Theories of ferromagnetic semiconductors (S. Das Sarma)

- Weiss Mean Field Theory: Localized and Delocalized
- Percolation Theory: Insulating DMS
- Dynamical Mean Field Theory: Impurity Band extended and Localized

- PRL87,227202(2001);PRL 88,247202(2002);PRB65,233206(2002)

Spin-Polarzied Transport in Semiconductors

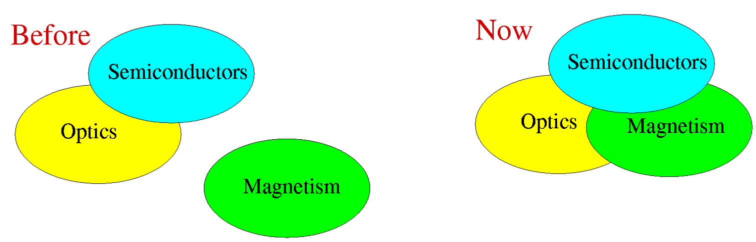
- Why semiconductors ?

versatility, signal amplification, easier integration,...

doping, variety of structures,..

tunable electronic properties

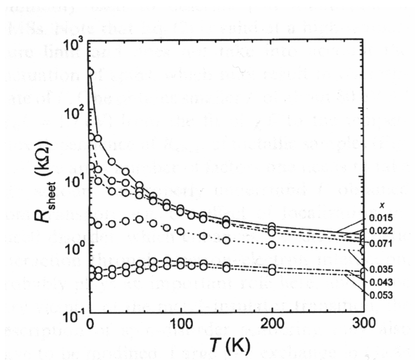
multifunctionality!



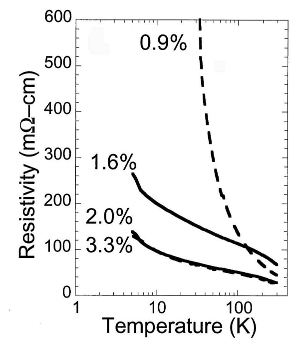
‘‘Magneto-opto-electronics’’

Signatures of charge carrier localization

$Ga_{1-x}Mn_xAs$



$Ge_{1-x}Mn_x$



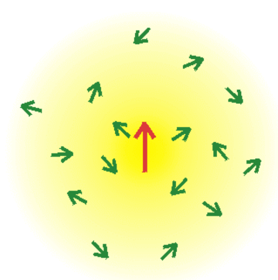
Bound magnetic polaron

localized hole $\quad \Psi(r) \propto \exp\left(-\frac{|r-r_0|}{a_B}\right)$

+

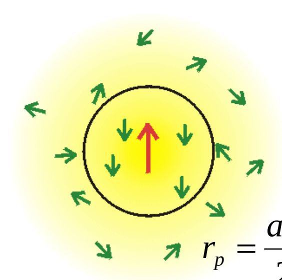
magnetic impurities $\quad (n_i >> n_h)$

$$\hat{H} = \sum_{i,h} J_{ih} \vec{S}_i \vec{s}_h \qquad J_{ih} = J_0 \exp\left(-\frac{2|r_i - r_h|}{a_B}\right)$$



lower T

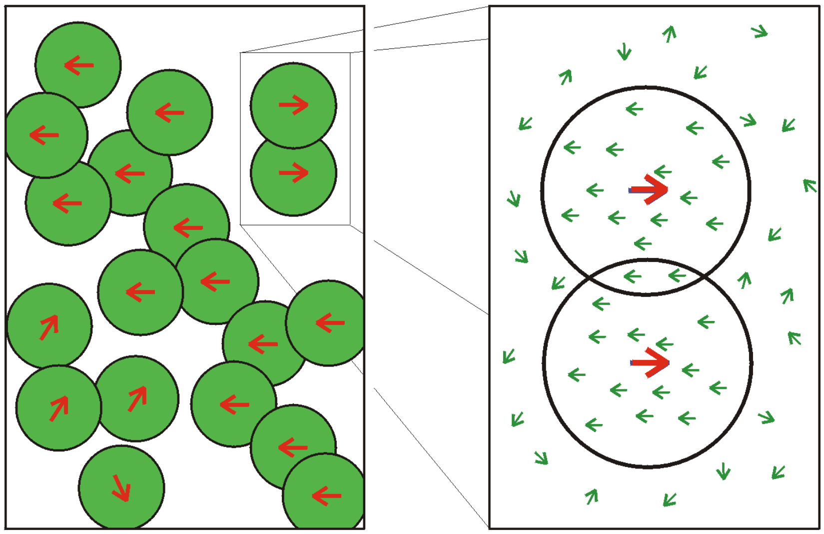
$\Rightarrow$



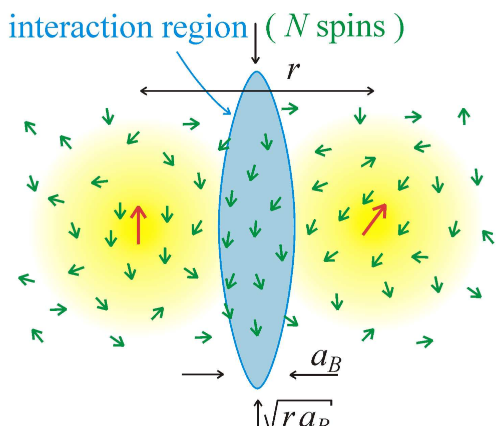
polaron radius:

$$r_p = \frac{a_B}{2} \ln \frac{AJ_0}{T}$$

Polaron percolation



Interaction of two polarons



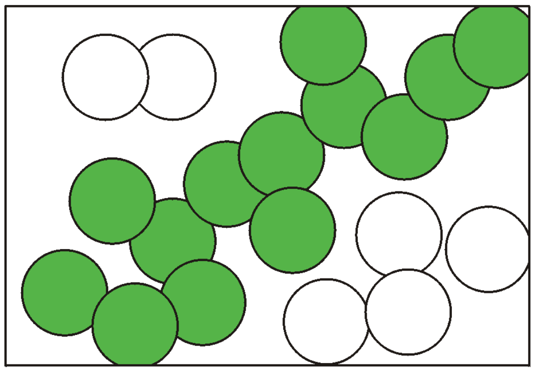
$$M^{(1,2)}_{\text{int.reg.}} \approx N \frac{1}{T} J(r/2) \quad \Rightarrow \quad "J_{12}" \approx \sqrt{N}\, J(r/2)$$

$$"r_{\text{polaron}}" = \frac{a_B}{2}\left[\ln\frac{|J_0|}{T} + \frac{1}{2}\ln\left(a_B^3 n_i \ln\frac{|J_0|}{T}\right)\right]$$

Percolation theory: the model of overlapping spheres

only one parameter: $r\sqrt[3]{n}$

known characteristics: $(r\sqrt[3]{n})_{crit} = 0.86$, $N\left(r\sqrt[3]{n}\right)$, $V\left(r\sqrt[3]{n}\right)$



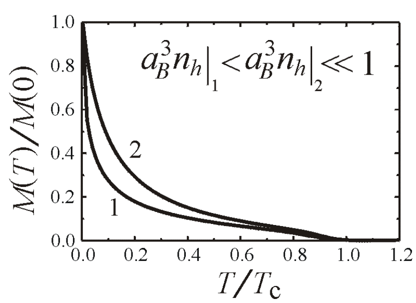
Results

$$T_c = \left(a_B\sqrt[3]{n_h}\right)\sqrt{\frac{n_i}{n_h}}|J_0|\exp\left(-\frac{0.86}{a_B\sqrt[3]{n_h}}\right)$$

$$\frac{M(T)}{M(0)} = V\left(0.86 + a_B\sqrt[3]{n_h}\ln\frac{T_c}{T}\right)$$

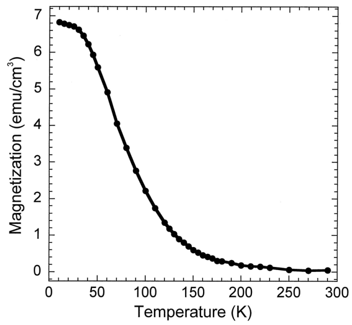
matches mean-field result

$$T_c = \sqrt{\frac{n_i}{n_h}}|J_0| \quad \text{at} \quad a_B\sqrt[3]{n_h} \approx 1$$



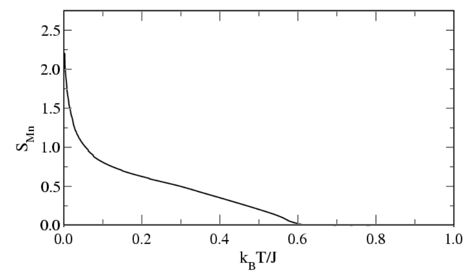
Comparison with experiments and numeric experiments

$Ge_{1-x}Mn_x$ (Park *et al.* (2002))

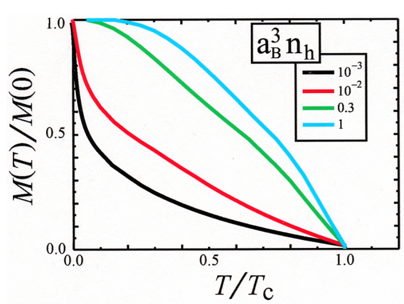


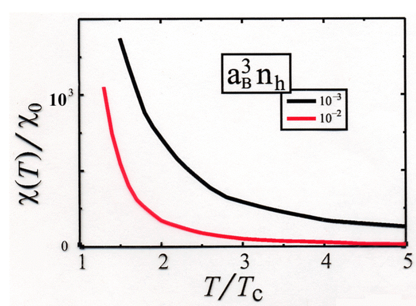
Also $In_{1-x}Mn_xAs$, $Ga_{1-x}Mn_xSb$, $Ga_{1-x}Mn_xAs$ (for x < 3%)

Monte-Carlo (Bhatt *et al.* (2000))



Magnetization and susceptibility



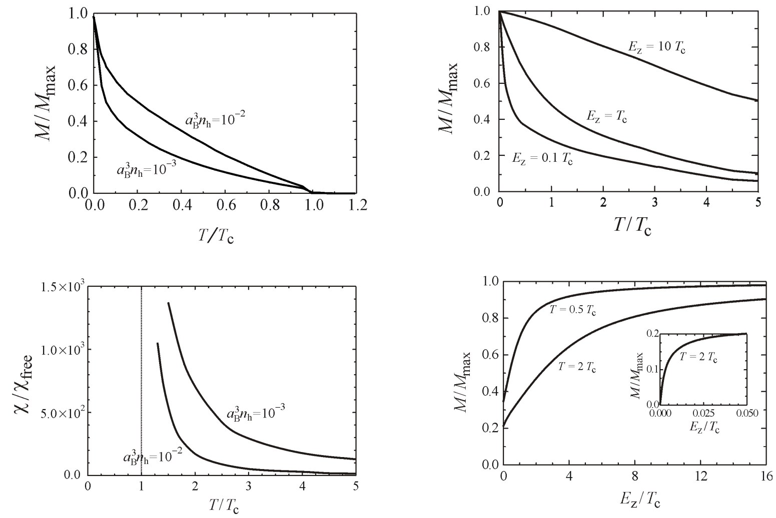


$M(T\to T_c)\propto(T_c-T)^{\beta};\quad \beta\approx 0.4$

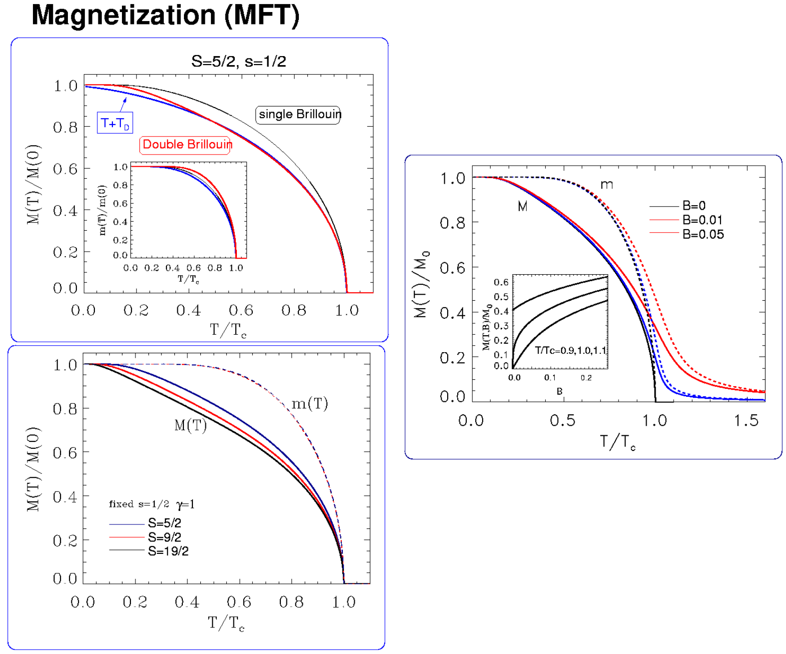
$\chi(T\to T_c)\propto(T-T_c)^{\gamma};\quad \gamma\approx 1.7$

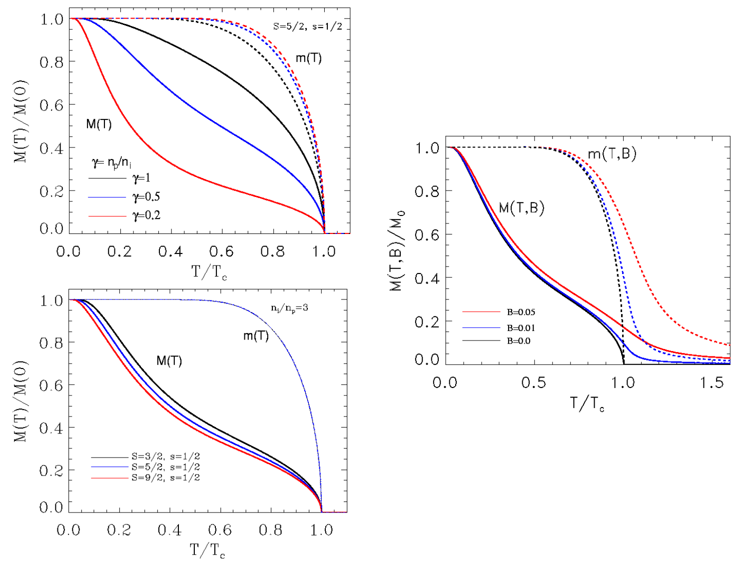
$$M(T\to 0)\approx\left(1-T^{\frac{\pi n_i a_B^3}{6}}\right)M(0)$$

$M(T,B)$ and $\chi(T,B)$



Magnetization (MFT)





· **Generalized Kondo lattice model**

Ferromagnetic order in Mn-based DMS is mediated by carriers.

$$H = H_{host} - \sum_{i,\alpha,\beta} J\hat{\mathbf{S}}_i \cdot \psi^{\dagger}_{\alpha}(R_i)\vec{\sigma}_{\alpha\beta}\psi_{\beta}(R_i) + W\psi^{\dagger}_{\alpha}(R_i)\psi_{\alpha}(R_i)$$

$$H_{host} = \sum_{\alpha} \int d^3x\,\psi^{+}_{\alpha}(x)\frac{\nabla^2}{2m}\psi_{\alpha}(x) + V_R(x)\psi^{+}_{\alpha}(x)\psi_{\alpha}(x)$$

V_R : random potential (non-magnetic defects in the material)

J : carrier-impurity (Mn) spin coupling

W : potential scattering

- **local Green function**

$$G_{loc} = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\omega - \epsilon_p - \Sigma(\omega)} = \delta \ln Z_{loc}/\delta g_0$$

- **partition function** $\rightarrow Z_{loc} = \int dS_i \exp[-S_{loc}]$

$$\text{magnetic site}: \quad S^a_{loc} = c^\dagger_\alpha(\tau) g^a_0(\tau - \tau') c_\beta(\tau') + J\mathbf{S} c^\dagger_\alpha \sigma_{\alpha\beta} c_\beta$$

$$\text{nonmagnetic site}: \quad S^b_{loc} = c^\dagger_\alpha(\tau) g^b_0(\tau - \tau') c_\beta(\tau')$$

- **self-consistent mean-field eq.**

$$g^a_0 = \omega + \mu - x\langle [g^a_0(\omega + J\mathrm{S}\sigma]^{-1}\rangle - (1-x)\langle g^b_0(\omega)^{-1}\rangle$$

- **semicircle density of state**

$$D(\epsilon) = \int \frac{d^3p}{(2\pi)^3} \delta(\epsilon - \epsilon_p) = \sqrt{4t^2 - \epsilon^2}/2\pi t^2$$

- **self-energy**: $\Sigma(\omega) = g_0(\omega) - G^{-1}_{loc}(\omega)$
- **Green function**

$$G(p,\omega) = [\omega + \mu - \epsilon_p - \Sigma(\omega)]^{-1}$$

Magnetic properties

- **magnetization**

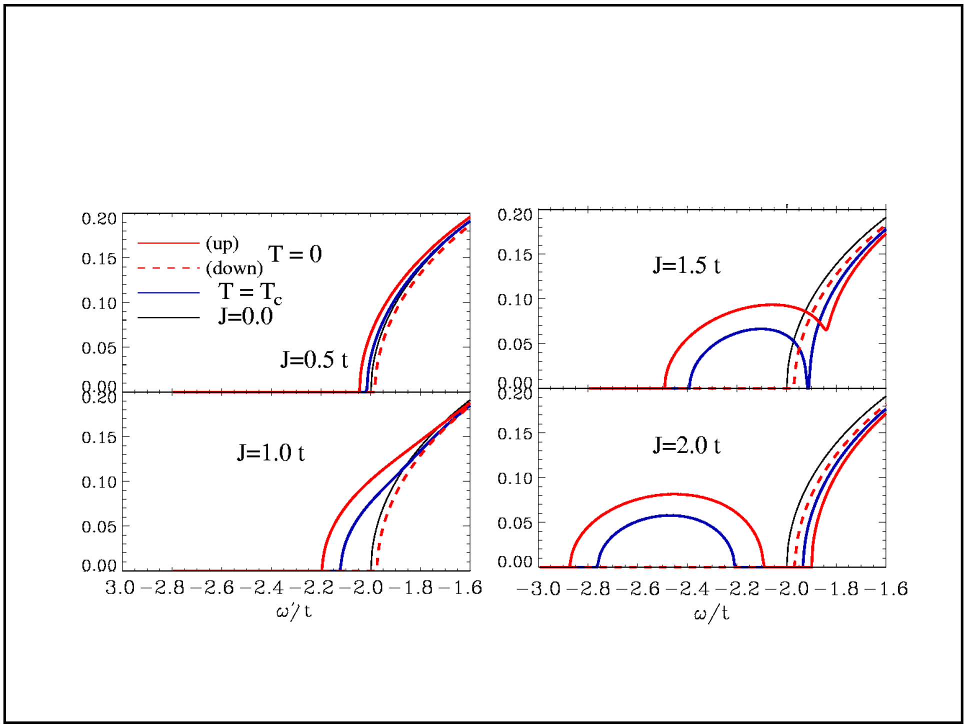
$$\langle m \rangle = \int dS_i \frac{m \exp[-S_{loc}]}{Z_{loc}}$$

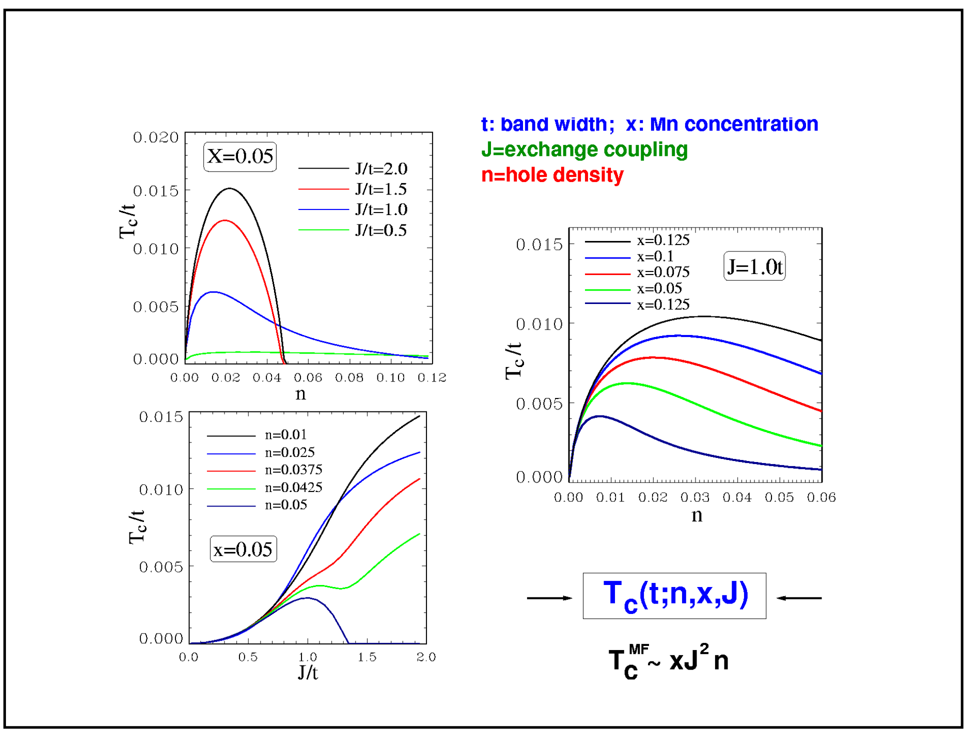
$$T_c = -\frac{2xJ^2}{3} \int_{-\infty}^{\infty} \frac{d\omega}{\pi} \mathrm{Im} \left[\frac{f_F(\omega - \mu)}{(g_0^2 - J^2)^2(1 - 1/g_0^2) - xJ^2(5/3 - J^2/g_0^2)} \right]$$

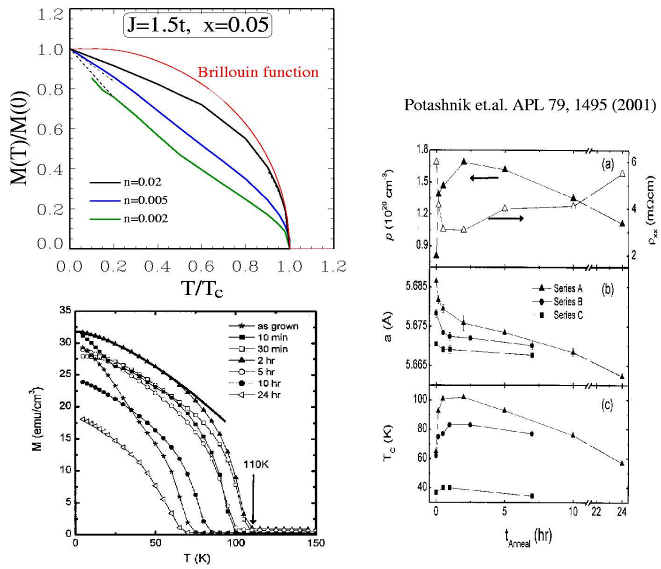
- static mean field theory : $T_c \sim J^2,\ x,\ n^{1/3}$

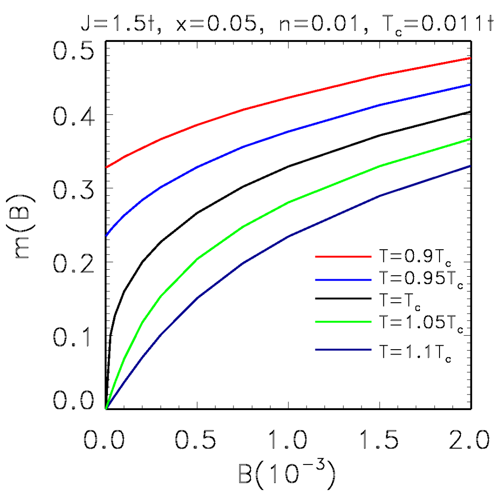
- $T \rightarrow T_c \qquad \langle m \rangle \propto (T_c - T)^{1/2}$
- $T \rightarrow 0 \qquad \langle m \rangle \propto T$

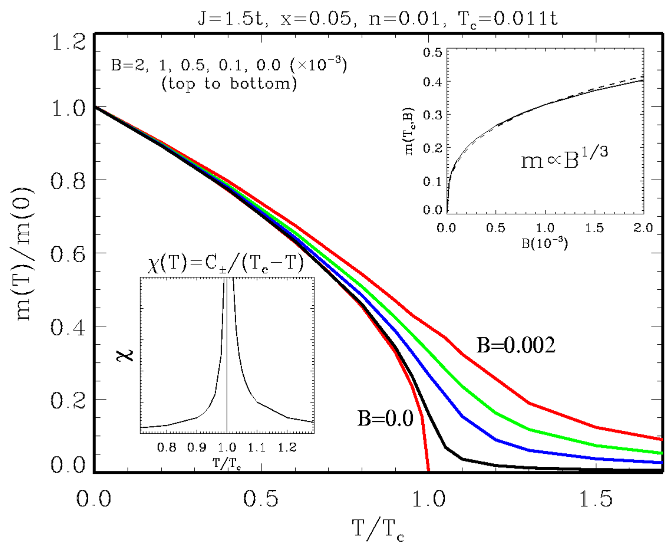
- $\chi(T) = C_\pm(x,n,J)/|T_c - T|$


(up)
(down)
T = 0
T = T_c
J=0.0
J=0.5 t
J=1.0 t
J=1.5 t
J=2.0 t
ω/t


t: band width; x: Mn concentration
J=exchange coupling
n=hole density
X=0.05
J/t=2.0
J/t=1.5
J/t=1.0
J/t=0.5
T_c/t
n
n=0.01
n=0.025
n=0.0375
n=0.0425
n=0.05
x=0.05
J/t
x=0.125
x=0.1
x=0.075
x=0.05
x=0.125
J=1.0t
T_c(t;n,x,J)
T_c^MF ~ xJ^2 n


J=1.5t, x=0.05
Brillouin function
M(T)/M(0)
T/Tc
n=0.02
n=0.005
n=0.002
Potashnik et.al. APL 79, 1495 (2001)
M (emu/cm³)
T (K)
110K
as grown
10 min
30 min
2 hr
5 hr
10 hr
24 hr
(a)
(b)
(c)
Series A
Series B
Series C
a (A)
t_Anneal (hr)


J=1.5t, x=0.05, n=0.01, Tc=0.011t
m(B)
B(10⁻³)
T=0.9Tc
T=0.95Tc
T=Tc
T=1.05Tc
T=1.1Tc


J=1.5t, x=0.05, n=0.01, T_c=0.011t
B=2, 1, 0.5, 0.1, 0.0 (×10^-3)
(top to bottom)
m(T)/m(0)
T/T_c
B=0.002
B=0.0
χ(T)=C_±/(T_c−T)
χ
m∝B^1/3
m(T_c,B)
B(10^-3)