Magnetization reversal of sub-micron ferromagnetic tunnel junctions in external magnetic fields

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Abstract

Sub-micron sized magnetic tunnel junctions are fabricated by electron beam lithography. Magnetoresistance measurements were done at crossed easy- and hard-axis fields and the critical switching curves for 3 different sub-μm junctions are discussed. Single domain like switching according to the Stoner and Wohlfarth model can be achieved, but Néel coupling effects and AAF stray field effects have to be controlled. © 2002 Elsevier Science B.V. All rights reserved.

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Magnetic tunnel junctions (MTJ) are a promising candidate for MRAM applications. In order to compete with conventional memory technologies, the area of the bit cell, i.e. the MTJ cell, has to shrink to sub-μm size. Moreover, for addressing a specific bit in an array, the writing of information has to obey the selection rule, which is based on the model of Stoner and Wohlfarth [1]. The analysis of switching curves (so-called astroids), obtained from magnetoresistance (MR) curves for different fixed hard-axis fields, helps understanding the physical switching behavior of the element. However, little is published on sub-μm [2] or micrometer [3] sized MTJs. Here, we present astroid measurements on three different sub-μm tunnel junctions (sample A, B, C) in the sub-μm range and will comment on specific features.

Samples were grown on Cu underlayer having the following layer sequence: AAF/Al2O3/Pt/cap. The artificial antiferromagnetic subsystem (AAF) is a CoFe/Ru/CoFe trilayer of about 1.5/0.9/2.2 nm and the Pt thickness was 1.5 nm (sample A and B) and 1 nm (sample C) (Fig. 1(a)). The Permalloy (Py) thickness was chosen 6 (A, B) and 3 nm (C). The sub-μm patterning was done by electron beam lithography and ion milling. Details for film preparation and junction patterning are described elsewhere [4]. The thicker top AAF electrode allows a compensation of the Néel coupling field [3,6]. The MTJ has smooth edges, but its edges are buried under a SiO2 passivation with high edge roughness (Fig. 1(b)). The AAF was saturated at about +400 kA m\(^{-1}\) parallel (P) to the long axis of the element. In a typical measurement, the easy-axis field \(H_x\) was P to the long axis of the elements and the hard-axis field \(H_y\) was perpendicular to that. The sweep rate along \(H_x\) was on the order of 0.25 kA m\(^{-1}\) s\(^{-1}\).

Reviewing Fig. 1(b), the junction A has an elliptical shape with dimensions 800 × 330 nm\(^2\) with 6 nm Py thickness. In Fig. 2(a), the switching field along \(H_x\) is plotted for a fixed hard-axis field \(H_y\). Repeated measurements showed no significant deviation of the switching fields. Assuming that the storage electrode can be approximated by an ellipsoid of the dimension 800 × 330 × 5 nm\(^3\) (with 1 nm Py subtraction for dead layer correction), the anisotropy constant is about \(K \approx 4000 \text{ J m}^{-3}\), which gives an anisotropy field \(H_K \approx 8 \text{ kA m}^{-1}\) for Py. This field is identical to the switching field in the model of Stoner and Wohlfarth when no hard-axis field is applied. By assuming a rectangular prism as an approximation, \(H_K\) would even...
be larger \([5]\). As can bee seen in Fig. 2(a) the experimental astroid lies within the critical switching curve of the theoretical model of Stoner and Wohlfarth. Compared to Stoner–Wohlfarth, the switching fields for small hard-axis fields are significantly reduced by about 40\%. This indicates that the magnetization reversal does not take place by a perfect homogeneous magnetization rotation as assumed in the model of Stoner and Wohlfarth. In an experimental device, the magnetization of storage electrode will mostly be inhomogeneous especially during the magnetization reversal, as the exchange anisotropy, which favors a uniform spin alignment, has to compete with large magnetostatic stray field energy. Also, the intersection of the switching curve with the easy-axis has smaller field values than with the hard-axis.

The center point \((C)\) of the experimental astroid data is approximately shifted by an offset field of \((0, +0.7) \text{kA m}^{-1}\). This shift indicates that additional magnetic fields are present and are superposed on the applied external field. This is the result of two main mechanism oppositely directed \([6]\), namely, the Néel coupling effect, which favors a P orientation of the storage and reference electrode, and the magnetostatic edge stray fields from the AAF electrode, which favors an antiparallel (AP) orientation. By vibrating sample magnetometer measurements on continuous A-type films, a Néel coupling field of \(H_N = 1.1 \text{kA m}^{-1}\) was measured. The edge stray field can be approximated by the demagnetizing field for an ellipsoidal particle, with the lateral sample dimension and a net thickness of 1.1 nm, which reflects the total net moment of the CoFe \((J_S = 1.9 \text{T})\) in the AAF system (after dead layer correction). A full orientation of the AAF net moment along the easy-axis yields a stray field of \(H_{\text{AAF}} = -2 \text{kA m}^{-1}\), while a 90\(^\circ\)-rotation into the hard-axis direction yields an almost 4 times higher stray field of \(H_{\text{AAF}} = -6 \text{kA m}^{-1}\). Note that the Néel coupling field is isotropic with respect to a rotation of the AAF net moment, however, the edge stray field is anisotropic. Hence, the stray field in hard-axis direction depends, sensitively, on small angle rotations of the AAF net moment. As a consequence, the ferromagnetic Néel coupling field and the antiferromagnetic edge stray field are almost compensated along the easy-axis even for small AAF rotation angles, while the antiferromagnetic stray fields along the hard-axis direction will dominate the small Néel coupling fields. The measured offset field of \((0, +0.7) \text{kA m}^{-1}\) corresponds within the precision of the simple model to an AAF rotation of about 10–15\(^\circ\), counterclockwise.

Fig. 2(b) shows the switching plot for an elliptical element (sample B) with 6 nm Py and a nominal size of \(600 \times 300 \text{nm}^2\). The switching curve is strongly distorted.
and is very reproducible for repeated measurements on the same junction. For a hard-axis field of around $H_y = +1 \text{kA m}^{-1}$, a discontinuity is observed (Fig. 2(b): (X)). The uncontrolled switching behavior is not clearly understood and appears to be due to a combination of different reasons. The lower aspect ratio and shorter length of the element causes a more inhomogeneous magnetization in the storage electrode, which leads to deviation from the coherent rotation model from Stoner and Wohlfarth. Pinning effects within the Py layer and also pinning due to interaction with the reference electrode may account for some irregularities. A magnetization fluctuation and imperfect alignment of the AAF electrodes generate stray fields in the Py layer, which may act as pinning centers or/and may induce additional, effective anisotropies for the storage electrode. Also, edge pinning, which is mainly seen on elongated structures [2], can play a significant role.

In Fig. 3(a), the switching curve of a 3nm thin Py storage electrode with nominal rectangular dimensions of roughly $350 \times 170 \text{nm}^2$ is shown but with rounded edges due to the lithography limitation. The switching characteristic of the 3nm Py is good. The width of the astroid is about 75% of its height. Obviously, the astroid in Fig. 3(a) (and also 2(a)) is asymmetric along the easy-axis. The right part of the astroid is elongated. We suggest that this is the result of inhomogeneous edge stray fields of the AAF. These fields are very strong near the left and right ends of the element, and will influence the magnetization pattern of the Py. In the case of an AP to P reversal of the Py electrode, the Py electrode is initially (in the AP state) more uniformly magnetized due to the intercolumn of flux and the assumption of a coherent rotation in the Stoner Wohlfarth model is better met—resulting in a higher AP–P switching fields (right astroid branch). However, in the case of a P–AP reversal, the Py electrode is initially (in the P state) more inhomogeneously magnetized due to the formation of edge quasi-domains [7] and the assumption of a coherent rotation is less valid than the for the AP–P reversal. This results in a smaller P–AP switching field (left astroid branch). In agreement with this, Portier et al. [8] have observed the formation of end domain in large $2 \times 5.5 \text{pm}^2$ MTJs by Lorentz transmission electron microscopy. Again, the astroid is shifted by an offset field of $(1.5, 3.5) \text{kA m}^{-1}$, which is also explained by a counterclockwise rotation of the AAF net moment. Due to the smaller element size compared to junction A the larger AAF stray fields along the easy-axis and more seriously along the short hard-axis direction can not be sufficiently compensated by the Néel coupling fields.

As a consequence, it is of great importance to control the shape size in combination with a perfect alignment and adjustment of the net moment of the AAF. Small deviations in the element size or small rotation of the reference electrode can significantly cause uncompensated demagnetizing edge stray fields, which gets more critical at smaller dimensions. However, we have shown that the switching of the Py layer obeys the Stoner–Wohlfarth to a high degree.

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References