Designing exchange bias in Heuslers

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Magnetic Heuslers with multiple magnetic sub-lattices provide a perfect platform for the design of anisotropic and acentric room-temperature magnets with flexible magnetic configurations. Based on these principles we have designed several new Heusler materials with extraordinary properties. We have discovered an anomalous zero field cooled exchange bias in a ferrimagnetic Heusler material with some ferromagnetic inclusions [1]. By taking this concept into account we designed a compensated magnetic state by combining two oppositely magnetized ferrimagnetic systems that shows an extremely large exchange bias and coercivity [2]. The large exchange anisotropy originates from the exchange interaction between the compensated host and the ferrimagnetic clusters that arise from intrinsic anti-site disorder.

Heusler compounds, X_2YZ (where X, Y are transition metals and Z is a main-group element), are well known for their multi-functional properties. The new materials in the Heusler family can be designed on the basis of simple rules taking into account the position of the atoms, the number of valence electrons, the degree of atomic disorder and the strength of the exchange interactions. Some of the important results based on our designing concept are discussed in the following.

Exchange bias (EB) corresponds to a shift of the hysteresis loop of a ferromagnet along the magnetic field axis due to interfacial exchange coupling with an adjacent antiferromagnetic layer. It is used for a variety of technological applications, including magnetoresistive read heads and sensors. Though both ferromagnetic (FM) and antiferromagnetic (AFM) subsystems are inseparable parts of an EB system, it is the latter that determines the magnitude of the EB in the system. Therefore, it is important to search for an appropriate magnetically compensated material to observe a maximum effect.

In this regard Mn_2YZ based magnetic Heuslers are perfect candidates to tune the magnetic states to achieve desirable properties. These materials, in general, show a ferrimagnetic ordering as the Mn atoms occupy two different crystallographic positions with antiparallel spin alignment. One of the best examples of tunable magnetic properties in these materials is the finding of zero field cooled exchange bias in Mn_2PtGa. This compound orders ferrimagnetically around 230 K. However, the ac-susceptibility measurements indicate a magnetic inhomogeneous state at low temperatures. Therefore we measured M(H) loops at low temperature as shown in Fig. 1. Interestingly, the hysteresis loop measured in ZFC condition shows a large shift in the negative field direction when the virgin curve starts in positive field

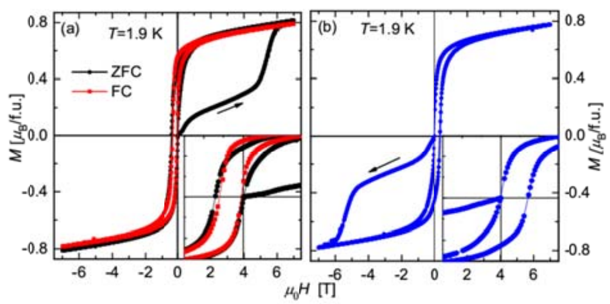

FIG. 1. (a) Zero field cooled (ZFC) and field cooled (FC) M(H) loops for M_2PtGa measured at 1.9 K. The measurements are performed as 0→+7 T→-7 T→+7 T (b) ZFC M(H) loop at 1.9 K performed as 0→-7 T→+7 T→-7 T. The insets show a magnified view of M(H) loops around H = 0.

direction. To confirm this effect we measure ZFC field hysteresis loop with virgin curve starting in negative field direction, where the loop is shifted in positive field direction. These effects correspond to the presence of ZFC EB in Mn_2PtGa. It can be noted here that EB is generally observed when a system is field cooled from a temperature above the blocking temperature. We found that the presence of FM clusters inside the ferrimagnetic background is an important ingredient for the appearance of a ZFC EB. The interaction between the FM clusters and ferrimagnetic background sets up during the virgin magnetization process. Therefore, a field cooling is not necessary in the present case. It can be also seen that the FC M(H) loop gives a same magnitude of EB as that of ZFC one.

Since we observe a considerable amount of EB in Mn_2PtGa with FM clusters in ferrimagnetic background, we focused in next step to design a material that can give a very large EB. It is known that the AFM material plays an important role in deciding the magnitude of EB in an EB system. Therefore, we propose to tune the EB by using a compensated Heusler material rather than the ferrimagnetic system.

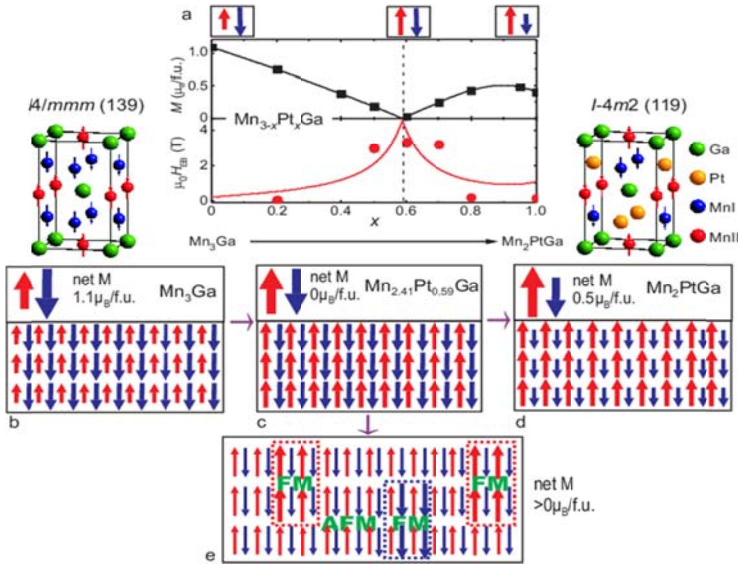

FIG 2. Design of a compensated magnetic state in $Mn_{3-x}Pt_xGa$. Perfect magnetic compensation is expected in $Mn_{2.41}Pt_{0.59}Ga$ by changing the composition from Mn_3Ga to Mn_2PtGa. FM domains appears inside the compensated AFM host due to antisite disorder in the sample .

It is known that Mn_3Ga displays a net uncompensated magnetization of about $1\mu_B$/f.u. as a result of ferrimagnetic ordering. Here, one Mn in the Mn-Ga with spin-up and two Mn in the Mn-Mn planes with spin-down, resulting a net moment in spin-down direction. In contrast, Mn_2PtGa consists of one Mn in the Mn-Ga with spin-up and one Mn in the Mn-Pt planes with spin-down. Due to more localized nature of the Mn moment in Mn-Ga plane a net moment of around 0.6 μ_B/f.u. with spin-up is found in Mn_2PtGa. This suggests that a compensated magnetic state can be achieved by moving from Mn_3Ga to Mn_2PtGa by tuning the Mn/Pt ratio. The design scheme is illustrated in Fig. 2. From the theoretical calculation we found that a compensated ferrimagnetic state can be achieved for x=0.6 in $Mn_{3-x}Pt_xGa$. This was verified by the magnetization measurements. Indeed, we have observed an AFM ordering in our temperature dependence of magnetization measurements.

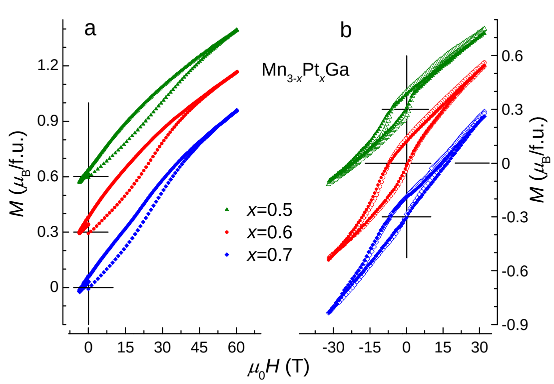

FIG. 3. (a) ZFC M(H) loops for $Mn_{3-x}Pt_xGa$ measured up to 60 T. (b) FC loops for different samples measured up to 32 T.

The hysteresis loops measured in 60 T pulsed magnetic field and 32 T dc magnetic field shows a giant EB of more than 3 T and a similarly large coercivity in the vicinity of the compensated point (Fig. 3). The achievement of a coercivity of more than 3 T based on exchange anisotropy proposes a new approach to permanent magnet design. We have also designed several other Heuslers that show EB [1-5]. In addition to exchange bias we have been working on non-collinear magnetism and skyrmions in Mn-Pt(Rh)-Sn based Heusler materials [6,7]. We also work on several Heusler shape memory materials that show magnetocaloric effect and large field induced irreversibility [8-13].

References

[1] A. K. Nayak et al., Nature Mater. 14, 679 (2015).
[2] *A. K. Nayak et al., Phys. Rev. Lett. 110, 127204 (2013).*
[3] *J. F. Qian et al., J. Phys. D: Appl. Phys. 47, 305001 (2014).*
[4] *A. K. Nayak et al., Appl. Phys. Lett. 100, 152404 (2012).*
[5] *T. Gasi et al., Appl. Phys. Lett. 102, 202402 (2013).*
[6] *O. Meshcheriakova et al., Phys. Rev. Lett. 113, 087203 (2014).*
[7] *A. K. Nayak et al., Under review in Science.*
[8] *A. K. Nayak et al., Phys. Rev. B 90, 220408 (2014).*
[9] *M. G. Zavareh et al., Appl. Phys. Lett. 106, 071904 (2015).*
[10] *C. S. Mejia et al., J. Appl. Phys. 117, 17E710 (2015).*
[11] *A. K. Nayak et al., J. Appl. Phys. 117, 17D715 (2015).*
[12] *A. K. Nayak et al., J. Appl. Phys. 113, 17E308 (2013).*
[13] *T. Gasi et al., J. Appl. Phys. 113, 17E301 (2013).*

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