Magnetic Semiconductor Superlattices

Currently a great deal of attention is being focused on spintronics, a new area of solid-state electronics. In spintronics not only the electric current but also its spin state is controlled. Spin valves and spin injectors are the first practical applications of spintronics. Further progress in developing new devices hinges critically on the availability of suitable materials. Such materials need to be "good" semiconductors, easy to integrate in typical integrated circuits, and their electronic properties should exhibit strong sensitivity to the carrier's spin, ferromagnetism being an especially desirable property.

EuS is one of the very few natural ferromagnetic (FM) semiconductors. Since it becomes FM at a low temperature (T_c = 16.6 K) it is an unlikely choice for applications. However, studying the properties of heterostructures made on its base may give an important insight into fundamental processes taking place in all classes of materials under consideration.

GaMnAs is a man-made FM semiconductor. It is an example of a diluted magnetic semiconductor (DMS) in which a fraction of nonmagnetic cations (Ga) is substituted with magnetic ions (Mn). Such a material can readily be incorporated into modern GaAs-based semiconductor devices. Its T_c is still below room temperature, but this limitation may be lifted in other materials of this class [1].

Interlayer exchange coupling (IEC) in superlattices (SL), composed of ferromagnetic and nonmagnetic layers, is a crucial element of all spin-valve type devices that utilize the giant magnetoresistance effect. In metallic SLs currently being used, conduction electrons transfer the interlayer interactions through nonmagnetic spacers [2]. Here we address the question whether IEC phenomena are possible in all-semiconductor superlattices, like EuS/PbS and GaMnAs/GaAs, where the carrier concentrations are many orders of magnitude lower than in metals.

The nonmagnetic spacer in EuS/PbS SLs is a narrow gap semiconductor with electron concentration of the order of 10^{17} cm^{-3} to 10^{18} cm^{-3}. For thin PbS layers (d_{PbS} < 70 Å) neutron reflectivity spectra, shown in Fig. 1, have revealed a pronounced maximum of magnetic origin at the position corresponding to the doubled structural SL periodicity, thus indicating the existence of antiferromagnetic (AFM) interlayer arrangements [3].

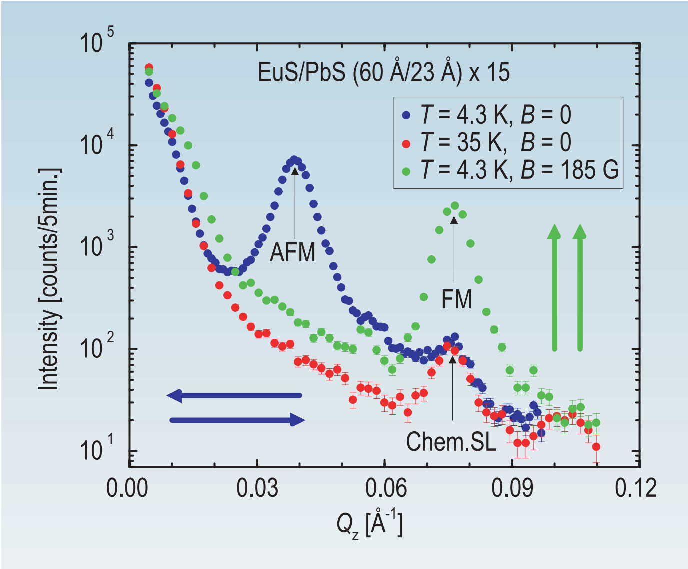

FIGURE 1. Unpolarized neutron reflectivity spectra for EuS/PbS SL with thin (23 Å) PbS spacer. Antiferromagnetic interlayer exchange coupling below T_c and at zero external field is clearly visible (blue curve). Applying a strong enough magnetic field (185 G in this case) parallel to the SL surface forces all the EuS layer's magnetizations to ferromagnetic configuration (green curve). Above T_c the system is nonmagnetic, the only Bragg peak comes from the chemical SL periodicity.

For much thicker PbS spacers (d_{PbS} > 120 Å) the only magnetic peaks visible in the reflectivity profiles, see e.g., Fig. 2, coincide with the chemical ones, thus leading to the conclusion that the magnetization vectors in adjacent EuS layers are parallel, which indicates FM IEC.

In the intermediate PbS thickness range (70 Å < d_{PbS} < 120 Å), both AFM and FM peaks are present. Polarized neutron analysis of these maxima gives evidence that the magnetization vectors of adjacent EuS layers are not colinear. Hence, the IEC found in EuS/PbS SLs has an oscillatory character similar to that occurring in metallic SLs, although the oscillation period is much longer than the one in metallic systems.

In order to confirm that the free carriers, present in the PbS layer in such a small amount, are the cause of the observed oscillatory IEC, a series of analogous measurements have been carried out on EuS/YbSe SLs. The structure and lattice constant of YbSe are the same as those of PbS. In contrast to PbS, YbSe is a semi-insulator with a negligible carrier concentration. Neutron reflectivity profiles have shown no evidence of any interlayer coupling in the all

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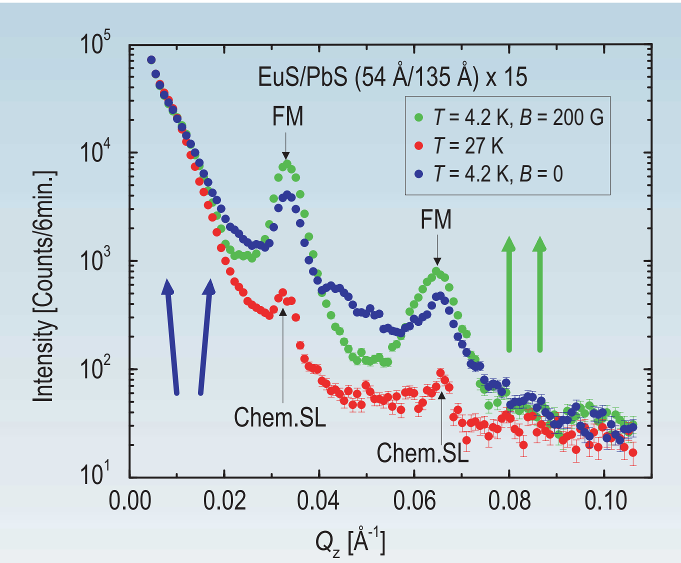

FIGURE 2. The sample with thick (135 Å) PbS layers is almost ferromagnetically coupled. Application of an external magnetic field enhances the FM Bragg peaks and lowers the intensity between them (at the AFM peak position).

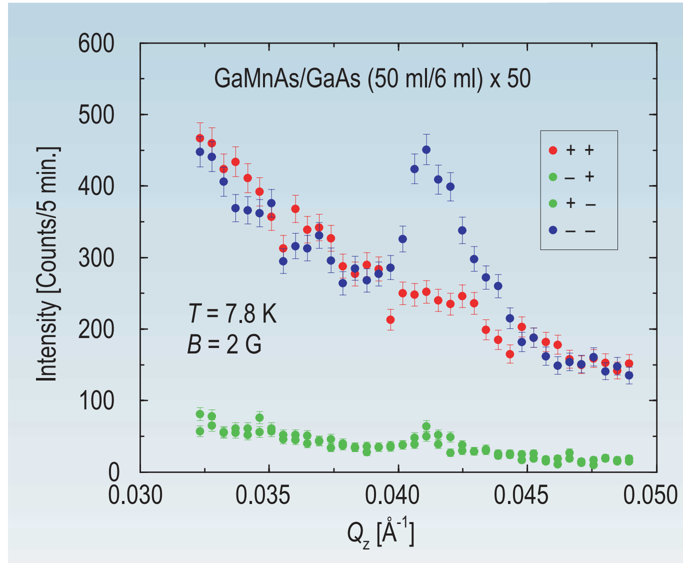

FIGURE 3. Polarized neutron reflectivity spectra for GaMnAs/GaAs superlattice.

investigated samples. That finding, together with the oscillatory character of coupling in SLs with PbS spacer, strongly points to the leading role of PbS free electrons in providing the necessary IEC mechanism, similar to that discovered in metallic multilayers.

Ferromagnetic ordering in GaMnAs is carrier (holes) induced; the Mn atoms, apart from being the magnetic element in the system, act also as acceptors providing the holes responsible for transferring exchange interactions between them. The details of the magnetic ordering, in particular its range, are still being disputed.

To address the latter issue, polarized neutron reflectometry has been performed on a number of GaMnAs/GaAs superlattices. Figure 3 shows an example of the obtained reflectivity profile in the vicinity of the first SL Bragg peak, for one of the samples. The very presence of the magnetic contribution to the structural SL Bragg peak is a strong confirmation of the FM IEC between consecutive GaMnAs layers. The absence of any spin-flip scattering shows that the sample is in a one-domain state, i.e., the FM ordering in GaMnAs is long range, and the sample is spontaneously saturated. The peak in (--) cross section, and its absence in the (++), is proof that the magnetization is directed oppositely to the external magnetic guide field, hence the long range ordering has formed spontaneously, without the influence of the external field. More details can be found in Reference 4.

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