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Semiconductor magnetism : excitements and promises

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Abstract : Beginning from a historical introduction, we present in this article the current excitements resulting from a possible hybridization of the two important areas of Condensed Matter Physics, namely, semiconductors and magnetism. Both the subjects have contributed to economically important technologies and rich physics, independently. We discuss the physics of diluted magnetic semiconductors (DMS) with special emphasis on the theory of light induced magnetism (LIM), keeping in mind both narrow gap and wide gap DMS.

Keywords : Light induced magnetization, photo-induced ferromagnetism, Diluted Magnetic Semiconductors

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1. Introduction

It is well known that both magnetism and semiconductors have contributed immensely for technological revolutions. While magnetism is an old subject discovered a few thousand years ago [1], the understanding of the semiconductors as a distinct class of materials began in the second quarter of the last century [2], with the advent of the quantum theory. Understanding of magnetism is also inseparable from the quantum theory. The physics of semiconductors resulted from a hybridization of the quantum theory (bands) and chemistry (bonds) [3]. In view of the importance of both the subjects, as mentioned above, the realization of materials that combine both has long been a dream of materials physicists.

Research in magnetism started with considerable focus on its nature in metals and insulators. On the other hand, semiconductors were not considered earlier as fashionable materials for research in magnetism, due presumably to the lack of exciting physics and possibilities for technologically useful applications. There were of course some studies on diamagnetism [4–9] and paramagnetism as related to the nuclear magnetic study of the Knight shift [10–12] and the chemical shift [13] involving orbital magnetism, in semiconductors.

2. Diluted magnetic semiconductors

One scheme for making systems that are simultaneously semiconducting and magnetic, initiated in late 1970's is to introduce local moments into reasonably well-understood semiconductors [14,15]. Thus research in the diluted magnetic semiconductors (DMS) [16–21] constituted one of the pioneering steps in the study of semiconductor magnetism. Over the last fifteen years, based on a series of important new publications [22–26] in a different direction in 1990's, it has been established that several III-V compound became ferromagnetic when heavily doped with Mn and that the ferromagnetic T_c's can be well above 100 K. In semiconductors like GaAs and InAs, Mn has been shown to act as an acceptor and as a source of local moments. Ferromagnetism in these semiconductors is mediated by carriers, electrons and/or holes [27–29]. Since the carriers are also responsible for electronics, the possibilities of ferromagnetism in these systems are important in the magnetic controlled electronics, or, spintronics [30].

One of the major aims, in this context, is to achieve high Curie temperature and low carrier densities in these semiconductors. Beginning in 1992 with a low T_c of 7.5 K in a *p*-type (In, Mn) As [24] the ferromagnetic T_c rose to a level 110 K after six years in 1998 in *p*-type (Ga, Mn) As [26]. Recent advances in MBE growth and post annealing technique made it possible to suppress extrinsic effects, pushing T_c in (Ga, Mn) As up to 173 K [31,32].

3. Possible mechanisms of ferromagnetism

In this section we shall outline briefly the possible mechanisms of ferromagnetism (FM) in general and the DMS in particular. Magnetic dipole-dipole interaction and relativistic effects that lead to spin-orbit coupling may be useful for some specific properties, but are not crucial for the onset of magnetic order. The universal ultimate origin of ferromagnetism is almost always the interplay between electronic spin degrees of freedom, the repulsive interaction between electrons and the fermionic quantum statistics of electrons. Because magnetic order in semiconductors became ferromagnetic associated with strong repulsive Coulomb interaction between electrons, it can persist up to very high temperatures, some times comparable to those at which crystalline order occurs. Ferromagnetism can be as strong as chemical bonds. Since ferromagnetism is a strong coupling phenomenon, a rigorous theoretical analysis is usually difficult. There is no universal theory of ferromagnetism. Understanding FM can be the most challenging of Solid State Physics problems.

The different approaches that are followed are the spin-density functional theory (SDFT) and model Hamiltonian theories. The latter often provide more important physical pictures of FM, provided the model is not too simplified. Magnetism in (Ga, Mn) As and other (III, Mn) V FMs originates from Mn local moments. The mechanisms [33] that are used are exchange interaction, itinerant exchange interaction, Kramer's super exchange, Zener's double exchange, kinetic exchange and RKKY type of interactions.

4. Photo-induced magnetism

The focus of the present article is photo induced magnetization and FM in the DMS. Interplay between light and magnetic field is not a new phenomenon. Magneto-optical properties such as Faraday and Kerr effects have been studied for quite a long time [34]. While Faraday effect involves measurement of transmitted light, the Kerr effect is a measurement of reflected light.

Photo-induced magnetism has emerged as an area of research that has attracted considerable attraction in recent times. This is partly due to its significant technological potential such as magneto-optic devices as well as novel phenomena itself. A new impetus to this field has been given by discoveries of materials in which photo induced magnetic phenomena coexist with cooperative magnetic behaviour and/or magnetic order. These novel materials include Prussian blue analogs [35], diluted magnetic semiconductors [36–40], doped manganites [41], spin ferrite films [42] and organic based magnets [43].

Photo induced magnetism has been observed in $Hg_{1-x}Mn_xTe$ [36,37], $Cd_{1-x}Mn_xTe$, $Pb_{1-x}Mn_xTe$ *etc*. The observation has been attributed to the generation of spin-polarised carriers by circularly polarized light, which in turn aligns the Mn ions thus resulting in the magnetization of the DMS.

We considered this problem recently [44]. Starting from a many-body Hamiltonian for a system of photo-generated electrons and holes which are spin split by magnetic ions aligned due to an effective optically induced magnetic field. An expression for photo-magnetisation was obtained following an equation of motion method, as a function of photon power and frequency. Damping of non-equilibrium carriers and spin-excitons is considered phenomenologically. The results reproduce some observed trends qualitatively in case of $Hg_{1-x}Mn_xTe$ [37].

Later, the work was improved as follows [45]. An expression for the magnetization for an interacting electron system is derived in the presence of a periodic potential, spin-orbit interaction and optically induced effective magnetic field. It is shown that, due to significant cancellation effects between the quasiparticle and correlation contributions, the final result of the magnetization is independent of explicit many-body effects except through the modification of the one-particle egenvalue and the eigenfunction. The magnetization is derived in terms of an effective g-factor that is important for narrow-gap semiconductors with large spin-orbit interaction.

Non-linear equations for the carrier spin densities are derived by using the Heisenberg's equations of motion and a many-body Hamiltonian that includes operators for carrier energies, carrier-light field, carrier-local moment and intra and inter carrier Coulomb interactions. The equations of motion for the carrier density and excitonic amplitudes are solved by following a mean-field decoupling mechanism and using damping processes phenomenologically. The inter-dependence of the carrier spin-density and the local moment magnetization is evaluated self-consistently.

Temperature dependence of the magnetization is also considered through the Brillouin function. The model is parameterised within reasonable physical limits as appropriate to the system and numerical results were obtained for photo-magnetisation as a function of incident laser power, temperature, concentration of local moments and laser frequency.

Qualitative agreement is obtained between theory and experiment for $Hg_{1-x}Mn_xTe$ [37] (Figure 1).

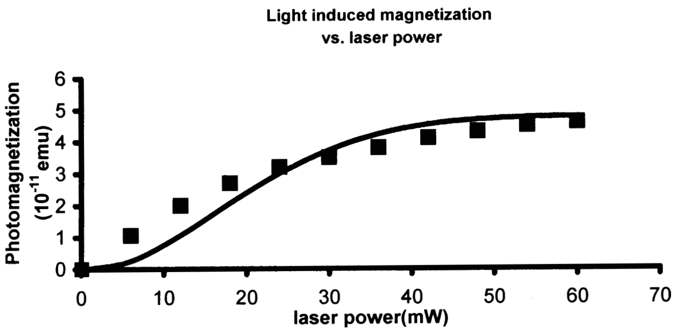

Figure 1. Light induced magnetization as a function of laser power for (Hg, Mn) Te for typical parameters. The bold curve represents the theoretical result [45] and the dark squares represent the experimental result [37].

An alternative approach has been developed, where we study the photo-induced ferromagnetism in the DMS by using a model Hamiltonian that consists of localized magnetic moments interacting with photo-excited itinerant carriers [46]. The spin-states of the itinerant carriers are split due to the interaction with the localized magnetic moments, which are assumed to be in thermal equilibrium in the local magnetic field due to the carriers. The time dependence of light-matter interaction term is eliminated by a unitary transformation and the resulting Hamiltonian is solved by making a Bogoliubov-Valatin (B-V) type transformation or by a variational approach using a Bardeen-Cooper-Schrieffer (BCS) type of wave function.

We assume that the carriers are due to only photo-excitation. These carriers mediate a ferromagnetic interaction between the localized magnetic moments with a transition to a paramagnetic state as the temperature is increased beyond T_c (Figure 2). The magnitude of T_c is determined by the parameters of the system such as the strength of the light matter coupling, the frequency of light, interaction strength of carriers with local moment, the carrier-carrier Coulomb interaction *etc*. Even for a sub-band gap light frequency, there are induced carriers, primarily due to Rabi oscillations, leading to a small but non zero T_c. We find that for typical parameters, T_c is a fraction of a degree or so, which is sizeable. In systems such as (Ga, Mn) As that are already ferromagnetic, the incident light would enhance the T_c by this amount, an effect that has been recently observed [47].

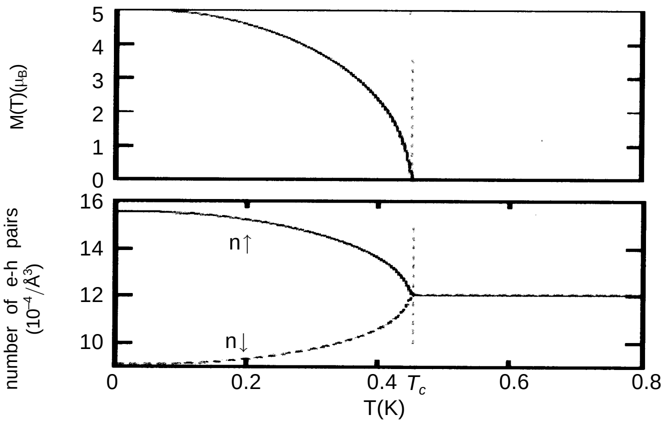

Figure 2. Number of e-h pairs as a function of temperature *T*(*K*). T_c is shown in the figure. n↑ denotes the number of electron-hole pairs with spin-up electrons and spin-down holes and n↓ denotes the corresponding pairs for spin-down electrons and spin-up holes. M is the magnetization of the Mn moments evaluated self-consistently. These figures are plotted for typical parameters of a model (Ga, Mn) As DMS [46].

5. Conclusion

In this invited article, we made a brief review of the progress made in the area of semiconductor magnetism and presented briefly some of our results in the subject of photo-induced magnetism in diluted magnetic semiconductors. It is a subject of considerable importance at present for possible applications in spintronics. We have made a serious effort, within the scope of the requirement of the invited talk, in presenting the basic features of the current excitements in semiconductor magnetism.

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References

[1] D C Mattis *Theory of Magnetism I : Static and Dynamics* (Berlin : Springer-Verlag) (1981)

[2] A H Wilson *Proc. Roy. Soc (London)* **A132** 458 (1931); ibid **A134** 277 (1931)

[3] J C Phillips *Bonds and Bands in Semiconductors* (New York : Academic) (1973)

[4] S Hudgens, M Kastner and H Fritzsche *Phys. Rev. Lett*. **33** 1552 (1974)

[5] T Sahu and P K Misra *Phys. Rev*. **B26** 6795 (1982)

[6] S N Lykov and I A Chernik *Sov. Phys. Semicond*. **14** 1112 (1980)

[7] M Gorska and J R Anderson *Acta Physica Polonica* **A75** 273 (1989)

[8] R L Hota, G S Tripathi and P K Misra *J. Appl. Phys*. **75** 5737 (1994)

[9] R C Patnaik, R K Das, R L Hota and G S Tripathi *Pramana-J. Phys*. **57** 795 (2001)

[10] C R Hewes, M S Adler and S D Senturia *Phys. Rev.* **B7** 5195 (1973)

[11] G S Tripathi, L K Das, P K Misra and S D Mahanti *Solid State Commun*. **38** 1207 (1981); *Phys. Rev.* **B25** 3091 (1982)

[12] R L Hota and G S Tripathi *Phys. Rev*. **B44** 1918 (1991)

[13] R L Hota, R C Patnaik, G S Tripathi and P K Misra *Phys. Rev*. **B51** 7291 (1995)

[14] J A Gaj, J Ginter and R R Galazka *Phys. Staus Solidi* **B89** 655 (1978)

[15] M Jaczyznski, J Kossut and R R Galazka *Phys. Status Solidi* **B88** 73 (1978)

[16] N B Brandt and M Moschalkov *Adv. Phys*. **33** 193 (1984)

[17] J K Furdyna *J. Appl. Phys*. **64** R29 (1988)

[18] M Averous and M Balkanski (ed.) *Semimagnetic Semiconductors and Diluted Magnetic Semiconductors* (USA Plenum) (1991)

[19] R L Hota, G S Tripathi and J N Mahanti *Phys. Rev*. **B47** 9319 (1993)

[20] R C Patnaik and G S Tripathi *Solid State Commun.* **112** 669 (1999)

[21] R K Das, G S Tripathi and P K Misra *Phys. Rev*. **B72** 035216 (2005)

[22] H Munekata, H Ohno, S von Molnar, A Segmuller, L L Chang and L Esaki *Phys. Rev. Lett*. **63** 1849 (1989)

[23] H Munekata *et al, Appl. Phys. Lett*. **63** 2929 (1993)

[24] H Ohno *et al, Phys. Rev. Lett.* **68** 2664 (1992)

[25] H Ohno, A Shen *et al, Appl. Phys. Lett*. **69** 363 (1996)

[26] H Ohno *Science* **281** 951 (1998)

[27] H Ohno, J Magn *Magn. Mater. Handbook of Magn. Mater*. (Netherlands : Elsevier) **Vol.14** (2002)

[28] F Matsskura, H Ohno and T Dietl *Handbook of Magn. Mater*. (Netherlands : Elsevier) **Vol.l4** (2002)

[29] A H MacDonald *et al, Nature Materials* **4** 195 (2005)

[30] Igor Zutic, Jaroslav Fabian and S Das Sarma *Rev. Mod. Phys*. **76** 323 (2006)

[31] T Jungwarth *et al, Phys. Rev*. **B72** 165204 (2005)

[32] K Y Yang *et al, Proc. 27th Conf. Phys. Semicond* (New York : AIP) p233 (2005)

[33] T Jungwarth, J Sinova, J Masek, J Kucera and A H MacDonald *Rev. Mod. Phys*. **78** 809 (2006)

[34] H J Zeiger and G W Pratt *Magnetic Interations in Solids* (Oxford : Clarendon) (1973)

[35] O Sato, T Iyoda, A Fujishima and H Kashimato *Science* **272** 704 (1996)

[36] H Krenn, W Zawadzki and G Bauer *Phys. Rev. Lett*. **55** 1510 (1985)

[37] H Krenn, K Kaltenegger, T Dietl, J Spalek and G Bauer *Phys. Rev*. **B39** 10918 (1989)

[38] S Kosihara *et al, Phys. Rev. Lett*. **78** 4617 (1997)

[39] Y Mitsumori *et al, Phys. Rev*. **B69** 033203 (2004)

[40] J Fernandez Rossier *et al, Phys. Rev. Lett*. **93** 127201 (2004)

[41] K Matsuda *et al, Phys. Rev.* **B58** R4203 (1998)

[42] Y Muraoka, H Tabata and T Kawai *Appl. Phys. Lett*. **27** 4016 (2000)

[43] D A Pejakovic *et al, Phys. Rev. Lett*. **88** 05720 (2002)

[44] G S Tripathi, B G Mahanty and S N Behera *Phase Transitions* **78** 229 (2005)

[45] G S Tripathi, B G Mahanty, P Tripathi and S N Behera AIP Conf. Proc. **1063** 138 (2008)

[46] S Mishra, G S Tripathi and S Satpathy *Phys. Rev*. **B 77** 125216–1 (2008)

[47] J Wang *et al, Phys. Rev. Lett*. **98** 217401 (2007)