Fe$_{1-x}$Co$_x$Si, a Silicon Based Magnetic Semiconductor

Fe$_{0.8}$Co$_{0.2}$Si

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Outline

• MnSi, FeSi, and CoSi – Itinerant magnet, Kondo Insulator, Simple metal. Fe\textsubscript{1-y}Co\textsubscript{y}Si

• Magnetotransport – Electron-electron interactions

• Optical conductivity – Less shiny in FM state

• The Anomalous Hall Effect

• Comparisons with ferromagnets, Heavy Fermions, and other magnetic semiconductors.

• Conclusions.
Magnetic Semiconductors

• Because of interest in Spintronics magnetic semiconductors have become popular.
  
• Advantages include potential for spin-polarized carrier sources and easy integration into semiconductor devices.
  
• Most thoroughly investigated is (GaMn)As, a Mn doped III-V semiconductor with $T_C < 150$ K.
  
• Here we describe a different way to produce magnetic semiconductors – Carrier doping of a strongly correlated, or Kondo insulator – FeSi.
Phase Diagram of Fe$_{1-x,y}$Mn$_x$Co$_y$Si
Magnetization

$M (\mu_B \text{ per Co ion})$ vs $H (\text{kOe})$

$Fe_{0.85}Co_{0.15}Si$
Phase Diagram II

**Fe\textsubscript{1-y}Co\textsubscript{y}Si** – Fully polarized – Half metallic (y<0.35)

- \textbf{Vegard’s Law}:
  - One hole per Mn dopant
  - One electron per Co dopant

- **T = 5 K**

- No Obvious trends

- Materials:
  - MnSi
  - Fe\textsubscript{0.5}Mn\textsubscript{0.5}Si
  - FeSi
  - Fe\textsubscript{0.5}Co\textsubscript{0.5}Si
  - CoSi

- Lattice constant (A)

- \(n (10^{22}/\text{cm}^3)\)

- \(\mu_H (\text{cm}^2/\text{Vs})\)
Results of Band Structure Calculations

$Fe_{0.8}Co_{0.2}Si$

$-Fe_{1-x}Co_xSi$ is predicted to be half metallic

$FeSi$
Magnetoresistance

Fe$_{0.8}$Co$_{0.2}$Si

$\rho$ ($\mu$Ω cm)

$\Delta \rho/\rho$ (%)

Positive MR in a ferromagnet

MnSi

$\rho$ ($\mu$Ω cm)

$\Delta \rho/\rho$ (%)
Magnetoresistance

Transverse and longitudinal MR very similar

MR not an orbital effect

Most likely due to coupling to electron spins

Fe$_{0.85}$Co$_{0.15}$Si
Low Temperature Conductivity

Conductivity $T$ and $H$ dependent down to very low $T$

$\Delta\sigma$ ($\Omega^{-1} \text{cm}^{-1}$) vs $T^{1/2}$ (K$^{1/2}$)

- $\propto \sqrt{T}$

$\Delta\sigma$ ($\Omega^{-1} \text{cm}^{-1}$) vs $H^{1/2}$ (T$^{1/2}$)

- $\propto \sqrt{H}$

Materials:
- $\text{Fe}_{0.9}\text{Co}_{0.1}\text{Si}$
- $\text{FeSi}_{0.95}\text{Al}_{0.05}$
- $\text{Fe}_{0.92}\text{Mn}_{0.08}\text{Si}$
Si:B near the MI transition

$\sigma \propto \sqrt{T}$ and $\sqrt{H}$

$H/T$ Scaling of conductivity

S. Bogdanovich et al.
Electron-Electron Interactions

• Altschuler-Aronov effect – disorder and interactions

• When in proximity to the metal-insulator transition
  – poor screening of electromagnetic fields.
  – Diffusive motion of the carriers
  – More than one carrier interaction during phase-breaking time

• Enhanced Coulomb interactions.

• Square-root singularity in the density of States
Electron-Electron Interactions

• For Paramagnetic FeSi\(_{1-x}\)Al\(_x\) we find good agreement of MR with theory.

\[
[\sigma(H,T) - \sigma_0] = f(g\mu_B H / k_B T)
\]

\(f(x) \propto x^2\) for \(x << 1\); \(f(x) \propto \sqrt{x}\) for \(x >> 1\)

• There is no theory for e-e interaction effects in a FM.

• Simplest approach taken:

\[H \rightarrow H_{\text{eff}} = H + \alpha M\]

• Best scaling of the data used to find \(\alpha\).
Scaling of the Conductivity

\[ \frac{(\sigma_0 - \sigma)}{T^{1/2}} (\Omega^{-1} \text{cm}^{-1} \text{K}^{-1/2}) \]

\( \text{Fe}_{0.7}\text{Co}_{0.3}\text{Si} \)

\[ a + b(\frac{H_{\text{eff}}}{T})^2 \]

\[ c + d(\frac{H_{\text{eff}}}{T})^{1/2} \]

\( 0.2 < T < 100 \text{ K} \)

\( 0 < H < 32 \text{ T} \)

Scaling of the Conductivity

$\sigma (\text{m} \Omega^{-1} \text{cm}^{-1})$

$T$ (K)

$\sigma_0$

$\text{Fe}_{0.7}\text{Co}_{0.3}\text{Si}$

$H_{\text{eff}} = 0$ model

$c + d(H_{\text{eff}} / T)^{1/2}$

$H = 0$

$H = 5 \text{ T}$

$a + b(H_{\text{eff}} / T)^2$
Density of States

Fe$_{0.85}$Co$_{0.15}$Si

Energy in meV

DOS (10$^{23}$ / eV cm$^3$)

M  Γ  2  0  2  1.9  2

85  90
Conclusions for MR

- $\text{Fe}_{1-y}\text{Co}_y\text{Si}$ has a large positive magnetoresistance unlike most ferromagnets.
- Conductivity obeys $H/T$ scaling when magnetization properly accounted for.
- Quantum interference effects are important for understanding transport.
- Important contribution to $\sigma$ for Temperatures up to ~100 K.
Optical properties of Semiconductors

- Intrinsic semiconductor
- Electron Doped Semiconductor
- Spin Polarized Electron Doped Semiconductor

Graph showing DOS (Density of States) in eV Formula Unit vs. E (eV).
(GaMn)As Optical Conductivity

Low frequency spectral weight increases for $x<0.052$

New resonance appears at $2000 \text{ cm}^{-1}$.

Singley et al *PRL* 89, 097203
(GaMn)As Temperature Dependence

Low frequency spectral weight increases below $T_C = 72$ K.

Scattering rate and $m^*$ decrease below $T_C$.

Singley et al. *PRL* 89, 097203
Optical Properties of Magnetic Semiconductors

Spin Polarized doped semiconductor

(GaMn)As

Fe$_{1-x}$Co$_x$Si

DOS 1/eV Formula Unit

E (eV)

0

0.5

10

10

0

0.5

0

0.5

E (eV)

E (eV)
Gap fills with temperature – $\sigma(\omega)$ is flat
– gap is gone by for $k_B T > \frac{1}{2} \Delta$
Spectral Sum rule not satisfied for $\omega < 80 \Delta$
Drude Spectral weight decreases below $T_C$.
Large discrepancy with band structure calculation.

$\sigma(\omega) (10^3 \Omega^{-1} \text{cm}^{-1})$

$\omega / 2\pi c$ [cm$^{-1}$]

$T_C = 36 \text{ K}$
Becomes less shiny below $T_c$

$\text{Fe}_{0.8}\text{Co}_{0.2}\text{Si}$
Change in the Optical Conductivity with Doping

\[ \sigma_1(\omega, T)_{Fe_{0.8}Co_{0.2}Si} - \sigma_1(\omega, T)_{FeSi} \]

Shows where added carriers reside

Loss of spectral weight
Results of Band Structure Calculations

FeSi

Fe\textsubscript{0.8}Co\textsubscript{0.2}Si

-Fe\textsubscript{1-x}Co\textsubscript{x}Si is predicted to be half metallic

FeSi

- Larger DOS in PM phase than in FM phase
Scattering Rate and Resistivity

Calculated $\Gamma$ - the width of the Drude peak as a function of Temperature

Compare with DC resistivity

Conclude that the carrier scattering rate increases below $T_C$. 

$\Gamma$ 

$T_C$ 

$\rho_{DC}$
Electron–electron interactions

Carriers interact more than once during a Phase breaking scattering time.

This increases the Coulomb interaction between carriers

Result = singularities in the DOS at Fermi Energy
Conclusions for Optics

• The low frequency $\sigma(\omega)$ evolves in a manner that is inconsistent with standard semiconductors, (GaMn)As, and itinerant magnets.

• Doping produces optical response throughout the gap region- carriers donated to the conduction band of the insulator – rather than an impurity band.

• Optical reflectivity decreases upon entering spin-polarized state – rise in scattering rate caused by Coulomb interactions in a disordered system – F.P. Mena et al. to be published.