Comment on "Size-dependent scaling of perpendicular exchange bias in magnetic nanostructures"

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From results at one given temperature (300 K), Malinowski *et al.* [Phys. Rev. B **75**, 012413 (2007)] draw the conclusion that lateral confinement of ferromagnetic-antiferromagnetic exchange-biased structures does not enhance thermally activated unpinning of the antiferromagnetic spins, which would thus contrast with a recent report [Phys. Rev. Lett. **94**, 117201 (2005)], as explicitly mentioned in their manuscript. In this Comment, we discuss why such a conclusion might need revision above a "crossover temperature," as evidenced in the literature. The value of such a crossover temperature certainly depends on the magnetic parameters of each system studied, e.g., anisotropy and exchange stiffness. From the above reasons, and contrary to the statement of Malinowski *et al.*, we rather think that their results might well agree with the report to which they refer to. In our Comment we notably aim at complementing the conclusion of Malinowski *et al.* by explaining why some differences between the two studies are observed at one given temperature, and why it might be expected to observe similar trends over a whole range of temperatures.

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Finite size effects on the properties of exchange biased layers have lately been widely investigated. Indeed, from the application side, whether these properties can be conserved in devices with reduced lateral dimensions, e.g., read heads and magnetic random access memories, constitutes a major issue. For fundamental reasons, wonders about the local spins configurations as the lateral dimensions are reduced down to the typical size of the antiferromagnetic (AFM) domains attract much interest.[1] In particular, exchange bias has been investigated in nanostructures with in-plane and out-of-plane anisotropy, when varying lateral sizes[1–9] and/or AFM[1,10–13] and ferromagnetic (FM)[1,3,4,12,13] layers thicknesses and/or temperatures.[1,5,6,9,12–16] Such studies underline the key role played by the reduced lateral dimensions of the nanostructures by imposing AFM domain size reductions. The presence of such effects notably leads to the observation of (i) an independence of the exchange bias field (H_E) on the AFM layer thickness (keeping constant the lateral size of the dots)[1,11,12] and (ii) an enhancement of H_E as the lateral dimensions of the nanostructures are reduced.[1–3,5,6,10–14] However, contrasting opposite trends have also been reported in the literature, such as reductions of H_E as the lateral dimensions of the nanostructures are reduced.[1,4,5,7–12,15,16] These latter results could not be explained by simply stating that the AFM domain size is reduced in the nanostructures. They could, however, be ascribed to the spatial constraints imposed on the formation of AFM domains, which might additionally lead to thermally activated loosely pinned AFM spins. The contrasting data from the literature could thus be interpreted as resulting from interplay between the AFM domain size reduction, which favors an enhancement of H_E in the nanostructures and thermal activation effects, which drive the opposite behavior.[5,11–13]

From the invariance of H_E with the AFM layer thickness in exchange biased nanostructures, in agreement with some previous results,[1,11,12] and from the further linear room temperature dependence of H_E with the inverse of the lateral size of the nanostructures, Malinowski *et al.* confirmed the importance of the limitation on the formation of AFM domains imposed by the finite size of the structures. From these results at room temperature, the authors additionally draw the conclusion that lateral confinement of the exchange-biased structures does not enhance thermally activated AFM spin reversal. Such a conclusion, which might require the support of results at various higher temperatures, would thus contrast with a recent report[12] and other previous results in the literature.[1,5,11,13] We rather think that the results from Malinowski *et al.* might well agree with these previous studies reporting on thermal activation effects on AFM spins.

Upon heating, a decrease of H_E is observed since the anisotropy and exchange energies in the AFM have to compete with thermal energy, which tends to reduce the stability of the AFM spin lattice and, consequently, the pinning strength that the AFM exerts on the FM. The temperature at which the exchange bias completely disappears is called the blocking temperature (T_B).[1] It has been reported that even in continuous FM-AFM bilayers, T_B is reduced when the AFM layer is exceedingly thin.[1,11,12,17] Furthermore, patterned bilayer systems with reduced lateral dimensions have also been reported to display lower T_B than their corresponding continuous films, either in systems with in-plane or out-of-plane anisotropy.[1,9,11–13] A recent work on out-of-plane exchange biased [Pt/Co]/IrMn nanostructures[13] studied the dependence of the exchange bias field on different annealing temperatures accompanied by a standard cooling procedure which allows estimating the blocking temperature distribution; it was shown that the exchange bias field for the nanostructures vanished at significantly lower temperatures than for the continuous film. This is a first clue that AFM spins in nanostructures are more prone to thermal activation than for continuous films. As evidenced in the literature, it is thus not unexpected that above a given first "crossover temperature" (T_{cross1}) size-dependent thermal activation effects will start to prevail over the contrasting effects arising from AFM domain size reduction. In principle, for sufficiently small dots, taking into account the constraints imposed by the lateral size of the dots on the AFM domain size, one would expect H_E to be always larger than for continuous films with the same composition.[10] However, as shown for example in Figs. 4(a) and in 5 of Ref. 11, this is not always the case. Therefore, we inferred that even though H_E in Fig. 4(a) was independent on the AFM thickness, thermal activation effects were already present at room temperature, i.e., T_{cross1} is smaller than room temperature for those particular samples. At higher temperatures, H_E starts to decrease faster for the thinnest AFM layers [Figs. 4(b)–4(d)] due to the fact that thickness dependant thermal activation effects start to prevail. As deduced from Fig. 4, this occurred at a crossover temperature T_{cross2}, which stands between 313 and 333 K in our case.

The values of the blocking temperature T_B, among with those of both crossover temperatures T_{cross1} and T_{cross2} certainly depend on the magnetic parameters of the AFM layer, e.g., anisotropy and exchange stiffness. These parameters prove to be difficult to accurately quantify so far. It is, however, very likely that they differ between the paper from Malinowski *et al.* and Ref. 12, namely, since the anisotropy direction is out-of-plane for the former study and in-plane for the latter. As notably stated in Ref. 1, "probably, the different parameters (e.g., AFM or FM domains, AFM uncompensated spins or FM magnetization reversal) influencing exchange bias in nanostructures will have different length scales for each specific system." It thus corroborates the idea that for given length scales, the interdependence of the parameters influencing exchange bias (e.g., T_B, T_{cross1}, T_{cross2}, AFM thickness, AFM anisotropy, and AFM exchange stiffness) will be different for each specific sample. The invariance of H_E on the antiferromagnetic layer thickness among with the larger values of H_E for the nanostructures observed by Malinowski *et al.* over the whole range of AFM layer thicknesses studied at 300 K, suggests that T_{cross1} and T_{cross2} are larger than room temperature. From these data, one cannot draw the conclusion that lateral confinement of ferromagnetic-antiferromagnetic exchange-biased structures does not result in thickness dependant thermally activated pinning of the antiferromagnetic. Some additional measurements, at temperatures higher than 300 K, would be needed to validate or not such a conclusion. Measurements of T_B would notably give some clues. One can thus probably only remark that the effects resulting from finite size and thickness dependant thermally activated pinning of the antiferromagnetic spins are negligible at room temperature for those specific samples. From the reasons discussed in the present Comment, we personally think that Malinowski *et al.* statement would need revision above a crossover temperature higher than 300 K and that their results might thus well agree with Ref. 12, after comparison over a whole range of temperatures.

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