Spin-transfer torque switching at ultra low current densities

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The influence of the tantalum buffer layer on the magnetic anisotropy of perpendicular Co-Fe-B/MgO based magnetic tunnel junctions is studied using magneto-optical Kerr-spectroscopy. Samples without a tantalum buffer are found to exhibit no perpendicular magnetization. The transport of Boron into the tantalum buffer is considered to play an important role on the switching currents of those devices. With the optimized layer stack of a perpendicular tunnel junction, a minimal critical switching current density of only 9.2 kA/cm² is observed. As of today, this value is the lowest reported value for current-induced magnetization reversal.

I. INTRODUCTION

Spintronic and spintronic effects in Co-Fe-B/MgO based magnetic tunnel junctions (MTJs) gained interest in recent research. Higher storage density, lower power consumption and faster access times are expected advantages. Current induced magnetization dynamics provide the opportunity to further enhance the storage density and performance of these devices.

This paper is focussed on lowering the critical current ($I_c$) by employing a perpendicular magnetization anisotropy. A low switching current is desired for high performance storage devices. Common switching current densities ($J_c$) of in-plane MTJs are in the range of $10^6$ A/cm². MTJs with a perpendicular magnetic anisotropy (PMA) promise the reduction of the critical switching current while maintaining a high thermal stability $\Delta = K \cdot V$, where $K$ is the anisotropy constant and $V$ is the ferromagnet’s volume. Ikeda et al. reported an average $J_c$ of 3.9 MA/cm² with an $I_c$ of 49 µA for PMA MTJs.

II. SAMPLE FABRICATION

The MTJ stack, grown on thermally oxidized silicon substrates, consists of Ta (15 nm) / Co$_{20}$Fe$_{60}$B$_{20}$ (1.0 nm) / MgO (0.84 nm) / Co$_{20}$Fe$_{60}$B$_{20}$ (1.2 nm) / Ta (5.0 nm) / Ru (3.0 nm). EDX measurements revealed a Co to Fe ratio of 32:68. Tantalum and Co-Fe-B are magnetron sputtered at an operating pressure of $1.3 \cdot 10^{-3}$ mbar Ar (base pressures approx. $5 \cdot 10^{-10}$). The MgO barrier and ruthenium capping layer are e-beam evaporated in an interconnected chamber at pressures below $5 \cdot 10^{-10}$ mbar. 5 nm tantalum are evaporated in this chamber prior to sample preparation to en-
hance the growth and remove moisture from the residual gas atmosphere (RGA). Afterwards, the RGA contains only N\textsubscript{2}. The partial pressure of other molecules, such as H\textsubscript{2}O, are below the detection limit of the quadrupole mass spectrometer (Pfeiffer QMA 200) of 10\textsuperscript{-12} mbar. To crystallize the Co-Fe-B electrodes, the prepared samples are annealed in a separate chamber at a base pressure below 5 \cdot 10\textsuperscript{-6} mbar for 60 minutes at 300\textdegree C without external magnetic field.

The samples are patterned using standard UV and electron-beam lithography as well as argon ion milling techniques. The junctions are of circular shape with nominal diameters between 100 nm and 250 nm. The top contact consists of 6 nm Cr and 63 nm Au. Top (Au) and bottom electrode (Ta) are insulated with 50 nm SiO\textsubscript{2}. The real diameter of the MgO barrier is determined using TEM. Due to the slope of the sidewall (see Fig. 1), resulting from the argon ion milling process, the radius of the MTJ increases from 75 nm at the top of the junction to 180 nm. TEM and electron energy loss spectroscopy (EELS) analyzes have been performed on an aberration corrected FEI Titan 80-300 ETEM G2 at 300 kV.

III. THE INFLUENCE OF THE BORON TRANSPORT ON THE PERPENDICULAR MAGNETIC ANISOTROPY

The interaction of the Co-Fe-B layer with the adjacent layers is crucial for the perpendicular magnetic anisotropy (PMA) whose origin is predicted in the hybridization of the Fe 3d and O 2p orbitals at the Co-Fe-B/MgO interface layers\textsuperscript{5}. That makes a deeper study of the influence of the Co-Fe-B/MgO interface on the magnetic behavior essential for obtaining a high PMA. In this context, Co-Fe-B/MgO based samples with a Co-Fe-B wedge were fabricated and their magnetic behavior was systematically studied.

The annealing step is crucial for the crystallization of the Co-Fe-B layer, because the Co-Fe-B crystallization starts at the MgO interface in this case in bcc structure, which is essential for the coherent tunneling process\textsuperscript{6}. During the annealing step, boron can move from the Co-Fe-B layer into the adjacent layers and influences the crystallization of the Co-Fe. Especially the boron transport into the Co-Fe-B/MgO interface can decrease the perpendicular magnetic anisotropy of the Co-Fe layer by changing of the crystallization behavior of Co-Fe\textsuperscript{7}. In order to increase the PMA of the MTJs composed of Co-Fe-B/MgO/Co-Fe-B, the influence of the tantalum buffer layer was studied. For that reason a layer-stack without a buffer layer (sample a) and one with a 5 nm tantalum buffer (sample b) are compared (Fig. 2). Both samples have a 1.3 nm Co-Fe-B layer and a capping layer of 2.1 nm MgO.

After the preparation in purpose to study the magnetic behavior of the samples the Kerr rotation was measured in the in-plane and out-of-plane directions (Fig. 2(a) und (b)). The in-plane hysteresis is depicted as red curves and out-of-plane hysteresises as blue curves. The hysteretic behavior of the sample b) (with tantalum buffer) shows a very low magnetization in the in-plane direction (with no measurable coercive field), while the in-plane hysteresis of the sample a) shows a hysteric behavior with a coercive field of 0.9 ± 0.02 mT. The out-of-plane hysteresis of the sample b) shows an easy-axis-loop with a coercive field of 1.8 ± 0.02 mT, while the hysteresis of the sample a) shows a hard axis behavior with a coercive field of nearly 0.75 ± 0.04 mT. For the magnetic anisotropy it means: on the sample a) (without buffer layer) we observe the in-plane anisotropy (Fig. 2(b)); while on the sample b) (with tantalum buffer layer) the perpendicular magnetic anisotropy (Fig. 2(a)) is observed. From the hysteresis curves we estimated an anisotropy constant using the Stoner-Wohlfarth model and setting saturation magnetization $M_s = 1.62$ T. We obtain a $K$ of 14.0 mJ/m\textsuperscript{2} for sample a) and 7.3 mJ/m\textsuperscript{2} for sample b) in a perpendicular field and 10.7 mJ/m\textsuperscript{2} for sample a) in an in-plane field. Since the hysteresis of sample b) in an in-plane field

![FIG. 2. Hysteresis of the samples a) (without tantalum buffer layer) and b) (with tantalum buffer layer) were both measured in a magnetic field in the in-plane (blue) and out-of-plane (red) direction: (a) Sample a) shows in-plane magnetic anisotropy and (b) Sample b) clearly out-of-plane magnetic anisotropy.](image)

![FIG. 3. (Left): HRTEM of the sample b); (right): boron concentration after annealing dependent on the layer. The concentration grows from right to left.](image)
was not observed to be saturated within the measured range of 100 mT, we do not provide any value. Thus we conclude, the corresponding energy barrier and the critical switching current is significantly lower, in case of the tantalum buffer. One has to keep in mind, that the obtained values were measured in unpatterned thin films and the shape anisotropy also influences the anisotropy. However, the qualitative result of a smaller \( K \) with a tantalum buffer layer remains valid and endorses the expectation of a reduced critical switching current. The tantalum layer influences the magnetic anisotropy behavior of the Co-Fe-B and even changes the magnetic anisotropy in our samples from in-plane to out-of-plane. To investigate this behavior, the EELS measurements on the sample b) (with tantalum buffer layer) were made and analyzed. The right part of Fig. 3 shows schematically the area of the background-corrected EEL spectrum in the range between 180 to 210 eV as a measure of the boron content. This measurement shows that boron moves into the tantalum layer during the annealing step. In sample b) the tantalum buffer acts as a sink for boron and prevents the boron transport into the MgO layer, so the higher perpendicular anisotropy can be observed due to better crystallization of Co-Fe.

Tantalum as buffer layer material is an essential parameter for the MTJs, because of the influence on the boron transport and thus as an important parameter for obtaining a high PMA. In this work all MTJs contain a tantalum buffer and capping layer.

**IV. ULTRA LOW CRITICAL SWITCHING CURRENTS IN PERPENDICULAR TUNNEL JUNCTIONS**

Here, we discuss a junction in which the smallest \( J_c \) was achieved. First, the magnetoresistive behavior of the junctions is characterized. The magnetic minor loop shown in Fig. 4 is recorded in two-terminal geometry by sweeping the external magnetic field, which is applied perpendicularly to the sample plane. We find TMR ratios of up to 64\% in typical PMA MTJs with a barrier thickness of 4 monolayers (ML). Here, a TMR ratio of 22\% is obtained.

Current induced switching is studied by recording the current-voltage-characteristics and shown in the top graph of Fig. 5 as a function of the applied magnetic bias field. The \( I_c \) is extracted from the data and shown in the bottom graph of Fig. 5.

The top graph of Fig. 5 contains the switching phase diagram. For bias fields between 7.3 mT and 20.4 mT, STT switching is observed. The STT data from Fig. 4 is marked by the vertical black line. The bottom graph depicts the calculated average critical currents for P to AP and AP to P switching at different bias fields. To compare our results with the \( J_c \) from Ref. 10 we calculate the average of the currents for parallel (P) to antiparallel (AP) and AP to P switching with \( J_c = (J_{P \rightarrow AP} + J_{AP \rightarrow P})/2 \). An averaged \( J_c \) is obtained by calculation the mean of eighteen measurements at bias fields between 13 and 18 mT. The \( I_c \) of 22.6 ± 4.6 µA corresponds to a \( J_c \) of 22.2 ± 4.5 kA/cm².

FIG. 4. Electrical characterization of a junction. The minor loop (top) yields a TMR ratio of 22\% with a perpendicularly applied magnetic field. At a bias field of 13.4 mT (bottom) the magnetization states are switched from P to AP alignment at an applied current of 13.5 ± 1.5 µA (corresponds to 13.3 ± 1.5 kA/cm²). AP to P switching is found at -5.3 ± 0.3 µA (5.2 ± 0.3 kA/cm²). The average of both critical switching currents (9.4 µA) equals a \( J_c \) of only 9 ± 2 kA/cm².

We now want to compare the experimentally obtained torque with the torque needed for thermally driven magnetization reversal (thermal spin-transfer torque). Assuming the smaller diameter of 150 nm in case of an inhomogeneous current distribution, \( J_c \) would still be on the order of 53 ± 8 kA/cm². As of today, values in this range were only reported by voltage induced switching, where a voltage pulse is used to reduce the energy barrier during the switching process [11].

The critical torque \( \tau_c \) can be estimated from the measured \( J_c \), as given in Ref. [17]:

\[
\tau_c = \frac{\hbar}{2e} J_c.
\]

where \( e \) is the elementary charge and \( \hbar \) the reduced Planck constant. \( \eta \) denotes the spin-torque efficiency parameter, which is depending on the spin-polarization and the relative angle between the magnetizations of the ferromagnets. According to Ref. [18] this parameter can be assumed to be equal to the spin-polarization \( P \) for the coherent tunneling process, which involves the ferromagnetic electrode and the barrier.
With the optimized MTJs, critical switching currents of $J_c = 9 \pm 2 \, \text{kA/cm}^2$, which is so far the lowest reported value for DC-STT measurements.

**V. CONCLUSION**

We have studied the influence of the tantalum buffer on the PMA of perpendicular MTJs. The boron is found to move from the Co-Fe-B film into the tantalum layer. With the optimized MTJs, critical switching currents of $J_c = 9 \pm 2 \, \text{kA/cm}^2$, which is so far the lowest reported value for DC-STT measurements.

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