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

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Our observation of size-dependent scaling effects at room temperature in exchange-biased multilayers grown onto arrays of polystyrene nanospheres [Phys. Rev. B **75**, 012413 (2007)] does not conflict with the observation by Baltz *et al.* of a crossover to thermally activated spin reversal in the antiferromagnetic layer upon patterning [Phys. Rev. Lett. **94**, 117201 (2005)]. We mention a few dissimilarities between the two systems that might account for a different behavior at room temperature.

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In a recent paper[1] we employed dense arrays of monodisperse spherical polystyrene particles to fabricate $[Pt(2\ nm)/Co(0.5\ nm)]_3/IrMn$ (t in nm)/Pt(2 nm) multilayers with a lateral diameter (d) varying from 58 to 320 nm. These nanostructures were characterized at room temperature using magneto-optical Kerr effect magnetometry and magnetic force microscopy. For comparison, the films were also simultaneously deposited on plain SiO_2 substrates, exhibiting perpendicular magnetic anisotropy and exchange bias.[2–4] By measuring the exchange bias field as a function of particle size (d) and antiferromagnetic (AFM) IrMn layer thickness (t) we were able to demonstrate that (1) the perpendicular bias field is inversely proportional to the sphere diameter when the AFM domains in the IrMn layer are confined by the size of the particles, (2) the exchange bias effect is independent of IrMn film thickness for $t \geqslant 10$ nm and all particle sizes, and (3) the exchange bias field of the magnetic nanocaps is larger than that of continuous multilayers. From these observations we concluded that the lateral confinement of the exchange-biased structures does not enhance thermally activated spin reversal in the IrMn layer.

An invariance of the exchange bias field with respect to the AFM layer thickness has previously been measured on lithographically defined magnetic nanostructures.[5,6] In these reports, Baltz *et al.* compare the exchange bias properties of continuous Ta(5 nm)/Py (12 nm)/IrMn (t)/Pt (2 nm) multilayers with those of square dots with a lateral size of 90 nm. The Py film exhibits in-plane magnetic anisotropy. Contrary to our paper,[1] the plot of the bias field as a function of IrMn layer thickness shows a crossover in the exchange bias values of the continuous and patterned films. The authors attribute this room temperature observation to more pronounced thermally activated effects in the IrMn layer of the nanodots. Measurements of the blocking temperature[5] and field annealing procedures[6] substantiate this explanation.

In a comment on our paper, Baltz *et al.* assert that although a lateral confinement of the exchange-biased structures in our study does not enhance thermally activated unpinning of the AFM spins at room temperature (and thereby a reduction of the exchange bias field), such effects may occur at elevated temperatures. This statement, which holds for any thermally activated process, is correct. We, however, stress that our conclusion refers to the bias properties at room temperature where thermally activated effects are negligible in the $[Pt/Co]_3/IrMn/Pt$ nanostructures we have studied. As a result, the perpendicular exchange bias field scales with the inverse of the particle diameter when $t \geqslant 10$ nm. This is clearly illustrated by Fig. 4 in Ref. 1 showing experimental data for nanostructure with four different sizes. Under these conditions the AFM domains are confined by the dimension of the magnetic nanocaps, i.e., the IrMn film is single domain and $D_{AFM} \approx d$. Our results therefore agree with Malozomoff's random field model predicting an inverse proportionality between the magnitude of the bias field and the AFM domain size.[7]

In the Ta/Py/IrMn/Pt multilayers of Baltz *et al.*,[5,6] thermally activated reversal in the IrMn film of the nanodots is already significant at room temperature. For small AFM layer thickness this results in a decrease rather than an increase of the bias field upon patterning the film into nanodots. The scaling behavior as predicted by Malozomoff's model is therefore obscured by a reduced stability of the AFM spin lattice. While differences in the anisotropy and exchange stiffness of the IrMn layer or the magnetization direction in the ferromagnetic film might account for dissimilar room temperature results, we wish to note another difference between the experiments. While Baltz *et al.* used electron beam lithography and reactive ion etching to prepattern Si substrates into 90 nm dots, we used arrays of polystyrene nanospheres to study size-dependent scaling of exchange bias in magnetic nanostructures. This technique, which was first pioneered with unbiased magnetic multilayers,[8,9] results in well-defined spherical nanocaps whose thickness gradually decreases towards the edges. As the edges become increasingly important upon size reduction, the preparation methods and/or different edge morphologies of the nanodots and nanocaps might well influence thermally activated reversal in the AFM film. For practical applications of exchange-biased films with reduced lateral dimensions in, e.g., magnetic field sensors, read heads, and magnetic random access memories, thermally activated reversal effects should be minimized at room temperature. The deposition of magnetic films on nanosphere arrays might offer a promising way to fabricate very small nanocaps with a stable and large exchange bias field.

In conclusion, we maintain that the lateral confinement of

the exchange-biased structures by the size of the nanospheres does, contrary to the experiments by Baltz *et al.*, not enhance thermally activated unpinning of the antiferromagnetic spins at room temperature. This is, however, not to say that thermally activated spin reversal in the IrMn layer is independent of the lateral structure size at higher temperatures. We anticipate that the different preparation methods and shape of the nanostructures influence their magnetic properties.

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