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INHOMOGENEITIES IN MAGNETIC SYSTEMS

Alberta Bonanni

Johannes Kepler University, Linz – Austria

Real samples may differ from what we assume in models. Crystals are rarely perfect and contain residual impurities. Bonds at interfaces may reconstruct in a different way we envisage. Alloy constituents may distribute in a non-random way….

This workshop, taking epitaxial films of diluted magnetic semiconductors as an example, aims at discussing the tools we have to visualize, control, and exploit a non-random distribution of transition metal cations in a semiconductor lattice. We will focus on five major issues:

1] an abundant literature reporting surprisingly high temperature ferromagnetism in a number of magnetically doped semiconductors and oxides [1] and even in materials containing nominally no magnetic ions [2] has called into question our understanding of magnetism in solids. In the course of the years, this topic has become one of the most controversial themes in today's materials science. We will present selected experimental results and show that the available models can explain the existence of a robust ferromagnetic coupling between randomly distributed localised spins, only in the presence of a high density of valence band holes [3].

2] we will show how the application to these systems of element-specific nano-analytic tools, particularly involving synchrotron radiation and electron microscopy, can be employed to visualise the actual distribution of magnetic ions [4-7]. We will show that the mentioned methods reveal the presence of aggregation of magnetic cations and that the nano-scale phase separation can appear in the form of a precipitation of a magnetic compound (crystallographic phase separation) or as chemical phase separation into alternating nano-scale regions with larger and smaller concentration of the magnetic constituent. We will give evidence that the regions with the high concentration of magnetic ions - self-assembled condensed magnetic semiconductors (CMSs) -, account for the ferromagnetic-like features observed in these systems and that interestingly, the CMSs can develop in the form of nanopillars [4] or nanodots [6,7].

3] with the participation of School attendees we will uncover the various ways in which the studied samples can be contaminated by magnetic nanoparticles [8] and we will try to complete a list of fundamental precautions that should be taken into account when measuring small magnetic signals, particularly by SQUID magnetometry. A competition among the students will be organised with the goal of finding the most spectacular example of a spurious magnetic measurement.

4] an important recent development is that the self-organised assembling of transition metal impurities in semiconductors can be controlled by co-doping with shallow donors or acceptors [6,7] This unique property of alloys with magnetic cations stems from the fact that in many relevant cases the levels introduced by magnetic dopants reside in the band gap, so that the magnetic ion valency (charge state) and, thus, the preferential bonding configuration can be altered by varying the Fermi level position during the growth [9].

5] we will provide a synopsis of the outstanding possibilities offered by self-organised semiconductor/ferromagnet nanocomposite media in room-temperature spintronics, plasmonics, photonics, thermoelectrics, and electronics [10]. They can also serve for magnetic cooling and give rise to *e.g.* novel spin-battery effects [11]. We will discuss this issue in the broader context of semiconductor epitaxy, which in addition to represent a major tool to synthesise complex high quality multi-layer structures, has already been successfully exploited to fabricate self-organised quantum dots, nanowires, and nanocolumns.

References

1. C. Liu, F. Yun, and H. Morkoç, 'Ferromagnetism of ZnO and GaN: A Review' *J. Materials Science: Materials in Electronics* 16 (2005) 555; S. A. Chambers, T. C. Droubay, C. M. Wanga, K. M. Rosso, S. M. Heald, D. Schwartz, K. R. Kittilstved, and D. Gamelin, 'Ferromagnetism in oxide semiconductors' *Materials Today* 9 (2006) 28; T. Fukumura, H. Toyosaki, and Y. Yamada, 'Magnetic oxide semiconductors', *Semicond. Sci. Technol.* 20 (2005) S103.
2. J. M. D. Coey, 'Dilute magnetic oxides', *Current Opinion in Solid State and Materials Science* 10 (2006), 83.

3. T. Dietl, H. Ohno, F. Matsukura, J. Cibert, and D. Ferrand, 'Zener Model Description of Ferromagnetism in Zinc-Blende Magnetic Semiconductors', *Science* 287 (2000) 1019.
4. M. Jamet, A. Barski, T. Devillers, V. Poydenot, R. Dujardin, P. Bayle-Guillmaud, J. Rotheman, E. Bellet-Amalric, A. Marty, J. Cibert, R. Mattana, and S. Tatarenko, 'High-Curie-temperature ferromagnetism in self-organized $Ge_{1-x}Mn_x$ nanocolumns' *Nature Mater.* 5 (2006) 653.
5. A. Bonanni, 'Ferromagnetic nitride-based semiconductors doped with transition metals and rare earths' *Topical Review, Semicond. Sci. Technol.* 22 (2007) R41-R57.
6. S. Kuroda, N. Nishizawa, M. Mitome, Y. Bando, K. Osuch, and T. Dietl, 'Origin and control of high-temperature ferromagnetism in semiconductors', *Nature Mater.* 6 (2007) 440.
7. A. Bonanni, A. Navarro-Quezada, Tian Li, M. Wegscheider, R.T. Lechner, G. Bauer, Z. Matej, V. Holý, M. Rovezzi, F. D'Acapito, M. Kiecana, M. Sawicki, and T. Dietl, 'Controlled Aggregation of Magnetic Ions in a Semiconductor: An Experimental Demonstration' *Phys. Rev. Lett.* 101 (2008) 135502.
8. T. Dietl, 'Self-organized growth controlled by charge states of magnetic impurities' *Nature Mater.* 5 (2006) 673.
9. P.J. Grace, M. Venkatesan, J. Alaria, J. Michael, D. Coey, G. Kopnov, and R. Naaman, 'The origin of the magnetism of etched silicon' *Advanced Materials* 21 (2009) 71.
10. H. Katayama-Yoshida, K. Sato, T. Fukushima, M. Toyoda, H. Kizaki, V. A. Dinh, and P. H. Dederichs, '**Theory of ferromagnetic semiconductors**', *phys.stat. sol. (a)* 204 (2007) 15; T. Dietl, 'Origin and control of ferromagnetism in dilute magnetic semiconductors and oxides', *J. Appl. Phys.* 103 (2008) 07D111.
11. P. Nam Hai, S. Ohya, M. Tanaka, S. E. Barnes, and S. Maekawa, 'Electromotive force and huge magnetoresistance in magnetic tunnel junctions' *Nature* 458 (2009) 489.