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## Electrical resistivity studies of quasicrystalline $\text{Ti}_{56}\text{Ni}_{28-x}\text{Fe}_x\text{Si}_{16}$ ( $0 \leq x \leq 15$ )

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**Abstract.** We report here high-resolution electrical resistivity studies on single-phase quasicrystalline samples of the series  $\text{Ti}_{56}\text{Ni}_{28-x}\text{Fe}_x\text{Si}_{16}$  ( $0 \leq x \leq 15$ ). We have also compared them with our data on amorphous and crystalline samples. Our quasicrystalline samples show some interesting features which are not reported for any other quasicrystalline systems. The value of the resistivity and its temperature dependence, the observation of a resistance minimum at fairly high temperatures and their variations with  $x$  have been discussed in the framework of the modified Ziman–Faber theory.

### 1. Introduction

The remarkable discovery of icosahedral symmetry in rapidly solidified Al–Mn alloys (Shechtman *et al* 1984) have generated an eagerness to look for other systems with such forbidden symmetries. Following this, an idea was mooted that, if an alloy with large number of icosahedra in the equilibrium crystalline structure (i.e. the Frank–Kasper phase) is rapidly solidified, a long-range icosahedral orientational order may result. This idea was verified by Ramachandra Rao and Sastry (1985) for  $\text{Mg}_{32}(\text{Al}, \text{Zn})_{49}$ , Zhang *et al* (1985) for  $\text{NiTi}_2$  and Dong *et al* (1986) for  $\text{FeTi}_2$ . Further, Chatterjee and O’Handley (1988) showed that the addition of Si to the Ti–Ni system helps one to obtain icosahedral crystallites of larger size but with a small amount of secondary phase. The addition of Fe at the Ni site in the Ti–Ni–Si system not only helped a single-phase icosahedral system to be obtained but also through detailed studies made it possible to derive a variety of information regarding icosahedral site symmetry for transition-metal atomic decoration and its relationship with amorphous and crystalline counterparts (Dunlap *et al* 1989, Bahadur *et al* 1989). On the basis of x-ray line intensity patterns, quasilattice constant and  $a/d$  ratio, it was inferred that the atomic decoration in this system is quite different from other icosahedral systems, for instance Al–Mn alloys. The fact that this system was single-phased related to Frank–Kasper phases and further it was possible to obtain its amorphous counterpart for which the electrical properties were thought to be of interest. Recently, Christie *et al* (1990) have reported the electrical resistivity data both for the amorphous and the quasicrystalline structures of  $\text{Ti}_{56}\text{Ni}_{28-x}\text{Fe}_x\text{Si}_{16}$ . The icosahedral compositions displayed a very complex and interesting behaviour, not reported for any other icosahedral systems so far. For instance, the observation of a resistivity minimum

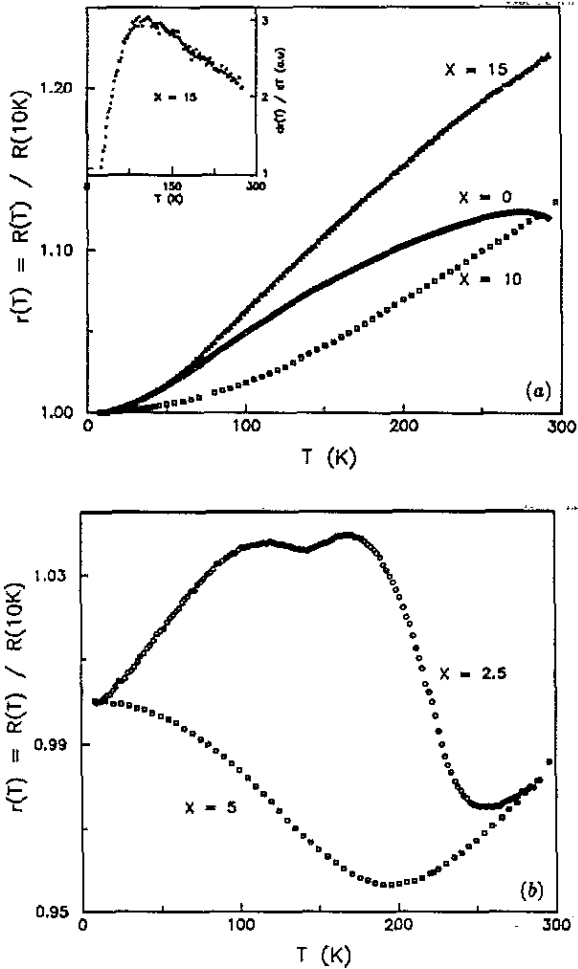


Figure 1. Plot of normalized electrical resistance versus temperature for quasicrystalline  $Ti_{56}Ni_{28-x}Fe_xSi_{16}$ : (a)  $x = 0, 10$  and  $15$ ; (b)  $x = 2.5$  and  $5$ . The inset in (a) shows the derivative of resistivity versus temperature for the composition with  $x = 15$ .

at fairly high temperatures, the shift in the minimum with composition, and a large positive temperature coefficient of resistivity (TCR) for samples with  $x = 10$  and  $15$  are rather unique. However, these have not been discussed at length and the data had much scatter. Now, we have carried out a high-resolution electrical resistivity measurement for icosahedral  $Ti_{56}Ni_{28-x}Fe_xSi_{16}$  ( $0 \leq x \leq 15$ ) alloys, tried to fit the data to various models and discussed possible origins of the resistivity minimum, its shift with  $x$  and the relationship with amorphous and crystalline phases. Electrical resistivity measurements for one amorphous and two crystalline compositions have also been carried out for comparison.

## 2. Experimental details

Quasicrystalline samples of  $Ti_{56}Ni_{28-x}Fe_xSi_{16}$  with  $x = 0, 2.5, 5, 10$  and  $15$  were prepared by melt spinning with a wheel surface speed of  $18 \text{ m s}^{-1}$  and amorphous samples were

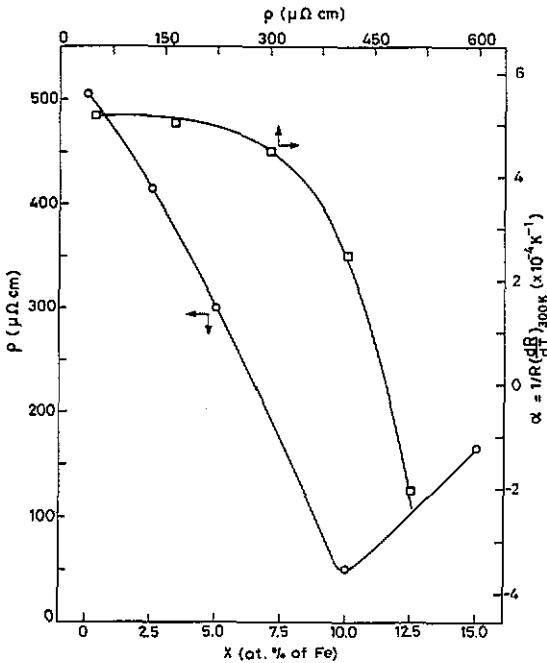


Figure 2. Plots of resistivity versus iron concentration,  $x$  and  $(1/R)(dR/dT)$  at room temperature versus resistivity for quasicrystalline  $\text{Ti}_{56}\text{Ni}_{28-x}\text{Fe}_x\text{Si}_{16}$  ( $x = 0, 2.5, 5, 10$  and  $15$ ).

produced with a speed of  $60\text{ m s}^{-1}$ . The crystalline compositions were arc melted. X-ray diffraction measurements were carried with a Rich Seifert Isodebyeflex 2002 diffractometer to reconfirm the single-phase icosahedral nature of the samples. Four-probe DC electrical resistivity measurements using  $10\text{ mA}$  current were carried out using a closed-cycle helium refrigerator (CTI and Cryosystems, USA). The temperature was controlled with a Lakeshore DRC-82C temperature controller to a stability of  $0.1\text{ K}$ . The resistance was measured with a Datron 1071 Autocal digital multimeter. The resolution in resistance was about 1 part in  $10^5$ . Low-thermal low-melting-point non-superconducting solder was used for the contacts. The subsequent x-ray pattern did not show any local crystallization.

### 3. Results and discussion

The plot of normalized electrical resistance ( $r = R(T)/R(10\text{ K})$ ) versus temperature for samples with  $0 \leq x \leq 15$  is shown in figure 1. The error bars (not shown) are much smaller than the size of the symbols. The inset in figure 1(a) shows the derivative of resistivity versus temperature for  $x = 15$ . The behaviour is very interesting and unlike the resistivity behaviour in other quasicrystalline systems reported so far (Kimura *et al* 1986, 1989, Anlage *et al* 1988). The general nature of the curves is essentially similar to what has been reported by Christie *et al* (1990) for the same system. However, the present high-resolution data have less scatter and therefore are expected to yield more information regarding the mechanism of conduction. Both the temperature and the composition dependence display some interesting and complex features. A broad res-

istivity minimum is observed at relatively higher temperatures and shifts to lower temperatures as the iron concentration increases. For instance, the minima for  $x = 0$ , 2.5 and 5 are found at around 330 K (not shown in figure 1(a)), 260 K and 200 K, respectively. For  $x = 10$  and 15, it could be below 8 K. For  $x = 7.5$ , Christie *et al* (1990) report a very broad minimum at around 150 K which is in line with the systematics that we observe. The nature of the minimum and the increase in resistance above and below  $T_{\min}$  are by and large similar. However, for  $x = 0$  and 2.5, the resistance has a maximum at lower temperatures. For  $x = 5$ , on the other hand, the resistance saturates at lower temperatures. An unusual feature of two closely spaced maxima at about 110 and 160 K for the sample with  $x = 2.5$  is not understood. However, these are not experimental artefacts and are confirmed by their reproducibility from sample to sample from the same batch. The percentage change in resistivity between maximum and minimum is large compared with amorphous materials. All the samples except for  $x = 10$  exhibit either a minimum and/or saturation behaviour at high temperatures. The derivative (figure 1(a)) peaks at a certain temperature  $T_0$  above which it decreases, indicative of a non-linear variation in resistivity with temperature.

Normally, most quasicrystals have been found to exhibit a small negative temperature coefficient of resistivity and a room-temperature resistivity value greater than  $150 \mu\Omega \text{ cm}$  as their most amorphous counterparts do. Different scattering mechanisms and conventional theories applicable to amorphous systems have been invoked to explain such behaviour, but a few systems such as icosahedral  $\text{Mg}_{32}(\text{Al}, \text{Zn})_{49}$  which is derived from the Frank–Kasper phase exhibit a small positive TCR (Wong *et al* 1987). The corresponding crystalline Frank–Kasper phase, however, shows a smaller resistivity and larger positive TCR. The resistivity values at room temperature of our samples are between 50 and  $500 \mu\Omega \text{ cm}$  for  $0 \leq x \leq 15$ . Owing to the highly irregular shape, wavy nature and possible microcracks, there could be a large error in the estimation of the geometrical factors and hence the absolute value of resistivity. The plots of resistivity versus Fe concentration  $x$  and versus  $(1/R)(dR/dT)$  at room temperature for different samples are shown in figure 2. The general trend, sign and values are in agreement with the thumb rule that the TCR approaches zero from the positive sign and crosses over to a negative sign as the value of resistivity increases. It is worthwhile pointing out here again that, for none of the quasicrystalline systems, is a resistance minimum reported. In fact, the observation of a resistance minimum at such high temperatures is rather uncommon even in amorphous systems (Howson and Gallagher 1988).

It is more or less established that the basic contribution to the resistivity is of structural origin. This has been exhaustively discussed in the framework of Ziman or modified Ziman–Faber theory (Cote and Meisel 1981, Howson and Gallagher 1988). According to this, the temperature dependence of the resistivity comes from the temperature dependence of the structure factor and the Debye–Waller factor. Within this diffraction model, there can be two competing mechanisms which can, in principle, give rise to a resistivity minimum. The temperature dependence of the resistance  $R$ , as is obvious from figure 1, cannot be explained by a single functional form. We have attempted here to fit the data over limited ranges of temperature to the conventional theories applicable for amorphous materials, for want of a comprehensive model suitable for this class of materials.

Samples with  $x = 0$ , 10 and 15 show a positive TCR in the range 8–300 K, and in the case of  $x = 2.5$  up to  $T \approx 100$  K. For these samples, between 8 and 50 K we have fitted the data to the relation

$$r(T) = R(T)/R(10 \text{ K}) = a + bT^2 \quad (1)$$

**Table 1.** Fits to the normalized resistance  $r$ : compositions, equations, ranges of fit, coefficients and the  $\chi^2$ -values for  $\text{Ti}_{56}\text{Ni}_{28-x}\text{Fe}_x\text{Si}_{16}$  quasicrystalline samples. The values of the coefficient  $a$  are not important and hence are not included in this table.

Fe concentration (at. %)	Equation for $r = R(T)/R(10 \text{ K})$	Range of temperatures (K)	Coefficients		$\chi^2$ <sup>a</sup> (10 <sup>-8</sup> )
			$b$ (K <sup>-2</sup> or K <sup>-1</sup> )	$c$ (K <sup>-2</sup> )	
$x = 0$	$a + bT^2$	8–40	$7.4 \times 10^{-6}$		0.9
	$a + bT - cT^2$	105–200	$8.7 \times 10^{-4}$	$1.1 \times 10^{-6}$	0.4
$x = 2.5$	$a + bT^2$	8–40	$8.0 \times 10^{-6}$		7.6
	$a + bT - cT^2$	50–90	$7.7 \times 10^{-4}$	$2.5 \times 10^{-6}$	3.7
$x = 5$	$a + bT - cT^2$	170–210	$5.4 \times 10^{-3}$	$1.6 \times 10^{-5}$	3.7
	$a - bT^2$	15–130	$1.7 \times 10^{-6}$		2.6
$x = 10$	$a + bT^2$	230–280	$6.7 \times 10^{-7}$		4.7
	$a + bT^2$	30–120	$1.8 \times 10^{-6}$		2.4
$x = 15$	$a + bT$	220–285	$6.1 \times 10^{-4}$		3.0
	$a + bT^2$	8–60	$7.5 \times 10^{-6}$		4.7
	$a + bT - cT^2$	150–300	$1.1 \times 10^{-3}$	$7 \times 10^{-7}$	6.8

$$^a \chi^2 \text{ is given by } \chi^2 = \frac{1}{N} \sum_{i=1}^N \frac{[Y_i(\text{fit}) - Y_i(\text{data})]^2}{[Y(\text{mean})]^2}.$$

as predicted by Cote and Meisel (1981) using the diffraction model. The  $T^2$ -dependence arises from the temperature dependence of the structure factor. The fit is reasonable and the values of  $\chi^2$  (of the order of  $10^{-8}$ ) are consistent with experimental accuracy (table 1). The coefficients  $b$  of  $T^2$  in the range 8–50 K have similar values within a factor of 2 (table 1), indicating their common origin.

In the high-temperature range the data with the exception of  $x = 10$  do not fit the expected relation

$$r = a + bT \quad (2)$$

as predicted by the above model. A typical plot of  $dR/dT$  versus  $T$ , as shown in figure 1, suggests that at higher temperatures the function is very different from that given by equation (2). In this region (the exact temperature range and coefficients are given in table 1) the data are fitted to an empirical relation of the form

$$r(T) = R(T)/R(10 \text{ K}) = a + bT - cT^2 \quad (3)$$

where the  $T$ -dependence arises from the electron-phonon interaction in the diffraction model. However, the origin of the  $-T^2$  term is not known.

In the case when  $x = 10$ , the data fit equation (2), unlike the rest of the samples in the series. From the coefficients one gets a reasonable value for the Debye temperature  $\Theta_D$  of 550 K.

The samples with  $x = 2.5$  and 5 show a resistance minimum at  $T \approx 200$  K and 260 K, respectively. We are unable to explain the origin of the double peak in the  $r(T)$  curves for  $x = 2.5$ . The sample with  $x = 5$  is free from such a complicated structure and thus is a suitable material for applying various models which predict a fall in resistance as the temperature increases. Between 15 K (at which the resistance shows a weak maximum) and 130 K the data fit well an expression of the form

$$r = a - bT^2. \quad (4)$$

This type of expression, as has been explained by Mizutani (1988) for non-magnetic

metallic glasses, arises from the temperature dependence of the Debye–Waller factor. This result is different from the behaviour predicted by the models (Mizutani 1988, Howson and Gallagher 1988) based on the localization and interaction effects, the Kondo effect and the two-level systems generally invoked to explain the resistance minimum. These models predict that  $-T$  or  $-\ln T$ , i.e.  $r$ , varies more slowly than  $T$  whereas here it varies more rapidly than  $T$ . Magnetic fields up to 16 kG at room temperature and the lowest temperature did not change the resistance by more than 1 part in  $10^4$ . It is interesting to note that, although a  $-T^2$ -dependence of  $r$  is obvious in the case of samples with a negative TCR, here we observe it in samples with a positive TCR as well. The coefficients are similar in both cases (table 1).

Of all the other possibilities of the origin of the resistance minimum at high temperatures, an obvious one could be due to the presence of more than one phase in the system. In principle, this is quite likely as most quasicrystals do have a small amount of secondary phase. In most cases, it is detected by x-ray diffraction. For the present samples, however, x-ray diffraction data do not show any evidence of a secondary crystalline phase. The possibility of a small amorphous component has been ruled out on the basis of recent Mössbauer studies, which is known to be much more sensitive than x-ray diffraction (Bahadur *et al* 1989).

Before we discuss some other possible mechanisms, it is pertinent to point out again that the value of the resistivity (figure 2) and the temperature of the resistivity minimum have a definite trend as a function of iron substitution at the Ni site. The trend indicates a delicate interplay between two competing mechanisms which vary as a function of iron and nickel concentrations. Now the question is what these two competing mechanisms are and how strongly they are influenced by replacing nickel with iron.

The present system is rich in 3d-electron elements. Further, magnetic susceptibility measurements show anomalous behaviour deviating strongly from the usual Curie–Weiss law, particularly for samples with  $x \leq 10$  (Christie *et al* 1990). Such deviations from Curie–Weiss behaviour are generally interpreted on the basis of spin fluctuations. Also, evidence of spin fluctuation is rather common when an early transition metal such as Zr or Nb is alloyed with late transition metals such as Fe or Ni in such a ratio that the system becomes nearly magnetic, i.e. in the phase diagram it exists somewhere close to the paramagnetic-to-ferromagnetic transition region (Strom-Olsen *et al* 1985). The level of spin fluctuations can be varied by changing the alloy composition without major changes in the structure. Further, the concept of spin fluctuations has been commonly invoked to explain minima in resistivity at fairly high temperatures (Hasegawa 1972, Sas *et al* 1988). The present system is also somewhat similar and it could, in principle, be expected to exhibit spin-fluctuation effects as one of the competitive mechanisms responsible for the resistivity minimum.

Also, there is an indication of domination of spin fluctuation in the resistivity plot, particularly for the sample with  $x = 15$  when, at low temperatures (below 60 K), only the  $T^2$ -term persists. However, as the temperature increases above 60 K, the exponent of  $T$  changes gradually, showing a tendency of  $r(T)$  to saturate. This behaviour is typical of systems with local spin-density fluctuations (Kolodziejczyk and Spalek 1984, Yomo 1983). The amplitude of local spin-density fluctuations increases with increasing temperature. Therefore, the magnetic scattering due to the spin fluctuation increases with increasing temperature, but the amplitude of the local spin fluctuations saturates at higher temperatures. Hence, resistivity due to this factor tends to saturate. Therefore, it is likely that the spin fluctuations contribute to the conduction mechanism in the present system. However, for further analysis, knowledge about the density of states at the Fermi level is quite important but is lacking at present.

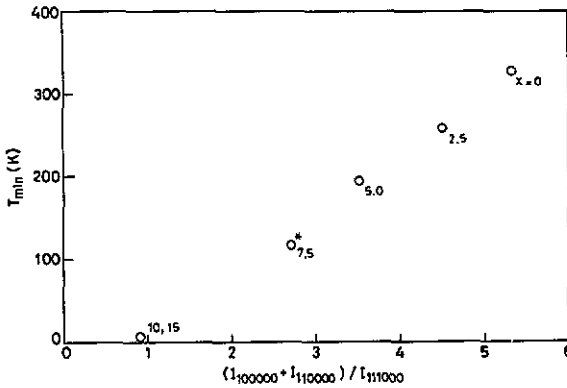


Figure 3. Plot of  $T_{\min}$  versus x-ray line intensity ratio  $I_{(100000)} + I_{(110000)} / I_{(111000)}$ ;  $\star$ , taken from the data of Christie *et al* (1990).

In the absence of this, let us assume that both the competing mechanisms arise from changes in structure-related properties which are influenced markedly by the composition as well as the temperature. It would now be instructive to obtain some insight into structure-related aspects. The x-ray diffraction patterns of these samples with  $0 \leq x \leq 15$  have already been published (Bahadur *et al* 1989) and we have just repeated these measurements to ensure the quality of our samples. X-ray and Mössbauer studies (Bahadur *et al* 1989, Dunlap *et al* 1989) have indicated that the structure of these icosahedral systems is quite different from other systems such as Al-Mn-Si or Al-Mg-Zn. In fact, the most significant difference which is quite pertinent to the present results is the variation in x-ray line intensity patterns as a function of  $x$ . For example, the intensity of the (100000) line decreases significantly compared with the (110000) line when  $x$  is changed from 0 to 2.5. Furthermore, the intensity of the line with the indices (111000) increases rather markedly for  $x > 5$  and this line becomes the most intense line for  $x = 10$  and 15. For no other icosahedral system, have such changes in intensities been reported as a function of composition. In that context, this is a unique behaviour related to the structure factor and could also help to explain the resistivity minimum. To illustrate this, we give the variation in  $T_{\min}$  as a function of  $[I(100000) + I(110000)] / I(111000)$  in figure 3. As mentioned, the intensities of both the lines in the numerator decrease whereas the intensity of the line in the denominator increases for larger  $x$ . There is almost a linear dependence, suggesting a correlation between the structure factor  $S(K)$  and the temperature of the resistivity minimum which in turn varies as a function of  $x$ .

The diffraction theory suggests that the resistivity and its temperature dependence are extremely sensitive to the relative position  $K_p$  of the first peak in the  $S(K)$  curve with respect to  $2K_F$ , where  $K_F$  is the wavevector at the Fermi level (Chen 1980, Cahn 1980). The relative position of  $2K_F$  with respect to  $K_p$  can be varied significantly by varying the composition and/or temperature. The position of  $2K_F$  can be substantially influenced by varying the composition, whereas  $K_p$  is dependent on temperature. The delicate interplay between these two terms determines the sign and the magnitude of the TCR. The shift of  $K_p$ , with respect to  $2K_F$ , as a function of temperature would perhaps be responsible for the resistivity minimum. Further, the shift in the minimum as a function of  $x$  could be ascribed to the movement of  $2K_F$ .



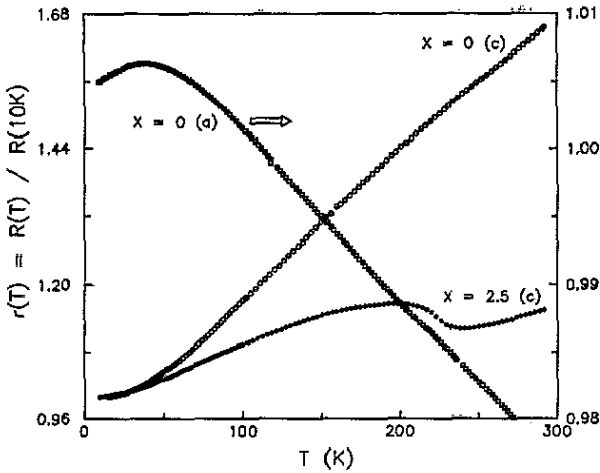


Figure 4. Plot of normalized electrical resistance versus temperature for amorphous (a)  $\text{Ti}_2\text{Ni}$  ( $x = 0$ ) and crystalline (c)  $\text{Ti}_{56}\text{Ni}_{28-x}\text{Fe}_x\text{Si}_{16}$  ( $x = 0$  and 2.5).

It is noteworthy that amorphous alloys of the same composition have been found to exhibit only a negative TCR throughout the temperature range which is almost independent of  $x$  unlike the results for their quasicrystalline counterparts (Christie *et al* 1990). This behaviour is typical of a group IV metallic glass as classified by Mizutani (1988). Structural effects appear predominant and the substitution of Fe for Ni has obviously little effect on the dominant electron scattering mechanism. This could in part be due to the nature of hybridization which is very different in the amorphous state where states can mix freely. Figure 4 shows the plot of normalized resistance of amorphous  $\text{Ti}_2\text{Ni}$  and crystalline  $\text{Ti}_{56}\text{Ni}_{28-x}\text{Fe}_x\text{Si}_{16}$  ( $x = 0$  and 2.5) versus temperature. Amorphous  $\text{Ti}_2\text{Ni}$  behaves like a group V glass as described by Mizutani (1988). This has a small maximum at  $T \approx 40$  K immediately above which it behaves as  $-T^2$  and at higher temperatures as  $-T$ .

It is rather surprising to observe a resistivity minimum in crystalline composition too with  $x = 2.5$ .  $T_{\min}$  is essentially the same as observed for the corresponding quasicrystalline sample. In fact, there is also a very close similarity between the x-ray diffraction of crystalline and quasicrystalline samples, implying a close relationship between these two phases. A similar observation has been made by Dong *et al* (1986) for  $\text{FeTi}_2$  and Zhang *et al* (1985) for  $\text{Ti}_7\text{Ni}$ . All these alloys are known to have a large proportion of icosahedra in the equilibrium structure (Kuo *et al* 1987). In view of these observations, it is perhaps not surprising to have observed similar resistivity behaviour for crystalline and quasicrystalline samples. The resistivity value for a crystalline sample, however, is smaller by a factor of 3 than that of the corresponding quasicrystalline sample, as would be expected for a more ordered structure. In fact, the resistivity behaviour of icosahedral  $\text{Mg}_{32}(\text{Al}, \text{Zn})_{49}$  and its corresponding crystalline composition (which is a Frank-Kasper phase and possesses a high degree of local icosahedral packing) have some characteristics in common (Wong *et al* 1987). For instance both have positive TCRs. The crystalline phase has a smaller resistivity than the quasicrystalline phase. Hence, it is possible that icosahedral phases derived from Frank-Kasper phases would behave in a similar fashion. By virtue of the close relationship between the icosahedral

and the corresponding crystalline phases, it is not surprising to see the similarity in their resistivity behaviour.

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### References

- Anlage S M, Johnson W L, Cotts E T, Follstaedt D M and Knapp J A 1988 *Phys. Rev. B* **38** 7802  
Bahadur D, Srinivas V, Dunlap R A, O'Handley R C and McHenry M E 1989 *Phil. Mag.* **B 60** 871  
Cahn R W 1980 *Contemp. Phys.* **21** 43  
Chatterjee R and O'Handley R C 1988 *Phys. Rev. B* **39** 8128  
Chen H S 1980 *Rep. Prog. Phys.* **43** 353  
Christie I A, Dunlap R A and McHenry M E 1990 *J. Appl. Phys.* **67** 5585  
Cote P J and Meisel L V 1981 *Glassy Metals 1 Springer Topics in Applied Physics* vol 46, ed H J Guntherodt and H Beck (Berlin: Springer) p 141  
Dong C, Hei Z K, Wang L B, Song Q H, Wu Y K and Kuo K H 1986 *Scr. Metall.* **20** 1155  
Dunlap R A, McHenry M E, O'Handley R C, Srinivas V and Bahadur D 1989 *Phys. Rev. B* **39** 1942  
Hasegawa R 1972 *Phys. Lett.* **38A** 5  
Howson M A and Gallagher B L 1988 *Phys. Rep.* **170** 265  
Kimura K, Hashimoto J and Takeuchi S 1986 *J. Phys. Soc. Japan* **55** 1810  
Kimura K, Iwashashi H J, Hashimoto T, Takeuchi S, Mizutani U, Ohashi S and Itoh G 1989 *J. Phys. Soc. Japan* **58** 2472  
Kolodziejczyk A and Spalek J 1984 *J. Phys. F: Met. Phys.* **14** 1277  
Kuo K H, Zhou D S and Li D X 1987 *Phil. Mag. Lett.* **55** 33  
Mizutani U 1988 *Mater. Sci. Eng.* **99** 165  
Ramachandra Rao P and Sastry G V S 1985 *Pramana* **25** L225  
Sas B, Kemeny T, Toth J and Williams F I B 1988 *Mater. Sci. Eng.* **99** 223  
Sectman D, Blech I, Gratias D, Cahn R W 1984 *Phys. Rev. Lett.* **54** 1951  
Strom-Olsen J O, Altounian Z, Cochrane R W and Kaiser A B 1985 *Phys. Rev. B* **31** 6116  
Wong K M, Lopdrup E, Wagner J L, Sheu Y, Poon S J 1987 *Phys. Rev. B* **35** 2494  
Yomo S 1983 *J. Magn. Magn. Mater.* **31-4** 331  
Zhang Z, Ye H Q and Kuo K H 1985 *Phil. Mag.* **A 52** L49