Neutron scattering studies of multilayers and superlattices containing semiconductors

W. Szuszkiewicz[1], B. Hennion[2], F. Ott[2], E. Dynowska[1], K. Fronc[1], E. Janik[1], J. Sadowski[1,3], P. Wandziuk[4], and T. Luciński[4]

[1]*Institute of Physics PAS, Al. Lotników 32/46, 02-668 Warsaw, Poland*
[2]*Laboratoire Léon Brillouin, CEA-CNRS, CE Saclay, 91191 Gif sur Yvette, France*
[3]*MAX-Lab, Lund University, 22100 Lund, Sweden*
[4]*Institute of Molecular Physics PAS, Smoluchowskiego 17, 60-179 Poznań, Poland*

Metal-semiconductor multilayers and superlattices containing magnetic semiconductors are extensively studied within the last years because of their potential application in electronics. They attract a lot of attention and are a topic of several investigations, related mainly to the problem of the exchange coupling between magnetic layers. Details of such coupling and various factors, which could influence its character or strength, are reported in numerous papers. Apart from the standard magnetic measurements (like, e.g., the magnetometry with use of the Kerr effect or of a SQUID) one can investigate several magnetic properties of systems under consideration by means of the neutron scattering techniques. Both the elastic neutron scattering (diffraction) and the spin-polarized neutron reflectometry are able to provide a valuable information about these properties. A few examples of recent experimental data obtained with use of this technique are shown in this paper.

Fe/Si is one of the best known today metal-semiconductor multilayer system. The neutron reflectometry spectrum can give us a direct evidence of possible antiferromagnetic exchange coupling (as an example, see Fig.1 taken from [1]). In particular, an influence of the interfacial Fe silicide phase on the magnetic properties of the multilayers mentioned above is of great interest. Recently, Fe/Si and Co/Si multilayers deposited by d.c. magnetron sputtering at room temperature onto oxidized Si wafers were studied by the magnetization measurements. The different magnetic behavior of both systems has been observed and analyzed in [2]. The strong antiferromagnetic exchange coupling well seen on selected Fe/Si multilayers did not appear on Co/Si multilayers with the same thickness of the non-magnetic spacer. The basic conclusions presented in this paper were recently confirmed by the neutron reflectometry data. The lack of a significant antiferromagnetic exchange coupling in the case of Co/Si multilayers was directly demonstrated by this technique.

GaMnAs is a new, attractive semimagnetic semiconductor, which is a ferromagnetic material at low temperatures. It is believed that GaMnAs and similar semiconducting compounds will play an important role in the development of electronics taking advantage of the electron spin (spintronics). According to former literature data a layer of GaMnAs mixed crystal thinner than about 5 nm did not exhibit the magnetic properties. A few years ago, an information about the magnetic exchange coupling between such layers separated by a non-magnetic spacer (like GaAs) was very limited.

The neutron diffraction studies with use of three-axis diffractometers and both thermal and cold neutron sources of the Orphée reactor of the Laboratoire Léon Brillouin (LLB) at Saclay, France, have been performed on GaMnAs-based thin layers and structures. The evidence of the low temperature ferromagnetic character and the exchange ferromagnetic coupling for the short-period GaMnAs/GaAs superlattices was shown [3]. The results of the neutron diffraction experiments were confirmed by the data obtained with use of the spin-polarized neutron reflectometry (Fig. 2). No trace of the antiferromagnetic exchange coupling was found for all samples.

The improvement of the neutron scattering technique, especially related to the use of focusing devices on three-axis spectrometers has strongly extended the possibility of inelastic scattering measurements. The samples of mm^3 size may now be investigated in favorable cases, which opens a possibility of magnetic excitations (magnons) studies on MBE-grown thin layers and superlattices containing magnetic semiconductors.

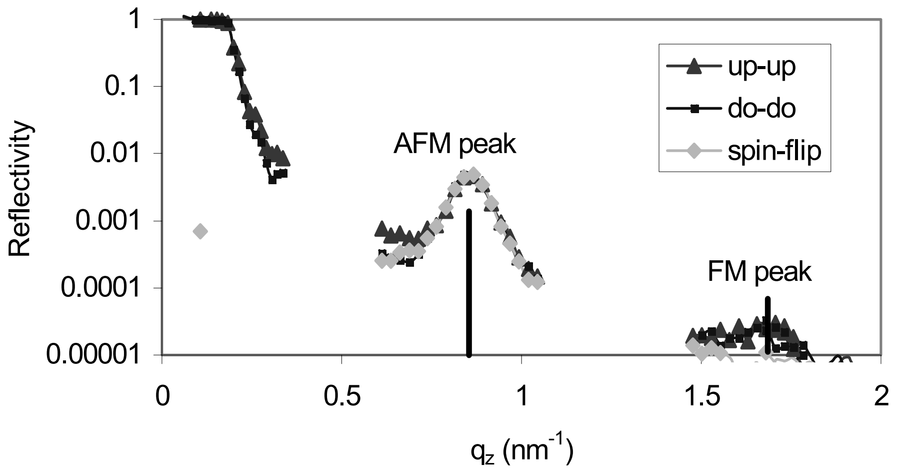

Fig. 1. Room-temperature neutron reflectivity curves taken for (2.5 nm Fe/1.0 nm Si)$_{22}$ multilayer as a function of the momentum transfer. Spectra were taken for three different combinations of spin polarization (up-up, down-down, spin-flip). No magnetic contrast is seen on the FM peak and the coupling is purely antiferromagnetic.

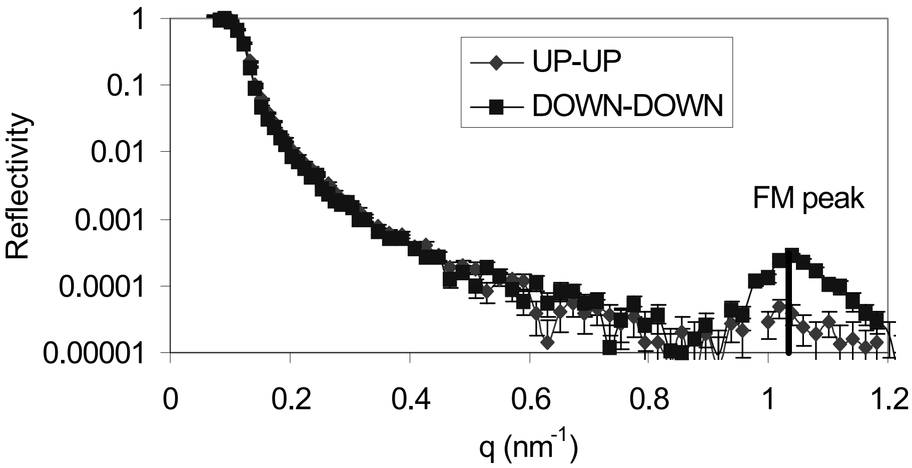

Fig. 2. Polarized non-spin-flip neutron reflectivity spectra taken for (GaMnAs)$_{16}$/(GaAs)$_6$ superlattice at T = 4.2 K. The observed structure evidences the ferromagnetic interlayer coupling.

Recent developments of the experimental technique at the Orphée reactor with a beam tube redesigned to optimize the thermal beam flux available on 2T three-axis spectrometer, offered the possibility to measure the spin-wave spectrum of AF-III MnTe. The results of these experiments are presented in [4]. This has been used as a preamble to a series of measurements performed on superlattices $(MnTe)_m/(ZnTe)_n$ obtained by the stacking of *m* MnTe monolayers spaced by *n* non-magnetic ZnTe monolayers (distance corresponding to one monolayer is about 0.31 nm). In these quantum structures, the MnTe layers still undergo a transition towards the AF-III structure. Surprisingly, a long-range coherency between MnTe layers with rather thick ZnTe layers (up to 10 monolayers) has been observed [5]. In our case, it was possible not only to study this coherency in detail but also to observe the magnon propagation along the growth direction of the superlattice [6]. Moreover, new interesting possibility appears when ZnTe layers are still thicker. As the magnetic MnTe layers are no longer correlated in this case, a magnon "standing modes" due to the effect of quantum confinement are expected. Very recently such phenomenon has been observed for the first time on $(MnTe)_7/(ZnTe)_{18}$ superlattice [6].

In summary, one could state that the neutron scattering techniques are powerful methods of studying thin layers and quantum structures containing modern magnetic materials. The continuous progress, both in the technology of such materials and in the measurements, took place during the last ten years. Due to this, we can now complete the data obtained by other experimental techniques (e.g., by means of SQUID magnetometer or the Kerr effect). We can also have an access to scientific fields untouched so far with other experimental methods.

Acknowledgments

This work was supported in part within European Community programs ICA1-CT-2000-70018 (Centre of Excellence CELDIS), G1MA-CT-2002-4017 (Centre of Excellence CEPHEUS), and Access to Research Infrastructures Action of the Improving Human Potential Programme (contract No. HPRI-CT-1999-00032). Partial financial support by the Polish grant No. PBZ/KBN/044/P03/2001 is also gratefully acknowledged.

[1] W. Szuszkiewicz, K. Fronc, M. Baran, R. Szymczak, F. Ott, B. Hennion, E. Dynowska, W. Paszkowicz, J. B. Pełka, R. Żuberek, M. Jouanne, and J. F. Morhange, J. Supercond. Incorporating Novel Magnetism 16, 205 (2003).

[2] T. Luciński, P. Wandziuk, F. Stobiecki, B. Andrzejewski, M. Kopcewicz, A. Hütten, G. Reiss, and W. Szuszkiewicz, J. Magn. Magn. Mater. (in press).

[3] W. Szuszkiewicz, E. Dynowska, F. Ott, B. Hennion, M. Jouanne, J. F. Morhange, and J. Sadowski, J. Supercond.: Incorporating Novel Magnetism 16, 209 (2003).

[4] B. Hennion, W. Szuszkiewicz, E. Dynowska, E. Janik, and T. Wojtowicz, Phys. Rev. B 66, 224426 (2002).

[5] J. Lin, J.J. Rhyne, J.K. Furdyna, and T. M. Giebultowicz, J. Appl. Phys. 83, 6554 (1998).

[6] W. Szuszkiewicz, B. Hennion, E. Dynowska, E. Janik, and T. Wojtowicz (unpublished).

Name of the presenting author: Wojciech Szuszkiewicz
e-mail address: szusz@ifpan.edu.pl
url's: http://ifpan.edu.pl