Ferromagnetic Semiconductors (Ga,Mn)As

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6.772
May 12, 2009
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Background - Motivation

- Difficult Scientific Problem for solid state physics – many body effects

- Material Applications – “Spintronics”
  - Possible post “Moore’s Law” solution?
    - Reduced power consumption
    - Faster computation
    - Quantum computation
  - Novel new materials available for Device Engineers
    - Nonvolatile Devices
    - Magnetic Tunnel Junctions (MJT)/ Gigantic Magnetic Resistance (GMR)
    - Spin Injectors / Spin Transistors
    - Electrically controllable ferromagnetism
  - Optical Isolators– Faraday Rotation
Background – History of Ferromagnetic Semiconductors (FS)

- **1961** – Europium Chalcogenides by Matthias – as a ferromagnetic semiconductor $T_c = 69K$
- **1978** – “Exchange Interaction of Manganese 3d5 States with Band electrons in (Cd,Mn)Te” – “Dilute Magnetic Semiconductors” (DMS)
- **1986** – “Carrier-concentration-induced ferromagnetism in PbSnMnTe”
- **1992** – “p-type (In,Mn)As diluted magnetic III-V semiconductors” - $T_c = 7.5 \text{ K}$
- **1996** – “(Ga,Mn)As: A new diluted magnetic semiconductocotr based on GaAs” – $T_c = 60K$, Mn = 0.035
- **2002** – “High-Curie- temperature Ga$_{1-x}$Mn$_x$As obtained by resistance-monitored annealing” – $T_c = 140 \text{ K}$, Mn = 0.06.
- **2003** – “Ferromagnetism and high Curie temperature in semiconductor heterostructures with Mn $\delta$-doped GaAs and $p$-type selective doping” - $T_c = 172 \text{ K}$
- Mn substitutes for Ga – Acceptor Doping
- 200-250 °C MBE growth avoid MnAs formation
  - Interstitial Mn defects
  - As\textsubscript{Ga} effects
- Low Temperature, Long Time Anneal ~ 190 °C, T > 10 Hours
- Curie Temperature ($T_c$) inversely proportional to thickness of (Ga,Mn)As film for a fixed anneal recipe
- Curie Temperature ($T_c$) linear with hole concentration
Theory - Ferromagnetism

- Weiss Molecular Field Model
  - $H_{\text{total}} = H + \lambda M$
  - $M \propto B_j(x) \propto x \propto H + \lambda M$
  - Nontrivial Solution $H = 0, M \neq 0$

- Curie Temperature ($T_c$)

- Exchange Energy – total wavefunction including spin must be antisymmetric – Pauli exclusion principle for many body systems

\[
\chi = \frac{C}{T - T_c}
\]
Theory of Dilute Magnetic Semiconductors (DMS) – III(Mn)-V

- Mn$^{2+}$ Ions, $S = 5/2$
  - Mn-Mn \( \uparrow \downarrow \)

- Carrier Induced Ferromagnetism
  - Hole mediated alignment between Mn ions \( \uparrow \uparrow \)

- Band Structure
  - Level Repulsion induced spin splitting
  - Mn & p \( \uparrow \downarrow \)
**Tunable Spin Polarization**

- **Experimental Setup** – Photoexcite e-p in QW.
- d = 5-9nm – magnetic layer induces carrier polarization
- Devices are biased with very little current flow < 0.25 mA/cm²
- HH wavefunction in QW has finite overlap with the magnetic layer.
  - PL quenching caused by carrier tunneling through the barrier resulting in nonradiative recombination.
  - Negative bias HH wavefunctions leans closer towards the MnAs layer.
  - Hypothesize the degree of polarizing due to the exchange and energy interaction between the Mn ions and the holes caused by increase wavefunction overlap.
Electric Field Control of Ferromagnetism

- Hole mediated ferromagnetism – gate induced holes in FS
  - \( R_{\text{hall}} = R_0/d*B + R_s/d*M \)
    - \( R_s = \rho^y \), \( \rho \) is resistivity
- Hysteresis Curve to identify the degree of ferromagnetism
- Hypothesis additional effect of the bias may shift the wavefunction of holes in the magnetic thin layer to effect the exchange interaction.
Conclusion

- Max $T_c < 170$ K, while interesting since above liquid nitrogen, still not high enough for robust devices.

- Low temperature processing after magnetic layer, all other layers and devices must be processed $< 200^\circ$C

- Theoretical Calculations predict room temperature ferromagnetism with increased Mn doping; however, current models seem to overestimate the $T_c$

- GaMnAs may not be the final material; but it is an interesting platform for studying what might be possible with ferromagnetic semiconductors.
References