Pressure-Induced Crossover in the Electronic State of Fe\textsubscript{70}Ni\textsubscript{30}

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1. Introduction

The temperature dependence of the electrical resistivity was measured for face-centered cubic (fcc) Fe\textsubscript{70}Ni\textsubscript{30} Invar alloy under high pressure between 2 and 8 GPa. It was found that the electrical resistivity below 6 GPa shows a minimum at a low temperature around 10 K (= \( T_{\text{min}} \)), which decreases with increasing pressure and disappears at 8 GPa. At 8 GPa, the electrical resistivity is proportional to \( T^2 \) below 30 K, which indicates the Fermi liquid property. The resistance minimum is caused by a new high-pressure magnetic phase such as a RSG phase. These results show the pressure-induced magnetic phase transition from the ferromagnetic phase to the RSG phase below 6 GPa and a crossover from the RSG phase to Fermi liquid around 8 GPa.

2. Experimental method

The sample was prepared by arc-melting of the two pure metals Fe (99.99%) and Ni (99.99%). Then it was homogenized for 2 weeks at 1100 °C in a vacuum of about 10\textsuperscript{-6} Torr and quenched rapidly into water. After cutting the sample, it was annealed at 1100 °C for 10 hours to remove the internal strains. Martensitic transformation temperature \( (M_s) \) and \( T_c \) were defined by electrical resistivity and ac susceptibility measurement, respectively. Effect of hydrostatic pressure on \( M_s \) was measured by piston-cylinder method up to 1 GPa. Electrical resistance was measured by means of the usual four-probe method in the temperature range between 4.2 K and 300 K. A cubic anvil high pressure apparatus was used to generate hydrostatic pressure higher than 2 GPa. The pressure transmitting medium was 1:1 mixture of Fluorinert, FC70 and FC77.

3. Results

3.1 Martensitic transformation at high pressure
$T_c$ and $M_s$ at ambient pressure are determined to be 390 K and 210 K, respectively. The temperature dependence of electrical resistance $R/R_0$ is shown in Fig.1 below 1 GPa, where $R$ and $R_0$ are the electrical resistance at $T$(K) and room temperature. The $R/R_0$ shows a large discontinuity at $M_s$ reflecting 1st order phase transition. The pressure dependence of $M_s$ is shown in Fig.2. $M_s$ decreases rapidly with increasing pressure with the rate of $\frac{d}{dP}M_s=-132$ K/GPa and it is extrapolated to zero around 1.4 GPa.

The resistance minimum is considered to be caused by reentrant spin glass (RSG). RSG and SG phases have been observed in Fe-Ni and Fe-Pt disordered alloy under high pressure and in the alloys which are the border of the magnetic transition from such as Fe$_{85}$(Ni$_{1-x}$Mn$_x$)$_{15}$ and magnetic dilute alloys$^9$. Taking into account these results, the phase above 2 GPa below 30 K is considered as a pressure induced new magnetic phase such as RSG state, which appears as a result of competition between ferromagnetic and antiferromagnetic interaction among Fe atoms under high pressure. As pressure increases, the ferromagnetic interaction weakens and RSG state becomes unstable. The decreasing of $T_m$ is caused by the pressure-induced instability of spin-glass states.
4. Discussion

4.1 Temperature dependence of $\rho$ above $T_{\text{min}}$

The mechanism of conductivity above $T_{\text{min}}$ may be different from the one below $T_{\text{min}}$. We analyzed $\rho(T)$ curves in detail above $T_{\text{min}}$ and below $T_{\text{min}}$. To examine temperature dependence above $T_{\text{min}}$, we assumed the following equation

$$\rho(T) = \rho_0 + AT^2 + BT^3 \quad (1)$$

where $\rho_0$ is the residual resistivity, $A$ and $B$ are the constant depending on pressure. The second term corresponds to electron-electron scattering and the third to phonon. $\rho_0$ is obtained by extrapolating the resistivity above $T_{\text{min}}$ to $T=0$ K.

Equation (1) is also rewritten as

$$(\rho(T) - \rho_0)/T^2 = A + BT^3$$

in Fig.6. It is found that the electrical resistivity under pressure up to 8 GPa is represented well by eq.(1) in the temperature range between $T_{\text{min}}$ and 30 K, which is shown by the solid lines in the Figure. The parameters of $A$ and $B$ in eq.(1) are given in Fig.7 as a function of pressure. The value of $A$ increases moderately below 5.5 GPa but rapidly from 6.5 GPa and then becomes to be about 15 times larger than that at 2 GPa. On the contrary, the value of $B$ does not change crucially from 2 GPa to 5.5 GPa and decreases rapidly above 6.5 GPa. At 8 GPa, $T^3$ term almost vanishes and then $T^2$ dependence becomes dominant. These results indicate that the electronic state above 8 GPa is described by normal Fermi liquid having a strong magnetic correlation. We will discuss this point in detail in the following section.

4.2 Temperature dependence of $\rho$ below $T_{\text{min}}$

The magnetic phase below $T_{\text{min}}$ is considered as RSG state, which shows the coexistence of ferromagnetic and antiferromagnetic interactions at low temperature. As pressure increases, the ferromagnetic and antiferromagnetic state are considered to be suppressed since $T_c$ and $T_N$ decrease at high pressure. By further pressurizing above 6 GPa, the RSG state becomes unstable.

In the SG phase, the electrical resistivity is well known to show log$T$ dependence, which is reminiscent of Kondo effect. Such Kondo-like behavior has been also observed in Fe-Ni-Mn ternary alloys. To examine the temperature dependence of $\rho(T)$ below $T_{\text{min}}$, we assumed the following equation

$$\rho(T) = \rho'_0 - C\log T \quad (2)$$

where $\rho'_0$ is the residual resistivity and $C$ is the constant depending on pressure. This indicates that the dilute Kondo regime is extended to concentrated one. $\rho'_0$ is obtained by extrapolating the resistivity below $T_{\text{min}}$ to $T=0$ K.

Fig. 8 $\rho(T) - \rho'_0$ as a function of log$T$ below 20 K under high pressure. The arrows indicate the temperature of the resistance minima. The solid lines are guides for the eye.
Fig. 8 shows the plot of $\rho(T) - \rho_{o}'$ as a function of log$T$. The result of these fits shows that $\rho(T)$ below $T_{min}$ is described well by eq.(2) which is shown by the solid lines in Fig.8. The parameter $C$ is plotted in Fig.9 as a function of pressure. $C$ has a broad maximum centered at 3.5 GPa and decreases rapidly above 4.5 GPa. $C$ is extrapolated to zero about 7.3 GPa (dash line) in Fig.9, which implies that the Kondo-like behavior disappears above 7.5 GPa. It should be noted that this pressure corresponds well to the pressure where $T_{min}$ is 0. Since $C$ is related to the density of state at the Fermi level and the strength of s-d interaction, the maximum in $C$ near 3.5 GPa may reflect the complex behavior of these quantities against pressure in the Invar alloys which exists near the magnetic instability due to magnetic or crystallographic inhomogeneity. These results imply the existence of magnetic phase boundary around 8 GPa.

The $T^2$-term has been well known to be enhanced near the phase boundary of magnetic instability. This indicates the large enhancement of the value of $A$ near 8 GPa which is shown in Fig.7 corresponds to magnetic phase boundary. The values of $C$ and $B$ vanish with disappearance of ferromagnetic phase and the electronic state becomes normal Fermi liquid at 8 GPa having a strong magnetic correlation. Taking into account of all the data obtained until now, the pressure induced crossover from RSG to Fermi liquid occurs near 7-8 GPa at low temperature.

5. Conclusion

In the present work we have measured the electrical resistance of Fe$_{70}$Ni$_{30}$ at high pressure and the main results are summarized as follows:
1) $\rho(T)$ shows resistance minimum at low temperature and above 2 GPa which is caused RSG phase.
2) $T_{min}$ decreases with increasing pressure. At 8 GPa, $\rho(T)$ does not have resistance minimum and shows $T^2$ dependence.
3) The crossover from RSG to Fermi liquid is observed around 8 GPa.

References

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