Offset fields in perpendicularly magnetized tunnel junctions

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Abstract

We study the offset fields affecting the free layer of perpendicularly magnetized tunnel junctions. In extended films, the free layer offset field results from interlayer exchange coupling with the reference layer through the MgO tunnel oxide. The free layer offset field is thus accompanied with a shift of the free layer and reference layer ferromagnetic resonance frequencies. The shifts depend on the mutual orientation of the two magnetizations. The offset field decreases with the resistance area product of the tunnel oxide. Patterning the tunnel junction into an STT-MRAM disk-shaped cell changes substantially the offset field, as the reduction of the lateral dimension comes with the generation of stray fields by the reference and the hard layer. The experimental offset field compares best with the spatial average of the sum of these stray fields, thereby providing guidelines for the offset field engineering.

Keywords: STT-MRAM, Magnetic tunnel junction, perpendicular magnetic anisotropy, interlayer exchange coupling

(Some figures may appear in colour only in the online journal)
2. Samples

Our objective is to understand the different offset fields that may alter the free layer behavior in perpendicularly magnetized MTJ. We thus study free layers embodied in state-of-the-art, hence bottom-pinned MTJs. Their composition is sketched in figure 1(a), with film growth and fabrication details described in [3]. From bottom to top, the stack organization is: hard layer/antiferro-coupler (Ir, 5.2 Å)/reference layer/MgO (rf)/free layer/MgO (rf)/cap. Following previous optimizations [4–8], the hard layer (HL) is \([\text{Co (5 Å)/Pt (3 Å)}] \times 5/\text{Co (6 Å)}\). It is strongly coupled antiferromagnetically to the reference layer (RL) by the iridium spacer. The reference layer is \([\text{Co (6 Å)/XFeCoB (6 Å)/FeCoB (9 Å)}]\), where X is an early transition metal and the XFeCoB paramagnet promotes both a strong ferromagnetic coupling and a texture transition from the fcc Co to the bcc iron-rich FeCoB layer [9, 10]. The free layer is \([\text{FeCoB (9 Å)/XFeCoB (6 Å)/FeCoB (9 Å)}]\), where X is an early transition metal and the XFeCoB paramagnet promotes both a strong ferromagnetic coupling and a texture transition from the fcc Co to the bcc iron-rich FeCoB layer [9, 10]. The free layer is \([\text{FeCoB (9 Å)/XFeCoB (6 Å)/FeCoB (9 Å)}]\), where X is an early transition metal and the XFeCoB paramagnet promotes both a strong ferromagnetic coupling and a texture transition from the fcc Co to the bcc iron-rich FeCoB layer [9, 10]. In contrast to [3], our present tunnel junctions are annealed at 400 °C. Ferromagnetic resonance [11] was used to obtain the free layer damping \(\alpha = 0.0062 \pm 0.0002\) as well as inhomogeneous linewidth broadening \(\mu_0 \Delta H_0 = 6 \pm 1\) mT, in line with previous optimizations [6]. For the blanket film studies, the growth conditions of the MgO are varied in order to yield resistance area product ranging from 2.5 to 5.5 Ω·μm². In the ultrathin film limit, the magnetizations are often different from their bulk counterpart, and that the presence of Boron and of potential interdiffusion can further modify their values. Vibrating sample magnetometry loops (figures 1 and 2) were used to measure the areal moments of each subsystem within the full MTJ. They were translated into magnetization using the nominal thicknesses (table 1). Note that as the FeCoB and Co parts of the reference layer behave as a strongly exchange-coupled single block, we have assigned arbitrarily the same magnetization to these two layers.

The MTJs were patterned into circular devices with diameters ranging from 30 nm to 500 nm. To fabricate the devices, a thicker oxide is used, yielding a TMR = 182% as well as a resistance area product of 9 Ω·μm². For the calculations of spin-torque amplitudes within the device, we shall consider that this TMR results from a spin polarization \(P\) of the current that tunnels between the free and the reference layer. \(P\) can be estimated from Julliere’s formula to be \(P = 69\%\).

3. Film level offset fields

We shall first study in detail the case of a representative MTJ blanket film having RA = 4 Ω·μm² before studying the RA dependence of the offset fields. The free layer offset fields are first characterized by vibrating sample magnetometry (VSM) and then vector network ferromagnetic resonance (VNA-FMR [11]) in out-of-plane fields.

3.1. Free layer offset field

The VSM minor loops (figure 1(b)) are square but off-centered. The offset field is typically of \(H_{\text{offset}} = 7\) mT when RA = 4 Ω·μm². In all our samples, this offset field favors the parallel orientation between the RL and the FL. Coercivities in extended thin films are often extrinsic and influenced by non-representative defects, such that we prefer to complement...
have now antiparallel (AP) magnetizations. In this case the RL to FL coupling field is opposite to the free layer magnetization and its experimental FMR frequency decreases suddenly by 430 MHz (figure 2(a)). The FL FMR is now expected to follow:

$$f_{AP} = \frac{\gamma_0}{2\pi} |H_z| + H_k - M_s - H_{offset}. \quad (2)$$

When further increasing the field, we cross the free layer coercivity and recover a state in which the FL and RL have parallel magnetizations (figure 2(b)) and equation (1) holds again. Fits of the free layer FMR (figure 2(a)) through equations (1) and (2) yield $\mu_0(H_k - M_s + H_{offset}) \approx 193$ mT and $\mu_0(H_k - M_s - H_{offset}) \approx 179$ mT. On this RA= 4 $\Omega \cdot \mu m^2$ sample, the free layer FMR shift thus confirms the value of the offset field (7 mT) measured formerly with the VSM minor loop.

### 3.2. Interlayer exchange through MgO and shift of reference layer FMR

It is interesting to describe the free layer offset field as an interfacial exchange energy resulting from interlayer exchange coupling through MgO [12, 13]. For this we assume a weak interlayer exchange coupling between layers (i.e. FL and RL) having different properties (see equation (5) of [14]) and define:

$$J_{MgO} = \mu_0 H_{offset} M_{FL}^s t_{FL}$$

(3)

where $t_{FL}$ is the thickness of the FL. Note that if the FL offset field is due to an exchange coupling between the FL and the RL through MgO, it should also influence the reference layer. Unfortunately a minor loop-based measurement is less easy to apply to the reference layer because its offset field adds to a very strong coupling with the hard layer. At the MTJ saturation field (i.e. when the RL saturated along the applied field), its coupling with the hard layer leads to a reversible (hysteresis-free) rounded RL switching in which the coercivity part and the offset part of the saturation field can not be separated by a minor loop strategy.

Instead of using the switching field, we can benefit from the joined field and frequency resolutions of VNA-FMR to measure selectively the effective fields affecting the dynamics of the reference layer in a manner similar that the previously used for the free layer (equations (1) and (2)). The lowest frequency mode of the synthetic antiferromagnet is essentially localized in the reference layer (see [5]); it undergoes a jump of $820 \pm 20$ MHz when the free layer magnetization reverses (figure 2(a), top curve) and gets parallel to the reference layer. Interestingly, we can [14] jointly use the frequency jumps of the FL and of the RL and write:

$$\gamma_0 J_{MgO}/(M_{FL}^s t_{FL}) = +820 \text{ MHz}$$

$$\gamma_0 J_{MgO}/(M_{RL}^s t_{RL}) = +430 \text{ MHz}.$$  

(4)

The two former expressions can be used to cross-check the consistency of the magnetizations listed in table 1. Indeed the ratio of the frequency jumps is consistent with the ratio of the FL and RL areal moments. This point should not be

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**Figure 2.** Ferromagnetic resonance modes and hysteresis of unpatterned MTJs (a) eigenmode angular frequency divided by gyromagnetic ratio minus applied field. This represents the sum of exchange coupling fields and anisotropy fields acting on the free layer (blue square symbols) and on the reference layer (green cross symbols). (b) VSM hysteresis loop. The horizontal arrows denote the field sweeping directions. The vertical arrows represent the orientations of the magnetizations of the free layer (blue), reference layer (green) and hard layer (red).

**Table 1.** Vibrating sample magnetometer estimation of the magnetizations of the sub-systems of the MTJs.

| Thickess ($\AA$) | $M_s (10^6 \text{ A} \cdot \text{m}^{-1})$ |
|------------------|----------------------------------|
| FeCoB            | 25                               |
| FeCoB            | 9                                |
| XFeCoB           | 6                                |
| Co               | 6                                |
| Co/[Pt/Co]$_{5,5}$ | 46                              |

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the VSM-measured offset field by VNA-FMR for a more reliable characterization. For out-of-plane fields $H_z$ large enough to saturate the full MTJ in one of the two parallel states (P), the FL FMR frequency is independent of the field history and can be modeled by:

$$f_0 = \frac{\gamma_0}{2\pi} |H_z| + H_k - M_s + H_{offset} \quad (1)$$

where $\gamma_0 \approx 230$ kHz $\cdot m \cdot A^{-1}$ is the gyromagnetic factor. The effective anisotropy fields $H_k - M_s$ and the offset field $H_{offset}$ cannot be separated when all layers have the same magnetization orientation. At smaller fields, the reference layer switches and together with the hard layer they form a synthetic antiferromagnet; at this stage such the reference layer and free layer

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overlooked at it means that the coupling through MgO propagates through the whole reference layer (FeCoB and Co), which confirms that the coupling through the XFeCoB layer is much stronger than \( J_{MgO} \).

3.3. Dependence of offset field with resistance area product

The application of equation (3) to the RA \( = 4 \, \Omega \cdot \mu m^2 \) sample yields \( J_{MgO} \approx 19 \, \mu A \cdot m^{-2} \). This value is by no means general since the offset field varies with the deposition conditions and the MgO thickness. To illustrate this point, we have measured jointly the local RA product by current-in-plane tunneling (CIPT [15]) and the local FL offset field and RL saturation field by Polar Kerr loops. The measurements were performed on three line scans on four 300 mm\(^2\) wafers with known (and minor) RA differences. The CIPT measurement locations are exactly the same as the polar Kerr locations. The results are gathered in figure 1(c) and indicate that the FL offset field varies in a correlated way with the resistance area product of the junction. The correlation shows that the RA versus \( H_{offset} \) trend is consistent within wafer and from wafer-to-wafer: measuring RA and measuring offset field are somewhat equivalent in our material system. As a side comment, we routinely use this correlation as a process diagnosis tool and we monitor the offset field as a predictor of RA and track any drift in the thickness of the deposited MgO.

We note that the correlation is also present in the saturation field of the RL (figure 1(c), green symbols); however as mentioned earlier the RL offset field can not be deduced from the saturation field in a rigorous manner, since the evolution of the RL saturation field may also reflect an increase of the anisotropy of the RL/MgO interface whose structural origin would also result in an increase of the offset field measurement. Finally, it is also worth noticing that our values of \( J_{MgO} \) and their trend from figure 1(c) are consistent with the \( 7 \, \mu A \cdot m^{-2} \) reported in [16] for larger resistance area products of \( 10 \, \Omega \cdot \mu m^2 \). This dependence with the thickness of MgO is an additional indication that the free layer offset field at blanket film level results from interlayer exchange coupling mechanism.

4. Device level offset fields

When passing from blanket level to device level, offset fields are generally much higher indicating that additional effects at also at play. Indeed when patterning, uncompensated magnetic charges appear at the system boundaries, such that the finite lateral dimension of the device results in the systematic generation of stray fields by the different layers of the MTJ, thereby complicating the understanding of the offset fields.

4.1. Defining offset fields in spin-torque devices

Before discussing the values of the offset fields at device level, it is worth describing first how we measure them. Indeed at device level, invasive magneto-resistance loops are used instead of the non-invasive VSM of Kerr effect that would be difficult to implement at device level. A finite current is passed through the device and the unavoidable associated spin-torque may affect the offset field measurement. To measure reliably the free layer offset field, we measure stability diagrams, i.e. conductance versus field loops at variable applied voltages, and export the fields and voltage values that yield transitions between low and high resistance states. This is illustrated in figure 3 for a representative device of diameter 36 nm. It is worth noticing that correcting for the field offset measured at zero bias voltage yields switching voltages that are equal and opposite, as expected for spin-torque induced reversal in tunnel junctions [17]. This is an important point as it means that the two possible definitions of offset field—average of the two switching fields in zero voltage, or applied field leading to equal back-and forth switching voltages—were equivalent for all our investigated devices. Let us now see how sensitive the offset field can be to its measurement method.

4.2. Sensibility of offset fields with voltage bias

On devices smaller than typically 50 nm, the boundaries of the stability diagram near the field compensation were found to be linear, parallel to each others and centrosymetric after field offset compensation (figure 3). In that field region of quasi-offset-compensation, the P to AP and the AP to P switching transitions seem equivalent. To illustrate this point we have superimposed on the experimental data (i) its centrosymetric construction and (ii) the expected stability diagram of a macrospin at zero temperature (figure 3), i.e. the curve [18]:

\[
\frac{V}{V_{\text{switch}}} = \frac{H}{H_{\text{switch}}} = \pm 1, \quad (5)
\]
where $V_{\text{switch}} = 0.24$ V is the switching voltage in compensated field and $\mu_0 H_{\text{switch}} = 240$ mT is the switching field after offset compensation. Note that in a macrospin model, the slope of the stability diagram $V_{\text{switch}}/H_{\text{switch}}$ is the spin-torque efficiency factor which depends on the ratio of $\alpha/P$. For the specific device of figure 3 the spin-torque efficiency factor would be consistent with $\alpha_{\text{device}} = 0.0096$. The difference with the film value ($\alpha_{\text{film}} = 0.0062$) is not understood.

An important point to be noticed on the stability diagram is that it has corners: the parallel branches that should theoretically extend to infinity (equation (5)) do not extend above fields of typically 250 mT. In these high field/high voltage regions, the resistance versus field loops are either rounded and reversible (not shown) or exhibit stochastic back-hopping (inset, figure 3) arguing for an instability of the reference layer at these large fields and large spin-torques. For very large devices only (diameters above 150 nm) this back-hopping sometimes leads to the full reversal of the HL + RL synthetic antiferromagnetic which can be evidenced as it changes the stimulus polarities in field-driven minor loops and in low field STT-driven loops.

The presence of ‘corners’ in the stability diagrams has implications for the measurement of the offset field. Indeed the linear branches (equation 5) of the stability diagram start to bend substantially already near zero voltage bias (figure 3). The bending is not always of comparable amplitude in the two switching transitions. A practical consequence is that when attempting to measure the offset field with a finite bias $V_{\text{bias}}$ one suffers an absolute error of $V_{\text{bias}} \times \Delta H_{\text{max}}$. This error can not be predicted by the measurement of the sole R(H) and R(V) loops; measuring the offset field using two polarities of $V_{\text{bias}}$, or using an ac bias minimize this error but overall an uncertainty of typically 0.5 mT mV$^{-1}$ can not be avoided. It adds to the naturally occurring thermal noise-induced fluctuation of the switching fields (typically $\pm 3$ mT). This error being minimized, we have gathered in figure 4 the offset fields of 320 devices of various sizes mainly ranging from 30 nm to 400 nm. These offset fields include the interlayer exchange coupling identified in section 3 and estimated to be a couple of mT only in these (relatively) high RA devices. Note also that part of the device-to-device dispersion of the offset field was expected from material non-uniformity identified from FMR inhomogeneous linewidth broadening (standard deviation of $\pm 6$ mT).

4.3. Profiles of the stray fields emanating from the RL and HL

Let us investigate whether these experimental offset fields can be understood from the dipolar coupling with the stray fields of the reference and hard layers. To estimate these stray fields, we assume that the layers composing the RL and the HL systems are uniformly magnetized along $z$. The first calculation step is to recall that the out-of-plane field generated at a vertical distance $z$ and a radial distance $\rho$ by a PMA magnet that is cylindrical of radius $a$ and thickness $t$ and centered at position $\rho = 0$, $z = 0$ is:

$$B_\bot (\rho, z) = \frac{\mu_0 M_s}{4\pi} \int_0^{2\pi} \int_0^a b_\bot (r, \rho, \phi, t, z) \, dr \, d\phi \quad (6)$$

where the integrand $b_\bot$ is the function

$$r_\bot (z) = (\frac{1}{z} - \frac{1}{2})^{(\frac{1}{z} + \rho^2 + r^2 - 2 \rho \cos(\phi))^{1/2}} + (\frac{1}{z} + \rho^2 + r^2 - 2 \rho \cos(\phi))^{1/2}.$$  

Similarly we shall use that fact that the in-plane radial field generated by a similar magnet is:

$$B_\rho (\rho, z) = \frac{\mu_0 M_s}{4\pi} \int_0^{2\pi} \int_0^a b_\rho (r, \rho, \phi, t, z) \, dr \, d\phi \quad (7)$$

where the integrand $b_\rho$ is now the function

$$r_\rho (\rho, \rho, \phi, t, z) = \frac{(\frac{1}{z} + \rho^2 + r^2 - 2 \rho \cos(\phi))^{1/2}}{(\frac{1}{z} + \rho^2 + r^2 - 2 \rho \cos(\phi))^{1/2}} \cdot \frac{(\frac{1}{z} + \rho^2 + r^2 - 2 \rho \cos(\phi))^{1/2}}{(\frac{1}{z} + \rho^2 + r^2 - 2 \rho \cos(\phi))^{1/2}}.$$  

The stray field profile at the free layer position is simply calculated by summing the contributions of all magnetic layers placed at their respective vertical positions. Conventionally the RL and the HL are magnetized along $+z$ and $-z$.

Examples of their radiated stray fields are reported in figure 5 for devices of diameters 60, 40 and 20 nm. It is worth noticing that the out-of-plane stray fields can be highly non uniform at the FL position (figures 5(c), (e) and (f)). Near the free layer edges, the free layer feels both the stray field from the (most proximal) reference layer (figure 5(a)), as well as that of the higher moment (but more distant) hard layer (figure 5(b)). Conversely at the center of the free layer, the out-of-plane stray field from the (most proximal) reference layer (green curve) is strongly reduced, such that the out-of-plane field seen by the free layer is dominated by the (higher moment) hard layer. Since the RL and HL are located at different distances from the free layer, the sum of the RL and HL stray fields results in a complicated profile (figures 5(c), (e) and (f)), with a marked waviness and overshoots near the free layer edges, but a rather constant stray field in the inner of the free layer, especially for devices of diameter near 40 nm. Note in addition that even when the out-of-plane stray field is rather uniform, there is still a substantial in-plane stray field converging towards the center of the free layer (figure 5(d)).

4.4. Dipolar offset field

In order to understand the dependence of the offset fields over the device diameter $2a$, we have calculated the spatial average $\langle B(z) \rangle$ of the out-of-plane component of the total stray field:
is due to interlayer exchange coupling through the MgO tunneling oxide. It decreases with the resistance-area product of the junction, from a maximum of 30 $\mu$A m$^{-2}$ at $R_{x}A = 3$ $\Omega \cdot \mu$m$^2$. Measurement of the offset field at device level requires to minimize its alteration by spin-torque. The device level offset field can be understood from the spatial average of the stray fields emanating from the other magnetic layers of the MTJ stack. As a result of its dipolar origin, the dipolar part of the offset field depends strongly on the device diameter.

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### References

[1] Kent A D and Worledge D C 2015 Nat. Nanotechnol. 10 187
[2] Hu G et al 2015 IEEE Int. Electron Devices Meeting pp 26.3.1–4
[3] Van Beek S, Martens K, Roussel P, Wu Y C, Kim W, Rao S, Swerts J, Crotti D, Linten D, Kar G S and Groeseneken G 2017 AIP Adv. 8 055909
[4] Swerts J et al 2015 Appl. Phys. Lett. 106 262407
[5] Devolder T, Couet S, Swerts J and Furnemont A 2016 Appl. Phys. Lett. 108 172409
[6] Couet S, Devolder T, Swerts J, Mertens S, Lin T, Liu E, Van Elshocht S and Sankar Kar G 2017 Appl. Phys. Lett. 111 152406
[7] Devolder T, Couet S, Swerts J, Liu E, Lin T, Mertens S, Furnemont A and Kar G 2017 J. Appl. Phys. 121 113904
[8] Devolder T, Kim J V, Swerts J, Couet S, Rao S, Kim W, Mertens S, Kar G and Nikitin V 2018 IEEE Trans. Magn. 54 1
[9] Gottwald M, Kan J J, Lee K, Kang S H and Fullerton E E 2013 APL Mater. 1 022102
[10] Liu E, Vaysset A, Swerts J, Devolder T, Couet S, Mertens S, Lin T, Elshocht S V, Boeck J D and Kar G 2017 IEEE Trans. Magn. 53 8001404
[11] Bilzer C, Devolder T, Crozat P, Chappert C, Cardoso S and Freitas P P 2007 J. Appl. Phys. 101 074505
[12] Faure-Vincent J, Tiusan C, Bellouard C, Popova E, Henn M, Montaigne F and Schuhl A 2002 Phys. Rev. Lett. 89 107206
[13] Li L, Zhang F, Wang N, Lv Y F, Han X Y and Zhang J J 2010 J. Appl. Phys. 108 073908
[14] Devolder T 2016 J. Appl. Phys. 119 153905
[15] Worledge D C and Troulloud P L 2003 Appl. Phys. Lett. 83 84
[16] Le Goff A, Garcia K, Vernier N, Tahmasebi T, Cornelissen S, Min T and Devolder T 2014 IEEE Trans. Magn. 50 1
[17] Słonczewski J C and Sun J Z 2007 J. Magn. Magn. Mater. 310 169 (Proc. of the 17th Int. Conf. on Magnetism)
[18] Butler W H, Mewes T, Mewes C K A, Visscher P B, Rippard W H, Russek S E and Heindl R 2012 IEEE Trans. Magn. 48 4684