Current-induced magnetization dynamics in single and double layer magnetic nanopillars grown by molecular beam epitaxy

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Abstract
Molecular beam epitaxy is used to fabricate magnetic single and double layer junctions, which are deposited in prefabricated nanostencil masks. For all Co|Cu|Co double layer junctions we observe a stable intermediate resistance state, which can be reached by current starting from the parallel configuration of the respective ferromagnetic layers. The generation of spin waves is investigated at room temperature in the frequency domain by spectrum analysis, demonstrating both in-plane and out-of-plane precessions of the magnetization of the free magnetic layer. Current-induced magnetization dynamics in magnetic single layer junctions of Cu|Cu|Cu has been investigated in magnetic fields, which are applied perpendicular to the magnetic layer. We find a hysteretic switching in the current sweeps with resistance changes significantly larger than the anisotropic magnetoresistance effect.

(Some figures in this article are in colour only in the electronic version)

1. Introduction
Spin-transfer-induced magnetization dynamics has been studied experimentally [1–7] since the theoretical predictions by Slonczewski [8] and Berger [9]. A standard spin transfer device consists of two ferromagnetic (FM) layers of unequal thicknesses, separated by a nonmagnetic (NM) layer forming a nanopillar with a lateral dimension on the 100 nm scale. Electrons flowing perpendicular to the sample plane get spin polarized by passing one of the ferromagnets and then repolarized at the other NM/FM interface. Thereby the spin component transverse to the second FM layer’s magnetization is absorbed and acts as a torque on its magnetization. Because of the difference in layer thicknesses, only the magnetization of the thin FM layer gets destabilized and can either be switched or excited in a precessional mode depending on the applied field and the passing current [10–12].

A sufficiently large electric current can affect the magnetization state of a ferromagnet not only in double FM layer systems, but also in single FM nanopillars [13–19]. A current flow generates a spin accumulation at both interfaces of the NM/FM/NM trilayer. To obtain an unequal torque on the magnetization the spin accumulations have to differ. This can be achieved by asymmetric NM leads. Again, the interface plays an important role for both switching behaviour and magnetization dynamics. One approach to better control the interfaces is the use of molecular beam epitaxy (MBE) [20]. We therefore fabricated magnetic nanopillars consisting of both magnetic single and double layer structures by MBE and analysed their current-induced switching behaviour by magneto-transport and by high-frequency (HF) probes.

2. Samples and experimental setup
Focused-ion-beam (FIB) milling is used to fabricate nanostencil templates, which are suited for the preparation of multilayered spin-valve structures in the current perpendicular
to plane (cpp) geometry [4, 21, 22]. This approach allows us to quickly modify and optimize both material combinations and growth conditions. The device dimensions are defined prior to the thin film deposition. In figure 1 we summarize the relevant process steps. First, a bottom electrode is fabricated by optical lithography and subsequent Ar⁺ etching of an extended Pt layer, which was sputtered onto a Si substrate. Subsequently, an insulator SiO₂ and a second Pt layer are sputtered. Next FIB (the FEI Strata 205 with Ga⁺ liquid metal ion source has been operated at 30 keV with a beam current of 1 pA) is used to open up an aperture in the top Pt layer. The size of the aperture directly defines the diameter of the magnetic nanopillar device. The aperture in the hard mask gives access to the underlying insulator for the subsequent HF dip, which yields an isotropic selective wet etching of the SiO₂. The resulting undercut (for schematic picture see figure 1(a)) can be easily imaged by scanning electron microscopy (SEM) in top view of the apertures (figure 1(b)). The nanostencil is then transferred into an MBE chamber for the growth of the desired thin film stack (figure 1(c)). Details about the crystallinity of the pillars will be discussed elsewhere [23]. As a final step the undercut is filled up with a thick Cu contact layer. Optical lithography and Ar⁺ milling is then used to define a top electrode in cross-point geometry which guarantees electrical access to both top and bottom electrodes.

Transport measurements were performed at room temperature in an external magnetic field. The differential resistance $dV/dI$ was measured in four-point geometry (see figure 2) by a lock-in technique with a 100 μA modulation current at $f = 1132$ Hz which is superimposed to a dc current.

The sample is connected to a HF sample holder. It consists of a flexible HF cable and a coplanar waveguide (not shown in figure 2) with a total bandwidth of $\sim$18 GHz. In order to detect the microwave emission of the junction we used a bias tee which separates dc from HF signals. The latter is amplified by 40 dB and analysed by a 44 GHz bandwidth spectrum analyzer.

Positive current is defined by electron flow from the thin to the thick FM layer in magnetic double layer samples while in magnetic single layer samples positive current is given by electron flow from the thin to the thick Cu metal layer.

3. Spin transfer studies in magnetic double layer systems

We first focus on magneto-transport and microwave emission data on magnetic double layer samples. The stack sequence of the pillar junction is $[3 \text{ nm } \text{Co} | 25 \text{ nm } \text{Cu} | 15 \text{ nm } \text{Co}]$. As an example, we discuss results on a $50 \times 150 \text{ nm}^2$ junction in more detail. In figure 3 we compare the magnetic switching as obtained in the differential resistance from magnetic field sweeps (figure 3(a)) and from current sweeps (figure 3(b)). Data are taken at room temperature with the magnetic field oriented in the sample plane close to the easy axis direction.
The magnetoresistance curve was taken at a small dc current of 0.1 mA (figure 3(a)). The device shows a clear hysteretic switching between a low resistive parallel (P) and high resistive antiparallel (AP) states with a magnetoresistance value of $\Delta R/R \approx 3.1\%$ (see black curve in figure 3(a)). By sweeping the magnetic field from large positive ($H > H_c$) to negative values the junction first remains in the low-resistance state for $H > 0$ and switches completely into the high-resistance state at small negative fields. Note that in contrast to the switching at the outer coercive fields the low field switching is not abrupt. It rather appears in two steps (see arrow in figure 3(a)).

We now discuss the current-induced switching behaviour for positive magnetic fields. The junction was first set into the P state by a large positive magnetic field. Current sweeps were then systematically recorded upon lowering the magnetic field. As an example, we show a current sweep at 300 Oe in figure 3(b). Hysteretic switching can be clearly observed. Note that the current-induced change in resistance is significantly smaller ($\Delta R/R \approx 1.9\%$) than the values obtained in the magnetic field sweep (see dotted lines in figure 3 as guides to the eye). For comparison, we added the current-induced high resistance values resulting from current sweeps obtained at 0.1 mA in figure 3(a) as red open triangles. It is obvious that we cannot reach the AP state of the junction at any magnetic field. We rather switch into a different magnetic state of the device. This new magnetic state is stable even for current values up to 20 mA. Note that the critical field value below which we observe current-induced switching does not match the coercive field of the free layer ($H_c = 1200$ Oe), which again indicates that we are not switching into the AP state. We want to emphasize that we observe such a switching into an unstable regime. Although we never reach the AP state by current sweeps in our devices, our phase diagram has striking similarities to previous results on sputtered Co/Cu/Co samples [11, 12, 22, 24]. The main difference in our MBE grown samples is that we switch into a stable intermediate state and not into the AP state. Note, that in all other studies, current-induced switching is observed right below the coercive field of the free layer and the junctions can be switched into the AP state at all positive fields.

In figure 4 we summarize the threshold currents for current-induced magnetization reversal in a false colour plot of the differential resistance $dV/dI$, which is subtracted from the parabolic background (see figure 3(b)) and averaged over both current sweep directions for a magnetic double-layer junction ($3 \text{ nm Co} \mid 25 \text{ nm Cu} \mid 15 \text{ nm Co}$, cross-sectional area $50 \times 150$ nm$^2$). Dashed lines indicate the boundaries between different magnetization configurations of the junction: low resistance (parallel alignment P), high resistance (intermediate state I), hysteretic regime (P/I) and unstable regime (U) for large fields and large positive currents. (Colour online.)

Figure 4. False colour plot of the differential resistance $dV/dI$, which is subtracted from the parabolic background (see figure 3(b)) and averaged over both current sweep directions for a magnetic double-layer junction (3 nm Co $\mid$ 25 nm Cu $\mid$ 15 nm Co, cross-sectional area $50 \times 150$ nm$^2$). Dashed lines indicate the boundaries between different magnetization configurations of the junction: low resistance (parallel alignment P), high resistance (intermediate state I), hysteretic regime (P/I) and unstable regime (U) for large fields and large positive currents. (Colour online.)

Although we do not reach the AP state by current, our phase diagram also shows an unstable regime. In comparison with previous microwave studies on the sputtered samples, it is therefore interesting to explore the magnetization dynamics of our samples in this regime. The microwave emission of the junction has been detected in the frequency domain by spectrum analysis. Figure 5(a) depicts selected HF spectra measured at 740 Oe on the identical junction as discussed in figures 3 and 4. The spectra are corrected by a background reference spectra of the transmission line which gives signals on the order of $\sim 60$ dBm. For better illustration, a false colour plot of all spectra is plotted in figure 5(b). No peaks are observed in the spectra for low currents. As the current is increased into the unstable regime up to 10 mA, a peak appears at $f = 4.5$ GHz. When further increasing the current, the peak shifts linearly to larger frequency. The power output also increases and does not even saturate at large currents. The observed blue shift indicates an out-of-plane precession of the free layer magnetization vector [25, 26]. We observe this behaviour only in a narrow field regime. A detailed
Figure 5. Microwave emission spectra from a magnetic double layer junction (3 nm Co | 25 nm Cu | 15 nm Co, cross-sectional area 50 × 150 nm²) at $H = 740$ Oe and $T = 300$ K for large positive currents. (a) Selected spectra at different current values. (b) Two-dimensional false colour plot of the emitted microwave power as a function of current. (Colour online.)

Figure 6. Microwave emission spectra from a magnetic double layer system (3 nm Co | 15 nm Cu | 15 nm Co, 50 × 100 nm²) at $H = 740$ Oe and $T = 300$ K. (a) Selected spectra at different current values which are marked in the differential resistance measurement (inset). (b) Two-dimensional false colour plot of the emitted microwave power as a function of current. (Colour online.)

4. Spin transfer studies in magnetic single layer systems

Most spin transfer devices consist of at least two FM layers. One of these layers provides the spin-polarized current and at the same time may act as a fixed reference layer for the detection of the magnetization reversal of a free second FM layer. Recently, it has been demonstrated that the distinction between a fixed and a free FM layer is not necessary [16]. Current-induced reversible changes in the resistance have been observed in junctions with only one FM layer for magnetic fields perpendicular to the plane of the layer. These resistance changes have been attributed to the onset of nonuniform spin wave modes. Even hysteretic switching has been observed at smaller perpendicular magnetic fields. The importance of an asymmetric spin accumulation on both sides of the FM layer—which can be realized by asymmetric leads—has been elaborated both theoretically and experimentally [13, 14, 16]. However, the actual magnetic microstructure in these junctions is not yet known. As crystallinity and interface roughness may affect the generation of nonuniform spin waves, we investigate the current-induced switching behaviour in MBE grown single layer junctions at room temperature.

In figure 7 we show magneto-transport measurements on a single layer junction with a stack sequence of 5 nm Cu | 8 nm Co | 100 nm Cu and a junction area of 30 × 60 nm². The data were taken at room temperature with magnetic fields applied perpendicular to the thin film plane. The current sweeps show pronounced reversible dips in the differential resistance (see figure 7(a)), which may occur for both current polarities. The dips move to larger current...
values with decreasing magnetic field (see figure 7(b)). We observe hysteretic switching in magnetic field ranges between −4.4 and −3 kOe and 2.8 and 4.8 kOe. The resistance changes by ~0.25%. This effect cannot be explained by the anisotropic magnetoresistance (AMR) which is significantly smaller (~0.1%, data not shown). Similar results have been published for junctions, which had been sputtered [16, 17] or had been deposited by e-beam evaporation [18].

5. Conclusion

In summary, we have used nanostencil mask templates to prepare magnetic nanopillars by MBE. We fabricated both single layer and double layer junctions with a stacking sequence of Cu/Co/Cu and Co/Cu/Co, respectively. Double layer junctions show a magnetoresistance of up to 3% at room temperature. By current sweeps these junctions cannot be switched from a low-resistance state into the AP high-resistance state. Instead, the free layer switches into a new magnetization state, which results in an intermediate stable resistance of the device. This intermediate state has not been previously observed in sputtered samples. Furthermore, we observed two distinct spin wave modes indicating both in-plane and out-of-plane precessions of the thin layer magnetization. For asymmetric single layer junctions our results give indirect evidence for a nonuniform magnetization distribution resulting in current-induced hysteretic switching with a magnetoresistance effect larger than that expected from the AMR effect.

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