Muon Spin Relaxation Studies of Dilute Magnetic Semiconductors: Spintronics *via* μSR

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Motivation

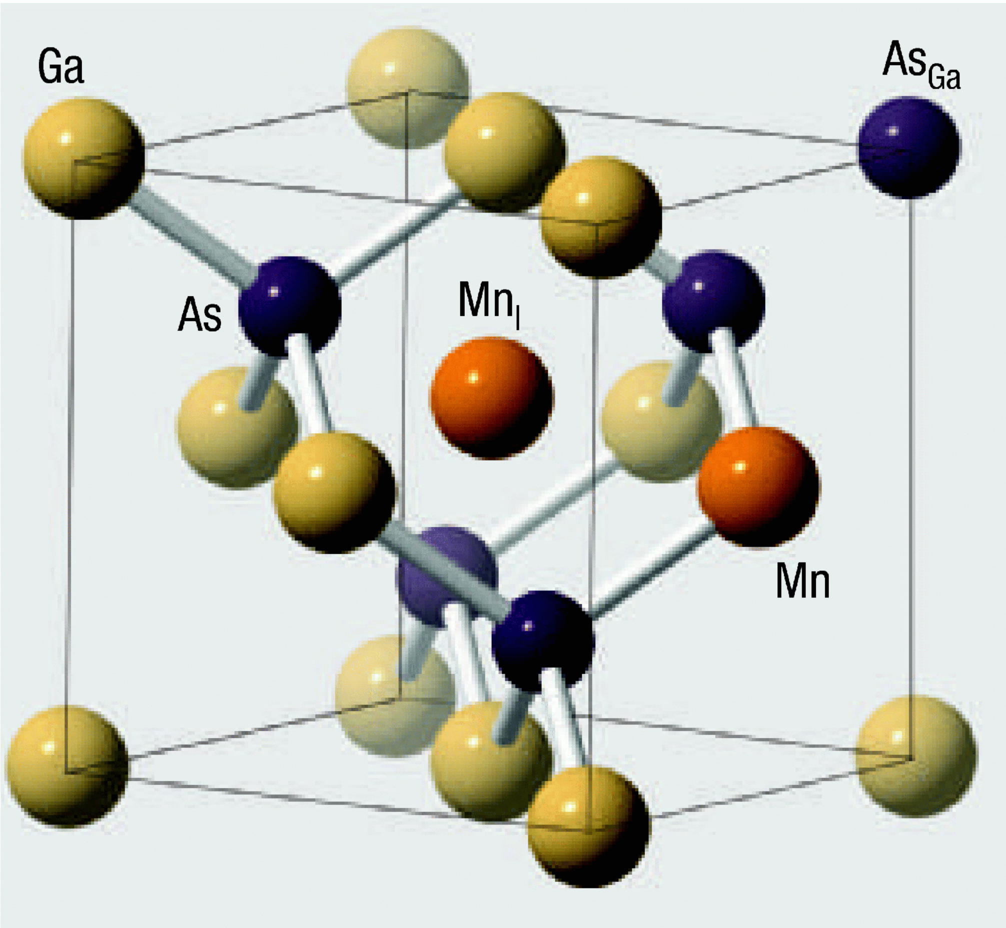
- Discovery of ferromagnetism (FM) in III-V semiconductors such as (Ga,Mn)As makes diluted magnetic semiconductors (DMS) good candidates for spintronics applications

- Practical spintronics applications of III-V DMS are limited by the fact that they are FM only at low temperature (below about 150K)

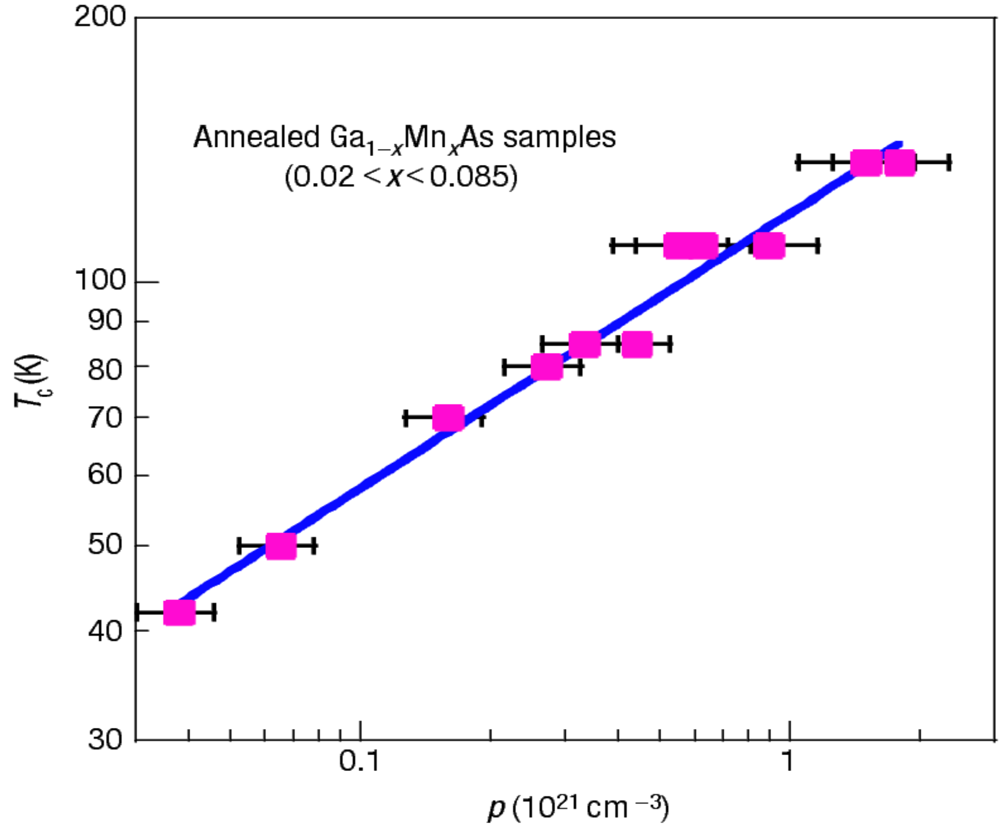
- Recently, room temperature ferromagnetism was reported in Mn doped chalcopyrite structures II-IV-V_2 in bulk samples

- Traditional techniques (magnetometry, anomalous Hall effect etc) cannot provide information on the distribution of magnetic fields in DMS

GaMnAs



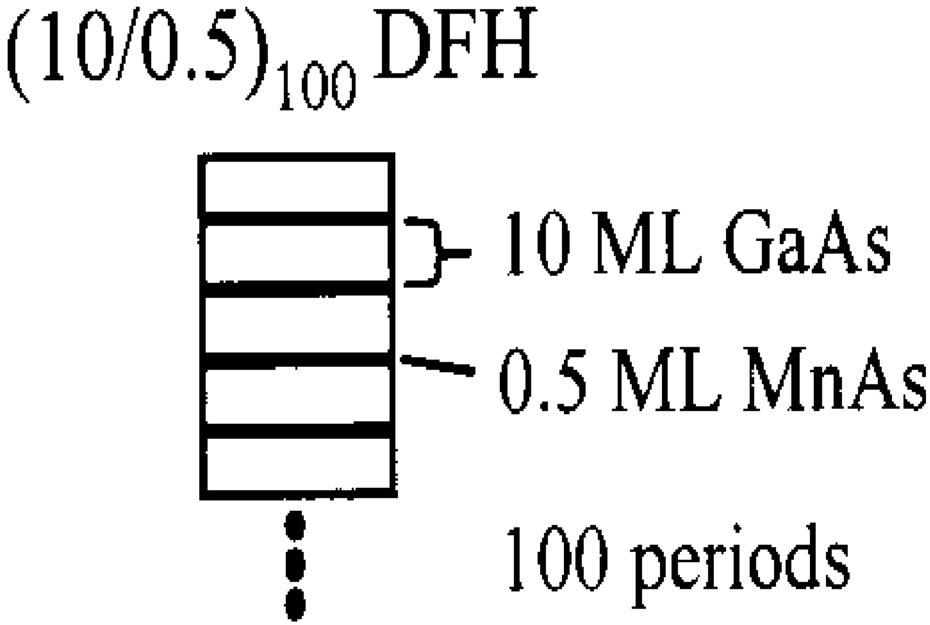
Ga
As_{Ga}
As
Mn_I
Mn

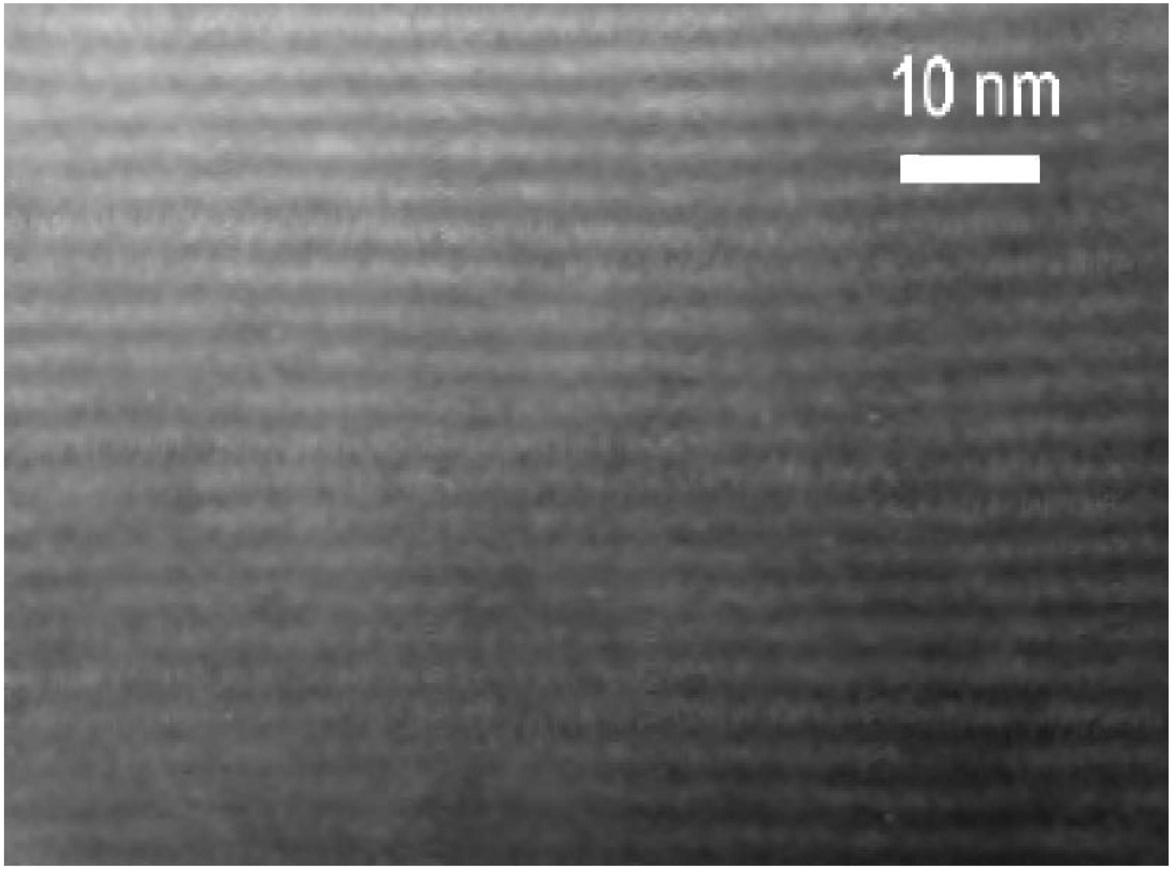


Annealed $Ga_{1-x}Mn_xAs$ samples
$(0.02 < x < 0.085)$
200
100
90
80
70
60
50
40
30
T_c (K)
0.1
1
p (10^{21} cm $^{-3}$)

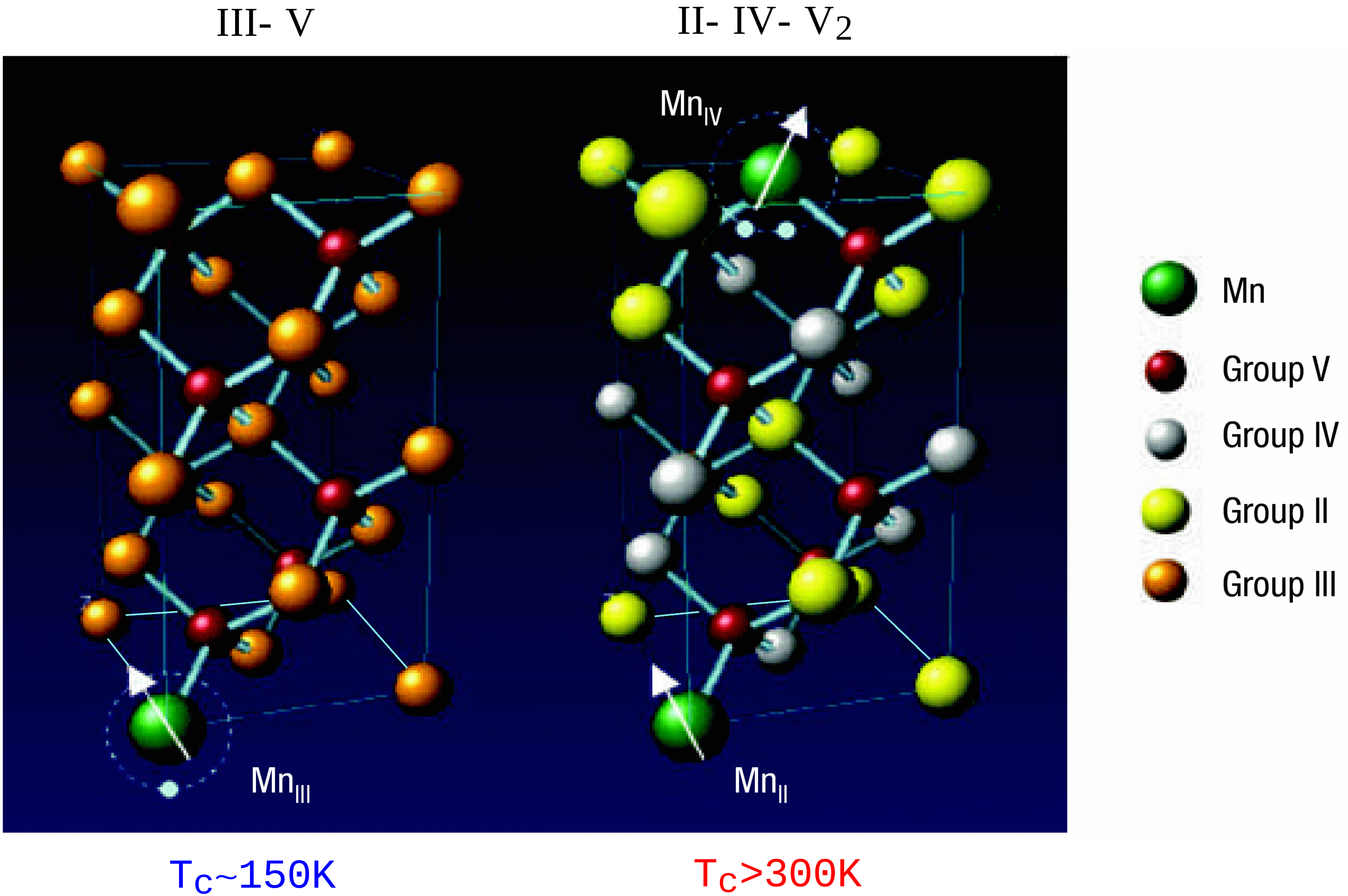
Digital alloys

TEM image



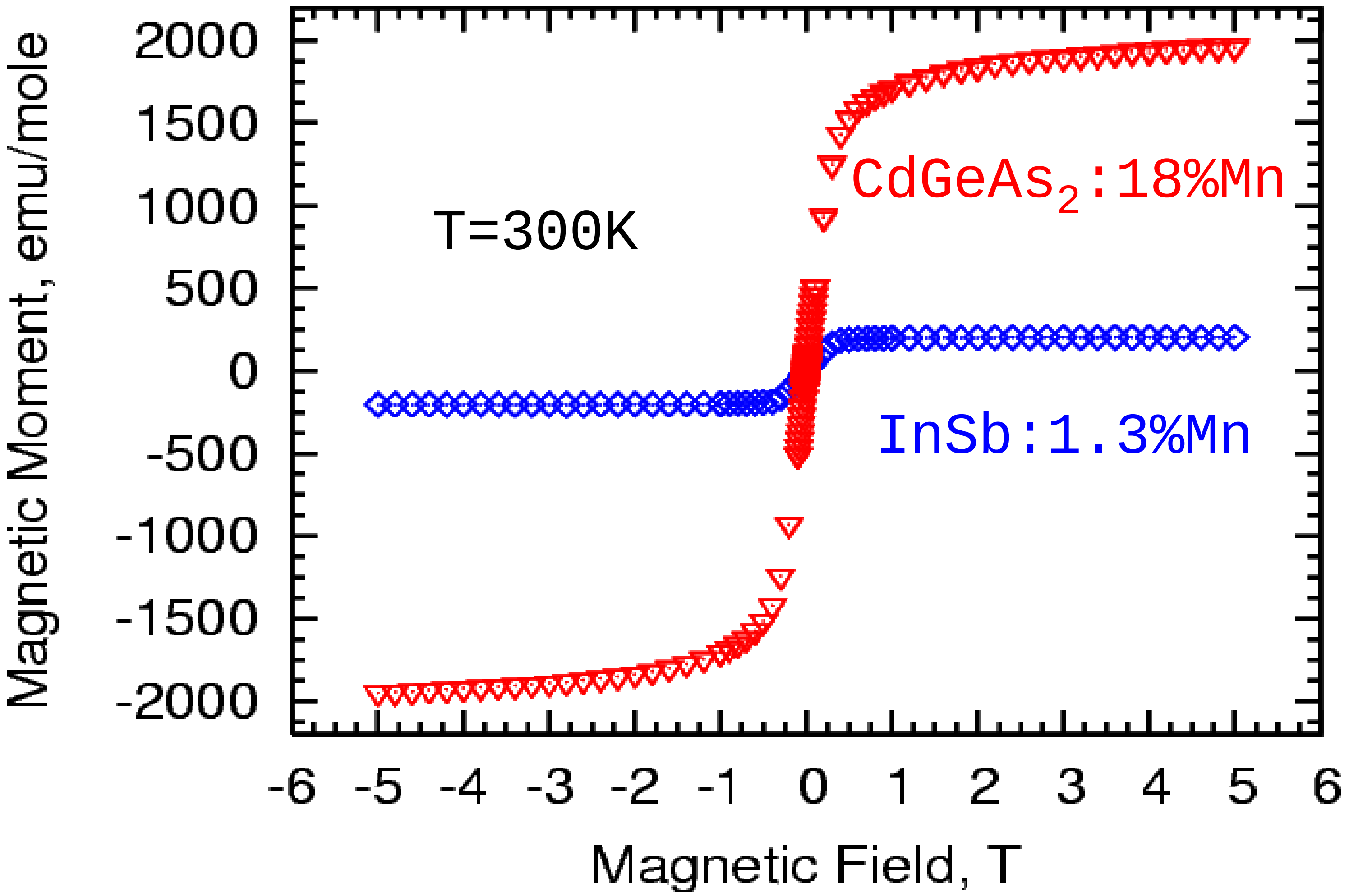


T_C~80K

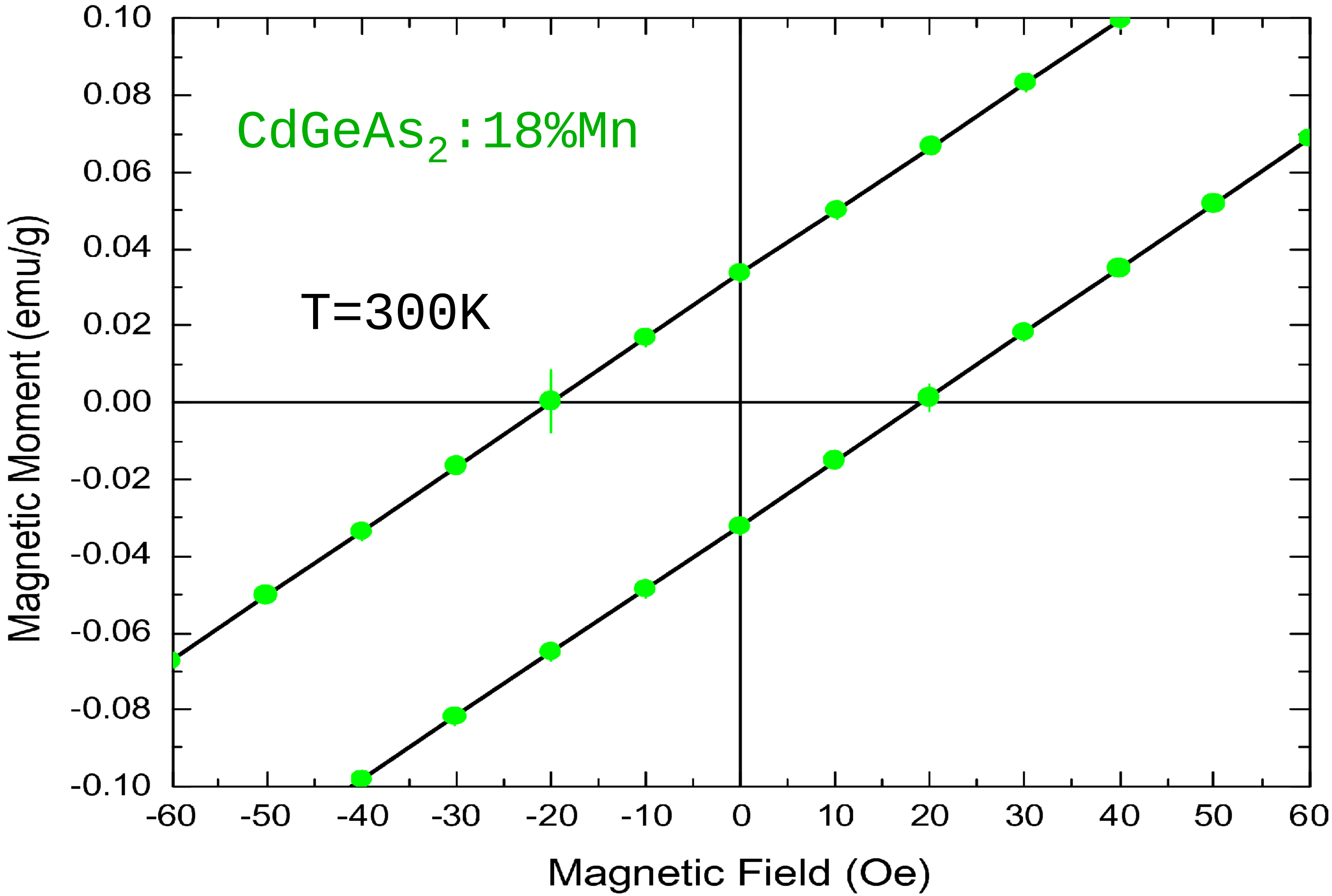


III- V
II- IV- V2
MnIV
MnIII
MnII
Mn
Group V
Group IV
Group II
Group III
Tc~150K
Tc>300K

Magnetization measurements

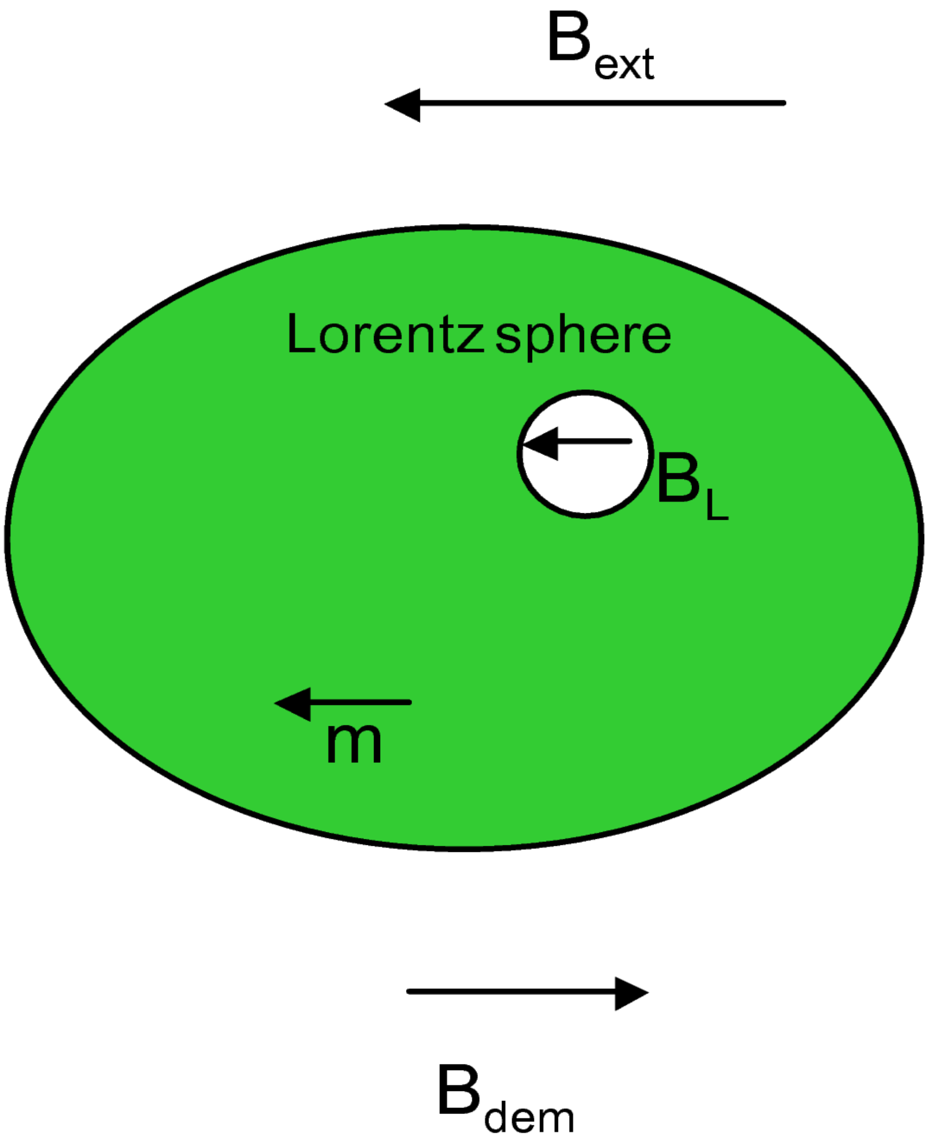


Magnetization measurements



Hysteresis loop with coercive field of 20 Oe

Local field seen by the muon



$B_\mu = B_{ext} - B_{dem} + B_L + B_{dip} + B_{cont}$

$B_L = 4\pi/3\ m$

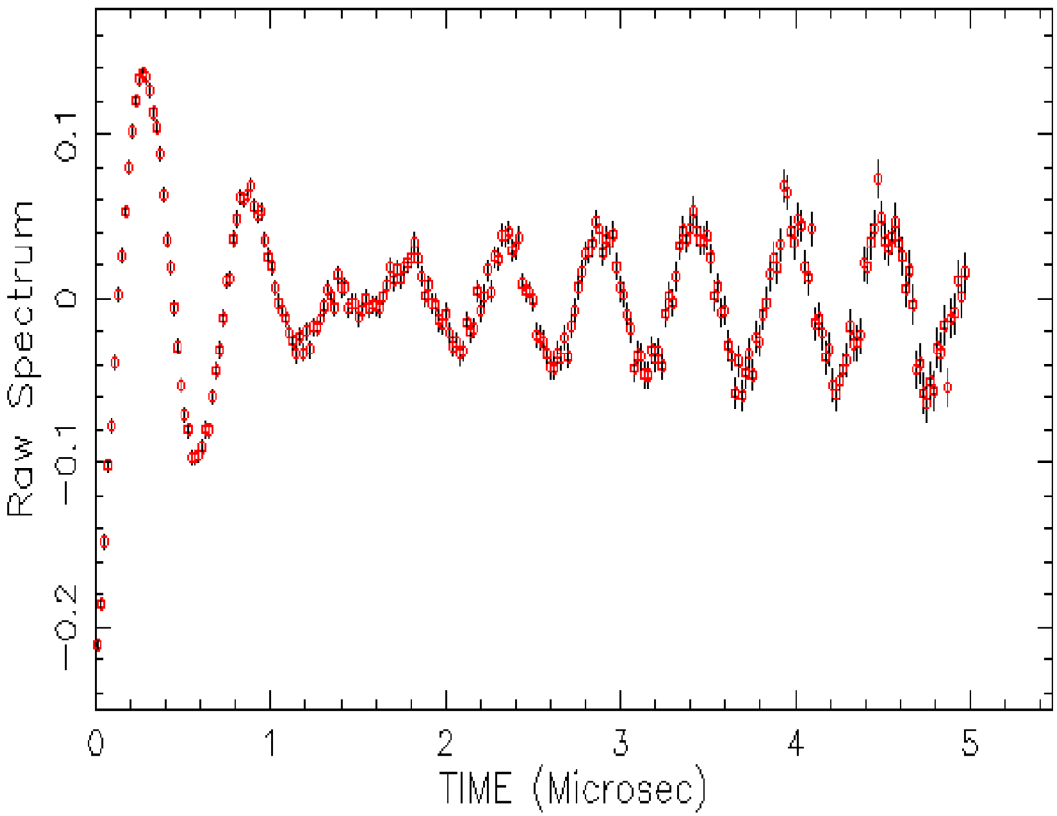
$B_{dem} = 4\pi N\ m$

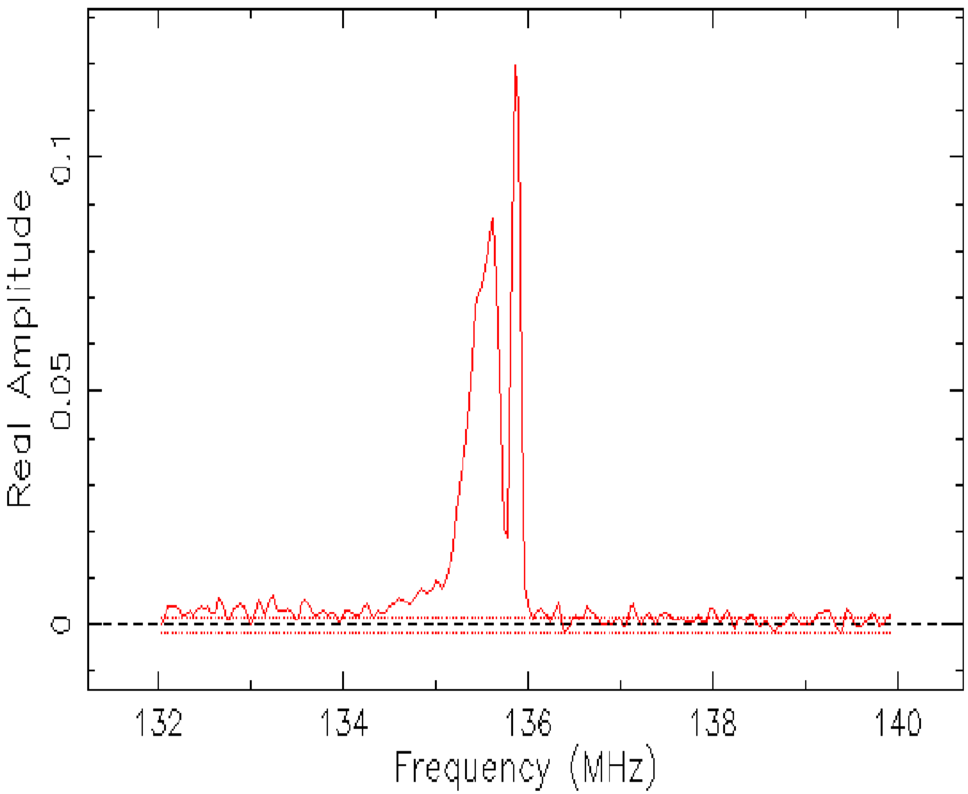
$B_\mu = B_{ext} + 4\pi(1/3 - N)\ m + B_{dip} + B_{cont}$

In our case (rectangular sample d~0.1a, field points perpendicular to the surface) N~0.8

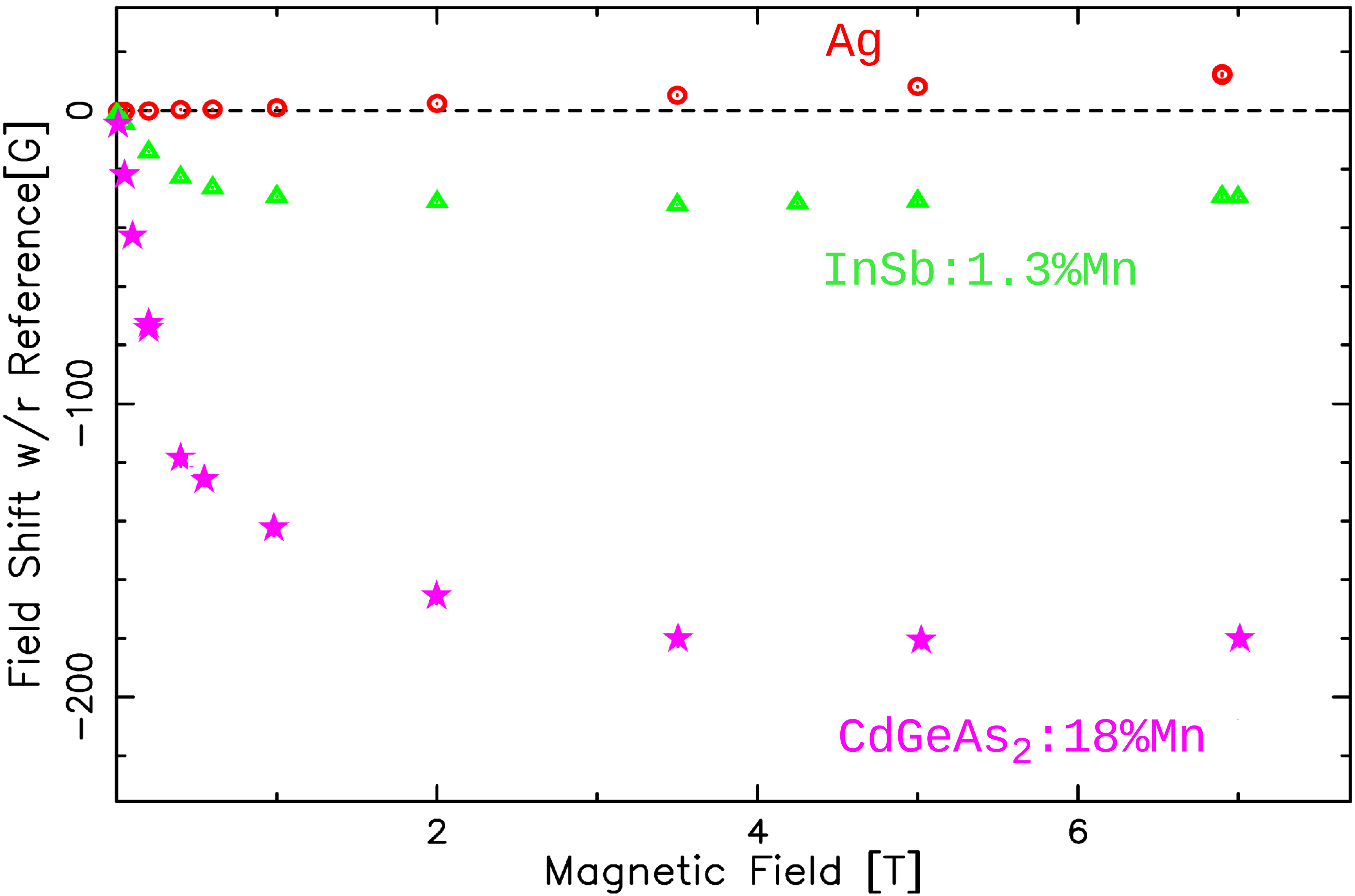
$CdGeAs_2$:18%Mn

T=300K H=1T

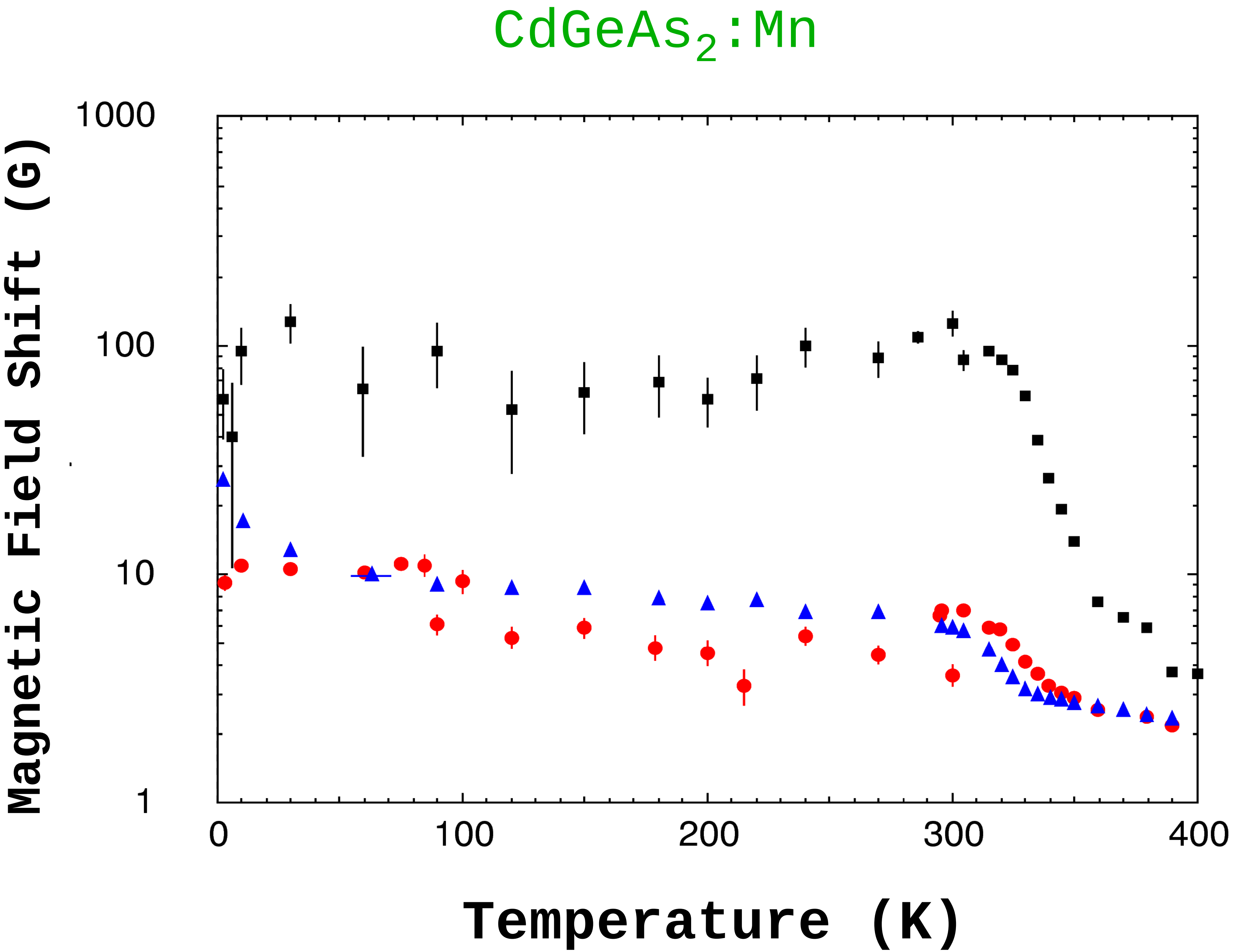




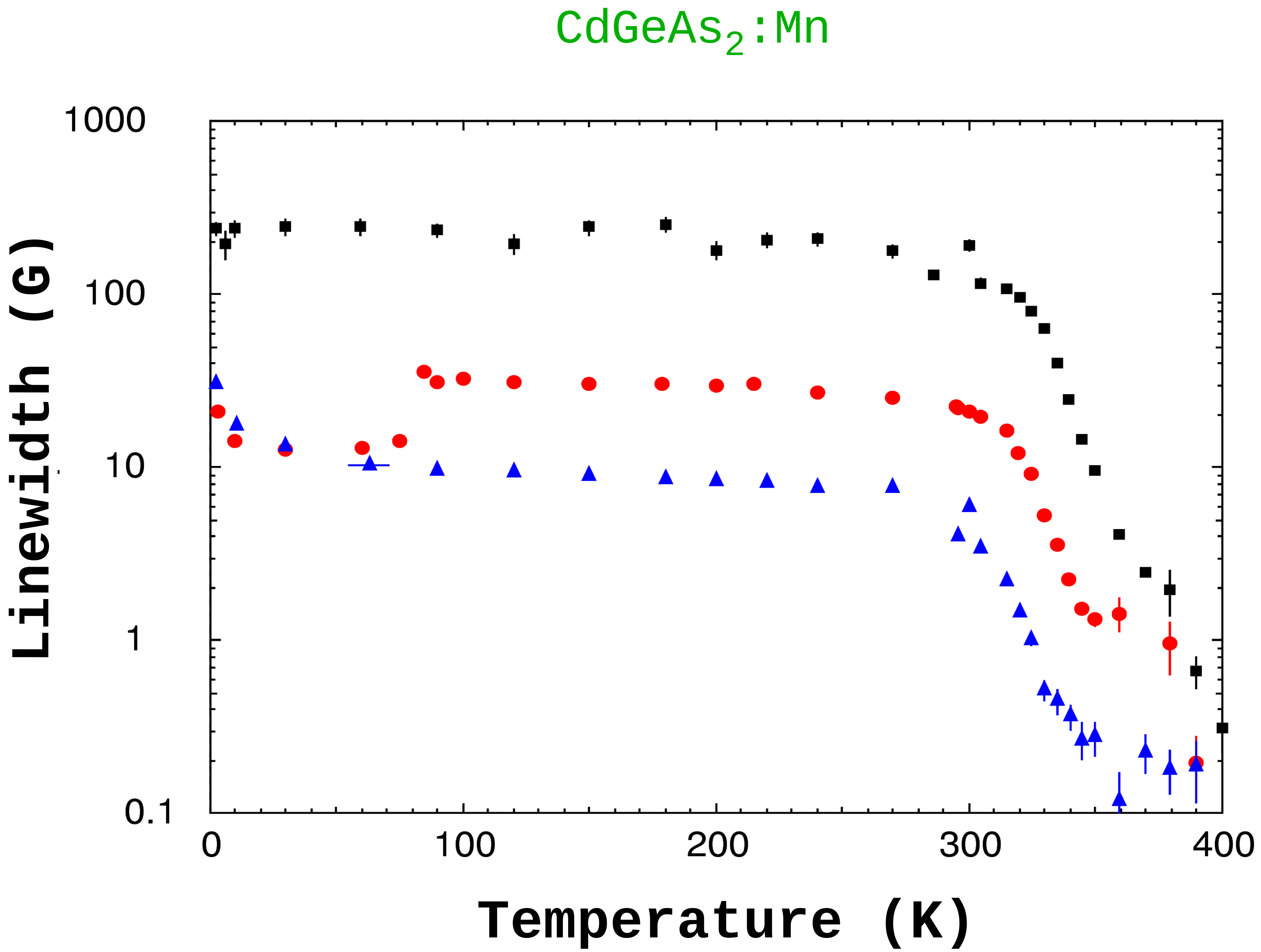
Magnetic field which muon sees is lower than the external field



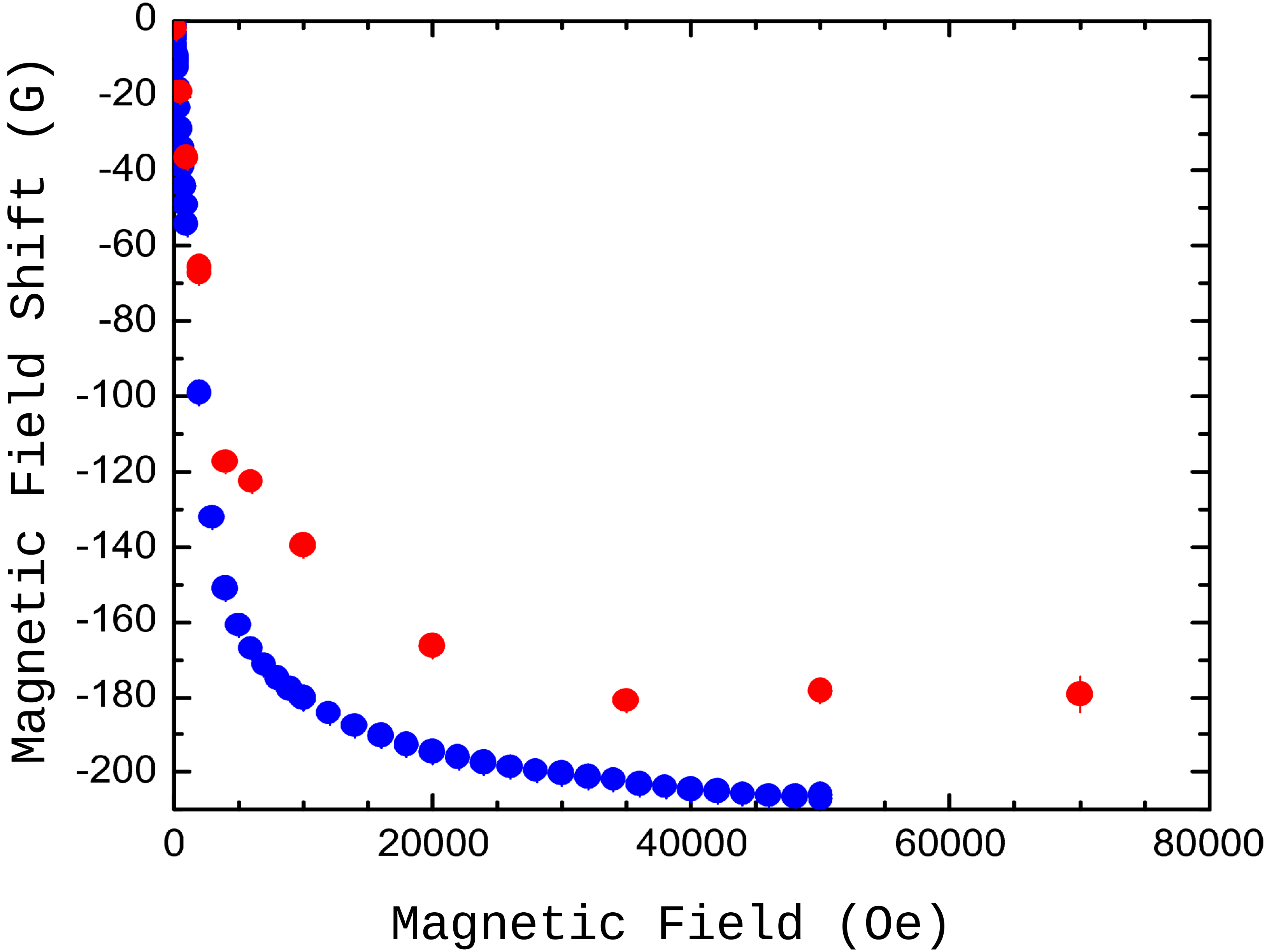
Ag
InSb:1.3%Mn
CdGeAs2:18%Mn
0
−100
−200
2
4
6
Magnetic Field [T]
Field Shift w/r Reference[G]



$CdGeAs_2$:Mn
Magnetic Field Shift (G)
1000
100
10
1
0
100
200
300
400
Temperature (K)


CdGeAs$_2$:Mn
Linewidth (G)
Temperature (K)
1000
100
10
1
0.1
0
100
200
300
400

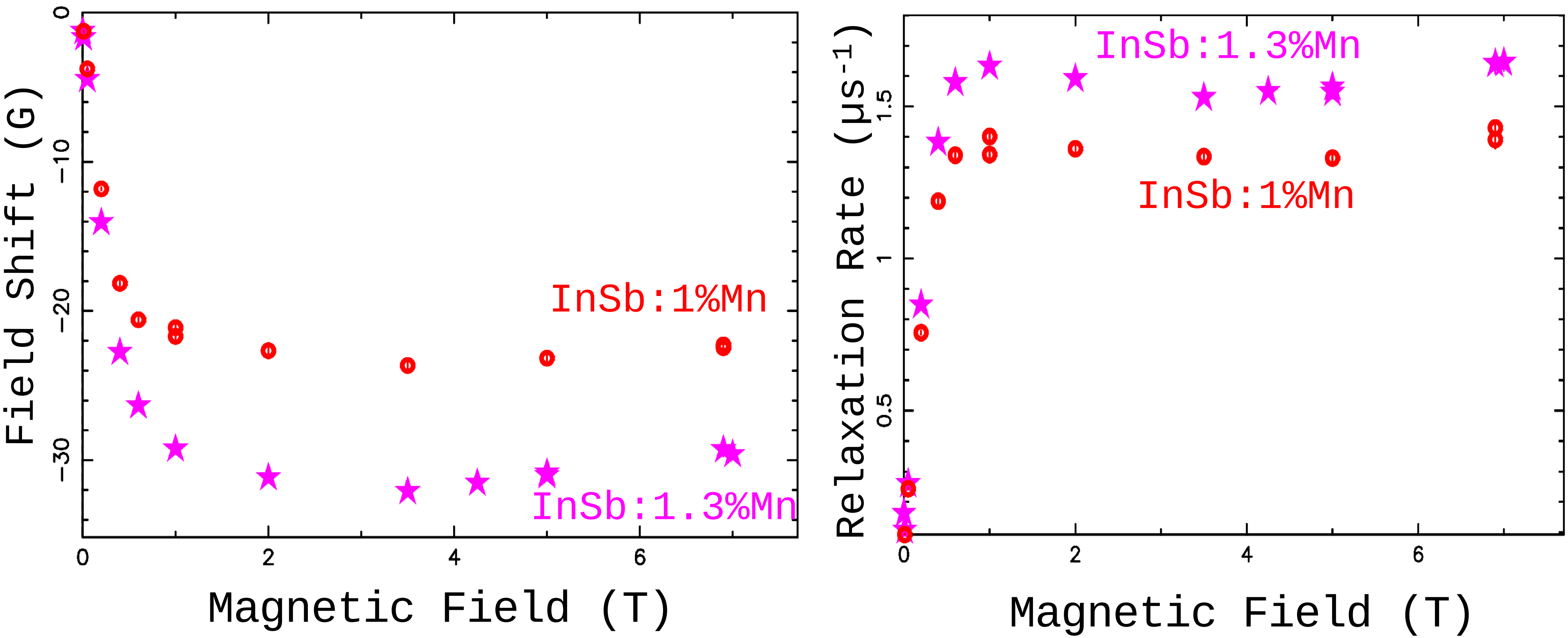
$CdGeAs_2$:18%Mn



Magnetic field inside the Lorenz sphere

$B_L - B_{dem} = 4\pi(1/3 - 0.805)m$

InSb:Mn

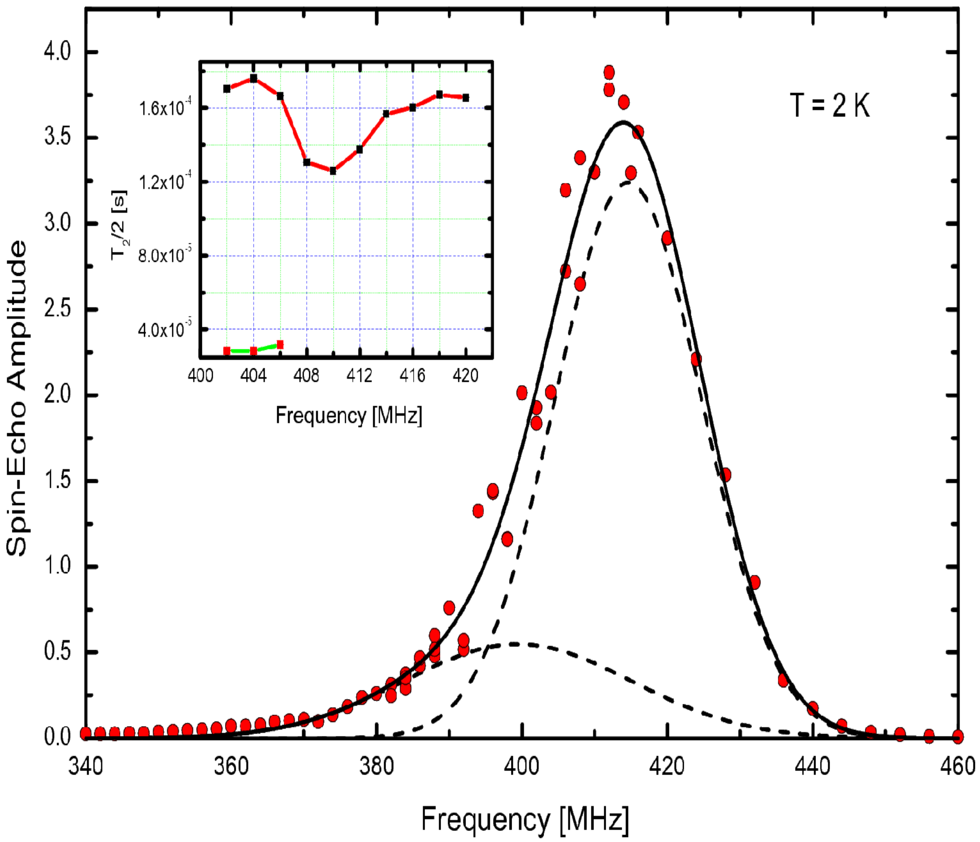


Line width (~10G) is several times less than the shift

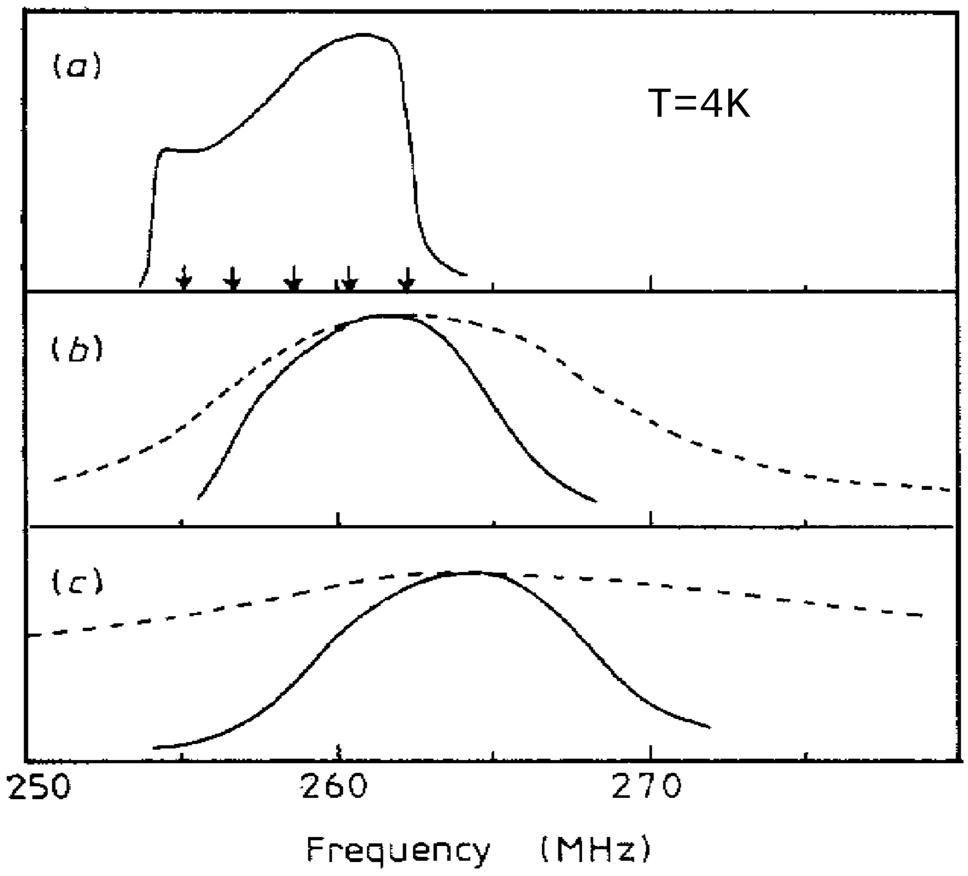
This fact is inconsistent with presence of MnSb inclusions as inclusions would produce a field distribution as broad as the shift

NMR on Mn^{55}

InSb:1%Mn

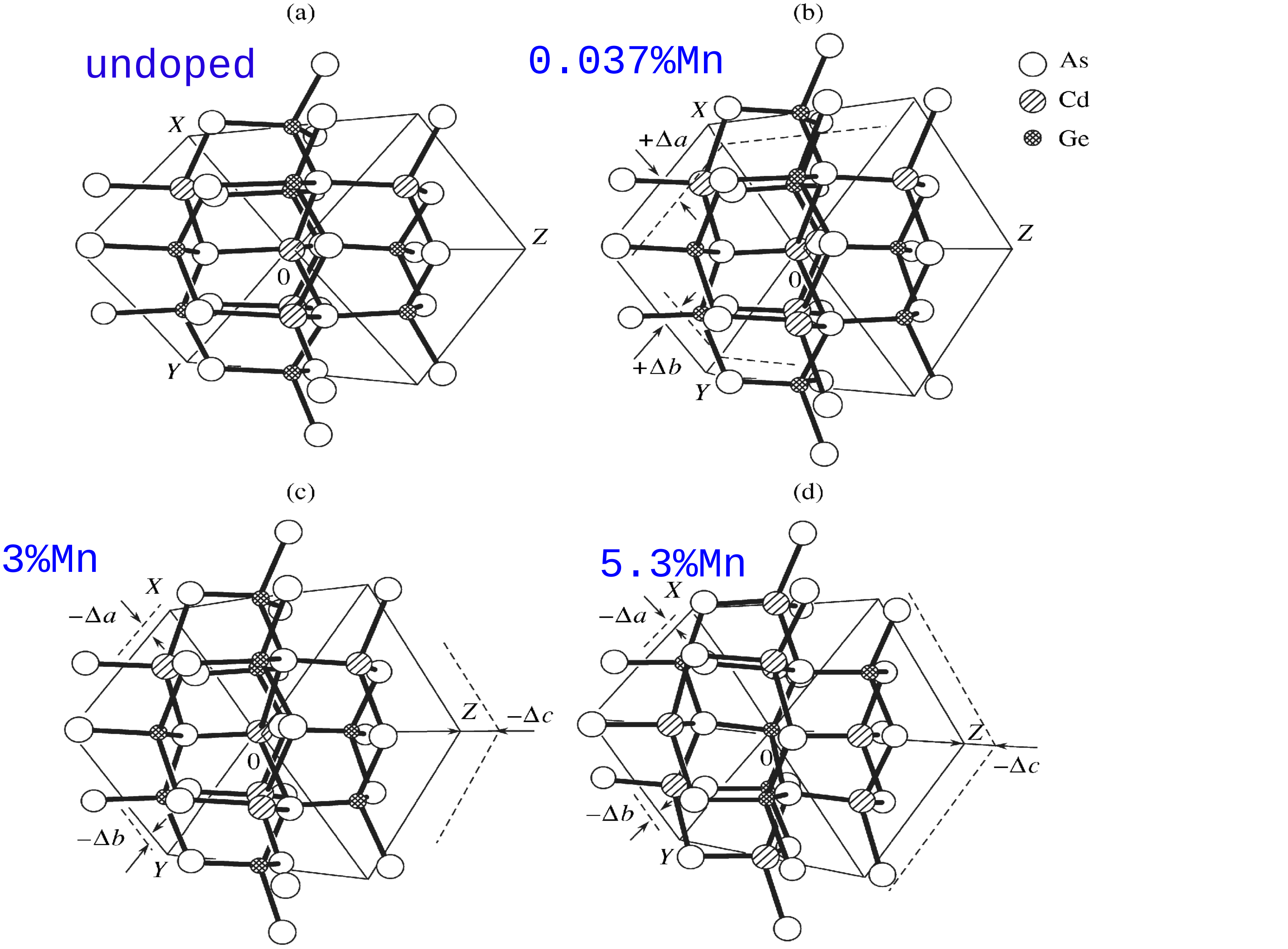


MnSb

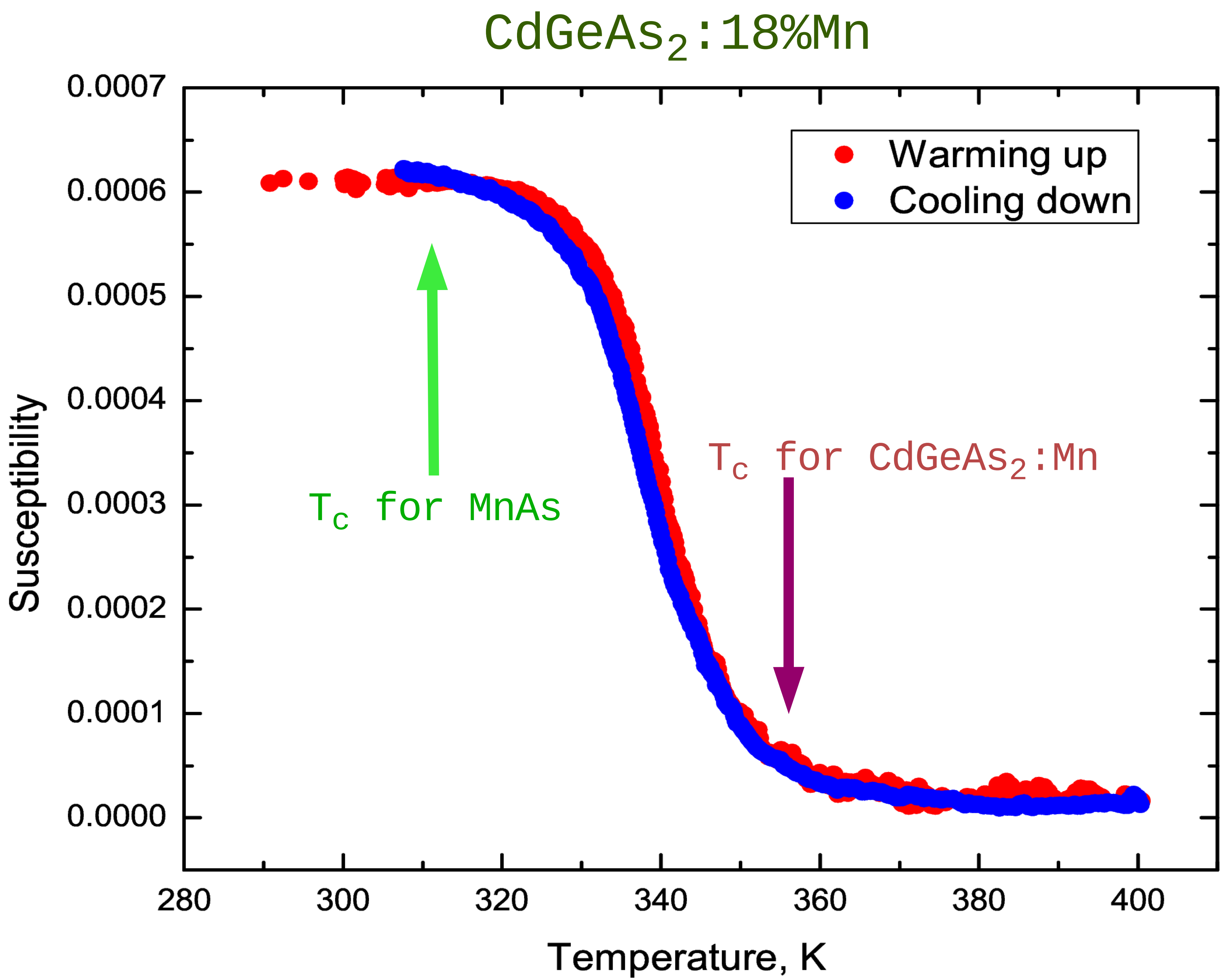


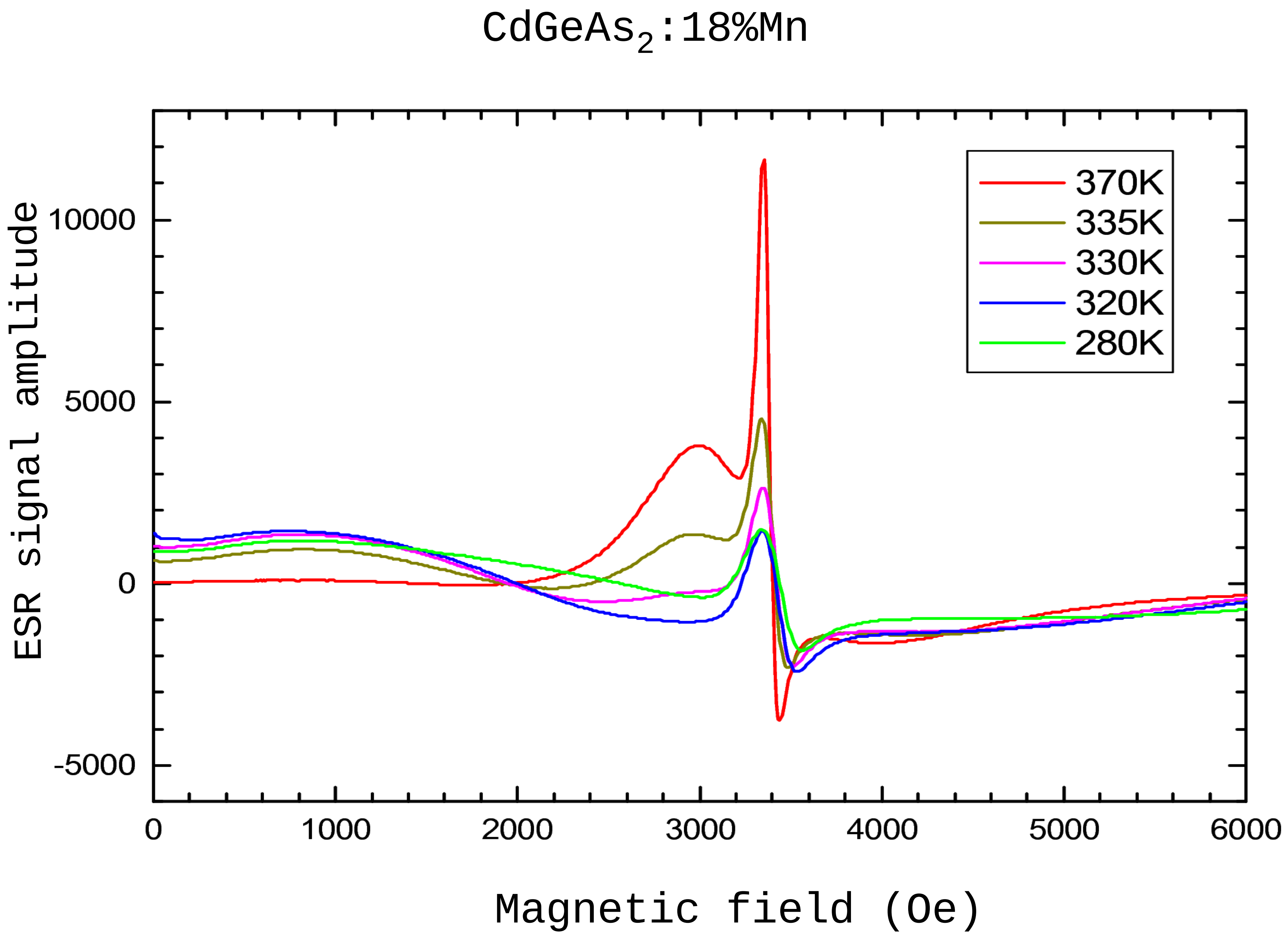
Le Dang et al., 1989

Effect of Mn doping on lattice parameters of $CdGeAs_2$

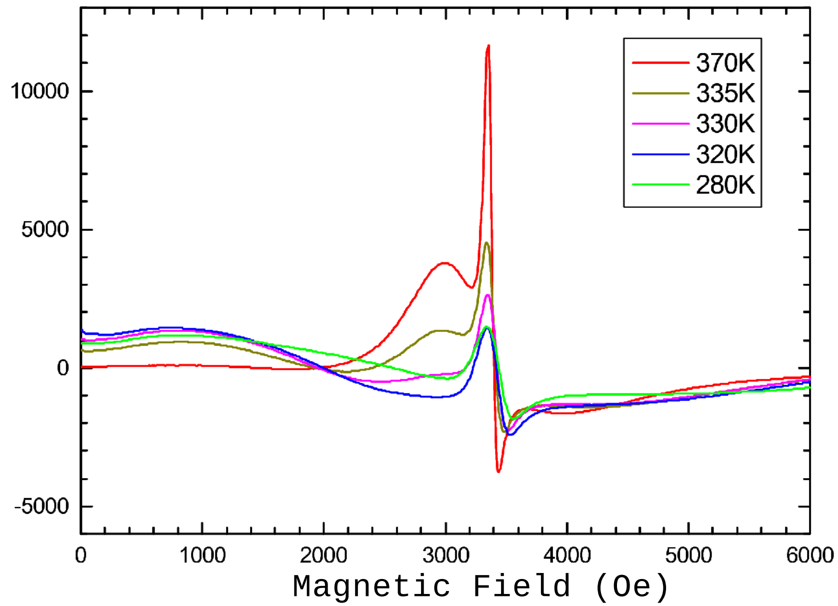


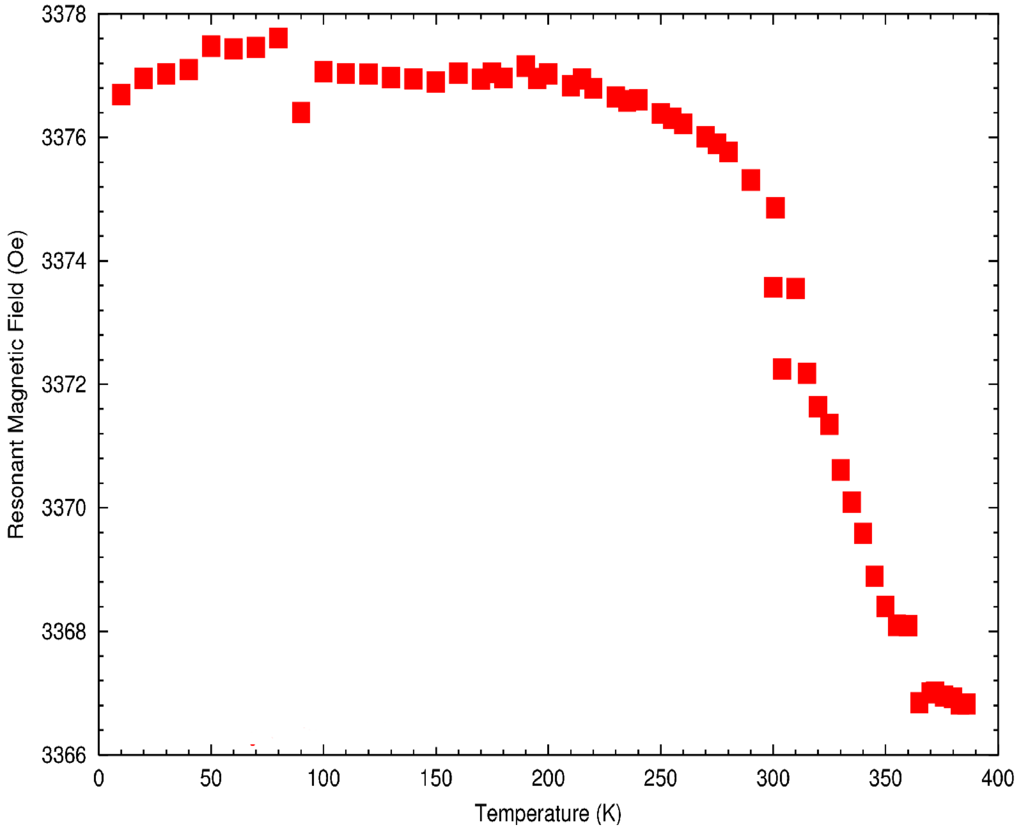
Changing of lattice parameters is inconsistent with significant amount of MnAs

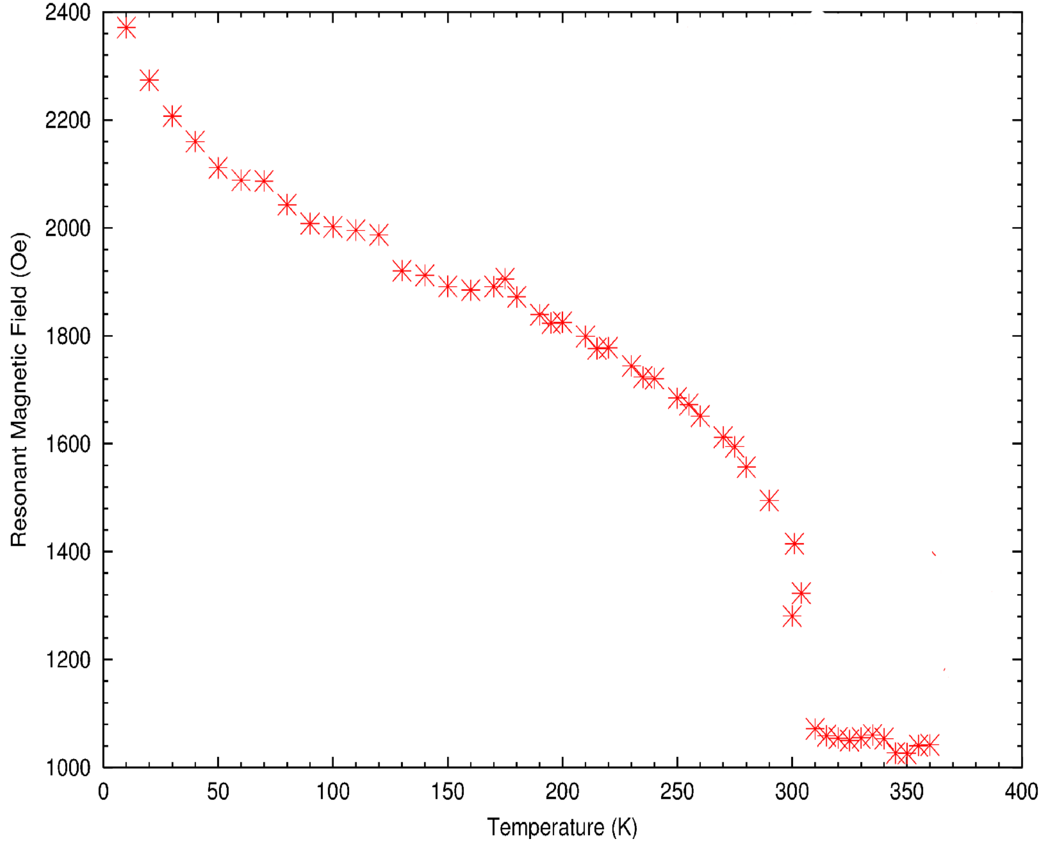

CdGeAs$_2$:18%Mn
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0.0000
Susceptibility
280
300
320
340
360
380
400
Temperature, K
Warming up
Cooling down
T$_c$ for MnAs
T$_c$ for CdGeAs$_2$:Mn



CdGeAs2:18%Mn
370K
335K
330K
320K
280K
ESR signal amplitude
10000
5000
0
-5000
0
1000
2000
3000
4000
5000
6000
Magnetic field (Oe)

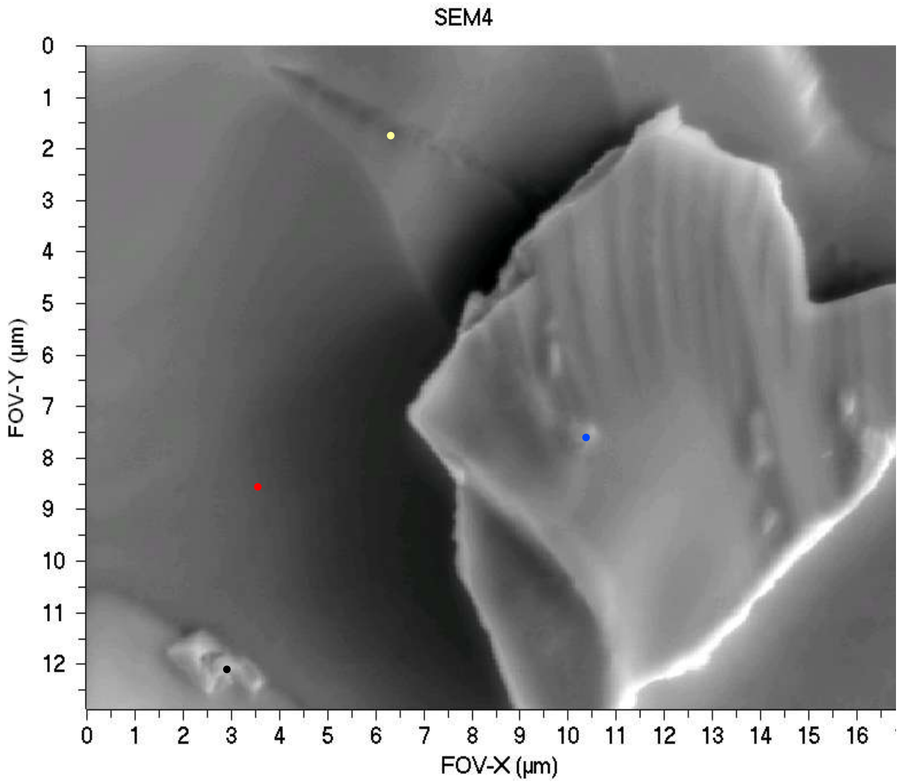

370K
335K
330K
320K
280K
10000
5000
0
-5000
0
1000
2000
3000
4000
5000
6000
Magnetic Field (Oe)


Resonant Magnetic Field (Oe)
3378
3376
3374
3372
3370
3368
3366
0
50
100
150
200
250
300
350
400
Temperature (K)

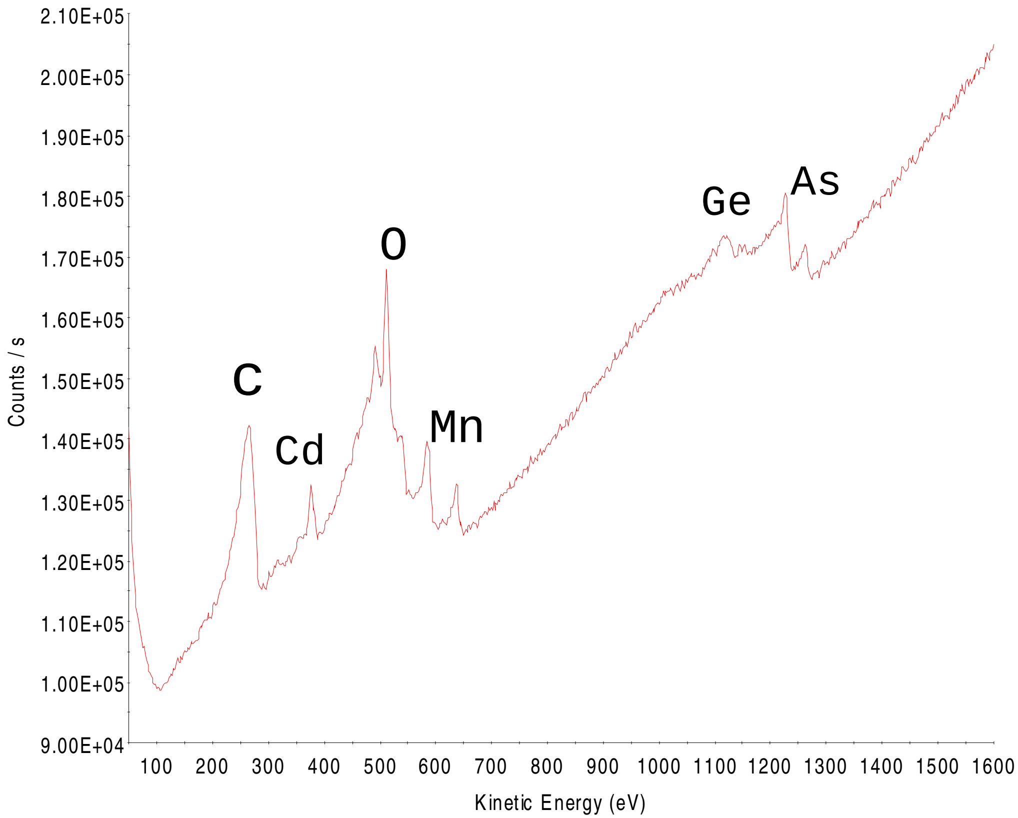

Resonant Magnetic Field (Oe)
2400
2200
2000
1800
1600
1400
1200
1000
0
50
100
150
200
250
300
350
400
Temperature (K)

$CdGeAs_2$:36%Mn

Scanning Electron Microscopy (SEM)

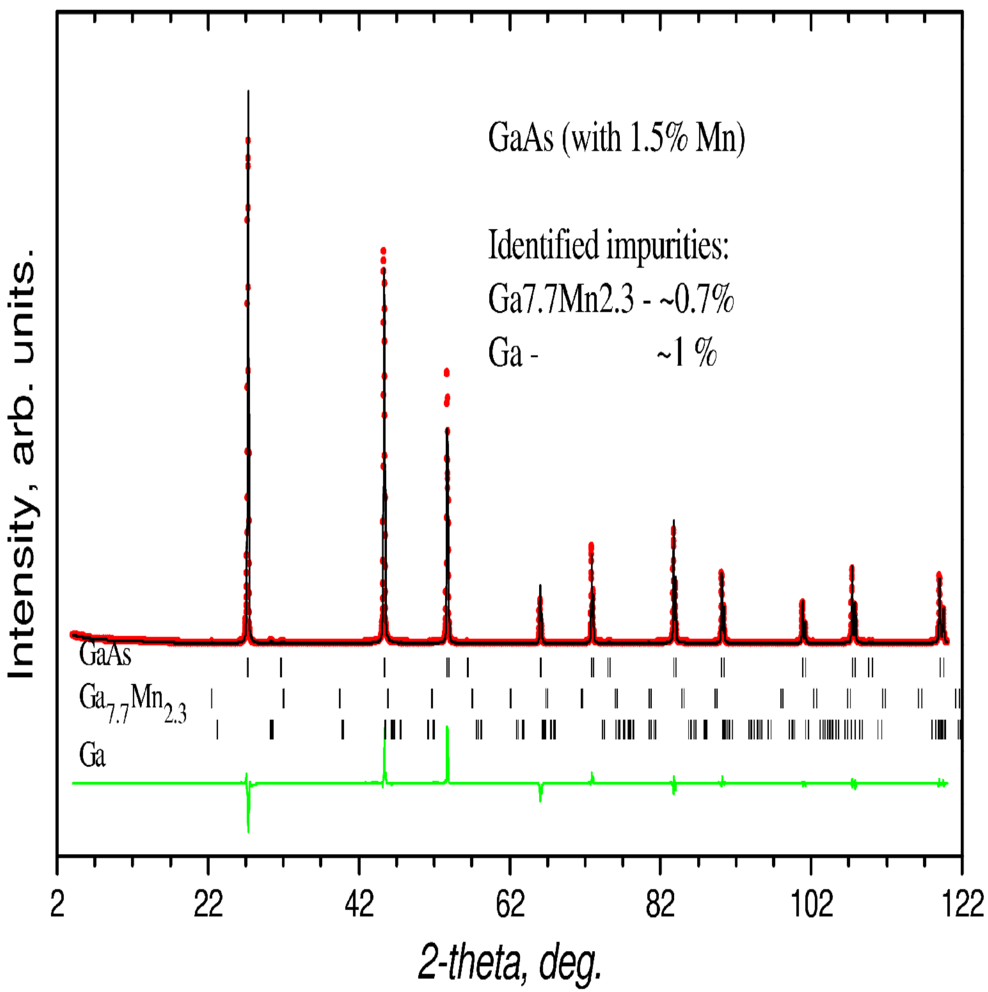


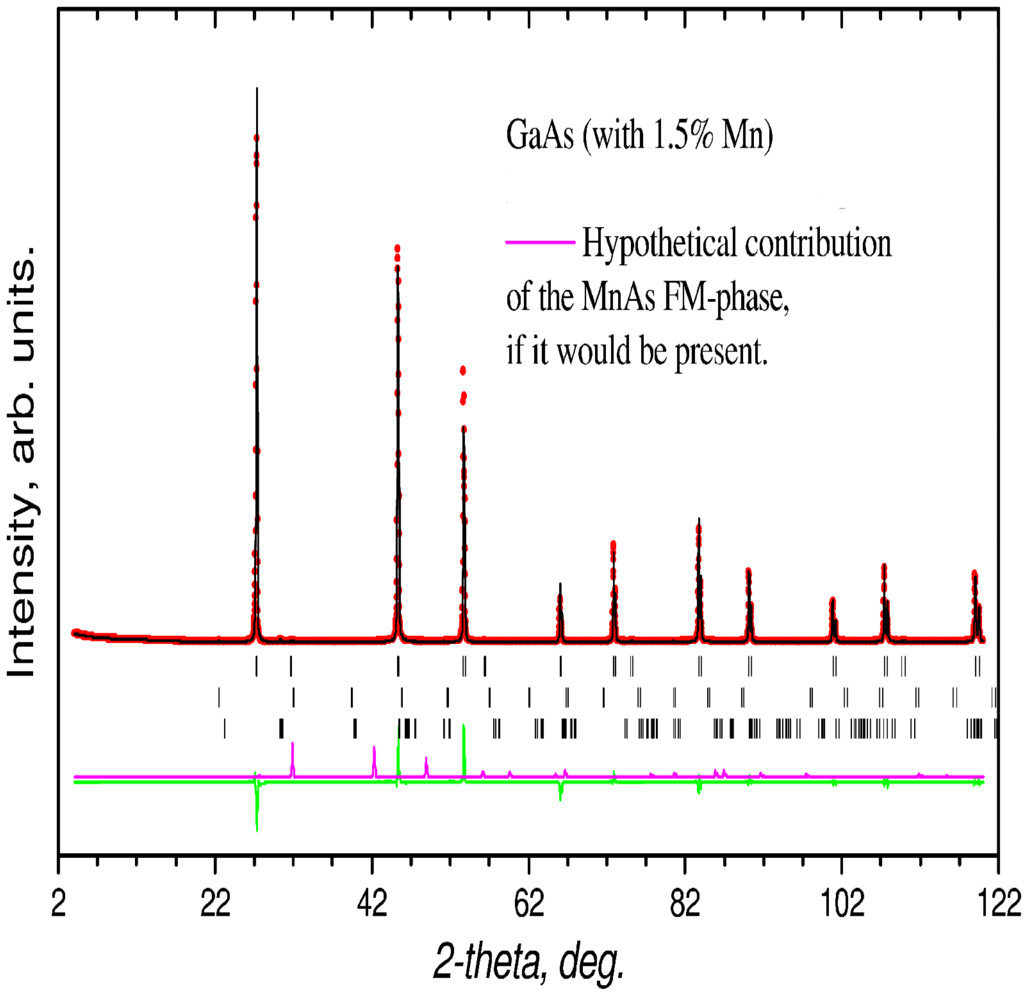
Auger Electron Spectroscopy (AES)



GaAs:1.5%Mn

XRD





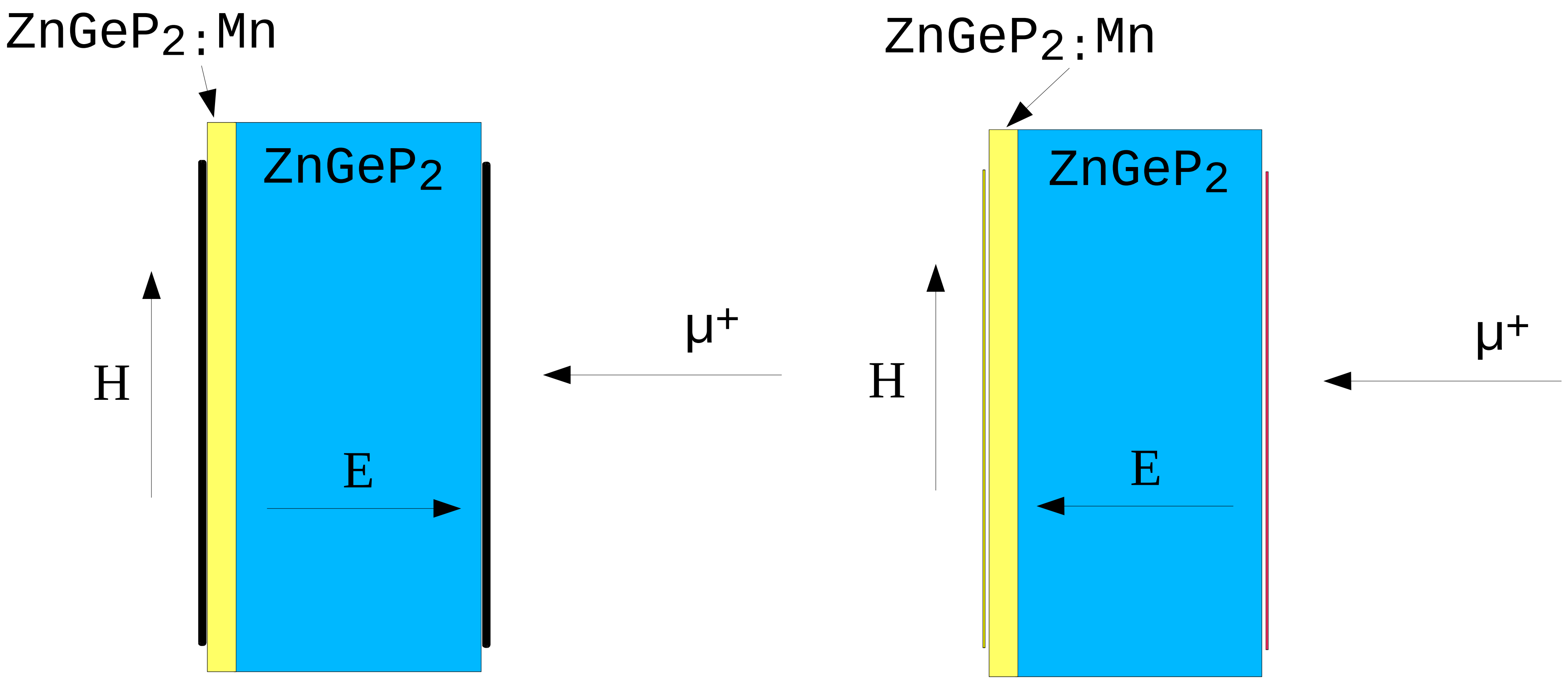
Conclusions

- We found magnetic field shift inside our samples suggesting bulk FM
- This FM is incosistent with mere presence of MnAs or MnSb inclusions

Sample characterization:

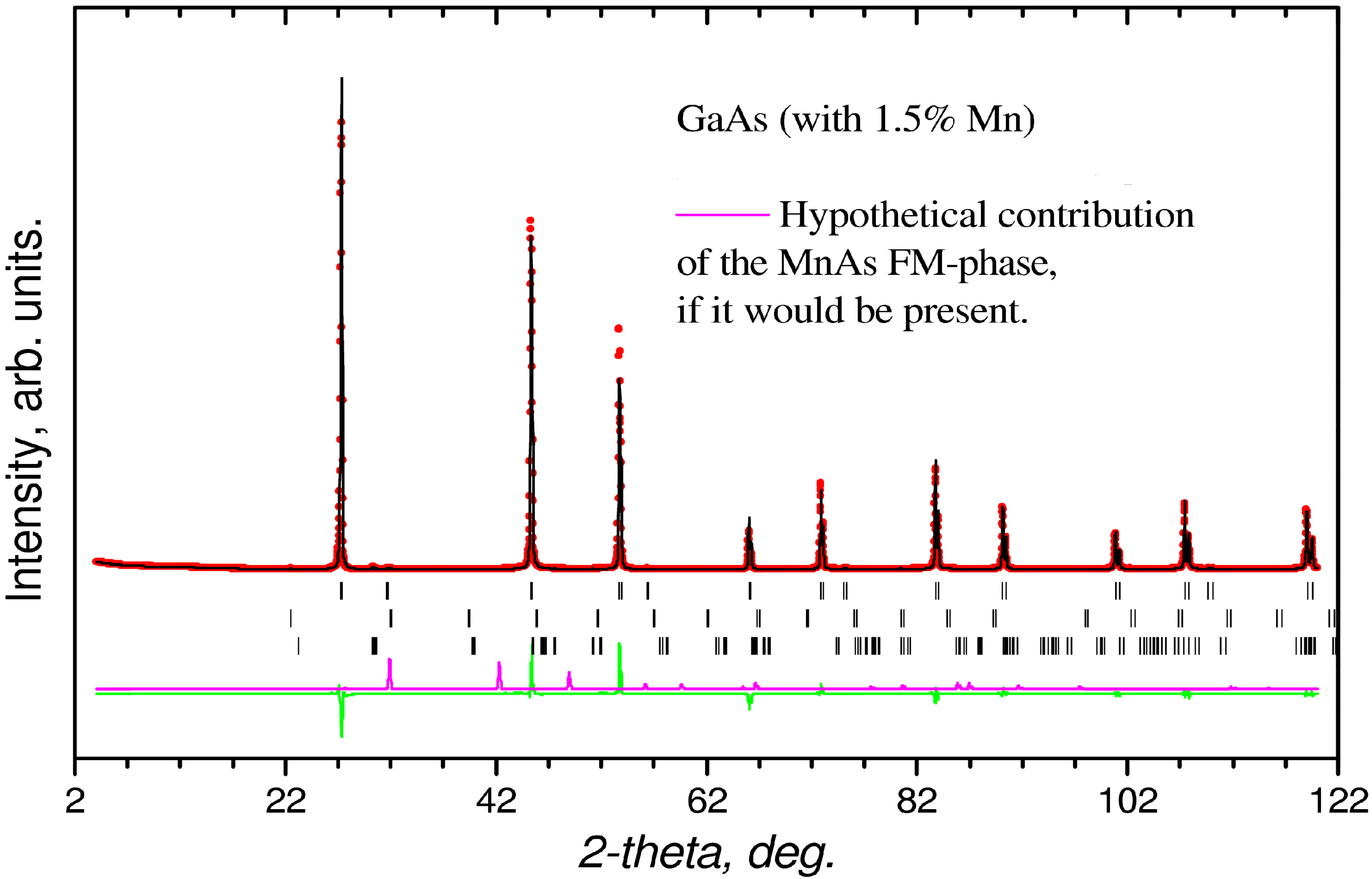
X-ray diffraction (PSI, Switzerland)
Auger electron spectroscopy (UBC)
atomic force microscopy (Nottingham, UK)
NMR (Parma, Italy)
ESR (Parma, PSI)
susceptibility (Moscow)
magnetization (Moscow, Switzerland)
galvanomagnetic (PSI, Moscow): resistivity
magnetoresistance
Hall effect

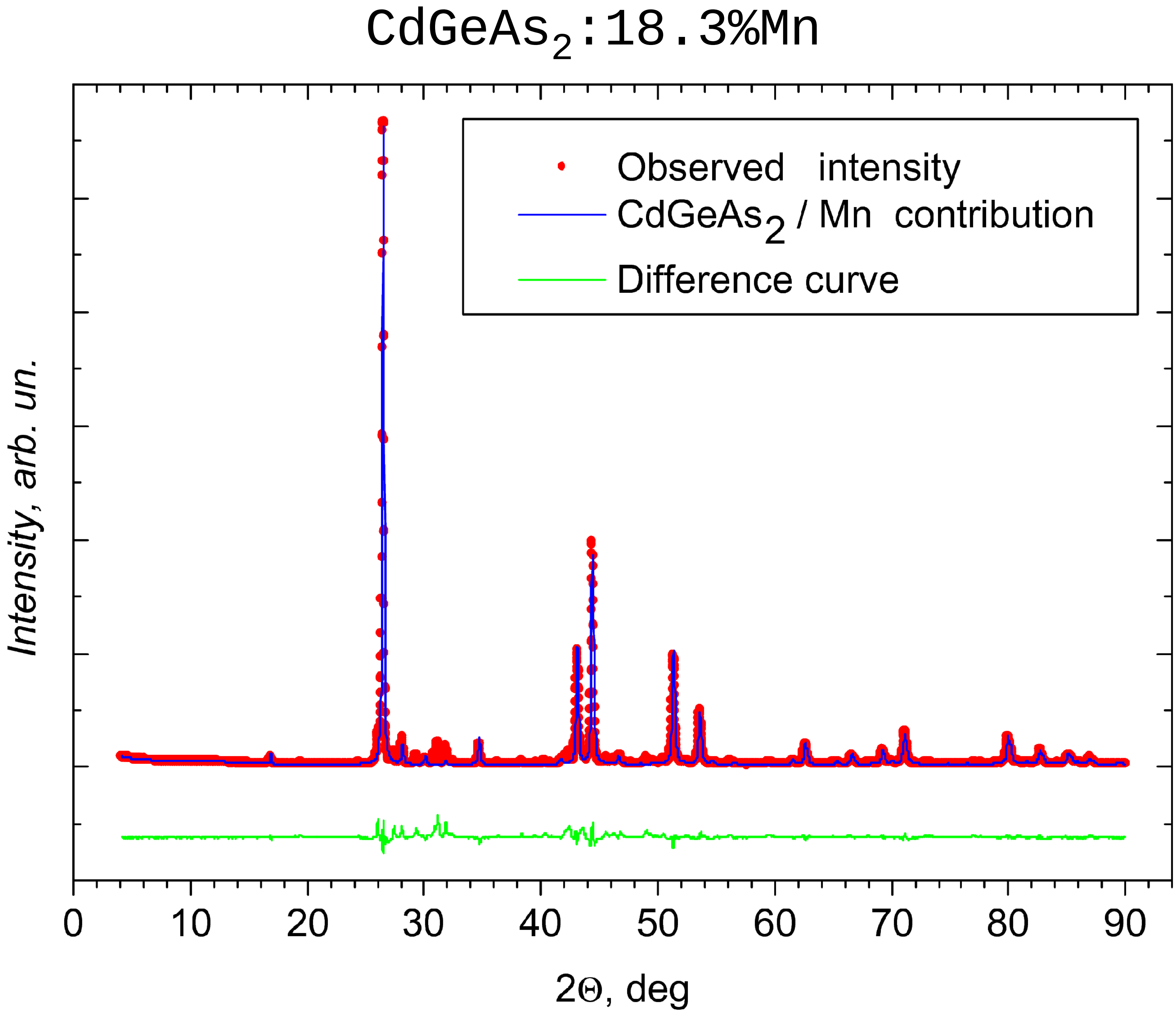
Additional request: E-field experiment (12 shifts)



Measurements of the magnetic field shift as a function of
a. amplitude of electric field (4 shifts)
b. frequency of the electric field switching (2 shifts)

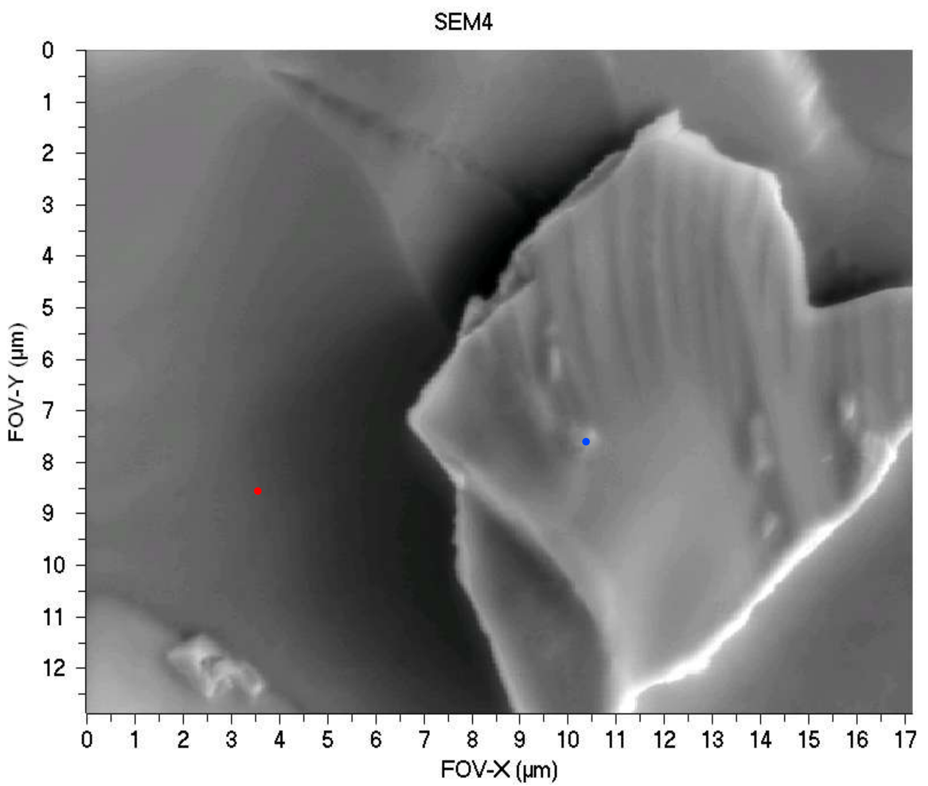
First we measure pure $ZnGeP_2$ (6 shifts)
then $ZnGeP_2$:Mn (6 shifts)


GaAs (with 1.5% Mn)
Hypothetical contribution of the MnAs FM-phase, if it would be present.
Intensity, arb. units.
2
22
42
62
82
102
122
2-theta, deg.

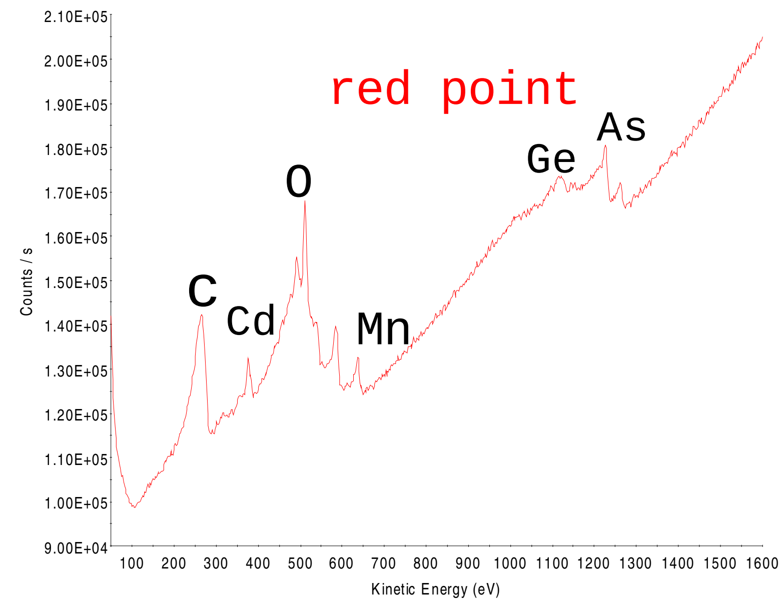

CdGeAs2:18.3%Mn
Observed intensity
CdGeAs2 / Mn contribution
Difference curve
Intensity, arb. un.
0
10
20
30
40
50
60
70
80
90
2Θ, deg

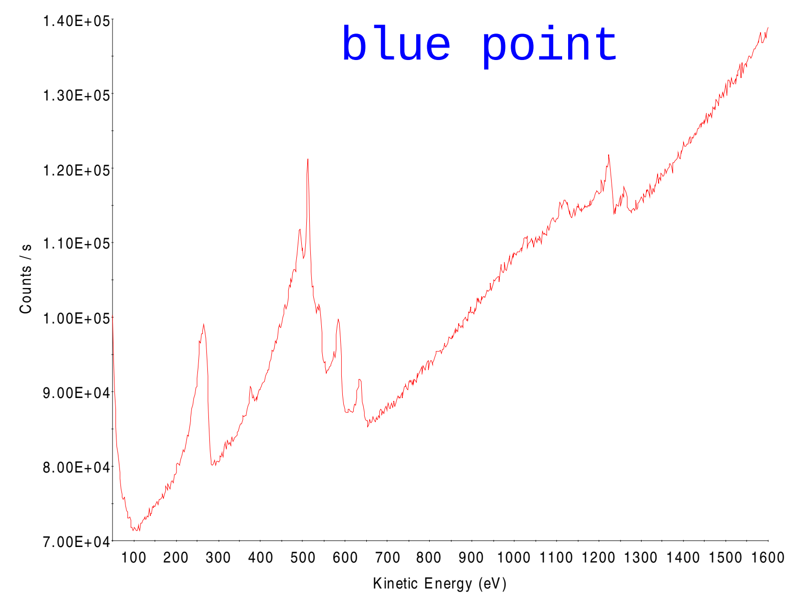
$CdGeAs_2$:36%Mn

Scanning Electron Microscopy (SEM)



Auger Electron Spectroscopy (AES)

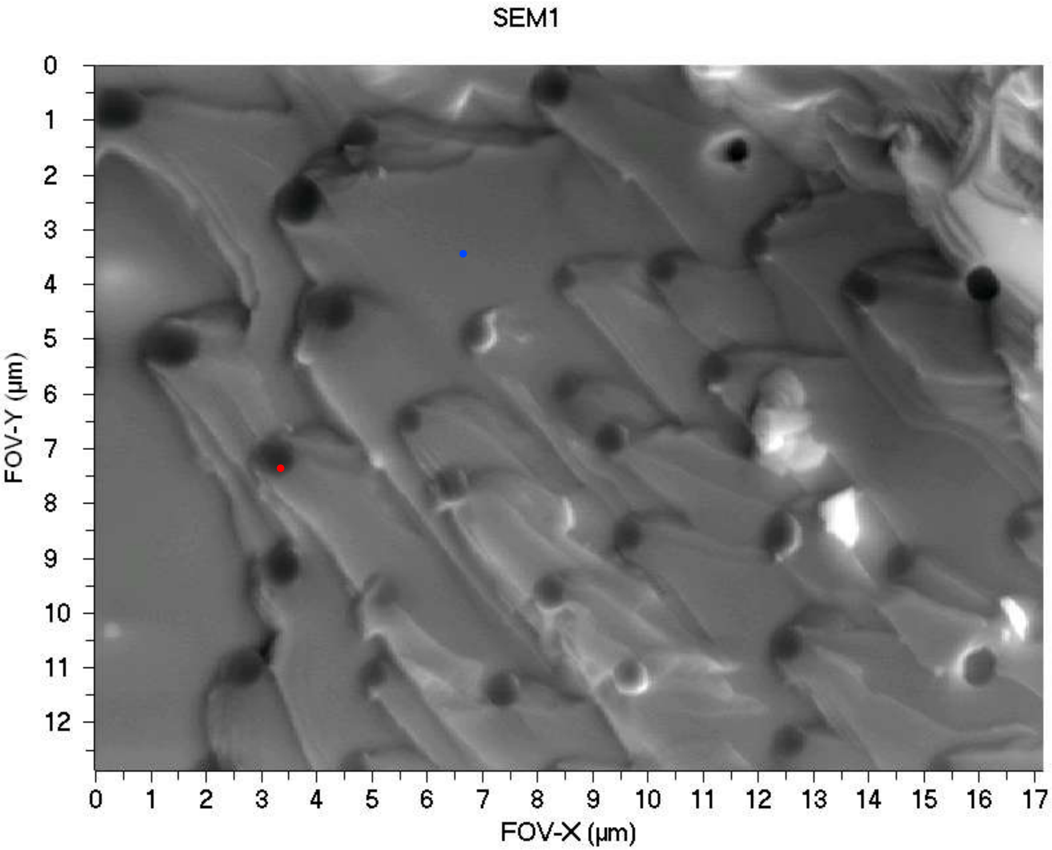


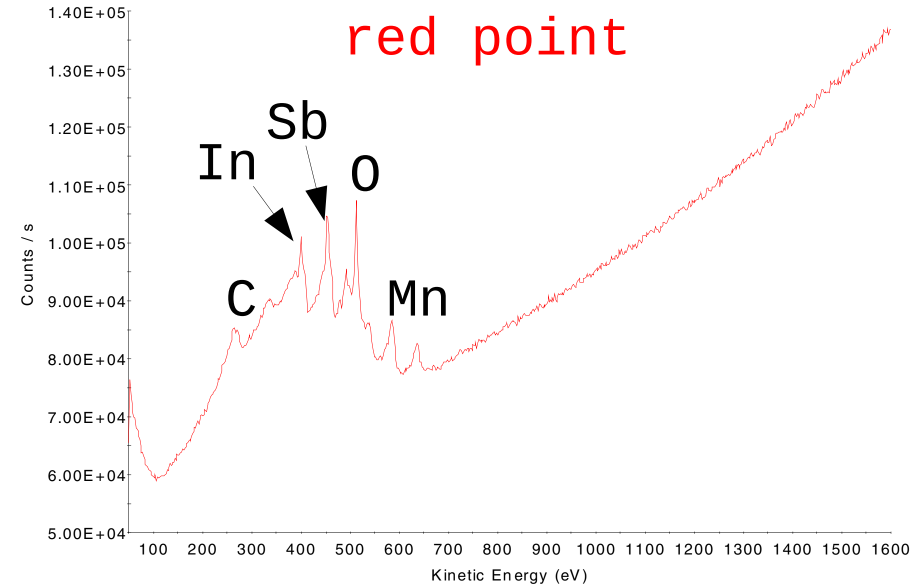


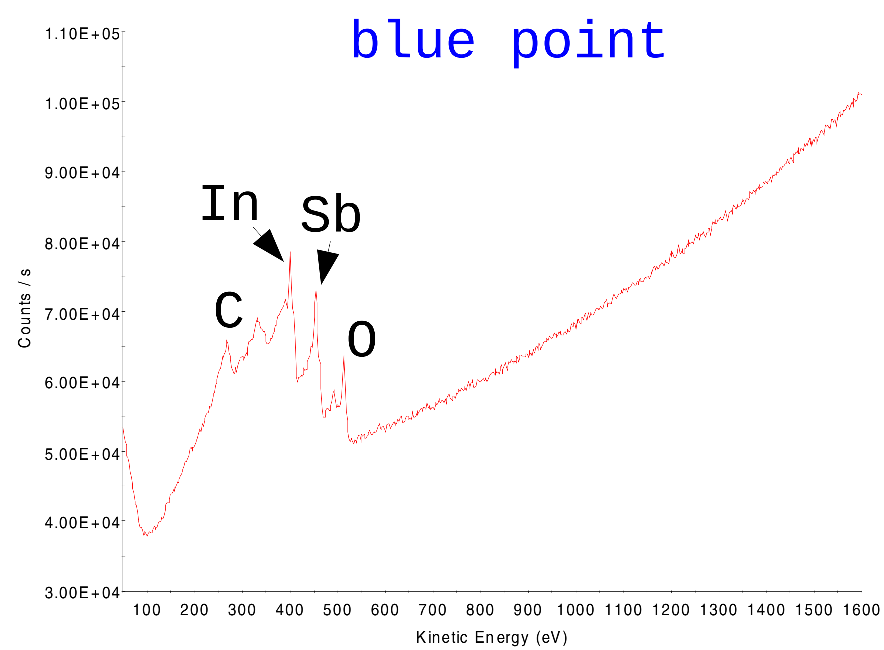
InSb:2%Mn

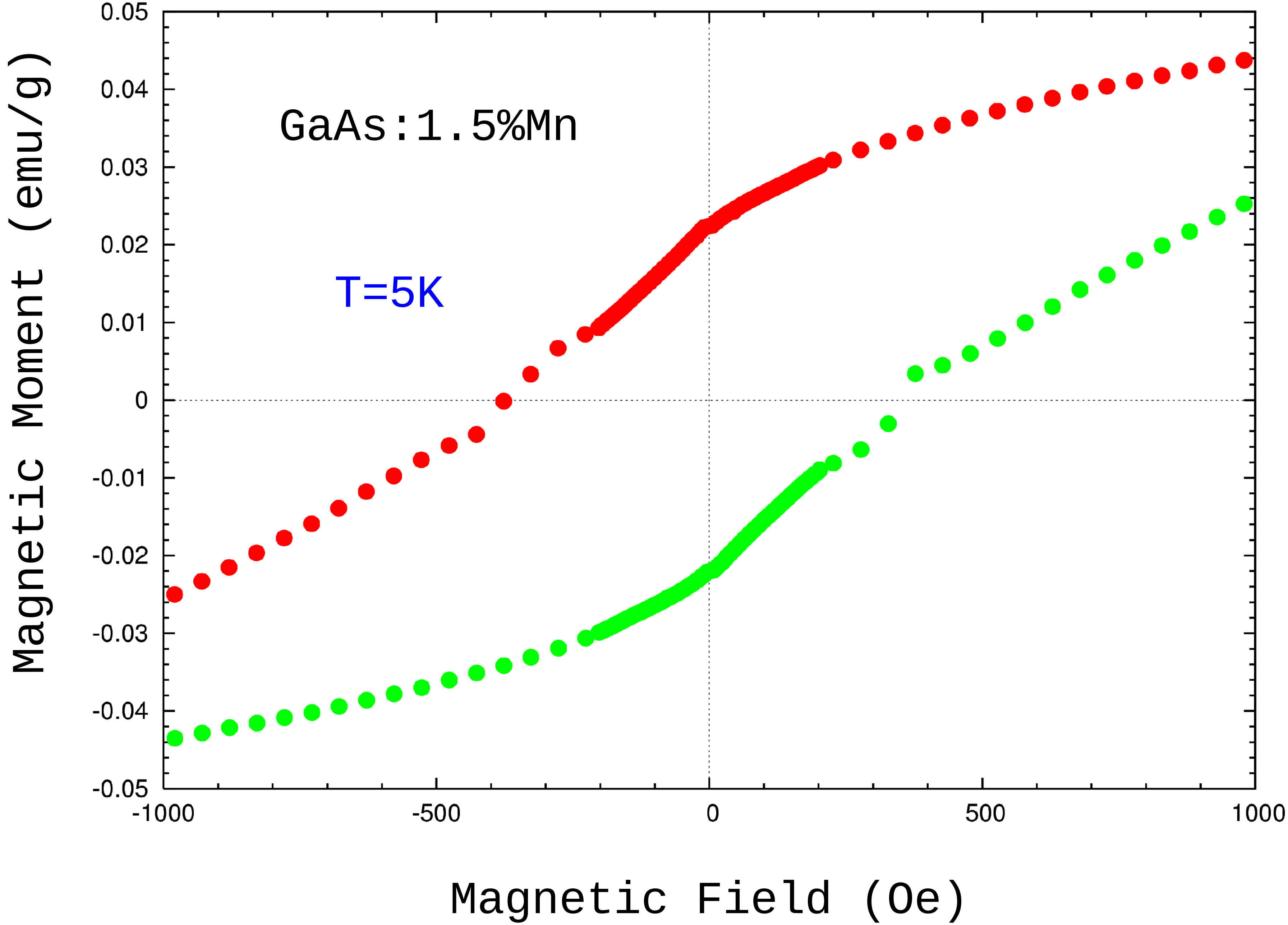
Auger Electron Spectroscopy (AES)

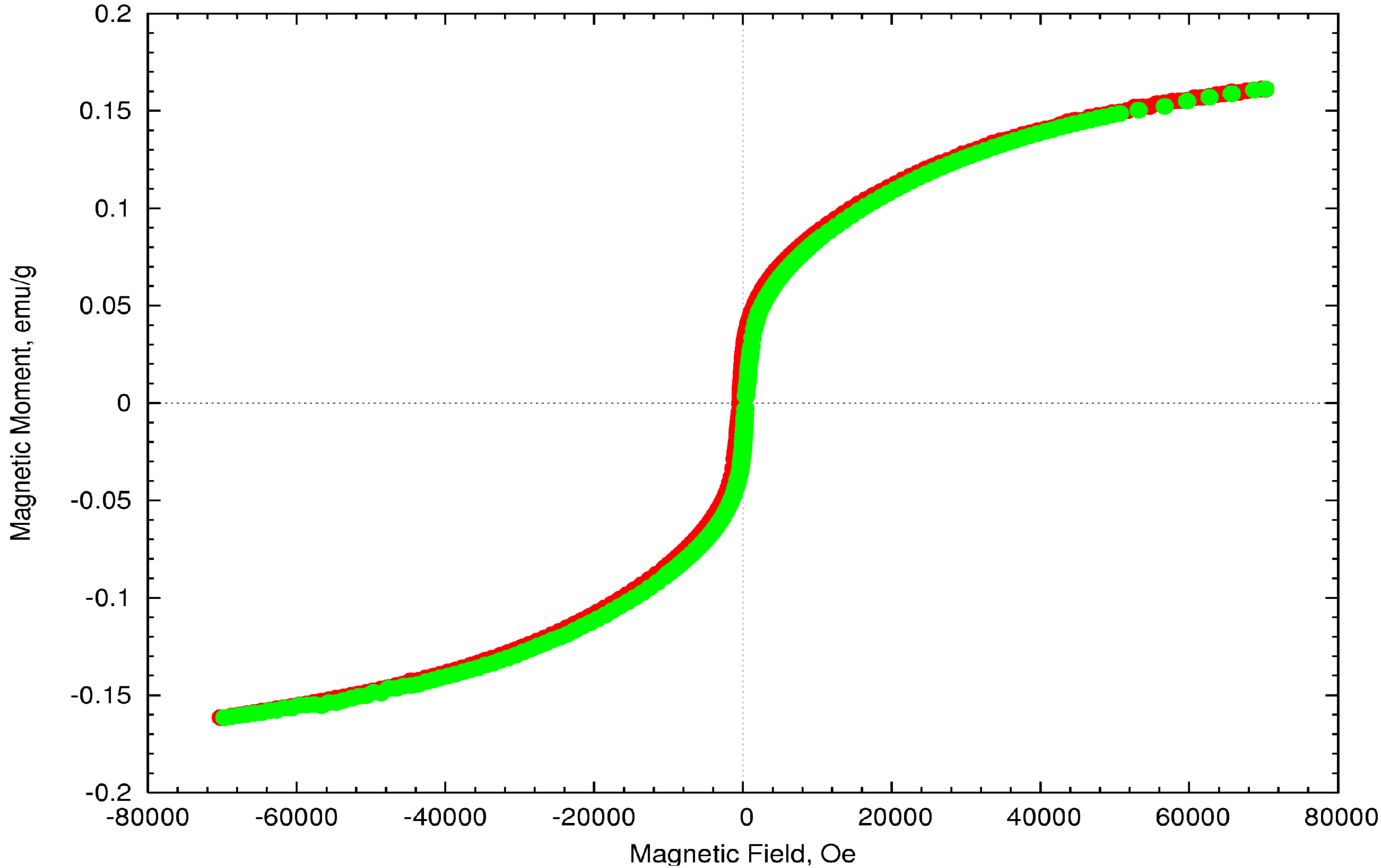
Scanning Electron Microscopy (SEM)








GaAs:1.5%Mn
T=5K
Magnetic Moment (emu/g)
Magnetic Field (Oe)
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
-1000
-500
0
500
1000



0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
Magnetic Moment, emu/g
-80000
-60000
-40000
-20000
0
20000
40000
60000
80000
Magnetic Field, Oe

$CdGeAs_2$:Mn T_C=355K