SOME CHARACTERISTIC FEATURES OF THE TEMPERATURE DEPENDENCE OF THE ELECTRICAL RESISTIVITY OF Mg ALLOYS CONTAINING HEAVY NONMAGNETIC IMPURITIES

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The impurity resistivity $\Delta\rho(T)$ of dilute Mg–Pb and Mg–Ag solid solutions was measured. It was found that, for small amounts of the second component (Pb or Ag), $\Delta\rho(T)$ depended linearly on the concentration at temperatures of 30–300°K. A pronounced maximum of $\Delta\rho(T)$ was detected in Mg–Pb at temperatures ≈55°K, and the temperature coefficient of the resistivity was found to be positive at high temperatures. A comparison with the theory [1] was made. The existence of a maximum of $\Delta\rho(T)$ for Mg–Pb was explained mainly by a quasi-local vibration frequency. [2-5]

INTRODUCTION

As is well known, the Matthiessen rule for the impurity electrical resistivity $\Delta\rho(T)$ of dilute substitutional solid solutions is satisfied only approximately. Kagan and one of the present authors [1] have proposed a theory for the electrical resistivity of metals containing nonmagnetic impurities. This theory consistently allows for the nature of the vibrations of the impurity atom and of its environment, as well as for the actual mechanism of electron scattering by perturbed regions in a crystal. The results obtained in [1] make it possible to predict and explain the nature of deviations from the Matthiessen rule for $\Delta\rho(T)$ over a wide range of temperatures.

At relatively low temperatures, such deviations should be observed, in particular, if an impurity atom vibrates mainly in a narrow range of frequencies near a quasi-local frequency (QLF, ω_*). [2,3] In this case, the classical temperature limit for the impurity and its environment is reached already at $T \sim \frac{1}{2}\omega_*$, so that $\Delta\rho(T \gtrsim \frac{1}{2}\omega_*) \propto T$, while the resistivity of an ideal matrix is proportional to T^5. The occurrence of the QLF has been deduced directly from the inelastic scattering of neutrons [4] and indirectly from the anomalous behavior of the lattice specific heat [5] of Mg–Pb alloys. Therefore, it was of interest to determine the temperature dependence $\Delta\rho(T)$ for the same Mg–Pb alloys in order to find the direct influence of the QLF on the impurity resistivity. For comparison, we also determined $\Delta\rho(T)$ for Mg alloys containing a much lighter impurity (Ag).

It must be mentioned that Mg alloys have been investigated by many workers. [6,7] In these investigations, the concentration of the second component was relatively high and $\Delta\rho(T)$ depended nonlinearly on the concentration c. In the present investigation, we found that $\Delta\rho(T)$ of alloys with very low impurity concentrations (0.03, 0.05, 0.1 at.% Pb) and 0.03, 0.05, and 0.3 at.% Ag) was a linear function of the concentration (with the exception of the lowest temperatures). This made it possible to compare the results directly with the theory, [1] and, in particular, to determine the role of the QLF in the impurity component of the resistivity.

EXPERIMENTAL METHOD

The Mg–Pb and Mg–Ag alloys were substitutional solid solutions. We used Mg with a resistance ratio $R(300°)/R(4.2°) = 1.2 \times 10^3$. To avoid the systematic errors associated with different conditions of preparation of the pure Mg samples and of the alloys, the Mg was re-melted in the same crucibles in which the alloys were prepared. The resistance ratio $R(300°)/R(4.2°)$ was then found to be 0.6×10^3. Samples of pure Mg and of Mg–Pb alloys were prepared in the form of wires, 1 mm in diameter and 50 mm long, by drawing through a die and annealing subsequently in a helium atmosphere at 350°C. The current and potential contacts were soldered directly to the samples. The measurements of the diameters of the samples, carried out at more than fifteen points along the length of a sample, showed that the deviation of individual measurements from the average value did not exceed 0.005 mm. The accuracy of the measurements of the length was 0.1 mm.

We used a cryostat similar to that described by Rose-Innes and Broom. [8] A large copper block was placed, together with the samples and thermometers, in a copper can containing activated charcoal. Low-temperature measurements at 1.2–4.2°K were carried out with the samples in contact with a helium bath. After the evaporation of the helium, the presence of activated charcoal around the copper block ensured that the temperature rose very slowly (in 6 hours) to 30°K, which allowed us to carry out measurements simultaneously on five samples. Heating was employed to cover the temperature range 30–80°K. For the measurements at temperatures of 80–300°K, the copper block and the samples were in thermal contact with a nitrogen bath via heat exchange through the helium.

The temperature of the samples was measured with carbon and platinum resistance thermometers, which were placed near the samples. The carbon resistance thermometer was calibrated as described in [6]. The resistance of the samples and of the thermometers was measured by a standard potentiometric circuit with a 5-decade PMS-48 potentiometer with a F-16 photocompensation amplifier used as a null indicator (sensitivity, 10^{-8} V/mm).

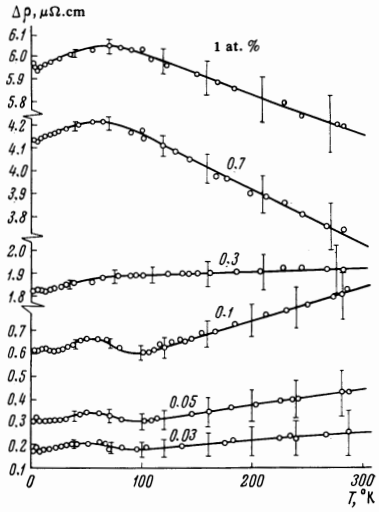

FIG. 1. Temperature dependence of the impurity resistivity of Mg – Pb alloys with various concentrations of Pb.

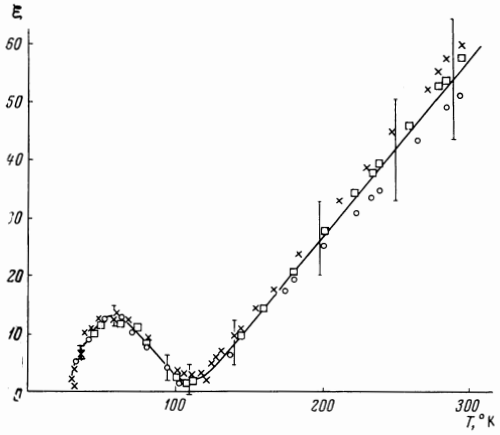

FIG. 3. Temperature dependence of the relative change in the resistivity $\xi = [\Delta\rho(T) - \Delta\rho(0)]/c\rho_{Mg}(273^\circ)$ for Mg – Pb alloys: X – 0.1 at.% Pb, □ – 0.05 at.% Pb, ○ – 0.03 at.% Pb.

RESULTS OF MEASUREMENTS

We investigated the temperature dependence of the electrical resistivity of pure Mg and of Mg–Pb alloys containing 0.03, 0.05, 0.1, 0.3, 0.7, and 1 at.% Pb in the temperature range 1.2–300°K. The results of the investigation are presented in Fig. 1.

It follows from these results that the nature of the impurity resistivity curves changes radically with the concentration. At the very lowest temperatures, from 1.2 to 30°K, the impurity resistivity depends nonlinearly on the concentration. The nature of the low-temperature dependence of the resistivity $\rho(T)$ of Mg–Pb alloys on T and c (Fig. 2) may be related to the presence of traces of paramagnetic impurities in our alloys.[9]

We have been able to establish that the impurity resistivity $\Delta\rho(T)$ of alloys with a very low Pb content (0.03, 0.05, and 0.1 at.%) varies linearly with the concentration in the temperature range 30–300°K. This is the impurity resistivity component which we have been seeking in order to compare it with the theory given in[1]. It follows from Fig. 3 that $\Delta\rho(T)$ of Mg–Pb alloys has a very pronounced maximum in the region of 50–70°K. It is worth noting also the positive sign of the derivative $\partial\Delta\rho/\partial T$ at high temperatures. It is interesting that the derivative $\partial\Delta\rho/\partial T$ changes its sign for alloys with higher concentrations of Pb.

We also investigated alloys of Mg and Ag (0.03, 0.05, 0.3, 0.7 and 1%) at temperatures from 1.2 to 300°K. We found that the impurity resistivity of Mg–Ag alloys, like that of Mg–Pb alloys, depends linearly on the concentration c only at low concentrations of the second component (0.03, 0.05, and 0.3%) in the temperature range 30–300°K. The linear dependence of $\Delta\rho(T)$ on the concentration of Mg–Ag alloys is shown in Fig. 4.

The scatter of the values of $\Delta\rho(T)$ and $\xi = [\Delta\rho(T) - \Delta\rho(0)]/c\rho_{Mg}(273^\circ K)$, represented by vertical lines in Fig. 1 and in Figs. 3 and 4, respectively, is associated with systematic errors, which are unavoidable in the determination of the absolute values of the resistivity. Since the error in the measurement of the value of the resistance R did not exceed ±0.1% at the very lowest temperatures and ±0.01% at high temperatures, it was clear that the main error (±1.2%) in the value of ρ was due to the inaccuracy in the determination of the geometrical dimensions (S, l). Analysis of the experimental data was most conveniently carried out using the right-hand side of the equation given below. Assuming that the thermal expansion can be neglected, we find that

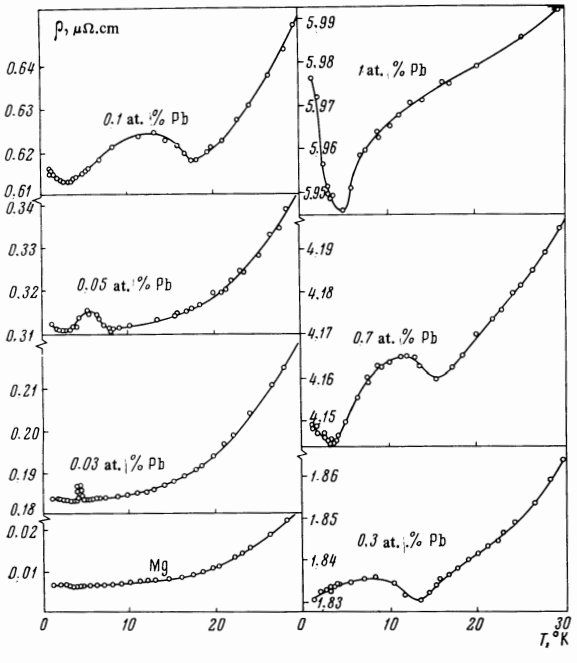

FIG. 2. Temperature dependence of the resistivity of pure Mg and of Mg – Pb alloys.

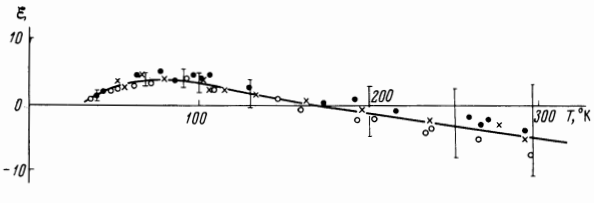

FIG. 4. Temperature dependence in the relative change in the resistivity of Mg – Ag alloys: ○ – 0.3 at.% Ag, X – 0.05 at.% Ag, ○ – 0.03 at.% Ag.

$$\xi = \frac{R(T)_{\text{alloy}} - R(0)_{\text{alloy}}}{cR_{\text{Mg}}(273°)} \frac{S_{\text{alloy}} l_{\text{Mg}}}{l_{\text{alloy}} S_{\text{Mg}}} - \frac{R(T)_{\text{Mg}} - R(0)_{\text{Mg}}}{cR_{\text{Mg}}(273°)}.$$

DISCUSSION OF RESULTS

The linear dependence of $\Delta\rho(T)$ on the concentration, observed in the present investigation over a wide range of temperatures, makes it possible to carry out a direct comparison with the theory of Kagan and one of the present authors [1] and, in particular, to estimate the role of the QLF in the impurity resistivity. Bearing this in mind, we carried out an approximate numerical calculation of $\Delta\rho(T)$ for Mg—Pb alloys within the framework of the results reported in [1]. In these calculations we used the Debye approximation for the phonon spectrum of the crystal matrix. The values of the Mg and Pb pseudo-potentials, given by Animalu and Heine, [10] were used for the amplitude of the electron scattering by atoms in the alloys. The pseudo-potential of Pb in Mg was assumed to be the effective potential of Pb divided by the calculated permittivity of Mg.

The results of a numerical calculation of the ratio $\eta = \Delta\rho(T)/c\rho_0^0(2\Theta/3)$ (for Mg, $2\Theta/3 \approx 270°$) are given in Fig. 5. Comparison of Figs. 3 and 5 shows that the theory gives a qualitatively correct prediction of the behavior of $\Delta\rho(T)$ near ω_* over a wide range of temperatures. We note that the pseudo-potentials of Mg and Pb in the region of large momentum transfer have been determined with a limited accuracy. By varying the numerical values of the pseudo-potentials in the region of large momentum transfer, we can obtain a much better agreement between the experimental and theoretical curves near the $\Delta\rho(T)$ maximum.

The complex temperature dependence of $\Delta\rho(T)$ of Mg—Pb alloys at moderate temperatures can be explained physically as follows. An impurity atom and its environment vibrate mainly in a narrow range of frequencies near the QLF. Therefore, in the temperature range $(\omega_*/2) \lesssim T \lesssim \omega_*$, where [2]

$$\omega_*^2 = (|\varepsilon|\langle\omega^{-2}\rangle)^{-1}, \quad \varepsilon = (M_{\text{Mg}} - M_{\text{Pb}})/M_{\text{Mg}},$$

the scattering of electrons on the vibrations of a heavy impurity and of its environment should be anomalously strong, $\Delta\rho \propto T$. [1] When the temperature is increased, the scattering of electrons by the lattice atom vibrations becomes mainly quasi-elastic and the impurity resistivity effects, associated with the deformation of the phonon spectrum in the approximation which assumes unchanged force constants, disappear completely. [1] Thus, the contribution to the impurity resistivity due to the deformation of the phonon spectrum passes through a strong maximum near $T \sim \omega_*$. On the other hand, in the classical temperature limit the sign of the impurity resistivity is determined, within the framework of the approximations assumed in [1], by the sign of the coefficient g_3 (cf. [1]). The sign of g_3 is, roughly speaking, governed by the sign of $\Delta Z = Z_{\text{Pb}} - Z_{\text{Mg}}$, where Z_{Pb} and Z_{Mg} represent the charge of Mg ions and the charge of Pb ions in a Mg matrix. For these reasons, the impurity resistivity near $T \sim \omega_*$ passes through a maximum mainly because of the QLF, and then increases monotonically.

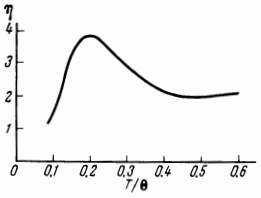

FIG. 5. Calculated temperature dependence of the relative change in the electrical resistivity of a Mg – Pb alloy; $\eta = [\Delta\rho(T) - \Delta\rho(0)]/c\rho_{\text{Mg}}(2\Theta/3)$.

In conclusion, we must mention that the qualitative nature of the behavior of $\Delta\rho(T)$ at $T \sim \omega_*$ does not change when the electron spectrum of Mg changes. This is because the contribution to the impurity resistivity due to such a change is proportional to T^5 at low temperatures, while the contribution to the impurity resistivity due to a change in the phonon spectrum is proportional to T. On the other hand, at high temperatures, the considerably steeper slope of the $\Delta\rho(T)$ curve than that predicted by the theory [1] is evidently due to a deformation of the electron spectrum.

A few words must be said about Mg—Ag alloys. The temperature dependence of the impurity resistivity of these alloys is in qualitative agreement with the theoretical results obtained in [1] (cf. Fig. 3 in [1]) over the whole temperature range. A quantitative comparison between the theory and experiment was not carried out.

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