with n outgoing lines, each of which corresponds to a definite frequency and momentum satisfying the conservation law in each block. The blocks of the first and second sublattices are shown by solid and dashed lines, respectively. To each point relating the solid or dashed lines there corresponds an effective interaction tensor $\hat{\Lambda}_{12q}(\omega, -\omega)$. The summation is carried out over all the internal frequencies and momentum.

The expression obtained for η_{2k} by summing the transformed diagrams takes the form (we neglect exchange inside each sublattice, i.e., $\alpha' = -\alpha$)

$$\eta_{2k} = \frac{\pi}{8\hbar N^2} n_{2k}^{-1} \sum_{q,k} \{(J_q + J_p + J_{k-q} + J_{k-p})^2 n_{2q} n_{2p} [1 + n_{2p+q-k}] \times \delta[\varepsilon_{2q} + \varepsilon_{2p} - \varepsilon_{2\,p+q-k} - \varepsilon_{2k}] + 2(J_q - J_p + J_{k-q} - J_{k-p})^2 \times n_{2q} n_{1p} [1 + n_{1\,p+q-k}] \delta[\varepsilon_{2q} + \varepsilon_{1p} - \varepsilon_{1\,p+q-k} - \varepsilon_{2k}]\}, \quad (8)$$

where $n_{1,2k}$ is the Bose distribution function for spin waves with energies ε_{1k} and ε_{2k}; J_k is the Fourier component of the exchange integral, see[8]. At low temperatures ($T \ll T_N$) and at small quasi-momenta ($(\varepsilon_{2k}/\varepsilon_{20} - 1) \ll 1$) we obtain

$$\eta_{2k} = \frac{1}{4\pi^3} \left(\frac{v_0}{R_0^3}\right)^2 \frac{4\gamma H_E}{s^2} \left(\frac{k_B T}{2\mu_B H_E}\right)^2 F\left(\frac{\varepsilon_{20}}{k_B T}\right), \quad (9)$$

$$F\left(\frac{\varepsilon_{20}}{k_B T}\right) = \int_0^{n_{20}} \frac{\ln(x+1)}{x(x+1)} dx,$$

where $(v_0/R_0^3)^2 = 1/27$ when account is taken of only the interaction between the nearest neighbors. We have

$$F\left(\frac{\varepsilon_{20}}{k_B T}\right) \leqslant 1 \text{ and } F\left(\frac{\varepsilon_{20}}{k_B T}\right) \approx \exp\left\{-\frac{\varepsilon_{20}}{k_B T}\right\} \text{ at } \frac{\varepsilon_{20}}{k_B T} \gg 1.$$

It is realistic in practice to obtain a state with collapsed spins in AF with small T_N. At $2H_E \sim 50$ kOe ($T_N \sim 10$ °K) and $T \sim 1$ °K we obtain $\eta_{2k}/\gamma \sim 1$ Oe. It follows then from (7) at $H_A \sim 3$ kOe and $\omega_p/\gamma \sim 13$ kOe (the 8-mm microwave band) that $h \sim 10$ Oe, which is perfectly attainable. We note in conclusion that a curious feature of the sf mode is that it has no linear connection with the phonons.

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Effect of hydrostatic pressure on the magnetization of the alloy MnSb

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Variation of the magnetization of an MnSb alloy, induced by hydrostatic pressure up to 8 kbar, is measured at temperatures of $T_1 = 83$°K and $T_2 = 294$°K. It is shown that the magnetization decreases under pressure: $\Delta\sigma/\Delta p = -(0.34 \pm 0.13)$ G-cm^3/g-kbar and $\Delta\sigma/\Delta p = -(0.45 \pm 0.13)$ G-cm^3/g-kbar respectively for each of the temperatures. The temperature dependence of the spontaneous magnetization of MnSb measured in the range between 83 and 358°K and at atmospheric pressure is satisfactorily described by the Stoner quadratic law. The experimental results obtained are analyzed on basis of the theory of band ferromagnetism.

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INTRODUCTION

The question of the nature of exchange interactions in the MnSb alloy has not been answered to this day. To describe the exchange mechanisms in MnSb, models were proposed based on the concept of interaction of localized spins (Lotgering and Gorter,[1] de Gennes[2]). Edwards and Bartel[3,4] have recently attempted to apply the model of collectivized electrons to a description of the pressure-induced change of the Curie temperature of the alloys MnSb and $MnSb_{1-x}As_x$.

The Stoner theory of band ferromagnetism was developed by Wohlfarth[5] for the particular case of compounds having close values of the Curie temperature and of the magnetization. A classical example of such weak band ferromagnets is $ZrZn_2$. Within the framework of Wohlfarth's theory of weak band ferromagnetism, relations were obtained between the pressure-induced change of the Curie temperature and the change of the magnetization. These relations were confirmed by experiment.

Edwards and Bartel,[3] following Wohlfarth's theory,

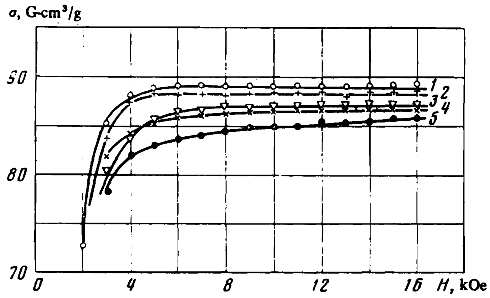

FIG. 1. Magnetization curves of MnSb alloy at room temperature 294 °K and at various pressures (kbar): 1—10^{-3}; 2—4.1; 3—5.6; 4—6.7; 5—8.2.

used Stoner's model of collectivized electrons for substances with large Curie temperatures and large magnetizations. They applied their theory to compounds of $3d$ transition metals, in which the d-electron states broaden into narrow bands that do not overlap the s and p bands, so that the number of electrons in the d bands remains constant with changing pressure. One such compound is MnSb. Starting from the one-band model with allowance for the electron correlations, they obtained for the Curie point of the MnSb alloy a pressure dependence that agreed well with experiment. [4]

Finally, it can be assumed, following Goodenough's qualitative model, [7] that exchange between localized spin and magnetism of the collectivized electrons coexist simultaneously in this compound. The contribution of the interaction in the system of the collectivized electrons can then be described either by the theory of weak band ferromagnetism or by the theory of Edwards and Bartel. [3]

It is of interest to analyze the temperature and baric dependences of the magnetic parameters of the alloy MnSb by starting from the band theory of ferromagnetism. In this paper we undertake a verification of the satisfaction of the relations between the baric derivatives of the Curie point and the magnetization, relations derived in the theory of weak band ferromagnetism, for the purpose of ascertaining the degree to which this theory can describe the alloy MnSb.

EXPERIMENTAL PROCEDURE

We investigated an MnSb sample produced by the method described by Lotering and Gorter. [1] The magnetization curves and the temperature dependence of the magnetization were measured by weighing with a Domenicali magnetic balance[8] in fields up to 16 kOe; the error in the measurements of $\Delta\sigma$ was ± 0.4 G-cm^3/g. The reproducibility of the magnetization curve after the removal of the pressure was verified every time by mea-

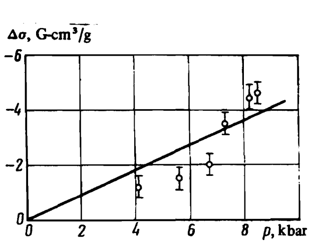

FIG. 2. Variation of the magnetization of MnSb at $T = 294$ °K with changing pressure.

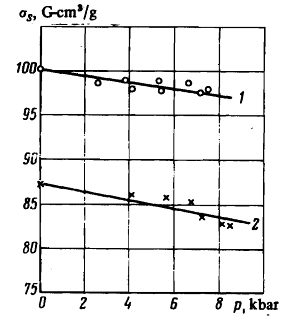

FIG. 3. Pressure dependence of the spontaneous magnetization of the alloy MnSb at $T_1 = 83$ °K (curve 1) and $T_2 = 294$ °K (curve 2).

suring the control curve at atmospheric pressure.

Hydrostatic pressure up to 8 kbar was produced in a miniature high-pressure cell made of nonmagnetic VTZ-1 alloy. [9] The pressure-transmitting medium was a 50% mixture of transformer oil with kerosene. The pressure in the cell was measured with a manganin resistance manometer, the temperature dependence of which was taken into account at each pressure; the pressure measurement accuracy was ± 100 bar. The temperature was measured accurate to 1 °K with a copper-constantan thermocouple placed inside the chamber near the sample.

EXPERIMENTAL RESULTS

To determine the effect of pressure on magnetization we plotted the magnetization curves $\sigma(H)$ at various pressures and at temperatures $T_1 = 83$ °K and $T_2 = 294$ °K. Figure 1 shows by way of example the magnetization isotherms of the alloy MnSb at room temperature $T_2 = 294$ °K, plotted at pressures up to 8 kbar. The magnetization isotherms were used to obtain the spontaneous magnetization σ_s at a given temperature T by extrapolating the $\sigma(H)$ to zero field, and the change of σ_s with changing pressure, $\Delta\sigma_s = \sigma_s(p) - \sigma_s(p_{atm})$ was calculated ($\sigma_s(p_{atm})$ is the spontaneous magnetization at atmospheric pressure and $\sigma_s(p)$ is the spontaneous magnetization at pressure p).

A plot of the magnetization against pressure at $T_2 = 294$ °K is shown in Fig. 2. From the experimental points on these lines we determined by least squares the baric derivatives of the magnetization for each of the two temperatures:

$$\frac{\Delta\sigma_s}{\Delta p}(T_1) = -(0.34 \pm 0.13)\,\frac{\text{G-cm}^3}{\text{g-kbar}},$$
$$\frac{\Delta\sigma_s}{\Delta p}(T_2) = -(0.45 \pm 0.13)\,\frac{\text{G-cm}^3}{\text{g-kbar}}.$$

Figure 3 shows for comparison plots of the spontaneous magnetization σ_s against pressure at temperatures $T_1 = 83$ °K and $T_2 = 294$ °K.

We measured the temperature dependence of the spontaneous magnetization of the alloy MnSb at atmospheric pressure in the temperature interval 83–358 °K. It can be represented as the quadratic function $\sigma_s^2(T^2)$, as is clearly seen from Fig. 4. When the straight line $\sigma_s^2(T^2)$ is extrapolated to the high-temperature region we obtain for the curie temperature the value $T_c = 576$ °K, which agrees well with the published data. [3] This fact can be

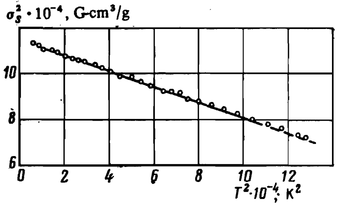

FIG. 4. Dependence of σ_s^2 on T^2 of the alloy MnSb at atmospheric pressure.

regarded as an indication that the linear character of $\sigma_s^2(T^2)$ holds true also at high temperatures up to T_c. Extrapolation of the line $\sigma_s^2(T^2)$ to $T=0\,^\circ$K yields a value $\sigma_s(0)=101.3$ G-cm^3/g, which is also in reasonable agreement with results by others.[1]

DISCUSSION OF RESULTS

In the band theory of ferromagnetism, the temperature dependence of the magnetization obeys the Stoner quadratic law

$$\sigma_s^2(T)=\sigma_0^2[1-(T/T_c)^2], \quad (1)$$

where σ_0 is the magnetization in zero field at $0\,^\circ$K and T_c is the Curie temperature. The fact that a quadratic dependence of type (1) holds for $\sigma_s(T)$ of the MnSb alloy in a wide range of temperatures indicates that the band-ferromagnetism model can be used for this compound.

The relation between the baric derivatives of the Curie point and of the magnetization, obtained in the theory of weak band ferromagnetism, is[6]

$$\frac{1}{\sigma_0}\frac{d\sigma_0}{dp}=\frac{1}{T_c}\frac{dT_c}{dp}. \quad (2)$$

To compare the theory with experiment we must take into account the temperature dependence of the magnetization. Then, taking (1) into account, we obtain for the alloy magnetization measured at finite temperature T

$$\frac{d\sigma_s(T)}{dp}=\left[1-\left(\frac{T}{T_c}\right)^2\right]\frac{d\sigma_0}{dp}-\frac{\sigma_0(T/T_c)^2}{[1-(T/T_c)^2]^{1/2}}\frac{1}{T_c}\frac{dT_c}{dp}, \quad (3)$$

from which it is seen that at this temperature T the change of the spontaneous magnetization with pressure is determined by two factors: the change of the spontaneous moment at $0\,^\circ$K and the change of the Curie temperature under pressure.

From the published data we know that $dT_c/dp=3.05\,^\circ$K/kbar for MnSb. We use for the estimate $T_c=576\,^\circ$K and $\sigma_0=101.3$ G-cm^3/g, which were obtained from extrapolation of the line $\sigma_s^2(T^2)$. At these values of the parameters we obtain from (2) and (3) the values -0.54 and -0.62 G-cm^3/g-kbar for $d\sigma_s/dp$ at $T_1=83\,^\circ$K and $T_2=294\,^\circ$K, respectively. Comparison with the experimental data shows that the signs of the derivatives coincide and the measured values are close to the theoretical ones.

It should be noted that the influence of the pressure on the magnetization increases with increasing temperature. This experimentally observed fact can be deduced also from an analysis of (3), where the coefficient of dT_c/dp increases rapidly as the temperature tends to the Curie point.

The experimental results allow us to state that the magnetization and the Curie temperature of the alloy MnSb are governed by the ferromagnetism of the system of collectivized electrons. The effect of the pressure on the magnetization in the collectivized-electron mode was analyzed by Mathon[10] as applied to nickel. The change of the magnetization under pressure is assumed to depend on two parameters, the change of the effective interaction with changing pressure and the electron $s-d$ transfer due to the relative shift of the s and d bands. The fact that the simple relations obtained in Wohlfarth's band theory of weak ferromagnetism hold true without allowance for the $s-d$ transfer can serve as proof of the presence of a special $3d$ band in the electron structure of MnSb. In this case the number of magnetic carriers in the $3d$ band does not change and there is no contribution of the $s-d$ transfer to the baric derivative of the magnetization.

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