In search for a ferromagnetic semiconductor

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The development of spintronics shows that an application of a semiconducting ferromagnetic material could solve many spintronics problems and to take a real advantage of spin freedom degree in future electronics. Unfortunately, there is no natural ferromagnet with semiconductor attributes. Neither the properties of metallic, nor those insulating ferromagnets can be modified by light or by applied voltages. Therefore, preparation of an artificial magnetic semiconductor is an important challenge for the modern materials science. Most of the well-evidenced cases of ferromagnetic order have been found in II-VI and III-V based, diluted magnetic semiconductors (DMS). Up to now, the highest Curie temperature in this class of material, T_c=172 K was achieved in $Ga_{1-x}Mn_xAs$, but the wide gap semiconductors, such as GaN or ZnO, were supposed to be more prospective matrix materials with higher critical temperatures.

Diluted magnetic semiconductors

The physics of DMS has been investigated in Poland for few last decades. Now the investigations are supported by the KBN grant "Spin electronics". The giant spin splitting of conduction bands, caused by the magnetization of magnetic impurities and mediated by sp-d exchange, is an essential attribute of DMS. Such splitting allows selective spin manipulation in excitons or in quantum dots. Moreover, DMS are the most effective spin injectors in spintronics devices. Unfortunately, in paramagnetic DMS, external magnetic field is required for magnetization of local spins, and this limits possible applicability of DMS. On the other hand, increased carrier concentration allows inducing an exchange (Zener-like) field which causes magnetization of the local spins. The occurrence of a ferromagnetic phase generated by such positive feedback has been evidenced in much material. In II-VI Mn based DMS, the high carrier concentration requires strong, additional doping and the typical T_c is of the order of few Kelvin.

Magnetic orders in $Ga_{1-x}Mn_xAs$

Mn ion in the GaAs lattice introduces a large local spin, S_{Mn}=5/2, and simultaneously plays the role of acceptor. Consequently, the high concentration of holes allows the ferromagnetism to occur. The magnetic order in semiconducting $Ga_xMn_{1-x}As$ is already well determined and the theoretical models explain well its origin, and also allow satisfactory estimation of the critical temperature. On the other hand, the details of the spin structure, the role of fluctuations, the puzzle magnetic anisotropy and the peculiar spectrum of spin waves are still under debate.

Our magnetic resonance studies allow distinguishing two different magnetic structures of $Ga_{1-x}Mn_xAs$. Metal-to-insulator transition is accompanied by a principal change of magnetic resonance spectra. The single isotropic line of ferromagnetically ordered Mn spins changes to a very complex, strongly anisotropic spectrum. We interpret this change to a transition from ferromagnetic to ferrimagnetic phase, where both spin sub-systems are magnetically correlated. The observed resonance frequency and magnetic anisotropy can be well described using the formalism of ferrimagnetic resonance. In that sense, one can conclude that in metallic phase the $Ga_xMn_{1-x}As$ constitute a ferrimagnetic system.

The complex structure corresponds to spin wave (SW) resonance. Just the fact alone that SW resonance is observed is intriguing, because it implies a long mean free path of SW,

which can occur in a very uniform magnetic medium. Also the observed dispersion of SW and its angular dependence is very different from the classical expectations. We are able to explain these peculiarities by taking into considerations the strong momentum scattering of holes. Therefore, the latter ones cannot be treated as a plane waves but rather as partially localized carriers. The localization affects neither Zener field nor mean Mn-Mn exchange field. In contrast, the mean range of Mn-Mn exchange for localized carriers corresponds with the localization range and it can be much longer if compared to the range of RKKY coupling. The long exchange range can be directly evaluated from the observed dispersion of SW and allows the explanation of the long mean free path of SW. The experimentally estimated number of coupled Mn spins is of the order 10^4-10^5. The resulting exchange field, responsible for the propagation of SW, is very well averaged.

The well averaged alloy disorder in semi-metallic $Ga_{1-x}Mn_xAs$ contrasts with the fluctuations in insulating crystals. In that case, local spins are coupled via a double-exchange mediated by effective mass holes occupying acceptor states. The characteristic length of interaction is that of the Bohr radius order, i.e., of the order of mean Mn-Mn distance. The alloy disorder, namely fluctuations of exchange and anisotropy fields seen by hole spins, does not allow any coherent precession of hole spins. As a consequence, only the Mn spins can form a macroscopic, ferromagnetic moment, while the role of hole spins is reduced to mediation of Mn-Mn interaction.

Search for a room temperature ferromagnetic semiconductor

The maximum critical temperature of $Ga_{1-x}Mn_xAs$ lies much below the room temperature. Various compounds are currently tested in many laboratories. A few years ago $Ga_{1-x}Mn_xN$ was the most promising candidate. It represents a system similar to $Ga_{1-x}Mn_xAs$, but – due to a smaller lattice constant – the p-d exchange is expected to be greater. Consequently, the Curie temperature, which scales with the square of p-d exchange, was expected to be considerably greater. Regrettably, nobody has grown crystals of p-type semi-metallic $Ga_{1-x}Mn_xN$. It was evidenced that, in contrast to GaAs, where $3d^5$ +hole is the ground state configuration of Mn impurity, in GaN the $3d^4$ is the main configuration and the corresponding energy level is located in the energy gap. As a consequence, the Fermi level is pinned to the Mn level and there are no carriers present which could mediate the Mn-Mn exchange. As a consequence, the system is semi-insulating and paramagnetic.

Similar situation, i.e., location of the energy level of transition metal impurities within the energy gap, occurs in the most of II-VI and III-V based DMS.

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