Electronic Transport Properties of Quasicrystalline Thin Films

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Abstract

Quasicrystals are assumed to be electronically stabilized by a Hume-Rothery type mechanism. This explains most of the peculiar properties of quasicrystals. The stabilization is investigated by electronic transport properties, as they depend sensitively on the stabilizing interaction between the static structure and the conduction electrons.

Thin-film techniques provide samples which are well suited for systematic investigations as a function of composition and structural quality for Al-Cu-Fe and Al-Pd-Re i-phases. For a narrow range of composition, large transport anomalies occur, reaching a metal-insulator-transition in thin films of i-Al-Pd-Re. We discuss this in the framework of a resonant scattering of the conduction electrons with the quasicrystalline structure, leading to a reduced electronic mobility and density of states (DOS) at the Fermi energy $E_F$.

1 Introduction

Electronic transport properties (see also [24, 29]) as for example the electrical conductivity, the thermopower, as well as the Hall effect are of particular interest due to their sensitivity to the interrelation between atomic structure and electronic system. As described in more detail in the contribution of Häussler [14], a correspondence between the wave length of the conduction electrons at $E_F$ and a frequently occurring distance in the atomic system leads to resonance-like interaction, causing an energy-lowering of the electronic system. This behaviour can, on one hand, stabilize an atomic structure like the quasicrystalline one and, on the other hand, it modifies the electronic system so that transport anomalies arise. Stable quasicrystals can exhibit transport properties which can neither be described as metallic nor as semiconducting (activated behaviour) as shown in fig. 9. The anomalies can be strong enough to cause a metal-insulator transition (MIT) in icosahedral Al-Pd-Re [23].

First investigations on quasicrystalline thin films were performed in order to investigate properties which could be relevant for technical applications, as
for example mechanical, tribological and corrosion properties [21, 28]. Additionally, thin films were used to measure transport properties, because of two reasons: first of all, thin films show a much higher electrical resistance than bulk samples and allow a much easier and more precise determination of the resistivity. Films were used to determine the very small magnetoresistance at low magnetic fields, which is useful to interpret some transport anomalies in the framework of quantum corrections [19]. Secondly, some work was performed to investigate the transition from 3 to 2-dimensional behaviour as a function of film thickness [30].

We want to show here that thin quasicrystalline films do not differ substantially from bulk materials, but offer many advantages with respect to the preparation as well as to measuring electronic transport properties. Additionally, thin films can be prepared in the amorphous phase (a-phase) and crystallized afterwards into the icosahedral phase (i-phase) without the intermediate formation of crystalline counterparts. Accordingly, one sample allows the comparison of the quasicrystalline with the amorphous phase as well as the investigation of the transition between both.

Thin-film techniques provide samples which are well suited for systematic investigations as a function of composition and structural quality. We show that for a narrow range of composition large transport anomalies occur, up to insulating films for i-Al-Pd-Re. We discuss this in the framework of resonant scattering of the conduction electrons with the quasicrystalline structure, causing a reduced electronic mobility and DOS at $E_F$.

We should address the question, which films are denoted as thin. The thickness should be compared to the length scales of structural units or relevant physical lengths. The smallest structural units, namely the building clusters of quasicrystals are of order 1 nm [17]. As clusters are selfsimilar, an upper limit for cluster sizes is not easy to specify, but 20 nm is a value of a quite large cluster shown in [16, 17]. Most of the relevant length scales of physical mechanisms are much shorter. The electronic scattering length for example is in the order of some atomic distances in the case of elastic scattering (intrinsic to good quasicrystals), while the inelastic scattering length increases with decreasing temperature and can reach $l_i = 10^2 \text{nm}$ at $T = 1 \text{K}$ [4]. From this it can be concluded that the thickness of a typical film is well inside the regime where a 3-dimensional behaviour can be expected. A film may be called ‘thin’ when it is prepared by a deposition process from the vapor phase.

Very thin films with a thickness starting at about $d = 10 \text{nm}$ were produced as selective solar absorbers [4]. It is not clear if films of such a thickness are homogeneous or behave more like a percolating network. There-
fore, samples for electronic transport measurements cover the thickness range $30 < d < 1000$ nm. The thickness of coatings for technical applications is much higher, up to $200$ µm [21].

2 Preparation of thin quasicrystalline films

The films considered here are prepared by evaporation or sputtering from one or more sources onto substrates at different temperatures. Two routes are possible: homogeneous samples may be prepared directly, or crystalline multilayers of the different components may be prepared first, followed by extensive heat treatments. While the first technique can lead directly to quasicrystalline (qc) films (if deposited at a sufficiently high temperature), the second needs interdiffusion between the layers and a solid state reaction to form a qc-film. First films for conductivity measurements were fabricated with the second technique by a sequential sputtering technique of Al, Fe and Cu. As the thickness of each layer could be controlled by a quartz oscillator with high accuracy, the overall composition has been adjusted such that the narrow range of the $i$-phase in the phase diagram was reached [19, 6]. Some groups have prepared thin films of Al-Cu-Fe by sputtering from a composite or area- sectional target [3, 4]. This results in samples with homogeneous composition and can lead to amorphous films if the substrate temperature is held below $T \approx 500$ K and to qc-films for $T > 750$ K. The amorphous films

![Figure 1: Sketch of a sequential flash evaporation](image)

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could be transformed to the qc state (780 K) via a cubic phase ($T_{\text{cryst}} = 580 \text{ K}$) by an appropriate heat treatment \cite{3}. A problem of this technique in order to gain samples with systematic varying compositions is the need of an individual target for each composition desired. The evaporation of a master alloy by an electron beam is another method which has been used \cite{30}. Here the films have compositions which are different from the master alloy and have to be determined afterwards.

In the present paper we report on a sequential flash-evaporation technique (fig.1) in order to prepare amorphous Al-Cu-Fe samples with an exactly defined stoichiometry as a precursor for the qc-phase. Grains of a premolten master alloy of the correct composition are fed to a hot tungsten filament where they flash evaporate. As each grain contributes one monolayer or less to the film thickness, even a complete segregation finally ends up with a homogeneous film of the nominal composition. As a second technique for Al-Pd-Re we use co-sputtering with two magnetron sources (fig.2a). Due to the positions of the two sources in respect to the substrate a defined composition gradient can be achieved along the substrate. With the latter technique in one preparation process a set of amorphous samples can be produced con-
Figure 3: Electrical resistivity (a) and conductivity (b) of a thin film of Al-Cu-Fe prepared at $T = 4$ K in the amorphous state. After some annealing steps in the still amorphous sample, (enlarged in the inset) the crystallization to the $i$-phase occurs at $T = 760$ K [9]

sisting of about 20 samples with a composition, slightly and systematically changing from one sample to the next, cutting the ternary phase diagram at, or close to the optimal composition (fig.2b). A defined shape of the evaporated or sputtered samples can be achieved by applying a mask or a structuring technique using microelectronic technologies, respectively. This allows to determine the absolute resistivity, which is difficult for most bulk samples because of their irregular shape and brittleness.

3 Amorphous to quasicrystalline transition

The amorphous state prepared by quenching of the vapor phase onto a cooled substrate is structurally similar to the liquid phase. Therefore, a direct transition from the amorphous to the qc-phase is possible for films at appropriate composition. In contrast to the transition from the liquid to the quasicrystal, the transition from the amorphous to the qc state is irreversible and occurs at much lower temperatures. Fig.3a shows the resistivity of a thin film of Al-Cu-Fe deposited by sequential flash evaporation onto a substrate cooled...
down to $T = 4.2 \text{K}$. The resistivity of the amorphous state at this temperature is $\rho(4.2 \text{K}) = 300 \mu\Omega\text{cm}$ and increases to a value of $\rho(4.2 \text{K}) = 470 \mu\Omega\text{cm}$ after an annealing up to $T = 550 \text{K}$. This behaviour is discussed later. Besides the quite small and continuous irreversible increase of the resistivity and its temperature coefficient, a distinct increase related to the direct transition from the $a$- to the $i$-phase can be seen at $T \approx 740 \text{K}$. Above, the sample is icosahedral as shown by electron diffraction \[11\]. The transition temperature is about 350 K lower than the solidus temperature of the same system. This offers new possibilities. First, the transition happens within the solid phase and allows the measurement of electronic transport properties at the transition (fig.4). Second, the transition plotted in fig.3 shows no indication of the formation of crystalline phases like the cubic $\beta$- or $\tau$-phases which occur whenever an Al-Cu-Fe melt is cooled down from the liquid state by melt-spinning or conventional casting. Therefore, in films produced via the amorphous route no long-term annealing treatments (typically some hours at $T = 1050 \text{K}$ for bulk samples) are necessary for removing crystalline phases. Third, the transition from the $a$- to the qc-phase happens not only at low $T$ but also on short time scales in the order of minutes. Fig.4 shows this transition of Al$_{63.5}$Cu$_{24}$Fe$_{12.5}$films for different heating rates. Together with a low surface roughness achieved by this preparation, this may have consequences for technical applications of qc coatings.
4 Comparing the a-with the i-phase - the scattering approach

The preparation of qc thin films via the route of the a-phase offers the possibility to compare directly the electronic system of the isotropic amorphous with the nearly isotropic quasicrystalline phase in one and the same sample.

The conductivity of very different quasicrystals, stable ones with strong transport anomalies like \(i\)-Al-Cu-Fe, \(i\)-Al-Pd-Mn, or \(i\)-Al-Pd-Re, as well as simple ones (without \(d\)-states at the Fermi level) with much smaller transport anomalies like \(i\)-Al-Mg-Zn have often been described by an inverse Matthiessen rule. That means that their \(T\)-dependencies of the conductivity \(\sigma(T)\) are claimed to be the sum of the conductivity \(\sigma_0\) at \(T \rightarrow 0\) K which depends on the particular system, its composition and structural quality, and on a temperature dependent increase \(\Delta \sigma(T)\) which is very similar for all qc phases and samples

\[
\sigma(T) = \sigma_0 + \Delta \sigma(T).
\]

This behaviour is inverse to that of ordinary metals, where the electrical resistivity instead of the conductivity shows a comparable behaviour. Astonishingly, fig.3b (conductivity) shows a parallel behaviour of the curves belonging to the amorphous and the icosahedral phases. Accordingly, also the behaviour of the a-phase can be described by the inverse Matthiessen rule, suggesting a strong similarity between the amorphous and the quasicrystalline phases.

For quasicrystals theories exist which are based on the particular features of the quasicrystalline structure and its relation to the electronic system. For example a scattering induced electronic hopping between badly propagating electronic states [22], the localization tendency of electrons in selfsimiliar clusters [16, 17] or a temperature dependent change of the band structure due to the decrease of elastic Bragg scattering at higher temperatures [8]. These models can explain only few aspects of electronic transport as for example the inverse Matthiessen rule. A different approach to understand the unexpected properties of quasicrystals is motivated by the electronic stabilization of their peculiar structure. This is due to the interaction between the electrons at the Fermi level (characterized by \(2k_F\)) and the structure (characterized by the Jones zone diameter \(k_{pe}\)). Such a behaviour corresponds to the Hume-Rothery mechanism in periodic crystals [18, 19] and was first discussed for quasicrystals by Smith and Ashcroft [27] and Friedel [3]. This description is obvious as the Jones zone of a quasicrystal (fig.3b) consists of many flat areas and hence can interact with a spherical Fermi surface in many directions.
Figure 5: Electron diffraction of an amorphous $\text{Al}_{62.5}\text{Cu}_{25}\text{Fe}_{12.5}$ film (20 nm) in comparison with the position of major $i$-Al-Cu-Fe peaks [9].

Fig. 5 shows that the strongest peaks of the $i$-phase are at the position of the electronically induced peak of the $\alpha$-phase [9]. This suggests that the size of the Jones zone as well as its shape (see fig. 6) is very similar for the $\alpha$- and the $i$-phase. It has been shown [13] that the stability and many other properties of a large class of amorphous systems can be understood by such an interaction. Thin films are well suited to investigate this aspect because they allow the comparison of the amorphous with the quasicrystalline state in one sample. Electronic transport properties of films can be measured in situ up to elevated temperatures due to easy preparation techniques and the high contact stability.

The interaction between electronic and atomic system is based on the elastic scattering of electrons with the Fermi wavenumber ($k = k_F$) at a pronounced peak in the structure factor $S(2k_F)$ describing the atomic structure. The elastic (Bragg-like) scattering of electrons reduces not only the mean free path, the main effect may be the depression of the DOS at $E_F$. If the matching of the $k$-vectors of the electronic and the atomic system is good, this results in a resonant-like scattering of electrons. The previously freely propagating electrons change partially to standing waves because of resonant scattering, resulting in a tendency of localization of the electrons at $E_F$. As a consequence, the electronic DOS at $E_F$ is reduced, the stability of the system increases and electronic transport anomalies arise. The aspect of stability is comprehensively discussed in [14], while the consequences for electronic transport in amorphous and quasicrystalline films will be briefly
discussed in the following. In the case of a weak scattering approach the Ziman formula
\[ \rho_z = \frac{1}{\sigma_z} \propto \int_0^{2k_F} S(K)|v(K)|^2 K^3 dk \]
\[ [31] \] has been used to describe the resistivity and its temperature dependence for liquid and amorphous systems. \( K \) represents the scattering vector, \( v(K) \) the pseudopotential and \( S(K) \) the static structure factor. This formula cannot strictly be applied to systems with strong scattering as are some amorphous systems or quasicrystals. But this relatively simple formula can be helpful to follow up the trends to stronger scattering. Due to the weighting with \( K^3 \) the elastic scattering strongly depends on \( S(2k_F) \), the structural weight at the upper limit of the integral. Thus, a pronounced peak in the structure factor at \( 2k_F \) leads to a strong elastic scattering and a low conductivity. As the temperature increases, the portion of the elastic scattering at \( K = 2k_F \) is reduced in favour of inelastic scattering. The latter is less effective on reducing the conductivity than the diffuse umklapp scattering. Thus, the conductivity increases with increasing inelastic scattering due to rising temperature. Additionally, the resonant like elastic scattering due to the coincidence of the electronic wavelength with structural distances opens a gap or a pseudogap at \( E_F \). This is similar to the case of periodic crystals where a matching of the wave length of the electron waves at \( E_F \) with the wave length of a reciprocal lattice vector causes a gap due to the energy difference for the two solutions of standing electron waves. In quasicrystals the matching may be slightly different. A resonance-like interaction is most effective, if not only the wavelength but also the waveforms of both systems are iden-
In quasicrystals and especially in amorphous alloys, it is well known that the atoms are onionshell-like located around ad-atoms. The distance between neighbouring shells $\lambda_P$ is in agreement with the Friedel wavelength $\lambda_F = \frac{2\pi}{2k_F}$. Each atom is surrounded by ‘mirror spheres’ analog to the equidistant separation of mirror planes in the crystalline case. The electrons should be treated as spherical waves in coincidence with the onionshell-like static structure. Under resonance, any plane wave which once may have been formed will by scattering immediately fall apart into spherical waves which are strongly localized due to the phase-coherent backscattering from all the neighbouring onionshells. The resonance-like coupling causes localization of the electrons at any site and hence a short mean-free path which itself helps to enhance the role of the spherical waves at medium range. In the electronic DOS pseudogaps arise. The onionshell-like position of the neighbouring atoms around any ad-atom may also be seen as a cluster-model with strongly interpenetrating clusters. Whereas in the amorphous phase the location of the atoms on the onionshells is still strongly random and in addition angular correlations are weak or absent, this is no longer the case in the qc-phase. The distances of the individual atoms to the ad-atoms are much better defined and strong angular correlations exist. The phase coherence of the backscattered spherical waves is better fulfilled and therefore the interference effects are even stronger. Accordingly the localization of the electron waves should be stronger and the pseudogap should become deep.
As the temperature rises the portion of the resonant elastic scattering is decreased in favour of inelastic scattering reducing the pseudogap both for amorphous and quasicrystalline systems. We mention that this behaviour is simply ruled by the Debye-Waller factor which describes the ratio of the elastic to inelastic scattering for the relevant peaks building up the Jones zone. This can be seen in fig.3b. The conductivity for all reversible parts (marked by $\leftrightarrow$) of the amorphous states and also for the quasicrystalline state increases with temperature in exactly the same manner. The conductivity irreversibly decreases (marked by $\downarrow$) with every annealing step reaching its smallest value in the qc-phase with its strong radial and angular correlation of atoms. The temperature dependence of the conductivity is discussed in detail in the Al-Pd-Re system as this icosahedral system shows even larger transport anomalies (reaching insulating behaviour) and has a much smaller contribution of low temperature effects from spin-orbit scattering.

The effect of resonance in amorphous and quasicrystalline samples can also be seen in the thermopower. For amorphous systems it is well known that a stronger resonance between static structure and electronic system causes a deviation from the free electron value of the thermopower $S_0$ to positive values [13]. Fig.7 shows the same behaviour for the icosahedral phase. The samples show a transition from a large negative to a large positive thermopower. This correlates with the increase of the resistance ratio $\rho(4K)/\rho(300K)$, which is an indication of the enhanced resonance effect between static structure and electronic system. Note that the i-phases show thermopowers which are much larger than the free-electron value. This can be attributed to a deep pseudogap which reduces the effective number of charge carriers at the Fermi-level.

5 The Al-Pd-Re system

The icosahedral Al-Pd-Re system shows the largest transport anomalies amongst all the quasicrystals, up to a metal-insulator transition (MIT) [23]. Thus it is interesting to check the concept of resonant interaction between the static structure and the conduction electrons on this alloy. Due to the extremely different vapor pressures of the constituents it is difficult to produce homogeneous bulk samples of a defined composition in a reproducible way. With the co-sputtering technique mentioned before, systematic and slightly different samples can be fabricated as thin films. As an example, Fig.8a shows the conductivity of such a sequence as a function of the Rhenium content for a constant Aluminium to Palladium ratio. There exists a systematic
variation of the low $T$ conductivity with a minimum around $\text{Al}_{72.3}\text{Pd}_{20.2}\text{Re}_{7.5}$. Simultaneously, some of the samples seem to be insulating \[12\], that means, the conductivity vanishes for $T \to 0 \text{K}$ (fig. 8b). A magnetic field enhances this behaviour and apparently leads to a vanishing conductivity at a small but finite temperature.

Thereby, the transport properties of $i$-$\text{Al-Pd-Re}$ match into the common behaviour of stable quasicrystals mentioned before in the $i$-$\text{Al-Cu-Fe}$ system. Fig.10b shows again the validity of the inverse Matthiessen-rule for the conductivity of the $a$- and $i$-phases of different structural qualities. In contrast to all other qc systems, the $\text{Al-Pd-Re}$ system offers two exciting aspects. First, the conductivity vanishes at $T \to 0 \text{K}$, which may be due a stronger resonant scattering because of heavier elements in the case of $\text{Al-Pd-Re}$. Second, at low $T$, there is no increase of conductivity, as for high quality $i$-$\text{Al-Cu-Fe}$ (fig. 7b) or for other stable quasicrystals like $i$-$\text{Al-Pd-Mn}$. Such a low $T$ increase of conductivity (attributed to strong spin-orbit scattering and electron-electron interaction \[7\]) makes a MIT unlikely and complicates interpretation. The model of a resonant-like interaction of the electronic and the static structure is able to explain the transport properties also for the insulating samples. Fig. 9 shows a fit to the conductivity data in a quite large temperature range.

Figure 8: Conductivity for a sequence of $\text{Al-Pd-Re}$ films of constant $\text{Al}/\text{Pd}$ ratio (a) and their low temperature conductivity (b) with a magnetic field of $B = 7.9 \text{T}$ (open symbols) and without field (solid symbols).
The fit is indirectly proportional to a function of the Debye-Waller factor $\exp(-cP(T/\Theta))$, with the Debye-temperature $\Theta$ and a constant $c$ which describes the temperature dependent decrease of the elastic scattering of the electrons at $2k_F$ at the Jones zone. There has been only one parameter ($c_3$ in the expression written in fig. 9) added which is related to the size of the gap between electron- and hole-like charge carriers and is related to the effective pseudopotential. A significant difference between fit and measured data occurs only at temperatures below 100 K. Fig. 9b shows that this difference is proportional to $\sqrt{T}$ which can be attributed to electron-electron interaction (EEI). In systems of strong elastic scattering, electrons are less able to screen charge variations and EEI is enhanced, leading to a small dip in the electronic density of states at $E_F$ [1]. In the case of amorphous alloys this behaviour can be computed quantitatively as a function of temperature and magnetic field [2,20]. In weakly insulating icosahedral systems the MIT seems to have two origins. First, the resonance-like interaction between the static structure leads to a deep pseudogap in the electronic DOS at $E_F$ and the localization tendency of the conduction electrons due to standing spherical waves in some structural clusters. Second, the EEI lowers the small DOS at $E_F$ addition-
ally. The sum of both effects leads to a vanishing conductivity at $T \to 0$ K. A magnetic field dephases the electronic wavefunction enlarging the EEI by a further decreased screening. The MIT occurs at a finite temperature.

The thermopower of $i$-Al-Pd-Re can be described in the resonance-model mentioned before. As shown in fig. 10, the thermopower increases to large positive values as the structural quality increases from the amorphous to the defective and finally the good icosahedral state. The conductivity of the same sample reduces in the same manner as the resonance effect increases.

6 Conclusion

Quasicrystalline thin films can be produced with high structural quality. The low temperature electrical conductivity, which is very sensitive to the structure quality, reaches values which are comparable to that of bulk materials. A MIT is achieved in both, the bulk samples as well as in thin films of $i$-Al-Pd-Re. Thin films provide the possibility to make systematic investigations as a function of composition and structural quality. Further understanding in the interpretation of the peculiar transport anomalies of quasicrystals could
be achieved by the comparison to the isotropic amorphous phase. This has been done on different annealing states of the same sample. Astonishingly, the temperature dependence of the conductivity is qualitatively very similar for both phases, the inverse Matthiessen rule which is thought to be peculiar to quasicrystals is also valid for amorphous samples of the same composition. We discussed this in the framework of a resonant scattering between the conduction electrons and the static structure. Hereby, the mechanism is the same for amorphous as well as for qc systems. Due to the sharp distance distributions and angular correlations in quasicrystals the quantity of the scattering is much larger in the quasicrystalline case, leading to a deeper pseudogap and a stronger localization tendency of the conduction electrons. The temperature dependence of the conductivity could be fitted due to the scattering approach by a simple function of the Debye-Waller factor for the temperature range from 100 to 900 K. At low temperatures the conductivity of i-Al-Pd-Re is additionally influenced by strong electron-electron interaction. This leads to an additional dip of the electronical DOS at $E_F$ and finally to the metal-insulator-transition. The thermopower increases to large positive values as the conductivity vanishes for high-quality qc samples. Again, this is a typical behaviour of electronically stabilized systems, which can be described by a strong interaction between the conduction electrons and the static structure.

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References

[1] Altshuler B.L., Aronov A.G., *Solid State Comm.* 30 (1979) 115

[2] Altshuler B.L., Aronov A.G., *Solid State Comm.* 46 (1983) 429

[3] Chien C.L., Lu M., *Phys. Rev. B* 45 (1992) 12793

[4] Eisenhammer T., Mahr A., Haugeneder A., Reichelt T., Assmann W., Proceedings of the 5th Int. Conf. on Quasicrystals. Eds. C. Janot, R. Mosseri, World Scientific (1996) 758

[5] Friedel J., *Helv. Phys. Acta* 61 (1988) 538
[6] Giroud F., Grenet T., Schaub T.M., Berger C., Barna B.P., Radi Z., Proceedings of the 6th Int.Conf. on Quasicrystals. Eds. Takeuchi S., Fujiwara T., World Scientific (1998) 712

[7] Haberkern R., Fritsch G., Schilling J., Z. Phys. B 92 (1993) 383

[8] Haberkern R., Fritsch G., Proceedings of the 5th Int.Conf. on Quasicrystals. Eds. Janot C., Mosseri R., World Scientific (1996) 460

[9] Haberkern R., Roth C., Knöfler R., Zavaliche F., Häussler P., Proceedings of the 6th Int.Conf. on Quasicrystals. Eds. Tekeuchi, T. Fujiwara, World Scientific (1998) 643

[10] Haberkern R., Roth C., Knöfler R., Zavaliche F., Häussler P., Proceedings of the 6th Int.Conf. on Quasicrystals. Eds. Tekeuchi S., Fujiwara T., World Scientific (1998) 716

[11] Haberkern R., Roth C., Knöfler R., Schulze S., Häussler P., in: Quasicrystals, MRS-Proceedings Vol. 553 (1999), eds. Dubois J.-M., Thiel P. A., Tsai P.-A., Urban K.

[12] Haberkern R., Rosenbaum R., Häussler P., to be published

[13] Häussler P., in: Glassy Metals III, eds Beck H., Günterodt H.-J. Topics in Applied Physics (Springer), Vol. 72 (1994) 163

[14] Häussler P., ”Quasicrystals - material on the path from disorder to order”, this volume

[15] Hume-Rothery W., J. Inst. Met. 35 (1926) 295

[16] Janot C., J. Phys., Condens. Matter 9 (1997) 1493

[17] Janot C., Dubois J.-M., ”Quasicrystals as hierarchical packing of overlapping clusters”, this volume

[18] Jones H., Proc. Phys. Soc. 49 (1937) 250

[19] Klein T, Symko O.G., Appl Phys. Lett. 64 (1994) 431

[20] Lee P.A., Ramakrishnan T.V., Phys. Rev. B 26 (1982) 4009

[21] Massiani Y., Ait Yaazza S., Dubois J.-M., Proceedings of the 5th Int. Conf. on Quasicrystals. Eds. Janot C., Mosseri R., World Scientific (1996) 790
[22] Mayou D., Berger C., Cyrot-Lackmann F., Klein T., Lanco P., *Phys. Rev. Lett.* **70** (1993) 3915

[23] Pierce F.S., Poon S.J., Guo Q., *Science* **261** (1993) 737

[24] Roche S., Mayou D., "Electronic conductivity of quasicrystals and approximants", this volume

[25] Rodmar M., Ahlgren M., Rapp Ö., Proceedings of the 5th Int. Conf. on Quasicrystals. Eds. Janot C., Mosseri R., World Scientific (1996) 518

[26] Roth C., Schwalbe G., Knöfler, Zavaliche F., Madel O., Haberkern R., Häussler P., Proceedings of the 10th Int. Conf. on Liquid and Amorphous Metals (1998), to be published

[27] Smith A.P., Ashcroft N.W., *Phys. Rev. Lett.* **59** (1987) 1365

[28] Sordelet D.J., Kramer M.J., Anderson I.E., Besser M.F., Proceedings of the 5th Int. Conf. on Quasicrystals. Eds. Janot C., Mosseri R., World Scientific (1996) 778

[29] Trambly de Laissardière G., Mayou D., "Magnetic properties of quasicrystals and approximants", this volume

[30] Yoshioka A., Edagawa K., Kimura K., Takeuchi S., *Jpn. J. Appl. Phys.* **34** (1995) 1606

[31] Ziman J.M., *Proc. Roy. Soc. , Ser. A* **318** (1970) 401