

Muon-Spin-Relaxation Study of Ferromagnetism in (Ga,Mn)(Bi,As) Dilute Magnetic Semiconductor

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Samples

- (Ga,Mn)As / GaAs & (Ga,Mn)As / InGaAs / GaAs
- (Ga,Mn)(Bi,As) / GaAs & (Ga,Mn)(Bi,As) / InGaAs / GaAs

All investigation were performed on the same set of annealed samples, grown with LT-MBE ($T_g = 230^\circ\text{C}$) technique on semi-insulating GaAs (001)-oriented substrate with an optional InGaAs buffer layer for structural & magnetization modulation. As-grown samples were point of interest only during HR-XRD measurements. Concentration of Mn (6%), Bi (1%) and top thin layer thickness (50 nm) are constant.

Introduction

GaAs-based ternary compound (Ga,Mn)As, in which a few percent of Ga lattice atoms have been substituted by Mn impurities, has become a prototype dilute ferromagnetic semiconductor, which exhibits spintronic functionalities associated with collective ferromagnetic spin ordering. As demonstrated in our recent investigations, the replacement of a small fraction of As atoms by much heavier Bi atoms in (Ga,Mn)As layers results, owing to increased spin-orbit coupling, in a strong enhancement of magneto-resistive effects in the quaternary (Ga,Mn)(Bi,As) compound, favourable to its spintronic applications.

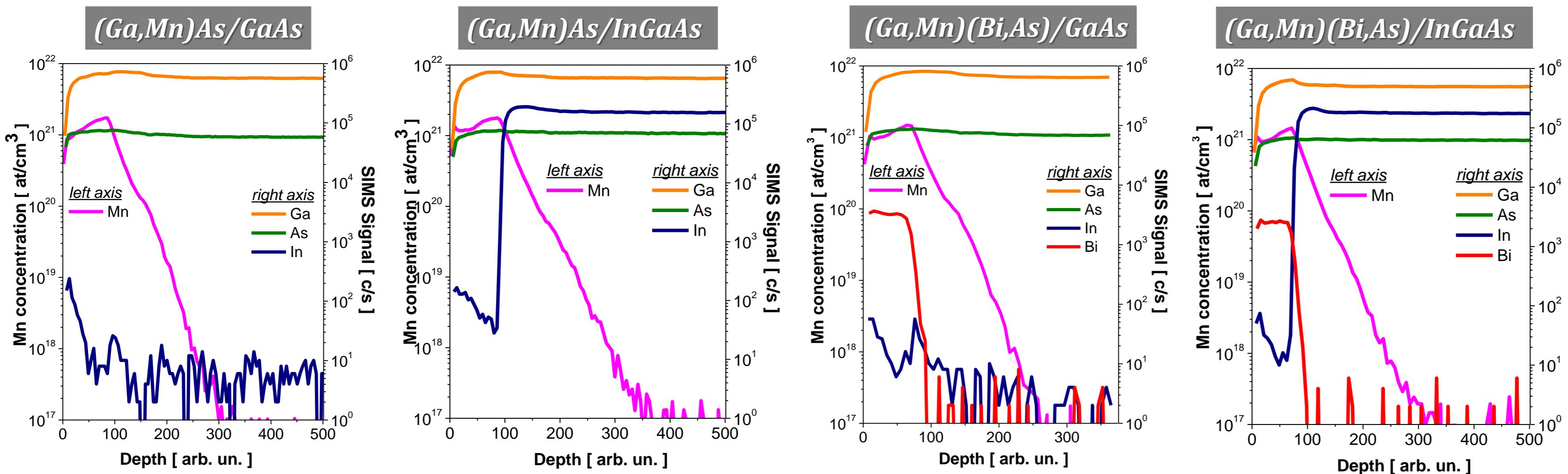


Table 1: Lattice and strain parameters for annealed & as-grown thin layers

	c [Å]	a _{rel} [Å]	Lattice mismatch [$\times 10^4$]
GaAs	5.65	5.65	(a _{rel} - a _{Sub}) / a _{Sub}
Annealed	5.62	5.67	-83.2 (tensile)
As-grown	5.65	5.68	-52.1 (tensile)
GaMnAs/ InGaAs	5.68	5.67	26.6
Annealed	5.68	5.67	34.2
As-grown	5.69	5.67	
GaMnBiAs/ InGaAs	5.63	5.68	-97.3 (tensile)
Annealed	5.65	5.69	-76.3 (tensile)
As-grown	5.70	5.68	45.9
GaMnBiAs/ InGaAs	5.71	5.68	53.3
As-grown			

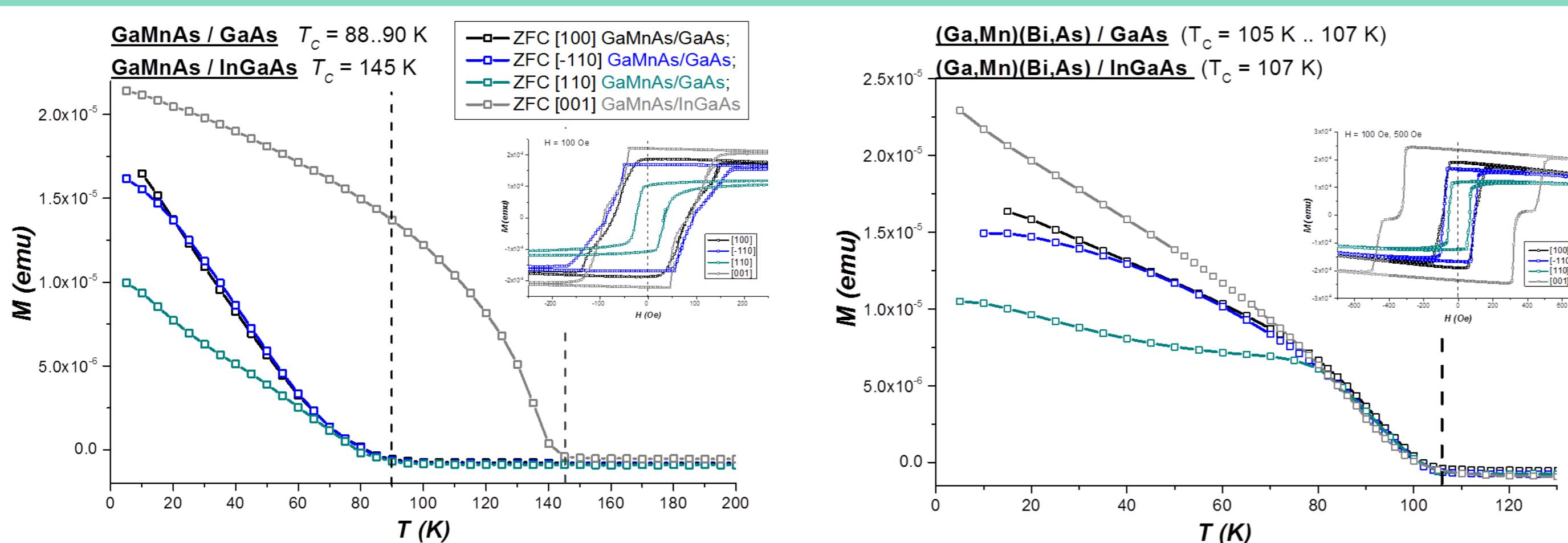
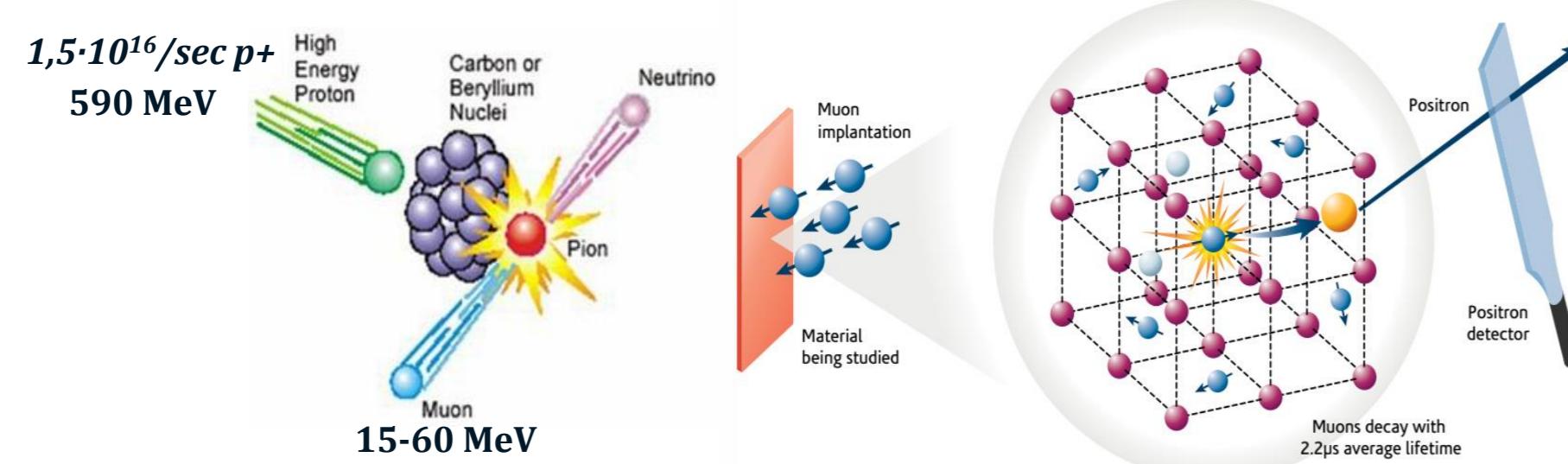
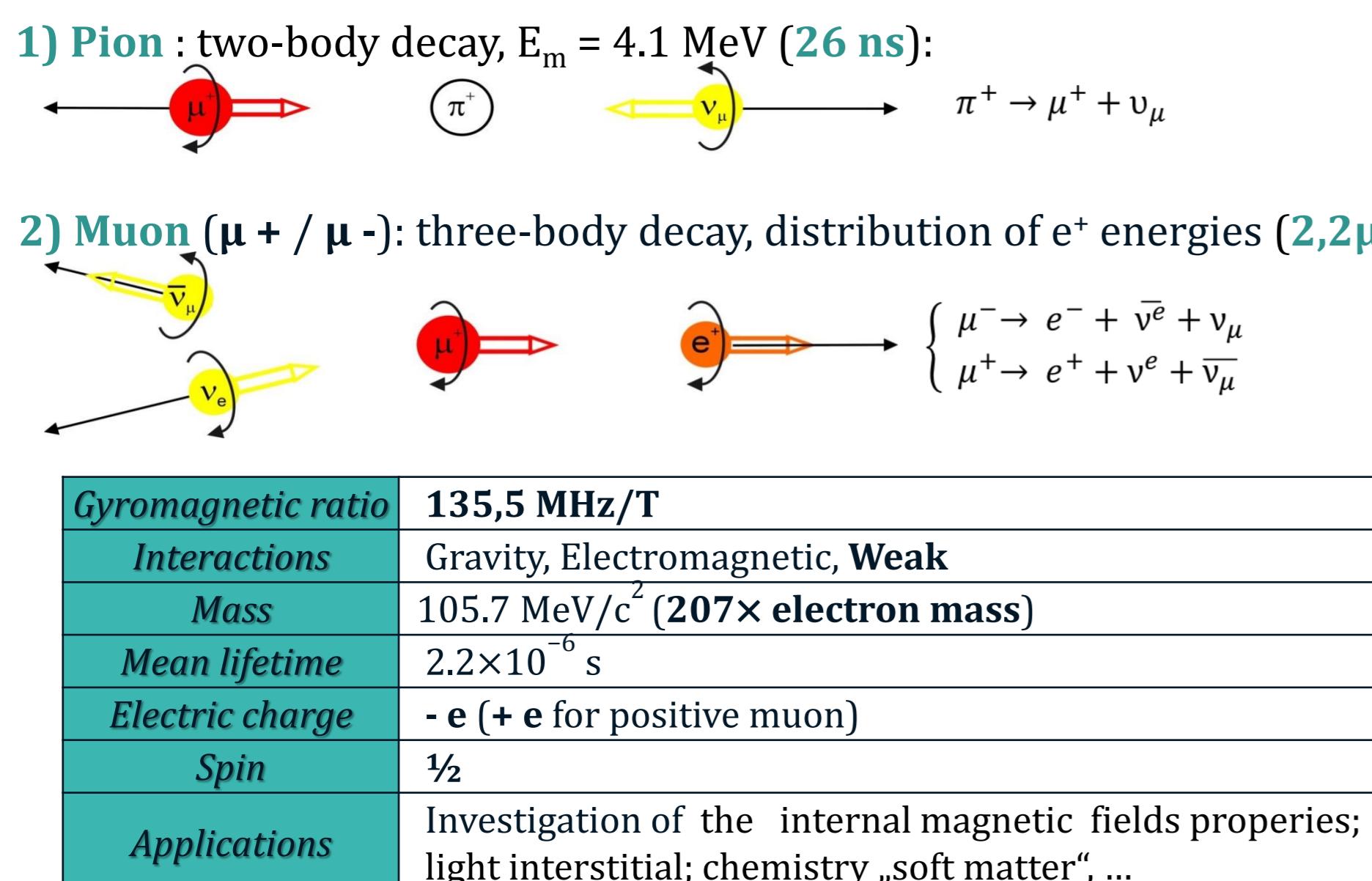


Figure 1: Magnetization as a function of temperature for (Ga,Mn)As & (Ga,Mn)(Bi,As) samples on different substrates. Corresponding magnetization loops as a function of applied magnetic field ($T = 5\text{K}$) are shown in the insets.

- High values of Curie temperature (T_c) for all the samples – (Ga,Mn)As/GaAs (90 K); (Ga,Mn)As/InGaAs (140 K); (Ga,Mn)(Bi,As)/GaAs & (Ga,Mn)(Bi,As)/InGaAs (~107 K).
- Disproportional influence of tensile strain on samples magnetization, conflict of Bi doping with InGaAs buffer (?).



$$N_L(t) = N_0 \exp(-t/\tau_\mu) [1 + A_L G(t) \cos(\omega t + \phi)] + N_{LB}$$

$$N_R(t) = N_0 \exp(-t/\tau_\mu) [1 - A_R G(t) \cos(\omega t + \phi)] + N_{RB}$$

$$AG(t) \cos(\omega t + \phi) \sim [N_L(t) - N_R(t)] / [N_L(t) + N_R(t)]$$

$\tau_\mu = 2.2\mu\text{s}$ – muon lifetime;
 A_L and A_R – decay asymmetries of positive muons (~ 0.25);
 N_L and N_R – left and right positron counter;
 $G(t)$ – time-dependent muon spin polarization function.

- $AG(t)$ contains the physics:
- frequency: $\omega = \gamma_\mu B$, value of field at muon site;
 - damping: width of field distribution, fluctuations;
 - amplitude: magnetic volume fraction, or μ fraction

Low-Energy μSR measurements

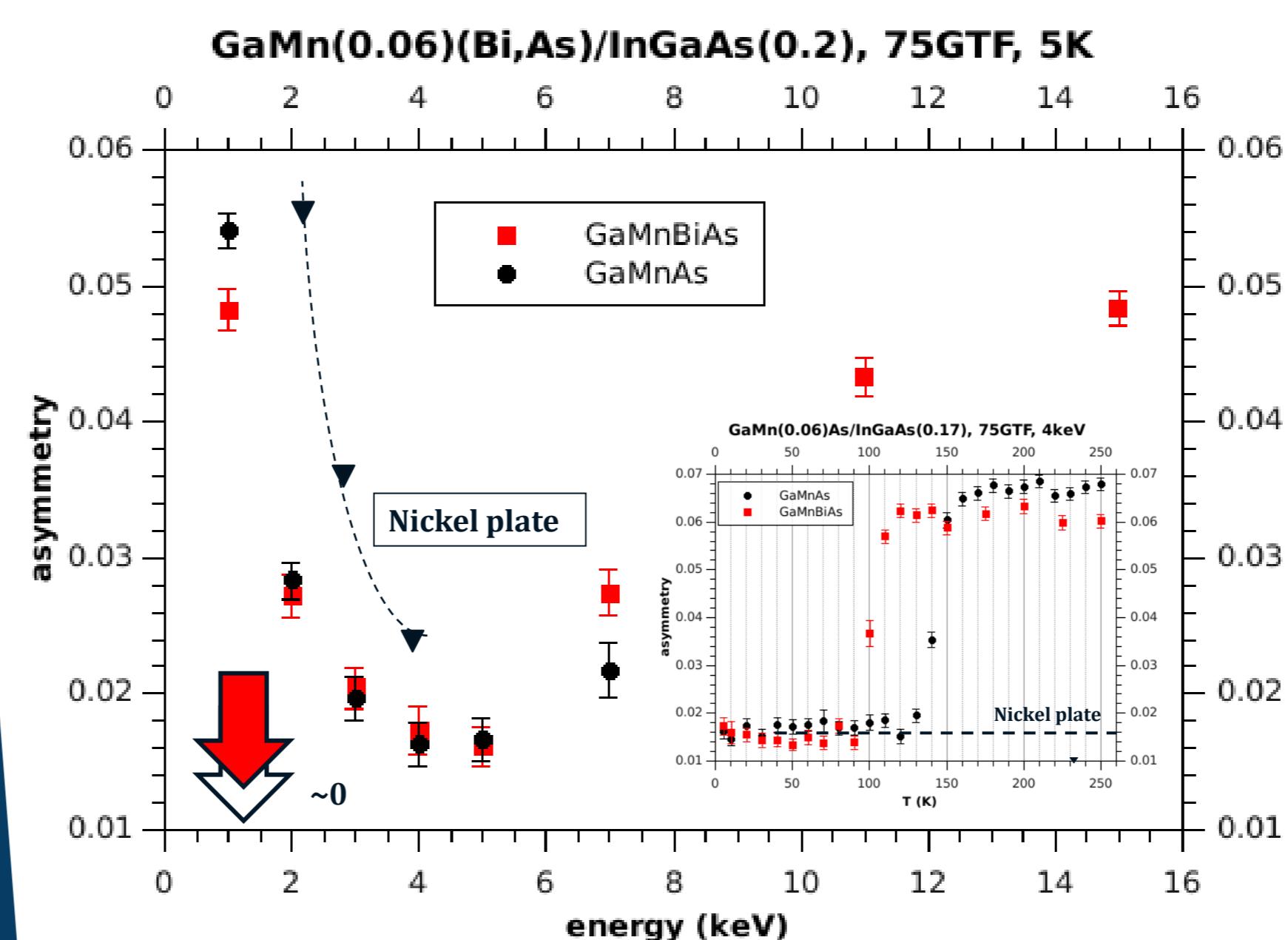
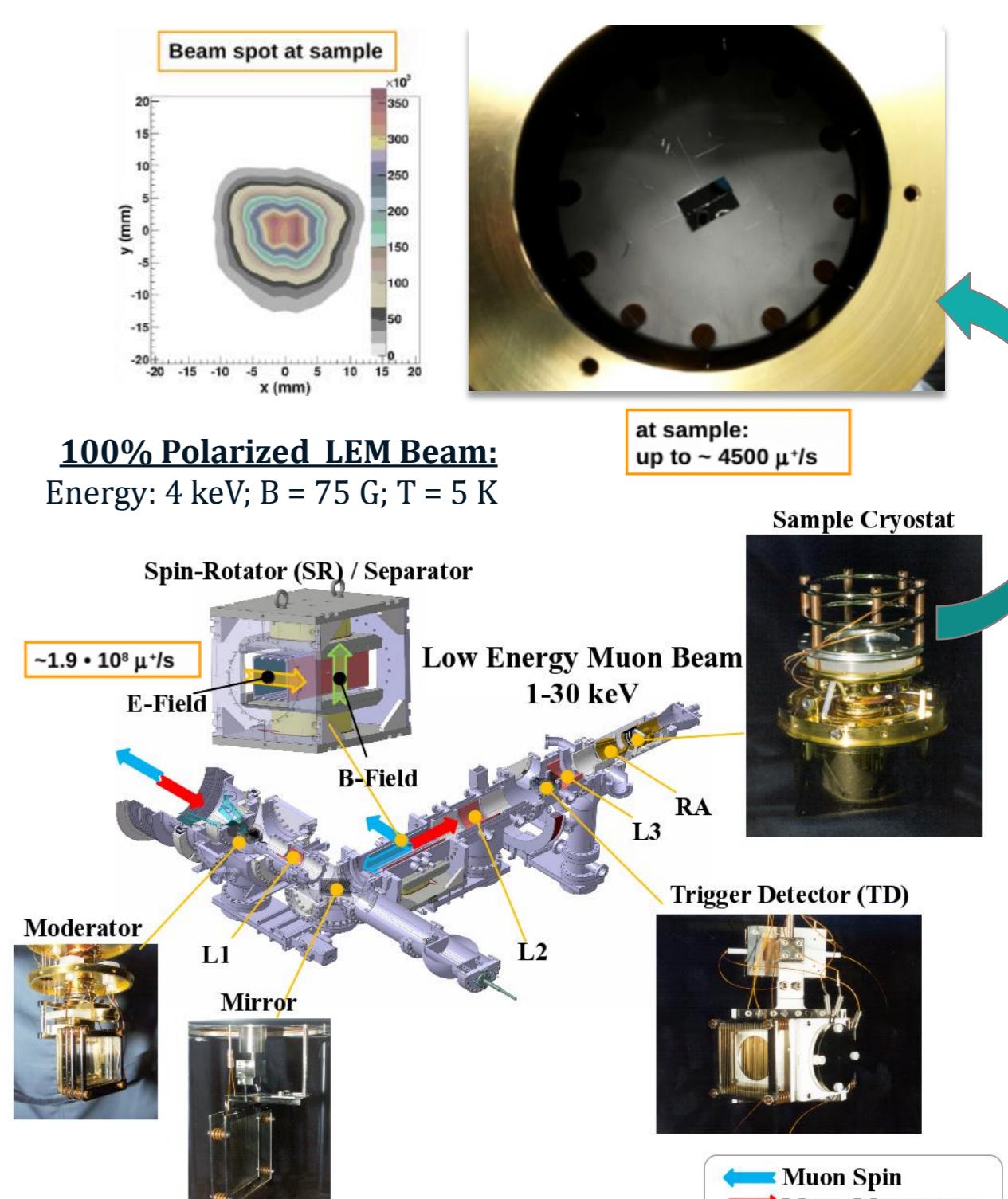


Figure 2 : μSR time spectra of (Ga,Mn)As & (Ga,Mn)(Bi,As) on different substrates. The background level from Ni plate is shown by the dashed line. Corresponding precession asymmetry loops as a function of temperature are shown in the insets.

- High magnetization homogeneity in all the samples as a result of low asymmetry signal from the thin layers;
- Obtained similar values of T_c for all the samples – (Ga,Mn)As/GaAs (~100K); (Ga,Mn)As/InGaAs (~140 K); (Ga,Mn)(Bi,As)/GaAs (~95 K) & (Ga,Mn)(Bi,As)/InGaAs (~100 K).



Conclusions

We present the results of structural (SIMS, HR-XRD) and magnetic properties (SQUID, μSR) of the investigated (Ga,Mn)As & (Ga,Mn)(Bi,As) DMS thin layers, proving their high crystalline quality, verifying growing parameters and evaluating magnetization. Special attention is drawn to a new technique – low-energy muon spectroscopy, that revealed high magnetization homogeneity from the precession symmetry graphs. T_c was determined from the asymmetry as a function of temperature loops, supported by more precise SQUID measurements. Performed investigations are a necessary step in understanding and controlling the magnetization behavior in GaAs, doped with Mn and/or Bi in order to reveal a full potential of this III-V DMS.