Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 334-335

F-3-1 (Invited)

Optical and Electrical Control of Ferromagnetism in II-VI Quantum Wells

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1. Introduction

Spin electronics is an interdisciplinary research field aiming at developing material systems, in which novel mechanisms of control over magnetization in magnetic compounds or over individual spins in nanostructures could lead to new functionalities in classical and quantum information hardware, respectively [1]. Today's spintronic research involves virtually all material families but particularly promising are ferromagnetic semiconductors [2], which combine recourses of both semiconductor and ferromagnetic materials systems. In particular, soon after the discovery of carrier-controlled ferromagnetism in Mn-doped III-V and II-VI semiconductor compounds, it has become clear that these systems offer unprecedented opportunities to exploit the powerful methods developed for tuning carrier densities in semiconductor quantum structures, in order to control the magnetic characteristics in these systems. Such a control opens new prospects for information storage and processing, as well as it makes it possible to examine the behavior of strongly correlated systems as a function of externally controllable parameters. In the case of III-V magnetic semiconductors, where Mn atoms introduce both valence band holes and localized spins, Koshihara *et al.* [3] detected enhancement of ferromagnetism by illumination of an (In,Mn)As/GaSb heterostructure, an effect assigned to the presence of an interfacial electric field that drives the photoholes to the magnetically active (In,Mn)As layer. More recently, Ohno *et al.* [4] demonstrated that a gate voltage of ±125 V changes the Curie temperature T_C by about 1 K in a field-effect transistor structure containing (In,Mn)As quantum well (QW). In the case of II-VI diluted magnetic semiconductors (DMS), Mn does not introduce any carriers. Hence, holes that can mediate ferromagnetic interactions have to be introduced by bulk or modulation doping of DMS [5]. Because of the valence band structure, T_C is typically lower in II-VI than III-V DMS. At the same time, however, it may be expected that, owing to the small background hole density, the strength of the carrier mediated ferromagnetic interactions can be tuned over a wider range in II-VI than III-V DMS.

2. Summary of the talk

In this talk, we review recent studies of modulation-doped *p*-type [6] and *n*-type [7] (Cd,Mn)Te QW. These results prove rather directly that the valence band hole transmit magnetic information between the localized Mn spins much more effectively than the conduction band electrons.

Properties of *p*-type (Cd,Mn)Te QW are assessed by photoluminescence and its excitation spectra. The (Cd,Zn,Mg)Te barriers are doped either *p*- or *n*-type, so that *p-i-p* or *p-i-n* structures are formed. The QWs in these systems are ferromagnetic below about 3 K. The data reveal that, depending of the sample layout, the ferromagnetism either destroyed or enhanced during illumination by photons with energy greater than the band gap of the of the barrier material. In both cases, the switching process is isothermal and reversible. Moreover, the results demonstrate that the reverse biasing of the *p-i-n* diode with the magnetic QW by a voltage as small as 1 V turns the ferromagnet into a paramagnetic material. Importantly, this strong effect of light and electric field can be readily explained by considering the distribution of carriers and photocarriers in given structures.

Thus, these findings show that both photon beam and electric field can isothermally drive the system between the ferromagnetic and paramagnetic phases, in a direction which can be selected by an appropriate design of the structure. This offers new tools for patterning magnetic nanostructures as well as for information writing and processing, beyond the heating effects of light exploited in the existing magneto-optical memories. Obviously, however, practical applications of the tuning capabilities put forward by the work in question have to be preceded by progress in the synthesis of functional room temperature ferromagnetic semiconductors. As far as II-VI compounds are concerned, according to theoretical suggestions [8,9], structures containing ZnO, such as *p*-type (Zn,Mn)O/(Zn,Mg)O, appear to be a prospective material system.

The above results demonstrate rather convincingly the decisive role of the valence band holes in setting on the ferromagnetic ordering in these systems. a conclusion corroborated by studying the Curie temperature T_C as a function of the acceptor concentration in p-(Zn,Mn)Te [10]. At the same time, in agreement with theoretical predictions, no ferromagnetic ordering was detected above 1 K in heavily doped n-type (Zn,Mn)O [11]. Nonetheless, an Ising ferromagnetic ground state of with T_C up to 2 K can be observed in quantum Hall effect measurements on high-quality modulation-doped *n*-(Cd,Mn)Te/(Cd,Mg)Te heterostructures [7]. The quantum Hall ferromagnetism leads to resistance "spikes" and hysteresis, which show up when two partly filled Landau levels with opposite spin directions are brought into a coincidence. Under such conditions, exchange interactions among electrons lead to their spontaneous spin ordering. This Stoner-like instability of the carrier liquid appears due to the enhancement of the density of states in two-dimensional systems in quantizing magnetic fields. This occurs for appropriate combinations of an external magnetic field and gate voltage that controls electron concentration and, thus, the degree of occupation of particular Landau levels. Incidentally, Landau level crossings occur in such structures owing to the enlargement of electron spin-splitting by the electron exchange interaction with the Mn spins.

Acknowlegments

The author thanks his co-workers listed in the references for fruitful interactions. Author's research in Germany is supported by Alexander von Humboldt Foundation, while the work in Poland by State Committee for Scientific Research, by FENIKS and AMORE EC projects as well as by Ohno Semiconductor Spintronics ERATO Project of Japan Science and Technology Corporation.

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