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# Nanoscale magnetic hysteresis of $Ni_{80}Fe_{20}$/Au/Co trilayers using ballistic electron magnetic microscopy

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Ballistic electron magnetic microscopy is used to study spin-dependent hot-electron transport and local magnetic switching of ferromagnetic thin films grown on a Au/Si(100) collector. For $Ni_{80}Fe_{20}$ films, the collector current is a factor of 2 larger than for Co, consistent with the shorter hot-electron attenuation length of Co. For $Ni_{80}Fe_{20}$/Au/Co spin valves, the collector current is reduced by a factor of 5 when the relative magnetization of the ferromagnetic layers changes from parallel to antiparallel. By sweeping the applied magnetic field, we obtain nanoscale hysteresis loops, where the hot electrons are collected from an area of about 10 nm. 
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Spin-dependent electronic transport in multilayer structures is the basis of magnetoelectronic devices that are applied in magnetic field sensors and magnetic random access memory.[1] Key to the development of such technologies is a sound understanding of the spin-dependent transmission of Fermi electrons and hot electrons through ferromagnetic thin films and their interfaces. Equally important is the local magnetic switching behavior and its relation with film structure. A useful technique for high-resolution imaging is ballistic electron emission microcopy (BEEM),[2] which provides a method to probe transport and interface properties of metal–semiconductor (M–S) systems with nanometer resolution.

In BEEM, the tip of a scanning tunneling microscope (STM) is used to locally inject a hot-electron current $I_T$ into a metal thin-film stack grown on a semiconductor substrate. In addition to the usual STM images of the sample surface, a contact at the back side of the semiconductor substrate is used to collect the hot electrons that are transmitted through the metallic thin films and are able to surmount the barrier at the M–S interface. The collector current $I_C$ consists of a small fraction of electrons that satisfy the energy and momentum constraints for collection. Due to the local nature of the tunnel current injected from the STM tip, and the energy and momentum selection at the M–S interface, the electrons that scatter at large angles are not collected.[2] This results in a high spatial resolution of a few nanometer.[3]

Recently, ballistic electron magnetic microscopy (BEMM) was introduced[4] as the magnetic counterpart of BEEM. It was used to image magnetic domains and magnetization reversal in Co/Cu/Co nanostructures.[4,5] BEMM is similar to BEEM except that it uses samples that contain a ferromagnetic spin valve in the metal layer stack and a magnetic field is applied. Since scattering of hot electrons in ferromagnetic materials is spin dependent,[6–8] the minority spin electrons are attenuated more strongly than the majority spins. The collector current is therefore high when the ferromagnetic layers of a spin valve are aligned parallel, and low when the alignment is antiparallel. Recording the collector current at a fixed location and constant tip bias and current in a varying external applied field gives a hysteresis loop of collector current, providing information about the nanoscale magnetic switching behavior. So far, such hysteresis loops have only been reported for Fe/Au/Fe spin valves.[9] Here, we study the local transport properties of ferromagnetic thin films (NiFe, Co, and NiFe/Au/Co) and present nanoscale hysteresis measurements on NiFe/Au/Co spin-valve structures using BEMM.

All of the samples used in this study were deposited by thermal evaporation in a molecular-beam epitaxy system with a base pressure of $10^{-10}$ mbar. Substrates consist of HF-etched Si(100) with a lithographically defined area of 150 $\mu$m in diameter, surrounded by a thick $SiO_2$ insulator. First, a 7 nm Au layer is grown to form a high-quality Schottky barrier of about 0.8 eV and a smooth interface. Subsequently, the rest of the metal layer stack is grown. Samples used here have a single Co layer (3 nm), a single $Ni_{80}Fe_{20}$ layer (3 nm), or a $Ni_{80}Fe_{20}$ (5 nm)/Au(7 nm)/Co(2 nm) spin valve. For the spin valve, the 7 nm Au spacer layer magnetically decouples the two magnetic layers. A thin (3 nm) Au cap layer is deposited in the end to provide a chemically inert surface for *ex situ* sample transfer. BEMM measurements are performed in a variable temperature UHV-STM, where the base pressure is $2\times10^{-10}$ mbar. Two current coils provide a homogenous in-plane magnetic field ($-175$ to $+175$ Oe). All measurements are recorded at a low temperature (150 K) except where stated otherwise. For all measurements, the metal surface of the sample is grounded and a negative bias is applied to the tip such that electrons are injected from the tip into the sample. The collector current is measured using a two-stage amplifier with a gain of $10^{10}$ or $10^{11}$ V/A and a 300 Hz low-pass filter. BEEM spectra are recorded by measuring $I_C$ while sweeping the tunnel bias, using the feedback loop to keep the tunnel current constant. The curves presented below are an average of 45 curves recorded at a fixed location.

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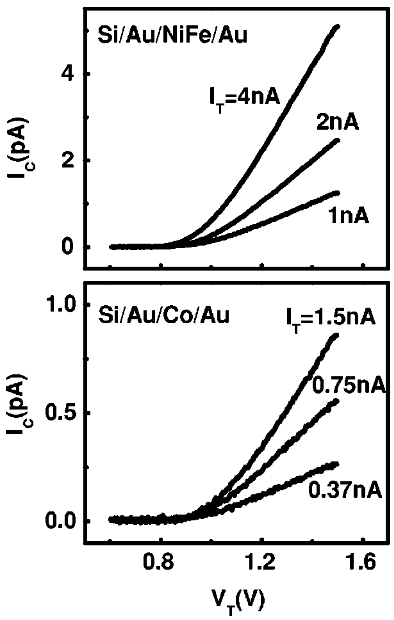


FIG. 1. BEEM spectra recorded at a fixed location for three different tunnel currents on Si(100)/7 nm Au/3 nm NiFe/7 nm Au (top panel), and Si(100)/7 nm Au/3 nm Co/3 nm Au (bottom panel). $T = 150$ K.

Shown in Fig. 1 are the BEEM spectra of the 3 nm NiFe film (top panel) and the 3 nm Co film (bottom panel) at three different constant tunnel currents. The collector current shows an onset close to a tip bias of $-0.8$ eV, corresponding to the Schottky barrier height of Au/Si, and scales with the tunnel current. At 1.5 eV, the ratio of the collector to tunnel current $I_C/I_T$ is $\sim 1.3\times 10^{-3}$ for the NiFe film and $\sim 6\times 10^{-4}$ for the Co film. The transmission of Co is lower than that of NiFe due to the shorter hot-electron attenuation length of Co. Using attenuation lengths for majority spin electrons of 43 Å for NiFe (Ref. 6) and 23 Å for Co,[8] the expected transmission of Co is $\sim$1.8 smaller than that of NiFe, which is close to our measured value of $\sim$2.1.

Figure 2 shows BEEM spectra for a NiFe/Au/Co spin valve at three different constant tunnel currents. The $I_C/I_T$ ratio is $\sim 1.6\times 10^{-4}$. Starting from the data for the 3 nm

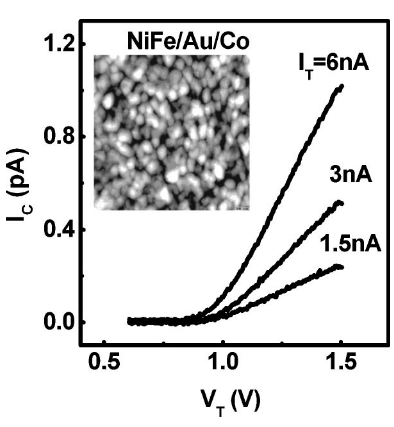


FIG. 2. BEEM spectra recorded at a fixed location for three different tunnel currents on Si(100)/7 nm Au/5 nm NiFe/7 nm Au/2 nm Co/3 nm Au at $T = 150$ K. The inset is a 200 nm×200 nm STM image recorded at $I_T = 400$ pA and $V_T = -0.4$ V at room temperature.

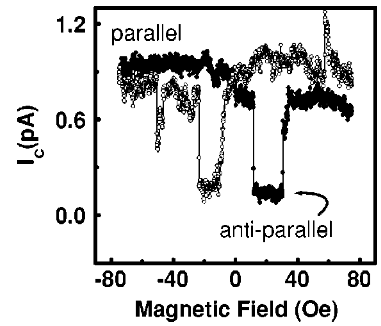


FIG. 3. BEMM hysteresis loop, displaying the collector current vs magnetic field at $T = 150$ K for the structure: Si(100)/7 nm Au/5 nm NiFe/7 nm Au/2 nm Co/3 nm Au. The collector current changes from low to high as the two ferromagnetic layers switch between antiparallel (AP) and parallel (P) magnetic alignment, as indicated. Open and solid symbols represent the branch of the loop for decreasing and increasing magnetic field, respectively.

NiFe film, we expect $I_C/I_T \sim 2\times 10^{-4}$ for the spin valve, using the attenuation lengths for NiFe, Co, and a value of 130 Å for Au,[10] and taking the different layer thickness into account. The measured value is lower most probably due to the scattering at the Au/Co interfaces.[11] The inset of Fig. 2 shows the granular structure of the NiFe/Au/Co spin valve, imaged at low tunnel current ($I_T = 400$ pA) and bias ($V_T = -0.4$ V) at room temperature.

In Fig. 3, the magnetic field dependence of the collector current for the NiFe/Au/Co structure is shown. The magnetic field was first increased to +75 Oe and then swept in small steps ($\sim$0.1 Oe) to $-75$ Oe and back to +75 Oe, while the collector current is recorded at constant tunnel current $I_T$ (6 nA) and tip bias $V_T$ ($-1.4$ V). We observe a considerable change of the collector current as the magnetic field is varied. For both field polarities, the collector current is minimum between $\sim$10 and $\sim$30 Oe, where the difference in coercivity creates a field region where the magnetizations of the NiFe and Co layers are in antiparallel alignment. In this state, the collector current $I_C^{\mathrm{AP}} \sim 0.15$ pA. At fields larger than 30 Oe, the spin valve is forced into a parallel magnetic alignment, resulting in a much higher collector current of $I_C^P \sim 0.8$ pA. Thus, we observe a change in the collector current by approximately a factor of 5 with an external applied magnetic field corresponding to a magnetocurrent of about 400%. The observed relative change in collector current in a magnetic field is comparable to what is observed in the spin-valve transistor[12] for similar layers in the metal base.[13]

The spatial resolution of BEEM is known[3] to be of the order of 5 nm. Although we have not yet determined the exact resolution of our BEMM system, we note that the STM tip moves relative to the sample by no more than about ±5 nm as the magnetic field varies from +75 to $-75$ Oe. Thus, the hysteresis loop shown here is based on information originating from a nanoscale area. The loop displays a sharp transition of the collector current from its maximum to minimum value when the spin valve switches from parallel to antiparallel alignment. Although the change in collector current has a similar magnitude for both positive and negative field branches of the loop, the switching is not symmetric. The origin of this asymmetry and possible local variations in coercive field are currently under further investigation.

In conclusion, we have used BEMM to study spin-dependent hot-electron transport and local switching behavior of ferromagnetic thin films. On a NiFe/Au/Co spin valve, we observe a clear change in $I_C$ by a factor of 5 when the ferromagnetic layers are switched between states of parallel and antiparallel alignment. Given the nanometer scale resolution, BEMM hysteresis loop measurements are a useful tool to study local switching behavior in ferromagnetic thin films and magnetic nanostructures.

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