a value averaged over an area of at least 1 μm^2. The top panel shows that the MC increases at larger thickness of the $Ni_{81}Fe_{19}$ layer, clearly ruling out a pure interface effect. The variation of the hole current with $Ni_{81}Fe_{19}$ thickness for P and AP configurations is shown in Fig. 3, middle panel. For both magnetic states we observe that the hole current decays exponentially with the thickness d of the $Ni_{81}Fe_{19}$ layer, as indicated by the straight solid lines. The collected hole current depends on the rate of e-h pair generation during inelastic decay of the injected hot electrons, as well as on the subsequent scattering of the created nonequilibrium holes. Therefore, the decay of the collected hole current is expected to be a combination of hot electron and hole attenuation lengths. However, one can define an effective attenuation length such that the hole current decays as $\exp[-d/\lambda_{eff}(E)]$ where $\lambda_{eff}(E)$ is the energy dependent effective attenuation length and E is the energy of injected hot electrons. From fits such as those shown in the middle panel of Fig. 3 we extracted λ_{eff} for the P and AP configurations. The results are shown in the bottom panel of Fig. 3 for electron injection energies between 0.8 and 1.6 eV. Over the full energy range investigated, the extracted values are $\lambda_{eff}^{P}=1.6\pm0.1$ nm and $\lambda_{eff}^{AP}=0.9\pm0.1$ nm for P and AP configurations, respectively.

The observed λ_{eff} is shorter than the hot-electron attenuation length in $Ni_{81}Fe_{19}$ previously found to be 4–8 nm using spin-valve transistors[15] or magnetic tunnel transistors.[16] However, in R-BHMM the effective attenuation length is determined by the inelastic scattering length of the injected (primary) hot electrons, as well as the scattering length of the created (secondary) hot holes. For Co, the attenuation lengths for holes are found to be significantly shorter (0.6–1.0 nm, see Ref. 8) than those for hot electrons, and the same may be expected for $Ni_{81}Fe_{19}$. Indeed, the measured values for λ_{eff} are between the scattering lengths of hot electrons and holes. Moreover, since at larger energy hot-electron attenuation lengths generally become shorter,[14,16] while scattering lengths for holes were found to increase at larger

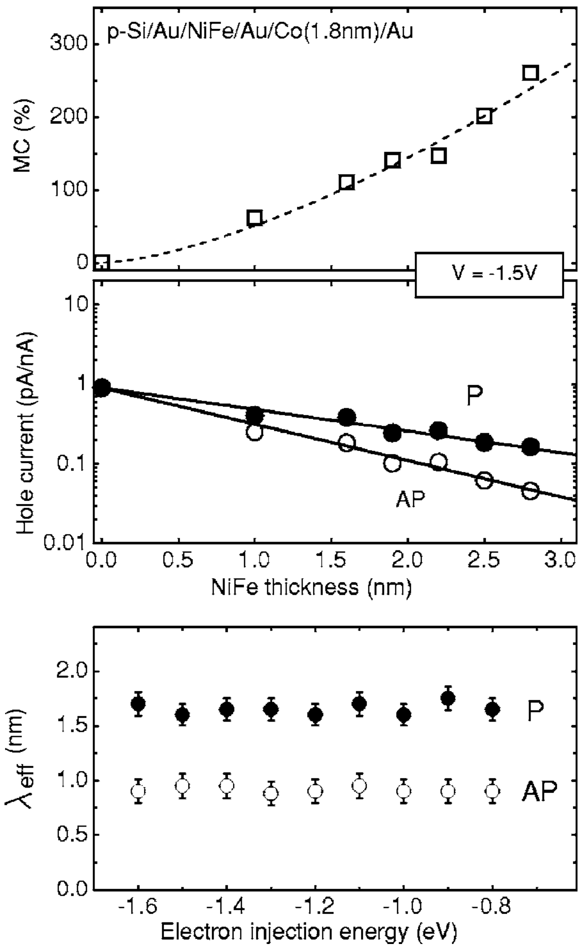

FIG. 3. MC (top panel) and hole current in P and AP states (middle panel) vs NiFe thickness for the structure p-Si/Au/$Ni_{81}Fe_{19}$/Au/Co(1.8 nm)/Au at $V_T=-1.5$ V. The dashed line in the top panel is a guide to the eye. The solid lines in the middle panel represent fits based on exponential decay. Bottom panel: variation of decay length λ_{eff} with electron injection voltage for P and AP states. $T=150$ K.

energy,[8] this opposite behavior would also explain why the observed λ_{eff} is rather insensitive to the injection energy.

Finally, we observe that the magnetocurrent is positive with $I_{hole}^{P} > I_{hole}^{AP}$. This is surprising, since to first order one might assume that the hole current is proportional to the number of e-h pairs created. It is well known that hot-electron transmission in a magnetic trilayer is much larger in P state than in AP state, which implies that more e-h pairs are created in the AP state. This would lead to a larger hole current in the AP state and thus a negative MC. A more detailed model is thus needed to describe the process of e-h pair excitation and the subsequent spin-dependent transmission and scattering of the excited holes in the ferromagnets and at their interfaces. Preliminary modeling suggests that the location where e-h pairs are created in the magnetic trilayer should be taken into account, as well as the spin of the excited holes and how it is related to the spin of the primary hot electron.

In conclusion, we presented a systematic study of the magnetocurrent in reverse mode BHMM in which hot electrons injected into a magnetic trilayer cause excitation of e-h pairs, followed by spin-dependent transmission of the excited holes. The magnetocurrent is found to be positive with values up to 250%, increasing with ferromagnetic layer thickness. The effective attenuation lengths in $Ni_{81}Fe_{19}$ are 1.6 and 0.9 nm for P and AP states of the magnetic trilayer, independent of electron energy.

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