Reply to comment on 'Particle size dependent exchange bias and cluster-glass states in $LaMn_{0.7}Fe_{0.3}O_3$ '

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REPLY

Reply to comment on 'Particle size dependent exchange bias and cluster-glass states in $LaMn_{0.7}Fe_{0.3}O_3$'

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Abstract
In reply to the comment by Geshev we emphasize that loop shift in the compounds is not a simplified phenomenon of minor loop effect of a ferromagnet rather, it is a genuine signature of exchange bias effect. The estimate of anisotropy field and the plot of exchange bias field at 5 K with the maximum field used for the measurement of hysteresis loop, in addition to the previously reported results such as temperature dependence of exchange bias field, training effect, etc, confirm the exchange bias effect.

(Some figures in this article are in colour only in the electronic version)

In a comment on a recent paper by Thakur *et al* [1], Geshev suspected that the observation of the exchange bias effect in $LaMn_{0.7}Fe_{0.3}O_3$ is simply a minor loop effect of a ferromagnet. In order to justify his suspicions Geshev referred to another of his comments [2]. In [2] it was stated that 'A loop is a minor one if $H_{max} < H_A$'. H_{max} is the maximum field applied for the loop trace and H_A ($\approx 2K_1/M_S$) is the anisotropy field of the system where K_1 is the first-order anisotropy constant and M_S is the saturation of magnetization.

We measured the initial magnetization curve at 5 K on the same sample ($LaMn_{0.7}Fe_{0.3}O_3$ with average particle size ~70 nm) where a signature of exchange bias was reported by Patra *et al* [3]. In order to get a rough estimate of H_A the initial magnetization curve at 5 K (figure 1) was fitted by the law of approach to saturation of magnetization, $M = M_S(1 - a/H - b/H^2) + \chi H$ where χ is the high field susceptibility. Constant b gives the estimate of magnetocrystalline anisotropy where $b = 4K_1^2/(15M_S^2)$ for the anisotropic ferromagnet [4]. The value of H_A ($=2K_1/M_S$) is ~12.6 kOe at 5 K. In [3] the value of H_{max} was 20 kOe and all the analyses based on the exchange bias field (H_E) were considered for the loops with $H_{max} = 50$ kOe in [1]. In both references the value of H_{max} was $> H_A$ which clearly indicates that the loop measured with $H_{max} \geqslant 20$ kOe is not the minor one.

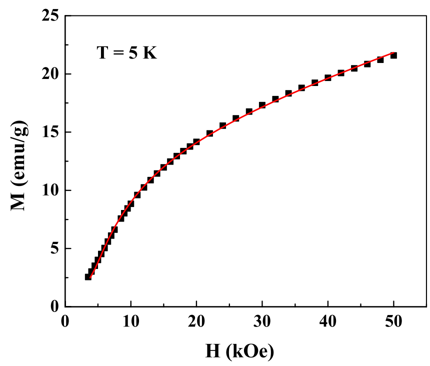

Figure 1. Initial magnetization curve at 5 K. The continuous curve exhibits the fit using the law of approach to saturation.

We carefully note that traces of hysteresis are the closed loops for $H_{max} \geqslant 15$ kOe ($>H_A$) for the same sample with average particle size ~70 nm which is shown in the top panel of figure 2. In the bottom panel of figure 2 the values of H_E are plotted against H_{max} for 15 kOe $\leqslant H_{max} \leqslant$ 50 kOe at 5 K where loops were measured after cooling the sample from 250 K with a cooling field, $H_{cool} = 4$ kOe. The

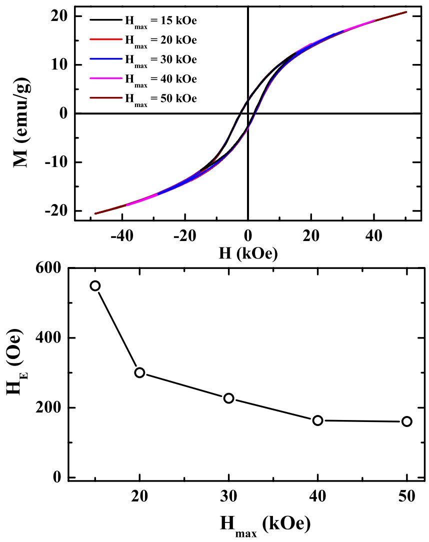

Figure 2. Top panel: field-cooled hysteresis loops at 5 K for different H_{max}. Bottom panel: plot of H_E against H_{max} at 5 K.

plot clearly demonstrates the non-zero asymptotic value of H_E ($>\sim 100$ Oe). Therefore, we would like to emphasize that the exchange bias effect in $LaMn_{0.7}Fe_{0.3}O_3$ is a genuine observation which is not a simplified phenomenon of the minor loop effect of a ferromagnet. We point out that the exchange bias effect was further investigated in $LaMn_{0.85}Fe_{0.15}O_3$ and $LaMn_{0.50}Fe_{0.50}O_3$ where any vertical or horizontal shift of the loop in the magnetization or field axis was absent even in case of low H_{max}. However, we observe the systematic shift in La-deficient $La_{0.87}Mn_{0.7}Fe_{0.3}O_3$ where the exchange bias effect is weaker than La-stoichiometric $LaMn_{0.7}Fe_{0.3}O_3$. The reason for the weak exchange bias effect was discussed in [5]. We further checked that the value of H_A is $\sim$7.6 kOe for $La_{0.87}Mn_{0.7}Fe_{0.3}O_3$, which is indicated by the coercive field (H_C) where H_C for $La_{0.87}Mn_{0.7}Fe_{0.3}O_3$ is almost half of the value for $LaMn_{0.7}Fe_{0.3}O_3$. Thus measurement of the loop with $H_{max} = 10$ kOe in [5] is not a minor one.

In the case of an exchange bias phenomenon the system must contain two exchange coupled phases consisting of reversible and rigid phases where magnetization of the first one can be reversed and the second one cannot be reversed. Since the exchange bias in $LaMn_{0.7}Fe_{0.3}O_3$ is driven by the cluster-glass state consisting of ferromagnetic (FM) and spin-glass (SG) like phases, let us concentrate on the exchange coupling at the FM/SG interface. When the system is cooled in an external magnetic field through the spin-freezing temperature (T_f) to the low temperature ($\ll T_f$), the spins of the SG phase are aligned and frozen along the direction of the cooling field creating the pinning force on the reversible spins. As a result of this an additional layer consisting of pinned or frozen FM spins is formed at the interface in between reversible FM and rigid SG phases which leads to the exchange bias effect. In [3, 5] H_E decreases considerably with increasing temperature and vanishes close to T_f, above which SG spins cannot apply the pinning force on FM spins. Thus temperature dependent results are consistent with the exchange bias effect at the FM/SG like interface. A training effect is one of the supportive results of the exchange bias effect which was reported by Patra *et al* and demonstrated in figure 4 of [3].

In conclusion, we emphasize that loop shift in $La_{1-\delta}Mn_{0.7}Fe_{0.3}O_3$ ($\delta = 0$ and 0.13) is not a minor loop effect of a ferromagnet which is a genuine signature of the exchange bias effect. H_{max} dependence of H_E (figure 2), temperature dependence of H_E [3, 5] and observation of a training effect [3] clearly demonstrate the exchange bias effect.

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