Supplemental material to the article

Anomalous spin relaxation and quantum criticality in $Mn_{1-x}Fe_xSi$ solid solutions

Magnetoresistance method of the determination of the magnetic phase diagram in $Mn_{1-x}Fe_xSi$ in the high field region.

The use of the magnetoresistance for determination of the magnetic phase diagram in the $Mn_{1-x}Fe_xSi$ system in the high field region corresponding to the magnetic resonance is based on the results of Ref.11 and Ref.13 of the article. It is shown that in pure MnSi the magnetic measurements don't lead to a correct determination of the phase boundary $T_{SP}(x)$ between paramagnetic (P) and spin-polarized (SP) phases and this magnetic transition corresponds to the negative magnetoresistance $\Delta\rho\ \rho = f(B = const, T)$ temperature dependence minimum. We find that the same statement is valid for $Mn_{1-x}Fe_xSi$ system in the concentration diapason $x < 0.3$.

The experimental data suggest that for all $Mn_{1-x}Fe_xSi$ samples studied the magnetoresistance is negative (see example in Fig. 1). The negative sign of magnetoresistance indicates importance of magnetic scattering. The simplest theoretical description of negative magnetoresistance for a medium containing magnetic ions on which band electrons are scattered is given by Yosida model. Assuming a system with the s-d exchange Yosida obtained following relation between $\Delta\rho/\rho$ and M

$$\Delta\rho/\rho = -a_0(M/M_\infty)^2 \tag{1}$$

where M_∞ denotes saturation value of magnetization. The proportionality coefficient a_0 depends on the spin S of the magnetic ion and the characteristics of the scattering potential (the analytical expressions for the a_0 can be found elsewhere [see Ref.11 and Ref.13 of the article]). In this way, for Yosida model it is expected that temperature and field dependences of magnetoresistance are determined by temperature and field dependences of magnetization, i.e. for given material the relation between $\Delta\rho/\rho$ and M^2 should be linear and universal.

This supposition exactly meets the case in the $Mn_{1-x}Fe_xSi$ system with $x < 0.3$. The typical plot of $-\Delta\rho/\rho$ as a function of M^2 for the sample with $x = 0.054$ is shown in Fig. 2. Universal scaling suggested by Equation (1) is valid for $T > T_{min} \sim 17$ K, whereas for $T < T_{min}$ the link between

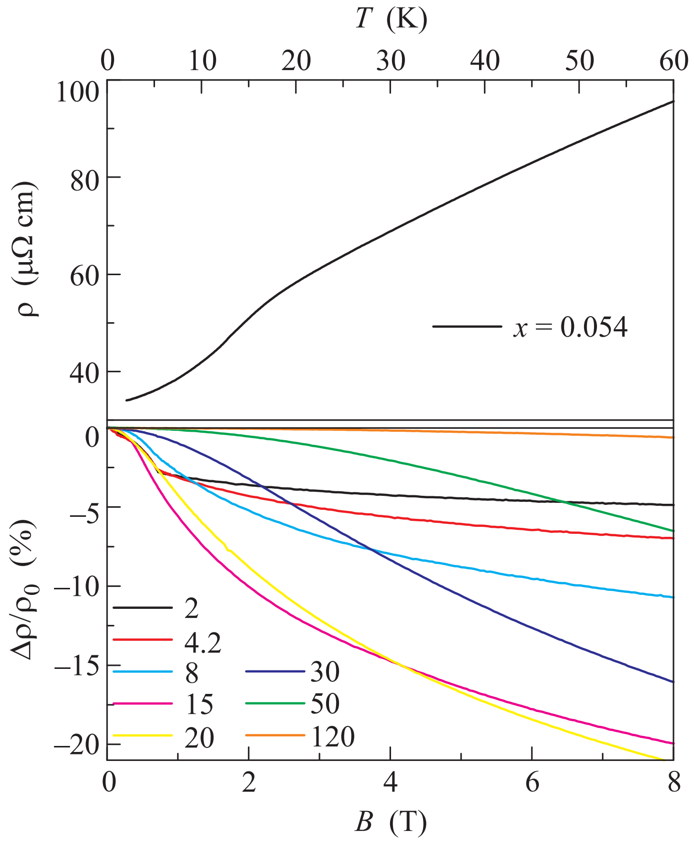

Figure 1: Resistivity and magnetoresistance, for the sample with $x = 0.054$. Digits in the legend denote different temperatures.

magnetoresistance and magnetization square becomes non-linear and non-universal. This result means that above characteristic temperature $T_{min}(x)$ the magnetoresistance in $Mn_{1-x}Fe_xSi$ is predominantly controlled by magnetic scattering and all other possible contributions to magnetoresistance are negligible.

The universal relation (1.1) appears as a consequence of specific physical situation. Firstly, it is assumed in the Yosida model, that there are localized magnetic moments (LMMs) scattering band electrons. Secondly, the scattering on LMMs may be divided into two channels, one of which corresponds to a parallel orientation of the electron and LMMs spins and another corresponds to an antiparallel one. The scattering probability in the latter channel will decrease with enhancement of the magnetic field and lowering

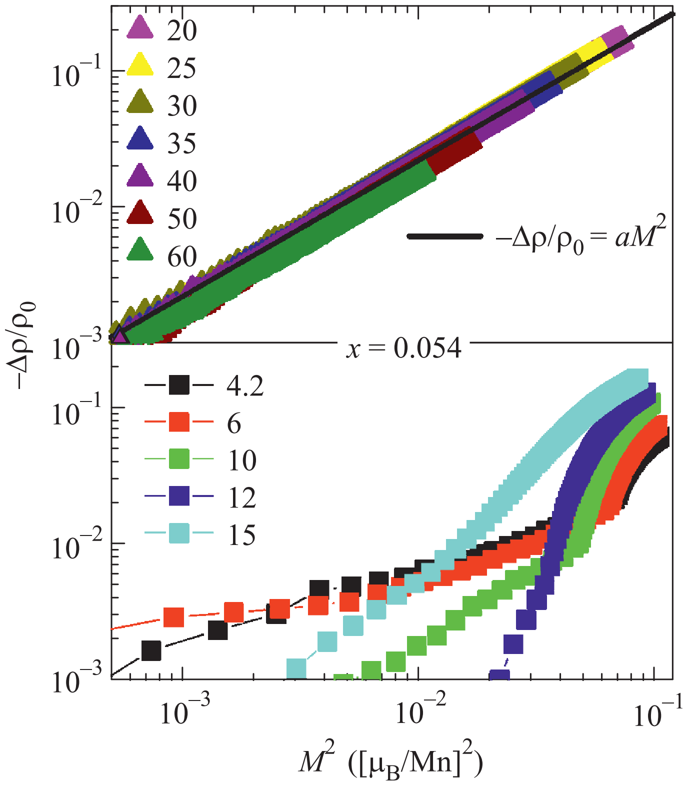

Figure 2: Typical example of the magnetoresistance scaling for $T > T_{min} = T_{SP}$ (upper panel) and violation of the scaling behavior at $T < T_{min}$ (lower panel) in $Mn_{1-x}Fe_xSi$ system.

temperature making scattering center more transparent and thus giving rise to negative magnetoresistance. Therefore it is natural to expect that magnetoresistance will depend on the average spin polarization rate M/M_∞ and, as long as magnetoresistance should be even function of magnetic field, the relation $\Delta\rho/\rho \sim (M/M_\infty)^2$ will be valid in agreement with exact calculation result.

The above arguments concerning Yosida model applicability to the case of $Mn_{1-x}Fe_xSi$ may be valid if scattering processes on each Mn site are not correlated and controlled by an average spin-polarization rate, i.e. in the case of the paramagnetic phase. In the magnetically ordered phase, the situation will change completely. In particular, it is reasonable to expect for the ferromagnetic (spin polarized) phase that both localized and moving spins are already polarized. For that reason, the basic assumption made in Yosida

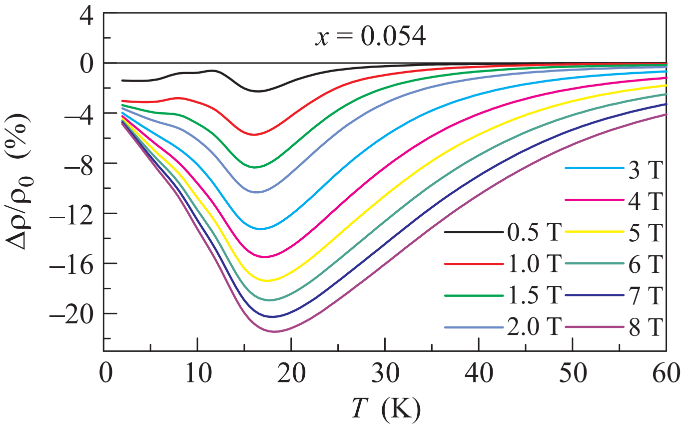

Figure 3: Temperature dependences of the magnetoresistance for the sample with $x = 0.054$. Digits in the legend denote different magnetic fields.

model about two spin dependent scattering channels fails and magnetoresistance should not depend on the spin states. As a result the universal magnetoresistance scaling (Equation (1)) will be no longer valid, and any temperature dependence of the spin dependent contribution to magnetoresistance in the spin-polarized phase will be likely caused by thermal fluctuations destroying "ideal" polarized state and consequently $\Delta\rho/\rho \to 0$ for $T \to 0$. Therefore it is expected that in the paramagnetic phase the magnitude of the negative magnetoresistance in fixed magnetic field firstly increases with lowering temperature (as long as magnetization also increases), reaches maximal absolute value at $T_{min}(x) = T_{SP}(x)$ corresponding to the transition between paramagnetic and spin-polarized phases and than drops in ferromagnetic phase. In addition, universal relation between magnetoresistance and magnetization holds in the paramagnetic phase.

Comparison with experiment for MnSi shows that the aforementioned scenario exactly meets the case (see example in Fig. 3). The $\Delta\rho/\rho(B = B_{res}, T)$ curves for various x used for determination of the $T_{min}(x)$ are presented in Fig. 4. These data were used for determination of the T-x magnetic phase diagram discussed in the paper text. It is worth noting that in the concentration diapason $0.19 \leq x \leq 0.24$ the minima of the $\Delta\rho/\rho(B = B_{res}, T)$ are not observed and we assume that for these concentrations $T_{SP} \approx 0$. At the same time, the maxima of the magnetic susceptibility $\chi(B = const, T) = \delta M/\delta B$, which were used in the past for the determination of the P-SP phase boundary (Ref.11 of the article) are located in the region of the Yosida scaling

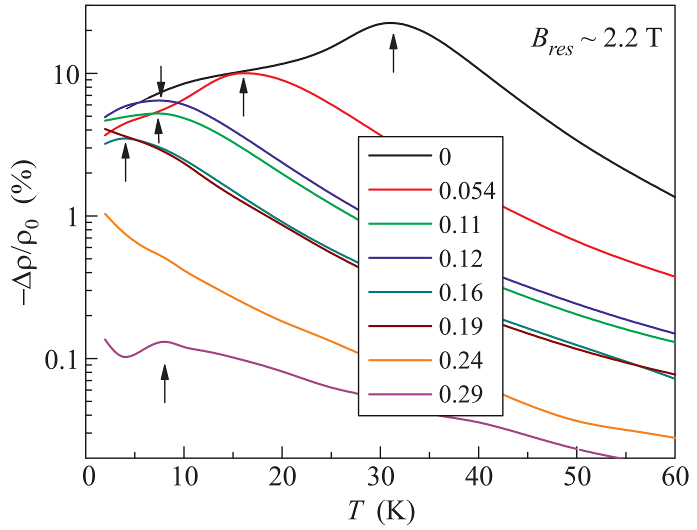

Figure 4: Temperature dependences of the magnetoresistance at the ESR resonant field used for determination of the magnetic phase diagram. Digits in the legend denote different iron concentrations. Positions of $T_{min} = T_{SP}$ are marked by arrows.

(Equation (1)), i.e. in the paramagnetic phase. For that reason, we believe that the most correct way for establishing of the phase boundary between paramagnetic and spin-polarized phases is the magnetoresistance rather than magnetization analysis, which is due to the specific character of the magnetic scattering in $Mn_{1-x}Fe_xSi$ system.