ВЛИЯНИЕ ОРБИТАЛЬНЫХ СТЕПЕНЕЙ СВОБОДЫ ЭЛЕКТРОНА НА МАГНИТОТРАНСПОРТ В ПОЛУПРОВОДНИКАХ

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Motivation

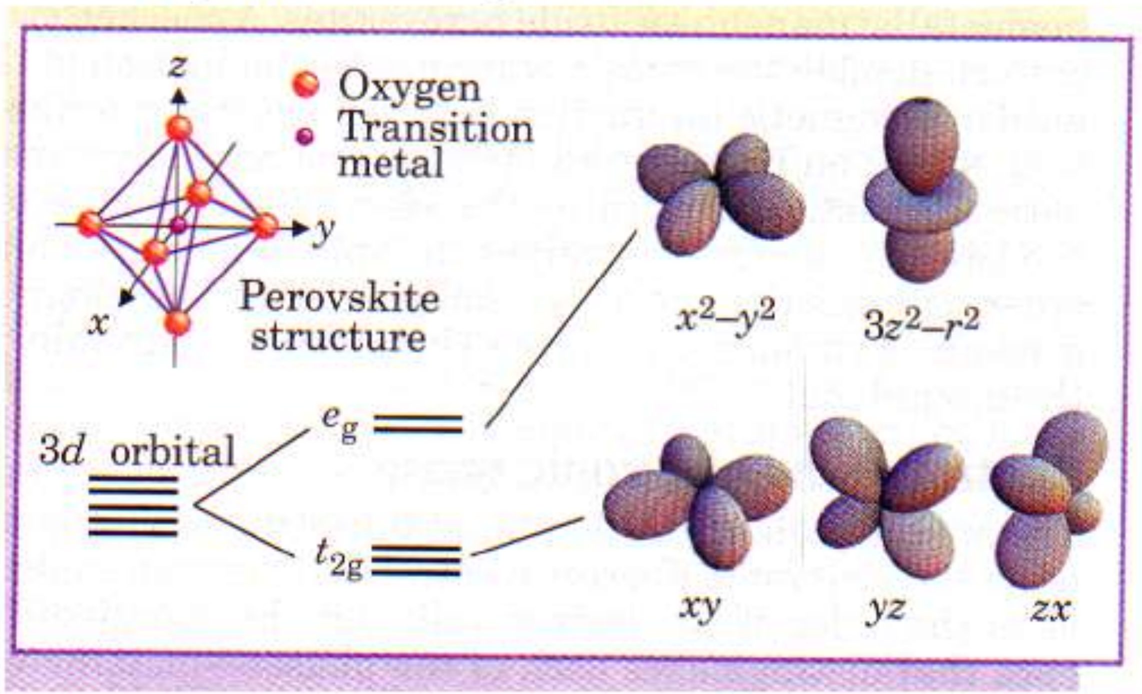
Searching and research of materials for spintronics on the basis of a magnetoresistance is an actual task. The materials reveled magnetoresistance in paramagnetic state in the room temperatures are interest.
The electronic doping of manganese sulfides in results of substitution of rare-earth ions with variable valance can induce spin, charging and orbital ordering with close relationship between them. Magnetic properties can change under electric field and dielectric properties under pressure.

Outline

1. Magnetoresistance in non-magnetic compounds and paranagnetic state
2. Resistance and I-U dependence of TmxMn1-xS versus magnetic field
3. Magnetoimpeduns and magnetocapacity
4. Polarization and pyrocurrent
5. Magnetic properties of TmxMn1-xS

Partially the filled t2g-level of d^1 (Ti^{3+}, V^{4+}), d^2 (Ti^{2+}, V^{3+}, Cr^{4+}) ions in an octahedral environment

3- d ион в кристаллическом поле кубической решетки

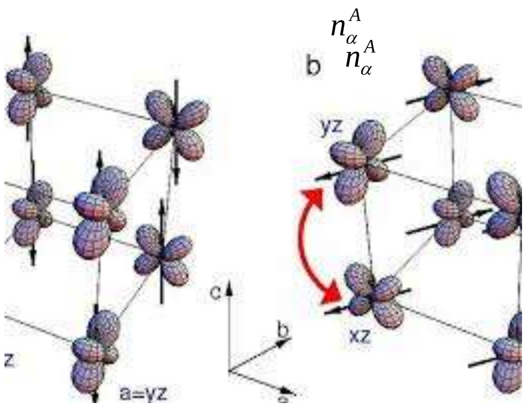


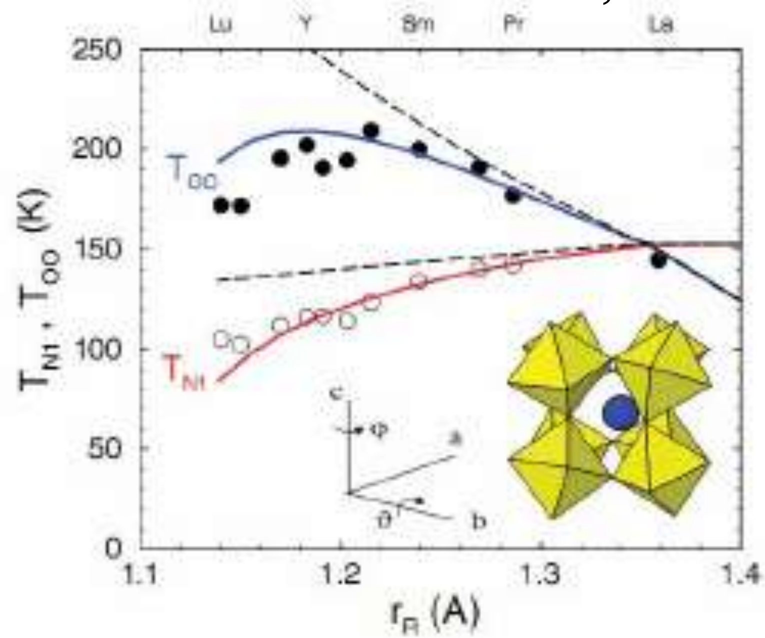
$$\frac{1}{\sqrt{2}}(|yz\rangle \pm |zx\rangle)$$

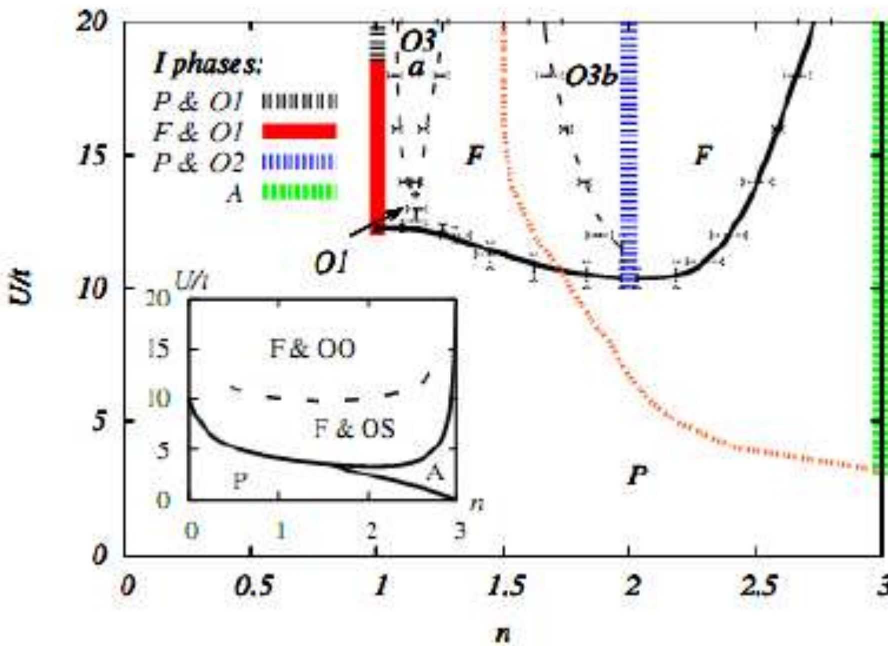
Orbital ordering: AFM, FM, incommensurate

J.-S. Zhou et al PRL, 2007, v. **99**, p. 156401

ReVO3, KCuCl3

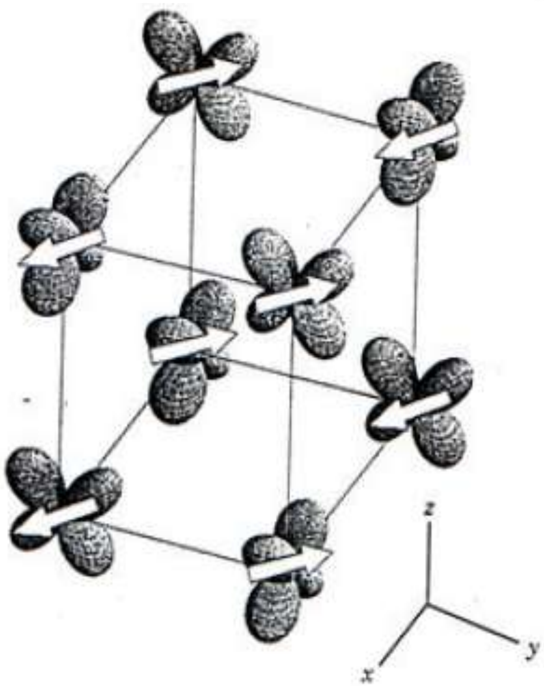


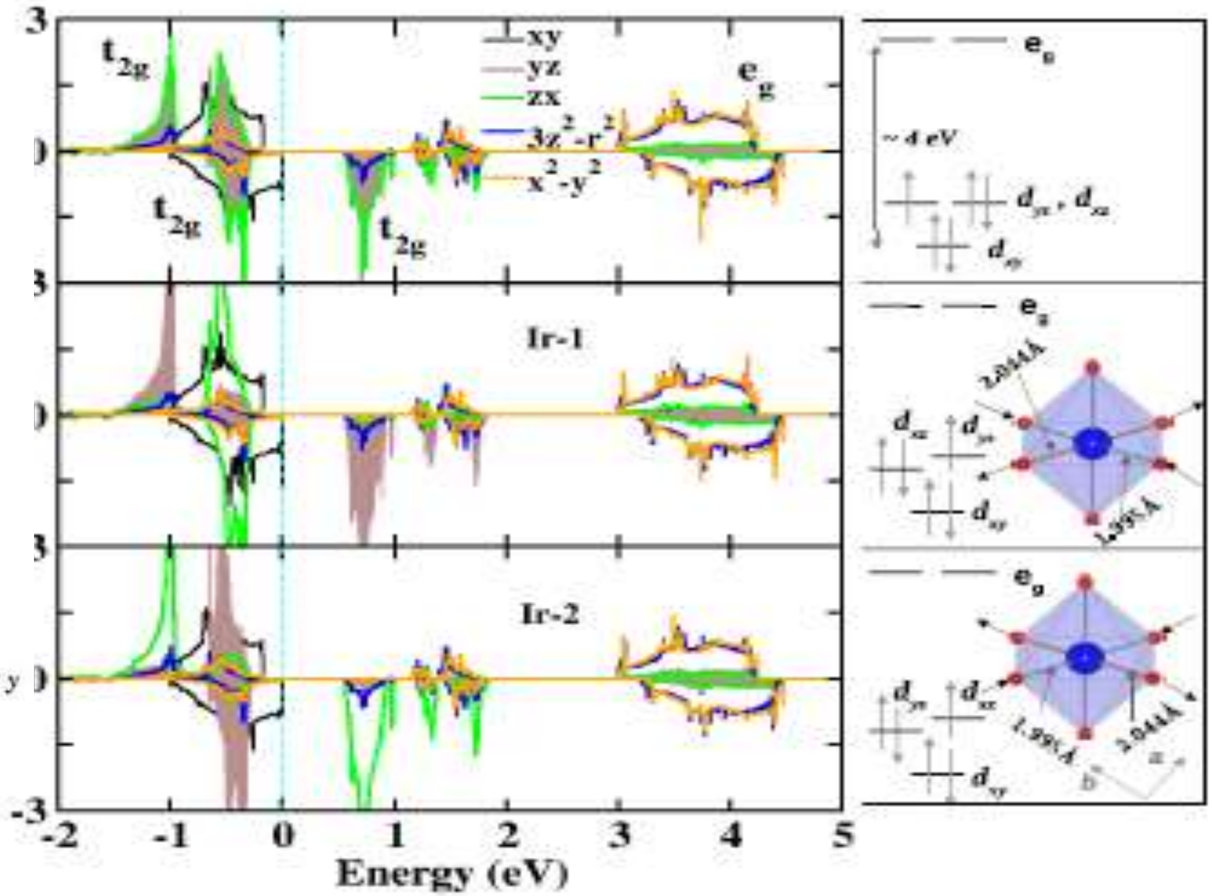




$(n_\alpha^A, n_\beta^A, n_\chi^A \mid n_\alpha^B, n_\beta^B, n_\chi^B)$	
$(1-\delta, \delta, \delta \mid \delta, \frac{1}{2}, \frac{1}{2})$	(↑↑↑|↑↑↑)
$(\frac{1}{2}, \frac{1}{2}, 1 \mid 1, 1, 0)$	(↑↑↑|↑↑0)
$(1-2\delta, 2\delta, \delta \mid \delta, 2\delta, 1-2\delta)$	(↑↑↑|↑↑↑)
$(2\delta, 1-2\delta, 1-\delta \mid 1-\delta, 1-2\delta, 2\delta)$	(↑↑↑|↑↑↑)

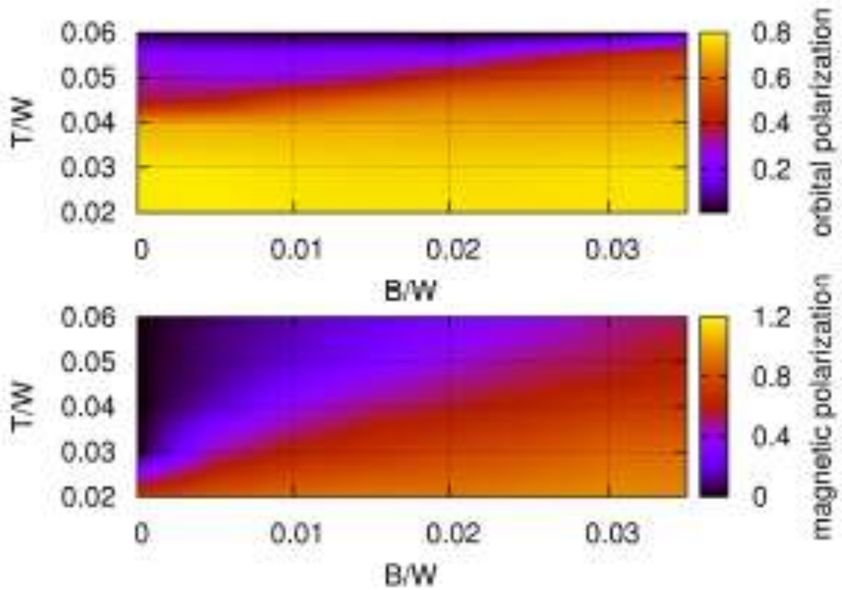
• Electron structure Sr2CeIrO6 with Ir^4 (5d 5, S=1 2) with AFM dyz и dxz orbital and two bond length . The experimental band gap (≈ 0.3 eV) agrees qualitatively with the Ir eff GGA+U+SOC (U eV) AFM band gap (≈ 0.35 eV) . Martin Jansen,∗ arXiv:1507.08682v1

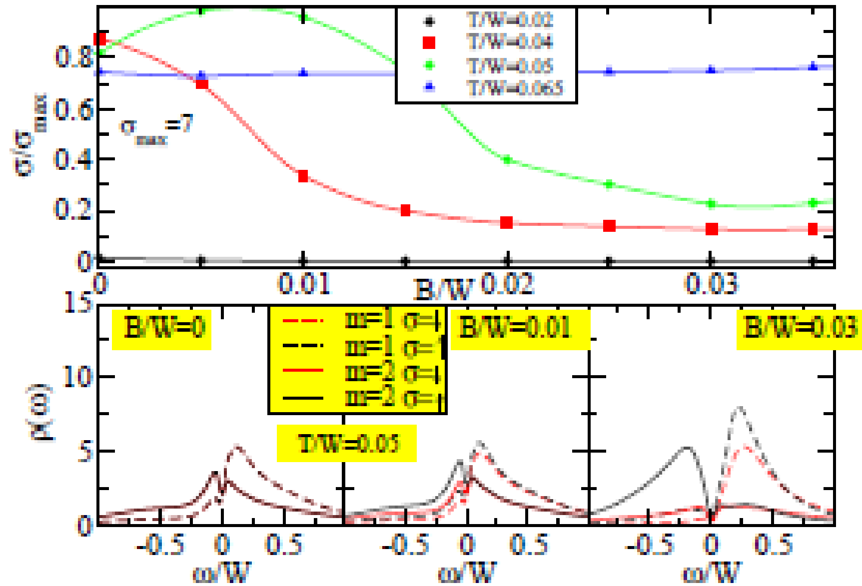




Change of resistance in a magnetic field upon transition to an orbital-ordered state.

Robert Peters* and Norio Kawakami PRL 117, 076801 (2011)





$$H = H_T + H_U$$

$$H_T = \sum_{<i,j>,\sigma,m} t_{i,j} c^\dagger_{i,\sigma,m} c_{j,\sigma,m} \qquad U/W = 4,$$

$$H_U = \sum_i \Big(\sum_m U n_{i,\uparrow,m} n_{i,\downarrow,m} + \left(U' - \frac{J}{2} \right) (n_{i,\uparrow,0} + n_{i,\downarrow,0})(n_{i,\uparrow,1} + n_{i,\downarrow,1}) - 2J \vec{S}_{i,0} \cdot \vec{S}_{i,1} \Big),$$

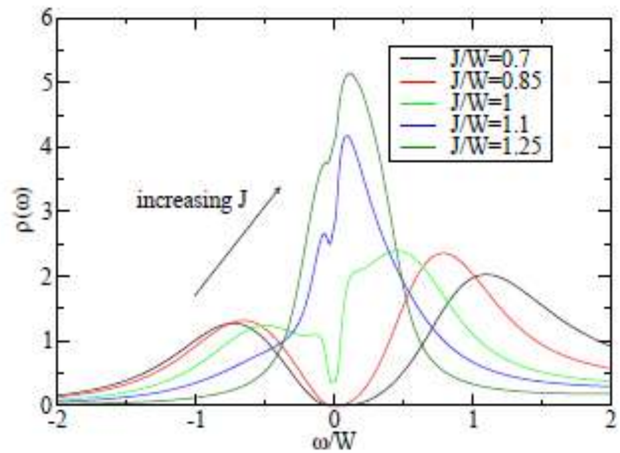


Figure 5. (color online) Spectral functions for $U = 4W$, $T/W = 0.08$, $U' = U - 2J$, and different J. For all shown spectral functions the system is in a paramagnetic state. For

Топологические изоляторы

$$H_{so} = \frac{\alpha_R}{\hbar}\vec{e}_z[\vec{\sigma} \times (\vec{p} - e\vec{A})].$$

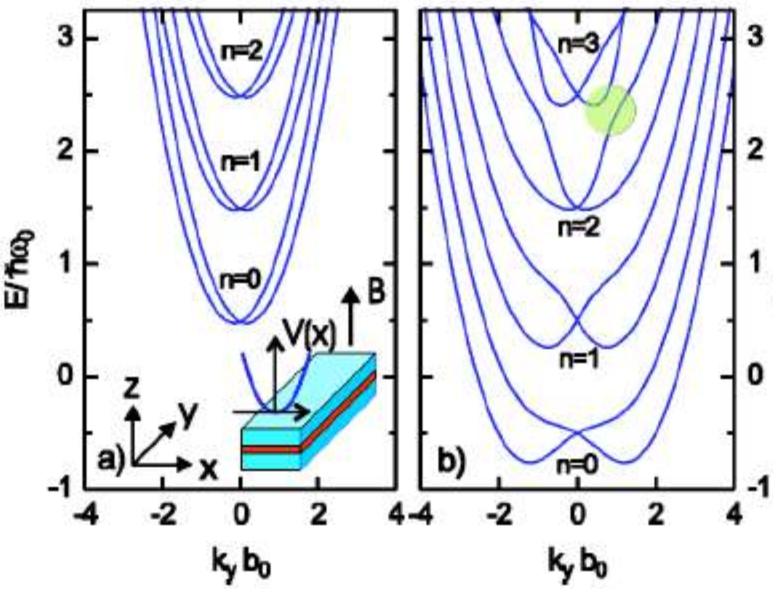
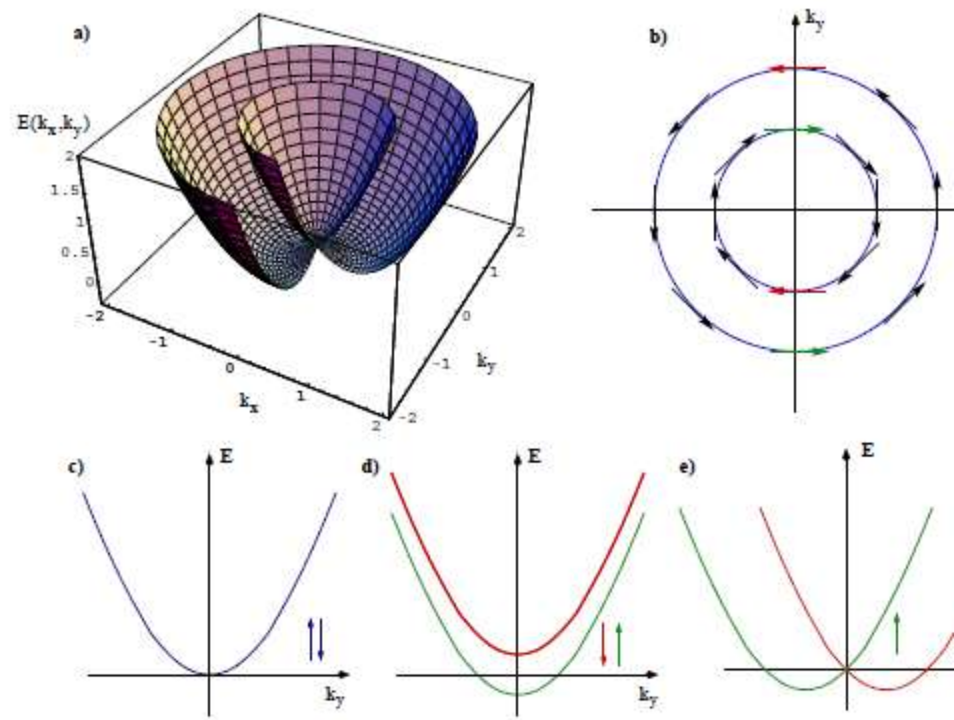
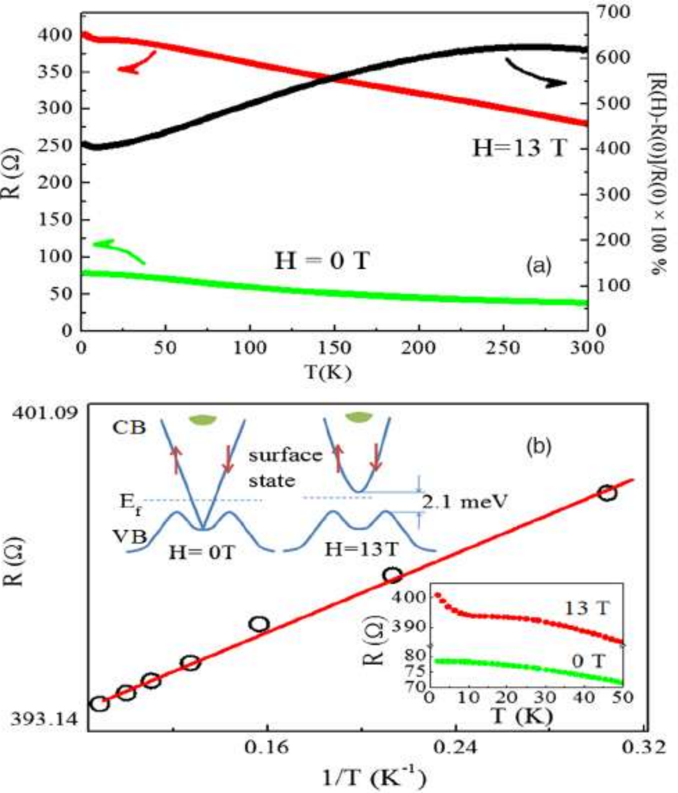


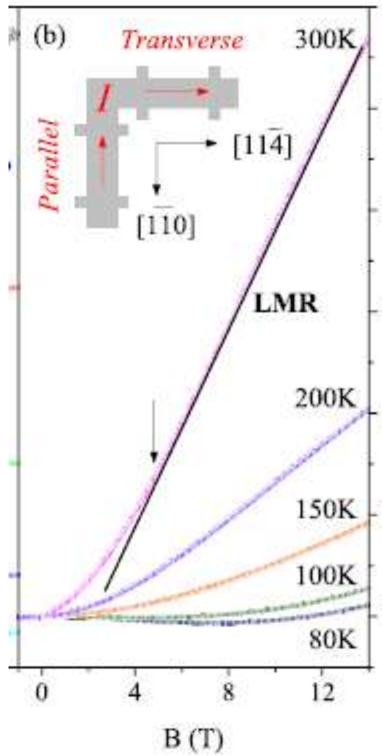
FIG. 1. (Color online) Energy dispersion of the spin-split su
bands at B=0 for weak spin-orbit coupling: $\Delta_{so}/\hbar\omega_0$=0.01 (a) a
for strong spin-orbit coupling for $\Delta_{so}/\hbar\omega_0$=1 (b). The anticrossi



$$\mathcal{E}_{\pm}(\vec{k}) = \frac{\hbar^2 k^2}{2m} \pm \alpha k = \frac{\hbar^2}{2m}(k \pm k_{\mathrm{SO}})^2 - \Delta_{\mathrm{SO}},$$

Магнитосопротивление в топологических изоляторах





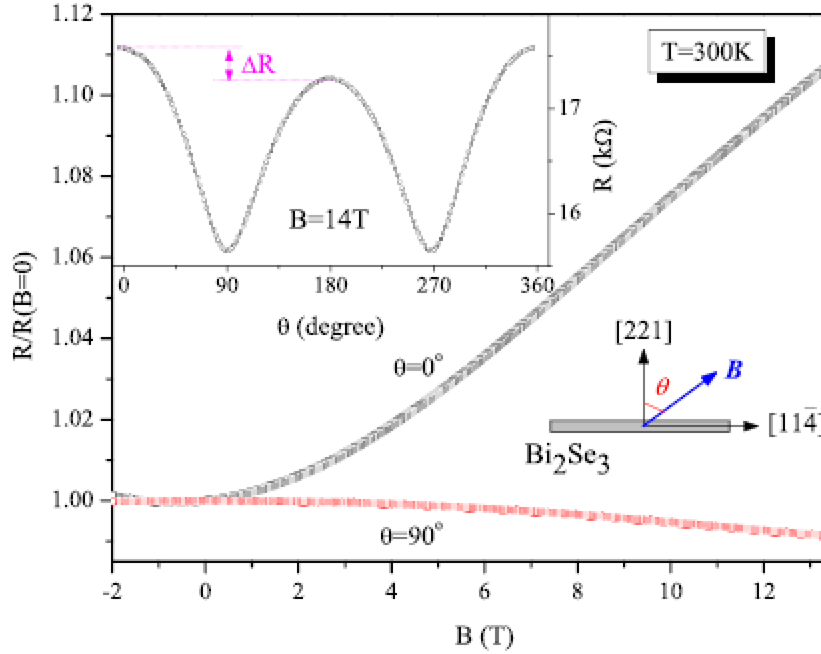


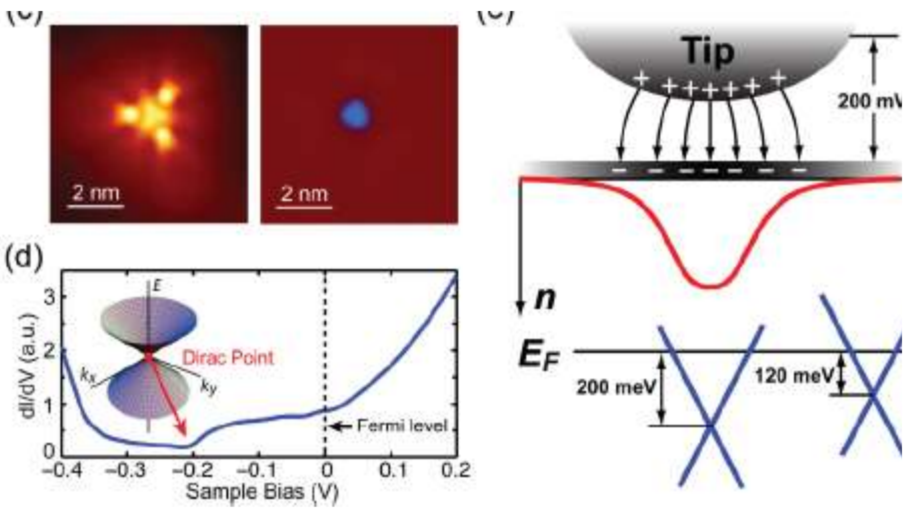
FIG. 2 (color online). (a) Temperature dependence of the esistance and magnetoresistance of a Bi_2Te_3 nanosheet.

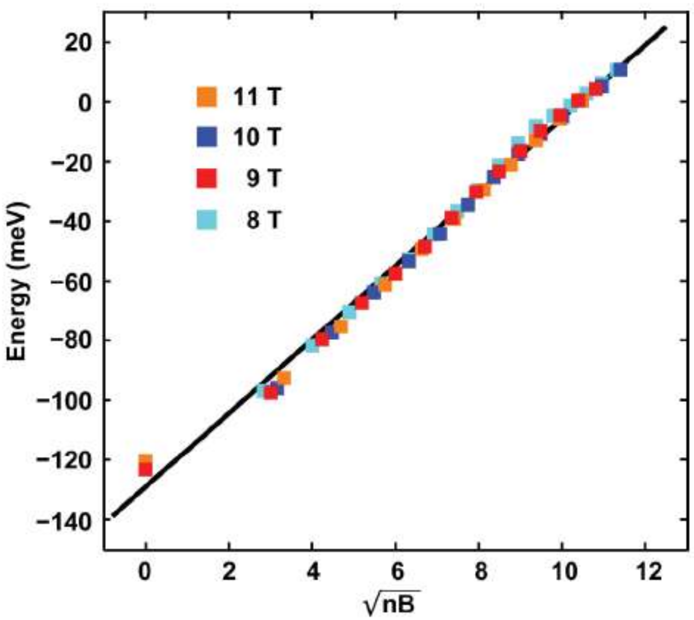
Xiaolin Wang PRL **108**, 266806 (2012)

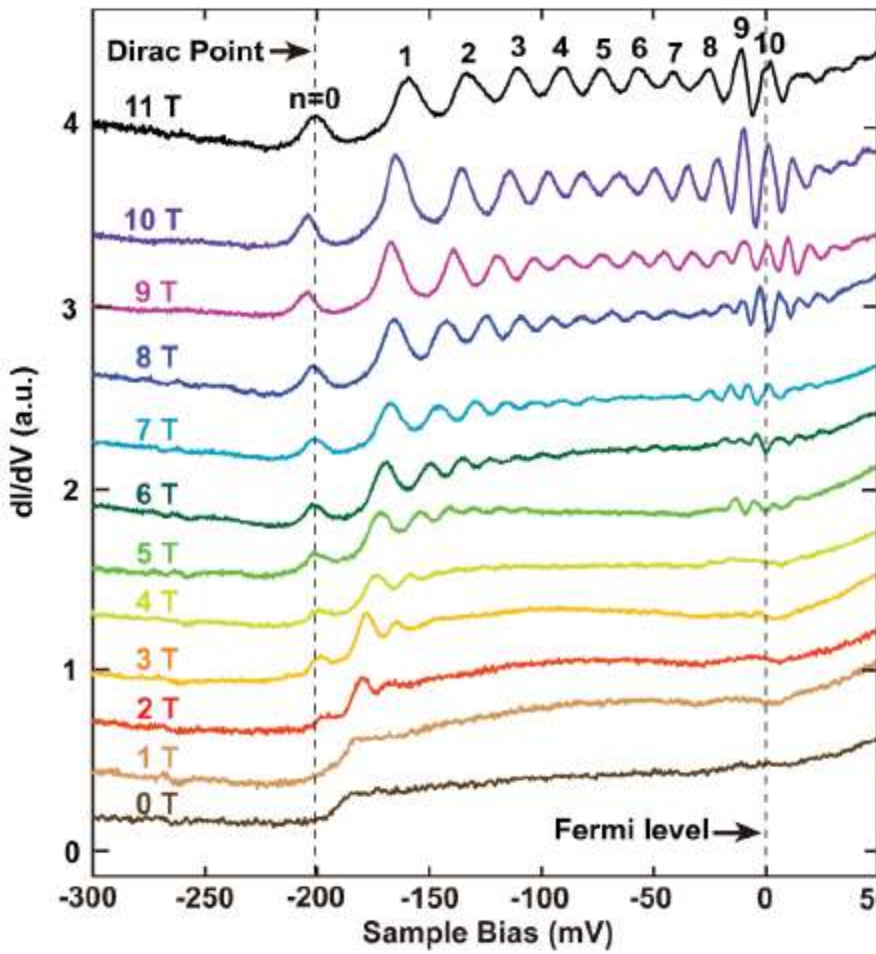
Appl. Phys. Lett. **103**, 031606 (2013)

Peng Cheng,[1] Canli Song,[1] PRL **105**, 076801 (2010)

Уровни Ландау в магнитном поле







IG. 2 (color). Landau quantization of the topological states. he film is 50 QL thick. The differential tunneling spectra were cquired for various magnetic fields from 0 to 11 T. The field is

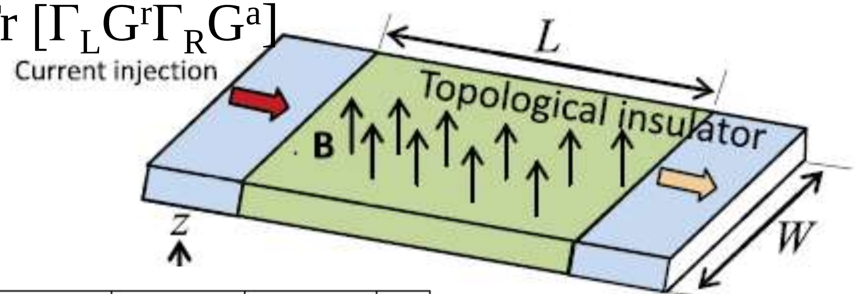
$$E_n = E_D^0 + \mathrm{sgn}(n) v_F \sqrt{2eB\hbar|n|}, \qquad n = 0, \pm 1, \pm 2, \ldots,$$

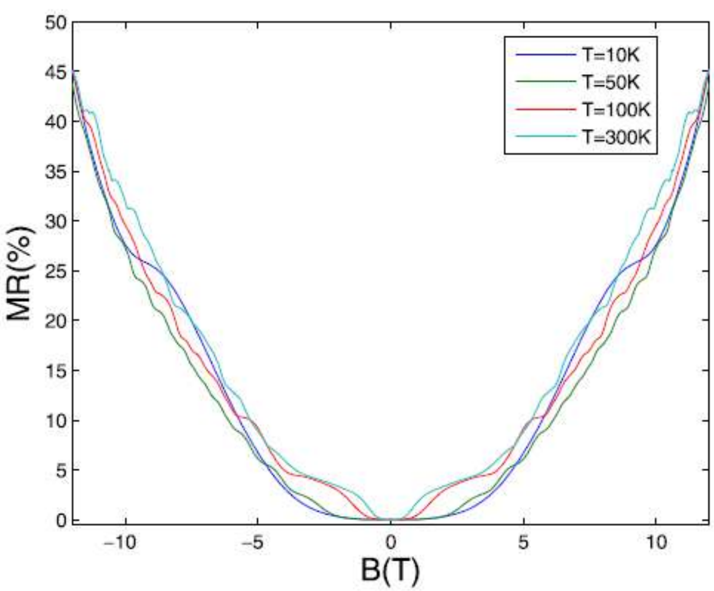
Вычисление магнитосопротивления в модели со спин-орбитальным взаимодействием

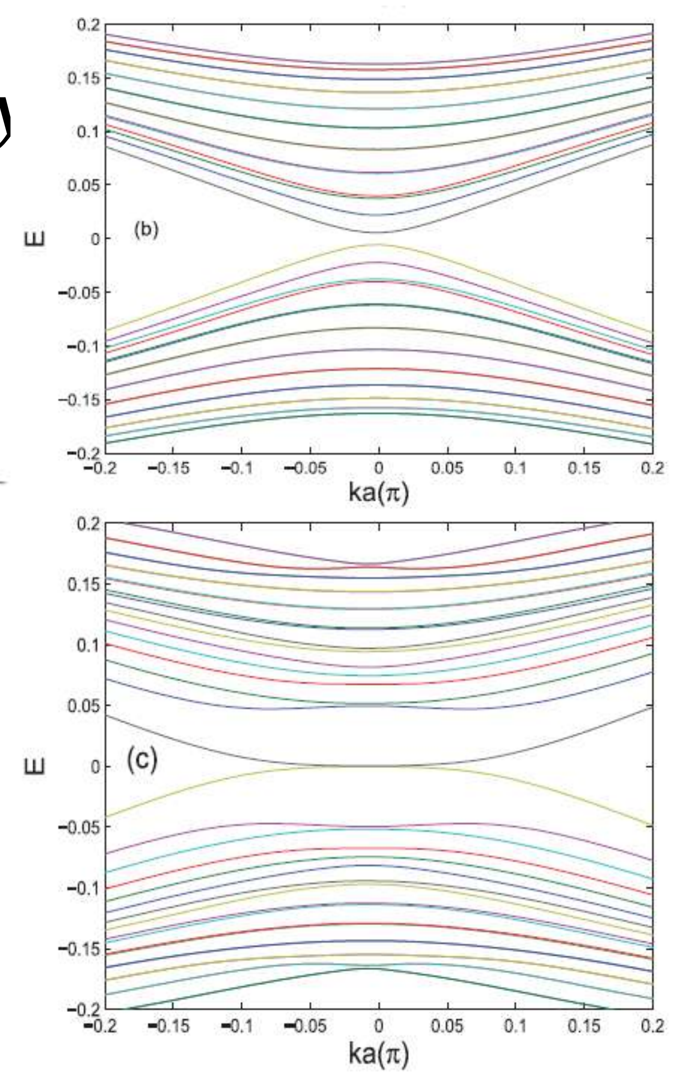
$$H = v_F((p+eA)\times\sigma)\cdot z + V(x,$$

$$J = \frac{e}{h}\int dE T_{LR}(E)[f_L(E) - f_R(E)]$$

, $T_{LR}(E) = \mathrm{Tr}\,[\Gamma_L G^r \Gamma_R G^a]$







. 2. Energy band structure of the TI waveguide confined in the y-directio the cases (a) $B=0$, (b) $B=2$ T, and (c) $B=8$ T. The lattice constant a i m, the length L is 60 nm and the width W is 40 nm, and the Fermi velocit is chosen as 5.0×10^5 m/s.

APPLIED PHYSICS LETTERS **103**, 031606 (2013)

H.T. He and et. al

Electrical-field induced giant magnetoresistivity in (non-magnetic) phase change films

Junji Tominaga, APPLIED PHYSICS LETTERS 99, 152105 (2011)

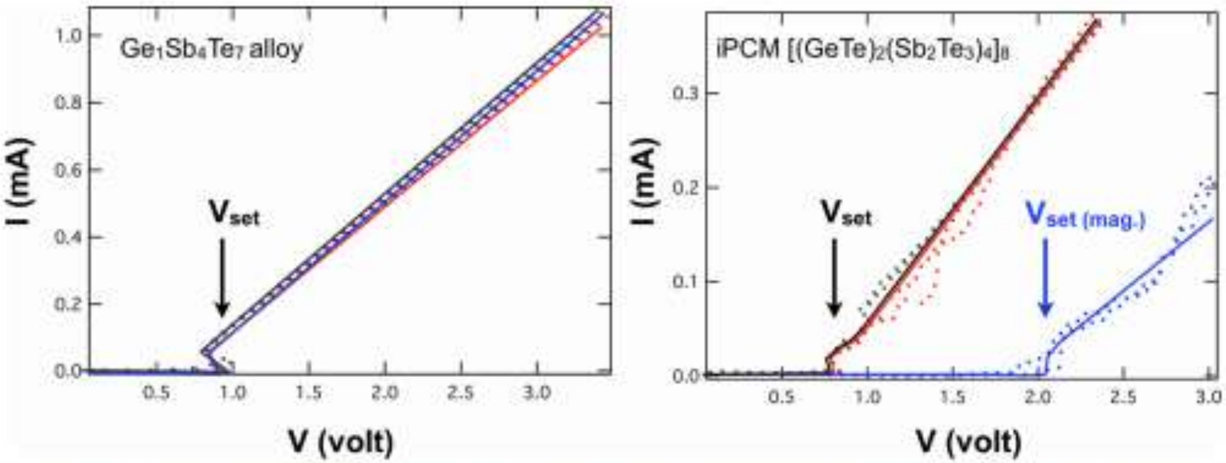
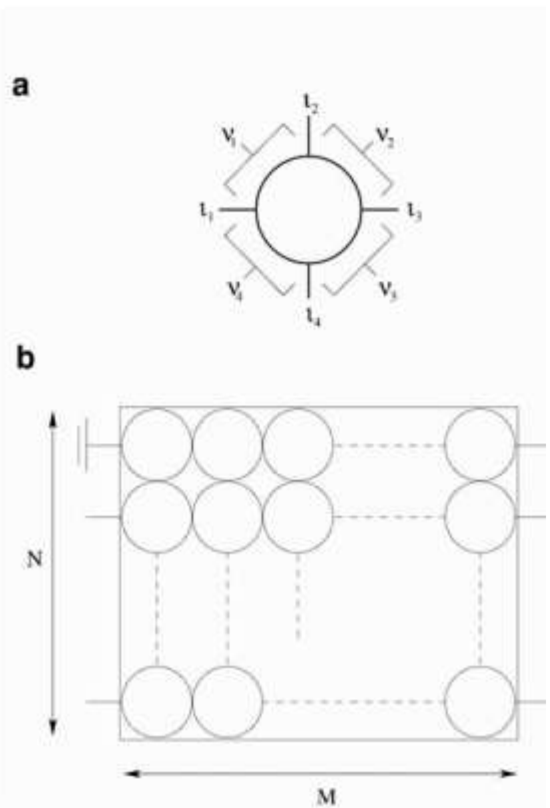
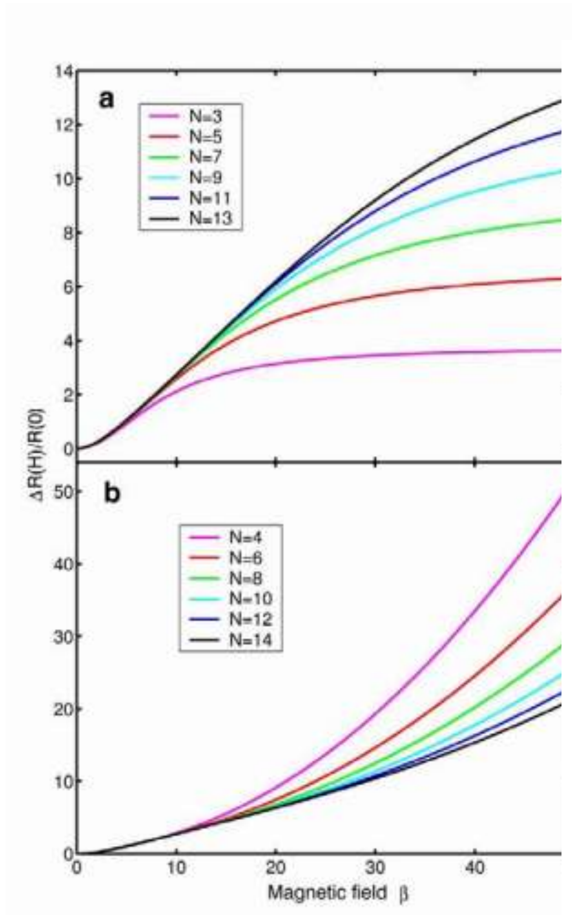


FIG. 2. (Color online) Current-Voltage characteristics of a PCRAM device fabricated using composite $Ge_1Sb_4Te_7$ (left) and an identical composition *i*PCM device (right). As the voltage reaches the threshold value of V_{set}, the device switches into the low-resistance state. Device characteristics prior to application of a magnetic field, with an external magnetic field of 0.1 T applied, and after removal of the field are shown. The composite device (left) did not show any change among the three states, while the iPCM device (right) clearly showed a voltage shift under the magnetic field, indicated as Vset(mag.). A sequence of 300 ns pulses was used for the measurements. Two scans for each state are shown to demonstrate reproducibility. Dots are experimental data and solid lines are guides for the eye.

Non-saturating magnetoresistance in heavily disodered semiconductors M.M. Parish, P.B. Littlewood. **Nature, 426, 162 (2003)**





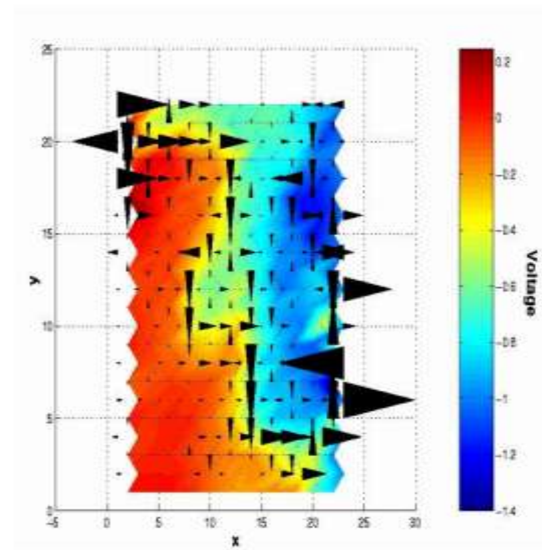


Figure 3 Visualisation of currents and voltages at large magnetic field in a 10×10 random network of disks with radii 1 (arbitrary units), where the potential difference $U=-1V$. The black arrows represent the currents, where arrow size depicts the magnitude of the current. The major current path is perpendicular to the applied voltage a significant proportion of the time, which implies that the magnetoresistance is provided internally by the Hall effect, which is therefore linear in H.

$$R_{NM} = \frac{U}{\sum_i I_i} = \frac{U}{\sum_i Z_{ij}^{-1} V_j}$$

where $\beta = \mu H$, μ is the carrier mobility

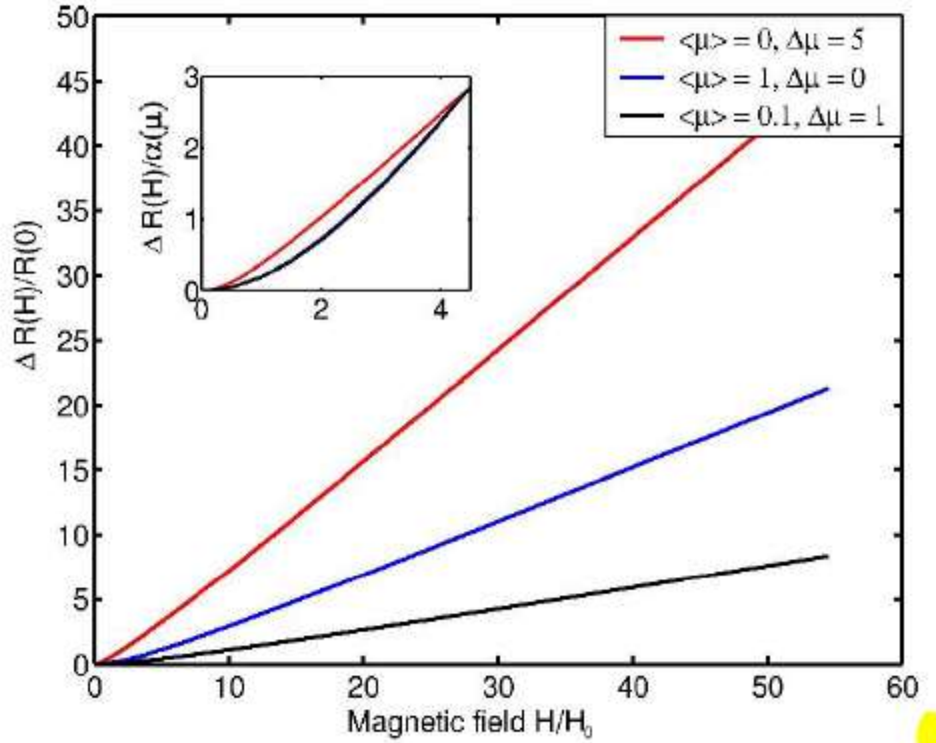


Figure 4 Average normalised magnetoresistance $\Delta R(H)/R(0)$ as a function of dimensionless magnetic field H/H_0 of 20×20 random resistor networks for different mobility distributions, where $H_0 = 1\mathrm{kOe}$ is a typical field scale. The magnetoresistance was averaged over 10 random network configurations and the mobility distributions were taken to be Gaussian and measured in units of

Magnetocapacitance in non-magnetic inhomogeneous media

Meera M. Parish PRL, 101, 166028 (2008)

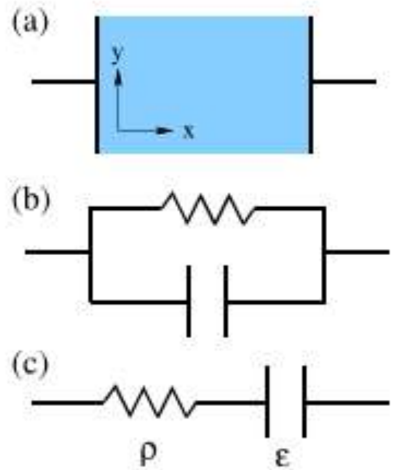


FIG. 1: Simple circuits of resistors $\hat{\rho} \equiv \hat{\sigma}^{-1}$ and capacitors ε that illustrate the basics of dielectric response. Diagram (a) depicts the measuring set-up, where a rectangular sample is confined between metallic plates and subjected to an applied electric field $E_x\hat{x}$, (b) represents a simple homogeneous medium, and (c) represents the simplest metal-insulator composite that exhibits the Maxwell-Wagner effect.

$$\Re[\varepsilon_{xx}(\omega)] = \frac{\varepsilon(1-\beta^2+(\omega\tau)^2(1+\beta^2)^2)}{1+(\omega\tau)^2(1+\beta^2)^2}$$

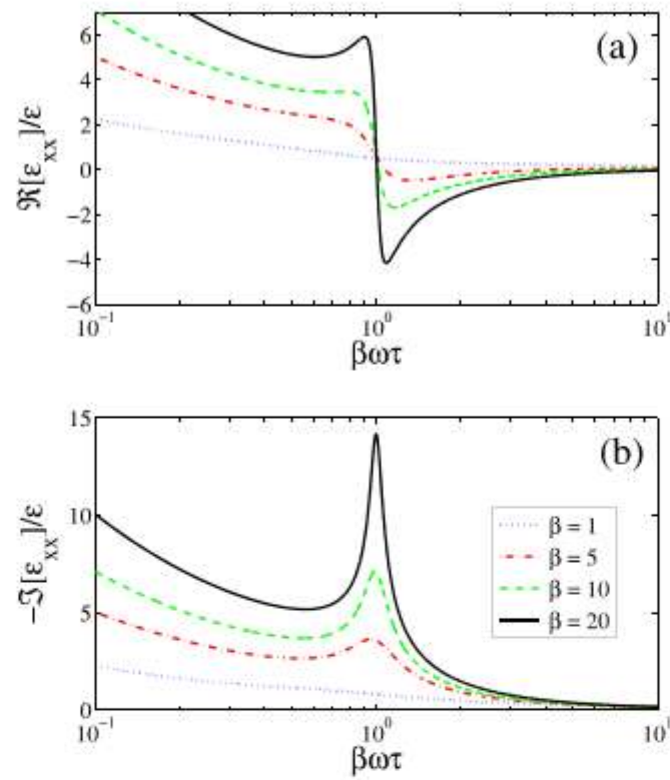
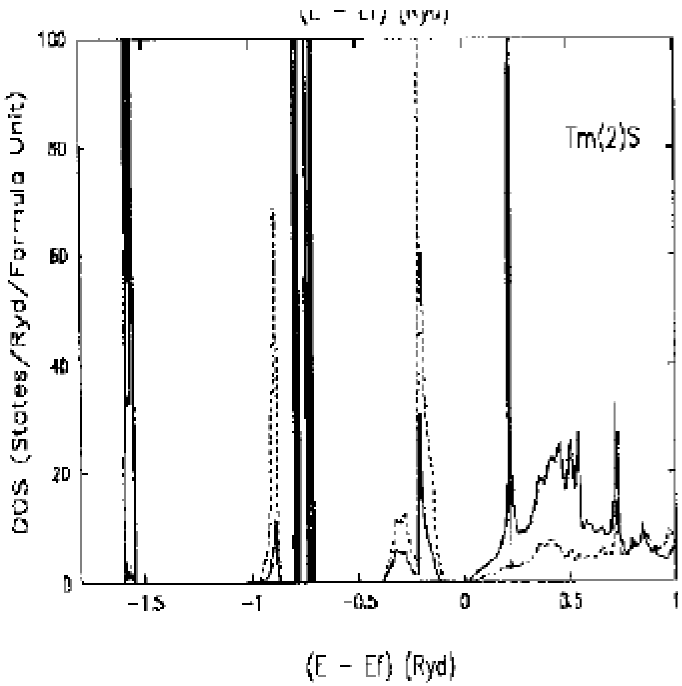
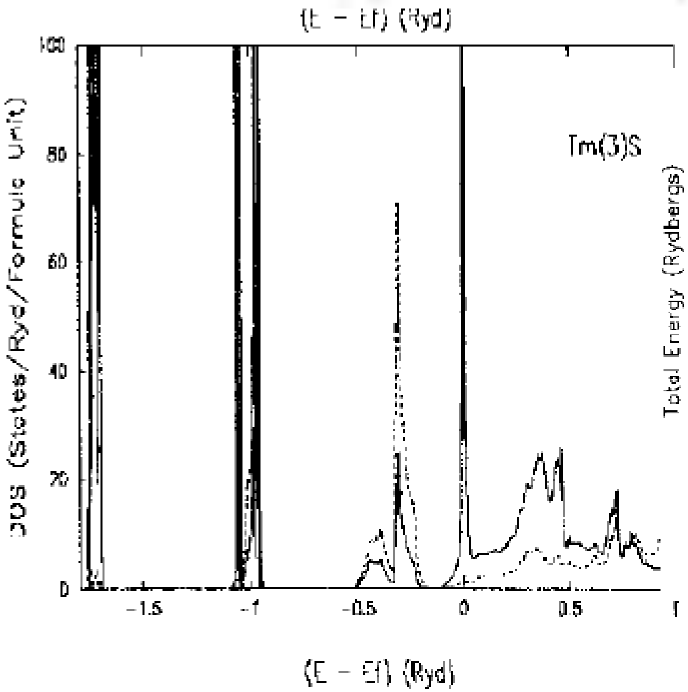


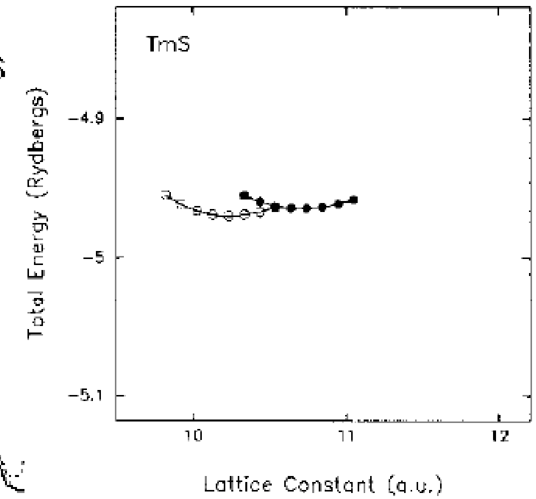
FIG. 2: Dielectric response versus frequency over a range of magnetic fields β for a 2D two-component medium with equal proportions ($p = 1/2$). When $\beta > 1$, there is a resonance at normalized frequency $\beta\omega\tau = 1$, where the real part (a) varies rapidly, eventually changing sign, while the imaginary part (b) exhibits a peak.

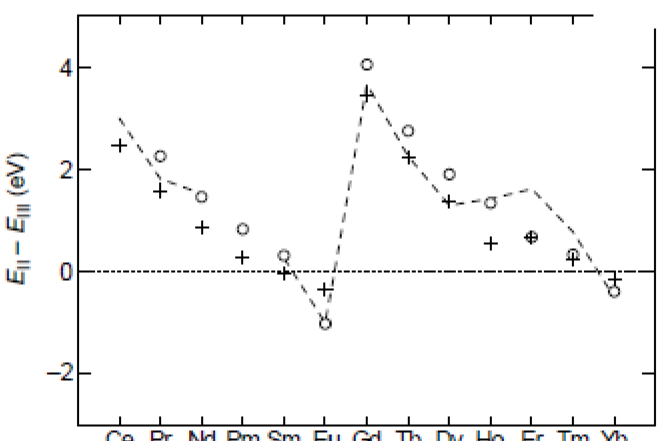
Electron structure of divalent and trivalent thulium in TmS

NATURE | VOL 399 | 24 JUNE 1999

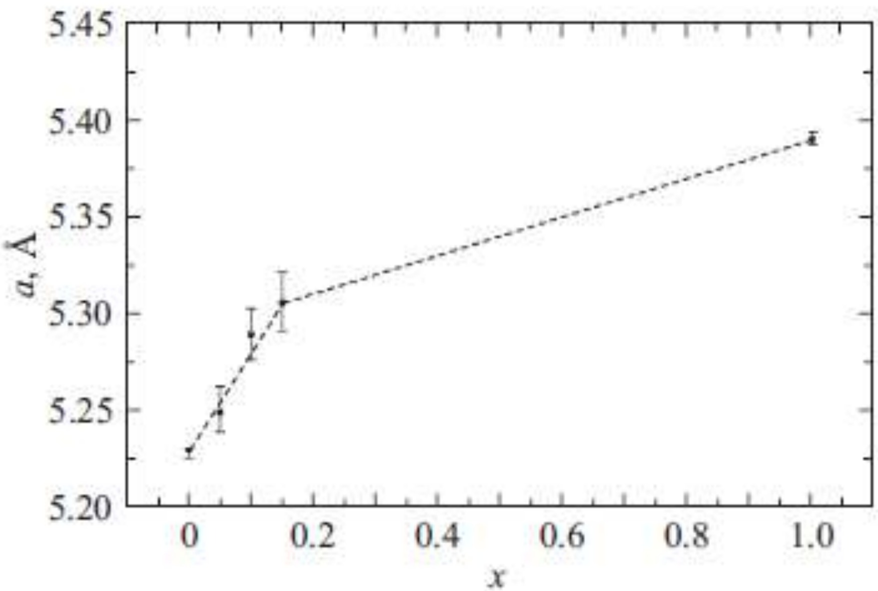


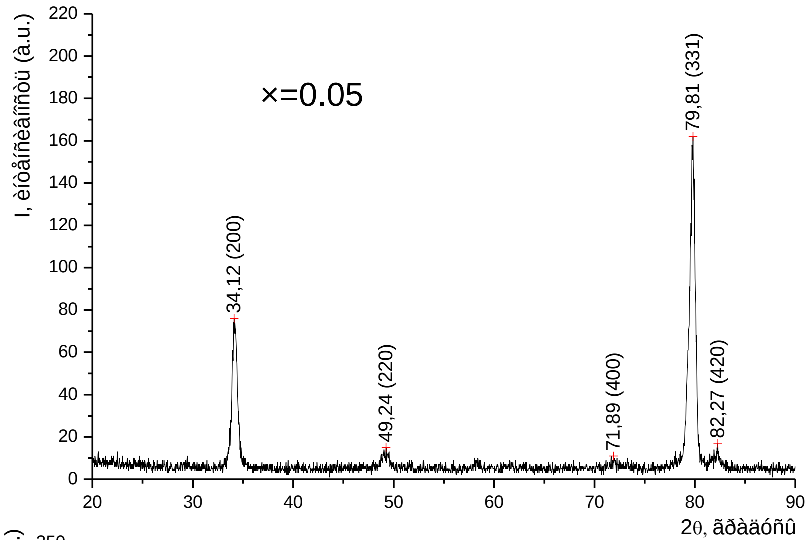


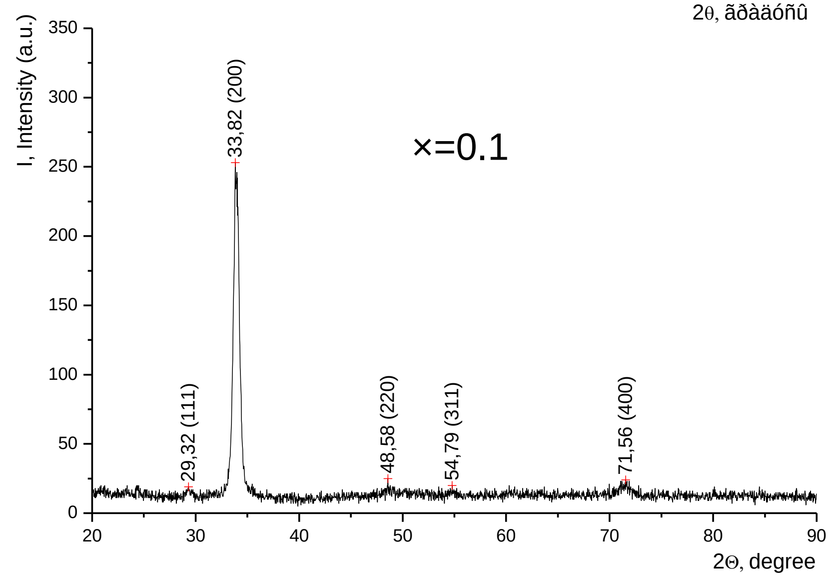




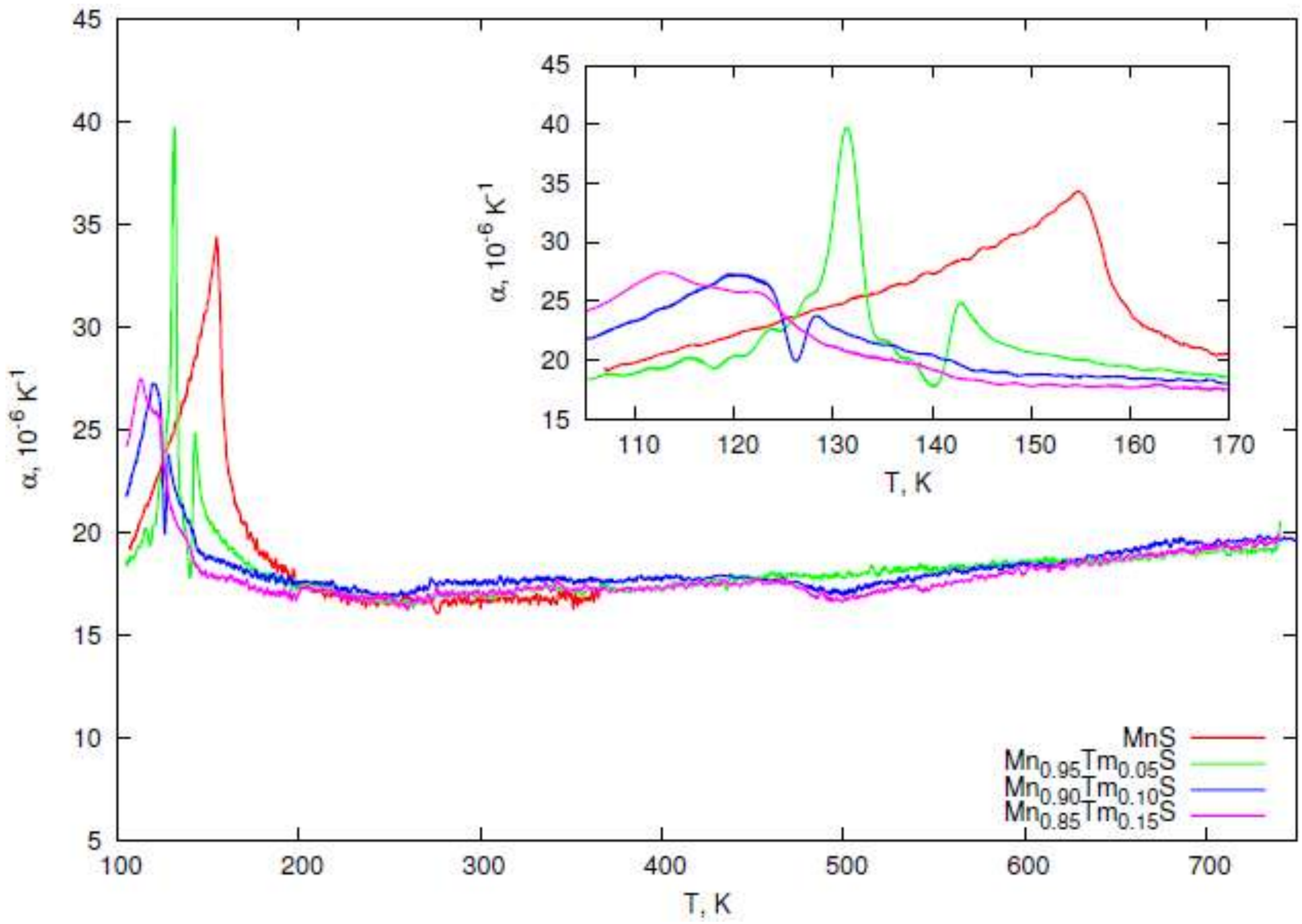
X-ray and lattice constant TmxMn1-xS



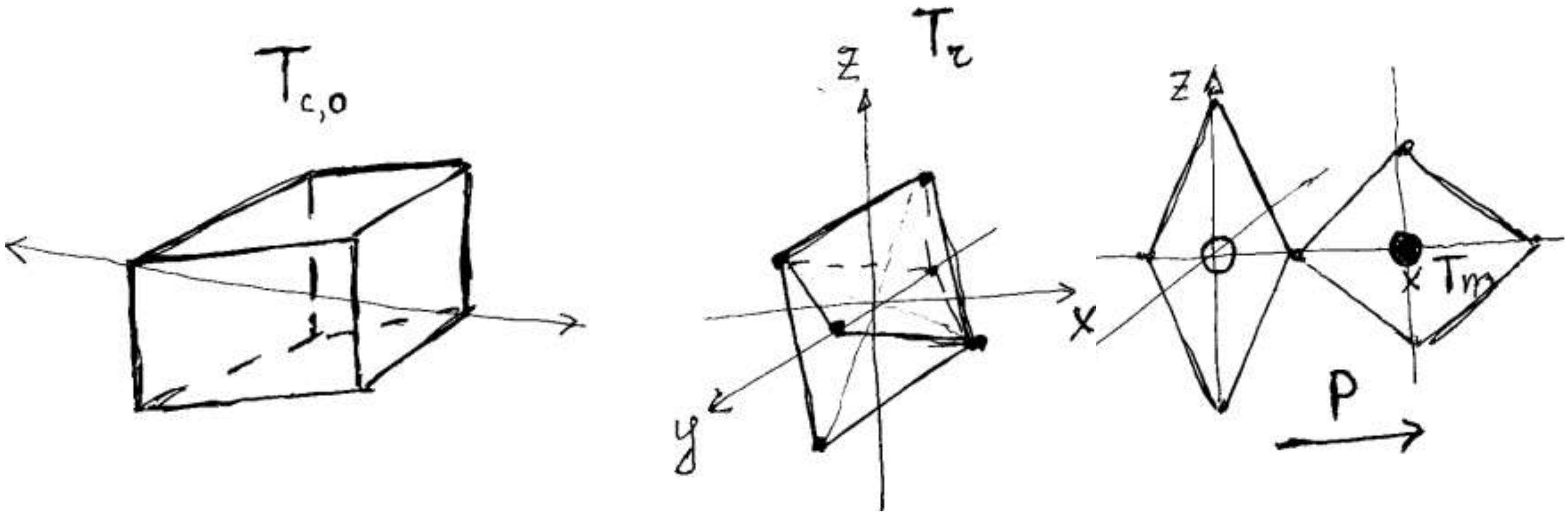




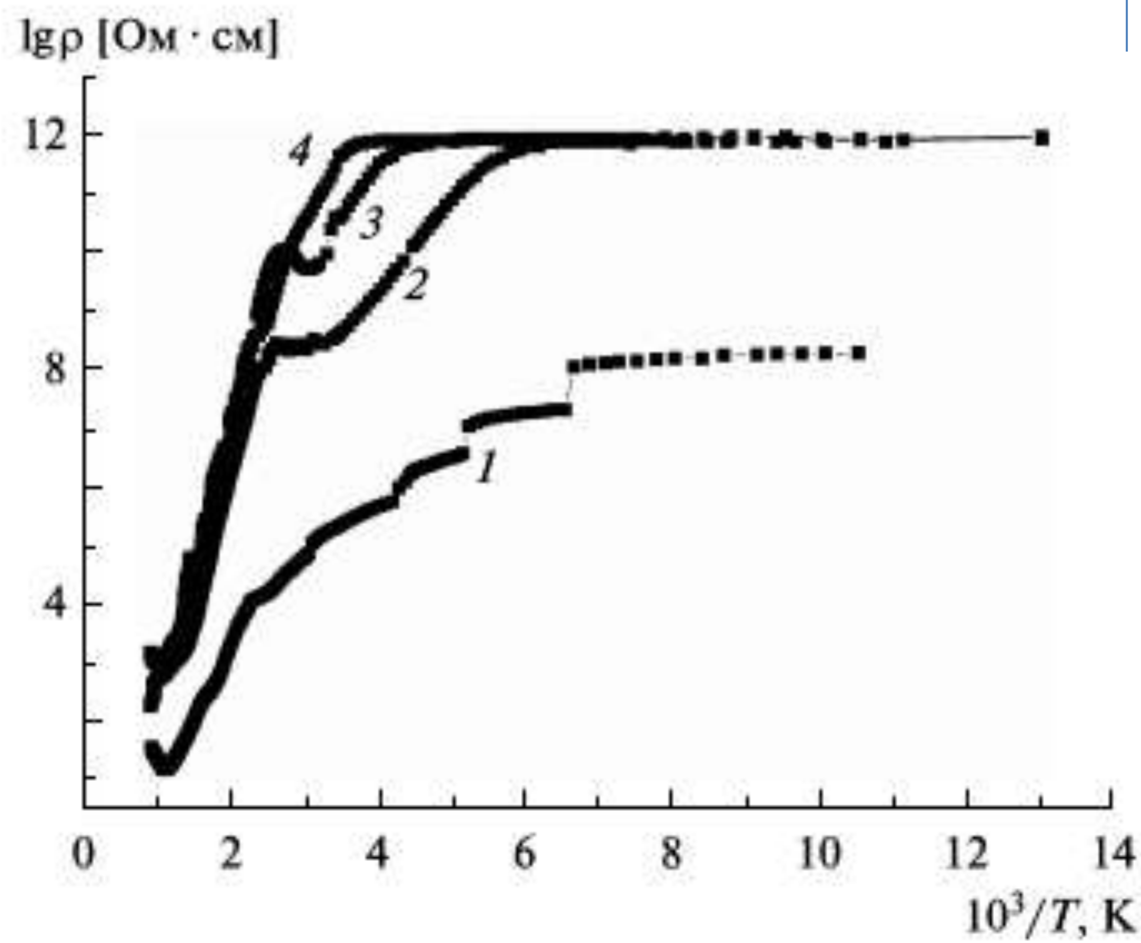
Thermal expansion coefficient TmxMn1-xS for x=0, 0.05, 0.1, 0.15.



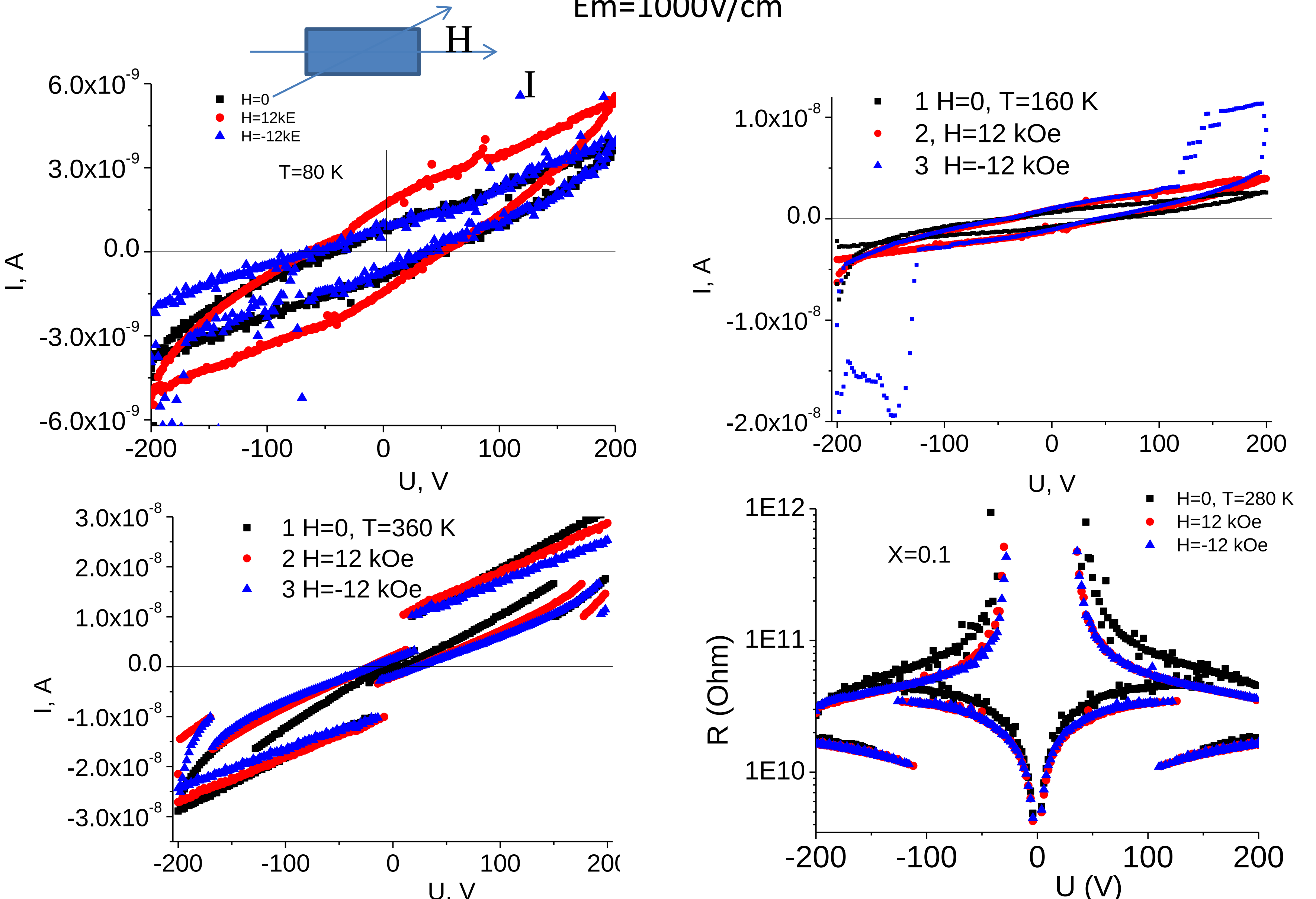
Deformation of crystal structure versus temperature



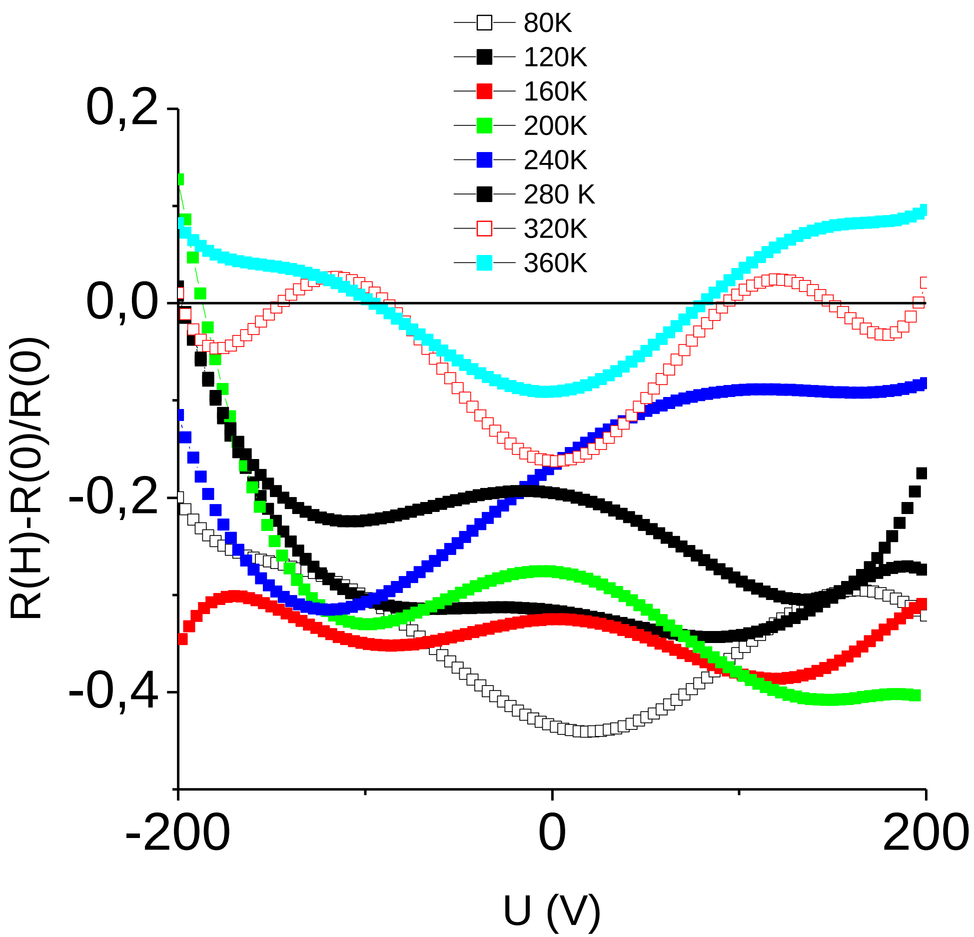
Resistance of TmxMn1-xS x=0.05 (2), 0.1 (3), 0.15 (4) measured by two contact method (b) .



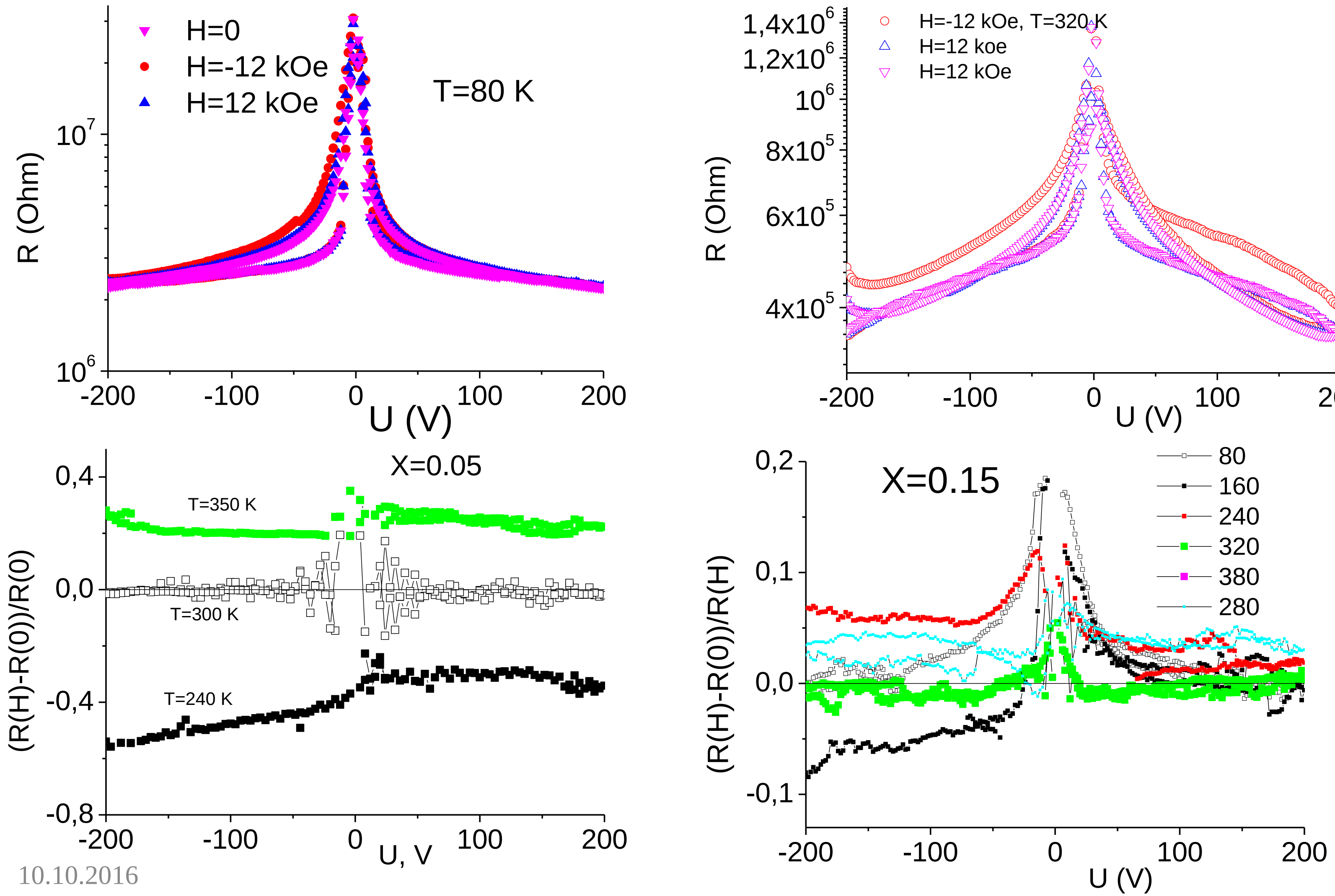
TmxMn1-xS with x =0.1 current voltage characteristic at temperatures T =80 K, 160 K, 360 K in magnetic fields H=0, 12 kOe, -12 kOe. Electric field maximum is Em=1000V/cm



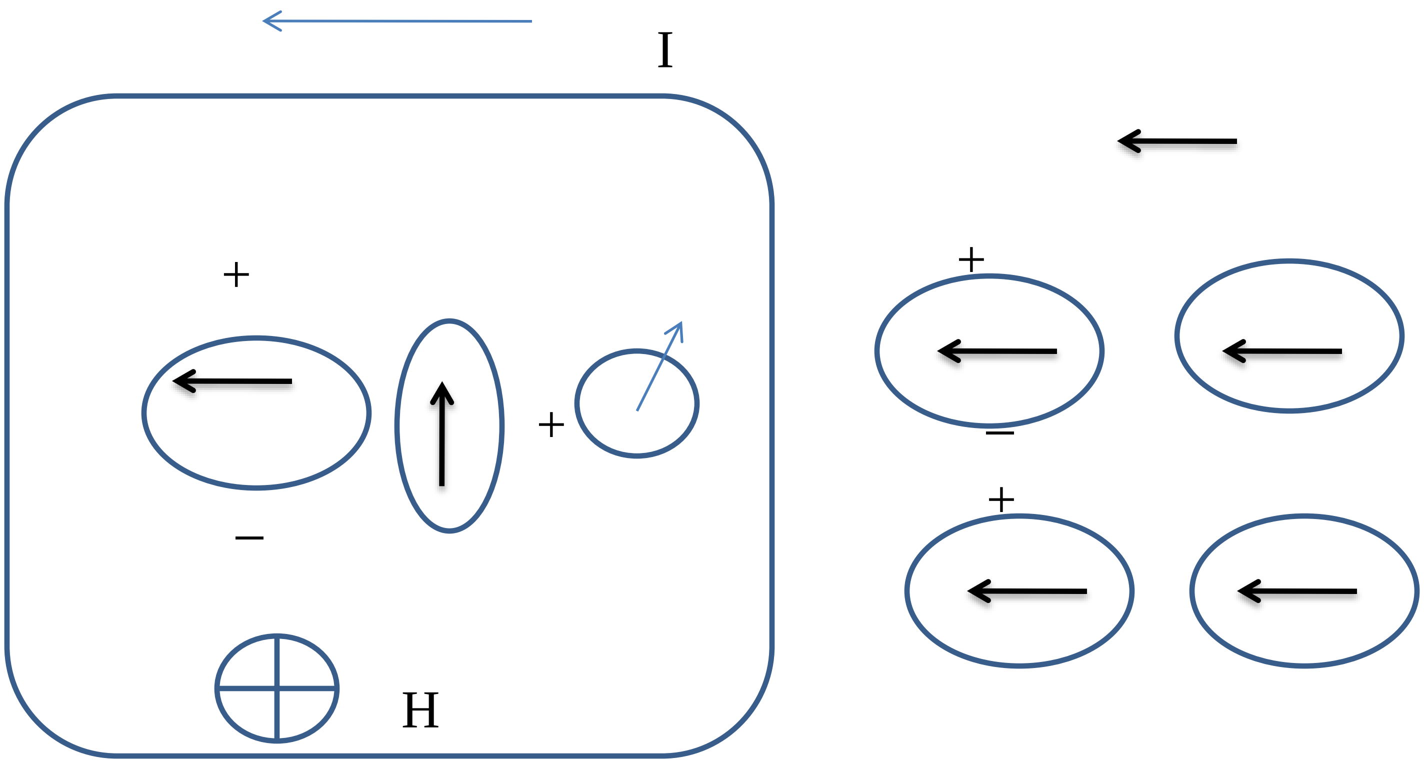
Magnetoresistance TmxMn1-xS with x =0.1 determined by current voltage characteristic at H=12 kOe

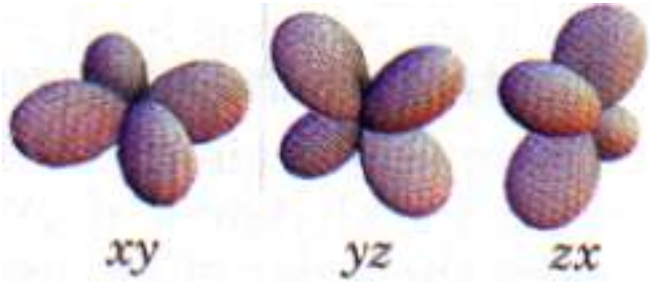


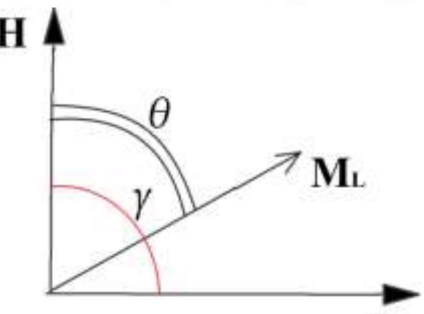
Resistance and Magnetoresistance TmxMn1-xS with x =0.05, 0.15 determined by current voltage characteristic at H=12 kOe

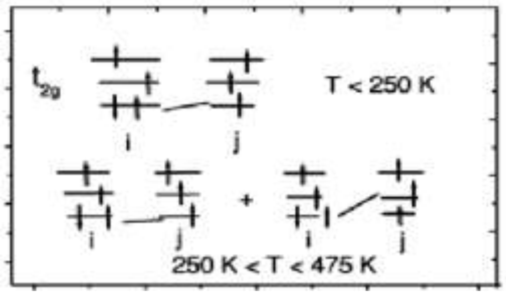


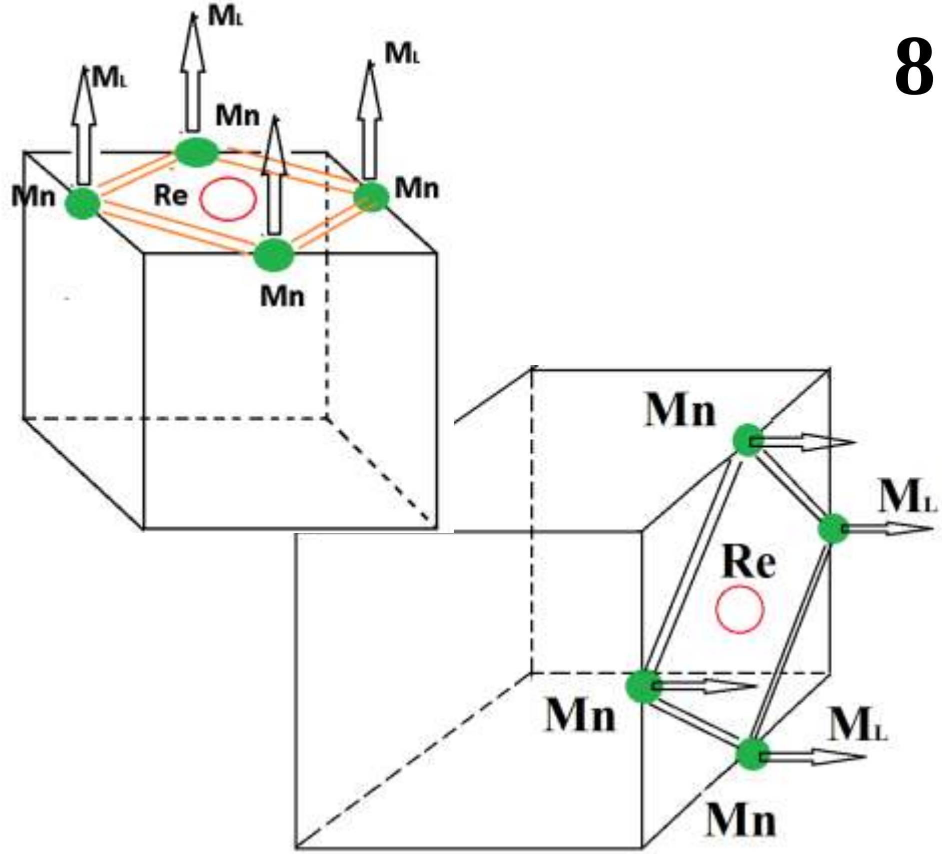
Charging region











$$\frac{\rho(H)-\rho(0)}{\rho(0)} = \frac{1}{1 + xP_1P_2\cos\theta} - 1,$$

$$W = M_L H\cos\theta + M_L H_A \cos(\gamma - \theta)$$

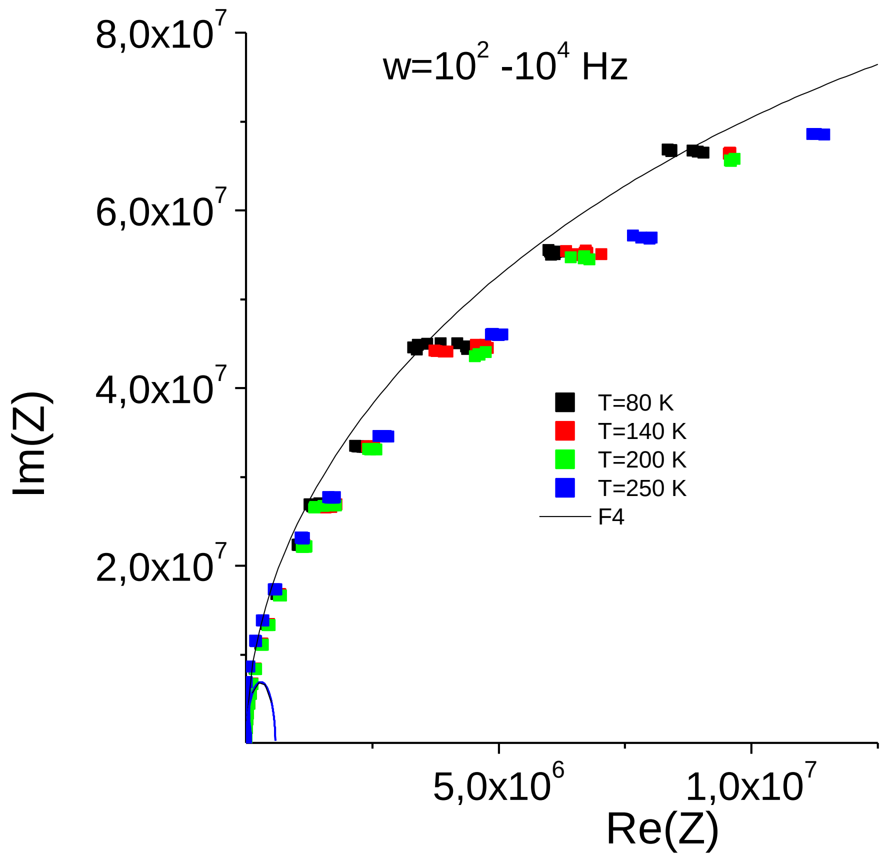
$$\cos\theta = 1/\sqrt{\left(1 + H_A^2\sin^2\gamma/(H + H_A\cos\gamma)^2\right)}.$$

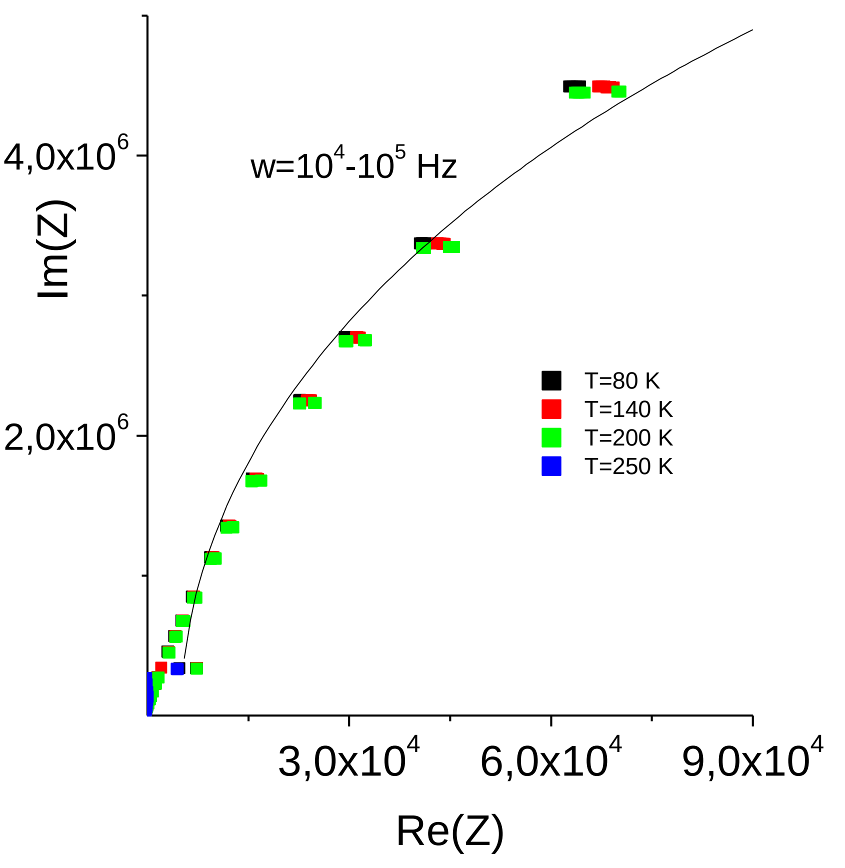
γ - угол между осью анизотропии и внешним магнитным полем

где $\boldsymbol{\lambda = H/K}$, ***К*** - константа анизотропии

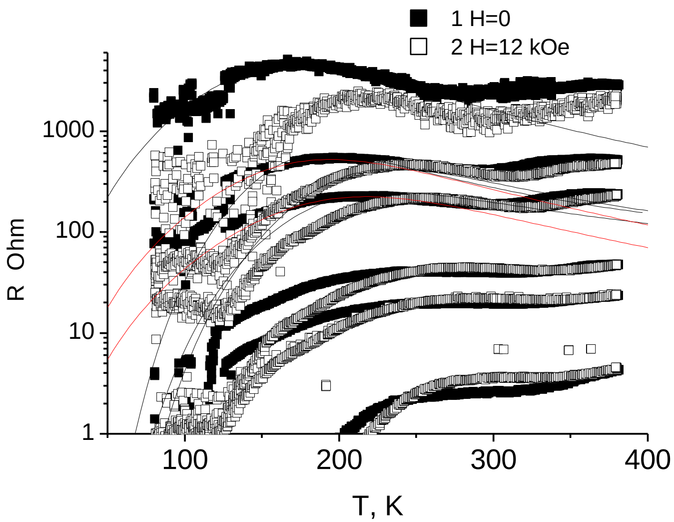
$$\mathrm{tg}\,\theta = H_A \sin\gamma/(H + H_A\cos\gamma).$$

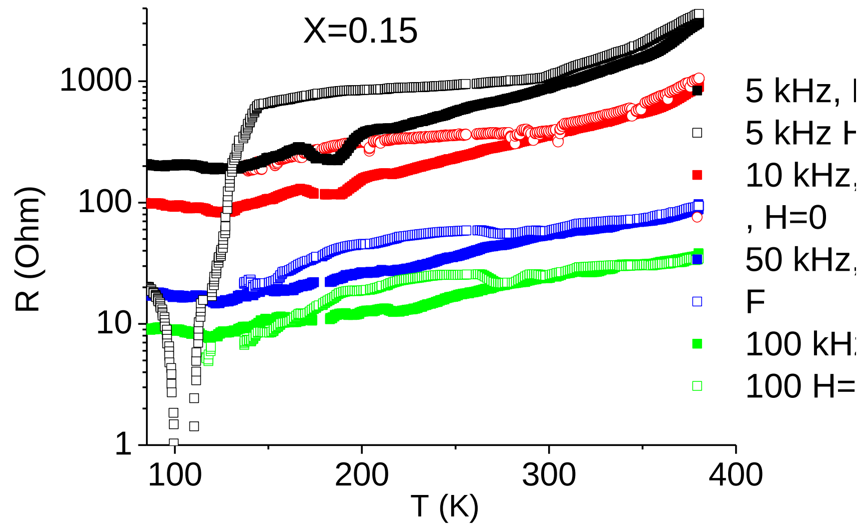
Годограф импеданса Tm01Mn09S

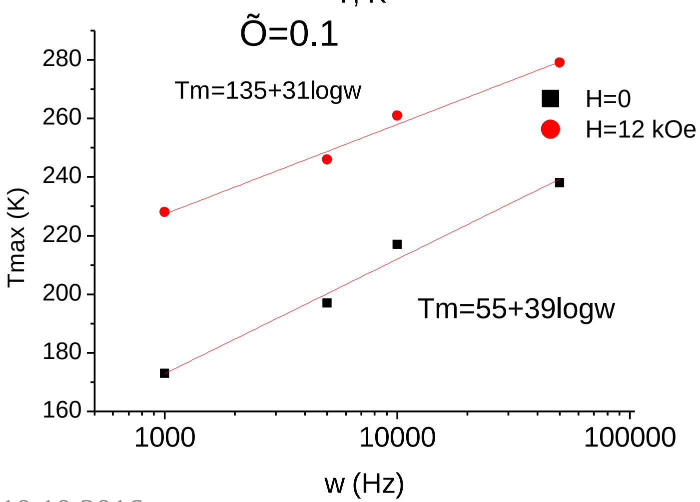




The active resistance in a zero magnetic field and in the field H=12 кЭ from temperature at frequencies w=1 kHz, 5 kHz, 10 kHz, 50, 100 , 300 kHz.

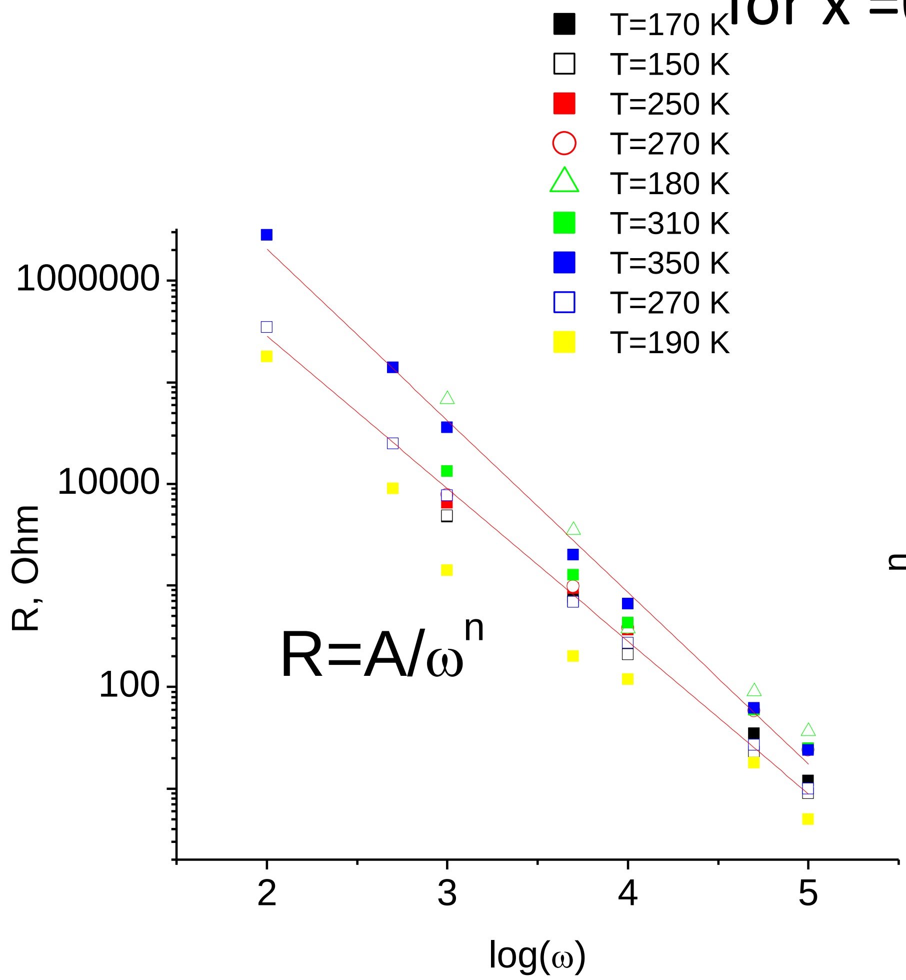


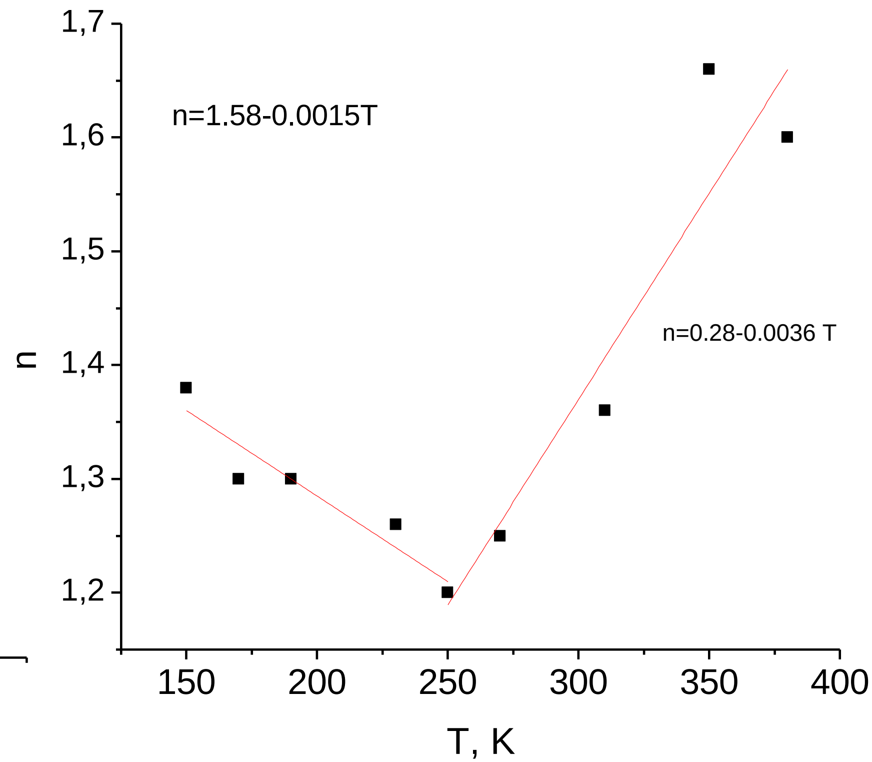




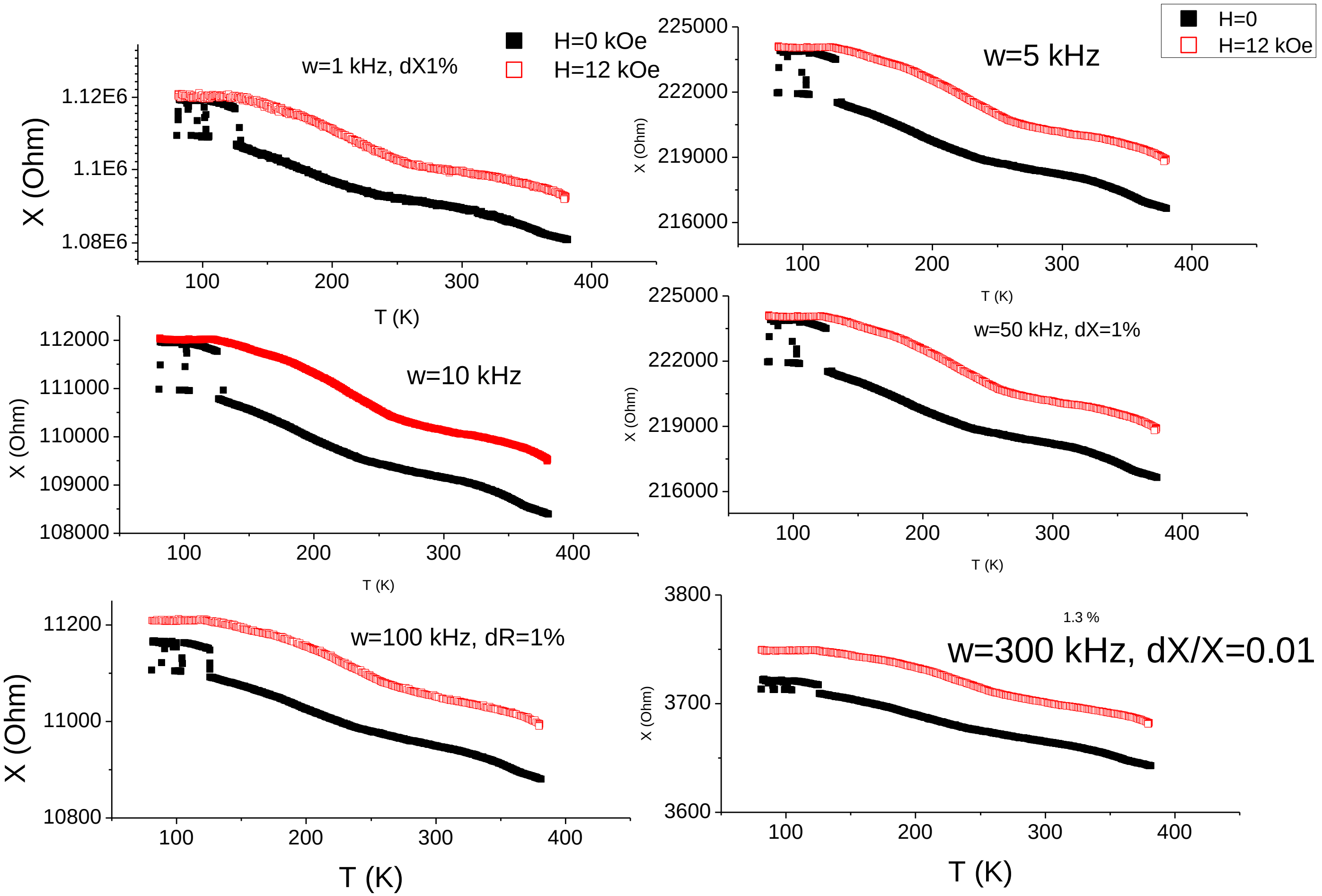
$$R = \frac{Im(\chi)}{\omega} = \frac{\tau}{1+(\omega\tau)^2} \quad \tau=(530-100\log\omega)/(\omega^{1/3}T^2)$$

Resistance from frequency at the fixed temperature for x =0.15



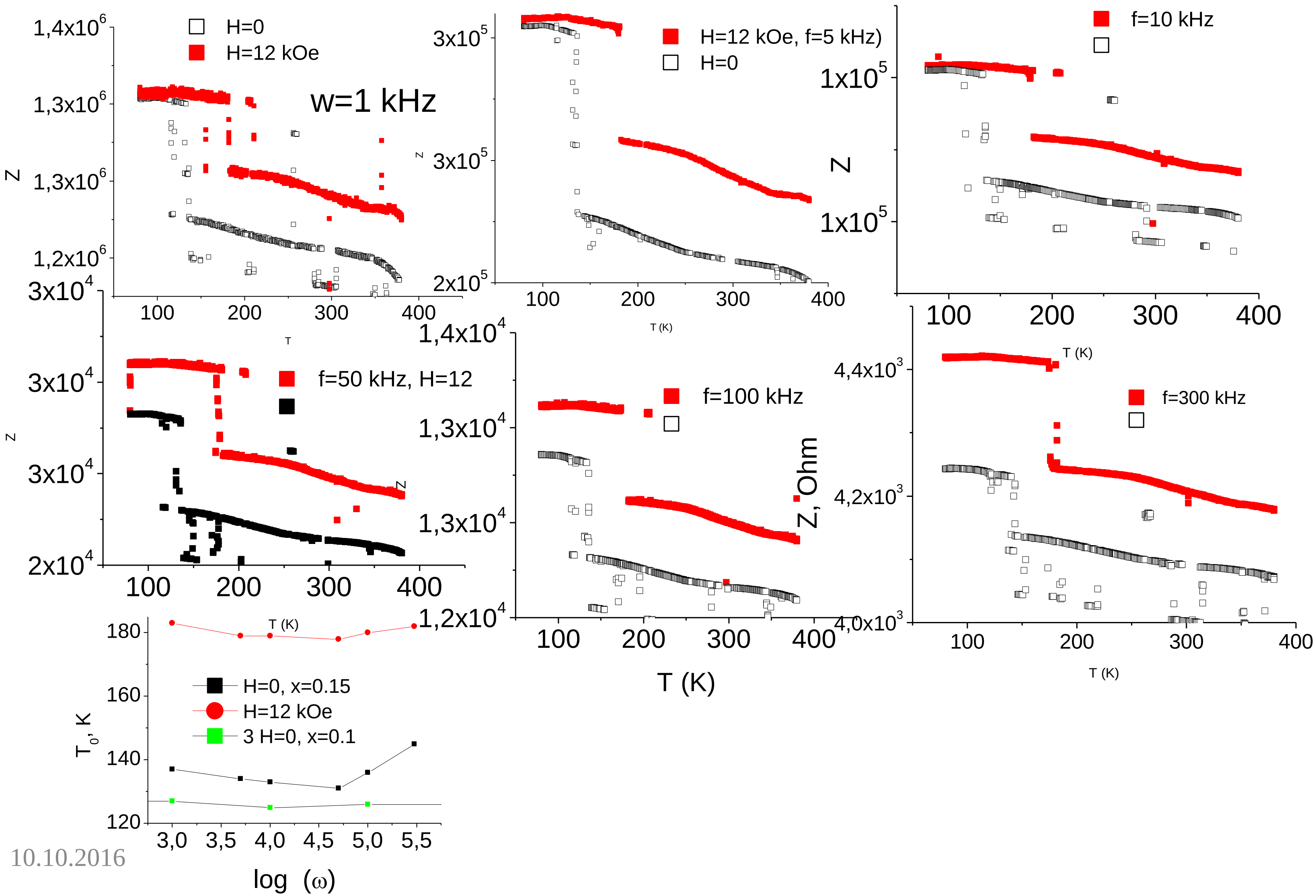


Imaginary resistance from temperature in TmxMn1-xS for x =0.1 on frequencies w=1, 5, 10, 50, 100 и 3000 kHz

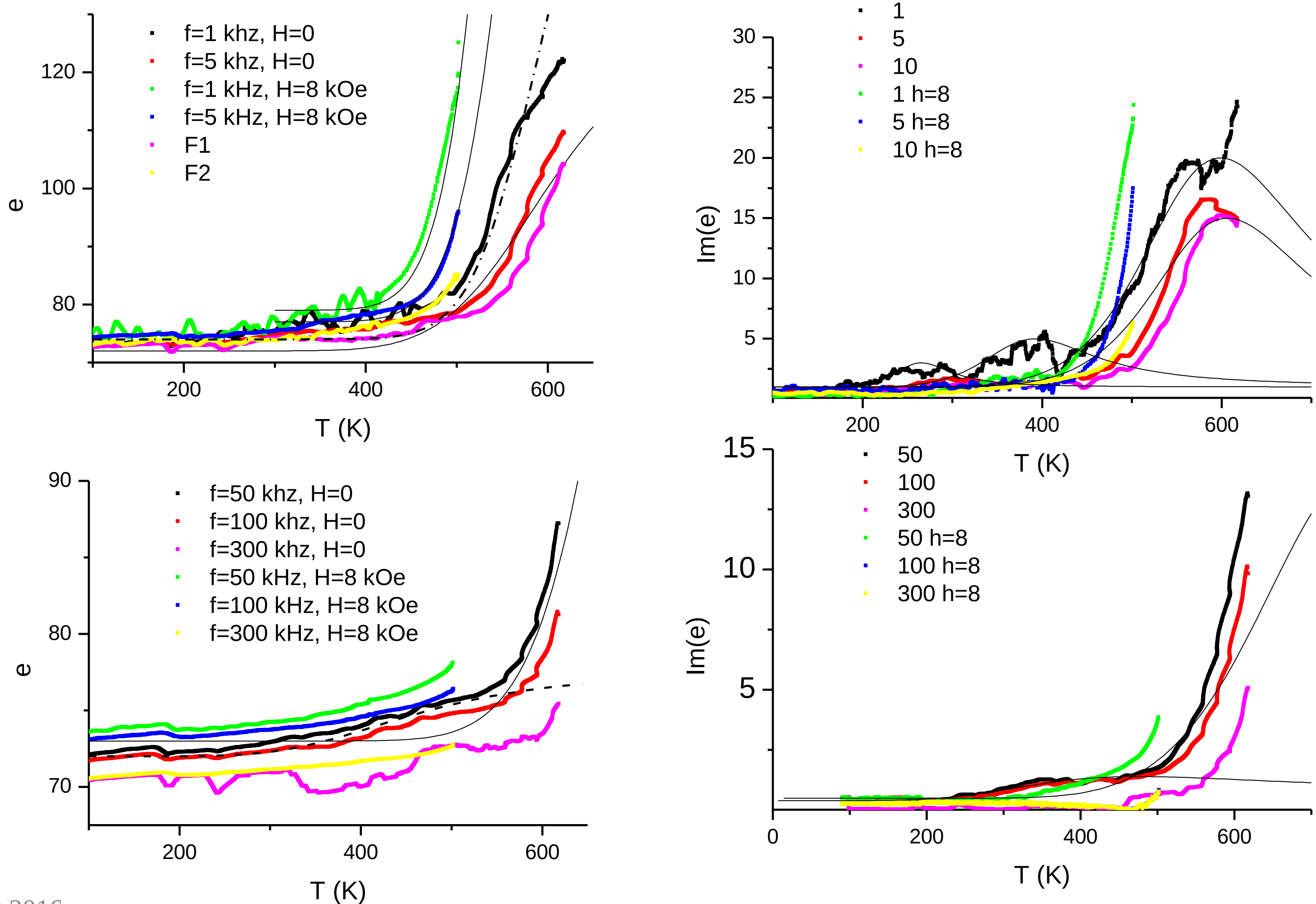


$$L_{induct} \sim <SiSj><LiLj>$$

Impedance from temperature in TmxMn1-xS for x =0.15 at frequencies w=1, 5, 10, 50, 100 и 3000 kHz



Real and imaginary permittivity from temperature without field and in a magnetic field for X =0.1

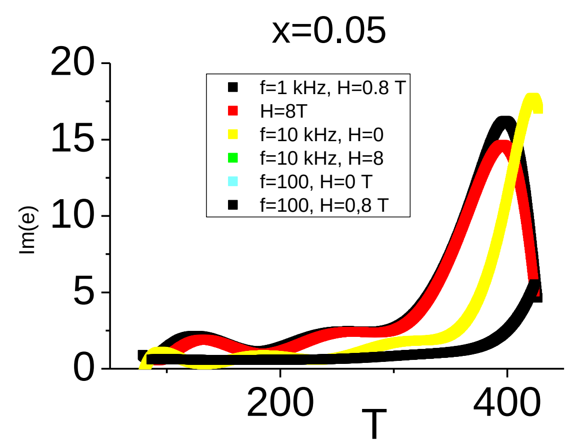


Диэлектрическая восприимчивость в модели Дебая

$$\mathrm{Re}(\chi)/N=\chi_{L0}+\chi_0/(1+(\omega\tau_g)^2)+\chi_0/(1+(\omega\tau_c)^2)$$

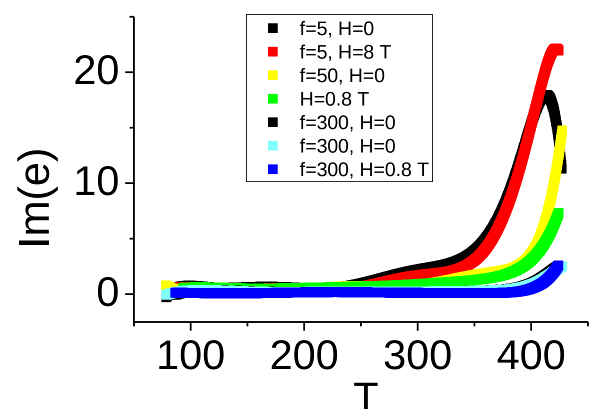
$$\mathrm{Im}(\chi)/N=\chi_0\omega\tau_g/(1+(\omega\tau_g)^2)+\chi_0\omega\tau_c/(1+(\omega\tau_c)^2)$$

Время релаксации диполей:
$\tau_g=\tau_0\exp(\Delta E/kT)$, где ΔE – энергия активации.

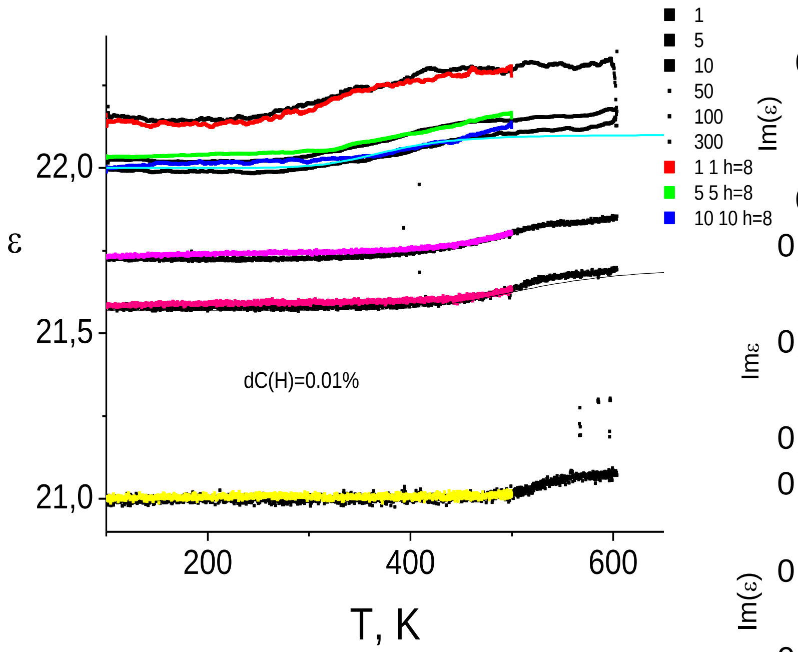


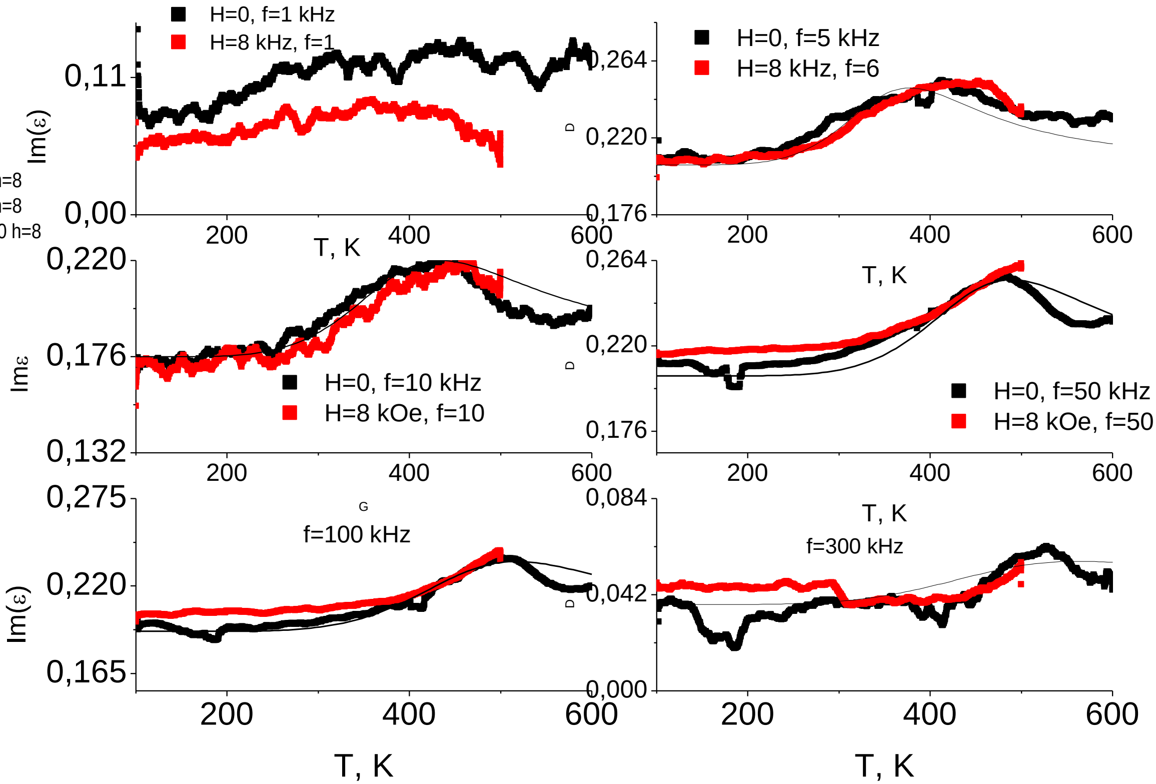
ΔE_1 =0.18-0.2 eV;

ΔE 2=0.36 eV, x=0.1



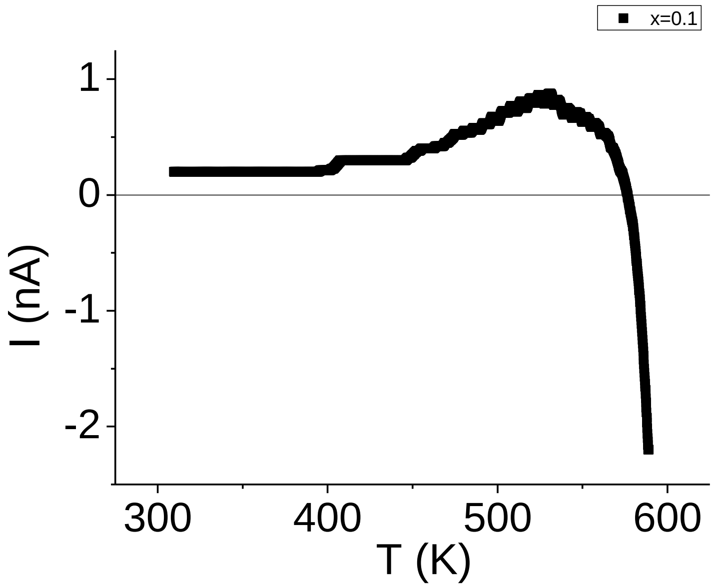
Real and imaginary permittivity without field and in a magnetic field for TmxMn1-xS   x=0.15.

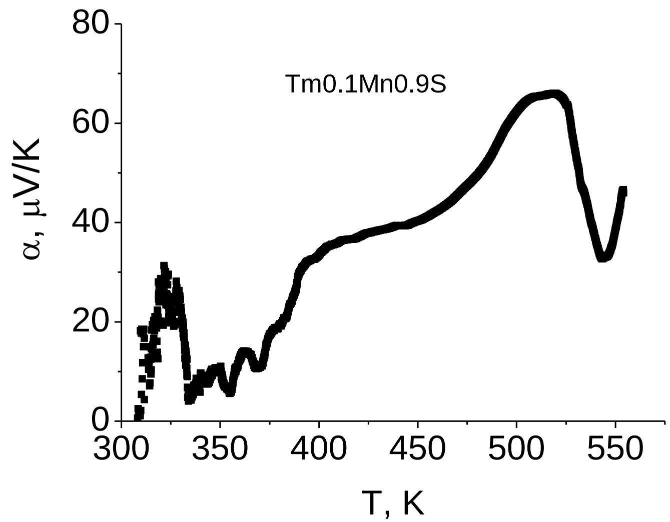


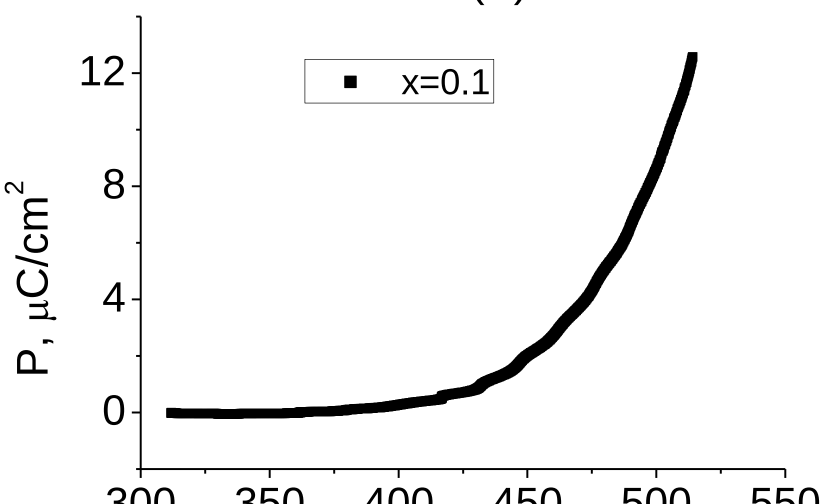


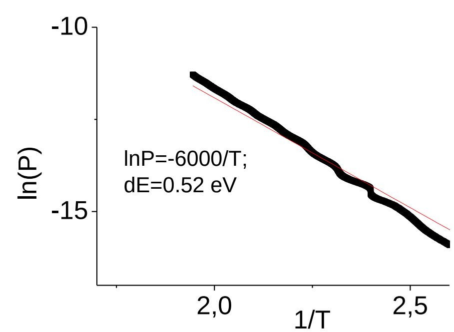
dE=0.18-0.21 eV

Pyrocurrent, polarization, thermoeds of Tm0.1Mn0.9S



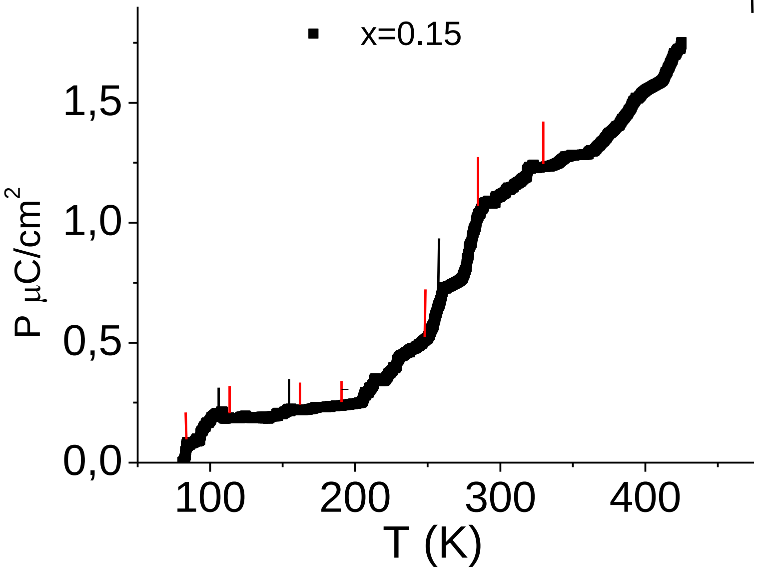


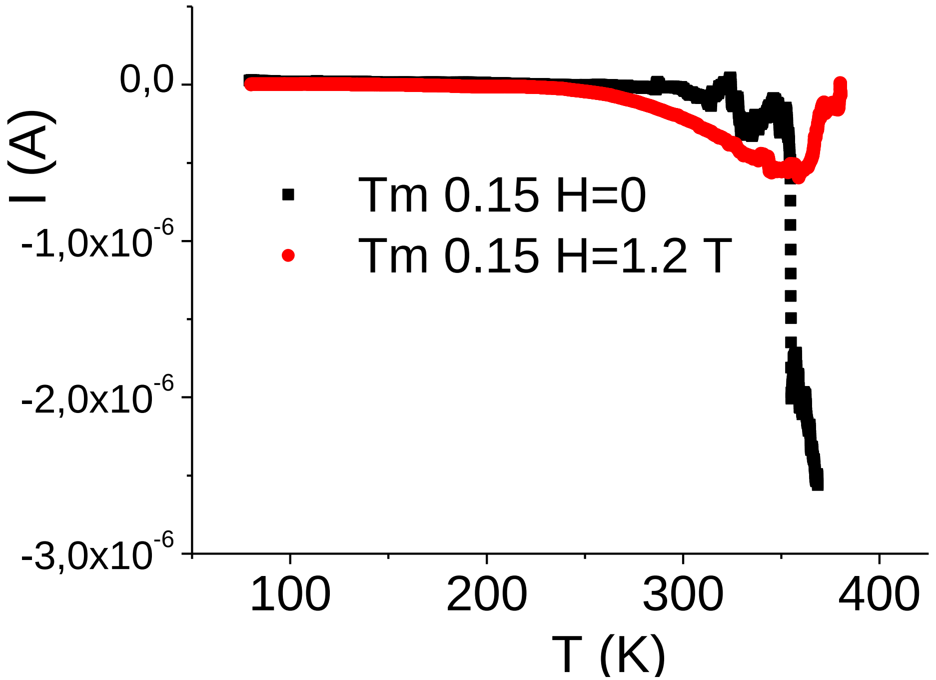




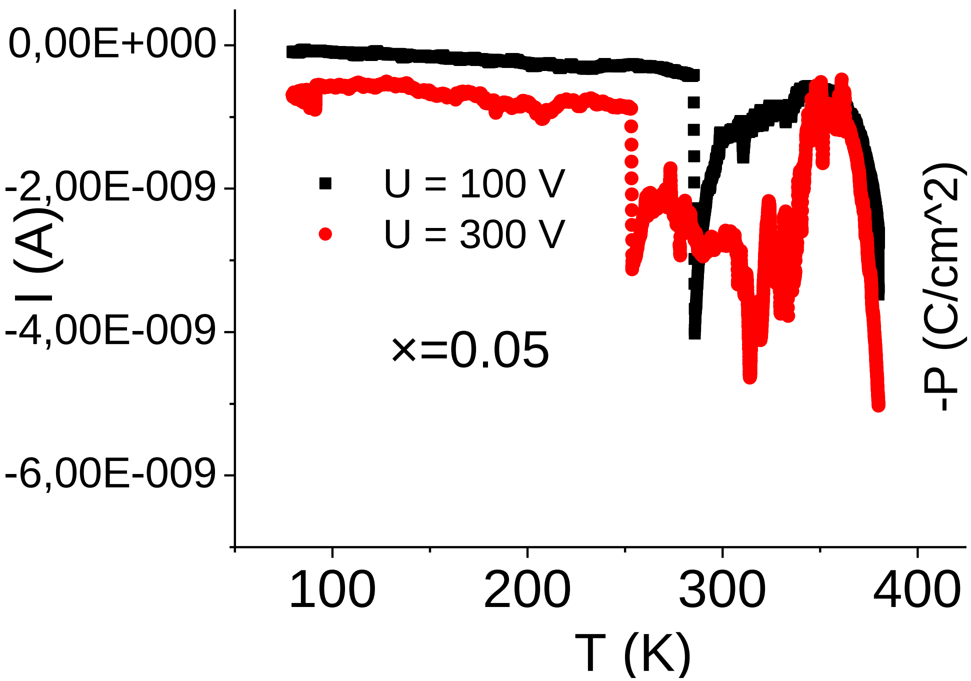
Polarization, pyrocurrent and thermal expansion coefficient for

TmxMn1-xS x=0.15.





Pyrocurrent, polarization of TmxMn1-xS versus temperature for x=0,05



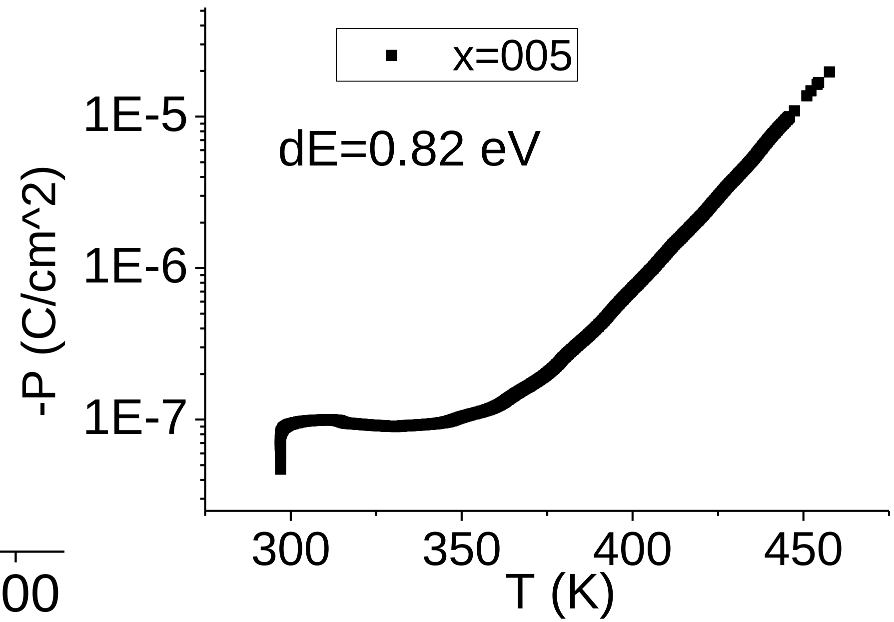
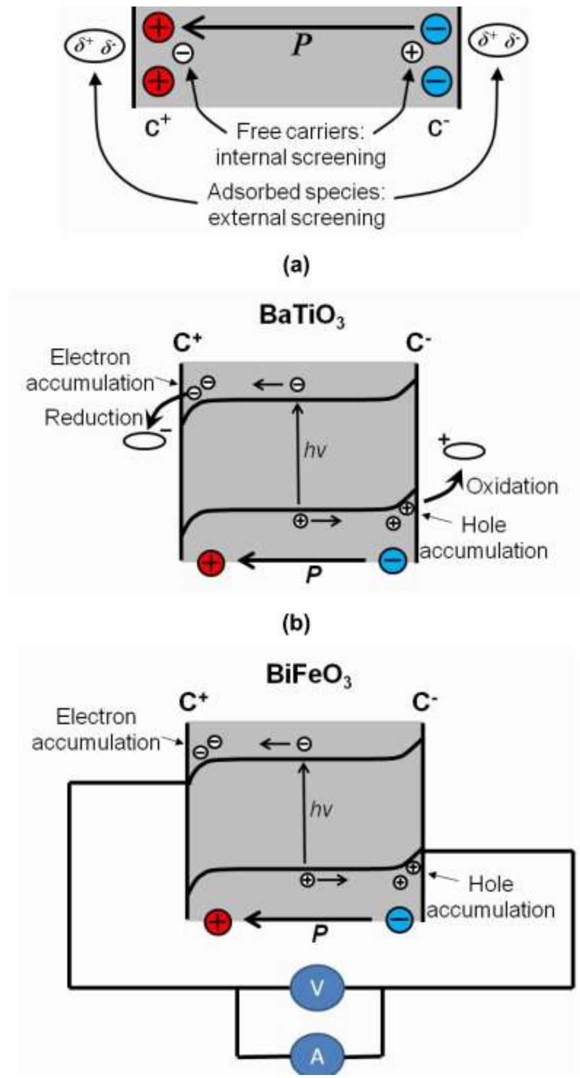
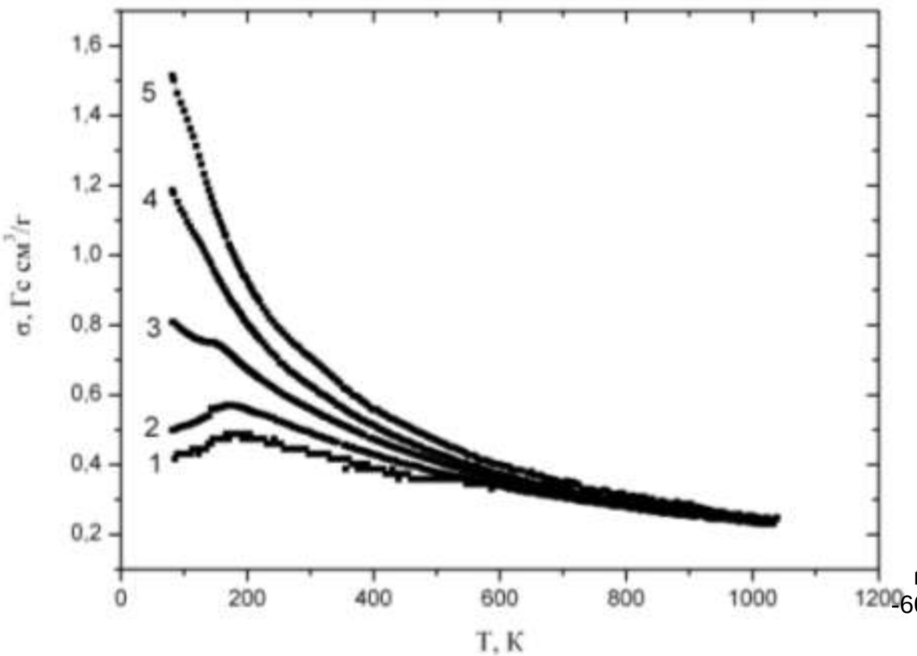
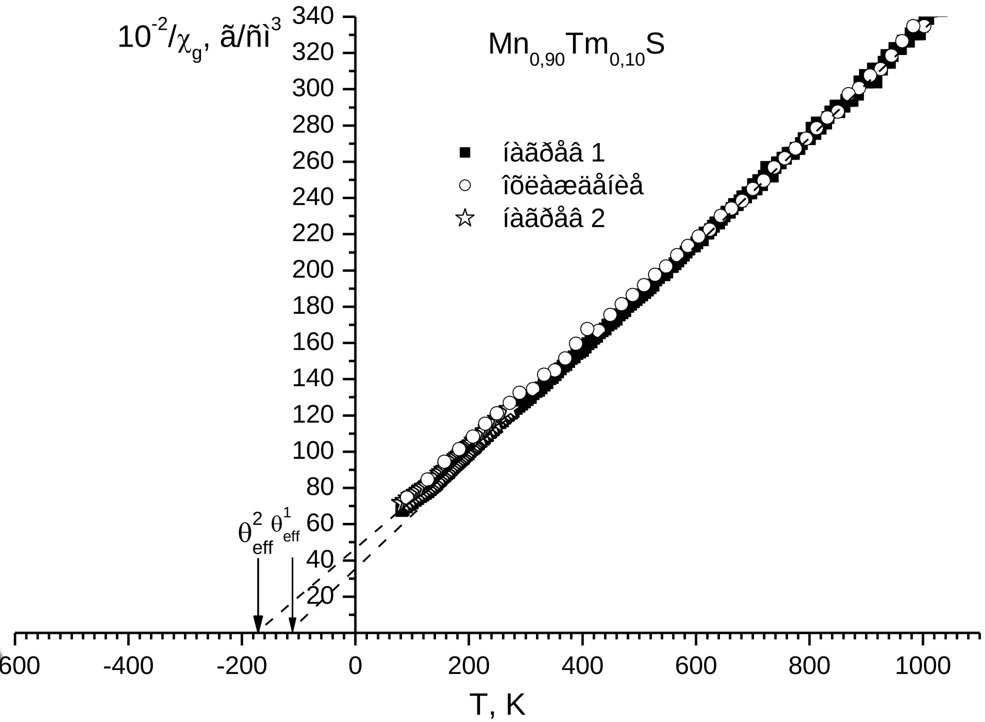


Figure 12: *Influence of ferroelectricity on carrier movement arising from (a) internal polarisation and screening mechanisms and (b) effect of free carrier reorganisation on band structure and photoexcited carriers. And (c), the influence on band bending in a ferroelectric material on carriers to generate a photovoltaic system.*



Magnetic moment in TmxMn1-xS for x =0, 0.05, 0.1, 0.15 in the field of H=8.6 kOe and the inverse susceptibility for x =0.1 from temperature





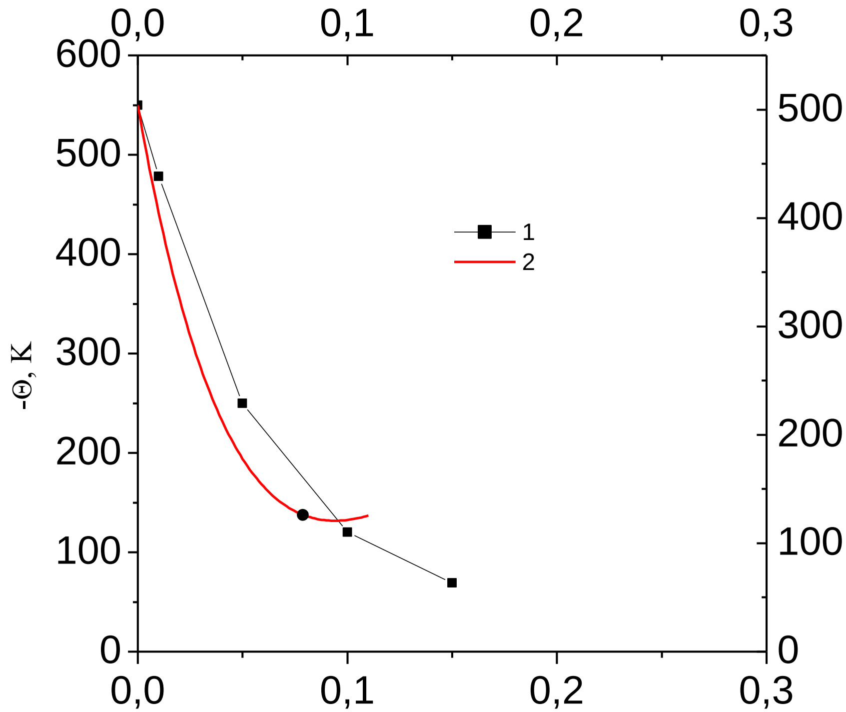
$$H=-\sum J_{ij}\, S_i S_j - \sum J_{so}\,(L_i L_j)(SiSj) - \sum J_0\,(L_i L_j)$$

$$\chi_s(Q) = \frac{T + J_m(Q)/4(1 - M_L^2)}{T^2 + \frac{T}{4}\left[J_m(Q) - J_s(Q)\right] - 9/4 J_m J_s (1 - M_L^2)}$$

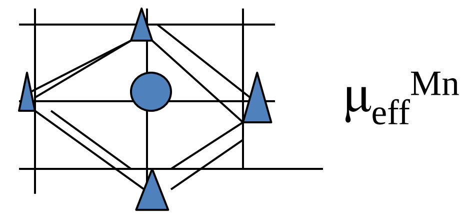
Э.Л. Нагаев, Наука, М. (1988), 231с

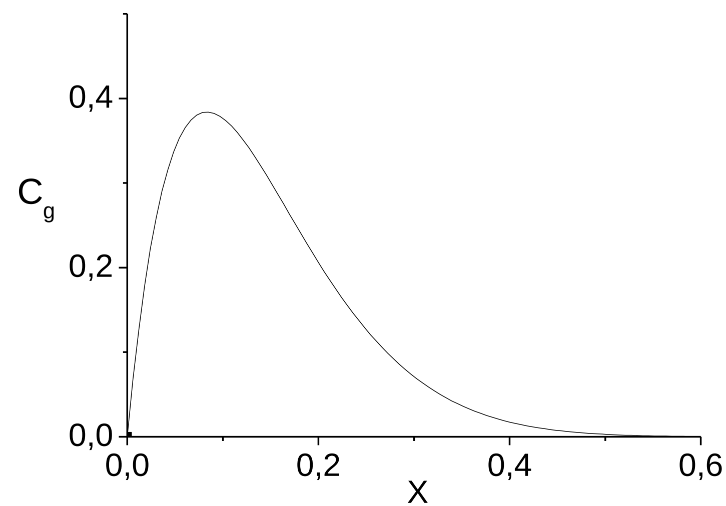
Paramagnetic Curie temperature: experiment (1) and calculation in a molecular field (2) Θ (x) = ΘMnS (1-x-λ cg) with fitting parameter λ= J *(Mn-Mn)/ J (Mn-Mn) =1.75,

$c_g=zx(1-x)^{z-1}$ TmxMn1-xS.



$$c_g = z\,x\,(1-x)^{z-1}$$





Магнитный момент на один ион от температуры

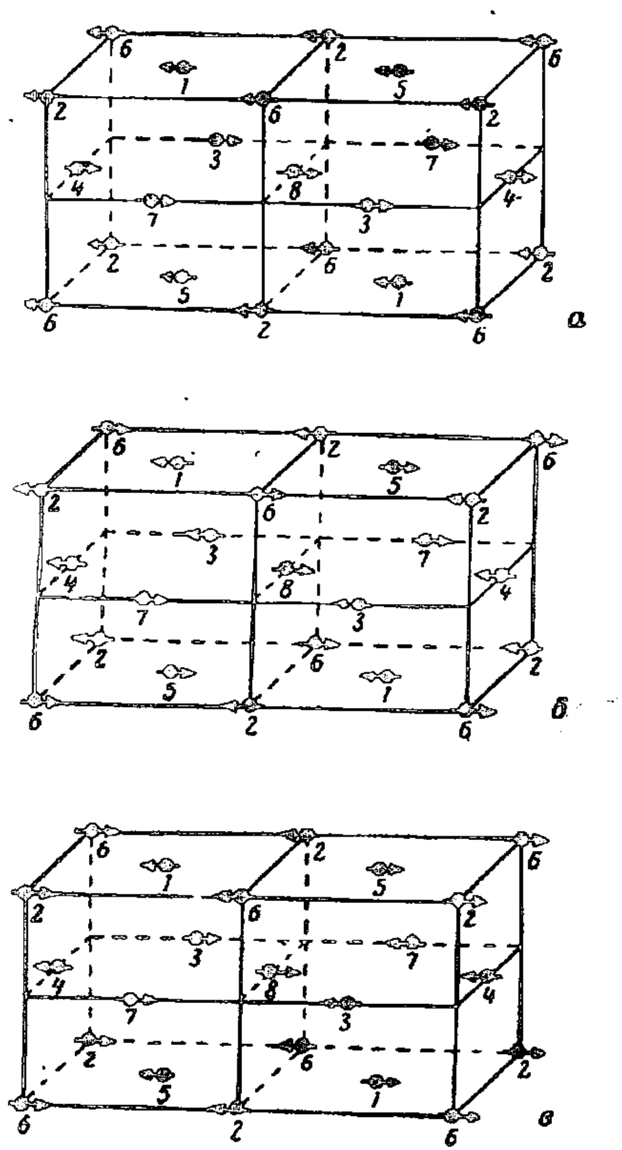
$\mu_{eff}=(3kC/N_{\mu B}^2)^{1/2}$ =**6-5.2**

Conclusion

- Sharp falling of paramagnetic Curie temperature in the range of concentration $0 < x < 0.1$ in solid solutions TmxMn1-xS is found in results of formation ferromagnetic exchange in the vicinity of thulium ions.
- For all compounds the magnetoresistance in TmxMn1-xS at temperatures several times exceeding Neel temperature is found .
- Magnetic characteristics and magnetoresistance is explained in terms of orbital-charging model.

Thank you for your attention

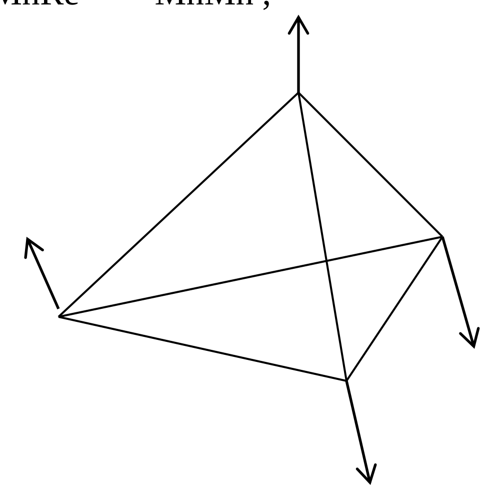
Антиферромагнитное упорядочение первого (а), второго (б), и третьего (в) родов в ГЦК решетке



$T_N = 2/3S(S+1)z_2\ J_2$, где J_2- обмен во 2-ой координационной сфере, $z_2=6$

$\Theta_P = 2/3S(S+1)\ (z_1\ J_1+z_2\ J_2)$, $z_1=12$

$\theta\ (x) = \theta_{MnS}\ (1 - x - \lambda_{MnMn}\ c_g - \lambda_{MnRe}\ x)$,
$\lambda_{MnRe} = I_{MnRe}\ /\ K_{MnMn}$,

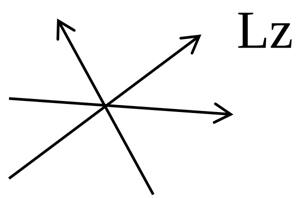


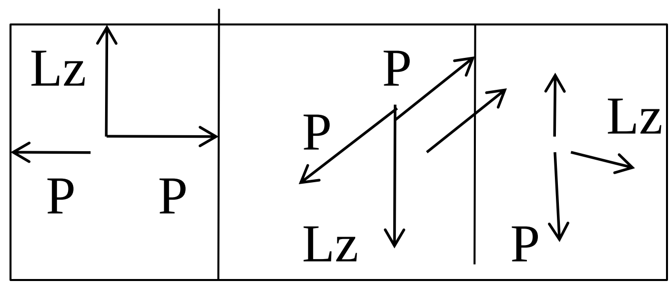
Блокировка кластеров (доменов) со случайной ориентацией орбитальных моментов

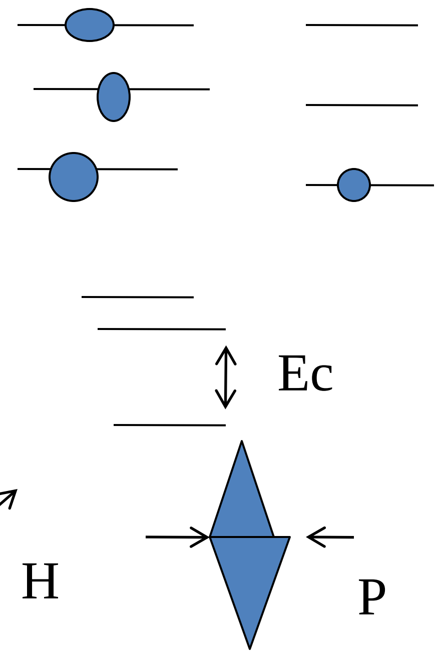
(R(H)-\R(0))/\R (0)=u(0)/u(H)-1=Aexp(-E_{sp}/kT)-1,

Esp=50 meV, A=9, X=0.1; Esp=3 meV, A=1.6, T< 320 K

Esp=90 meV, A=28, T> 320 K, T>320 K X=0.15

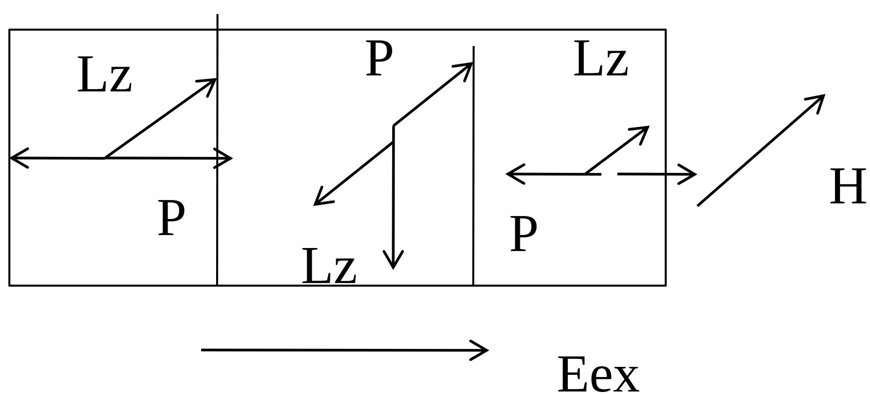






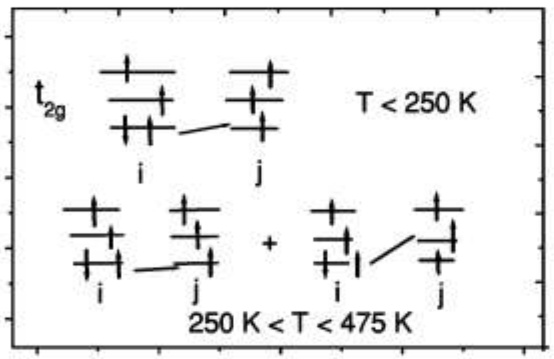
$E=E_{ex}\pm E'$

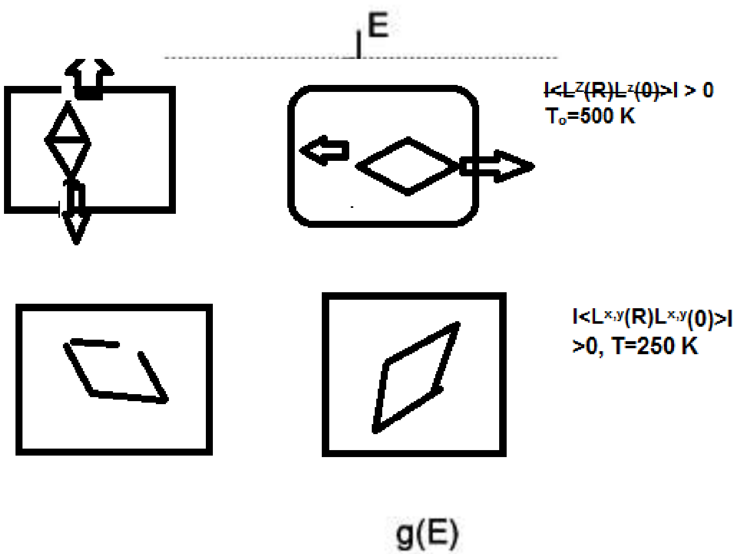
$E_{ex}>A\acute{\varepsilon}_0\,P$

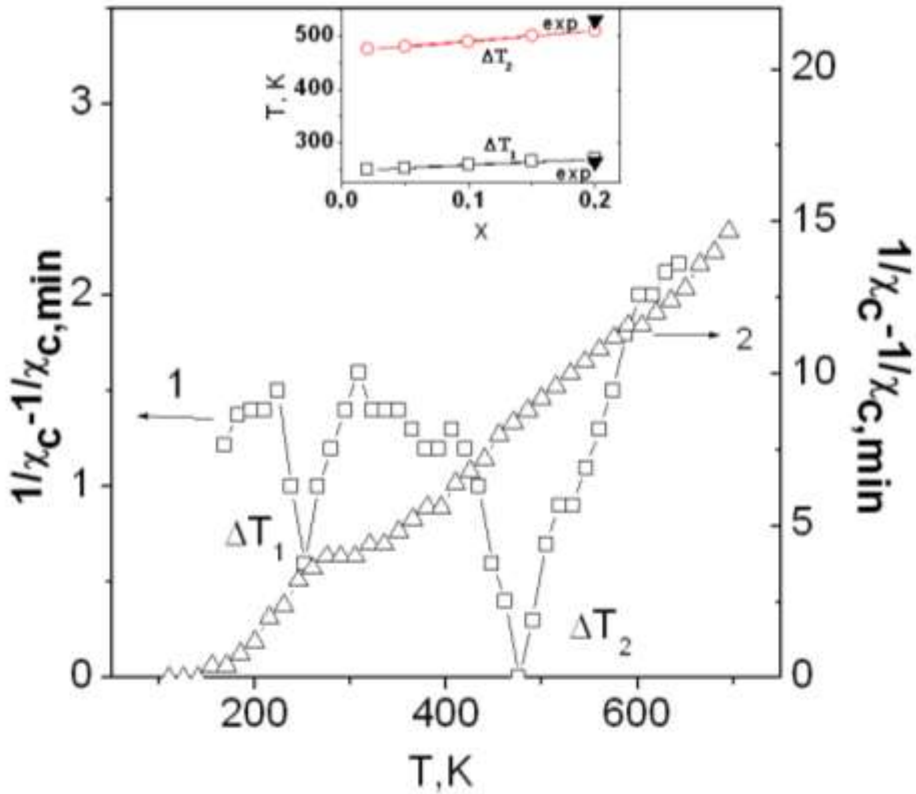


The value of the normalized charging susceptibility of electrons in t2g (1) and eg (2) bands from temperature

1 S.S. Aplesnin, L.I. Ryabinkina, G.M. Abramova et al., Phys. Rev. B **71**, 125204 (2005)

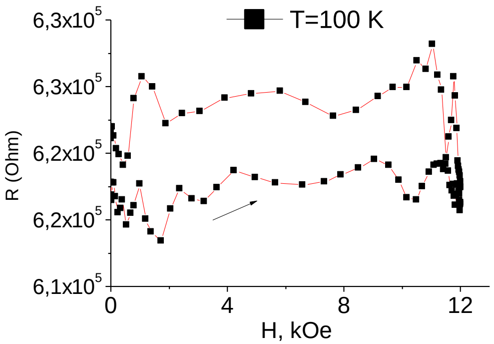


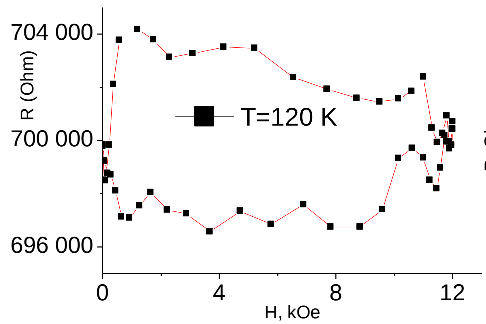


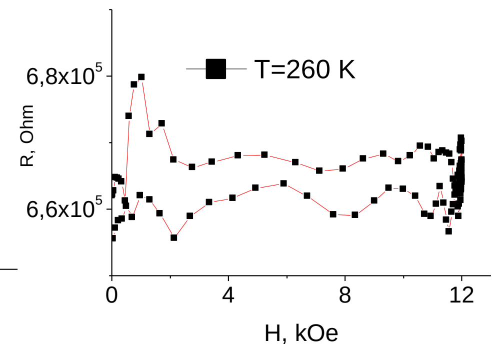


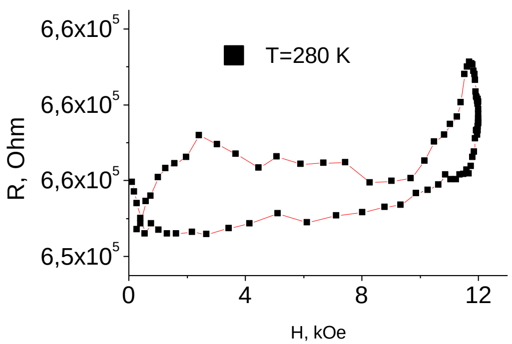
$\chi c = dn/d\mu$

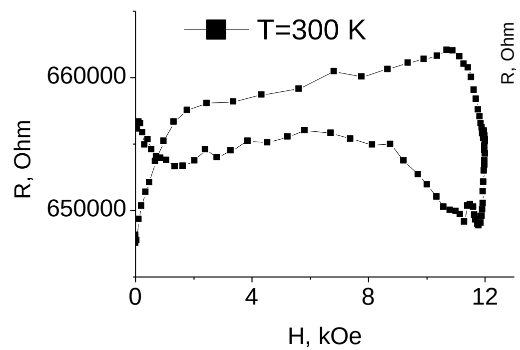
Resistance from a magnetic field in TmxMn1-xS for x =0.1 and annealing in the field H=12 kOe from time.

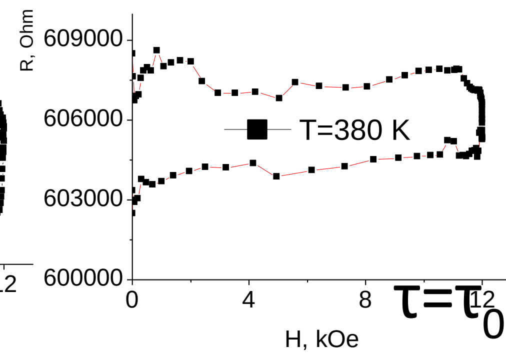






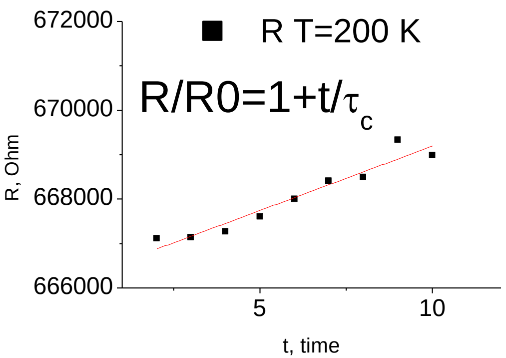


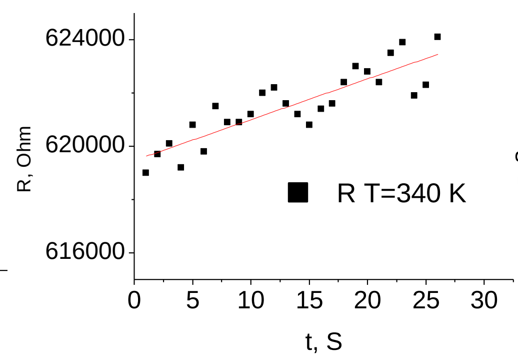


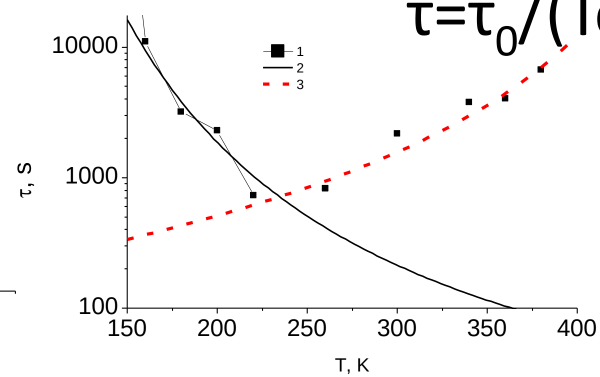


$\tau=\tau_0\exp(\Delta E/kT)$,

$\tau=\tau_0/(T_c-T)^{z\nu}$, $z\nu=1.6$







Resistance from a magnetic field in TmxMn1-xS for x =0.15 and annealing in the field H=12 kOe from time