Conductivity of icosahedral AlPdRe

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The electrical conductivity $\sigma(T)$ of icosahedral (i) AlPdRe has been studied in order to address current problems and controversies. Two new approaches are presented. The temperature T_0 below which variable range hopping occurs was estimated directly from $d\sigma(T)/dT$, avoiding the problem of the finite $\sigma(0)$ in i-AlPdRe. Secondly, $\sigma(T)$ is compared in detail for samples with radically different defects and morphologies. The temperature dependence of $\sigma(T)$ is found to be independent of these varying sample conditions. This finding rules out some proposed conduction mechanisms.

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I. STATUS AND PROBLEMS

Icosahedral (i) AlPdRe has been intensely studied since its discovery 20 years ago.[1] This interest has been triggered both by the unveiling of a number of remarkable properties and by the new problems that have occurred in the progress of this work. A brief background is given for the electrical resistivity.

In polygrain samples with nominal composition $Al_{70.5}Pd_{21}Re_{8.5}$, the resistivity ρ at 4 K can be varied over several orders of magnitude with concomitant variation of the average temperature dependence, $R = \rho(4\text{ K})/\rho(295\text{ K})$ from about 2 to well above 200.[2,3] The large values of R are unique among quasicrystals. Already from early results, it was suggested that i-AlPdRe was insulating-like.[4,5] However, $\rho(T)$ is not consistent with activation over a semiconducting gap. Demonstration of variable range hopping in the low-temperature conductivity $\sigma(T)$ is often a straightforward way to verify insulating properties. For i-AlPdRe, however, such results have been inconclusive since numerous varying results have been obtained in the huge range from 1 mK to 1000 K for the characteristic temperature T_0, below which variable range hopping occurs.[6,7]

It was only when both the temperature and magnetic field dependencies of the magnetoresistance were analyzed that the stringency of analyses was much improved, and a metal-insulator transition was claimed to be confirmed.[8,9] A metal-insulator transition has also been justified from a scaling analysis of the zero-field metallic conductivity above 400 mK.[10] The transition from a metallic phase at low R to insulators at large R has been estimated in various types of investigations[8,10,11] to occur around $R \approx 20$. In the transport results quoted above, $Al_{70}Pd_{22.5}Re_{7.5}$ was studied in Ref. 9 and $Al_{70.5}Pd_{21}Re_{8.5}$ in the other references. However, nor have these results been fully accepted. The problems are manifold; (i) the microscopic mechanism that accounts for large changes of properties in phase pure icosahedral alloys is not known. These different properties are observed in alloys of the same nominal chemical composition that have been prepared in different series of annealing temperatures, T_a^i. (ii) The two standard procedures for producing polygrain i-AlPdRe samples are arc melting followed by melt spinning, which gives ribbons of typical thickness 30 μm, and arc melting of an ingot, which is subsequently cut to a thin parallelepiped of cross section $\approx 1 \times 1$ mm^2. Appropriate heat treatments finalize sample preparation in both cases. Ribbons and ingot samples have significantly different morphologies. Ingots have voids in the form of needles, which may occupy roughly 30% of the sample volume, while ribbons are homogenous without voids. In both cases, scanning electron micoscopy and microprobe analyses have shown traces of a second phase.[11] Therefore a concern has been raised: what is the influence of these differences on transport results and does conduction really take place in the icosahedral phase. (iii) There is no control of the metal-insulator transition by a parameter as perspicuous as, e.g., the carrier concentration for doped semiconductors. In lack of a better choice, one uses R. However, the meaning of R for this purpose is not that clear and, secondly, R is not well controlled in the preparation procedures. One can only obtain R values in a region around a chosen target value. (iv) Single grain i-AlPdRe samples have been prepared with composition close to $Al_{71.7}Pd_{19.4}Re_{8.9}$,[12] and with varying Pd and Al concentration from $Al_{78}Pd_{15}Re_7$ to $Al_{71}Pd_{22}Re_7$,[13] with R values of 1.85 or in the range 1.2 to 2.5, respectively. The difference from polygrain samples is remarkably large and the question has been raised if single grain samples would better represent the intrinsic properties of i-AlPdRe.[14] The observed properties of high R polygrain samples have been suggested to be due to, e.g., granularity[15] or impurities or oxygen bridges.[14] (v) For an insulator, one expects a zero-temperature conductivity $\sigma(0) = 0$. Low-temperature extrapolations for i-AlPdRe indicate instead that $\sigma(0)$ is finite and decreases exponentially with increasing R for ingot and ribbon samples of $Al_{70.5}Pd_{21}Re_{8.5}$.[16] It has been problematic to reconcile this observation with the transport properties.

A schematic listing of the parameters that affect or may affect ρ illustrates the complexity of the problems. Presently, we are mainly interested in the temperature dependence, and omit here the magnetic field:

$$\rho = \rho\left(c_{\mathrm{Re}},\ T_a^i,\ \text{morphology, impurities},\ R,\ T\right). \qquad (1)$$

Impurities refer to the varying purity of the starting materials and to impurities introduced in the different preparation processes. The Re concentration c_{Re} is probably the most crucial part of the composition but variations in Al and Pd concentrations should also be considered. The parameters of Eq. (1) have been shown to be or assumed to be inter-related in a way that is not well understood, e.g., the relation between

T_a^i and R, and the sometimes claimed R dependence of both morphology and impurities, respectively.

A few of these problems have been treated in recent work. From band structure calculations in approximants, Krajčí and Hafner[17] found for an 1/1 approximant of composition $Al_{88}Pd_{32}Re_8$ and 128 atoms/unit cell that the energy bands were disconnected between the 324th and 325th bands. This does not necessarily imply a real gap in the electron spectrum. They introduced the notation topologically induced semiconductivity to describe i-AlPdRe. The asymptotic composition of their model in the quasiperiodic limit was $Al_{70.7}Pd_{20.6}Re_{8.6}$, which is fairly close to the composition studied by us.

A topological insulator is a different but related material with an insulating bulk and conducting surface states.[18] It is interesting to note that these two classes of materials have the common property that a modest degree of defects leads to formation of localized states in the gap, which may fill the band gap and give a finite $\sigma(0)$. For i-AlPdRe, the experimental result that $\sigma(0)$ decreases strongly with increasing R[16] is in qualitative agreement with this picture, since a larger R at fixed concentration indicates fewer quasicrystalline defects.

Secondly, it is well known that electronic properties of some quasicrystals can be sensitive to minute changes of concentration, e.g., in i-AlCuFe, the Hall coefficient jumps from negative to positive values for an increase of the Fe concentration by only 0.05 at %.[19] It was early conjectured that a similar sensitivity could occur also in i-AlPdRe.[20] Very recent results by Mori and coworkers[21] have shown that such a strong concentration dependence is indeed observed also in i-AlPdRe. They succeeded to vary the Re content, c_{Re}, in the icosahedral phase in steps of 0.1 at% and found that the ratio $\rho\,(15\ \mathrm{K})/\rho\,(300\ \mathrm{K})$ for polycrystalline $Al_{70.5}Pd_{21.5-x}Re_{8+x}$ was peaked around 8.5 at% Re. The hypothesis that the large differences in transport properties of polygrain samples compared to single-grain samples of different Re content would evidence nonintrinsic effects in polygrain samples[14] must therefore be abandoned.

In the present paper, we set out to deal with some of the remaining problems. First, a new method is described to determine the temperature T_o below which variable range hopping occurs, using only σ(T) without applying an excessive numbers of parameters or relying on some estimate of $\sigma(0)$. Then, we make a detailed comparison between transport properties in ribbons and ingot samples in the temperature interval of 1–300 K. Consequences of these results for some of the problems listed above will be discussed.

II. σ(T) IN THE VRH REGION

A. Analysis method

A general expression for the conductivity in the region of variable range hopping is

$$\sigma(T) = \sigma(0) + \sigma_\circ e^{[-(T_\circ/T)^{1/\nu}]}, \tag{2}$$

where $\sigma(0)$ is the zero-temperature conductivity, $\sigma_\circ$ is a prefactor, which is generally assumed to be temperature independent, $T_\circ$ is a characteristic temperature, and $1/\nu$ is an exponent, which depends on the hopping mechanism. For Mott variable range hopping (VRH), one has $\nu = 4$ and for Efros-Shklovski (ES) VRH, $\nu = 2$. Equation (2) has four free parameters when it is used to fit data for σ(T). This is overflexible for a smooth function and, as mentioned, such results have been inconclusive. One can use data for σ(T) at very low temperatures, estimate $\sigma(0)$ from extrapolation to $T = 0$, and plot data for $\ln[\sigma(T) - \sigma(0)]$ to evaluate $T_\circ$. Such procedures have been used in conjunction with analyses of the magnetoresistance.[22] An extrapolation is nevertheless a weak part of this method.

Analysis of the derivatives of σ(T) offers an alternative that does not require any predetermined value of a parameter in Eq. (2). However, the conventional assumption that $\sigma_\circ$ depends, at most, weakly on temperature is retained. One then finds from Eq. (2) that an inflection point T_i, where $d^2\sigma/dT^2 = 0$, occurs at

$$T_i = \frac{T_\circ}{(1+\nu)^\nu}. \tag{3}$$

The sign of this inflection point implies that $d^2\sigma/dT^2$ passes from positive to negative values when T increases through T_i. For Mott VRH, $\nu = 4$ and $T_\circ = 625T_i$. For ES VRH, $T_\circ = 9T_i$.

B. Sample and results

An ingot sample of nominal composition $Al_{70.5}Pd_{21}Re_{8.5}$ with $R = 250$ was prepared by melting in an arc furnace, and annealing at 940 °C, followed by annealing at 600–650 °C and then quenching into water. Samples prepared with this method have been investigated with atom absorption spectroscopy. For each element, the composition was found to be within ≈2% of the nominal one.

In order to obtain such large R values, it is of utmost importance to use a clean arc furnace and oxygen-free environment.[2] Detailed properties of samples this far into the insulating side of i-AlPdRe have not been reported before. For comparison, a previously investigated ingot sample with $R = 40$ was also studied with the present method.

The conductivity was measured in a dilution refrigerator from 20 mK to 1.5 K and in a standard cryostat to 300 K. The relative accuracy in the temperature measurements was of order 1 mK. Resistance was measured to about 10 ppm. The main panel in Fig. 1 shows the results for the normalized conductivity $\sigma_n(T) = \sigma(T)/\sigma(295\ \mathrm{K})$ for the $R = 250$ sample. On this scale, data describe a smooth curve.

Data up to 23 K are shown in the lower right inset. Changes of curvature can be seen at ∼4 and 10 K, and a closer inspection reveals a third inflection point at about 20 K. In insulating i-$Al_{70.5}Pd_{21}Re_{8.5}$ samples, $\sigma(T)$ can display one or more inflection points, which for increasing temperature, are characterized by a maximum of $d\sigma/dT$, followed by a minimum and then by a maximum again.[3] This is also the sequence observed in our data in Fig. 1. The inflection point at about 10 K has the opposite sign to one associated with variable range hopping and the one at about 20 K would correspond to an unreasonably large $T_\circ$. These two inflection points are therefore associated with other phenomena. Delahaye and coworkers[3] ascribed them to transitions between different critical regimes of σ(T).

To describe data empirically, one hence requires a fifth-degree polynomial. Such a polynomial is shown by the full

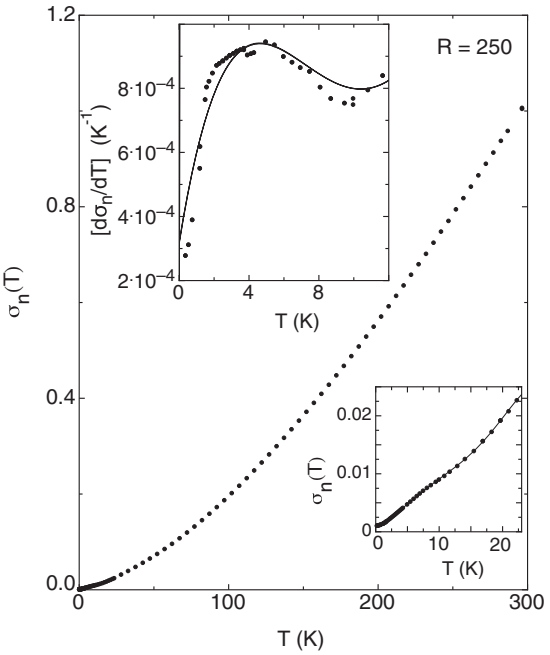

FIG. 1. Normalized conductivity $\sigma(T)/\sigma(295\ \mathrm{K})$ and its low-temperature derivative for a sample with $R = 250$. Main panel: data up to 300 K. Lower inset: data in the temperature range up to 25 K display a few inflection points. Upper inset: analysis of the lowest inflection point where $d/dT[\sigma(T)/\sigma(295\ \mathrm{K})]$ for increasing T goes from an increasing to a decreasing function. The points were obtained from a polynomial fitted to a few data points and allowed to slide over the data. The full curve is the derivative of the fit to data shown in the lower inset. An inflection point is located at about 4.5 K.

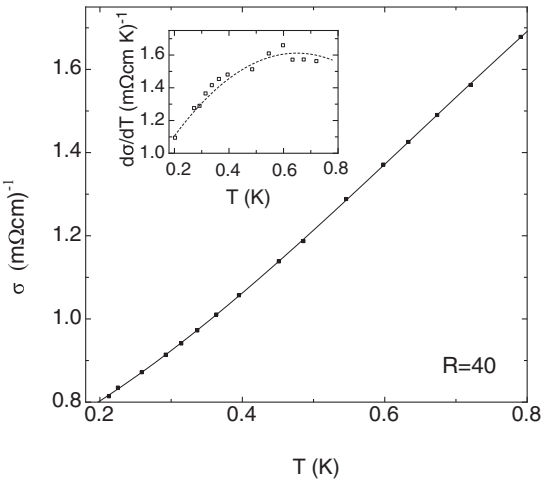

FIG. 2. Same analysis as in Fig. 1 for σ(T) of an $R = 40$ sample. Full curve is a polynomial fit to data. Its derivative is the curve in the inset and the points are the calculated derivative from a sliding polynomial to a few data points. An inflection point is located at 0.6 K.

curve through data in the lower right panel. The temperature derivative of this polynomial is shown by the full curve in the upper inset in Fig. 1, limited for clarity to the interesting region below 10 K. High-degree polynomials through data could possibly introduce artificial structure of curvatures. Therefore the derivative was also calculated from a second-degree polynomial fitted to a few data points and allowed to slide over data. The result is shown by the points in this inset. The scatter of these data of $\approx 2\times10^{-5}$ K^{-1} gives an estimate of the errors in $d\sigma_n/dT$. The agreement of these data with the polynomial derivative is fairly good. We conclude that there is an inflection point at ≈4.5 K where the first derivative has a maximum.

A similar analysis is shown in Fig. 2 for the $R = 40$ sample. In this case, a third-degree polynomial was adequate. A maximum in $d\sigma/dT$ occurs at 0.6 K. These results give $T_\circ = 40.5$ and 5.4 K for $R = 250$ and 40, respectively. The temperature dependence of the magnetoresistance rules out Mott VRH and shows that hopping is of Efros-Shklovski type.[22] However, with the presently observed T_i, Mott VRH is ruled out also by the unphysical results for $T_\circ$, which would result from $625T_i$.

III. COMPARISON BETWEEN INGOTS AND MELT-SPUN SAMPLES

We want to compare samples of different morphologies and impurities. This question has been somewhat concealed in the literature, likely due to the difficulty to control the magnitude of ρ and R in preparation processes, to the large range of variation of ρ as a function of R and T, and to the lack of theoretical justification for a given form of $\rho(T)$. Furthermore, the observed strong sensitivity of transport properties to Re concentration,[21] briefly described above, underlines the importance of comparing samples of similar compositions.

Avoiding an awkward interpolating scheme for $\rho(R,T)$, we have instead taken advantage of the result that a decrease of R can be continuously monitored by an increasing dose of high-energy neutron irradiation.[23] An ingot sample with $R = 67$ was exposed to neutron doses from 5×10^{17} to 7.6×10^{18} cm^{-2}, giving samples with R values of 57.1, 12.9, and 3.90, respectively. Ribbon samples of the same nominal composition with R values of 56.5, 13.3, and 4.03, in fair agreement with those of irradiated ingot samples, could be selected from previous work.[11,24] The inset of Fig. 3 illustrates the variation of ρ(4.2 K) for R up to ≈60 for melt-spun and ingot samples of i-$Al_{70.5}Pd_{21}Re_{8.5}$.

For the small and sometimes irregularly shaped melt-spun ribbon samples, the error in determination of ρ is significant, and error bars of ±25% have been marked for two samples in the inset of Fig. 3. For the barlike ingot samples, this error is smaller, and furthermore, it does not affect the slope of the fitted straight line, since the same ingot was used in successive irradiations. However, another error is important for these samples. Due to the voids in ingots, calculations of ρ based on sample dimensions overestimate the resistivity. Using models for calculations of the conductivity in inhomogeneous media, it was estimated that a correction factor of about 0.5 should be applied to the resistivity of our ingot samples.[25] A factor of two roughly corresponds to the difference between ingots and ribbon samples in the inset of Fig. 3.

To avoid the problems of poorly known shape factors and approximate corrections for porosity, we compare the normalized resistivities ρ(T)/ρ(295 K). Results are shown in the main panel in Fig. 3. Data for ingots and ribbon samples

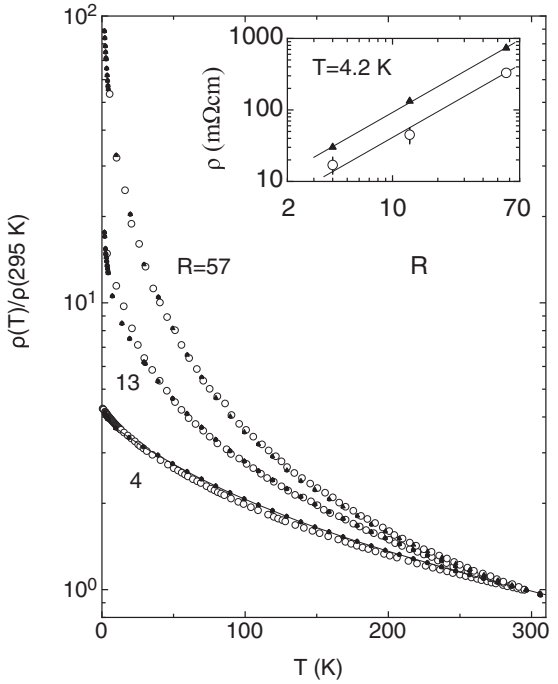

FIG. 3. Normalized resistivity $\rho(T)/\rho(295\ \mathrm{K})$ for ribbons and ingots. Open circles: ribbons. Filled circles: ingots. Inset: ln ρ at 4.2 K vs $\ln R = \ln[\rho(4.2\ \mathrm{K})/\rho(295\ \mathrm{K})]$. Errors in ρ for the ribbon samples are shown on some data. Errors for ingot samples are discussed in text.

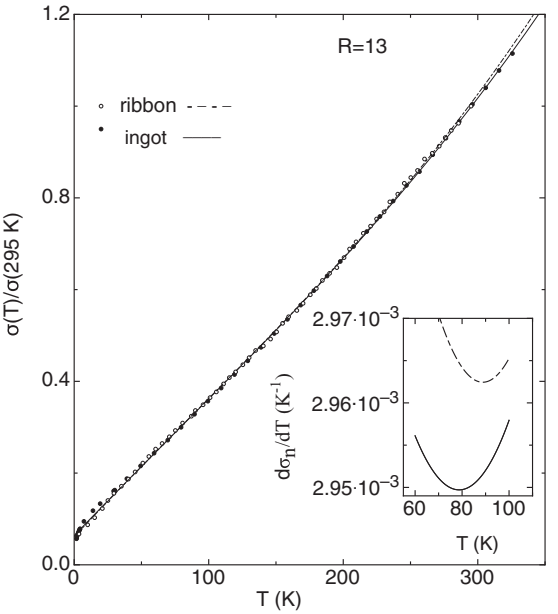

FIG. 4. Normalized conductivity $\sigma(T)/\sigma(295\ \mathrm{K})$ for ribbon and ingot samples with $R = 13$. Polynomials were fitted separately to each sample. These fits are almost indistinguishable in the main panel. Inset: $d\sigma_n/dT$ vs T for both samples. [$\sigma_n = \sigma(T)/\sigma(295\ \mathrm{K})$.] On this scale, the magnitude of the differences between the samples can be seen. The upper curve is for the ribbon sample, the lower one for the ingot.

almost collapse onto one curve for each value of R. This observation thus shows that samples with similar values of $\rho(4\ \mathrm{K})/\rho(295\ \mathrm{K})$, also have similar $\rho(\mathrm{T})/\rho(295\ \mathrm{K})$ for all temperatures in the range from about 1 to 300 K.

To what precision are the temperature dependencies of ribbon and ingot samples similar at similar values of R? Again, since an explicit form for $\rho(\mathrm{T})$ is not known, one must rely on comparisons of some characteristic features of the curves. $|d\rho/dT|$ in Fig. 3 decreases smoothly with increasing temperature for each sample. However, $\sigma(\mathrm{T})$ may display changes of curvature. Figure 4 shows $\sigma(T)/\sigma(295\ \mathrm{K})$ versus T for two $R = 13$ samples, close to and below the metal insulator transition, and Fig. 5 displays the corresponding results for two $R = 57$ samples well into the insulating side of the transition.

A change of curvature can be seen below 100 K for the $R = 13$ samples and barely discerned above 250 K for the $R = 57$ samples. Third-degree polynomials were therefore fitted to each ingot and ribbon sample at $R = 13$ and 57. At $R = 57$, these polynomials are indistinguishable on the scale of the figure, while at $R = 13$, a minor difference occurs only above about 290 K. These polynomials are further compared by calculating the derivatives. An upper limit for the error in $d\sigma_n/dT$ is obtained from the error of the slope of a straight line between adjacent data points (≈10 K apart), and is roughly $2\times10^{-6}\ \mathrm{K}^{-1}$. As illustrated in the insets of Figs. 4 and 5, the inflection points occur at rather different temperatures and have opposite signs for the different R values. However, the temperatures at the inflection points are similar at each R. To separate these inflection points from that of Eq. (3), they are denoted T_i^*. For the $R = 13$ samples, $T_i^* = 84 \pm 5$ K and for the ribbon and ingot samples at $R = 57$, $T_i^* = 281 \pm 3$ K.

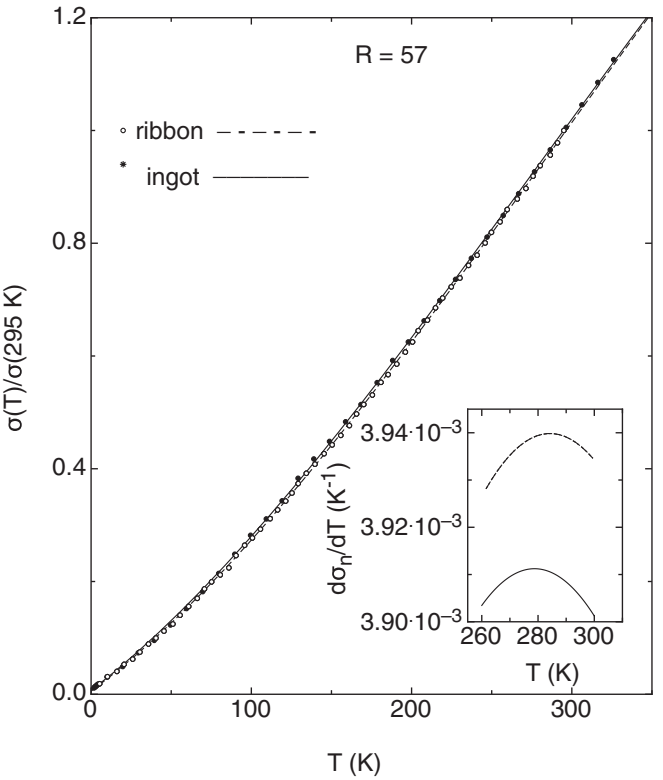

FIG. 5. Same analysis as in Fig. 4 for two $R = 57$ samples. The inflection points for the ingot and ribbon samples are illustrated in the inset.

The agreement between ingot and ribbon samples at $R = 13$ and 57 thus extends into considerable details of the behavior of $\sigma(T)$. For the $R = 4$ samples, the overall agreement on the scale of Fig. 3 is fairly good. In this case, a further analysis did not give evidence for an inflection point, nor may this be expected, since this sample is in a state of weak electronic disorder as evidenced by the quantitative description of the magnetoresistance at $R = 4$, in terms of quantum interference effects.[11]

IV. DISCUSSIONS

A. Results for $T_\circ$

To put our results for $T_\circ$ into perspective, we compare them in Fig. 6 with previously obtained estimates on alloys of the same composition where, as mentioned, Eq. (2) was used with the result $\nu = 2$ from the magnetoresistance and with $\sigma(0)$ taken from extrapolations of very low-temperature data for $\sigma(T)$.[22,26]

At $R = 40$, estimates for $T_\circ$ from both methods almost agree. The metal-insulator transition (MIT) occurs at $T_\circ = 0$. The straight line fitted empirically to data in Fig. 6 gives $R = 18$ at the MIT, which is in agreement with the generally accepted estimates of R around 20 for i-$Al_{70.5}Pd_{21}Re_{8.5}$.[3,8,10,22]

In a study of various regimes of the conductivity of i-$Al_{70.5}Pd_{21}Re_{8.5}$,[3] the inflection point occurring at the lowest temperature was interpreted as the entrance to a VRH region when temperature was decreased. Evaluating $T_\circ$ from these estimates of T_i would give smaller values than those in Fig. 6, and an extrapolation of three data points to $T = 0$ would correspond to a value for $T_\circ$ above 50 K, significantly larger than the estimates quoted above. However, an estimation of $T_\circ$ was not the purpose of this investigation, and an identification of T_i from visual inspection of $\sigma(T)$ gives an error that is magnified by the relation $T_\circ = 9T_i$.

The trend of $T_\circ$ versus R can be qualitatively understood. In VRH, $T_\circ$ determines the T range over which the resistivity rises rapidly for decreasing T. The higher the $T_\circ$, the wider the T range over which $\rho(T)$ increases rapidly, resulting in a larger R. We conclude from Fig. 6 that the scheme advanced here to determine $T_\circ$ directly from $\sigma(T)$ without the use of predetermined values for some parameters in Eq. (2) is a viable method to study transport in i-AlPdRe.

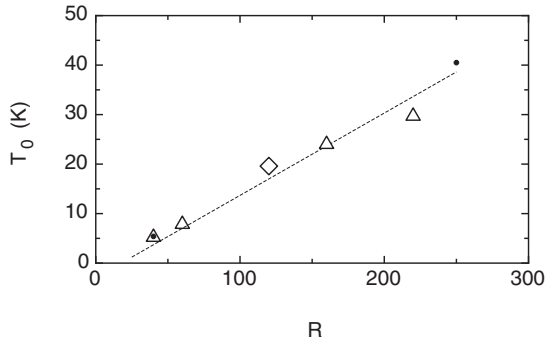

FIG. 6. $T_\circ$ vs R. Filled circles: present results from Eq. (3) for two ingot samples. Open symbols: results obtained from Eq. (2) as described in text. Triangles are ingots and the rhomboid a ribbon sample. At $R = 40$, a triangle and a filled circle almost coincide. The straight line is an empirical description.

B. Ingots and melt-spun samples

The similarities observed between $\sigma(T)$ of ingots and ribbons impose strong restrictions on reasonable conductivity models. Let us briefly summarize some characteristics of the state of the samples studied.

Ingots and ribbons are phase pure icosahedral samples in standard x-ray diffraction. Minor impurities could be observed in scanning microscope analyses (SEM) in both sets of samples. The samples were prepared in different laboratories by different techniques and from different lots of starting elements. Impurities are therefore expected to be different in concentration and nature between ribbons and ingots. The traces of a second phase found in both ingots and ribbon samples have different compositions.[11] In addition, defects have been introduced into the icosahedral structure of an ingot sample by the neutron irradiation used to control the variation of R. Formation of an amorphous phase in such irradiations can not be ruled out from the outset. However, the observation that a short-time low-temperature annealing of an irradiated sample partly recovers both the icosahedral structure and the R value,[27] does not support a formation of an amorphous phase. Furthermore, the different preparation techniques included different sequences of annealings and coolings, which gave significantly different sample morphologies, with a porous structure and voids in ingots and a homogenous quasicrystalline phase in ribbon samples.

The detailed similarities of the conductivities of ingots and ribbon samples from 1–300 K suggest that none of the differences listed above affects electrical transport and that conduction takes place in the icosahedral phase. A similar conclusion was inferred previously from the observed decrease of $\sigma(0)$ with increasing R for ingots and melt-spun samples of different R values, where $\sigma(0)$ had been estimated from low-temperature extrapolations of $\sigma(T)$.[20] Equation (1) can now be simplified to read

$$\rho = \rho\left(c_{\mathrm{Re}}, T_a^i, R, T\right). \tag{4}$$

This finding does not clarify the major problem, why the empirical parameter R has such a decisive influence. What is the nature of the changes in samples of similar c_{Re}, which after varying annealing sequences T_a^i, display such drastic changes in electronic properties? However, our results help to rule out propositions that are not relevant.

In particular, the suggestion that conduction in polycrystalline i-AlPdRe would be due to the high porosity and oxygen-rich weakly insulating regions[14] is not tenable. $\sigma(T)$ is almost identical between 1 and 300 K at similar R in porous samples and in samples where this structure is absent, nor is there any basis for a hypothesis that (accidental) oxygen impurities should appear in similar amount and configuration in differently prepared samples of similar R values, let alone the bizarre consequence that one would also have to assume that such oxygen concentration should change in a similar way in different samples after similar changes of R (see Fig. 3).

The present comparison extends over the temperature range 1–300 K. At lower temperatures, data are not available for making analyses similar to the present ones. However, preliminary conclusions can be drawn from published results below 1 K for ribbon samples and ingots.[25] Although in this case, the R values of ribbons and ingots were dissimilar, the forms of curves for $\sigma(T)$ were different enough to suggest that ribbons and ingots may be different in this temperature region. This problem deserves more attention.

This concern does not affect the conlcusions drawn above from the similarities between ribbons and ingot samples. In the work by Dolinšek *et al.*,[14] the large R values (as compared, e.g., to single-grain i-AlPdRe and i-AlPdMn) are in focus, and this is a property in the temperature range presently studied. The suggestion of i-AlPdRe as a granular conductor[15] deals with VRH and VRH-like transport, which is a low-temperature phenomenon. However, there is no granularity in ribbon samples and consistent results for ES VRH have been found for the magnetoresistance, $\Delta\rho(B,T)/\rho(0,T)$, and $\sigma(T)$ at temperatures somewhat above 1 K for ribbons as well as for ingots of large R values.[8,22] A modeling of i-AlPdRe as a granular electronic conductor cannot explain why $\sigma(T)$ of ingot samples is so similar to melt-spun samples.

V. BRIEF CONCLUDING REMARKS

Two methods have been explored to obtain detailed information about electrical transport in i-AlPdRe using the curvature of the experimental $\sigma(T)$. Firstly, an inflection point in the low-temperature $\sigma(T)$ is related to variable range hopping in insulating samples and can be used to obtain estimates of the parameter $T_\circ$ without involving the zero-temperature conductivity. Secondly, studies of the curvature of $\sigma(T)$ in the region 1–300 K have shown in some detail that samples in the form of ingots and ribbons have similar properties. Models for conduction mechanisms in quasicrystals can thus not be limited to a particular morphology.

The similarity of transport properties for ingots and ribbons apparently extends also to the magnetoresistance, $\Delta\rho/\rho$. An ingot and a ribbon sample at $R \approx 13$ and 4.2 K were found to have quite similar $\Delta\rho/\rho$ up to at least 10 T, while for an $R = 45$ ribbon sample, $\Delta\rho/\rho$ was somewhat larger than for an ingot sample at $R = 51$ already above 5 T at 4.2 K.[23] Since the magnetoresistance decreases strongly with increasing R in this region of R values, such a difference is expected.

Finally, one can note that Krajčí and Hafner when discussing their calculations,[17] remarked that comparisons between ribbon and ingot samples could provide a stringent test of their predictions. Our present results together with their calculations mutually confirm each other and strengthen the conclusions about the properties of icosahedral AlPdRe.

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