Micromagnetic calculations of bias field and coercivity of compensated ferromagnetic antiferromagnetic bilayers

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Exchange bias in polycrystalline IrMn/NiFe was found at perfectly compensated interfaces. The energy associated with unidirectional anisotropy is stored in lateral domain walls in the antiferromagnet. In addition to exchange bias, this mechanism leads to a training effect. The bias field shows a maximum of $\mu_0 H_b = 4$ mT at an antiferromagnetic layer thickness of 22 nm. The coercivities are on the order of $\mu_0 H_c = 10$ mT. The coercive field increases with decreasing intergrain exchange interactions within the ferromagnet.
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Since the work of Meiklejohn and Bean[1] the exchange bias effect of ferromagnets has been the subject of theoretical and experimental investigations. Meiklejohn and Bean phenomenologically introduced a unidirectional anisotropy to explain a shift in the hysteresis loop of small Co particles with a CoO shell. The exchange bias effect is used to stabilize the pinned layer in spin valve sensors. Commonly used materials are bilayers of FeMn/FeCo, IrMn/NiFe, and IrMn/FeCo. In these multilayer systems, both the antiferromagnet and the ferromagnet are polycrystalline. Various models were proposed to explain exchange bias but all of them required the assumption of partly uncompensated interfaces.[2] In the following we will present a model that explains exchange bias at perfectly compensated interfaces.

Originally, Koon[3] proposed a mechanism for exchange bias at fully compensated interfaces. Koon assumed that the antiferromagnetic spins are restricted to planes parallel to the interface. The loop shift can be attributed to partial domain walls would up in the antiferromagnet. Allowing full three dimensional rotations of the antiferromagnetic spins, Schulthess and Butler[4] showed that the domain walls are unstable due to out of plane rotations of the antiferromagnetic spins. They conclude that spin flop coupling at compensated interfaces enhances the coercivity but does not lead to exchange bias. Stiles and McMichael[5] drew a similar conclusion introducing spin flop coupling in their model for polycrystalline ferromagnetic–antiferromagnetic bilayers. Kiwi and co-workers[6] propose a model of exchange bias at compensated interface. In their model energy is stored in domain walls within the ferromagnet. In this article we show numerically that exchange bias can occur at fully compensated interface. The essential features of the model are grains in the antiferromagnet which exhibit random uniaxial anisotropy and are weakly exchange coupled.

In a global picture the exchange bias effect can be understood by the change of the total Gibbs' free energy after the reversal of the ferromagnet. After field cooling the total energy of the system is low. During field cooling the ferromagnetic spins are fixed in the field direction, the antiferromagnetic spins arrange in such a way that they occupy low energy states. Several experiments like rotational hysteresis measurements and ferromagnetic resonance studies suggest that irreversible processes occur in the antiferromagnet when the ferromagnet is reversed.[5] Many antiferromagnet/ferromagnetic systems show the so-called training effect.[7] The loop shift decreases with increasing number of hysteresis cycles. This suggests that after each cycle the system is in a different state. After field cooling the system has loss energy. The energy will increase if the system changes its state from the state after field cooling to a different state. If the ferromagnet is reversed, some antiferromagnetic grains switch irreversibly. These irreversible processes are initiated by the reversal of the ferromagnet. They occur for uncompensated as well as for compensated interfaces. Owing to the intergrain exchange coupling between antiferromagnetic grains the energy increases. Different mechanisms contribute to the partial switching of the antiferromagnetic grains. Xi and White[8] found a varying interface coupling in NiFe/CrMnP bilayers prepared by substrate bias sputtering. However, it is sufficient to take into account the random magnetocrystalline anisotropy in the AF grains to observe that some and not all AF grains switch irreversibly.

In the upper sequence in Fig. 1 the antiferromagnet switches irreversibly as the ferromagnet (F) is rotated by a rotational external field. The angle of the field direction increases following the subfigures from left to right in Fig. 1. Initially, the ferromagnet points perpendicular to the antiferromagnet owing to spin flop coupling. The antiferromagnet points parallel to the easy axis that is parallel to the interface plane. The material parameters are chosen to mimic a Permalloy/IrMn bilayer.[9] The simulations are performed using a finite element approach for ferromagnet/antiferromagnet structures. Details can be found in Ref. 9.

In the sequence at the bottom of Fig. 1 the angle between the easy axis and the interface plane is 10°. When the ferromagnet is rotated by 90° the antiferromagnet starts to rotate out of the plane parallel to the interface. As a consequence the antiferromagnet rotates back close to the initial configuration. Thus the switching of the ferromagnet did not switch the antiferromagnet.

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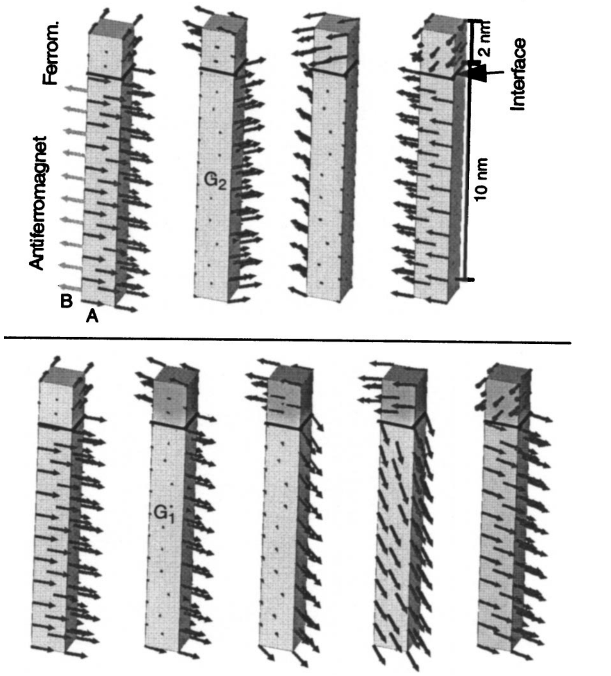

FIG. 1. Spin structure in an AF/F bilayer during switching of the ferromagnet. In the upper left picture both spin sublattices (A and B) are shown in the antiferromagnet. In all the other pictures only sublattice A is shown. (Upper sequence) Irreversible switching of the antiferromagnet. (Lower sequence) Reversible switching of the AF.

If these two grains are exchange coupled in a granular AF/F film the switching of one grain and the not switching of the other grain can lead to exchange bias. Suppose that the two grains are oriented that the initial state after field cooling is represented by the left image of Fig. 2. If the grains are exchange coupled the spins after field cooling will arrange in such a way that the total energy is minimized. Consequently the spins in grain G_1 and G_2 are almost parallel and not antiparallel.

Only G_1 switches and the two grains point almost antiparallel after the ferromagnet is reversed. As a consequence in the reversed state the total energy is higher than in the field cooled state owing to intergranular exchange coupling. Generally, we found that the field that is required to switch the ferromagnet from the low energy state to the high energy state is larger than the field required to switch the ferromagnet in the other direction. This explains the loop shift observed in antiferromagnetic/ferromagnetic structures.

In the following results are presented using a simple micromagnetic model to calculate the exchange bias field for granular AF/F bilayers. We assume a polycrystalline antiferromagnetic film of thickness t_{AF} coupled to a polycrystalline ferromagnetic film of thickness t_F. For small grain size and low intergrain exchange coupling the magnetization within a grain remains nearly uniform. Thus we treat the magnetization within every grain with one spin vector. We assume a compensated interface and therefore use a biquadratic coupling term between the ferromagnet and the antiferromagnet as proposed by Stiles and McMichael[5] and as derived by Stamps.[10] A weak Heisenberg exchange coupling is assumed between the AF grains. Only the ferromagnet interacts with the external field. Shape effects for the ferromagnetic film are approximated by assuming an in plane anisotropy energy

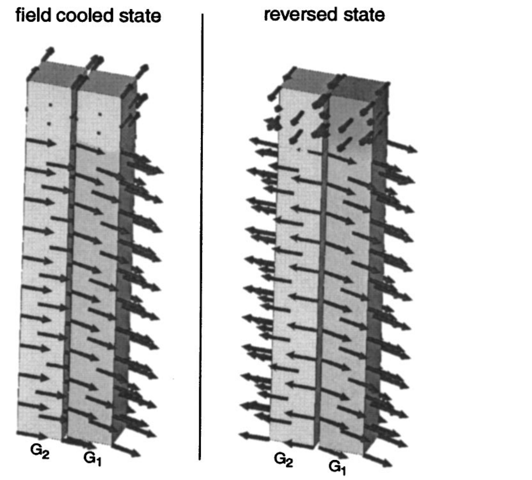

FIG. 2. Spin configuration in two exchange coupled antiferromagnet grains and the ferromagnet after field cooling and after the reversal of the ferromagnet, respectively. The magnetization of one sublattice is shown. The easy axis of G_1 is parallel to the AF/F interface. The angle between the easy axis of G_2 and the interface is 10°. After field cooling the magnetization of the two grains points almost parallel. After switching of the ferromagnet only G_2 reverses.

proportional to the square of the magnetization. The material parameters are chosen to approximate materials used in giant magnetoresistance read-heads, such as IrMn. In the antiferromagnet, the anisotropy constant $K_1 = 1\times10^5$ J/m^3 $J_{\mathrm{AF}} = 0.023$ meV. The antiferromagnetic layer consists of 60×60 rectangular grains with a basal plane area of 10×10 nm^2. The grain structure in the ferromagnet is the same as in the antiferromagnet. The thickness of the ferromagnet is 10 nm in all cases. The intergrain interaction between ferromagnetic grains is $J_F = 0.45$ meV. The coupling between the ferromagnet and antiferromagnet is completely compensated, with the effective interface exchange, $J_{\text{AF-}F} = -0.45$ meV. Field cooling is simulated using a Metropolis Monte Carlo algorithm. The initial state for the hysteresis loop calculation is the magnetization configuration obtained after field cooling. The hysteresis loop is obtained by the subsequent calculation of equilibrium states for decreasing or increasing external field. Details of the method are presented elsewhere.[11]

Figure 3 shows the calculated hysteresis loops for a

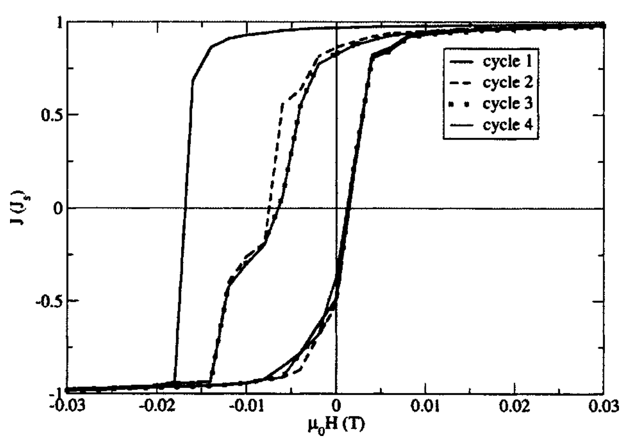

FIG. 3. Hysteresis loop for a IrMn/Permalloy bilayer with 3600 grains and perfectly compensated interface between ferromagnet and antiferromagnet. The thickness of the ferromagnet and antiferromagnet is 10 and 20 nm, respectively. The AF grains are weakly exchange coupled.

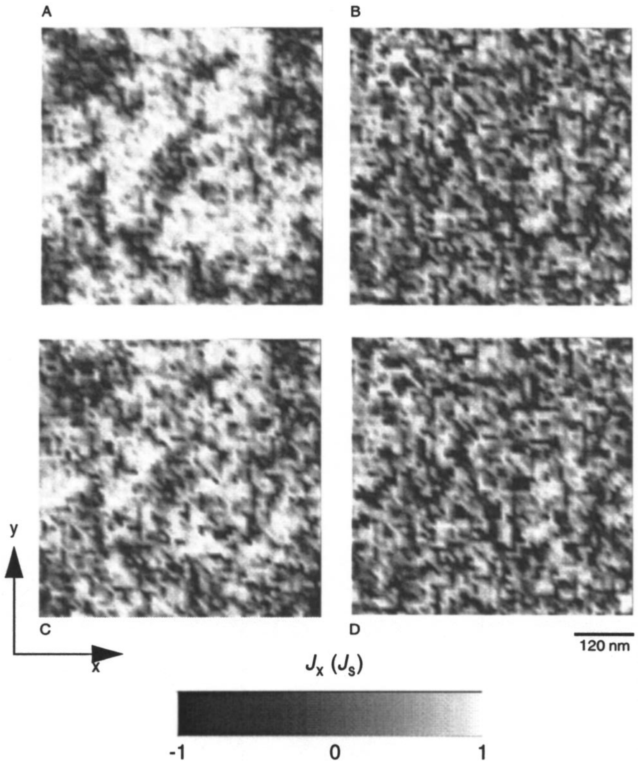

FIG. 4. Domains in the antiferromagnet. The x component of one sublattice of the antiferromagnet is color coded. (A) state after field cooling. The external field is $H_{\mathrm{ext}}=0.1$ T. (B) Domain structure in the antiferromagnet after the switching of the ferromagnet. $H_{\mathrm{ext}}=-0.1$ T (C) Domain structure after the first hysteresis cycle. $H_{\mathrm{ext}}=0.1$ T (D) After switching the ferromagnet again. $H_{\mathrm{ext}}=-0.1$ T.

thickness of the antiferromagnet of 20 nm. The initial field is applied parallel to the y-axis with a field strength of $\mu_0 H=0.1$ T. It is decreased in steps of $\mu_0 \Delta H=0.002$ T. In order to investigate the training effect several hysteresis cycles are calculated. Cycle 1 of the loops in Fig. 3 is calculated starting from the field cooled state as the initial configuration. It shows a bias field of ($\mu_0 H_b=7.7$ mT). The next cycle (cycle 2) shows a reduction of the bias field by about 65%. Thus a training effect can be found although the simulation is performed at zero temperature. The origin of the training effect are the different domain configurations in the antiferromagnet after field cooling and after the first hysteresis cycles. Figure 4(A) shows the domain configuration after field cooling. The external field is $\mu_0 H_{\mathrm{ext}}=0.1$ T. The magnetization of one sublattice of the antiferromagnet parallel to the x axis is color coded (left = black, right = white). Large domains, with diameters of several hundred nanometers are formed. Figure 4(B) shows the domain configuration at $\mu_0 H_{\mathrm{ext}}=-0.1$ T. The large domains break up into a larger number of smaller domains. The formation of small domains costs domain wall energy. Figures 4(C) and 4(D) show the domain configuration at $\mu_0 H_{\mathrm{ext}}=0.1$ T and $\mu_0 H_{\mathrm{ext}}=-0.1$ T after the first cycle, respectively. Again the number of domains increases when the external field points antiparallel to the field cool direction.

The thickness of the antiferromagnet influences the bias field. The bias field shows the maximum of $\mu_0 H=4$ mT for a thickness of 22 nm. For decreasing antiferromagnetic thickness the domain wall energy approaches zero, resulting in a vanishing energy difference between the reversed state (large number of domains) and the initial state (small number of large domains). Consequently, the bias field goes to zero. For large thicknesses the high anisotropy energy hinders switching of the antiferromagnetic grains. Thus the reversed state is symmetric to the field cooled state, which results in a symmetric hysteresis loop with zero bias. The model predicts the bias fields of IrMn/NiFe bilayers in the right order of magnitude. In addition, the thickness dependence of the bias field is in good qualitative agreement with the experimental data reported by van Driel and co-workers.[12]

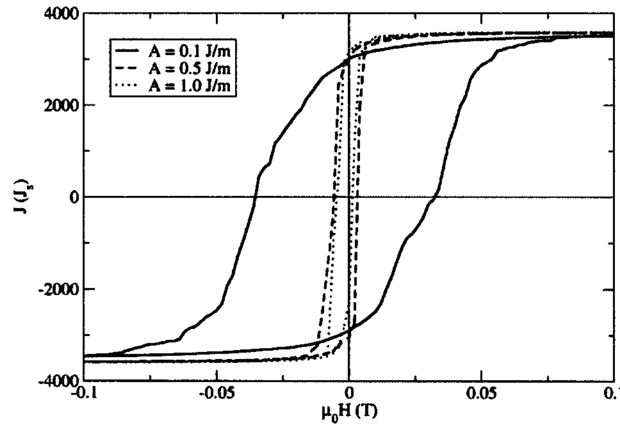

FIG. 5. Hysteresis loops for different intergranular exchange in the ferromagnet. The shown hysteresis loops are taken after the 10th field cycle. The AF and F thickness is 15 and 10 nm, respectively.

The coercivities are on the order of $\mu_0 H_c=10$ mT but significantly depend on the exchange constant in the antiferromagnetic film as shown in Fig. 5. The coercive field increases with decreasing exchange integral of the ferromagnet. For an exchange integral in the ferromagnet of $J_F=0.045$ meV the coercive field is $\mu_0 H_c=35$ mT, whereas for $J_F=0.45$ meV the coercive field is only $\mu_0 H_c=3$ mT. The increase of the coercive field of partly uncompensated ferromagnetic/antiferromagnetic bilayers with decreasing exchange constant in the ferromagnet was also reported by Stiles and McMichael.[13]

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