Low-energy μSR and transport studies of (Ga,Mn)As

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The III-V semiconducting materials (Ga,Mn)As exhibit an unusual long range interaction between Mn ions which is mediated by charge carriers, the Mn atoms simultaneously acting as a magnetic species and charge donors. The resulting ferromagnetic order and metal-insulator transition in thin films of (Ga,Mn)As have been studied by low-energy μSR at PSI, in addition to magnetization and transport measurements at Tohoku University, on specimens with Mn 1.0 % [sample A], 3.0 % [B], 3.4 % (as grown) [C] and Mn 3.4 % (annealed) [D]. In transport studies, samples A and B show semiconducting behavior, while C and D exhibit metallic conductivity. In μSR measurements in zero field (ZF) and a weak transverse field (WTF) of 100 G, ferromagnetism with nearly full (at least more than 80 %) volume fraction was observed in B ($T_c \sim 30$ K), C ($\sim$45K), and D ($\sim$75K), with a very sharp transition in C and D, and a slightly gradual one in B. The sample A remained paramagnetic down to T = 2K. These results indicate: (1) unlike general concerns over the rather inhomogeneous nature of the phase transitions in (Ga,Mn)As, ferromagnetic order occurs sharply at T_c and prevails over the entire volume; and (2) the semiconductor-to-metal transition and para-to-ferromagnetic transitions occur at different Mn concentrations, as a semiconducting film shows a static ferromagnetism. We will compare these results with μSR studies of quantum phase transitions in itinerant-electron heli/ferromagnets MnSi, (Sr,Ca)RuO_3 [1] and a geometrically spin-frustrated insulator Cu(Cl,Br)La(Nb,Ta)$_2O_7$ [2].

[1] Y.J. Uemura, T. Goko, I.M. Gat-Malureanu, J.P. Carlo, P.L. Russo, A.T. Savici, A. Aczel, G.J. MacDougall, J.A. Rodriguez, G.M. Luke, S.R. Dunsiger, A. McCollam, J. Arai, Ch. Pfleiderer, P. Boeni, K. Yoshimura, E. Baggio-Saitovitch, M.B. Fontes, J. Larrea J., Y.V. Sushko, and J. Sereni, Nature Physics 3 (2007) 29 - 35.
[2] Y. J. Uemura, A. A. Aczel, Y. Ajiro, J. P. Carlo, T. Goko, D. A. Goldfeld, A. Kitada, G. M. Luke, G. J. MacDougall, I. G. Mihailescu, J. A. Rodriguez, P. L. Russo, Y. Tsujimoto, C. R. Wiebe, T. J. Williams, K. Yoshimura, and H. Kageyama, submitted for publication (2008); H. Kageyama, invited talk at this conference.