Making Semiconductors Ferromagnetic: Opportunities and Challenges

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Ferromagnetic (FM) Semiconductors: Outline

• Why make semiconductors ferromagnetic?
• Properties of III$_{1-x}$Mn$_x$V alloys
• Mn interstitials: their role and detection
• Effect of the Fermi energy on the growth of III$_{1-x}$Mn$_x$V alloys
• Future directions
• FM semiconductor devices
Motivation: semiconductor-based “spintronics”

Today’s electronics and data processing uses semiconductor chips that take advantage of the electrical charge of electrons.

Recently a new field of semiconductor technology began to emerge, with the hope of using electron spin in addition to its charge in semiconductor devices (“spintronics”).

This could combine many functionalities (information storage, logic and data processing, communications) in a single chip.

Ultimate goal: quantum computation via spin entanglement
Examples of ferromagnetic semiconductors

- $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ ($T_c \sim 170K$)
- $\text{In}_{1-x}\text{Mn}_x\text{As}$ ($T_c \sim 60K$)
- $\text{Ga}_{1-x}\text{Mn}_x\text{Sb}$ ($T_c \sim 30K$)
- $\text{In}_{1-x}\text{Mn}_x\text{Sb}$ ($T_c \sim 12K$)

Note: Mn goes into the III-V lattice as divalent $\text{Mn}^{++}$ substitutionally for the Group-III element. In this situation it is both a magnetic moment and an acceptor.
How to make III-Mn-V ferromagnetic?

Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction – carrier mediated – can be ferromagnetic

Requirements:

Large Mn conc. very high $p$

II-Mn-VIs difficult to dope

III-Mn-Vs easier, since Mn also provides holes

$\text{Ga}_{1-x}\text{Mn}_x\text{As } T_C=170K$
In practice, high Curie temperature $T_C$ will be needed for many applications; Mean field theory predicts:

$$T_C = C N_{Mn} \beta^2 m^* p^{1/3}$$

$N_{Mn}$: concentration of uncompensated Mn spins;  
$\beta$: coupling constant between localized Mn spins and the free holes ($p$-$d$ coupling),  
$m^*$: effective mass of the holes,  
$p$: free hole concentration.
The $x$ and $p$ dependence of $T_C$ in GaMnAs
Carrier-controlled ferromagnetism in In$_{1-x}$Mn$_x$As
Fabrication
Typical growth temperature for $\text{Ga}_{1-x}\text{Mn}_x\text{As}$: 260 °C
Structures used in our studies

Growth method: Low Temperature (LT) MBE

100–250nm Ga$_{1-x}$Mn$_x$As; Ga$_{1-y}$Be$_y$As; Ga$_{1-y-z}$Be$_y$Al$_z$As or Ga$_{1-x-y}$Mn$_x$Be$_y$As
or Ga$_{1-x}$Mn$_x$As/Ga$_{1-z}$Al$_z$As:Be
$T_s \approx 260–270$ °C

~3nm LT-GaAs
$T_s \approx 265$ °C

~450nm GaAs buffer
$T_s = 590$ °C

~4.5 µm CdTe buffer

(100) GaAs substrate

230 nm In$_{1-x}$Mn$_x$Sb
$T_s \approx 160$ °C

100 nm LT-InSb
$T_s \approx 210$ °C

2$^{nd}$ MBE process

1$^{st}$ MBE process (Poland)
**Ion Implantation & Pulsed Laser Melting (II-PLM)**

**Ion Implantation**
- kinetic process $\rightarrow$ exceed equilibrium solubility
- crystal damaged (annealing necessary)

**Pulsed Laser Melting**
- ultra-fast solidification
- non-thermal equilibrium growth
- can model PLM & Mn incorporation
Pulsed Laser Melting (PLM)

- ultra-fast solidification
- m/s front velocity → solute trapping
- can model PLM & Mn incorporation

PLM: repair lattice & maintain supersaturation
Magnetic Anisotropy
Magnetic Anisotropy and Strain – an Overview

Perpendicular Uniaxial Anisotropy

GaMnAs/GaAs
- $H/[110]$
- $H/[001]$

GaMnAs/InGaAs
- $H/[110]$
- $H/[001]$

Magnetization $M$ (emu/cm$^3$)

Magnetic Field $H$ (T)

GaMnAs
GaAs
GaMnAs
GaInAs
Biaxial compressive strain induces uniaxial anisotropy: Easy axis is typically in plane.

Dietl, Ohno, Matsukura, PRB 2001
Magnetic Domain Structure
Method for mapping domains in III-Mn-V alloys

Faraday rotation of linearly polarized light in the MO layer (Bi: yttrium - iron - garnet)

Map of the normal component of the local magnetic induction at / near the sample surface

Field sensitivity: 0.5 G; resolution: 1µm


* Collaboration with Ulrich Welp and V. K. Vlasko-Vlasov at Argonne National Laboratory
Magneto-optical images of domain boundaries in Ga$_{1-x}$Mn$_x$As

$H \parallel [100]$, $T=15$ K (left) and 35 K (right); each square is 1 mm $\times$ 1 mm

*U. Welp et al. PRL (2003).*
Planar Hall Effect (PHE) in GaMnAsSb alloy

(a) $\phi = 135^\circ$ $H_1$, $H_2$

$\phi = 104^\circ$

$\phi = 92^\circ$

$\phi = 88^\circ$

$\phi = 74^\circ$

$\phi = 45^\circ$

150$\Omega$

-6 -4 -2 0 2 4 6

Applied magnetic field (kOe)

(b) $V_{\text{Hall}}$

(c) $H_1$, $H_2$, $H_3$, $H_4$, $H_5$
Attempts to increase $T_C$ by doping to increase the hole concentration and the role of Mn ions in Interstitial lattice positions
Temperature dependence of resistivity of $\text{Ga}_{1-x-y}\text{Mn}_x\text{Be}_y\text{As}$ with $x=0.055$

Does $T_C$ decrease with Be co-doping?
Role of lattice location of Mn in III$_{1-x}$Mn$_x$V alloys

- **Substitutional Mn**
  - Mn$^{III}$ acceptor
  - $Mn_{Ga}$ with $E_{act} = 110$ meV

- **Interstitial Mn**
  - $Mn_I$ double donor
  - (passivates 2 Mn$^{III}$ acceptors)

- **Random clusters**
  - Not commensurate
  - Electrically inactive
  - Mn-related small clusters (and possible MnV precipitates)

- No direct measurement of Mn location in III$_{1-x}$Mn$_x$V alloys

III (Ga, In)

V (As, Sb)

Mn
Combined channeling Rutherford backscattering (RBS) and particle induced x-ray emission (PIXE)

Lattice location determined by angular scan of c-RBS/PIXE
PIXE/RBS angular scans for Ga$_{1-x-y}$Mn$_x$Be$_y$As

Huge increase of Mn$_I$ with Be content
• \([Mn_I]\) and random Mn-related clusters increase with Be content.
• \(Mn_I\) are unstable and form random clusters after LT-annealing
• Hole concentration relatively constant at \(~5 \times 10^{20} \text{cm}^{-3}\)
Angular scans for $\text{Ga}_{1-x}\text{Mn}_x\text{As}$

- Random fraction $\text{Mn}_{\text{Ran}}$ (clusters) typically $\leq 0.05$
- $[\text{Mn}]$ up to $\sim 0.15-0.2$ for high $x$ ($>0.05$)
  - Attempts to correlate $T_C$ with $x$ not meaningful
  - XRD cannot accurately determine $x$
Low Temperature annealing
LT-annealing: resistivity and magnetization

$T_C$ increases for optimal annealing

- resistivity decreases
- saturation magnetization $M_S$ increases when the samples are annealed at around 280°C (indicates that the concentration of magnetically–active Mn ions increases).
LT-annealing: Mn location, $p$ and $T_C$

- LT-annealing (280°C) breaks antiferromagnetically coupled $Mn_I$-$Mn_{Ga}$ pairs ⇒ Mn clusters, increases
  - $p = 1 \times 10^{21} \text{ cm}^{-3}$ ([Mn$_{Ga}$]-2[Mn$_I$])
  - [Mn$_{Ga}$] active spins
    ⇒ higher $T_C$=110K

- 350°C annealing drives the system towards equilibrium
  ⇒ random Mn precipitates and/or clusters from Mn$_{Ga}$

- Changes observed are unlikely due to As$_{Ga}$ defects (stable up to 450°C)
• $[\text{Mn}_I]$ and random Mn-related clusters increase with Be content.
• Mn$_I$ are unstable and form random clusters after LT-annealing.
• Hole concentration relatively constant at $\sim 5 \times 10^{20} \text{cm}^{-3}$
Role of interstitials in limiting (reducing) $T_C$

- Electrical compensation by interstitial $\text{Mn}_I$ leads to a reduction of the hole concentration (and $T_C \sim p^{1/3}$)

- $\text{Mn}_I$ donors tend to drift toward $\text{Mn}_{\text{III}}$ to form $\text{Mn}_{\text{III}}$-$\text{Mn}_I$ pairs in $\text{III}_{1-x}\text{Mn}_x\text{V}$ alloys

- Such $\text{Mn}_{\text{III}}$-$\text{Mn}_I$ pairs then couple antiferromagnetically
Direct evidence of Fermi-energy-dependent formation of Mn interstitials in Ga$_{1-x}$Mn$_x$As: Studies of modulation doped Ga$_{1-x}$Mn$_x$As/Ga$_{1-y}$Al$_y$As:Be heterostructures
GaMnAs Quantum Well Geometry

50 ml AlGaAs:Be

20 ml (Ga,Mn)As

100-nm GaAs Buffer

(001) GaAs Substrate
Temperature dependence of resistivity of MD Ga$_{1-x}$Mn$_x$As/Ga$_{1-y}$Al$_y$As:Be heterostructures

vs. thickness of doped region ($d_{Be}$)

vs. Be doping level ($T_{Be}$)

Temperature dependence of resistivity of MD Ga$_{1-x}$Mn$_x$As/Ga$_{1-y}$Al$_y$As:Be heterostructures

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Temperature dependence of resistivity of MD Ga$_{1-x}$Mn$_x$As/Ga$_{1-y}$Al$_y$As:Be heterostructures

vs. thickness of doped region ($d_{Be}$)

vs. Be doping level ($T_{Be}$)
Temperature dependence of remanent magnetization of MD Ga$_{1-x}$Mn$_x$As/Ga$_{1-y}$Al$_y$As:Be heterostructures.

- Increase of $T_C$ in qualitative agreement with self-consistent calculations (Vurgaftman and Meyer).
- Decrease of $T_C$ consistent with strong dependence of Mn$_i$ formation on Fermi energy during growth.
Conclusions

- Directly identified $Mn_I$ in $Ga_{1-x}Mn_xAs$ and $In_{1-x}Mn_xSb$ thin films
- $Mn_I$ are responsible for creation of AF pairs and for the limiting the Curie temperature in ferromagnetic $Ga_{1-x}Mn_xAs$ and $In_{1-x}Mn_xSb$
- LT- annealing drives $Mn_I$ to random clusters
  $\Rightarrow$ increase of $p$, of active spins, and of $T_C$
- Incorporation of nonmagnetic acceptors increases concentration of $Mn_I$ and decreases $T_C$.
- Counter doping with donors as a method to enhance $T_C$.
- Modulation doping – first experimental results that confirms our model of Fermi-energy dependent creation of $Mn_I$
Incorporation of $\text{Mn}_\text{Ga}$ (and $\text{Mn}_\text{In}$) and creation of $\text{Mn}_I$ results from the value of $E_F$ during the growth!

This is what limits $T_C$
Devices
Giant domain wall magnetoresistance in planar devices with nano-constrictions

Giant Planar Hall Effect in Epitaxial (Ga,Mn)As Devices

FIG. 1 (color). (a)–(c) Planar Hall resistance for Hall bars (1 mm, 100 μm, 6-μm-wide) at 4.2 K as a function of in-plane magnetic field (at fixed orientation $\varphi_H = 20^\circ$). (d) Field-dependent sheet resistance of a 100-μm-wide Hall bar. (e) Sketch of the relative orientations of sensing current $I$, external field $H$, and magnetization $M$. A SEM micrograph of a 6-μm-wide device is also shown. (f) Barkhausen jumps that are evident solely in 6-μm-wide devices near the resistance transitions.

Electrical Manipulation of Magnetization Reversal in a Ferromagnetic Semiconductor

Fig. 1. (A) Hall bar-shaped field effect transistor having a ferromagnetic semiconductor (In,Mn)As channel. To probe the magnetization $M$ of the channel, Hall resistance $R_{Hall} = V_{Hall}/I$ proportional to the channel magnetization is measured. (B) Temperature dependence of $R_{Hall} (\propto M)$ versus magnetic field $\mu_0 H$ curves with square-shaped hysteresis up to temperatures below 50 K in sample A. Sample A has a ferromagnetic transition temperature of 52 K. No electric field is applied ($E = 0$). Magnetic field sweep rate is 3.7 mT/min.

Current-driven magnetization reversal in a ferromagnetic semiconductor based (Ga,Mn)As/GaAs/(Ga,Mn)As magnetic tunnel junction


FIG. 4. Magnetoresistance curves of the $1.5 \times 0.3 \, \mu m^2$ device at 30 K measured at $V_d = +10 \, mV$ starting from three different states. MR curves (a) and (b) are obtained from a state prepared by applying a positive current pulse with current density of $J_{\text{pulse}} = +2.2 \times 10^5 \, A/cm^2$ on initial configuration A (see the rightmost diagram for $M$ configuration). MR curves (c) and (d) are obtained from a state prepared by the same manner but starting from initial configuration B.
Current-induced domain-wall switching in a ferromagnetic semiconductor structure

Figure 4 MOKE images of sample A using 546-nm light at ~80 K. Black and white regions in the channel correspond to positive and negative values of $M$, respectively.

- **a.** The MOKE image of the initial state, where the domain wall is at the left edge of region III. Regions I, II and III are indicated by arrows in the image.
- **b.** The MOKE image after application of a current pulse $I = -300 \mu$A (100 ms), showing that the domain wall is now at the right edge of region II.
- **c.** A positive current pulse of $I = +300 \mu$A (100 ms) switches the domain wall back to its original position.

Magneto-transport devices on vicinal GaMnAs

(a) Schematic diagram showing the orientation of the magnetic field (H) and current (I) along different crystallographic axes of GaMnAs.

(b) Graph showing the temperature dependence of the resistance ratio $r_{xx}(T)/r_{xx}(T_c)$ for different angles $\alpha$ between the current and the plane of the film. $T_c \sim 60$K.
\[ \alpha = 5^\circ \]

- **M close to +H**
- **M close to -H**
Counter doping with donors as a method to enhance $T_C$.

Modulation doping – first experimental results that confirms our model of Fermi-energy dependent creation of Mn$_I$. 

Major challenge: Need for strategies to increase $T_C$.