Electronic transport properties of high-resistivity icosahedral AlPdRe below 1 K

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The temperature dependence of the conductivity, $\sigma(T)$, and the magnetoresistance up to $B=6$ T have been studied in the temperature range 0.01 K$\leqslant T \leqslant$1 K for two differently prepared *i*-AlPdRe samples on the insulating side of the metal-insulator transition. $\sigma(T)$ for both samples was observed to saturate in zero magnetic field below about 20 mK. With increasing magnetic field the temperature dependence of the conductivity increased, and at 6 T, $\sigma(T,B=6\text{ T})$ was found to decrease linearly with decreasing temperature down to the lowest measurement temperature of 10 mK. The estimated value of the conductivity at $T=0$ K, $\sigma(0\text{ K})$, was found to decrease strongly with increasing resistance ratio R $[=\rho(4\text{ K})/\rho(295\text{ K})]$ over a wide range of R values and for differently prepared samples, suggesting that a finite $\sigma(0,R)$ is a characteristic property of the icosahedral phase of high-resistivity *i*-AlPdRe. The magnetoresistance is positive below 1 K. The relation $\Delta\rho(B)/\rho \sim B^2$ is followed at larger fields by a $B^{2/3}$ dependence. With decreasing temperature these characteristic field regions are successively depressed towards smaller magnetic fields and eventually become unobservable. A scaling of the magnetoresistance is found for data in the region $T\leqslant 1$ K, $B\leqslant 6$ T of the form $[\Delta\rho(B)/\rho]/T^{\alpha}=f(B/T)$ for each sample, with α about 0.3 for both samples.

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I. INTRODUCTION

The low-temperature conductivity $\sigma(T)$ of highly resistive icosahedral *i*-AlPdRe quasicrystals (QC's) is a subject of strong debate. The interest springs from the large resistivities that can be attained in *i*-AlPdRe, making this alloy system the most promising candidate among the quasicrystals to study a metal-insulator transition. Measurements of $\sigma(T)$ at very low temperatures are furthermore the most direct way to decide whether a material is metallic or insulating. However, the results published for the low-temperature $\sigma(T)$ give a rather confusing picture of the situation.[1–12] At present, there is no consensus how to interpret these results.

One major difficulty is the interpretation of the tendency of the conductivity to saturate, which apparently is observed in all measurements taken to low enough temperatures. This is seen below 100 mK for samples of moderately high-resistance ratios R $[=\rho(4.2\text{ K})/\rho(295\text{ K})]<60$,[3,5,6,11] while for samples with $R>100$ similar observations have been made in experiments extending to below 20 mK.[9,12] It is not known what is the reason for such behavior. Explanations advanced include (i) a metallic ground state of *i*-AlPdRe, (ii) minor metallic impurities (below the resolution limit in standard x-ray diffraction), which precipitate in grain boundaries, (iii) defects of the icosahedral phase, or (iv) inadequate shielding or thermal contact, aggravated by the strong increase of the specific heat of *i*-AlPdRe with decreasing temperature due to an important hyperfine contribution from the Re nuclei.[13] Another difficulty is the varying results from different attempts to analyze $\sigma(T)$ in terms of variable-range hopping (VRH) models. The numerical flexibility when using an additional constant $\sigma(0)$ in the VRH expressions for $\sigma(T)$ to account for the saturation, as well as sample differences and different temperature regions of analyses, may all contribute to the exceptionally wide range of reported results. For example, estimates of the characteristic temperature T_0 in the hopping process range from 1 mK (Ref. 8) to 1600 K (Ref. 10), with several results in between.[4,7,9,11]

It thus appears that measurements of $\sigma(T)$ of *i*-AlPdRe by themselves cannot resolve these problems. Studies in magnetic fields have been found to give useful additional information in many cases. For example, recent experiments have shown that the anomalous conductivity of a dilute (2D) electron system in silicon metal-oxide-semiconductor field-effect transistors observed in the absence of a magnetic field was strongly suppressed by a magnetic field.[14] Alternatively, a system which is in the insulating state (*n*-CdSe) could be driven towards a metallic behavior by the application of a magnetic field.[15] Finlayson *et al.* have demonstrated the importance of ultralow-temperature experiments in conjunction with detecting an impure electronic phase in a host close to the metal-insulator transition (MIT).[16]

The problems with impurity phases in high-resistivity quasicrystals are largely circumvented by measurements of the magnetoresistance (MR). E.g., structural investigations and a consistent behavior of the MR as a function of resistance ratio R for i-AlPdRe indicated negligible contributions from high-resistivity impurity phases.[17] Furthermore, an extended correlation between the maximum MR and $\rho(4\text{ K})$ has been found for a range of different materials including also phase-pure and -impure quasicrystals, indicating that the measured MR is that of the icosahedral phase.[18] In particular, any metallic impurity would have a much smaller resistivity and a negligible contribution to the MR.

In the present paper the low-temperature $\sigma(T)$ and MR of high-resistivity i-AlPdRe have been studied down to 10 mK. The results for $\sigma(T)$ suggest that a finite $\sigma(0)$ is not due to impurities extrinsic to the icosahedral phase. The MR of i-AlPdRe has been investigated below 1 K. These measurements extend to lower temperatures than previously studied. The results show that the negative component becomes unobservable below 1 K. The MR at these temperatures appears to be a difficult problem since at present there is no theoretical framework for describing these data. However, we attempt to establish an empirical scaling relation for the MR in the temperature region 50 mK to 1 K.

The plan of the paper is as follows: in Sec. II the samples and the experimental environment are described, and problems of sample thermalization at the lowest temperatures are discussed. Results for $\sigma(T)$ and MR are presented in Sec. III, followed by a discussion of the results in Sec. IV and a brief summary in Sec. V.

II. SAMPLES AND EXPERIMENTAL TECHNIQUES

Two samples of i-AlPdRe were studied which were prepared by two different methods. In both techniques a wide range of R values can be obtained in samples made from different batches, while samples from the same batch have similar R values. For both the present preparation techniques the nominal composition was $Al_{70.5}Pd_{21}Re_{8.5}$. One sample was melted in an arc furnace, subsequently annealed at 940 °C and 600–650 °C and then quenched into water. A sample piece of approximate dimensions $1\times1\times5\text{ mm}^3$ was cut from the ingot (''ingot sample'') and had a resistance ratio $R=160$. For the second sample, after melting in an arc furnace, the ingot was melt spun, annealed in the temperature range 800–1000 °C, and then furnace cooled (''melt-spun sample''). This sample had a thickness of about 40 μm and resistance ratio $R=110$.

Both samples were of high structural quality as observed from a single icosahedral phase and narrow peaks in standard x-ray diffraction. In scanning electron microscopy (SEM) investigations of similarly prepared samples[17] a minor second phase could be detected both in ingots and in melt-spun samples, and was found to consist mainly of Al and Re, with larger Al concentration in melt-spun samples than in ingots. Further details of the preparation and results from sample characterization have been given previously.[17] Our use of differently prepared samples may control, to some extent, the unknown influence of impurities on particularly the zero-field properties of i-AlPdRe. Common trends in a measured property as a function, e.g., of R suggest insignificant contributions from varying impurity phases.

Electrical transport measurements were made with a conventional four-probe ac technique at 16 Hz using an ac inductance and resistance bridge (Linear Research LR700). Electrical contacts to the sample were made using thin gold wires (diameter 25 μm) attached to the sample with a minute amount of silver paint. The experiment was mounted to the experimental flange of a copper nuclear demagnetization cryostat with the sample located in the center of one of the main magnets of the cryostat.[19] The cryostat including all electronic equipment is situated in an electromagnetically shielded room which provides an experimental environment with a very low noise level.

In the experiments reported in this work, the main interest has been measurements of $\sigma(T)$ at different magnetic fields B and measurements of the magnetoresistance as a function of B at some selected temperatures. Zero-field measurements were performed during warm-up and cooling cycles of the cryostat, whereas measurements in magnetic fields were restricted to cooling periods only, mainly due to the larger heat capacity of the nuclear stage in the magnetic field, which also limits the minimum temperature of the experiment in $B=6$ T to about 12 mK. Cooling the sample from about 80 to 12 mK in 6 T took about 30 h.

In all figures, the temperature indicated is that of one of the standard thermometers (Pt NMR and PdFe magnetic susceptibility at low T, RuO_2 and germanium resistors at high T). At the lowest temperatures of the experiment, we do not have unambiguous proof that the temperature of the thermometer indicated the temperature of the sample. However, the strongly different behavior of the samples observed in measurements with and without magnetic field suggests that down to the minimum temperature of the experiment the samples follow the temperature of the cryostat very well (see Sec. III). For a more detailed discussion of the problems encountered with the experimental situation at very low temperatures, we refer to Ref. 9.

III. RESULTS

The temperature dependence of the conductivity below 1 K for the two i-AlPdRe samples is shown in Fig. 1. Down to about 50 mK the temperature dependence of $\sigma(T)$ for the $R=110$ sample is quite similar to that observed in a similarly prepared sample with $R=117$ in Ref. 8. Below about 20 mK, $\sigma(T)$ saturates for both samples in Fig. 1, as illustrated in the inset. This point will be further discussed in Sec. IV.

$\sigma(T)$ is shown in Fig. 2 at 0, 2, and 6 T for the melt-spun sample in panel (a) (Ref. 20) and for the ingot sample in panel (b). $\sigma(T,B)$ decreases with magnetic field in this temperature region, and the magnetoresistance is positive. A striking feature of the results is that $d\sigma/dT$ increases with magnetic field at the lowest temperatures in Fig. 2. For both samples an almost linear relation between σ and T is reached at 6 T.

The magnetoresistance as obtained from temperature sweeps at constant B is illustrated in the main panel of Fig. 3 for the melt-spun sample $(R=110)$. The inset shows the MR at low temperatures and 6 T for both samples. The results show that the MR is positive and increases with decreasing temperature in the measurement range down to 12 mK. The

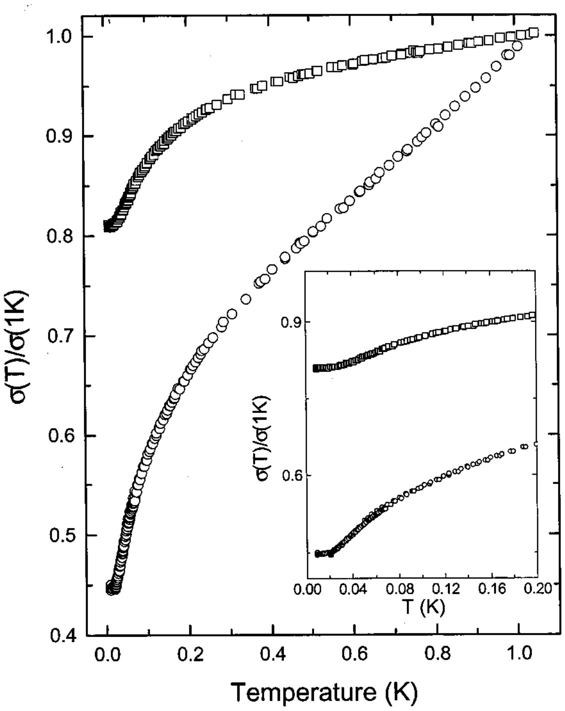

FIG. 1. Temperature dependence of conductivity for melt-spun sample, $R=110$ (□) and ingot sample, $R=160$ (○) normalized to approximately 1 K (1.02 K). Inset: enlargement below 0.2 K.

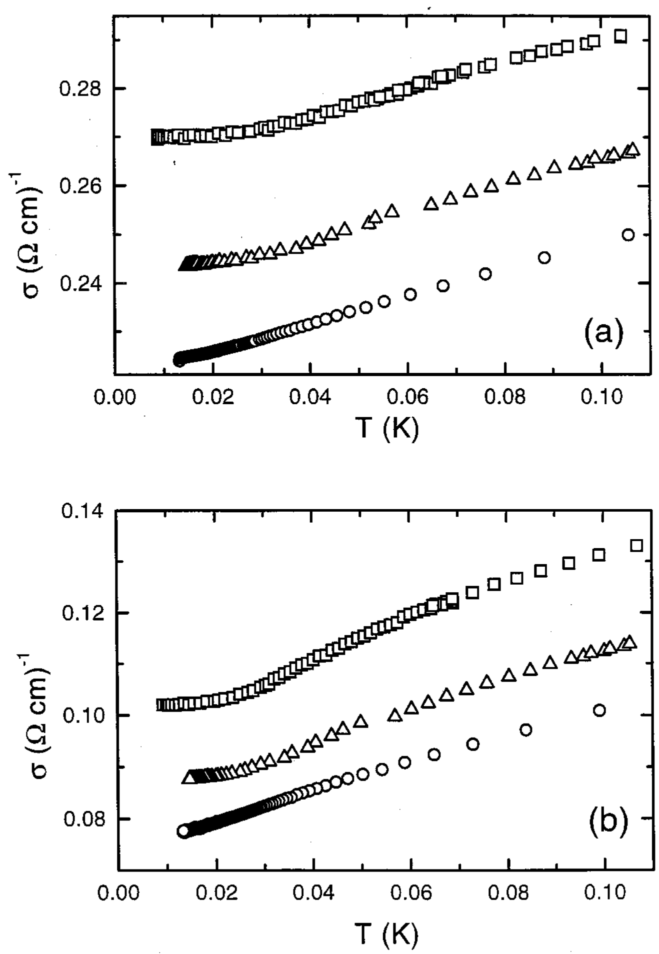

FIG. 2. Conductivity vs temperature for (a) the $R=110$ sample and (b) the $R=160$ sample. The magnetic field from top to bottom in each panel was 0, 2, and 6 T.

strong increase of $\Delta\rho(B)/\rho$ with decreasing temperature at the lowest temperature in this figure corresponds to the increased slope of $\sigma(T)$ with B in Fig. 2.

Figure 4 shows the MR for the ingot sample in a range from 50 mK to 1.5 K, where magnetic field sweeps at constant temperatures could be conveniently performed. The tendency for a shift of the MR with decreasing temperature in the direction of a weaker negative component and a stronger positive one is in agreement with previous observations for high-resistivity *i*-AlPdRe down to about 2 K (Refs. 21 and 22) or 0.6 K.[2] Our results show that the negative component of the MR becomes unobservable at lower temperatures and that the positive MR continues to increase in magnitude with decreasing temperature down to the lowest measurement temperature.

The MR above 1.5 K of *i*-AlPdRe was previously analyzed[23] within the Efros-Shklovskii (ES) VRH theory. According to this theory, shrinking wave functions give an MR$\sim +B^2$ in a certain field region, while at larger magnetic fields one expects MR$\sim +B^{\beta}$, with exponents β smaller than 2.[24] This trend is apparent in Fig. 4, when one approximately measures magnetic field strength by B/T. At 1.5 K the B^2 term is observed in a field region above about 1 T, while at 0.7 K it is depressed towards smaller magnetic fields, and for increasing field at constant temperature, the MR vs B relation is characterized by a successively weaker field dependence. These observations form the basis for the attempt to scale the MR, which will be described below.

IV. DISCUSSION

A. Conductivity

It should be noted that the present range of resistivity values is very much larger than that found recently for single-grain *i*-AlPdRe.[25] For instance, at the temperatures of Fig. 2, ρ is about 3.6 Ω cm for the $R=110$ sample, corresponding to about 1 Ω cm at 4.2 K, while the corresponding values for the single-grain sample were $R=1.8$ and $\rho(4.2\text{ K})\approx 5.5$ mΩ cm. These latter values, on the other hand, are more in line with observations for *i*-AlPdRe at the lower end of R values which can be obtained by melt spinning and can be compared, e.g., to the observations for an $R=2$ polygrained melt-spun sample of $\rho(4.2\text{ K})=6.1$ mΩ cm.[17] Analogous differences have been observed in the *i*-AlPdMn system, where ρ(4.2 K) reaches about 10 mΩ cm with $R\approx 2$ in polygrained samples,[26] while corresponding values for high-quality single-grain materials are $\rho(4.2\text{ K})\approx 2.5$ mΩ cm, $R\approx 1.05$ (Ref. 27) or $\rho(4.2\text{ K})\approx 2$ mΩ cm with R also slightly larger than 1.[28] These differences are a striking and poorly understood property of qua-

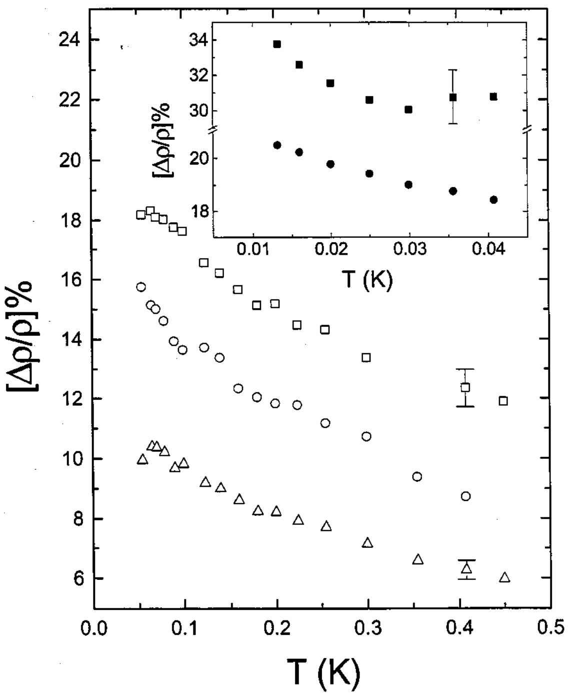

FIG. 3. Magnetoresistance $\Delta\rho/\rho$ vs temperature. Main panel sample $R=110$ in magnetic fields (from top to bottom) 6, 4, and 2 T. Inset: low-temperature data at 6 T: $R=160$ (■) and $R=110$ (●). Data were obtained as the difference between two temperature sweeps at constant fields, giving fairly large errors as illustrated at some points in both panels.

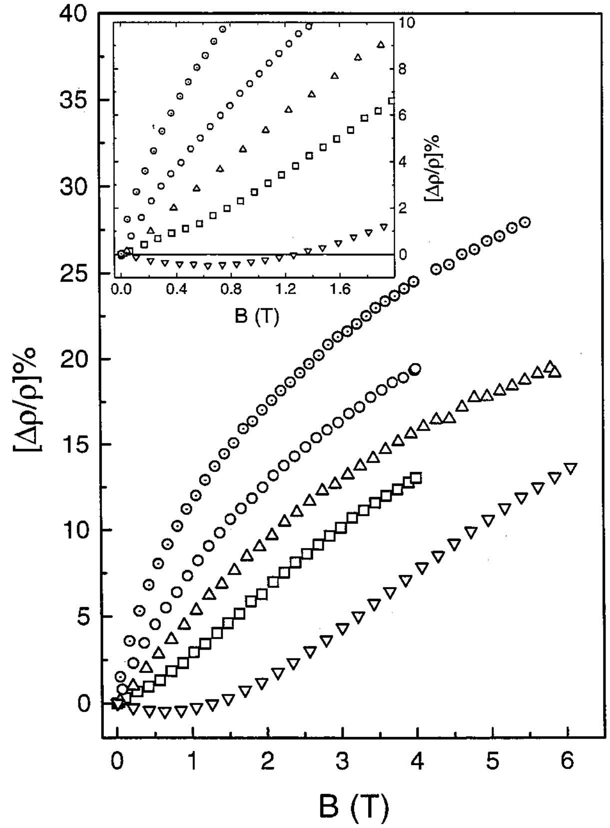

FIG. 4. Magnetoresistance of the ingot sample ($R=160$). Temperatures are, from top to bottom, 0.05, 0.2, 0.4, 0.7, and 1.5 K. Inset: the low-field region of the same data illustrating that the negative contribution to the MR vanishes at temperatures below 1 K.

sicrystals. However, these data are correlated in the sense that a larger ρ(4 K) corresponds to a larger R value in each alloy system. Impurities would therefore not seem to be the cause for the higher resistivity in polygrained samples. For *i*-AlPdRe, the small concentration differences should be noted between $Al_{71.7}Pd_{19.4}Re_{8.9}$ of Ref. 25 and the nominal composition $Al_{70.5}Pd_{21}Re_{8.5}$ in ingots and melt-spun samples studied presently and in Ref. 17. It is well known that quasicrystals may show an extreme sensitivity to compositional variations, but this has not yet been studied for single-grain *i*-AlPdRe. In view of the similarity between ρ(4.2 K) for polygrained and single-grain samples of R about 2, such concentration effects do not appear to be prominent in transport properties. Another possibility is phason disorder or other defects in the icosahedral phase, which could be reflected in the varying R value, although also in this case firm experimental confirmation is lacking. The correlation between conductivity and R will be further discussed below.

There is no experiment on *i*-AlPdRe which demonstrates as convincingly as for *i*-AlCuFe (Ref. 29) that an increasing R value reflects increasing quasicrystalline perfection. Nevertheless, some observations give suggestive evidence that an increasing R value leads to a more insulating state. The large values of ρ at 4 K of *i*-AlPdRe are themselves of course one indication. A pseudogaplike feature in the density of states was found to be more pronounced for a sample with larger R value.[30] The description of the MR in terms of weak localization and electron-electron interaction breaks down for large R values[17] in about the same range of R where a negative contribution to the MR starts to appear at low fields and temperatures above 1 K.[23]

In this situation it is useful to look for further empirical relations between different resistive properties. Different relations between R or other parameters reflecting the temperature dependence of the resistivity as a function of ρ(4.2 K) or σ(4.2 K) have been used in the past.[6,26] Clearly, such relations are the more useful when differently prepared samples are included over a wide range of R values. For *i*-AlPdRe, ingots and melt-spun samples of similar large R values were found to have similar $\rho(T)$ behavior between 295 and 4.2 K, while significant differences were observed at lower temperatures, e.g., with the normalized resistivity differing by factors of order 5.[17] To circumvent this problem one can attempt to include low enough temperatures where, as mentioned, all published results for $\sigma(T)$ show tendencies to saturate.

Figure 5 shows the estimated zero-temperature conductivity $\sigma(0)$ vs R in zero magnetic field for *i*-AlPdRe with ρ(4.2 K) in the range above 30 mΩ cm for several ingots (solid symbols) and melt-spun samples (open symbols) and with each type of samples covering a fair range of R values. Circles show data obtained at $T\leq 15$ mK. To our knowledge all results from measurements taken to this temperature

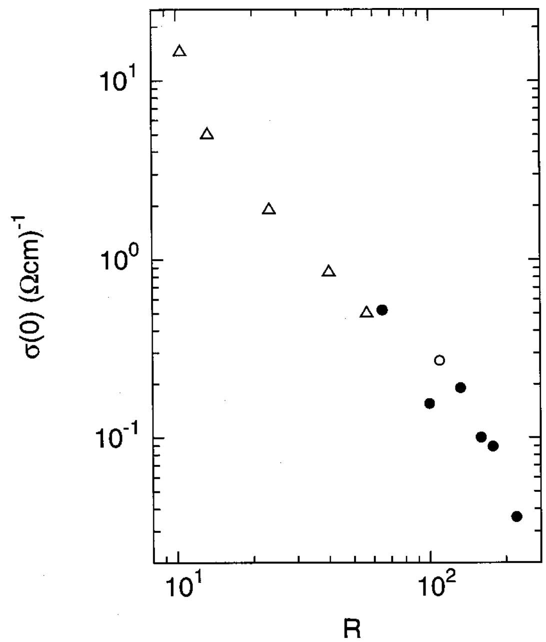

FIG. 5. Zero-temperature conductivity $\sigma(0\ \mathrm{K})$ vs R. The circles were obtained from measurements down to 15 mK or below: $R=110$ and 160: present results. $R=65$, 100, 133, and 178: Ref. 9. $R=220$: Ref. 31. △: data for samples of intermediate R values from Ref. 6, which saturated at higher temperatures allowing $\sigma(0)$ to be estimated from measurements down to 40 mK. Open symbols refer to melt-spun samples, solid symbols to ingots.

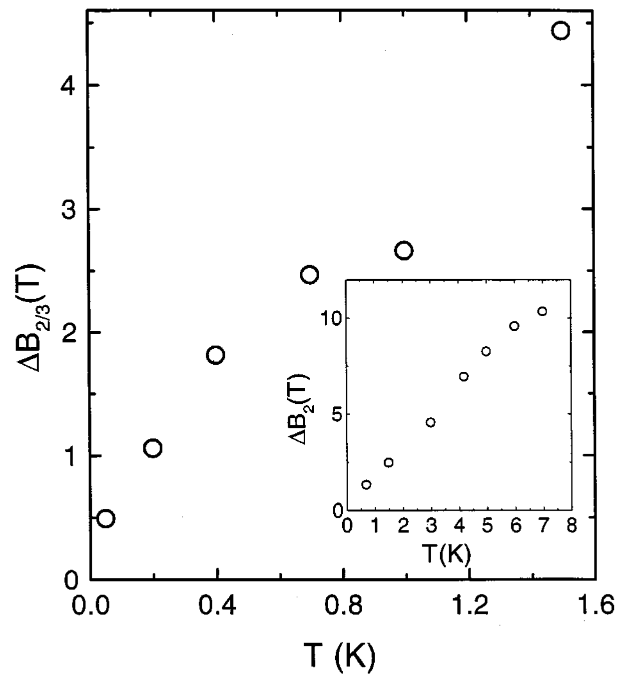

FIG. 6. Temperature dependence of the midpoint $\Delta B_{2/3}$ of the field range in which the data in Fig. 4 follow $\Delta\rho/\rho \sim B^{2/3}$. Inset: corresponding data for ΔB_2, midpoint of the field range where $\Delta\rho/\rho \sim B^2$. Data above 1.5 K in this panel were obtained from measurements in Ref. 23.

range have been included. Samples with R values in the range 10–57 are shown by open triangles. In this case $\sigma(T)$ saturated at higher temperatures and $\sigma(0)$ could be fairly reliably extrapolated from measurements extending down to 40 mK.[6] The room-temperature resistivity values for the ingot samples were corrected for voids, according to a model described previously.[9] The scatter of the data in Fig. 5 is probably dominated by random errors in geometrical form factors, with errors in the measured σ of $\pm 25\%$.

Figure 5 shows that $\sigma(0)$ decreases strongly with increasing R, approximately as $\sim R^{-2}$ in this graph. No particular physical significance should be attached to this R dependence. E.g., if $\log \sigma(0)$ is plotted versus R on a linear scale, data above the metal-insulator transition at about[23] $R \approx 30$ are fairly well described by a straight line, suggesting instead that $\sigma(0)$ decreases exponentially with R in the insulating state. However, these observations show a consistent relation between $\sigma(0)$ and R including different experiments and differently prepared samples, with differences in impurity concentration and composition, and it extends over more than two orders of magnitude in $\sigma(0)$. This indicates that some of the possible origins of a finite $\sigma(0)$ mentioned in the Introduction are unlikely and that instead a finite $\sigma(0)$ appears to be a property of the icosahedral phase, which is described by a general relation with R. One scenario could be based on the quantum tunneling of residual critical states in the high-resistivity samples. Multifractal-like critical states, i.e., wave functions falling off as a power law, have been found in perfect quasicrystals.[32] Meanwhile, the quasicrystalline structure in the high-R (>100) samples was reported to exhibit inhomogenous disorder due to linear phasons.[33] It was conjectured that the presence of linear phason strain would tend to localize the critical states. However, given the inhomogenous disorder, there are still residual critical states in the samples. These residual states can conduct current via quantum tunneling, leading to a temperature-independent small σ. In this picture the systematic decrease of $\sigma(0)$ with R would thus reflect the shrinkage of the conducting region.

The results for $\sigma(0\ \mathrm{K},\ B)$, estimated from the data at the lowest temperatures in Fig. 2, are qualitatively in line with this hypothesis. The decreasing residual conductivity with increasing magnetic field could, e.g., be due to shrinking of critical states under magnetic field.

B. Scaling of the magnetoresistance

In view of the lack of quantitative theories at low temperatures for the magnetoresistance of high-resistivity *i*-AlPdRe, it could be helpful to look for scaling relations. In metallic *i*-AlPdRe, weak localization (WL) and electron-electron interactions (EEI's) account for the MR.[17] These are well-developed quantitative theories, and scaling of the MR should in principle be possible. Metallic Si:B gives one example, albeit a simpler one.[34] From a scaling analysis of the MR for fields up to 9 T and temperatures between 70 and 500 mK, it was shown that EEI's contributions dominate the MR.

For insulating *i*-AlPdRe at very low temperatures we have no clear guidance from quantitative theories and must proceed more tentatively. As mentioned above, the B^2 region of the MR is successively displaced towards smaller magnetic

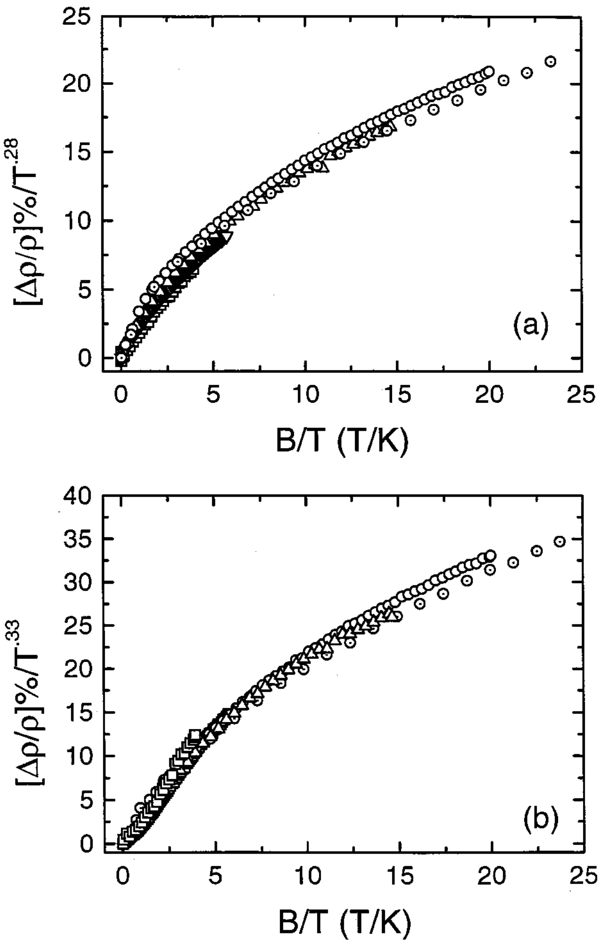

FIG. 7. Scaling of the magnetoresistance. (a) $R=110$ sample and (b) $R=160$. $(\Delta\rho/\rho)/T^{\alpha}$ vs B/T is shown for both samples with $\alpha=0.28$ and 0.33, respectively, as shown. Except for data at 1.5 K (with partly negative MR), all data in Fig. 4 are shown (with the same symbols for corresponding temperatures). Measurements at 1 K not shown in Fig. 4 are included by solid symbols. The measurement temperatures for the $R=110$ sample were the same.

fields with decreasing temperature and eventually becomes unobservable. According to ES-VRH theory,[24] the B^2 region is followed at larger fields by $B^{2/3}$ dependence of the MR. We investigated which part of the MR follows a B^2 and $B^{2/3}$ behavior, respectively, from Fig. 4 and previous data for the same sample at higher temperatures.[23] The notation ΔB_{β} with $\beta=2$ or 2/3 is used for the value of B at the center of a field region with characteristic field dependence given by β. It can be seen from Fig. 6 that ΔB_2 and $\Delta B_{2/3}$ both decrease with decreasing temperature. The B^2 region is unobservable at 0.4 K and the $B^{2/3}$ behavior is expected to become unobservable somewhat below the lowest measuring temperature of 50 mK in Fig. 4.

It therefore seems reasonable from general considerations as well as from Fig. 6 that B/T is an independent parameter in a scaled MR. We used the form

$$[\Delta\rho/\rho]/T^{\alpha}=f(B/T), \qquad (1)$$

with varying values of α to examine the observed MR. The results are illustrated in Fig. 7 and include all MR data up to 6 T at 0.05, 0.2, 0.4, 0.7, and 1 K for the melt-spun sample in panel (a) and similar data for the ingot sample in panel (b). Both data sets collapse satisfactorily, supporting a reasonable scaling. This result is obtained only in a narrow range of α values for each sample. A clear deterioration of the scalings was observable when α was changed by ± 0.01. Therefore, the difference between the exponents α of 0.28 and 0.33 for the two samples, albeit small, appears to be significant.

The most useful results from scalings are obtained when the abscissa measures the distance δ to the metal-insulator transition, e.g., $\delta=|n/n_c-1|$ for doped semiconductors, where n is concentration and n_c the critical concentration. For quasicrystals one could use R as a scaling parameter, which empirically measures the distance to the MIT.[23] However, scaling of $\sigma(T,R)$ for high-resistivity quasicrystals would not seem tractable at low temperatures with the additional problem of the finite $\sigma(0)$ discussed above. In the MR one is faced with three independent parameters—magnetic field B, temperature T, and resistance ratio R—and complete scaling becomes more complicated. For the MR of Si:B on the metallic side of the transition, this problem was solved by first scaling a suitable function of the MR vs B/T for each sample and then finding a sample-dependent K value, multiplying the MR, which collapsed all results onto one curve.[34] Although a reasonable picture of the sample dependence of K was obtained, this approach is empirical, and since we have low-T data for only two samples, we have not pursued it.

The form of $\delta(B)$ is not known for quasicrystals, but one expects that for increasing B one moves farther into the insulating side, somewhat increasing δ. It is therefore interesting to note that scalings of $\sigma(T,\delta)$ in doped semiconductors, also including insulating samples, have been successfully made in a form σ/T^{μ} vs δ/T^{ν}, resembling that in Fig. 7.[35,36] The results for μ and ν were in the range 0.1–0.7, comparable to the present results.

For the magnetoresistance on the metallic side of the MIT, scalings of the form of Eq. (1) with $\alpha=0.5$ are successful when EEI's dominate the MR.[34] f is then expected to be a known EEI function of B/T.[37] On the other hand, close to the MIT in metallic Si:P, scalings of the form of Eq. (1) could be performed,[38] and in this case, similarly to our results on the insulating side, α was different from 1/2 and sample dependent. On the other hand, in Ref. 38, $[\Delta\rho/\rho]/T^{\alpha}$ was the same function of B/T for all samples in contrast to our two samples. This partial similarity of scaling functions for the MR across the MIT is interesting. However, the physical interpretation of Eq. (1) with $\alpha\neq 1/2$ is not known, and this result is empirical.

Scaling of the low-temperature MR on the insulating side of an MIT appears to have been little studied. The MR in this region is a complex problem, and conflicting theories have been advanced.[39] In i-AlPdRe, as mentioned, the low-temperature MR on the insulating side is not understood. In view of the successful scalings and the apparent reasonable form of the scaling function, we therefore consider the results in Fig. 7 as a first promising approach to scaling of the magnetoresistance on the insulating side of the MIT in *i*-AlPdRe.

V. BRIEF SUMMARY

The conductivity and magnetoresistance of high-resistivity *i*-AlPdRe have been studied in the temperature region 10 mK$\leqslant T \leqslant$1 K in magnetic fields up to 6 T for two differently prepared samples with R values of 110 and 160. The zero-field conductivity of both samples saturate at temperatures below 20 mK, while in a 6-T magnetic field $\sigma(T,$ 6 T) continues to decrease with decreasing temperature down to 10 mK. These data and published results show that for samples of different origins the estimated zero-field residual conductivity σ(0 K) as a function of R is a general relation over more than two orders of magnitude of $\sigma(0)$. It is hence suggested that a finite $\sigma(0)$ is a property of the icosahedral AlPdRe phase. We conjecture that $\sigma(0)$ is associated with conductance through quantum tunneling between residual critical states and that the decrease of $\sigma(0)$ with R reflects a shrinking of these conductive regions.

The MR is positive below 1 K in all magnetic fields studied. The B^2 region of the MR was found to be displaced towards smaller fields and to eventually become unobservable with decreasing temperature. A similar result is anticipated slightly below 50 mK for the $B^{2/3}$ term, which according to ES-VRH theory follows after the B^2 region for increasing field strength. These results suggest that scaling of the MR on the insulating side should be feasible. Empirically, we find reasonable scaling of the form MR/T^{α} $= f(B/T)$ for each sample, with α of order of 0.3. These results can be considered as a first promising attempt to scale the MR on the insulating side of the MIT. Further work should include samples with different resistivities to explore the possibility to scale all results for MR=MR(B,T,R) for insulating samples. In such a relation R would approximately measure the distance to the MIT, providing a basis for gaining further information on this unusual metal-insulator transition.

Very recently scaling was studied of the conductivity of *i*-AlPdRe.[40] This work concerned $\sigma(T)$ for metallic samples in a wide temperature range above 0.4 K, thus circumventing the problems with the very low temperature σ discussed above, and is not directly comparable to the present work. However, it appears that scaling may be a new promising tool to investigate some particularly poorly understood problems on transport properties of quasicrystals, such as $\sigma(T)$ and the MR of insulating samples.

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