Journal of Magnetism and Magnetic Materials 198–199 (1999) 412–414

Heat-induced coupling in multilayers with semiconducting spacers

P. Walser*, M. Landolt

Laboratorium für Festkörperphysik der ETH Zürich, CH-8093 Zürich, Switzerland

Abstract

Two ferromagnetic films separated by an amorphous semiconducting spacer are exchange coupled across the spacer layer. The coupling is reversibly temperature dependent with a positive temperature coefficient. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Semiconducting spacers; Heat-induced coupling; Magnetic multilayers

Due to the growing importance of magnetoelectronics, research on magnetic multilayers has attracted renewed interest. While the origins of exchange coupling and electronic transport in metallic multilayers are well understood, the main emphasis is nowadays on obtaining systems with properties, that are useful for applications. The contribution of pure research in this situation has to be a description of possible mechanisms by which such properties can be influenced. Maybe the heat-induced magnetic coupling in heterostructures with iron and amorphous semiconducting layers, first found in multilayers with silicon spacers [1,2], is such a mechanism. The effective exchange coupling between two iron layers across a particular spacer material can reversibly be tuned by an external parameter, namely the temperature.

In this paper we give an overview on experiments of the phenomenon of reversibly heat-induced exchange coupling. As a first step, Fe/a-Si/Fe trilayers prepared by evaporation at temperatures around 40 K have been investigated. In these heterostructures we find a weak coupling between the two iron layers across the amorphous silicon (a-Si) spacer, the coupling showing two sign changes [1] and, most importantly, indeed reversibly heat-induced behavior [2]. Then we use a-Ge as spacer material. Multilayers with Ge spacers were originally reported to exhibit only ferromagnetic coupling for all spacer thicknesses [3]. However, with a careful heat treatment of a complete multilayer, an irreversible transition to a system showing reversibly heat-induced antiferromagnetic coupling at certain spacer thickness is attained [4].

The occurrence of reversibly heat-induced coupling in multilayers with a-Si or a-Ge spacers is very sensitive to the preparation conditions of the multilayers. To avoid interdiffusion on a large scale, the structures have to be prepared at temperatures around 40 K. Yet the heat treatment at temperatures around 200 K required to produce the coupling in systems with Ge spacers suggests that certain reactions at the interfaces are crucial for the coupling to occur [4]. On the other hand, when there is too much interdiffusion, a completely different type of coupling is observed. There has been extended experimental work on Fe/Si heterostructures prepared at *room temperature* [5–9]. These multilayers proved to exhibit a much stronger coupling with exciting properties, but do not show heat-induced coupling behaviour [10,11].

For the coupling measurements we use surface magnetometry by spin polarized secondary electron emission (SPSEE). A 1–5 keV primary electron beam produces a cascade of secondary electrons on the sample surface.

* Corresponding author. Tel.: +41-1-6332362; fax: +41-1-6331080.

E-mail address: walser@solid.phys.ethz.ch (P. Walser)

PII: S0304-8853(98)01135-4

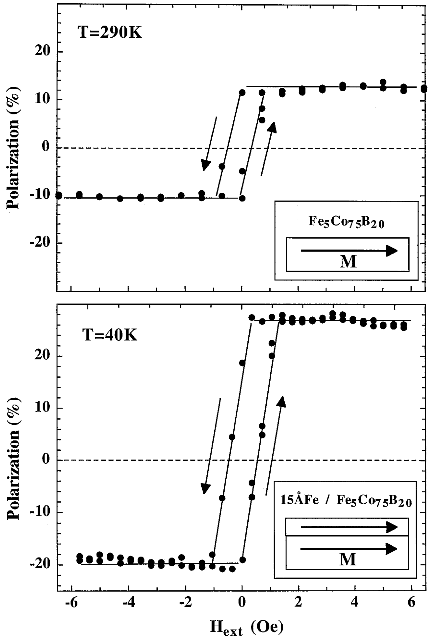

Fig. 1. Spin polarization P of secondary electrons versus applied magnetic field of the $Fe_5Co_{75}B_{20}$ substrate (top panel) and a 15 Å Fe layer on top of the substrate. The Fe layer adopts the coercivity of the substrate, but enhances the polarization signal.

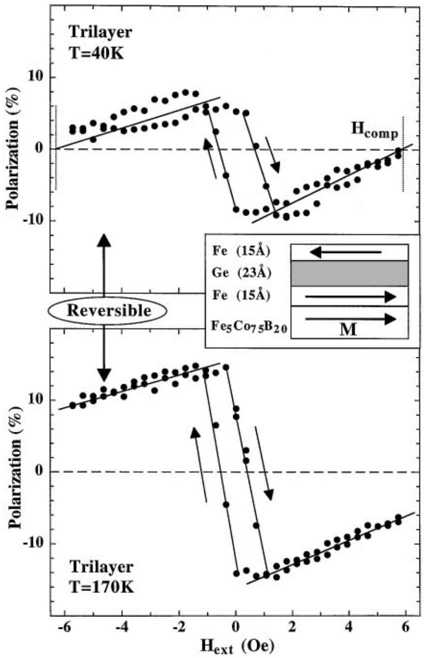

Fig. 2. Spin polarization of secondary electrons versus applied magnetic field at $T = 40$ K (upper panel) and at $T = 170$ K (lower panel) of an antiferromagnetically coupled Fe/a-Ge/Fe trilayer deposited on the substrate. The dotted line in the top panel indicate the compensation field H_{comp} at $T = 40$ K. At $T = 170$ K H_{comp} is about twice as large as at $T = 40$ K.

A spin analysis of the emitted secondary electrons with reference to the two in plane quantization axes is carried out in a 100 keV mott detector. The spin polarization P, defined as $P = (N\uparrow - N\downarrow)/(N\uparrow + N\downarrow)$, is proportional to the magnetization of the sample at the surface [12,13]. $N\uparrow$ and $N\downarrow$ are the number of electrons with magnetic moment parallel and antiparallel to the chosen quantization axis, respectively. In a multilayered system, because of the high-surface sensitivity of SPSEE, the signal reflects the magnetization of the topmost layer. This fact can be used to probe exchange coupling between magnetic layers.

A Fe/a-semiconductor/Fe structure is evaporated at temperatures around 40 K under UHV conditions onto a low-coercivity magnetic substrate. The first magnetic layer is directly and strongly coupled to the substrate. Then, we monitor the response of the exchange coupled surface layer with respect to the magnetization of the substrate and in this way study the exchange coupling across the spacer material. This procedure is demonstrated in Figs. 1 and 2. Top and bottom panel of Fig. 1 depict the SPSEE hysteresis loop of the substrate and the Fe/substrate structure, respectively. The SPSEE signals of the completed structure shown in Fig. 2 reflect the response of the exchange coupled top layer. Clearly, the signals jump from positive to negative while the substrate magnetization goes from negative to positive, and vice versa. This indicates, that for the example chosen here the iron layers are coupled *antiferromagnetically*.

The most important property of the magnetic heterostructures with amorphous semiconducting spacers is certainly the positive temperature coefficient of the effective exchange coupling between the magnetic layers. To address this temperature coefficient and to compare coupling strength' at different temperatures we use the compensation field H_{comp}. H_{comp} is an analogue to the saturation field measured in experiments with the magneto-optical Kerr effect MOKE. It is the external magnetic field necessary to compensate the negative exchange coupling field, i.e. to cancel out the antiferromagnetic coupling. It is reached, when the polarization signal, originating from the topmost layer, is driven to its remanent state, which means zero magnetization the present case, see below. H_{comp} is completely independent of the detailed magnetic response of the top layer.

In Fig. 2, the temperature of the completed sample exhibiting antiferromagnetic coupling is varied. For $T = 40$ K (upper panel) an external field of about 6 Oe is sufficient to compensate the coupling, whereas for $T = 170$ K (lower panel) the compensation field can be estimated to be twice as large. This is definite evidence for a positive temperature coefficient of the effective exchange interaction, which we name reversibly heat induced behavior. We note that the polarization signals in Fig. 2, outside the reversal of the substrate response, react continuously and almost linearly to the applied external field, suggesting that the top layer is far away from being a perfect Fe film. This behaviour is rather suggestive of a complicated domain structure with zero remanence originating from unknown chemical and structural properties.

Further steps towards an understanding of the phenomenon of heat-induced coupling will include investigations towards a more thorough knowledge of the detailed properties of the layers involved as well as theoretical modeling of the coupling properties so far assumed to be based on resonant tunneling across localized states in the semiconductor [2].

References

[1] S. Toscano, B. Briner, H. Hopster, M. Landolt, J. Magn. Magn. Mater. 114 (1992) L6.
[2] B. Briner, M. Landolt, Phys. Rev. Lett. 73 (1994) 340.
[3] B. Briner, U. Ramsperger, M. Landolt, Phys. Rev. B 51 (1995) 7303.
[4] P. Walser, M. Schleberger, P. Fuchs, M. Landolt, Phys. Rev. Lett. 80 (1998) 2217.
[5] E.E. Fullerton, J.E. Mattson, S.R. Lee, C.H. Sowers, Y.Y. Huang, G. Felcher, S.D. Bader, J. Magn. Magn. Mater. 117 (1992) L301.
[6] K. Inomata, K. Yusu, Y. Saito, Phys. Rev. Lett. 74 (1995) 1983.
[7] A. Chaiken, R.P. Michel, M.A. Wall, Phys. Rev. B 53 (1996) 5518.
[8] J. Kohlhepp, F.J.A. den Broeder, J. Magn. Magn. Mater. 156 (1996) 261.
[9] J.J. de Vries, J. Kohlhepp, F.J.A. den Broeder, R. Coehoorn, R. Jungblut, A. Reinders, W.J.M. de Jonge, Phys. Rev. Lett. 78 (1997) 3023.
[10] F.J.A. den Broeder, J. Kohlhepp, Phys. Rev. Lett. 75 (1995) 3026.
[11] E.E. Fullerton, S.D. Bader, Phys. Rev. B 53 (1996) 5112.
[12] M. Landolt, Appl. Phys. A 41 (1986) 8395.
[13] H.C. Siegmann, J. Phys.: Condens. Matter 4 (1992) 8395.