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The metal–insulator transition in icosahedral AlPdRe thin films

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Abstract. Thin 2200 Å icosahedral films with compositions near Al₇₂Pd₂₀Re₈ have been fabricated on quartz glass substrates. Some of the films exhibited *insulating* transport properties down to 0.07 K where their resistivities followed an activated ‘Mott’ variable-range hopping law. Other films exhibited *metallic* transport properties. In addition, the *precursor amorphous* AlPdRe films were observed to make *superconducting transitions* below 0.6 K; thus the amorphous and icosahedral structures exhibit contrasting metallic and insulating transport behaviours.

1. Background

One of the most anomalous properties of quasicrystals (QC) is that they show very high resistivity values in the liquid-helium temperature region. The physical origin for the highly resistive behaviour currently is not well understood for a system composed only of metals. This behaviour has challenged experimentalists to determine whether a metal–insulator transition (MIT) exists in some of the QC systems, such as in icosahedral (i-)AlPdRe or i-AlCuOs [1].

Although samples of the icosahedral i-AlPdRe show the highest resistance amongst the QCs, the experimental conductivity data on *bulk* i-AlPdRe samples are very contradictory as regards the existence of a metal–insulator transition. At least two different experimental groups observed *finite* conductivities and hence *metallic* behaviour at $T \rightarrow 0$ K. These groups include the Swedish team of Rodmar and Rapp, who investigated thick 30 μm melt-spun ribbons down to 40 mK [2, 3] and recently made measurements on bar-shaped ingot samples down to 0.1 mK [4]. The Grenoble team of Gignoux *et al* studied melt-spun ribbons and concluded that there was a *residual* conductivity at $T = 0$ K [5]. Guo and Poon fitted their data using a variable-range hopping (VRH) law with an additional residual constant term to describe ‘saturation’ of the resistance at low temperatures [6]. In these last two cases, we classify the samples as *metallic* if there is evidence of ‘saturation’ of the resistance as $T \rightarrow 0$ K.

In contrast, a second group has presented strong experimental evidence for *insulating* behaviour. The group of Lin from Taiwan has published very convincing evidence for a Mott VRH law ($\rho(T) = \rho_{\text{Mott},0} \exp(T_{\text{Mott}}/T)^{1/4}$) operative in some of their bar-shaped AlPdRe bulk samples [7]. Unfortunately, their measurements were limited to rather high temperatures between 0.5 K and 7 K; nevertheless, Wang *et al* reported relatively large characteristic

Mott temperatures, T_{Mott} , ranging between 61 K and 107 K [7]. The Grenoble group of Delahaye *et al* studied melt-spun ribbons from 0.6 K down to 20 mK and reported a Mott VRH conductivity law [8]. The group of Poon *et al* claimed a metal–insulator-transition-like behaviour in $1 \times 1.5 \times 5$ mm bulk samples [1].

Moreover, there is a third group who are uncommitted on the existence of the MIT—the University of Tokyo group of Tamura *et al*, who investigated bulk samples of AIPdRe [9]. Thus, there is no definite consensus amongst all the experimentalists on the existence of the metal–insulator transition in icosahedral AIPdRe samples.

From the theoretical aspect, there are definitive predictions from Janot’s group of *insulating* behaviour in QCs, namely $\sigma(T = 0) = 0$; they also predict that the conductivity at *low* temperatures follows a simple temperature power law of $\sigma(T) = CT^{1/2}$ based upon a model of hierarchical self-similar packing of atomic clusters [10–12]. Using a fractional multi-component Fermi-surface model, Burkov *et al* predict zero conductivity at $T = 0$ K and hence *insulating* behaviour [13] for the case of a *perfect* quasicrystal structure with no scattering centres. These same authors predict a *nearly vanishing conductivity* for ‘real’ quasicrystals having some structural and phase disorder [13]; hence, ‘real’ quasicrystals are predicted always to be *metallic*. Moreover, Kitaev analysed the motion of an electron in a 3D icosahedral quasicrystal [14]; using a weak-coupling approximation, he came to the conclusion that an ideal quasicrystal has a finite conductivity. Thus, there is also no clear consensus amongst the theoreticians on a MIT transition in quasicrystals.

The majority of theoreticians have not predicted a Mott VRH conductivity law for the insulating quasicrystal structure. According to the experimental results of Delahaye *et al*, their i-AIPdRe melt-spun ribbons followed a VRH law with a hopping exponent very close to $1/4$ [8]. The Grenoble group associated this activated temperature dependence with the Mott VRH model [15, 16]. The problem with their interpretation is that the characteristic Mott temperatures, T_{Mott} , observed experimentally were of the order of 1 mK while the lowest measurement temperature, T , was 20 mK. One important prediction from the Mott model is that the optimum hopping distance, R_{hop} , must be of the order of or greater than the localization distance ξ [17]. If the hop distance is much less than the localization distance, then the electron wave functions are no longer localized and are extended; and hence the sample should display metallic behaviour. The entire Mott formalism should break down when $R_{\text{hop}} < \xi$ or when $T_{\text{Mott}} < T$ as for the case of the Delahaye data [8]. Thus, a new unique explanation is needed to explain the VRH results of the Grenoble group. The experimental Mott results of Lin’s group do not exhibit this problem [7].

Owing to the controversial experimental results and conflicting theoretical predictions, we have taken an impartial and unbiased position on interpreting our conductivity data taken on thin 2200 Å *films* of i-AIPdRe. We present our findings as regards *insulating* behaviour in some of these films in the following sections.

2. Theoretical considerations—low-temperature conductivity and the metal–insulator transition

Films may be classified electronically as being either insulating or metallic. *Insulating* 3D films exhibit *infinite* resistivities or *zero* conductivities at absolute zero in temperature. In contrast, *metallic* 3D films always display finite resistivities or positive conductivities at absolute zero. Note that films that exhibit decreasing conductivities with decreasing temperatures still can be *metallic*.

Strongly insulating samples (perhaps also including *insulating* quasicrystal films) exhibit activated hopping conductivities which can be described by the VRH expression in zero

magnetic field:

$$\sigma(T) = \sigma_0 / [\exp(T_0/T)^y] \quad (1)$$

where σ_0 is the prefactor, T_0 is a characteristic temperature, and y is the hopping exponent.

In contrast, the conductivity of a 3D *metallic* sample (most probably including *metallic* quasicrystal films) at sufficiently low temperatures can be described by the power-law expression

$$\sigma(T) = \sigma(0) + CT^z \quad (2)$$

where $\sigma(0)$ is the positive zero-temperature conductivity, C is the prefactor, and z is the exponent of the temperature power law. Equation (2) might approximate the conductivity contribution from the 3D electron–electron interaction theory and/or that from the 3D weak-localization theory. Note that, in the above procedures, the exponents y and z are free fitting parameters.

A useful and sensitive technique for identifying the metal–insulator transition was introduced previously [18, 19]. The mathematical function $w(T)$ exhibits distinctively different temperature behaviours for insulating and metallic films:

$$w(T) = d \ln \sigma / d \ln T = (T/\sigma) d\sigma/dT. \quad (3)$$

For *strongly insulating* films exhibiting variable-range hopping conductivity, inserting equation (1) into equation (3) yields

$$w(T) = y(T_0/T)^y. \quad (4)$$

Notice that $w(T)$ increases to *infinity* as the temperature approaches absolute zero. A least-regression fit through the $\log(w)$ versus $\log(T)$ data will determine the hopping exponent y and the characteristic temperature T_0 that appears in the VRH law.

For 3D *metallic* films exhibiting slowly decreasing conductivities with decreasing temperatures at low temperatures, equation (2) can be substituted into equation (3) to yield

$$w(T) = zCT^z / [\sigma(0) + CT^z] = zCT^z / \sigma(T). \quad (5)$$

Observe that if the film is indeed *metallic* and exhibits a finite positive conductivity $\sigma(0)$ at absolute zero, then $w(T)$ should extrapolate to *zero* as $T \rightarrow 0$ K.

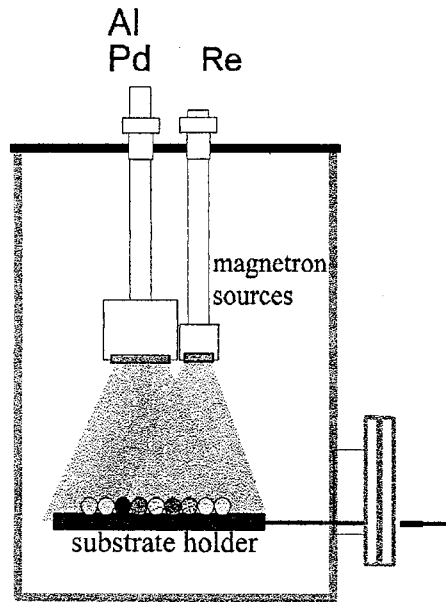
For the special *insulating* case of the conductivity following a simple power law with $\sigma(0) = 0$ in equation (2)—that is,

$$\sigma(T) = CT^z \quad (6)$$

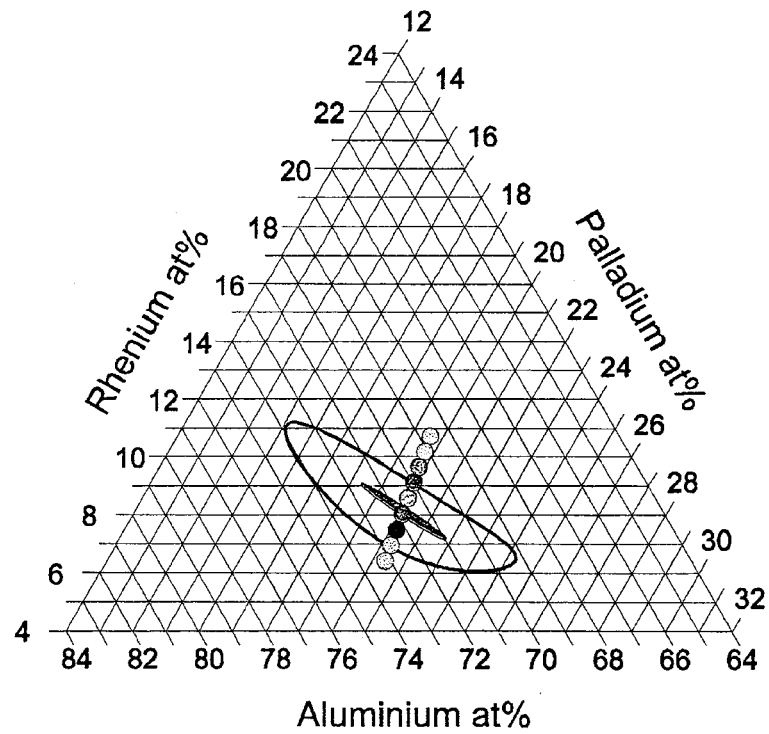
equations (3) and (6) predict that the values of w are independent of temperature and that $w = z$. Thus, Janot's prediction of a simple power law for the conductivity with $z = 1/2$ can be tested experimentally [10–12].

3. Film preparation and measurement details

Thin amorphous 2200 Å films with nominal compositions near $\text{Al}_{72}\text{Pd}_{20}\text{Re}_8$ were prepared by co-sputtering with two magnetron sources onto quartz glass substrates, as illustrated in figure 1 [20]. One target source contained an AlPd alloy and the second source contained the Re element. Due to the positions of the two sources with respect to the substrate, a *well defined* composition gradient could be achieved along the substrate holder of about 0.4 at.% Re between adjacent quartz substrates. The substrate holder mechanically supported three rows of substrates, each row containing ten quartz substrates of 10×15 mm dimension. Thus, a set of 30 *amorphous* samples were produced cutting the ternary phase diagram close to the optimum



(a)



(b)

Figure 1. A schematic diagram of the sputtering apparatus used to prepare the *precursor amorphous* AlPdRe films and (b) the quasicrystalline phase diagram.

composition for obtaining the quasicrystal structure, as shown in figure 1. The amorphous films were individually heated in a vacuum where the transition to the icosahedral structure took place. The individual annealing time and maximum temperature were optimized according to the maximum of the resistance, measured *in situ* during the conversion. For example, the insulating film A2 was heated to 950 K for 21 h; in contrast, the metallic film C5 was heated to 880 K for 11 h. The insulating film A2 has a nominal composition of 72.0 at.% Al, 20.5 at.% Pd, and 7.5 at.% Re. This composition is to be compared to the composition of the metallic film C5 which has 71.0 at.% Al, 20.1 at.% Pd, and 8.9 at.% Re. The substrate of the insulating film A2 was located directly below the Al–Pd target, while the substrate of the metallic film C5 was situated between the two targets. There was a difference of 30 mm between the positions. The films of this series were not covered by insulating protective top layers. Thus, the possibility of a small shift in composition due to preferential evaporation losses of Al and maybe of Pd cannot be excluded. Details of the film preparation are reported in reference [20].

X-ray diffraction, SEM, and TEM showed that the resulting films are single-phased icosahedral with grain sizes up to 1 μm [20]; the electron micrographs displayed fivefold-symmetry patterns [21]. The icosahedral 2200 Å AlPdRe films are quite unique. The films appear to be extremely inert under exposure to organic solvents and subjection to harsh physical treatment. Their resistance reproducibility upon cycling from liquid-helium temperature to room temperature is incredibly good; their room temperature resistances appear stable over periods of months to years.

The films were initially allowed to age at room temperature for a couple of months. Then contacts were made to the films using silver paint.

Measurements below 1 K were first performed at Tel Aviv University (TAU) with the films placed *inside* the mixing chamber of a small dilution refrigerator. Thermometry was based upon an extrapolated CMN thermometry scale. The CMN salt pill thermometer was calibrated against the vapour pressures of ^3He and ^4He liquids and against a calibrated Ge thermometer from Scientific Instruments. A Keithley 617 electrometer or a Stanford Instruments SR510 lock-in amplifier was used to measure the resistances of the samples; and care was taken to prevent Joule heating of the films inside the mixing chamber with power dissipation limited to less than 10^{-9} W. We note that the TAU dilution refrigerator was *not* located in a shielded room; and the electrical wiring of the refrigerator did *not* have any filters against rf and ac pick-up. We mention that the location of TAU is close to many commercial and military rf- and radar-transmitting stations. Hence, there is a very high possibility of rf heating of the samples below 0.5 K. This external source of heating could well explain the observed ‘saturation’ in the resistances of the insulating film A2 below 0.2 K in the TAU measurements.

All of the data now to be presented below 0.6 K were taken *inside* the mixing chamber of an Oxford Instruments TLM400 dilution refrigerator located at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida. Calibration of the ruthenium oxide thermometer located inside the mixing chamber was based upon nuclear orientation ^{60}Co thermometry below 70 mK and an Oxford Instruments calibration scale above 70 mK. The high ^3He circulation rate of $700 \mu\text{mol s}^{-1}$ (compared to $70 \mu\text{mol s}^{-1}$ at TAU) seemed to enhance the thermal contact between the samples and the dilute mixture inside the mixing chamber. To ensure conditions of thermal equilibrium between the samples and the mixing chamber thermometer, waiting periods of over one hour between major temperature changes in the mixing chamber were used. This experimental procedure is particularly important for the NHMFL dilution refrigerator, which employs a high ^3He circulation rate. For example, the data taken during the *very fast* cool-down stages were incorrect and discarded since the sample temperatures lagged significantly behind the thermometer temperatures.

The NHMFL dilution refrigerator was not located in a shielded room; and its electrical leads to the samples had no filtering against rf pick-up. Even the electrical terminal sample outlet box outside the cryostat was unshielded. Yet, the rf background of the Tallahassee area appears to be orders of magnitude smaller than that of the Tel Aviv area. Again, signatures of rf heating were strongly present below 50 mK; for this reason, only data taken above 70 mK were analysed. Recall that ‘saturation’ of the sample resistances was observed below 200 mK in the Tel Aviv University refrigerator.

The resistances of the samples were measured by passing a small 17 Hz ac current of 10^{-9} A magnitude through the sample and measuring the resulting ac voltages with Stanford Instruments SR830 lock-in amplifiers. This 10^{-9} A current produces a power dissipation of 2×10^{-13} W, which is a factor of 100 less than at the onset of film heating. The Joule heating curve at 50 mK for higher sample currents is shown in figure 2. The much noisier Stanford Instruments SR510 lock-in amplifier was also avoided [22]. We were then surprised to observe that the Keithley 617 Electrometer greatly overheats the samples in the mK region, perhaps owing to digital noise introduced from its input terminals, as clearly displayed in figure 2. We do not recommend using this instrument for mK measurements. We then accidentally discovered that the low input impedance of the Stanford Instruments SR830 lock-in amplifier was partially ‘shorting out’ the sample resistances, which were of the order of 200 to 400 k Ω . Stanford Instruments claim that the SR830 has an input resistance, R_{in} , of 10 M Ω . According to our measurement results using known standard resistors, the input resistances, R_{in} , of the SR830 units are only of the order of 4.725 M Ω . Therefore, the measured resistance was corrected according to the expression $R_c = R_m / (1 - R_m / R_{in})$, where R_m is the measured value and R_c is the corrected value. In addition *no* computer acquisition was used in order to avoid rf noise from the digital electronics of the PC motherboard. Once all of these experimental

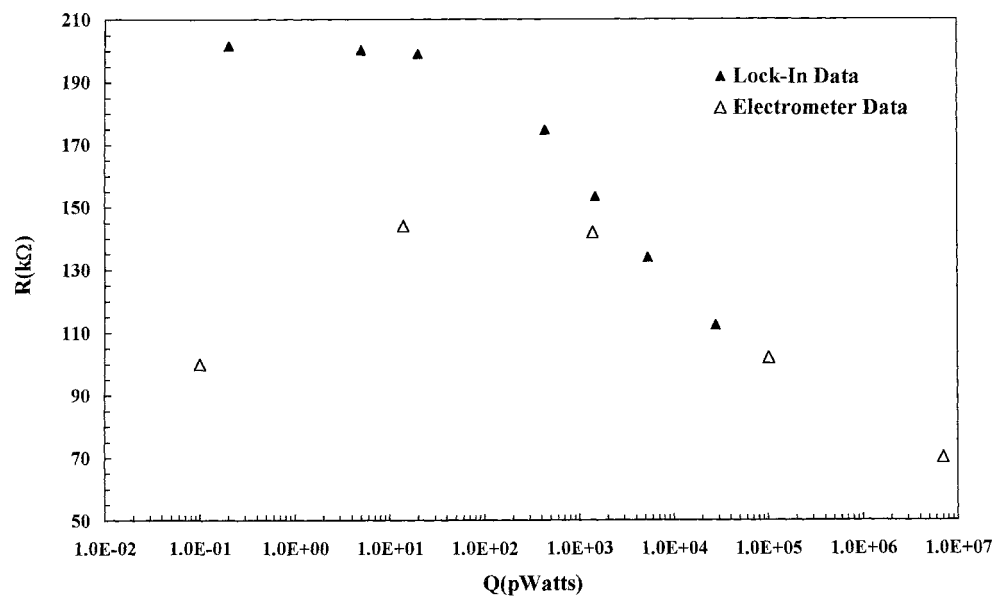


Figure 2. The heating effect of the measuring electronics upon the resistance of the QC i-AIPdRe film No A2 at $T = 50$ mK. The Keithley 617 Electrometer is unsuitable for mK measurements; in contrast, the Stanford Instruments SR830 lock-in amplifier works well, provided that corrections are made owing to its relatively low input resistance of 4.73 M Ω .

procedures were adopted, we observed that the measured QC resistance values at 100 mK in the NHMFL refrigerator were two times greater than those values observed at Tel Aviv on the same quasicrystalline film at 100 mK. Above 0.5 K, the Tel Aviv data agreed well with the Florida data. Thus, *correct* experimental procedures and a *low* rf background are absolutely essential for obtaining meaningful results in the mK region.

4. The conductivity data

An example of *metallic* behaviour is shown in figure 3 where the quasicrystal i-AlPdRe Film No C5 exhibits w -values which tend to *zero* as $T \rightarrow 0$ K. This film has $r = R(4.2 \text{ K})/R(300 \text{ K}) = 2.9$. Note that we do not attach any physical significance to the magnitudes of the resistance ratios r , unlike many other investigators. For this metallic case, a least-regression fit of the $\log(w\sigma)$ versus $\log(T)$ data using equation (5) yielded values for the exponent z and the prefactor C appearing in equation (2). A value for $\sigma(0)$ follows directly from one of the data points. The empirical fit to the zero-field low-temperature conductivity data for film No C5 below 1.6 K is shown in figure 4 where the solid line is given by $\sigma(T) = 73.01 + 1.24 T^{0.71}$ in $\Omega^{-1} \text{ cm}^{-1}$. The exponent of 0.71 of the second term is larger than the EEI theory prediction of an exponential value of 0.50 [23]. We have seen this discrepancy for many metallic films located *just above* the MIT. The magnetoconductance (MC) data on this film can be explained using the weak-localization and electron–electron theories. The MC results are summarized in reference [24]. The main result from fitting these theories to the metallic MC data is that the inelastic scattering time $\tau_{\text{in}}(T) \propto 1/T$; this surprising T^{-1} -dependence can be explained by two possible theoretical models [25, 26].

In contrast, figure 5 shows that the w -behaviour for the quasicrystal i-AlPdRe film No A2 is a *slow increase* below 1.5 K, indicating activated hopping of the conductivity according to

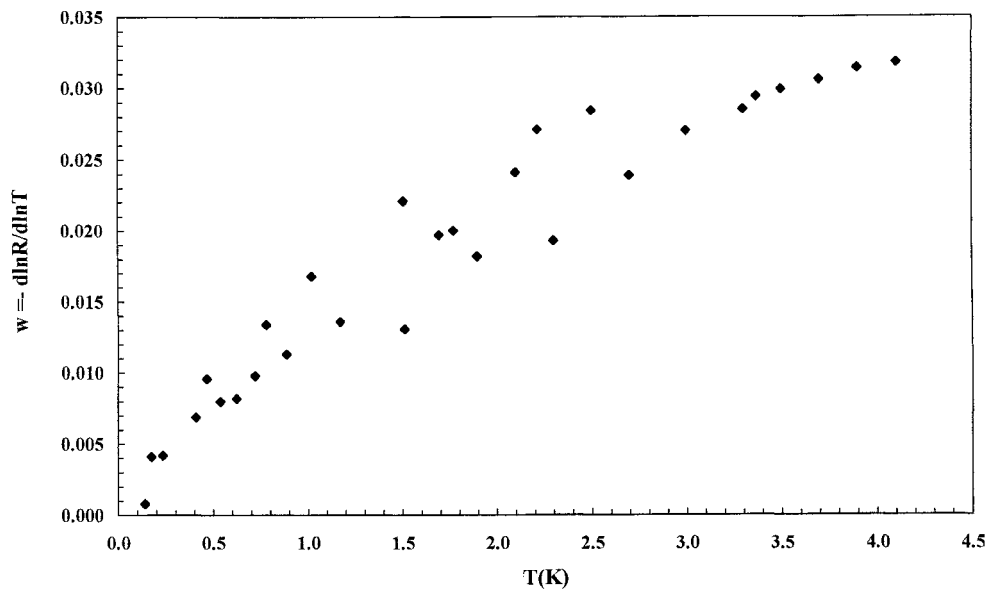


Figure 3. The dependence of $w = d \ln \sigma / d \ln T$ upon temperature for the quasicrystalline i-AlPdRe film No C5; the tendency for the w -values to extrapolate to *zero* as $T \rightarrow 0$ K suggests that this film is *metallic*.

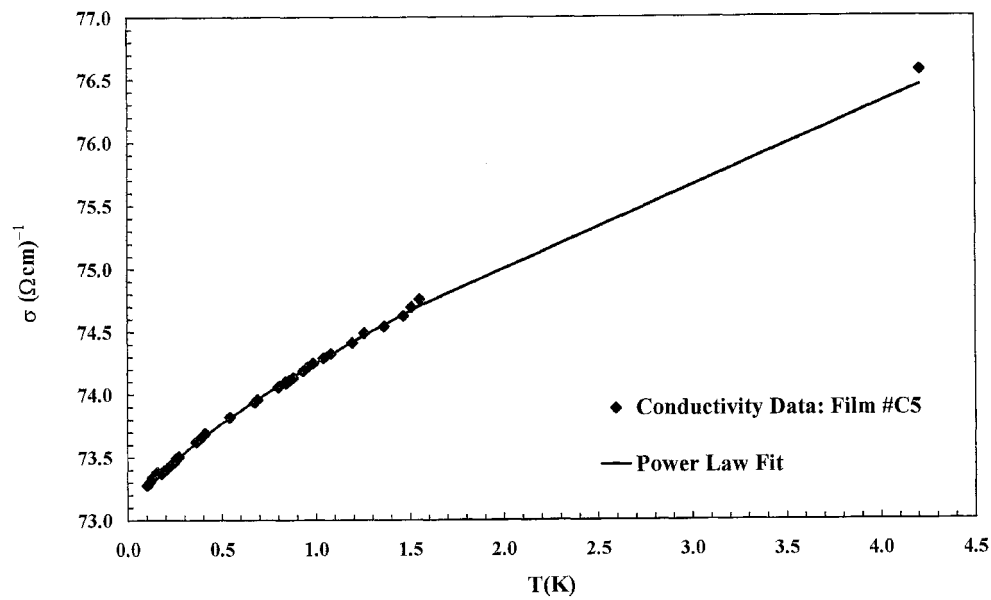


Figure 4. The zero-magnetic-field conductivity data for film No C5 compared to the empirical power fit $\sigma(T) = 73.01 + 1.24T^{0.71}$ in $\Omega^{-1} \text{ cm}^{-1}$. Note the tendency for the conductivity to extrapolate to a finite positive value of $73 \Omega^{-1} \text{ cm}^{-1}$ at $T = 0 \text{ K}$, suggesting that this film is *metallic*.

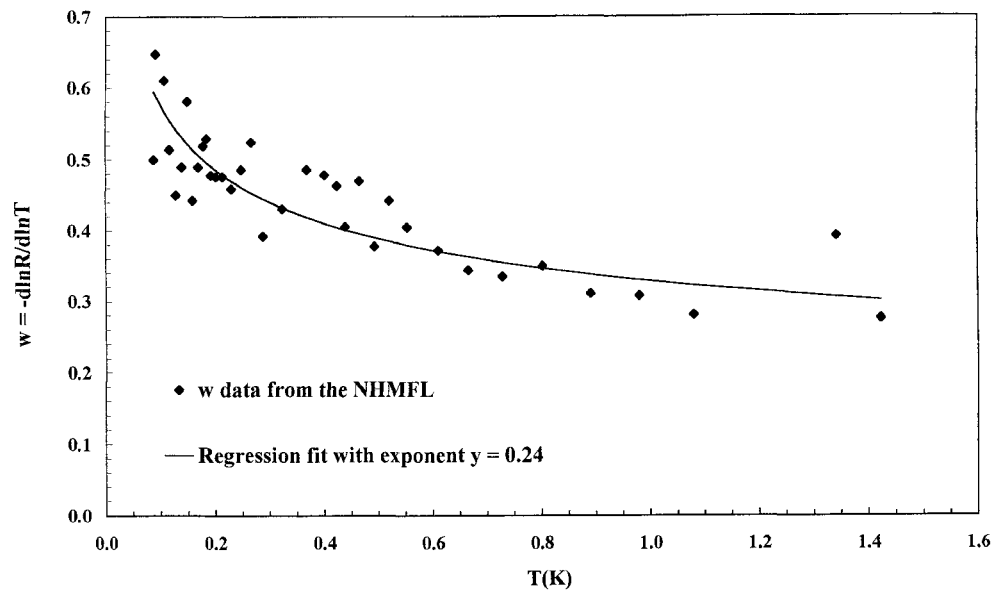


Figure 5. The w -dependence at *low* temperatures for the quasicrystalline film No A2. The w -data *slowly increase* as $T \rightarrow 0 \text{ K}$ implying an *activated* power-law dependence, $\rho(T) = \rho_0 \exp(T_0/T)^y$. The solid line is a least-regression fit representing equation (4) with a hopping exponent $y = 0.24$ and a characteristic temperature $T_0 = T_{\text{Mott}} = 3.43 \text{ K}$.

equation (4). This film has a resistance ratio $r = R(4.21 \text{ K})/R(300 \text{ K}) = 8.7$. The solid line through the w -data is a least-regression fit using equation (4) where $T_0 = T_{\text{Mott}} = 3.43 \text{ K}$ and where the hopping exponent y is $y = 0.244$, extremely close to the Mott exponent value of $1/4$. This result reconfirms the Mott VRH law observed by Wang *et al* [7] and by Delahaye *et al* [8]. Even from the high-temperature w -data above 4 K, as illustrated in figure 6, the w -values *do not extrapolate to zero* as $T \rightarrow 0 \text{ K}$ but intercept the vertical axis around 0.2; this observation clearly suggests that this film is *insulating*. An exceptionally good fit of the Mott VRH law to the resistivity data using $\rho(T) = 0.0457 \exp(3.43 \text{ K}/T)^{0.244}$ in $\Omega \text{ cm}$ is shown in figure 7; the Mott temperature $T_{\text{Mott}} = 3.43 \text{ K}$ is greater than the measurement temperatures, thus ensuring that the hopping distance is equal to or greater than the localization length. Note the tendency towards saturation of the resistivity below 70 mK in figure 7, probably arising from inadequate rf shielding of the electronics at NHMFL.

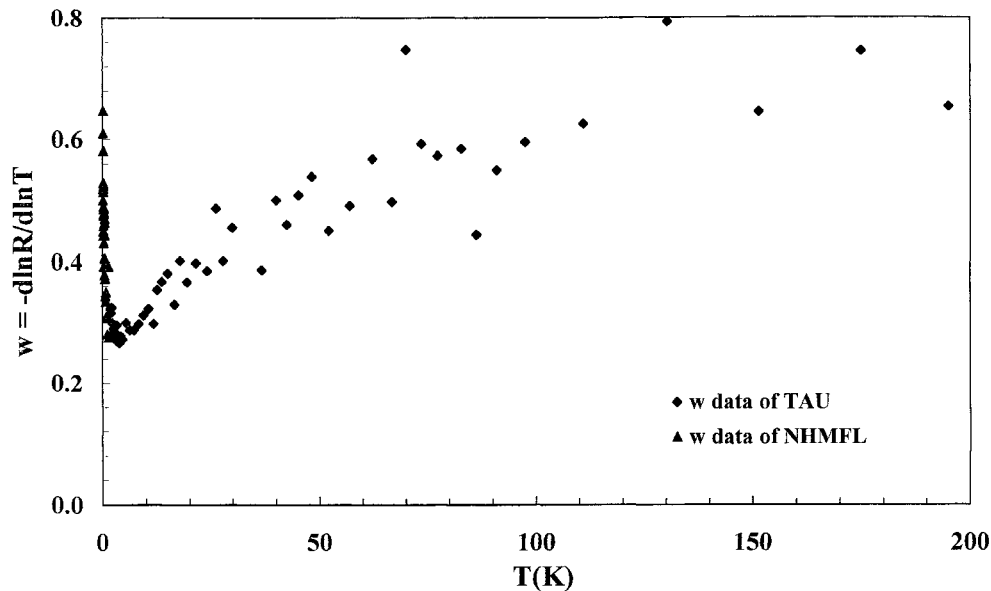


Figure 6. The w -dependence at *high* temperatures for the quasicrystalline film No A2. Notice that the w -data *do not* extrapolate to a *zero* value as $T \rightarrow 0 \text{ K}$ but to the *finite* value of 0.25, implying that this film is *insulating*.

There is additional strong experimental evidence that film No A2 is on the *insulating* side of the MIT. The magnetoresistance (MR) ratio data $R(B, T)/R(0, T)$ for film No A2 are compared to the MR ratio data for the metallic film No C5 in figure 8 near 150 mK. The film No A2 insulating behaviour is entirely different from the film No C5 metallic behaviour as shown in the same figure. Whereas the MR for the metallic film No C5 is small in magnitude and can be well described by the weak-localization (WL) and the electron–electron interaction (EEI) theories in 3D [24], the MR ratios for film No A2 are extremely large and almost linear in B over the entire magnetic field region. The ‘wave-function shrinkage’ theory for *insulating* 3D Mott VRH films can explain these results, as described in references [27, 28]. A forced fit using the weak-localization and electron–electron interaction theories for metallic films can also be made to such large MR ratios as are observed for insulating film No A2, but the values for the fitting parameters are *no longer physical* or there is a *major inconsistency* between the predicted zero-field conductivity values and the predicted MR values [24]. Thus,

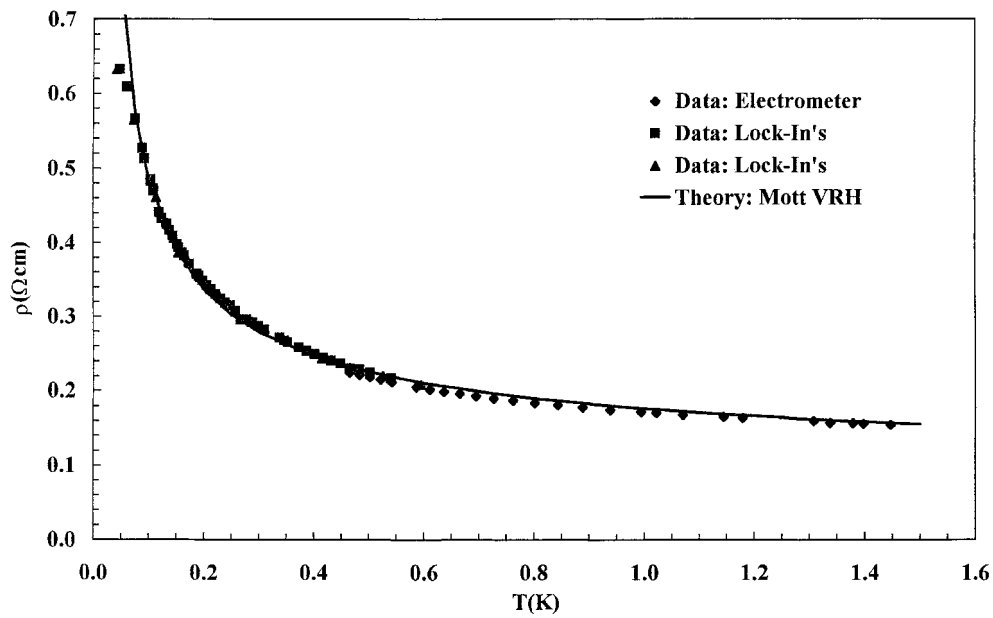


Figure 7. A VRH fit $\rho(T) = 0.0457 \exp(3.43/T)^{0.244}$ in $\Omega \text{ cm}$ to the resistivity data for film No A2. The fit is valid only below $T \approx 3 \text{ K}$ below the minimum in w .

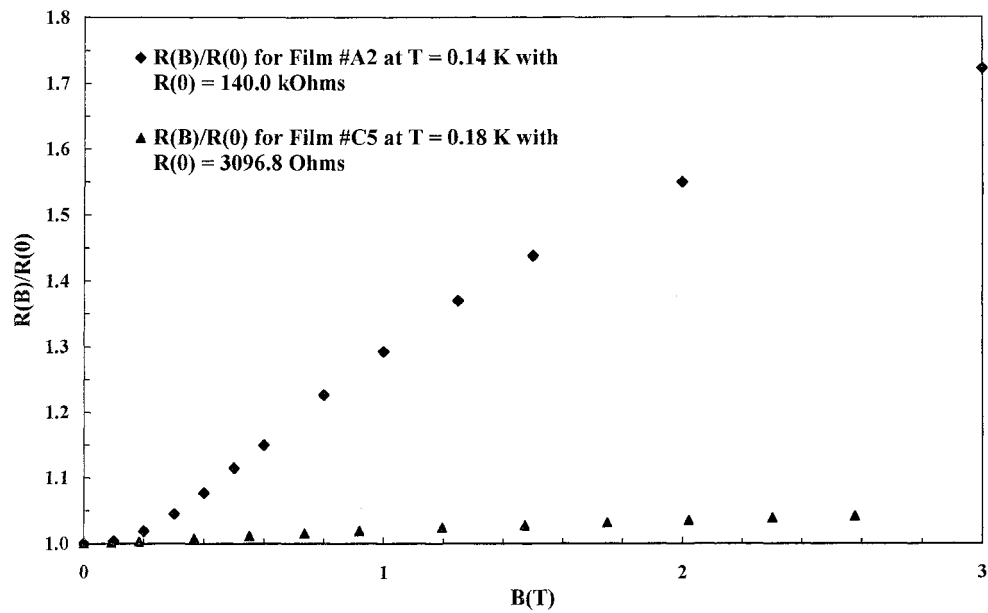


Figure 8. The contrasting magnetoresistance (MR) ratio behaviours of the insulating film No A2 and the metallic film No C5 at 150 mK. The magnetoconductance (MC) data for *metallic* film No C5 can be fitted well using the weak-localization and electron–electron interaction theories in 3D. The MR ratio data for the *insulating* film No A2 can be explained using the wave-function-shrinkage model applied for the case when the conductivity follows a Mott 3D VRH law.

low-temperature MR measurements give a simple and sensitive method that distinguishes between insulating and metallic samples.

We have observed very similar transport results to those for film No A2 for a second insulating i-AlPdRe film, film No C3, located slightly closer to the metal–insulator transition (MIT). Thus, there appears to be a true MIT in these quasicrystalline films.

5. Conductivity of the precursor films—the *amorphous* AlPdRe films

The icosahedral quasicrystal structure is obtained by heat treatment in vacuum of the *precursor amorphous* AlPdRe structure at about 920 ± 50 K. The *precursor amorphous* films exhibit some electronic transport properties which are quite similar to those of the metallic i-AlPdRe films [24] as shown in the high-temperature conductivity data of figure 9. But there is one outstanding difference in the conductivity behaviour between the amorphous and quasicrystal structures in that the conductivity of the amorphous film exhibits superconducting fluctuations below 3 K followed by a sharp transition to the superconducting state just below 0.5 K, as illustrated in figure 10. Recall that bulk Al has a superconducting transition temperature at 1.19 K.

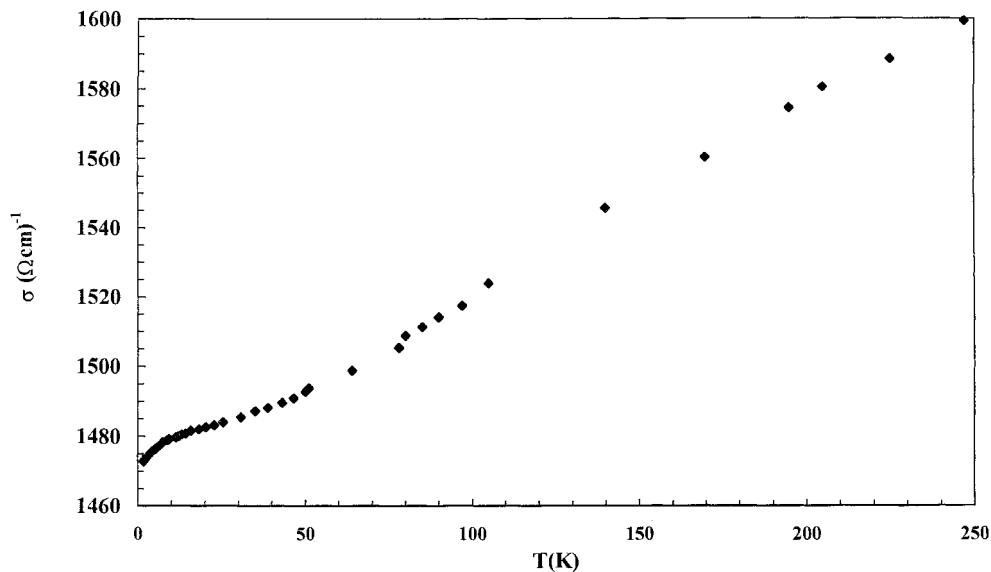


Figure 9. The conductivity of the *precursor amorphous* AlPdRe film No D1 at high temperatures. This behaviour is very similar to that of the conductivity of the metallic film No C5 except that the conductivity magnitudes for this amorphous film are a factor of twenty times greater than those for the quasicrystal film. For clarity, the superconducting transition at 0.5 K is not shown.

The resistivity behaviour as seen in figure 10 results from a competition between (i) the electron–electron interactions which increase the resistivity with decreasing temperature and (ii) the superconducting fluctuations and weak-localization contributions with strong spin–orbit scattering which lower the resistivity values with decreasing temperature.

In figure 11, the magnetoconductance data, $MC = \Delta\sigma = \sigma(B) - \sigma(0)$, for the *precursor amorphous* AlPdRe film are compared with the 3D predictions of the weak-localization and electron–electron interaction theories only. The fit to the data at $T = 4.21$ K is quite acceptable, yielding a value of 10^{-13} s for the spin–orbit scattering time τ_{so} and a value of 5.5×10^{-11} s for the inelastic scattering time τ_{in} . The inelastic scattering in the *precursor amorphous* film

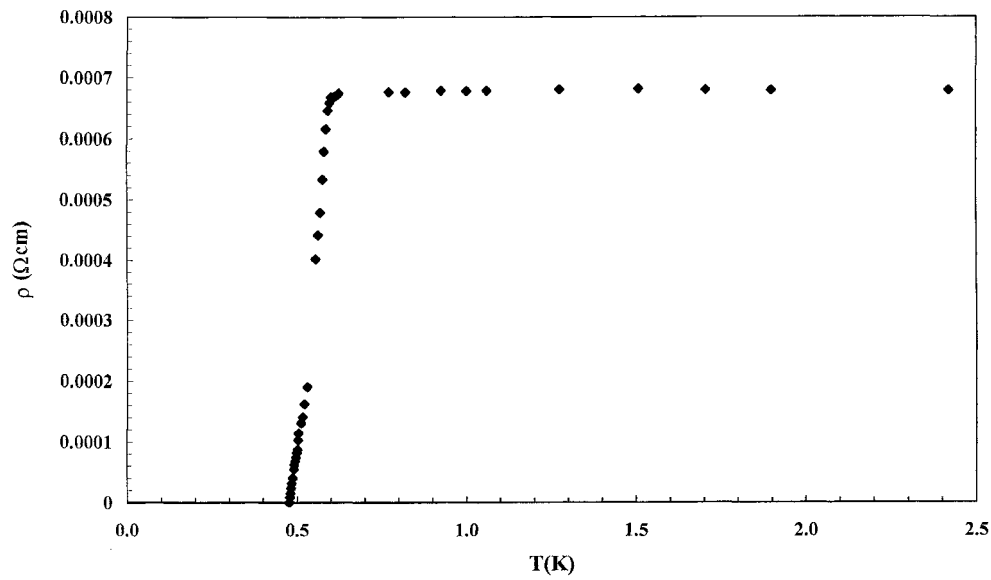


Figure 10. The superconducting transition near $T = 0.5$ K for the precursor amorphous AlPdRe film No D1. The plateau in the resistivity above 1 K arises because of the competition of (i) electron–electron interaction effects with (ii) superconducting fluctuations and weak-localization effects in the limit of strong spin–orbit scattering.

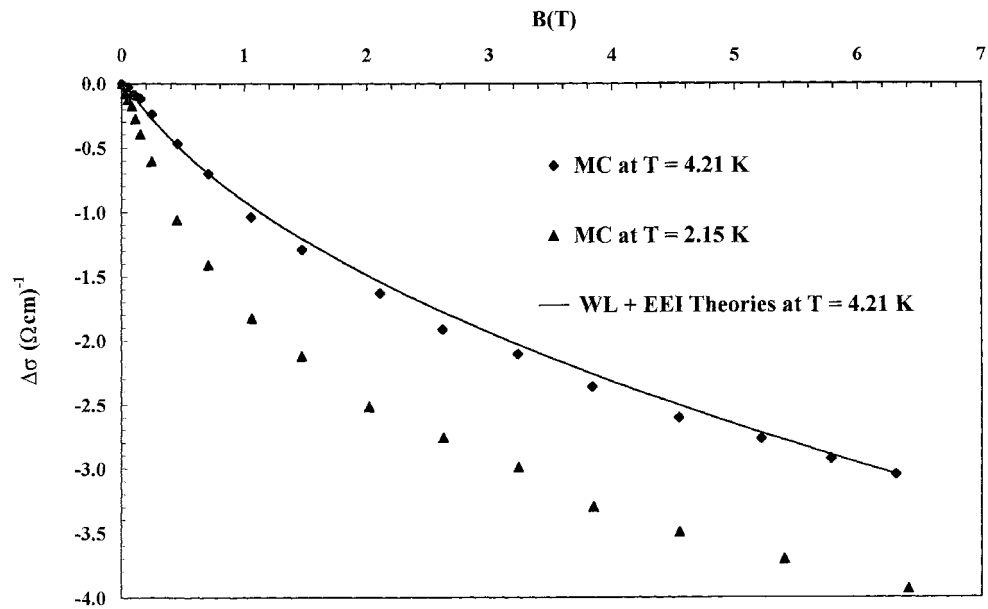


Figure 11. Magnetoconductance data for the precursor amorphous AlPdRe film No D1. An inelastic scattering time was derived from the 4.2 K data, and τ_{in} was found to be a factor of ten larger (weaker scattering) than the inelastic scattering times observed for the icosahedral metallic film No C5 at the same temperatures.

is considerably *weaker* than the inelastic scattering in the *quasicrystalline* film where, at the same temperature of $T = 4.21$ K, a value for τ_{in} of 3.6×10^{-12} s was observed [24]. A fit to the MC data at $T = 2.15$ K was not possible owing to the omission of the important contribution to the MC from superconducting fluctuations. The reason for the omission is that there has yet to be published a suitable superconducting fluctuation theory for the MC *in 3D* [47]; this is in contrast to there being some very successful theories for the MC *in 2D* [29]. In these MC fits, we chose a value of $D_{\text{dif}} = 4.5 \text{ cm}^2 \text{ s}^{-1}$ for the diffusion constant. The electron screening parameter was set to $\tilde{F}_\sigma = 0.2$.

We believe that the inelastic scattering time τ_{in} arises from an electron–electron scattering process. In the liquid-helium temperature region, $\tau_{\text{in}} \propto T^{-1}$. Altshuler *et al* have shown for a *thin 2D film* that the inelastic scattering time is inversely proportional to the resistance per square, R_\square , of the metallic 2D film [30]. We generalize their predictions to a 3D metallic film and speculate that the inelastic scattering time should be inversely proportional to the resistivity of the 3D film. Since the QC resistivity is a factor of ten greater than that of the amorphous 3D film, the inelastic scattering of the QC film should also be a factor of ten times stronger (with τ_{in} ten times smaller in magnitude), consistent with the observation.

At temperatures greater than $T > \theta_D/10$, where θ_D is the Debye temperature, the inelastic scattering time should be dominated by electron–phonon scattering. According to Schmid, $\tau_{\text{in}} \propto T^{-4}$ [31]. From the specific heat measurements of Pierce *et al*, $\theta_D \approx 425$ K for the AlPdRe system [32]. Unfortunately, we are not able to perform the MR measurements at temperatures greater than 20 K, and hence we were not able to observe the crossover to electron–phonon scattering.

6. Discussion

One possible explanation for the metal–insulator transition in *quasicrystals* involves the interaction between the electrons at the Fermi surface characterized by the diameter $2k_F$ and the structure characterized by the Jones zone or Brillouin zone diameter k_p [33, 34]. Here k_p is the reciprocal wave vector where the structure factor $S(k)$ has a major peak. When $2k_F \approx k_p$, a *resonance-like* interaction between the conduction electron system and the static structure system takes place which causes an opening of a pseudogap in the density of states (DOS) at E_F with major consequences for the electronic transport properties. Such a behaviour was first discussed for quasicrystals by Smith and Ashcroft [35] and by Friedel [36]. A recent band-structure calculation for the 1/1 approximant to i-AlPdRe suggests the possibility that even minor structural modifications in the icosahedral phase can result in the Fermi energy being placed into a real gap, creating an insulating phase [37]. We speculate that small changes in the chemical content will also place the Fermi energy in the region of the DOS gap minimum.

The *amorphous metallic* alloy systems also display *shallow* pseudogaps in the DOS near E_F . The theoretical prediction of a shallow pseudogap has a long history, starting with the important papers of Ballentine [38], Lifshitz [39], Nagel and Tauc [40], and Nicholson and Schwartz [41]. Mott [42] and Mott and Davis [43] summarize these theoretical papers in their books. Experimental confirmation of the shallow pseudogap has been reported by Häussler’s group [44, 45] for amorphous metallic alloys. The above theoretical models are based upon the *random locations* of the atomic sites and *not* upon the *random depths* of the *potential wells* at the various sites.

Mott made some intriguing predictions for the conductivity behaviour for the case when the Fermi energy is centred in the middle of a *deep* pseudogap of the DOS, as outlined in reference [42]. Mott speculated that electrons in this deep-gap region will be *localized*, and hence the system should be insulating and the conductivity should display a *Mott variable-range hopping*

law. In addition, on the metallic side of the MIT where the pseudogap of the DOS is *shallow* to *intermediate* in depth, Mott predicted [42] the conductivity to be proportional to the *square* of the normalized DOS ratio g ; that is, $\sigma \propto g^2$ where $g \propto \text{DOS}(E = E_F)_{\text{actual}}/\text{DOS}(E = E_F)_{\text{free}}$. Mott estimates for a *barely metallic* sample located just above the MIT that $0.25 \leq g \leq 0.30$; this case should apply to our metallic i-AIPdRe film No C5. For the *precursor amorphous metallic* AIPdRe films, we speculate that the DOS ratio varies in the range $0.75 \leq g \leq 0.90$. Thus, we would anticipate that the conductivity of the amorphous film should be a factor of ten greater than that of the QC metallic film. Experimentally, we observe a conductivity ratio of 20 between the amorphous and converted QC metallic films. Mizutani [46] has written a very informative article on the resistivity dependence upon the measured *DOS* at E_F both for amorphous and for QC systems. He demonstrates that for amorphous alloys as well as the sp-electron quasicrystals and also for the Mackay icosahedral-type quasicrystals, all three systems have a $\sigma \propto [\text{DOS}(E_F)_{\text{actual}}]^2$ dependence for conductivity data at $T = 300$ K in the gap region. At $T = 4.2$ K, all of the systems also follow this dependence except for the extremely resistive AIPdRe samples [46]. Thus, the amorphous films should have considerably higher conductivities compared to the conductivities of the QCs.

In conclusion, there is a definite metal–insulator transition in this i-AIPdRe film series. The *precursor amorphous* films exhibit *metallic* behaviour with superconductivity below 0.5 K, in strong contrast to some of the *icosahedral* films that exhibit *insulating* behaviour with their resistances tending to infinity.

It is clear that more experimental efforts are needed to extend resistance measurements to the low-mK temperature regime, first, to reconfirm the existence of a Mott activated hopping law; and second, to explore the possibility of a ‘crossover’ of the resistance behaviour from a Mott VRH law observed at these ‘high’ temperatures to an Efros–Shklovskii VRH law at much lower temperatures. The ‘crossover’ behaviour is commonly observed in amorphous insulating films above 4.2 K [17].

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