Appearance of the itinerant-electron character in $(Co_{0.6}Ni_{0.4})_{78}Si_8B_{14}$ observed by the resonance-magnetic-field shift induced by current

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A shift of the Curie point induced by current in $(Co_{0.6}Ni_{0.4})_{78}Si_8B_{14}$ has been observed. The electron-phonon interaction or the single-particle excitation is the origin of the resonance-magnetic-field shift induced by current.

I. INTRODUCTION

Recently, the influence of dc current on magnetic properties such as hysteresis loop, permeability, and resonance magnetic field has attracted the attention of several authors.[1–6] The detailed studies of the resonance-magnetic-field shift caused by dc current are of interest to the author. Some phenomena connected with this problem have been presented earlier[3–5] and were observed at low current density, up to 500 A/cm^2.

The aim of this paper is to report and interpret the results obtained after applying the high current density. The resonance-field shift induced by dc current has been measured.

II. EXPERIMENT

The $(Co_{0.6}Ni_{0.4})_{78}Si_8B_{14}$ amorphous alloy was chosen for this experiment. The amorphous specimen used in this experiment was prepared in the form of a rectangle using a single-roll quenching technique. The ribbon was 30 μm thick, 1 mm wide, and 3 mm long. The dc current was applied parallel to the long axis of the ribbon. The sample was placed in the microwave cavity and the ferromagnetic resonance at $f=9.36$ GHz was observed at room temperature (RT). The dc current was applied and the resonance field was measured when the magnetic field was perpendicular to the current direction and to the ribbon surface. This field shift is marked $\Delta H_\perp(90°)$.

The situation when the resonance magnetic field is perpendicular to the ribbon surface can be described by the resonance equation presented below;

$$\omega/\gamma = H - 4\pi M + H_u \ , \tag{2.1}$$

where H_u is the uniaxial perpendicular anisotropy. We omitted the uniaxial anisotropy lying in the ribbon plane. So, when the dc current causes the change of the resonance field we can directly calculate the change of the effective anisotropy—$4\pi M - H_u$. The resonance field shifts to lower values and the amplitude of the ferromagnetic signal decreases. This means that the effective anisotropy $4\pi M - H_u$ decreases simultaneously.

Furthermore, the width of the ferromagnetic line increases. Figure 1 presents the obtained results of $\Delta H_\perp$ versus applied current density. At a certain value of the current density $j_{max}=1.3\times10^3$ A/cm^2 for our sample the resonance line vanishes, and no resonance line is further observed. The simplest solution of this phenomenon is to attribute the usual heating process as the origin of the observed effect. So, one should measure the temperature of the sample during the flowing of current. This was done with a copper-Constantan thermocouple placed at the ribbon. The bath temperature was fixed and the current was then varied, which changes the sample temperature. The current induces a change in the resonance magnetic field and so the effective anisotropy $4\pi M - H_u$. We can calculate the effective anisotropy $4\pi M - H_u$ at each current density value and thus at each measured temperature. We assumed that the change of H_u (similar to treating the anisotropy lying in the ribbon plane[3]) plays a minor role. We have compared the plots of the reduced magnetization $M(T)/M(\mathrm{RT})$ versus T obtained in our experiment with those obtained by the magnetic balance method in Fig. 2. The latter experiment was done at the external magnetic field $H=H_{min}^{res}=3600$ Oe—the lowest resonance magnetic field. It is astonishing that the decreasing rate of the re-

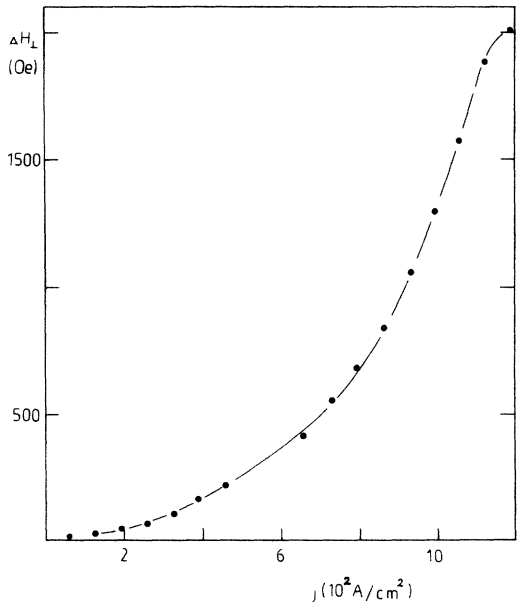

FIG. 1. The resonance-magnetic-field shift H versus current density j at room temperature.

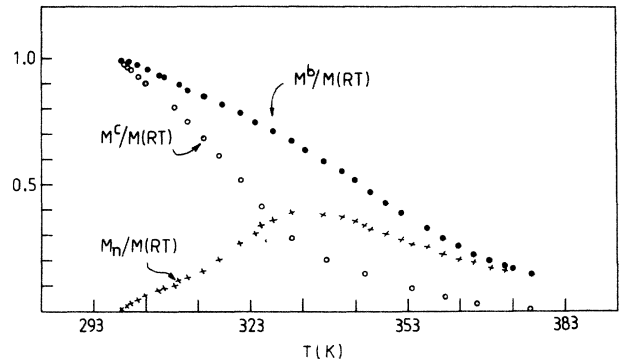

FIG. 2. The reduced magnetization $M^b(T)/M(\mathrm{RT})$ measured by the magnetic balance method at the external magnetic field $H=3600$ Oe=(the lowest resonance field) versus temperature T. The values of the reduced magnetization $M^c(T)/M(\mathrm{RT})$ measured by the "current" experiment and calculated values of the $M_n/M(\mathrm{RT})=(M^b-M^c)/M(\mathrm{RT})$.

duced magnetization is so large in the high-current-density experiment. This effect appears to be unknown in the usual temperature dependence of the magnetization in the alloys investigated until now.

III. DISCUSSION

One can imagine that flowing current induces the interactions between conduction electrons from one side and ions from the other side. The direct scattering effect on electrons which are responsible for magnetization is possible also. So, these "magnetic" electrons become more itinerant and we can expect that they are thermally excited. The manifestation of such excitation can be described by the Stoner term CT^2 which is the measure of the change in reduced magnetization.[7] Therefore, one of the ways to describe our results is by treating our case as an itinerant-electron ferromagnet forced by current.

To learn more about the origin of the new effect we subtracted the experimental results obtained from the high-current-density experiment from those obtained by the magnetic balance method. The obtained reduced magnetization $M^b(T)-M^c(T)/M(\mathrm{RT})$ is the new term that appears in the high-current-density experiment. M^b is the magnetization measured by the magnetic balance method, and M^c is the magnetization calculated from the (2.1) equation. This method was used earlier to obtain the single-particle excitation.[7,8] In our case the situation is a little different from that presented in Refs. 8 and 9. We treat magnetization in the following way:[9]

$$M=M_0-M_{\mathrm{SW}}-M_n\ , \tag{3.1}$$

where M_0 is the saturation magnetization at absolute zero; M_{SW} is the deviation arising from the collective spin-wave excitations; M_n is the deviation arising from the high-current-density effect.

We assumed that our magnetic balance method represents the results associated with the M_0-M_{SW} term. The new magnetization M_n which was induced in the high-current-density experiment will be treated as a single-particle excitation in the first approach. The results $M^b(T)/M(\mathrm{RT})$, $M^c(T)/M(\mathrm{RT})$, and $M_n(T)/M(\mathrm{RT})$ are presented in Fig. 2 where $M_n(T)=M^b(T)-M^c(T)$.

The temperature of the phase transition, T_C (Curie temperature), may be given approximately by the largest slope of the $M^{b,c}(T)/M(\mathrm{RT})$ curve. For the high-current-density case this transition temperature has been shifted to a lower value. Furthermore, I expect the maximum of the $M_n(T)/M(\mathrm{RT})$ curve to indicate the beginning of the phase transition more exactly. If we treat the new effect as a single-particle excitation induced by current, then the initial increase of M_n is associated with the change in reduced magnetization caused by thermal excitation. Such an effect is described by the so-called Stoner term[9] given by the term CT^2. Fitting it to experimental results, we obtained $C=4\times10^{-4}$. The maximum of M_n should be explained by the rapid decrease of the magnetic part in the whole excitation energy near the new Curie point. To summarize, the single-particle excitation shifts the Curie point to the lower value.

One can also imagine a second explanation of the present experiment. When we pass the current through the sample we must expect that we disturb the screening behavior of conduction electrons. The ion-ion interaction is screened by the conduction electrons, so the change of the screening condition affects the ion-ion interaction. Finally we can say that by passing the current through the sample, we modify the electron-phonon interaction. As stated previously,[10] this interaction influences the sample magnetization. It is the direct reason why the other approach to the problem considered in this paper may be associated with the electron-phonon interaction. The significant role of this interaction in the faster decrease of magnetization as opposed to temperature has been indicated by Kim.[10–14] He emphasized that the exchange energy between electrons should enhance the electron-phonon effect in the decrease of magnetization.

The electron-phonon interaction decreases the magnetization (above the Debye temperature) so the coefficient of proportionality n [$M_{\mathrm{ph}}/N\mu_B=-n(T/\Theta)$ (Ref. 14)] may reach the value up to 1 μ_B per atom. The factor n determines the electron-phonon effect per atom while T/Θ causes the increase of the effect during a temperature increase. M_{ph} represents the magnetization due to the electron-phonon interaction, and Θ is the Debye temperature. If we treat our experimental results M_n as an effect of the electron-phonon interaction on the magnetization, we must conclude that the coefficient n decreases when

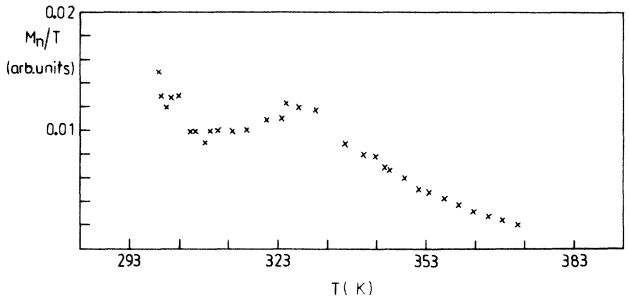

FIG. 3. The magnetization M_n/T versus temperature T.

the temperature increases. This effect is evident from Fig. 3, which presents M_n/T versus temperature T. According to the Kim theory the electron-phonon effect strongly depends on the exchange energy. The important result from this theory is that the phonon effect is generally substantial and increases with increasing exchange energy when the Fermi energy is not located at or near the maximum of density of states.[14] But with a temperature increase, the exchange energy decreases, so the electron-phonon effect decreases as well, which should explain the decrease of M_n/T versus T in our case. If we take two experimental points lying near each other, the following equation can be obtained according to the Kim theory:

$$M_{\rm ph}^{(1)}-M_{\rm ph}^{(2)}=n^{(1)}(T^{(2)}-T^{(1)})/\Theta+\Delta nT^{(2)}/\Theta\ , \tag{3.2}$$

where Δn is the change of factor n versus temperature. If $\Delta n/\Delta T\rightarrow 0$ Eq. (2.2) is reduced to the form

$$n^{(1)}\simeq(M_{\rm ph}^{(1)}-M_{\rm ph}^{(2)})\Theta/(T^{(2)}-T^{(1)})\ . \tag{3.3}$$

Using the experimental values and assuming $\Theta\simeq 10^2$, we obtained

$$n_{\rm max}\simeq 0.3\mu_B/\text{atom}\ .$$

The magnitude of n is in the same order as predicted in the Kim theory and 1 order larger than electron-phonon effect without exchange energy between electrons ($10^{-2}\mu_B$/atom).

The maximum value of M_n/M(RT) can be explained by two opposite phenomena:

(i) the increase of temperature, which is the reason for the increasing values of M_n/M(RT).

(ii) the dependence of M_n/M(RT) on the exchange energy. It increases or decreases with exchange energy accordingly as the Fermi energy is located at or near the maximum value of density of states, respectively.

The essential problem is to determine the exact value of Debye temperature needed to calculate the exact value of parameter n. This problem still exists.

IV. CONCLUSION

The present results indicate that the induced "itineracy" is the origin of the resonance-magnetic-field shift.

By using the high-current-density experiment we determined the induced single-particle excitation and the shift of the Curie point to lower value. The second approach to the present experiment allows us to treat the resonance-magnetic-field shift as an effect of electron-phonon interaction. This interaction estimates the value of this effect as approximately $0.3\mu_B$ per atom.

At this time it is difficult to state which of the proposed mechanisms is more valid and truly decides about the magnitude of resonance-magnetic-field shift induced by current. In earlier work it was shown that the rate of the magnetization change depends strongly on the state of strains and of the history of the sample.

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