4 Exchange Bias in Magnetic Heterosystems

This chapter deals with the exchange-bias phenomenon in prototypical magnetic heterostructures. Special emphasis is laid on model systems involving uniaxial anisotropy. Here, the limited number of spin degrees of freedom minimizes the complexity of the problem. The discussion of the exchange-bias effect starts with the presentation of a generalized phenomenological Meiklejohn–Bean approach. It takes into account finite anisotropy and thickness of the antiferromagnetic pinning layer. In addition, microscopic mechanisms which create the antiferromagnetic interface magnetization are investigated and discussed. They are of major importance for the understanding of the exchange-bias effect. This holds, in particular, in the case of antiferromagnetic pinning layers with compensated surfaces. This monograph pays special attention to piezomagnetism and its contribution to the interface magnetization. Piezomagnetism is a well-known bulk phenomenon among the effects of weak ferromagnetism. However, its significance in the framework of the exchange-bias effect has been overlooked so far. In addition, the temperature dependence of the exchange-bias field is studied. The rare case of non-zero exchange bias above the Néel temperature of the pinning layer is presented and analyzed in terms of local quasi-critical temperatures. This analysis takes advantage of the close analogy between the enhancement of the blocking temperature and the non-analytic behavior in the Griffiths phase of dilute magnets. Finally, the training of the exchange-bias effect is investigated. It is a clear signature of the non-equilibrium nature of the exchange-bias phenomenon.

4.1 A Generalized Meiklejohn–Bean Approach

The exchange bias describes a magnetic coupling phenomenon between FM and AF materials. Although this proximity effect implies a mutual interaction between the FM and AF constituents, its most striking feature affects the FM hysteresis which shifts along the magnetic field axis after field-cooling of the heterosystem to below the Néel temperature. In addition to this spectacular effect, the coupling also modifies the coercive field of the ferromagnet. Typically, the coercivity is enhanced and its temperature dependence is related to the temperature dependence of the exchange-bias field that quantifies
the shift of the hysteresis [1]. Exchange biasing and coercivity enhancement usually vanish at the blocking temperature in the vicinity of the Néel temperature. Moreover, torque measurements reveal a unidirectional anisotropy which originates from the coupling and is at the heart of the phenomenon [2].

Since the pioneering observation in 1956 of the exchange-bias effect on small ferromagnetic Co particles which are embedded in their AF oxide [3, 4], there is a renewed interest in the investigation of the exchange-bias effect in well-defined FM/AF layered heterosystems. As a typical example Fig. 4.1 exhibits the magnetic hysteresis loop of Fe$_{0.6}$Zn$_{0.4}$F$_2$(110)/Fe 14 nm/Ag 35 nm which generates an exchange bias field of $\mu_0 H_e = -3.1$ mT. While the details of this heterostructure are discussed in paragraph 4.3 the sketches of the FM/AF interfacial spin alignments illustrate the basic influence of the coupling on the magnetization-reversal. On cooling the system in an applied magnetic field to below the Néel temperature, the interface moments of the ordered antiferromagnet couple to the polarized FM interface moments via the exchange interaction $J$ (see Fig. 4.1 a). For simplicity the cartoon-like sketches refer to an uncompensated AF interface and suggest a positive exchange coupling. In contrast with the magnetic hysteresis of a coherently rotating single FM layer, the coupling between the FM layer and the AF substrate pins the ferromagnet. This, on the one hand, hampers the reversal of the magnetization with decreasing magnetic field (Fig. 4.1 a $\rightarrow$ b $\rightarrow$ c) but, on the other hand, supports the reversal from negative to positive magnetization with increasing magnetic field (Fig. 4.1 c $\rightarrow$ d $\rightarrow$ a). Consequently, the hysteresis loop is shifted by $\mu_0 H_e$ along the field axis.

Beyond this intuitive picture, a more quantitative description of the coupling has been introduced by Meiklejohn and Bean (MB) [4, 5]. They started from the well-established Stoner–Wohlfarth free-energy expression which describes the coherent hysteretic magnetization-reversal processes of single-domain particles and magnetic thin films [6]. In order to take into account the interaction between the FM/AF interface moments they added a bilinear exchange which gives rise to an additional unidirectional anisotropy energy. Under the assumption of a perfect FM/AF interface there is in general no quantitative agreement between the MB model and experimental results. Extrapolating from the exchange energies in the bulk material to the strength of the coupling at the interface, the MB approach overestimates the exchange-bias effect by typically two orders of magnitude in comparison with experimental findings [7, 8, 9, 10]. Although the actual microscopic interface interaction is in general unknown, this extrapolation is usually judged as a failure of the MB model which has stimulated an abundance of theoretical and experimental work.

One of the rare, albeit also indirect attempts to determine the modified interlayer and intralayer exchange coupling has been done in the case of Eu monolayers deposited on Gd(0001) [11]. The layer-resolved magnetization has