Chapter 2

Some general aspects of exchange bias (EB)

Exchange Bias (EB) is an induced magnetic anisotropy. This anisotropy occurs in ferromagnetic (FM) materials when coupled to an antiferromagnet (AFM). The EB effect appears as the FM/AFM system is field-cooled through the Néel temperature of the AFM, starting from a temperature T between $T_{Néel} < T < T_{Curie}$. Alternatively, the EB effect can be induced if an AFM material (i.e. materials with $T_{Néel}$ much above room temperature) is deposited on an FM layer while applying a sufficiently large field (i.e. FM is saturated) during growth. The magnetization curve at temperatures below $T_{Néel}$[1] is then shifted away from the zero field axis, usually opposite to the cooling field direction. The difference between the center of the hysteresis loop and the zero field axis is called the exchange bias field H_{EB} and is schematically illustrated in Fig. 2.1.

As an example for a possible technical application, the figure illustrates a spin valve system, consisting of a simple ferromagnetic layer (top), a non-magnetic spacer layer and an EB-pinned ferromagnetic layer, together with the corresponding hysteresis loops (right). This system can define two well defined states, depending on whether the two ferromagnetic layers are aligned parallel or antiparallel. These two states have drastically different magneto-resistances, commonly called the GMR (Giant Magneto Resistance). This effect provides great advantages in magnetic sensor and computer memory technology.

Nowadays there exist several models which try to explain the EB effect [MB56, Mei62, MKSH87, Mal87, Koo97, SB98, SM99a, SM99b, SM01]. For example, the EB coupling was experimentally found to be increased by a factor

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[1] In some cases, the EB effect occurs at a blocking temperature T_B considerably below the Néel temperature

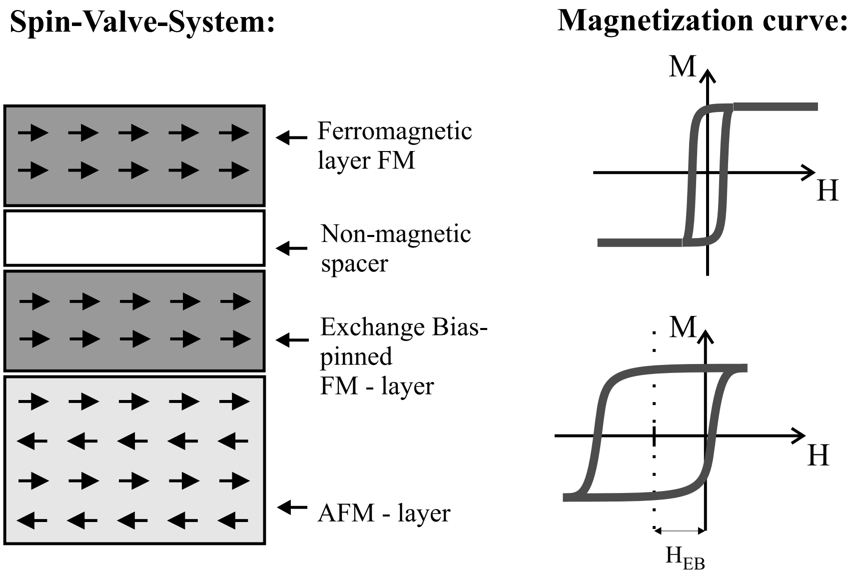

Figure 2.1: The induced unidirectional anisotropy (EB) and its technological application in spin-valve systems.

of 2-3 if the AFM layer was diluted by non-magnetic ions. This dependence can be qualitatively modeled by Monte Carlo simulations of a ferromagnetic layer on a diluted AFM Ref. [MGK$^+$00]. These findings support domain models in the spirit of the work of Malozemoff [Mal87, Mal88a, Mal88b]. However it is still not possible to fully explain the effect on a microscopic level. One reason for the difficulty in understanding the effect and the related phenomena is its dependence on a huge variety of different parameters which are difficult to control: e.g. intrinsic anisotropies, interface roughness, spin configurations, FM- and AFM- domain structures, which can be formed either perpendicular or parallel to the FM/AFM interface.

Nevertheless there are some systematic dependencies and related phenomena which occur in many EB systems. These are listed below (a good review is given by J. Nogués [JS99]):

- EB dependence on FM layer thickness d_{FM}:

  The majority of the layer systems investigated reveal that the strength of the EB shift of an FM/AFM layer system is inversely proportional to the FM layer thickness ([CLD$^+$91, JCJ$^+$94, MSBK87, NLSR96, THL81]):

$$H_{EB} \simeq \left(\frac{1}{d_{FM}}\right) . \tag{2.1}$$

This suggests that EB is an interface effect. However the previous relation is not valid for ultrathin FM layers, since considerable changes in the interface structure are to be expected. The latter are caused by tension and depend on the specific material used.

- EB dependence on AFM layer thickness d_{AFM}:

  For many investigated systems it has been found that the EB increases with the AFM layer thickness. Above a certain critical thickness, which is material dependant, the EB shift is independent of the AFM layer thickness. For very thin AFM layers the effect often vanishes ([JCJ$^+$94, SPS88, TKB$^+$97, THL81]). This behavior suggests that the intrinsic anisotropy of the AFM has to be much stronger than the exchange interaction between FM and AFM to induce the EB effect [JS99]). This can be expressed as follows:

  $$K_A d_{AFM} \geq J_{int}. \tag{2.2}$$

  The AFM anisotropy is represented by the anisotropy constant K_A. J_{int} describes the exchange coupling between FM and AFM. Furthermore, in other systems a peak in the EB shift was observed, as the AFM layer thickness was decreased, before the effect finally vanished for very thin layers ([JCJ$^+$94], [vdZBF$^+$96]). This behavior was theoretically predicted by A.P. Malozemoff [Mal88a] for the case of changes in the domain structure as the AFM layer thickness is decreased.

  On the other hand, for very thick AFM layers the EB effect has been found to decrease in some special systems. This can be attributed to considerable changes in the microscopic structure of the AFM with increasing thickness ([AC93, JCJ$^+$94, KL91, THL81]).

- Blocking Temperature

  The EB effect vanishes above a critical temperature, called the blocking temperature T_B. For some systems $T_B = T_N$ is valid, but for many others T_B is below T_N:

  $$T_B \leq T_N. \tag{2.3}$$

- EB dependence upon the cooling field:

  In most of the layer systems investigated, no significant dependence of the EB effect upon the magnitude of the cooling field was observed. However there are some layer systems, such as FeF_2/Fe and MnF_2/Fe ([NLSR96, NS97]), where the strength of the EB field changes with the strength of the cooling field.

The phenomenon of the so-called 'positive Exchange Bias' should be mentioned here. In that case, the magnetic hysteresis curve is shifted towards the cooling field direction and not against it, as is usual for most EB systems. This effect occurs in some EB systems [NLSR96] when they are field-cooled below T_N in very large magnetic fields (usually several Tesla). Up to now there are very few studies dealing with the dependence of the EB effect upon the cooling field ([TYTS80, PLH$^+$97]).

- EB dependence upon the temperature:

  In most of the EB systems the EB shift decreases linearly with increasing temperature until the effect vanishes on approaching T_N (T_B) ([NLSR96, MGG$^+$99, SJRD97, TKB$^+$97, CL82]).

- Enhanced coercivities:

  Another frequently observed phenomenon related to the EB effect is the strong dependence of the coercive fields upon the temperature, i.e. after field-cooling an EB sample through the blocking temperature, the coercive fields increase strongly with decreasing temperatures. In comparable layer systems with similar AFM materials, this increase of the coercivity was found to be stronger in those materials with weaker AFM anisotropy [NS97, CB92, LMW$^+$96, LBWA97]. This can be explained by the FM pulling the spins of a weak AFM irreversibly from their easy direction during the magnetization reversal, whereas the spins in a strong AFM decouple from the FM spins during the reversal process. In this case, the FM can easily follow the applied field direction which reduces the coercive field.