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Ground state and constrained domain walls in Gd/Fe multilayers

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Abstract

The magnetic ground state of Gd/Fe multilayers and the evolution of domain walls is modelled with micromagnetics. The ground state is determined not only by the ratio $M_s^{\rm Fe}:M_s^{\rm Gd}$ but also by the thickness of the layers. Thicker layers can prevent the Fe aligned state.

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The study of spin-polarised transport is key for the understanding of processes involved in spin-electronics. Gd/Fe multilayers are of special interest for three main reasons: firstly the Gd/Fe interface is an antiferromagnetic (AFM) sharp boundary, so it is ideal for the study of spin diffusion and spin-flip. Secondly, there is a large resistance mismatch across the interface, making the system very similar to metal–semiconductor interfaces. Finally, in certain conditions as explained below, Gd/Fe multilayers can support in-plane domain walls (DWs) close to the interface, so their transport properties can be studied in detail. These domain walls have been magnetically characterised in bilayers. In this paper we study the effect of the thickness of the layers on the magnetic behaviour of Gd/Fe multilayers.

In Gd/Fe multilayers, at low temperatures and zero field, each layer is expected to be fully FM aligned, and antiparallel with respect to the adjacent layers, creating an interface angle $\alpha_{\rm i}$ of 180°, with $\alpha_{\rm i}=|\phi_{\rm b}^{\rm Gd}|+|\phi_{\rm b}^{\rm Fe}|$, where $\phi_{\rm b}$ is the angle at the boundary. Depending on several parameters, like temperature, field history, layer thickness and thickness ratio, all moments in either the Fe layer or the Gd layer align with an applied small field. These states are the Fe aligned (F) or Gd aligned (G) states. Generally one reports G for low temperatures, e.g. $T<120\,{\rm K}$ [2], and F for high temperatures, where $M_s^{\rm Gd}$ is significantly reduced. Both states are characterised by $\alpha_{\rm i}\sim 180°$.

Upon application of a large external field, most of each layer will align parallel with the field. The angle ϕ of the magnetisation with the applied field will be nonzero near the interfaces only. This is the twisted (T) state. The AFM coupling at the interfaces remains, albeit with $\alpha_{\rm i}\ll 180°$.

In this paper we model Gd/Fe multilayers using the LLG micromagnetics software [1]. All modelled multilayers have three Fe and two Gd layers. The simulation volume is $10\times 10\times t\,{\rm nm}^3$, where t is the thickness of the multilayer. In-plane magnetisation is obtained by periodic boundaries on the xz and yz planes. The typical cell size is $1\times 1\times 1\,{\rm nm}^3$, and $M_s^{\rm Fe}=1700\,{\rm emu\,cm^{-3}}$ and $M_s^{\rm Gd}=1508\,{\rm emu\,cm^{-3}}$. $M_s^{\rm Gd}$ was reduced to 75% of the bulk value in agreement with experimental results [3,4]. The Gd/Fe system was studied as a function of $t_{\rm Fe}=t_{\rm Gd}$ while decreasing the in-plane field from 7.5 to 0 T. A typical result is given in Fig. 1.

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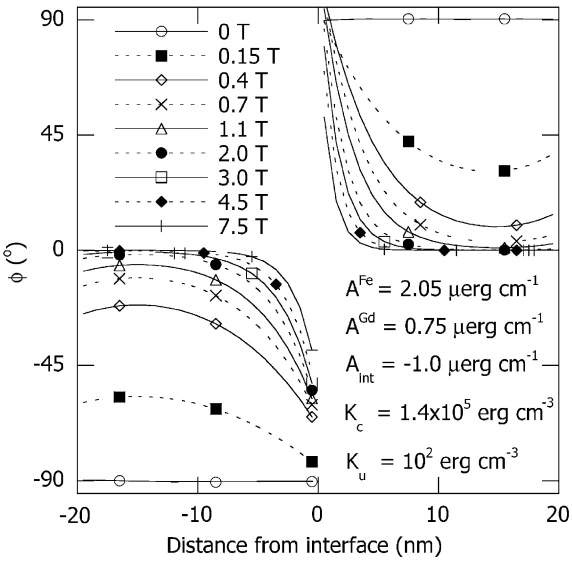

Fig. 1. ϕ vs. position showing the Gd/Fe interface for $t_{Fe} = t_{Gd}$ =30 nm.

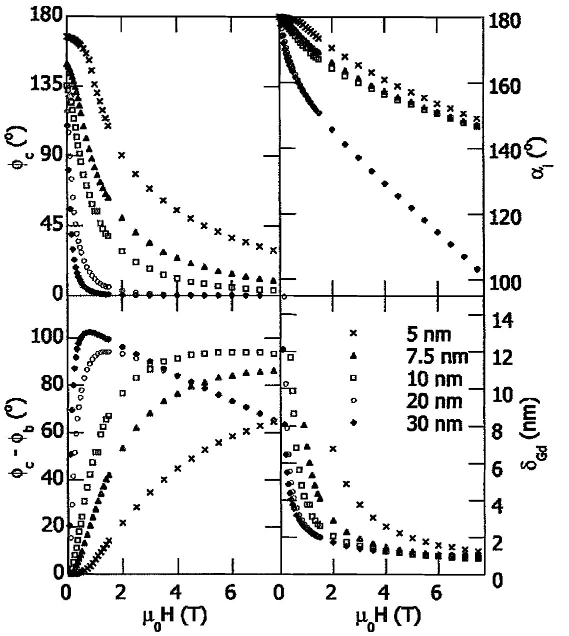

Fig. 2. The simulation of Gd/Fe multilayers for various $t_{Fe} = t_{Gd}$.

In Fig. 2 we plotted as a function of $\mu_0 H$ for different values of $t_{Fe} = t_{Gd}$ the angle at the centre of the Gd layer ϕ_c; α_i; the twist in the Gd DW $\phi_c - \phi_b$; and the width δ_{Gd} of the Gd DW.

Fig. 1 shows that $\alpha_i = 180°$ at $\mu_0 H = 0$. With increasing field, α_i is reduced. This is in agreement with the experimental results reported on antiphase boundaries in Fe_3O_4 [5] and AFM coupled interfaces in Gd/Fe multilayers [6]. At higher fields narrower DWs are formed. We find that $\delta_{Gd} < \delta_{Fe}$.

At low fields and $t_{Fe} = t_{Gd} < 10$ nm the F state prevails, as expected since $M^{Fe} > M^{Gd}$ in these $t_{Fe} = t_{Gd}$ multilayers. Only for higher fields a transition to the T state takes place and α_i starts to decrease. For larger $t_{Fe} = t_{Gd}$ however, the multilayer adopts the T state at all fields even though $M^{Fe} > M^{Gd}$. α_i is smaller than 180° at any $\mu_0 H > 0$ T.

This different behaviour can be explained by the overlap of DWs in the centre of each layer. For high fields $2\delta_{Gd} \ll t_{Gd}$ and the two DWs do not overlap; they act independently. However at smaller fields (larger δ_{Gd}) or smaller t_{Gd} the DWs do overlap. At $\mu_0 H = 2.5$ T and $t_{Fe} = t_{Gd} = 5$ nm, for instance, Fig. 2 shows that δ_{Gd} =4.8 nm. The overlap of the DWs reduces the twist by means of the surface tension in the DW and the thin layers become FM aligned, resulting in the F state, $\phi_c^{Gd} \sim 180°$. For thicker layers, the FM aligned state only occurs at zero field, and both layers are perpendicular to the applied field, $\phi_c \sim 90°$.

We conclude that the ground state is influenced by the thickness of the FM layers. Larger thicknesses can prevent the occurrence of the F state at small fields leading to hysteretic behaviour.

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