Hot Electron Transport and High Resolution Magnetic Imaging on Co/Cu/Co and Co/Cu/NiFe Spin Valves

A. Kaidatzis[1*], S. Rohart[1], A. Thiaville[1] and J. Miltat[1]

[1] *Laboratoire de Physique des Solides, CNRS, Université Paris Sud, UMR 8502, 91405 Orsay cedex, France*

**andreas.kaidatzis@gmail.com*

The research of magnetic systems with reduced dimensions implies the capability of imaging magnetic structures down to the nanometer scale. The scanning tunnelling microscope (STM) is a powerful tool for high resolution imaging [1]. For magnetic imaging, we develop a variant of the STM named the ballistic electron emission microscope (BEEM) [2]. Beyond imaging, this microscope offers perspectives for local hot electron transport studies in magnetic structures. This allows a better understanding of the physics of components like the spin valve transistor [3], or the magnetic tunnel transistor [4], operating on the basis of hot electron transport.

BEEM is a three terminal modification of the STM (see Fig. 1). A BEEM sample is constituted by a thin metallic layer or multilayer (10 to 20 nm thick), deposited on a semiconductor. The STM tip is used as a local, adjustable energy electron source (injector). When injecting electrons at a given energy above the sample Fermi level, a fraction of them crosses the metallic layers without being scattered (ballisticaly) and conserve their initial energy (hot electrons), while the others are thermalized to the Fermi level. Thanks to the Schottky barrier present at the metal/semiconductor interface that acts as an energy filter, only the hot electrons enter into the substrate. Two sample contacts are utilized: one on the metallic layer (base), and the other on the semiconductor (collector). The yield of the hot electrons entering into the semiconductor is measured using the collector terminal, while the thermalized electrons are evacuated by the base terminal. Thus, it is possible to measure locally the hot electron transmission of the multilayer with a nanometre scale resolution.

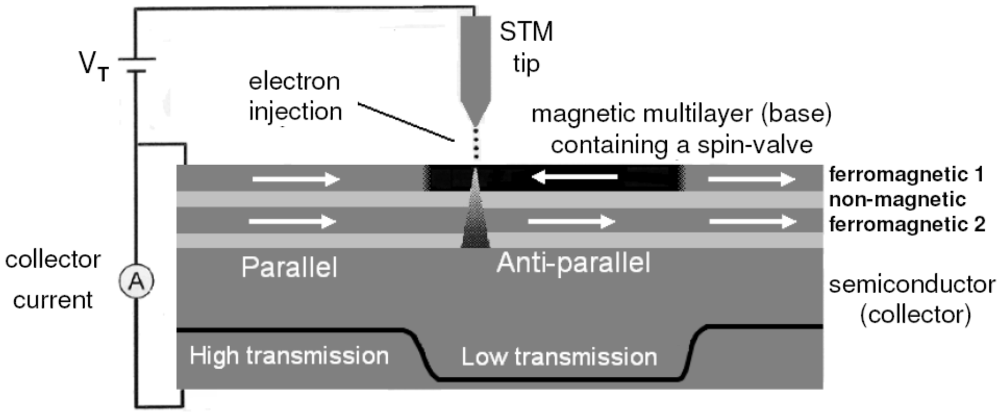

Figure 1: Configuration of a BEEM experiment for high resolution magnetic imaging. The STM tip (injector), the magnetic multilayer (base), and the semiconductor substrate (collector) are apparent. For parallel magnetic configuration of the spin valve the multilayer hot electron transmission is high, while it is low for anti-parallel configuration.

When the metallic multilayer contains a "spin valve", two ferromagnetic layers separated by a non-magnetic layer, the transmission depends on the relative magnetization orientation of the two layers (see Fig. 1). This is a consequence of the mean-free path difference between the hot majority and minority electrons in a ferromagnetic metal. An important magnetic contrast, up to several hundred percent at room temperature, can be thus observed. For performing magnetic imaging, the one of the ferromagnetic layers is magnetically saturated, acting as an "analyzer" of the hot electrons "polarized" when crossing the magnetic structures of the other ferromagnetic layer.

Multilayers were deposited in an ultrahigh vacuum (UHV) chamber (base pressure $<10^{-9}$ mbar) using an e-gun evaporator. The hydrogenated Si(111) surface was used as a substrate. Initially a Au layer of some nanometers was deposited to form a homogeneous Schottky interface. Afterwards, a Cu/F1/Cu/F2/Cu multilayer was deposited, with F1 and F2 being 2 nm thick ferromagnetic layers (Co or NiFe). All the experiments were performed at room temperature using a UHV-STM. Samples containing single ferromagnetic layers have been also fabricated and measured, in order to serve as a reference for analyzing the hot electron transport in the spin valves.

First, the hot electron transport properties of the single Co and NiFe layers will be presented. The transmission study as a function of the layer thickness yields the hot electron mean free path in each metal. By comparing the results obtained on the single ferromagnetic layer samples with those of the spin valve samples, it is possible to separate the hot electron mean free path as a function of their spin, in the range 1 to 2 eV above the Fermi level [5]. It is demonstrated that the mean free path is 2 to 3 times longer for the majority electrons. Consequently, in the spin valve samples, a transmission contrast of 50 to 200% between the parallel and anti-parallel state is observed, well above the giant magnetoresistance value measured for the same samples (approximately 1%).

Magnetic images obtained from the spin valve samples, will be also discussed [5]. The magnetization reversal of the Co and NiFe layers by nucleation and growth is observed as a function of the externally applied magnetic field. The observation of 360° domain walls in the Co layers (see Fig. 2) will be discussed in detail. The microscope resolution allows discussing their shape and size. It is demonstrated that the domain wall has an asymmetric profile when a magnetic field is applied in a non-collinear direction with respect to the domain wall direction. These results are compared to micromagnetic calculations, and it is shown that the microscope magnetic resolution is better than 50 nm.

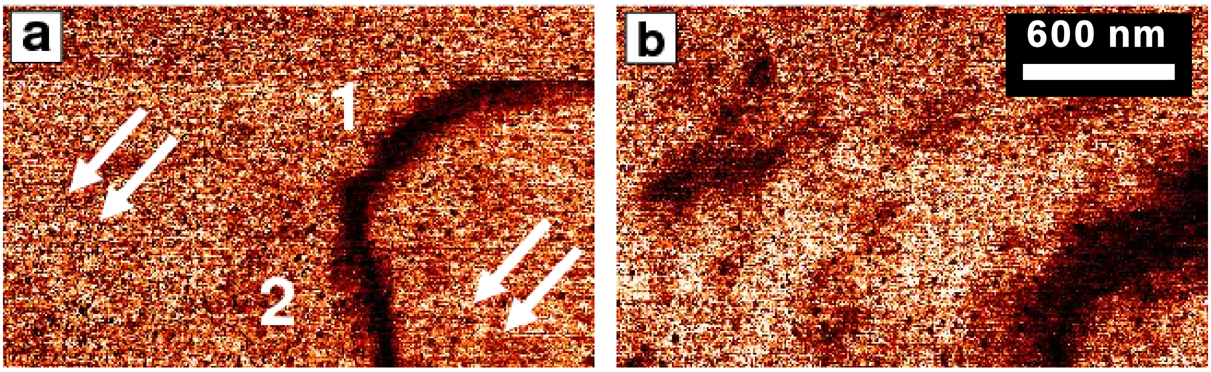

Figure 2: BEEM imaging of a Co/Cu/Co. The scanning area is 2.4 × 1.5 μm^2. (a) Imaging in a 100 Oe externally applied magnetic field. The white arrows indicate the direction of the magnetization in the two magnetic layers, which is saturated by the applied field. The observed dark structure corresponds to a 360° domain wall in one of the two Co layers. Part 1 corresponds to a domain wall collinear to the directioin of the applied magnetic field and presents a symmetric profile; part 2 corresponds to a non-collinear to the applied field domain wall and presents an asymmetric profile. (b) Imaging in a 20 Oe externally applied magnetic field (same field direction and scanning area as before) obtained after image (a). The domain wall has been displaced and it is less narrow than in the previous image.

In conclusion, the capacity of our microscope to perform spin-dependent hot electron transport studies in magnetic multilayers and to obtain high resolution magnetic domain images has been demonstrated. This microscope allows for precise studies of magnetic configurations in multilayers and nanostructures.

[1] Binnig G., Rhorer H., IBM J. Res. Develop. 30, 279 (1986)
[2] Rippard W.H. and Buhrman R.A., Phys. Rev. Lett 84, 971 (2000)
[3] Monsma D.J. et al., Science 281, 407 (1998)
[4] van Dijken S. et al., Appl. Phys. Lett. 83, 951 (2003)
[5] Kaidatzis A. et al., Phys. Rev. B 78, 174426 (2008)

Acknowledgments The authors gratefully acknowledge the help of J. Ferré for magneto-optical characterization, M. Aprili for e-beam evaporation and the loan of his deposition setup, and A. Gloter for band-structure calculations. Financial support was provided by C'Nano Île de France (STCalib project). A.K. received funding from the EC Marie Curie host training site Emergent CondMatPhys (Grant No. MEST-CT-2004- 514307).

.