Low-energy $\mu$SR 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 $\mu$SR 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 $\mu$SR 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 ($\sim45$K), and D ($\sim75$K), with a very sharp transition in C and D, and a slightly gradual one in B. The sample A remained paramagnetic down to $T = 2$K. 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 $\mu$SR 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)$_2$O$_7$ [2].
