Carrier controlled ferromagnetism in magnetic semiconductors

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A successful implementation of spintronics relies strongly on the development of new materials that would exhibit both semiconductor properties and above room temperature ferromagnetism. Such materials, possessing both spins and an effective mechanism coupling them with charge carriers could offer not only new functionalities, but would allow to take the full technological advantage of the compliance to the nano-scale processing abilities developed for semiconductors.

Among many candidates, the most promising seem to be those semiconducting compounds that employ long-range hole-mediated ferromagnetic exchange between localized moments, from whose Mn ions are the most extensively studied. Until now ferromagnetic state has been confirmed in IV-VI alloys (p-$Pb_{1-x-y}Mn_xSn_yTe$; Story*, et al.'86)*, III-V: ($In_{1-x}Mn_xAs$ and $Ga_{1-x}Mn_xAs$; *Munekata, Ohno, '89-'96*), II-VI: ($Cd_{1-x}Mn_xTe/Cd_{1-x-y}Zn_xMg_yTe$:N QW; *Haury, et al.'97, Kossacki, et al.'99; bulk* $Zn_{1-x}Mn_xTe$:N; *Ferrand, et al.'99*), and in group IV elements ($Ge_{1-x}Mn_x$: *Jonker et al. '01*). The confirmation is based on fulfilling of such important operational criteria like observation of the T_C and M_S scaling with both Mn content and hole density, and by presenting a direct interplay between semiconducting and ferromagnetic properties (spin-LED and Ferro-FET).

Recently, a variety of theoretical methods have been put forward to elucidate the nature of ferromagnetism in Mn-based II-VI and III-V DMS. Nevertheless, there is a growing amount of evidences that the mean-field model that takes into account band structure effects describes correctly the main features of ferromagnetism in Mn-based semiconductors. In this model the sp-d (carriers - magnetic electrons) interactions are regarded as an effective magnetic field

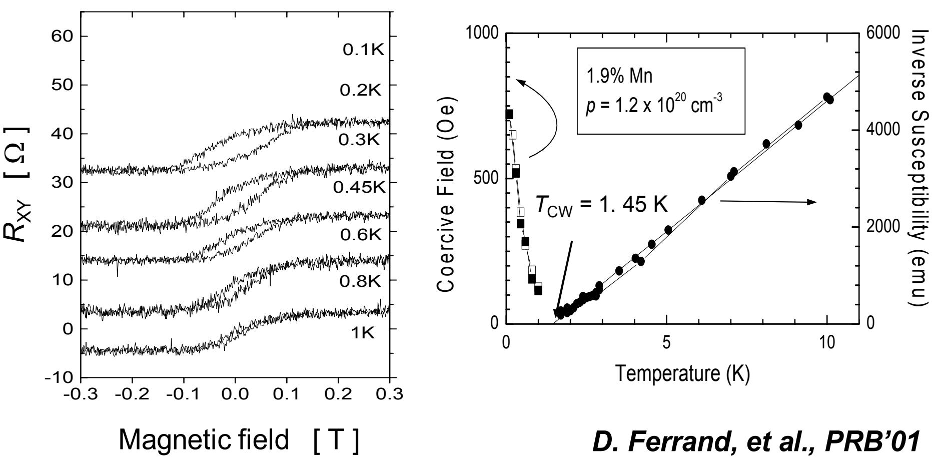

Fig. 1. Experimental evidences for holes driven ferromagnetism in MBE grown p-type metallic $Zn_{1-x}Mn_xTe$. Free carrier induced ferromagnetism in II-VI DMS: T_C ~ 50 times greater for the holes: large m^*, large β.

acting on the carriers. A collective effort of both carries and d-electrons can lead to a spontaneous magnetisation whose free energy increase may be compensated by carriers' energy loss due to the relevant band splitting. This is known as Zener ferromagnetism and the temperature at which the energy gain and loss balances defines the Curie temperature in this approach.
The paper starts from (II, Mn)VI compounds, where carrier mediated ferromagnetism must compete with intrinsic Mn-Mn antiferromagnetic superexchange. The latter pushes the Curie-Weiss temperature down, nevertheless it remains easy detectable at liquid helium temperature range.

This is, however, not a too high price for the versatility that II-VI compounds offer: thanks to the iso-electronic nature of Mn in II-VIs they can be independently doped either p- or n-type. In particular, the later is of great interest and preliminary findings suggesting the formation of the ferromagnetic coupling in n-type (Zn,Mn)O:Al at millikelvin temperature range will be presented.

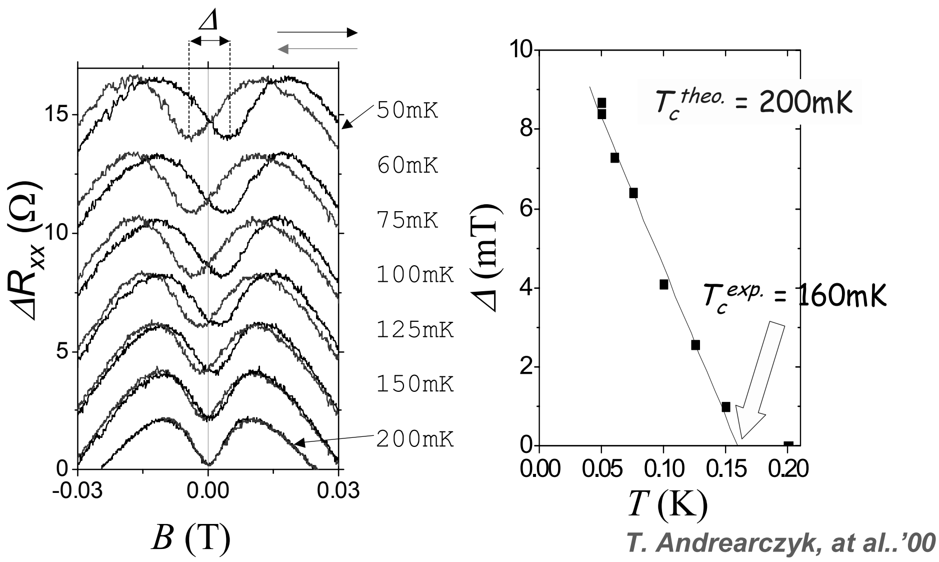

Fig. 2. Experimental indications for electrons driven ferromagnetism in MBE grown $Zn_{1-x}Mn_xO$ (magnetoresistance hysteresis for x = 0.03).

In the most extensively studied (III,Mn)V compounds (antimonides and arsenides) Mn substitutes the trivalent cations and its *d* state (d^4) is degenerate with the valence band. In this case, the Mn impurities act as effective mass acceptors supplying both holes and localised spins, as the Mn ground state corresponds to d^5 + hole configuration. This relatively high concentration of both holes and magnetic moments combined with lack of direct antiferromagnetic Mn-Mn coupling (at least on substitutional sites) results in stimulating, approaching nowadays 200 K, Curie temperatures. However, the orbital momentum of the majority hole subbands depends on strain and confinement. Hence, the magnetic anisotropy (easy-axis direction) that exists due to the spin-orbit interaction in the valence band depends on epitaxial strain and the degree of occupation of particular hole subbans. The latter is determined by the ratio of the valence-band exchange splitting to the Fermi energy, thus by the magnitude of spontaneous magnetisation. As the result, these systems exhibit a rich and a complex pattern of magnetic anisotropy. So, after a brief introduction to these systems, the magnetic anisotropy of (Ga,Mn)As/GaAs will be explored in greater details.

Perhaps the most striking feature is the existence of a temperature-induced switching of the easy axis direction from perpendicular to plane at low temperatures to in plane on increasing temperature. This effect is observed only in samples with appropriately low hole density.

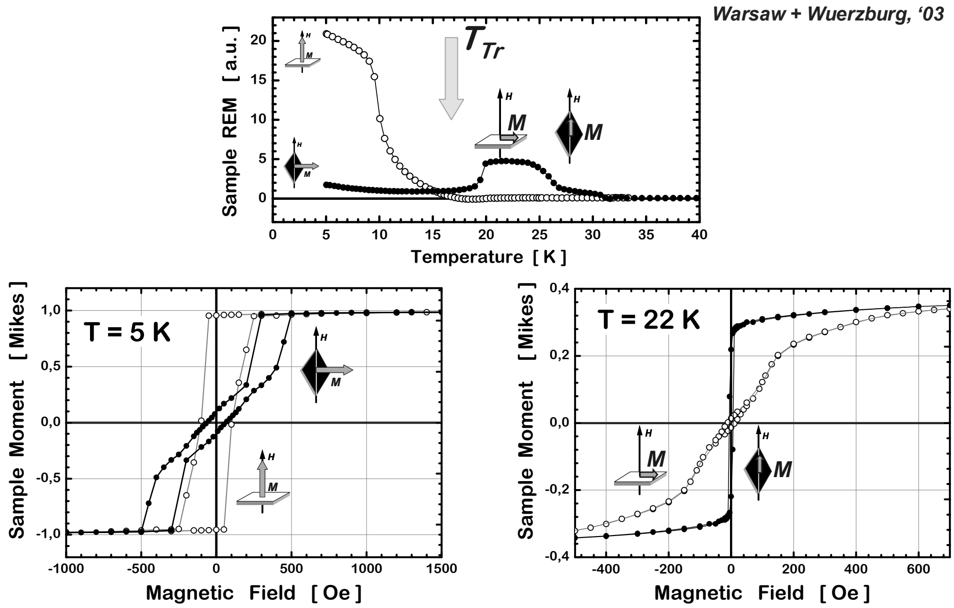

Fig. 3. Evidences of perpendicular magnetic anisotropy (MA).

The in-plane anisotropy is also examined, and it is found that the (Ga,Mn)As layers are characterised by a mixed anisotropy composed of a natural cubic anisotropy of the zinc-blende structure and a uniaxial anisotropy with [110] the easy axis. Since the former dominates at low temperature and the latter at elevated ones, a transition between the two modes is clearly

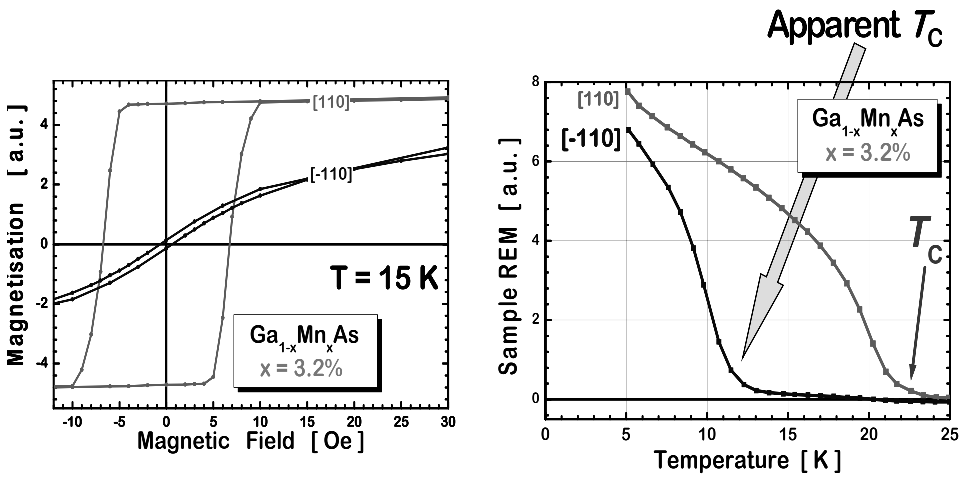

Fig. 4. $D_{2d} \rightarrow C_{2v}$ symmetry lowering (result: strong uniaxial anisotropy on [110] direction).

observed when temperature is changed. By group theoretical considerations this unexpected anisotropy can be linked to the top/bottom symmetry breaking in epilayers and thus to lowering the point symmetry to C_{2v}, in which [110] and [-110] directions are not equivalent.

The final part will concentrate on annealing induced changes of the magnetic properties of (Ga,Mn)As. In particular a 90 deg rotation of the uniaxial easy axis takes place for all the studied layers with Mn content greater than 4 %. Presented findings evidence against those models that connect the existence of the uniaxial anisotropy with growth related effects and quite strongly advocate that the in-plane uniaxial anisotropy is not due to surface effects and that the easy axis direction can be controlled by Mn and hole concentrations.

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