Growth and Characterization of Magnetic 6.1 Å Materials

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Collaborators

University at Buffalo

- **X. Chen, M. Cheon and S. Wang:** ***growth***
- **K.P. Mooney, F. Gasparini:** ***magnetism***
- **T. Yeo, F. Lehmann, M.H. Na, B.D. McCombe:** ***transport/magneto-transport***
- **G. Kioseoglou, Y.L. Soo, S. Kim, Y.H. Kao:** ***x-ray***
- **M. Furis, G. Itskos, G. Kioseoglou, A. Petrou:** ***optics and magnetooptics***
- **G. Comanescu:** ***IR spectroscopy***

Notre Dame: **Y. Sasaki, X. Liu, J.K. Furdyna:** ***growth***

Penn. State University: **P. Schiffer:** ***SQUID***

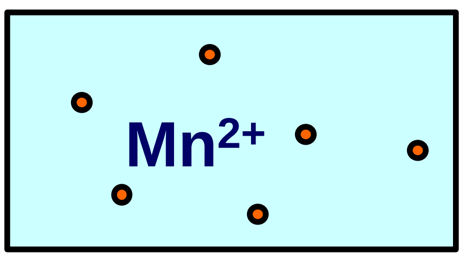
NRL: **J. Meyer:** ***theory***

$III_{1-x}Mn_xV$ Materials
(InMnAs and GaMnAs)

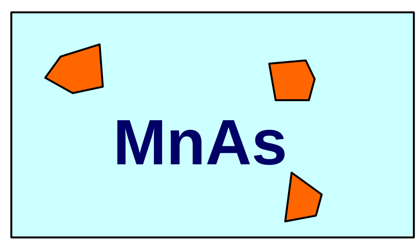
- **Started by H. Munekata and H. Ohno (late 80s)**
- **$III_{1-x}Mn_xV$'s without precipitates (grown below 300°C for GaMnAs)**

- **All $III_{1-x}Mn_xV$'s are heavily p-type**

- **Mn is a dopant (acceptor) in III-V's; not desirable for alloying**



T_{growth} < 300°C (GaMnAs)



T_{growth} > 300°C (GaMnAs)

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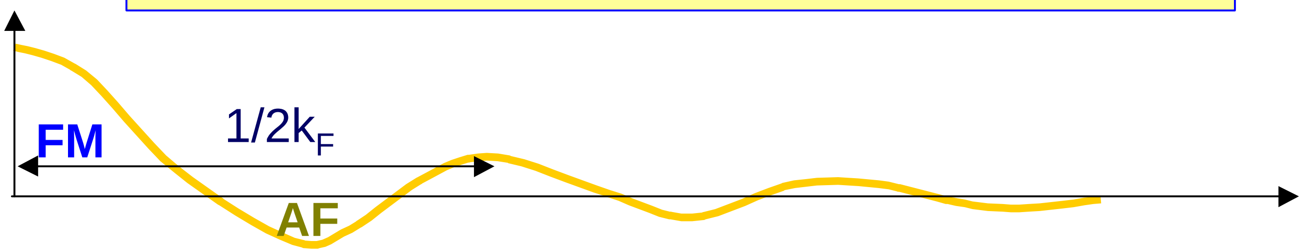
MAGNETIC INTERACTION

RKKY (Carrier Mediated Exchange)



Free carrier – Mn^{++} interaction can be either ferromagnetic or antiferromagnetic

Important parameters

- **Mn-Mn spacing and carrier density**

Things to consider

- electronic, transport, optical and *magnetic* properties

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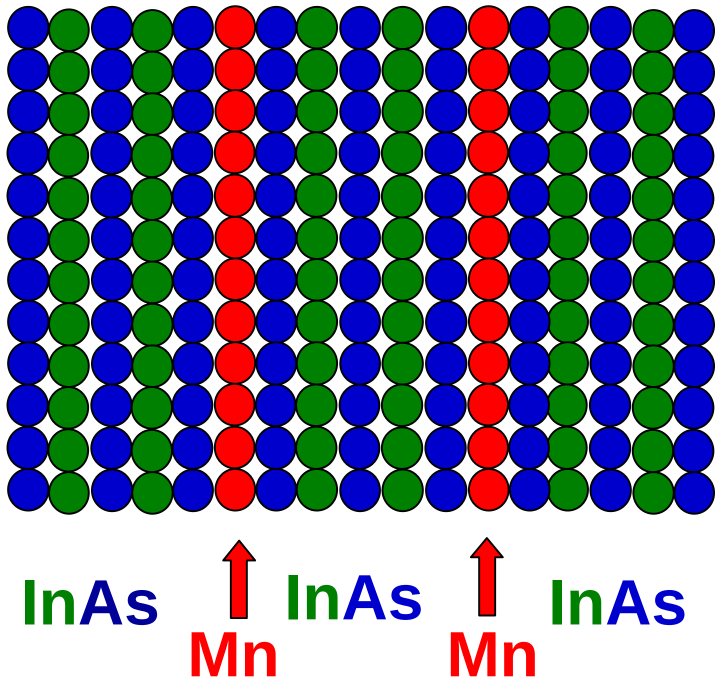
APPROACH



III-V/Mn Digital Alloys

- Controlled Mn spacing in the growth direction
- δ-Doping

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Magnetic 6.1 Å Materials

"Multifunction" + Spin (Light) Polarization

- **IR detectors and light emitter**
- **Resonant tunneling diodes (RITDs)**
- **High Electron Mobility Transistors (HEMT's)**

6.1 Å Materials + Mn ➔ New Opportunities

- **Natural advantages**
- **Charge separation and induced magnetism**

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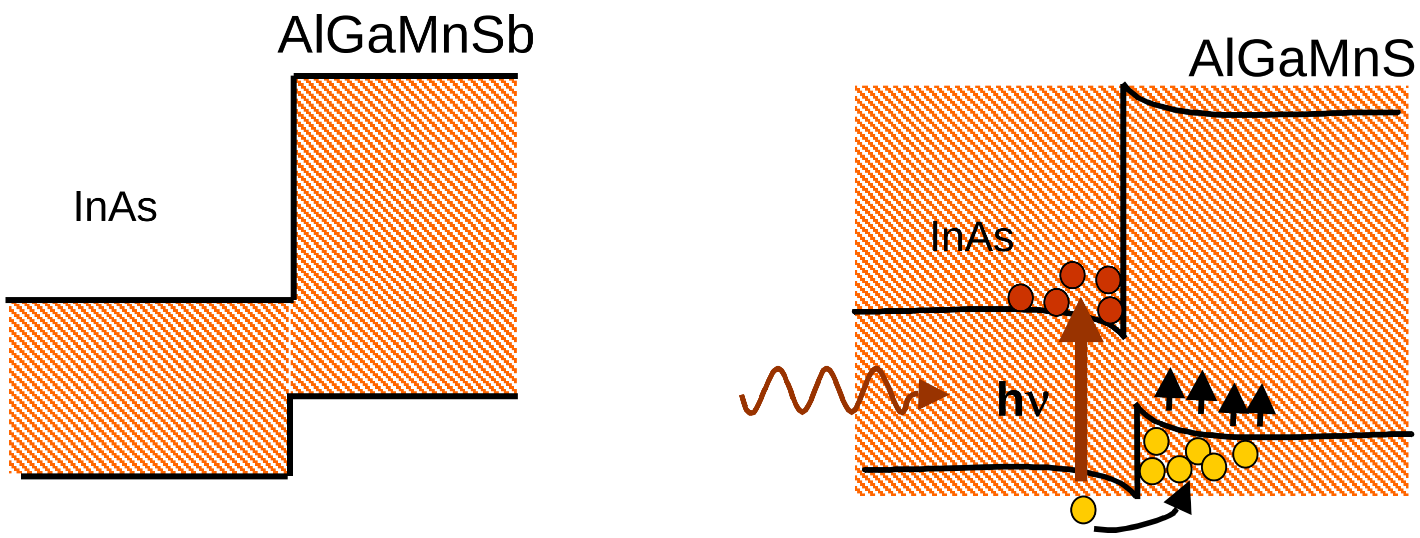
Photo(carrier)-induced Ferromagnetism

Type-II Band Alignment ➔ electron-hole separation
➔ control of hole concentration by either light or an applied electric field
• Mechanism for ferromagnetism is carrier-induced

Photo-induced ferromagnetism



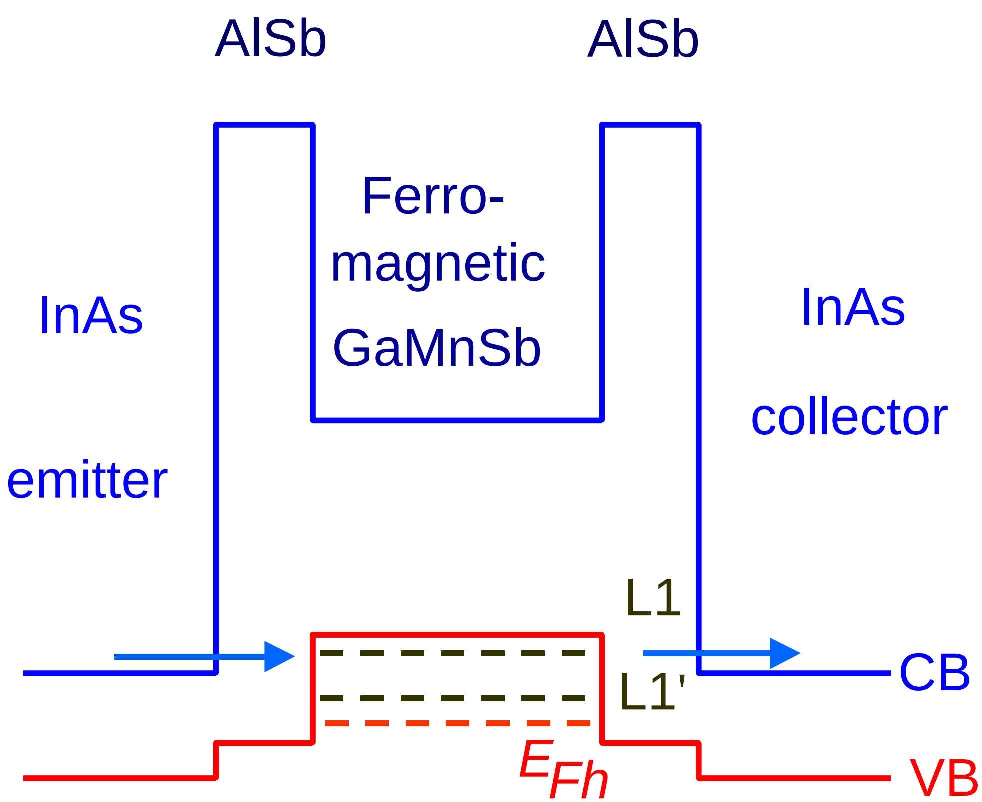
No Illumination

E_g (InAs) < hν < E_g (AlGaMnSb)

Munekata *et al*, PRL **78,** 4617 (1997) (InMnAs)

A DEVICE EXAMPLE

Ferromagnetic resonant interband tunnelling diode (FRITD)



- Spin splitting of the light hole level allows spin polarized tunneling
- Mostly electron transport
- Electrically tunable

J. Meyer and L.R. Ram-Mohan

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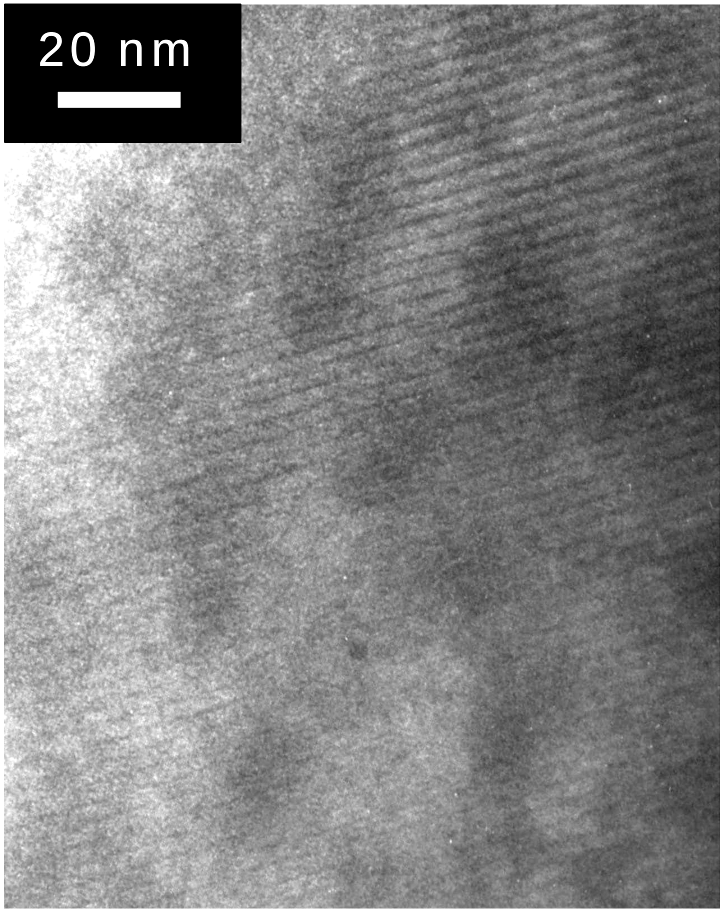
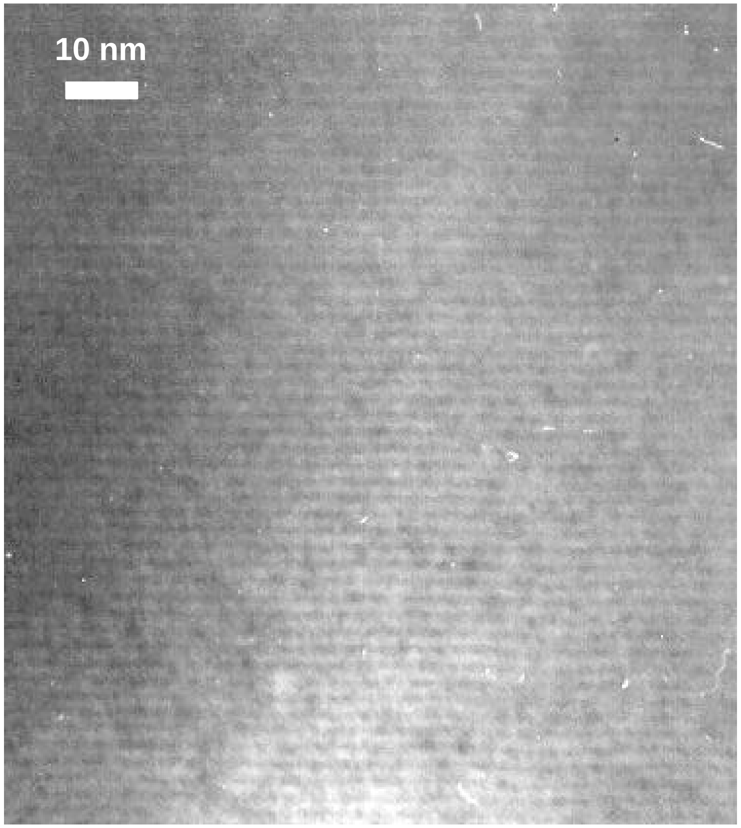
TEM of III-V/Mn Digital Alloys



GaSb (10 ML)/Mn (.5 ML)



GaAs (7 ML)/Mn (.5 ML)

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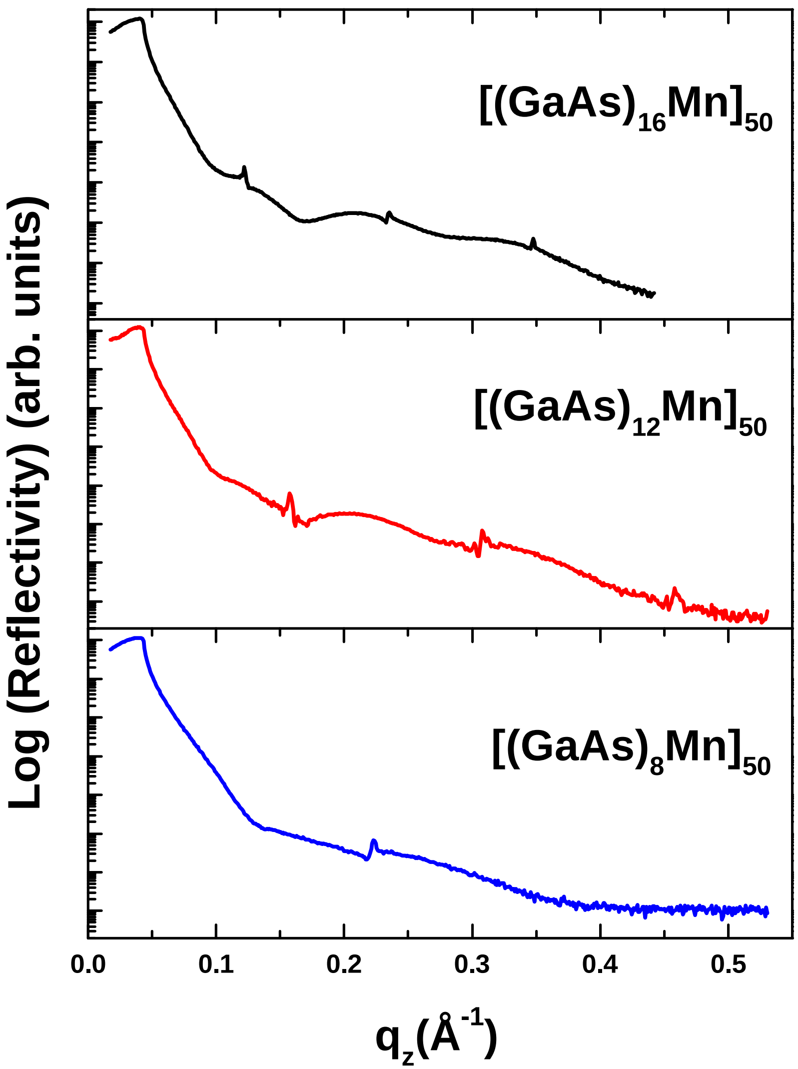
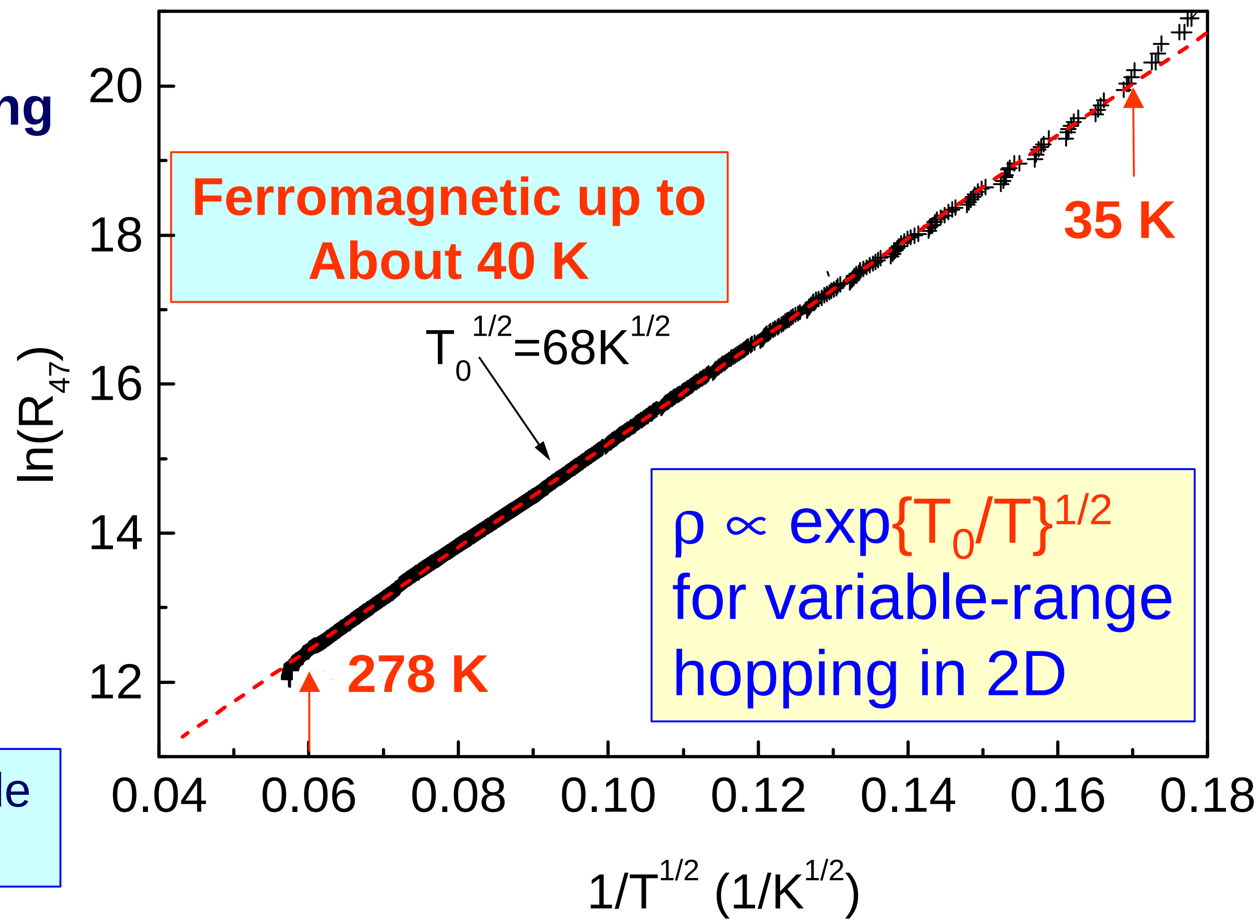
X-RAY REFLECTIVITY



- Periods of digital alloys from Bragg peaks agree well with thickness measured *in situ*
- Good structural quality

GaMnAs DIGITAL ALLOY (16 ML GaAs/0.5 ML Mn)

Samples are all insulating (resistance vs. temperature)



Behavior observed over wide temperature range

B.I. *Shklovskii and A.L. Efros, Electronic Properties of Doped Semicond., ed. M. Cardona, (1984).*

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GaAs/Mn DIGITAL ALLOYS

Current Status

- High resistivity
- Weak interlayer coupling
- Low T_C (~50 K)

Future Work

- Optimize growth conditions to obtain conducting samples
- Understand and improve carrier-mediated exchange interaction between Mn layers

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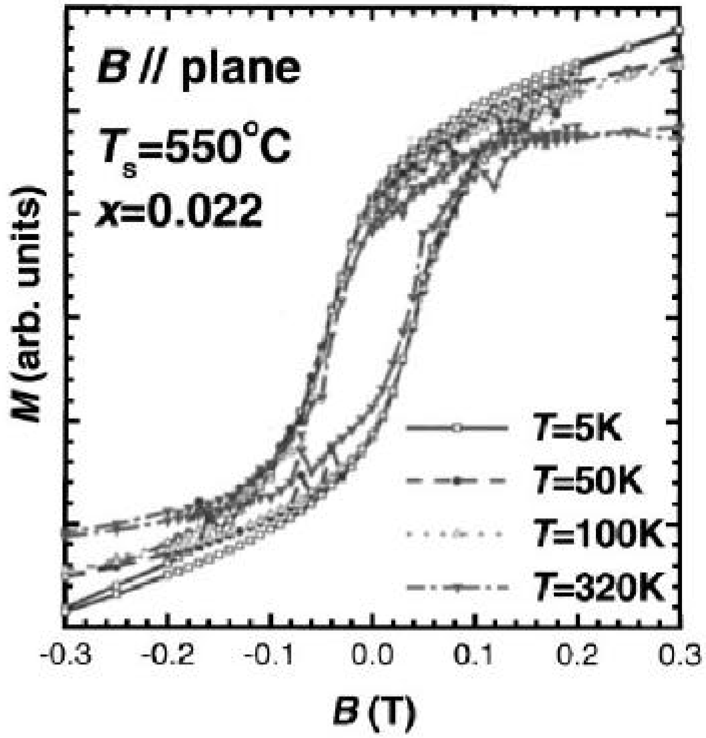
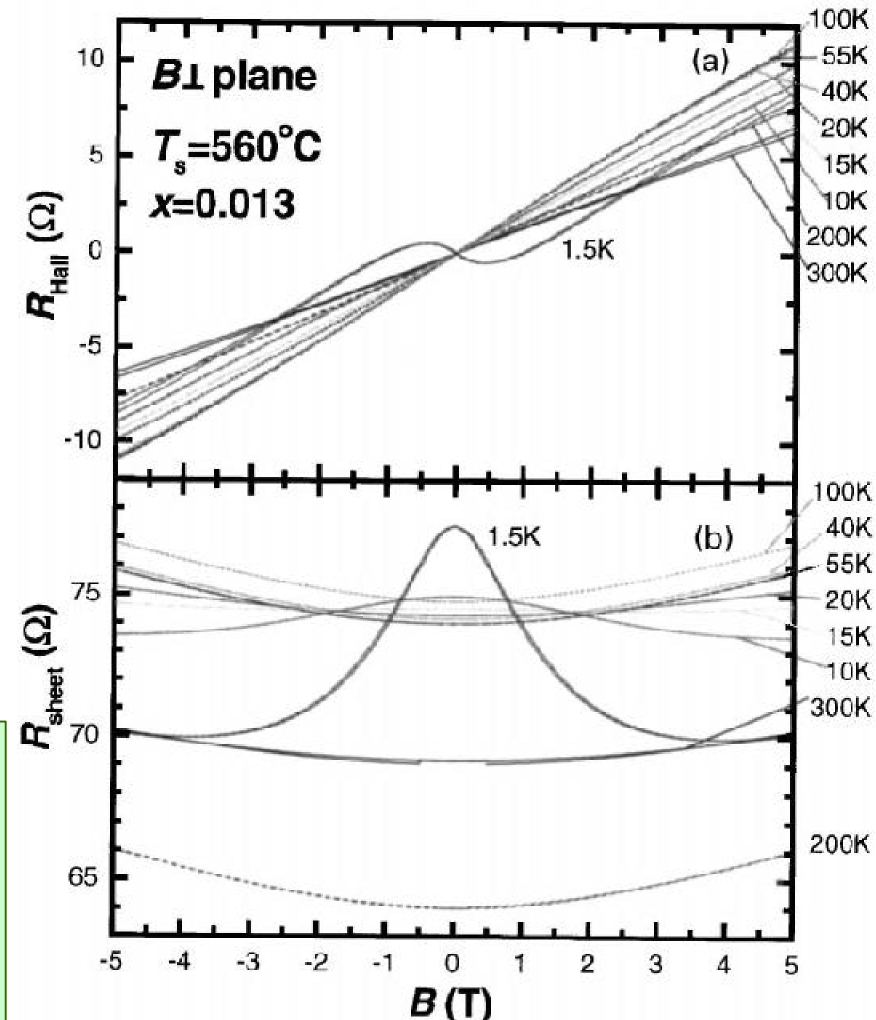
GaMnSb
(HIGH TEMPERATURE GROWTH)





- Temperature independent and isotropic hysteresis loops ➔ precipitates
- Carriers do not interact with precipitates, in the absence of Schottky barriers between MnSb and GaSb

*E. Abe, et al., Physica E **7**, 981 (2000)*

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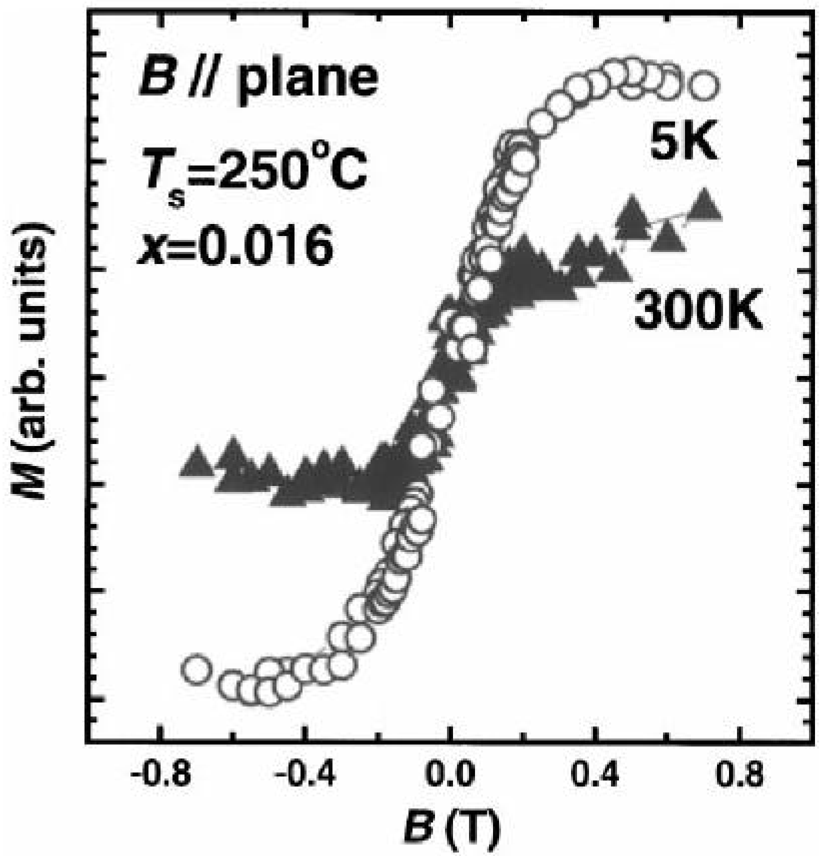
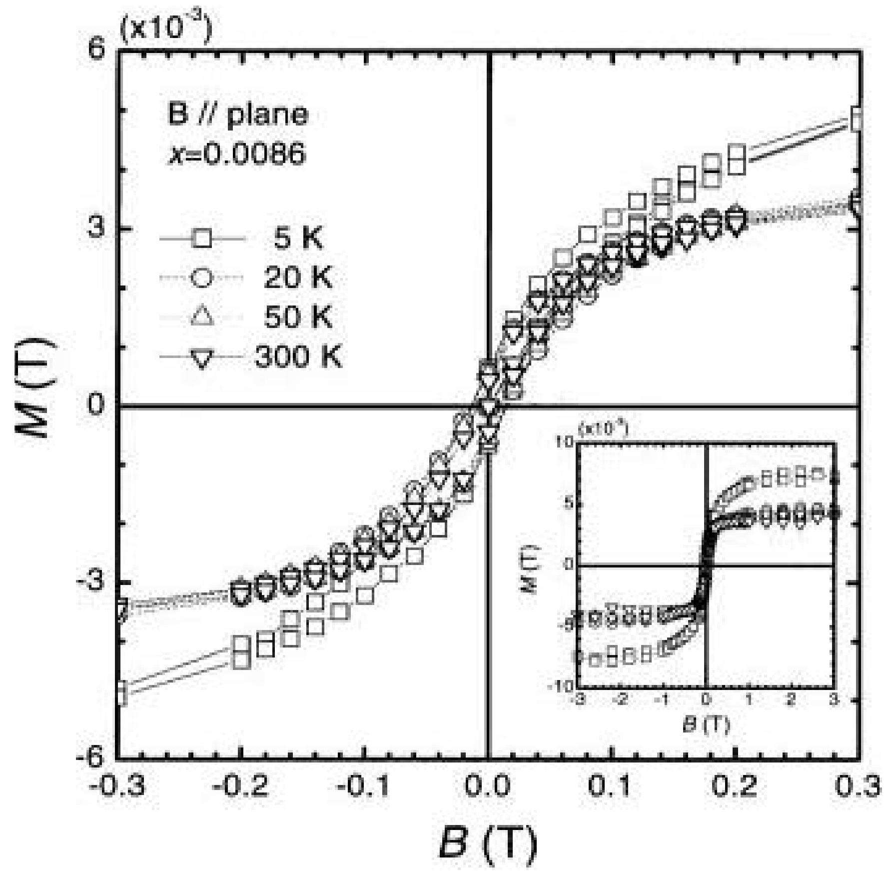
GaMnSb
(LOW TEMPERATURE GROWTH)



*E. Abe, et al., Physica E **7**, 981 (2000)*



F. Matsukura, et al., JAP 87, 6442 (2000)

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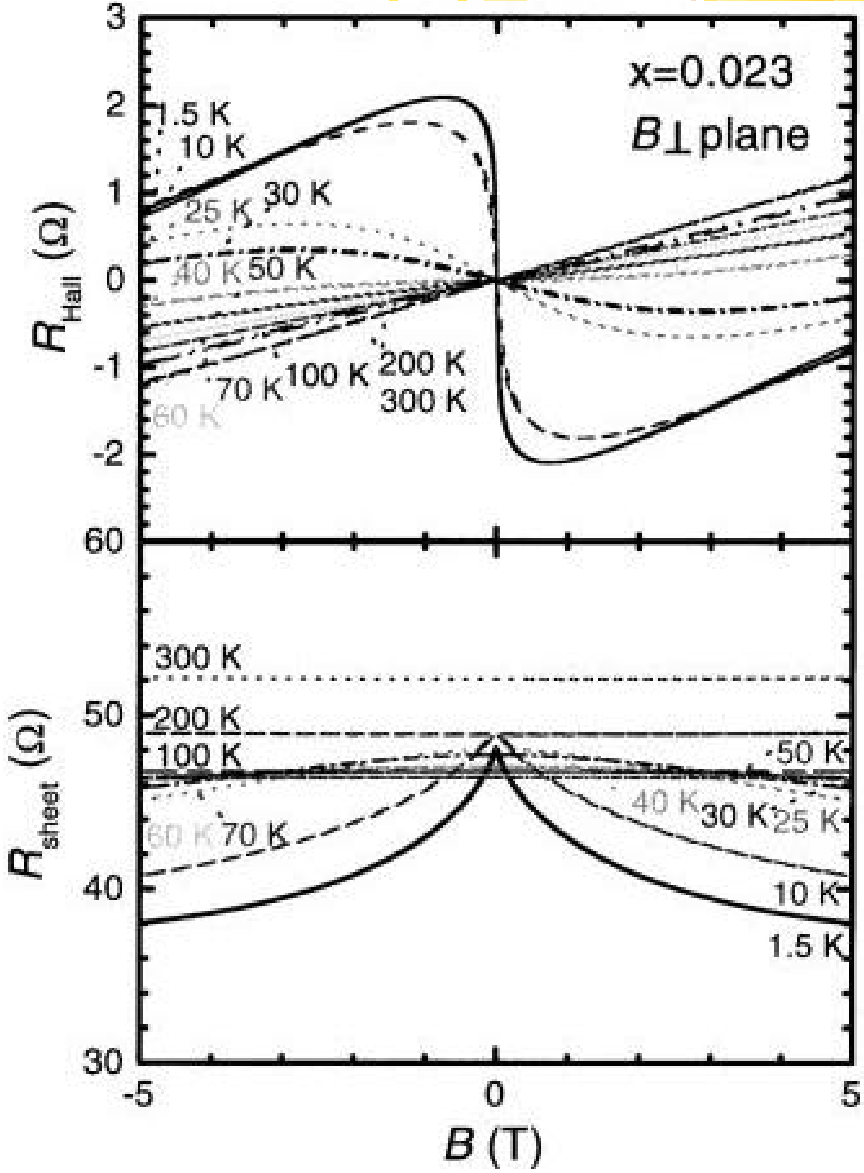
LT GaMnSb



- Clear anomalous Hall effect observed (with negative anomalous Hall coefficient)
- Two phases
  - Ferromagnetic MnSb clusters
  - Ferromagnetic GaMnSb
- No interaction between ferromagnetic clusters and holes
- $T_C \sim 25$ K

F. Matsukura, et al., JAP 87, 6442 (2000)

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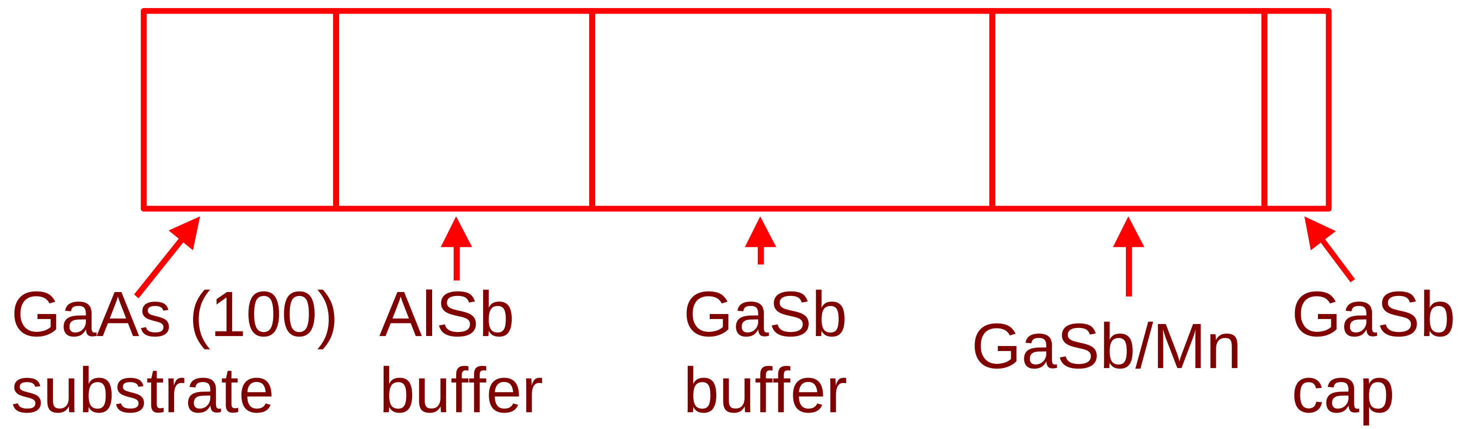
GaSb/Mn DIGITAL ALLOYS

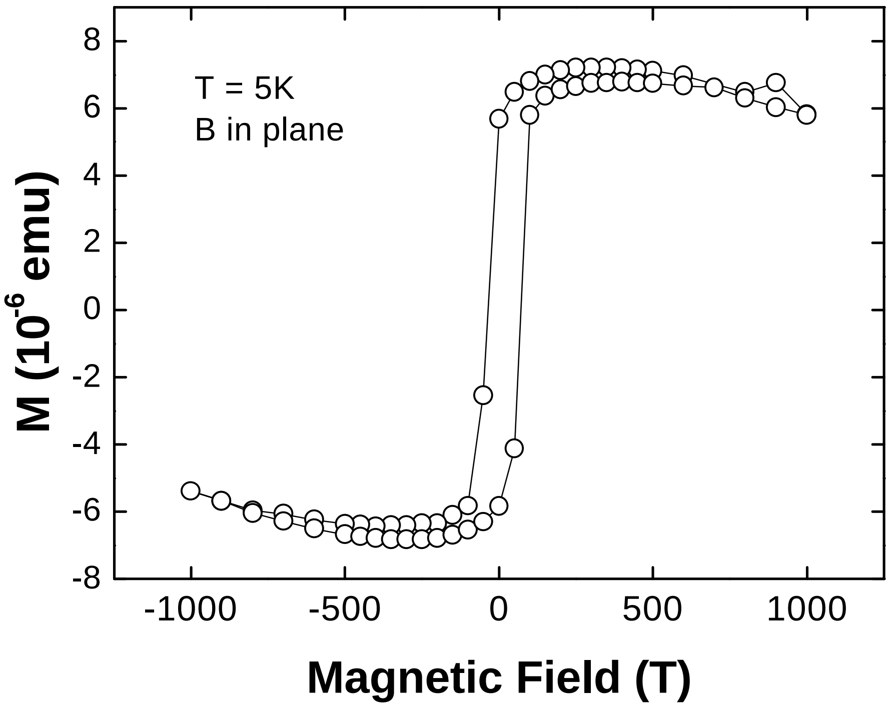
Higher valence band ➡ higher doping efficiency

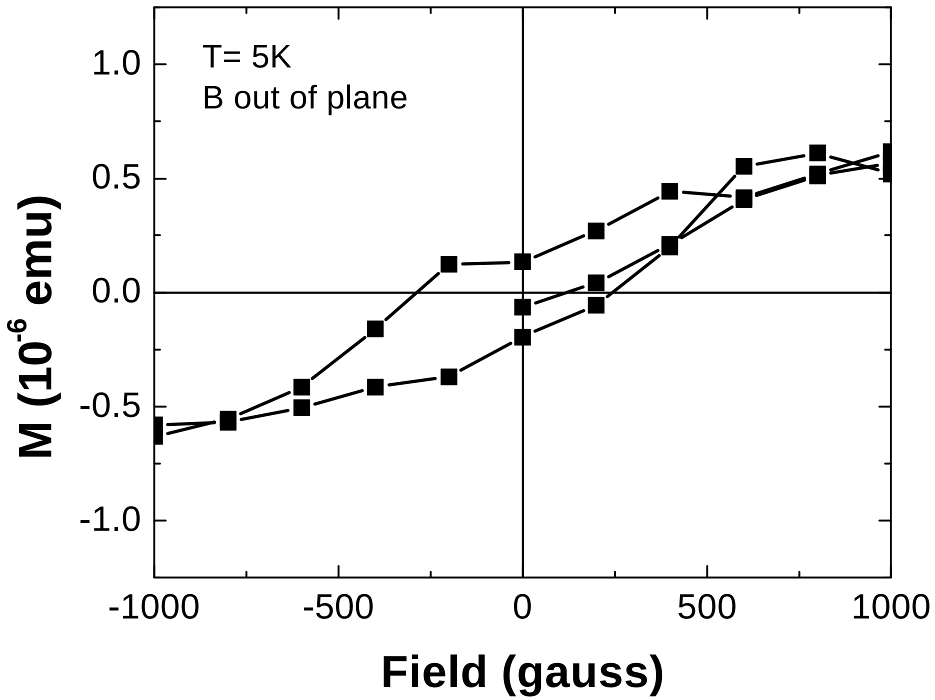
- **Structure:**



- Variation of Mn layer spacing
- Variation of Mn layer coverage
- GaSb/Mn growth temperature: 250°C

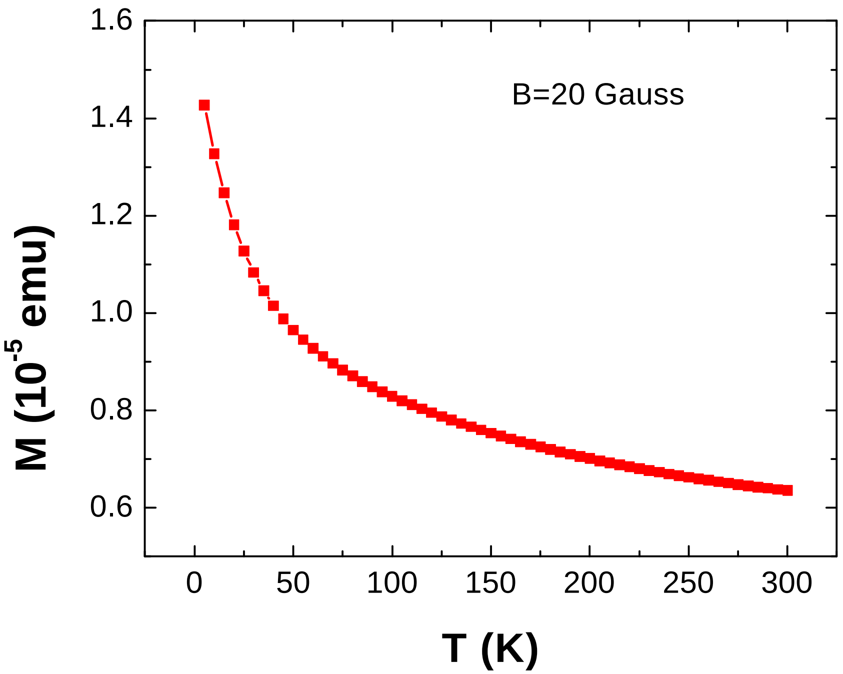
MAGNETIC ANISOTROPY

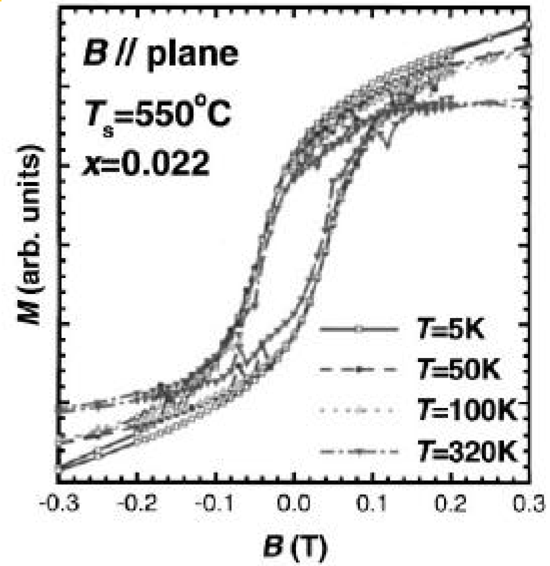




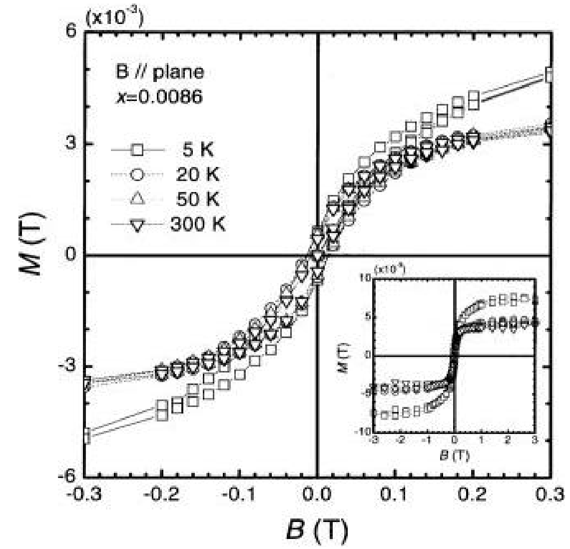
Anisotropic hysteresis loops (in-plane easy axis)

HYSTERESIS AND T_C



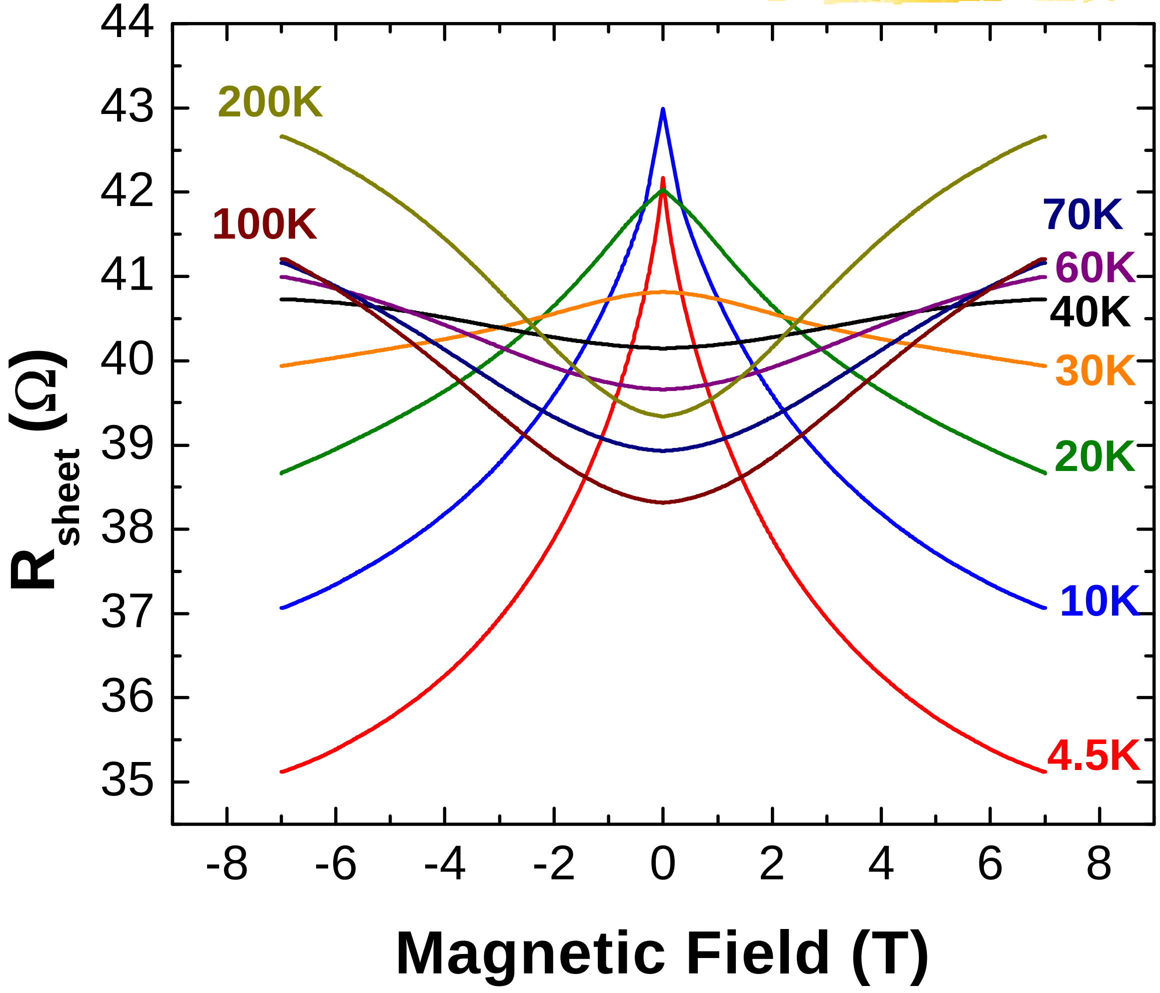


High T_{sub}



Low T_{sub}

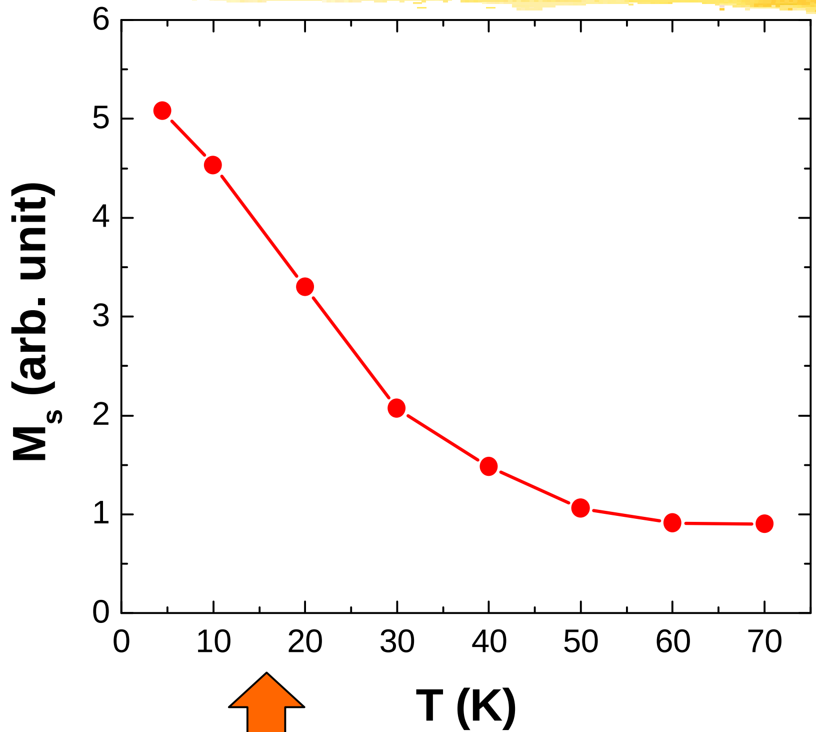
MAGNETORESISTANCE



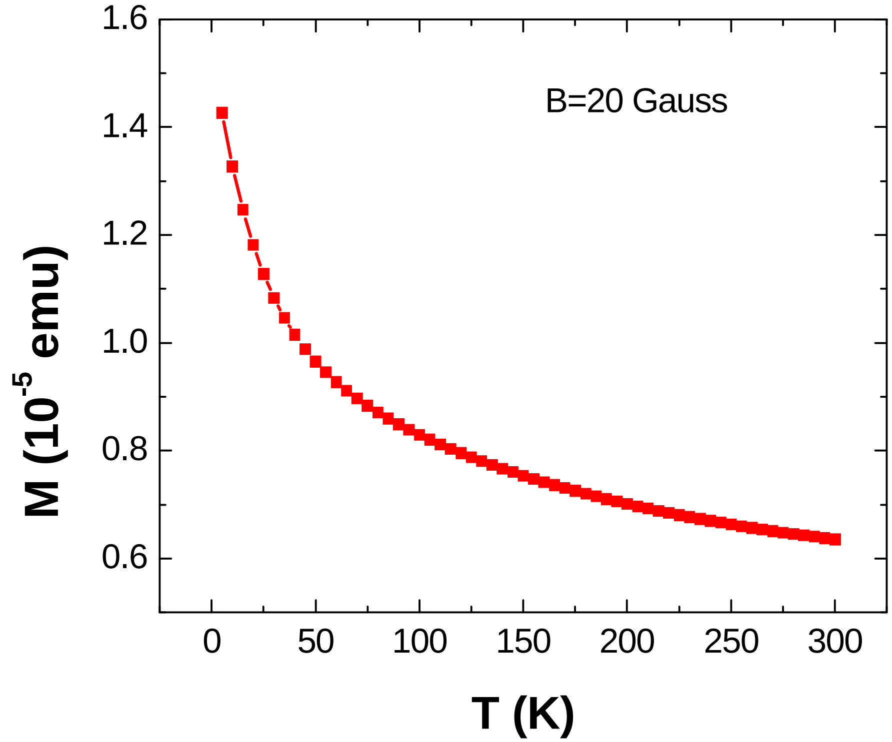
Negative magnetoresistance
< 35 K

Positive magnetoresistance
> 35 K

ARROT PLOT AND T_C



Similarities between transport and magnetization results



Saturation magnetization derived from the anomalous Hall effect

Magnetization as seen by holes (with one T_C around 50K)

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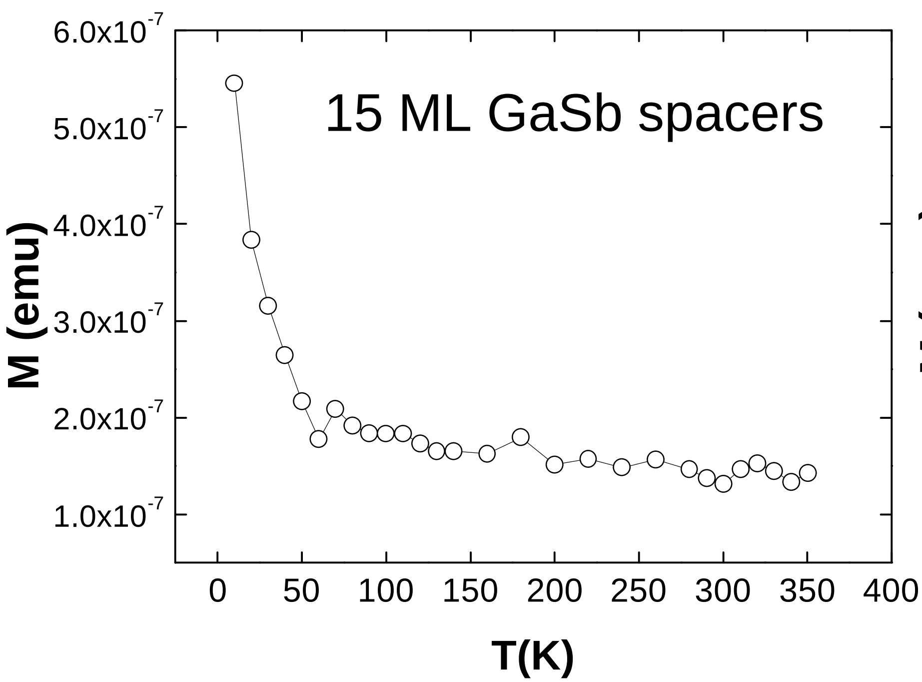
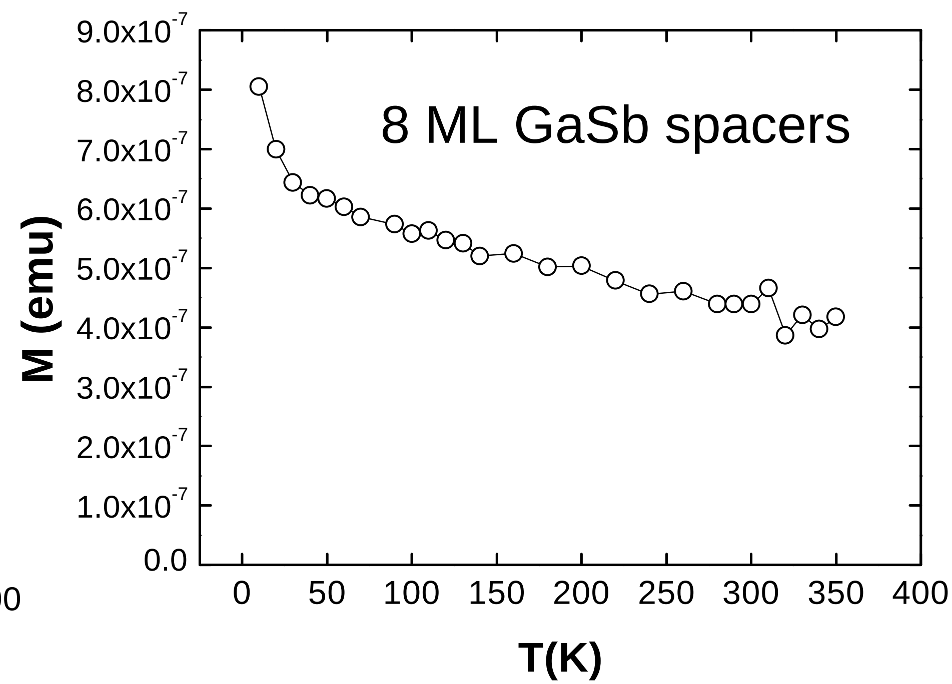
TEMPERATURE DEPENDENCE





Indication of two phases, one with T_C around 50 K and another with T_C above room temperature (precipitates)

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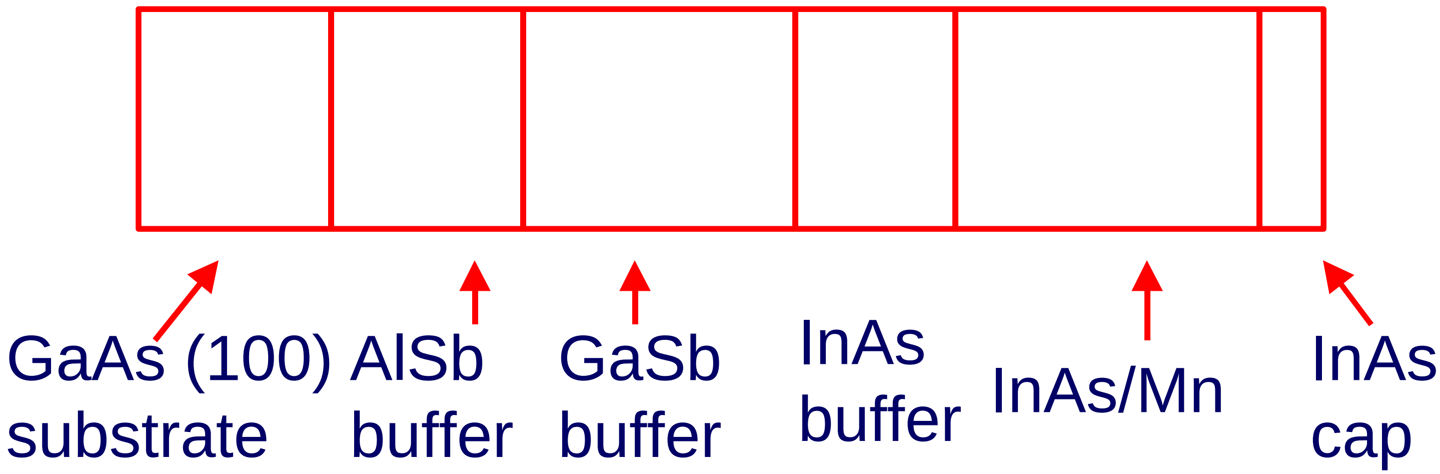
InAs/Mn Digital Alloys

- Structure:



- Variation of Mn layer spacing
- Variation of Mn layer coverage
- InAs/Mn growth temperature: 325^{o}C

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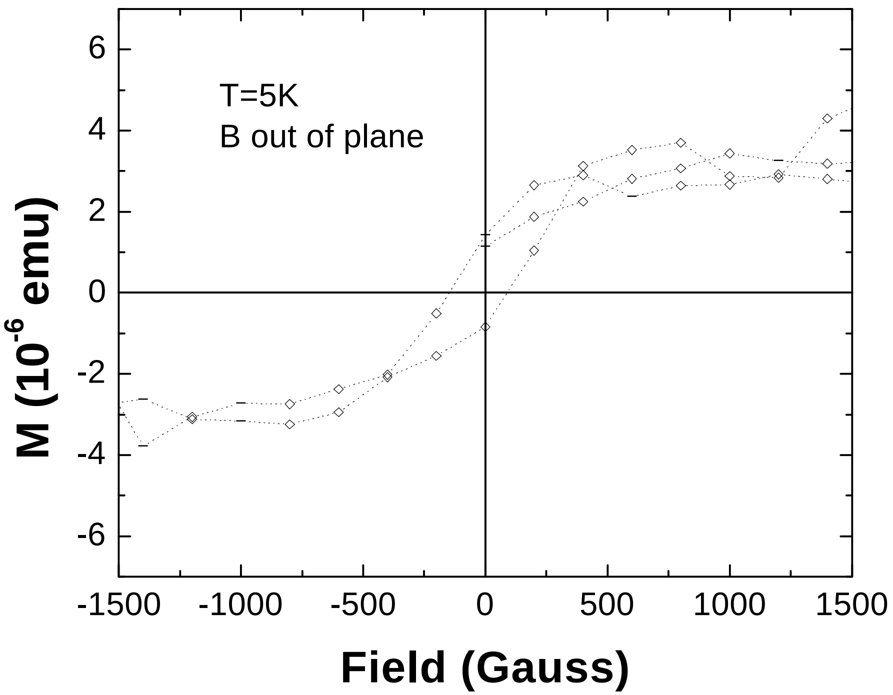
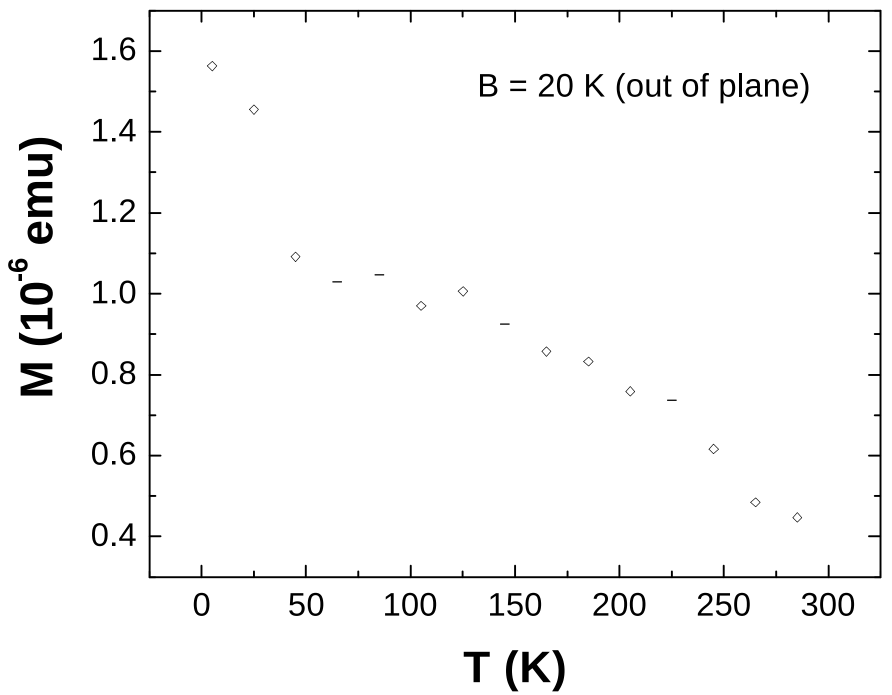
InAs/Mn DIGITAL ALLOYS





- Out-of-plane easy axis
- Presence of multiple phases in the system

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SUMMARY

- **Observation of hysteresis loops in GaSb/Mn digital alloys with T_C at least around 50 K (from both transport and SQUID measurements)**
- **MnSb clusters in GaSb/Mn with higher T_C**
- **Similar effects observed in InAs/Mn digital alloys**

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