Magnetic Tunnel Transistors Studied by Ballistic Electron Emission Microscopy

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In this work, spin valve structures as they are employed in the base layers of magnetic tunnel transistor devices are locally characterized by BEEM. For the experiments, n-type (N_D=10x17cm^{-3}) GaAs [100] bulk wafers were used. As base layer, the following sequence of polycrystalline metal layers was sputtered onto the substrate: Co 4.5 nm, Cu 4.2 nm, Py 3.5 nm. The layers were deposited in the presence of a magnetic bias field along the [100] direction of the GaAs which causes a uniaxial anisotropy in both layers. For STM operation, an additional layer of Au (4.0 nm) was sputtered on top.

Figure 1 (a) shows two typical BEEM spectra, which are the measured collector current as a function of STM bias. At zero magnetic field after saturation of the magnetization, the current onset is observed at V_t = 1.0V which is determined by the Schottky barrier height at the Co-GaAs interface. Above that bias, the collector current increases in a roughly quadratic dependence on the bias, as it is typical for BEEM signals on bulk GaAs samples. If the magnetization of the spin-valve is oriented in antiparallel directions at an applied magnetic field of H = 26 Oe, however, the ballistic collector current is considerably quenched. Here, the collector current is below the detection limit for voltages smaller than V_t = 1.2 V and then increases just slowly. In addition, the spectral behavior does not appear typically quadratic and even shows some hints of saturation. This behavior is currently not fully understood and will be subject of further investigations. As a consequence of the significantly quenched BEEM current in the antiparallel state, the “magnetocurrent” MC, usually defined as the ratio of the ballistic current in the parallel ($I_{C,P}$) and antiparallel ($I_{C,AP}$) magnetization configuration minus one (MC = $I_{C,P}$ /$I_{C,AP}$ – 1), is surprisingly high. At V_t = 1.5 V, $I_{C,P}$ = 0.7 pA and the value of $I_{C,AP}$ is just 0.1 pA yielding a MC value of 600% at room temperature.

Figure 1 (b) shows the ballistic current as a function of magnetic field along the easy magnetization axis at a fixed value of V_t. The curves were measured at V_t = 1.5 V and I_t = 20 nA. At H = –67 Oe, the magnetic layers are in parallel configuration and in saturation magnetization. Running from H = –67 Oe to H = +67 Oe, the magnetic layers flip into the antiparallel configuration at H = +19 Oe and the BEEM current is quenched. At H = +43 Oe the hard magnetic layer changes its orientation too, and the spin filtering effect is switched off again. This behavior is symmetric on the H-field axis. The states are well separated indicating a negligible magnetic interaction between the layers. The sharp switching between the two states can be understood by the local character of the BEEM method. It is caused by a sudden transition of a single domain wall underneath the tip. Within the scanning range of our STM, however, the switching position was always exactly at the same field value within the experimental error and in the absence of pinning centers.

On large area scans (4 µm x 4 µm), magnetic domains are observed in the BEEM images. Figure 2 shows such magnetic domains, which only occur in the vicinity of the switching field of the spin valve. Note, the sample was not exposed to the maximum magnetic field level of H = 73 Oe during the imaging. The values were varied between

H = 0 Oe (parallel spin configuration) and H = 30 Oe (antiparallel spin configuration). The magnetic field level to reach the parallel spin configuration coming form the antiparallel state was H = 12 Oe. In image (a), at zero magnetic field, the transmission is high and almost constant in the scanning area. An imperfection in the film is weekly visible on the upper right hand side of this image. Note that this imperfection is just visible in the BEEM image, not in the topographic image, which is not shown here. Image (b) was taken at the switching field of the spin valve from the antiparallel state to the parallel state at H = 12 Oe. On the left hand side, the transmission is high, whereas on the right hand side, a domain with low transmission is formed. The imperfection is now clearly visible as a wormshaped and bright feature. The domain is obviously pinned at this defect. Image (c) shows the transmitted current in antiparallel configuration of the spin valve at H = 30Oe. Here the transmission is low everywhere except in the region of the film imperfection. Switching back to the magnetic field of image (b) H = 12Oe, the domain appears again as shown in image (d). However, it has changed its shape. In addition, the overall transmission appears to be somewhat reduced.

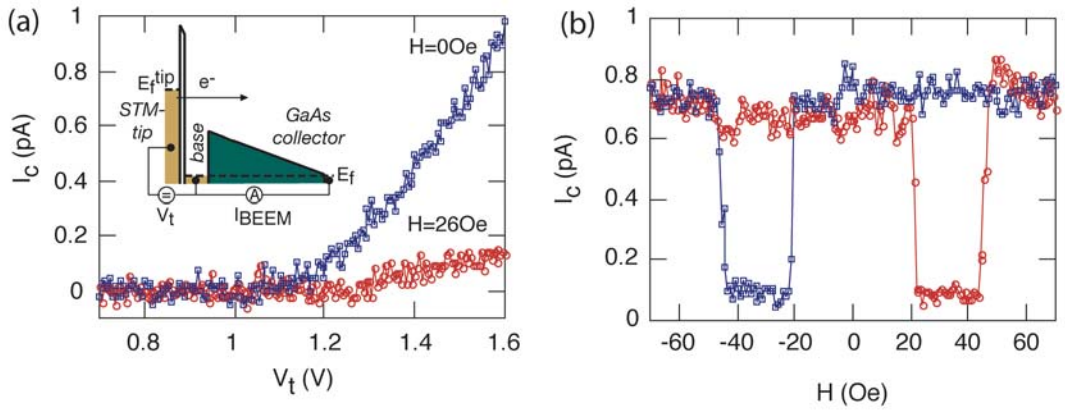

Fig 1: (a) Typical BEEM spectra recorded at H = 0 Oe and H = 26 Oe. The tunneling current I_t was 20 nA and the temperature 300 K. A schematic setup of the experiment is shown in the inset.
(b) Collector current measured as a function of the magnetic field. (V_t = 1.5 V, I_t = 20 nA, T = 300 K)

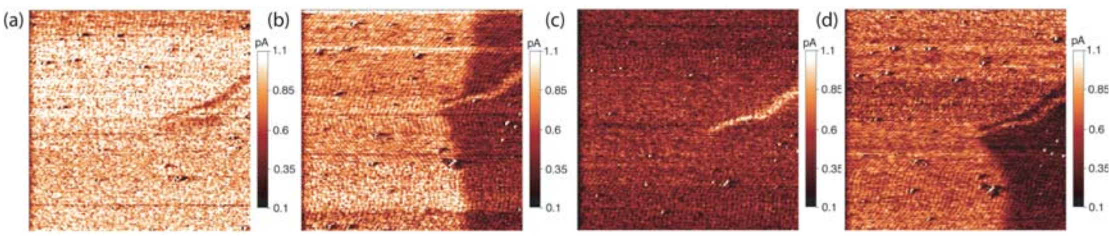

Fig. 2: Large area BEEM images showing magnetic domains in the vicinity of the switching field of the spin valve. Images (a) – (d) were recorded sequentially on the same position at different magnetic field levels of a minor loop. A film imperfection is visible on the upper right hand side of all images. The scan size is 4 µm x 4 µm and the images were recorded V_t = 1.8 V, I_t = 20 nA and T = 300 K)