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The temperature dependence of the conductivity in the critical regime of the metal–insulator transition in conducting polymers

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Abstract. The metal–insulator (M–I) transition in conducting polymers is particularly interesting; critical behaviour has been observed over a relatively wide temperature range in a number of systems, including polyacetylene (CH)_x, polypyrrole (PPy), poly(*p*-phenylenevinylene) (PPV), and polyaniline (PANI). In each case, the metallic, critical, and insulating regimes near the M–I transition have been identified from plots of $W = (\Delta \ln \sigma / \Delta \ln T)$ versus T : in the metallic and insulating regimes $W(T)$ exhibits positive and negative temperature coefficients, respectively, while in the critical regime $W(T)$ is temperature independent. Thus, in the critical regime, the conductivity follows a power law, $\sigma(T) = AT^\beta$, where β is the critical exponent which is predicted by scaling theory to be between one-third and unity. In conducting polymers, the critical regime is easily tunable by varying the extent of disorder, or by applying external pressure and/or magnetic fields. The transitions from metallic to critical behaviour and from critical to insulating behaviour have been induced with a magnetic field, and that from insulating to critical and then to metallic behaviour with increasing external pressure. The detailed evolution of $\sigma(T)$ in the critical regime at low temperatures can be observed in $W(T)$ plots as the system is changed from metal to insulator. Although $W(T)$ is temperature independent for a wide range of temperatures below 50 K, β systematically increases from values less than one-third on the metallic side towards unity as the system is moved toward the insulating side.

1. Introduction

According to scaling theory (Abrahams *et al* 1979), the localization length (L) and the dc conductivity (σ) at the critical point of the disorder-induced metal–insulator (M–I) transition (the Anderson transition) should diverge as power laws (Kramer and MacKinnon 1993),

$$L \propto (E - E_c)^\nu \quad \sigma \propto (E - E_c)^s \quad (1)$$

where E is the energy variable which describes the electronic structure within the partially filled electronic energy band, E_c is the energy of the mobility edge (Mott 1990), $\nu = s$, and the numerical and experimental values of critical exponents range from 0.5 to 2 (Thomas and Paalanen 1985, Kramer *et al* 1990). The critical exponent μ characterizes the transition to zero-temperature conductivity, $\sigma = \sigma_0[(n/n_c) - 1]^\mu$, and is assumed to be the same as the critical exponent for the correlation length. McMillan (1981), and later Larkin and Khmel'nitskii (1982), showed that a power law temperature dependence is to be expected for the conductivity near the critical regime of Anderson localization,

$$\sigma(T) = AT^\beta \quad 0.33 < \beta < 1. \quad (2)$$

Although power-law behaviour has been observed (Zabrodskii and Zinovjeva 1984), the exact nature of this critical behaviour near the M–I transition is not very well understood. We assume that because the M–I transition is quite sensitive to the doping level and to the extent of the disorder, etc, it is difficult to find real systems that are precisely in the critical regime. Thus, the exact trajectory of the evolution of the transition from metal to insulator remains a topic of considerable discussion.

There are a number of unresolved issues. Is the power law expected only at the critical point or is there a range within the critical regime where the power law is observed over a limited temperature interval? In the latter case, is there a systematic behaviour for β as the system evolves from metal to insulator (e.g. as a function of the strength of the disorder)? If there is a range of β -values within the critical regime, extension of the power law dependence to $T = 0$ requires that the system be *precisely* at the critical point; otherwise, at sufficiently low temperatures, the conductivity will either become constant (a metal) or the conductivity will go to zero (an insulator). Is there a specific β at the critical point, or do the fluctuations in the randomness of the disorder potential, fluctuations in the wave function of electronic states near the mobility edge, correlation effects, quantum interference effects, etc give rise to a distribution of β -values? We have addressed some of these questions through experimental studies of $\sigma(T)$ in the critical regime for a series of conducting polymers.

A significant power-law dependence of $\sigma(T)$ near the critical regime has not been observed over a wide range of temperatures in inorganic systems. In some systems, a transition from $\sigma(T) = a + bT^{1/3}$ to $\sigma(T) = bT^{1/3}$ has been discussed as the system approaches the critical regime from the metallic side (Maliepaard *et al* 1986, Newson and Pepper 1986, Biskupskii *et al* 1991). Moreover, a magnetic-field-induced transition from the metal to insulator, sometimes called ‘magnetic freeze-out’, has been reported by several groups (Maliepaard *et al* 1986, Biskupskii *et al* 1991). This effect has been attributed to the field-induced change of the Bohr radii of the dopants; the extrapolated zero-temperature conductivity (σ_0) was found to increase linearly with the field. For magnetic freeze-out near the M–I transition, $\sigma(T) = a(H) + bT^{1/3}$, where $a(H) \rightarrow 0$ as $H \rightarrow 0$; and variable-range hopping (VRH) conduction occurs at very high fields.

The power law dependence for $\sigma(T)$ has been observed over a wide temperature range in a number of conducting polymers near the M–I transition (Reghu *et al* 1993, 1994a, b, 1997). Moreover, in conducting polymers, the transport properties can be tuned across the M–I transition, from insulator to metal with pressure and from metal to insulator with magnetic field. Realizing, therefore, that conducting polymers offer a special opportunity for studying the M–I transition in detail, we have re-analysed the $\sigma(T)$ data available in the literature, including data obtained by a number of research groups from polyacetylene, $(\text{CH})_x$, polypyrrole (PPy), polyaniline (PANI) and poly(*p*-phenylenevinylene) (PPV) near the critical regime of the M–I transition. We find that log–log plots of $W(T) = (\Delta \ln \sigma / \Delta \ln T)$ versus T are quite sensitive and enable the precise identification of the critical regime. Moreover, the detailed evolution of $\sigma(T)$ in the critical regime at low temperatures can be observed in $W(T)$ plots as the system is changed from metal to insulator (by changing the extent of the disorder or by tuning with pressure or magnetic field). We find that although $W(T)$ is temperature independent for a wide range of temperatures below 50 K, β systematically increases from values less than one-third on the metallic side towards unity as the system is moved toward the insulating side.

In general, conducting polymers are complex systems, since chain conformation, chain extension, and chain orientation, as well as sample morphology and microstructure, affect the physical and electronic properties (Heeger and Smith 1991). The extent of disorder,

including disorder in the dopant distribution (Kivelson and Heeger 1989), is of obvious importance in determining the electrical properties. The magnitude of the interchain transfer integral is of particular importance, since conducting polymers are quasi-one-dimensional in nature (Heeger *et al* 1988). Disorder is an inherent feature of polymers; structurally, these materials range from partially crystalline to amorphous. Nevertheless, the existence of a large electrical conductivity as $T \rightarrow 0$ K implies metallic behaviour; the disorder-induced localization typical of one-dimensional (1D) systems can be avoided in high-quality materials (Reghu *et al* 1997).

The resistivity, $\rho(T)$, and the resistivity ratio, $\rho_r = \rho(1.4 \text{ K})/\rho(300 \text{ K})$, have been successfully used to quantify the relative disorder in different samples and for sorting out the various regimes (Reghu *et al* 1993, 1994a, b, 1997). In general, as the disorder increases, the materials become more insulating, and the conductivity decreases more rapidly upon lowering the temperature; i.e. ρ_r increases.

In highly oriented, doped $(\text{CH})_x$ (Kaneko and Ishiguro 1994, Reghu *et al* 1994a) and PPV (Ahlskog *et al* 1996), the conductivity parallel to the chain direction is comparable to that in conventional metals, $\sigma_{\parallel} \sim 10^4\text{--}10^5 \text{ S cm}^{-1}$. In such oriented samples, the anisotropy in the conductivity ($\sigma_{\parallel}/\sigma_{\perp}$), is also large, $\sigma_{\parallel}/\sigma_{\perp} \sim 100$ or even greater (Cao *et al* 1991). Thus, although the transport and magnetotransport data imply that conducting polymers are 3D (rather than 1D) conductors (Reghu *et al* 1993, 1994a, b, 1997), conducting polymers are highly anisotropic materials. This large intrinsic anisotropy implies that intrachain transport dominates even in isotropic (non-oriented) samples. From a theoretical perspective, it is not clear how the intrinsic anisotropy affects the details of the M–I transition. For example, one might anticipate that the quasi-one-dimensionality would extend the range of temperature and/or disorder potentials over which critical phenomena are observed.

2. $W(T)$ plots near the M–I transition

To explicitly describe the characteristic behaviour of $\rho(T)$ or $\sigma(T)$, we define the reduced activation energy, W , as the logarithmic derivative of $\rho(T)$ (Zabrodskii and Zinovjeva 1984),

$$W = -T \{d \ln \rho(T)/dT\} = -d(\ln \rho)/d(\ln T) d(\ln \sigma)/d(\ln T). \quad (3)$$

The temperature dependences of W in various regimes near the M–I transition are as follows:

- (i) In the metallic regime, W has a positive temperature coefficient.
- (ii) In the critical regime, W is temperature independent for a wide range of temperatures.
- (iii) In the insulating regime, W has a negative temperature coefficient.

In the metallic regime, the zero-temperature conductivity remains finite, and $\sigma(T)$ can be expressed as follows:

$$\sigma(T) = \sigma_0 + f(T) \quad (4)$$

where $f(T)$ is mainly determined by the interaction and localization contributions to the conductivity (Reghu *et al* 1994a, b, 1997, Ahlskog *et al* 1996).

For a 3D system in the critical regime of the M–I transition, the correlation length diverges with critical exponent ν , $L_c = a\delta^{-1/\nu}$ where a is a microscopic length, $\delta = |E_F - E_c/E_F| < 1$, E_F is the Fermi energy, and E_c is the mobility edge (Mott 1990). In this critical region, the resistivity follows a power law (Larkin and Khmel'nitskii 1982):

$$\rho(T) \approx (e^2 p_F / \hbar^2) (k_B T / E_F)^{-1/\eta} = aT^{-\beta} \quad (5)$$

where p_F is the Fermi momentum and e is the electron charge. The range of validity of equation (5) includes $1 < \eta < 3$ ($1/3 < \beta < 1$). The power law is universal and requires only that the disordered system be in the critical regime. A value of $\beta \leq 1/3$ indicates that the system is just on the metallic side of the M–I transition. As noted above, however, extension of the power law dependence to $T = 0$ requires that the system be *precisely* at the critical point.

In the insulating regime, when the resistivity follows the typical VRH, $\ln \rho \propto (T_0/T)^x$, the reduced activation energy becomes

$$\log_{10} W(T) = A - x \log_{10} T \quad (6)$$

where $A = x \log_{10} T_0 + \log_{10} x$. Using (6), one can determine x from the slope in the plot of $\log_{10} W$ against $\log_{10} T$. Equations (3)–(6) are used in the data analysis discussed in section 3.

3. Results and discussion

The first task is to demonstrate the existence of the critical regime for a given polymer system and then to extract the experimental values of the critical exponent from the data. To accomplish this, we have built a data base consisting of the results from our previous experimental studies (Reghu *et al* 1993, 1994a, b, 1997) supplemented by data from the literature (Kaneko *et al* 1993, Kaneko and Ishiguro 1994, Madsen *et al* 1989). The latter were scanned, digitized, and then analysed to make the W versus T plots. Additional power law data indicative of the critical regime near the M–I transition were also recently reported for PANI–CSA (Holland *et al* 1996, Kohlman *et al* 1996). Although not included here, these critical regime data are in close agreement with those obtained earlier for polyaniline (Reghu *et al* 1993).

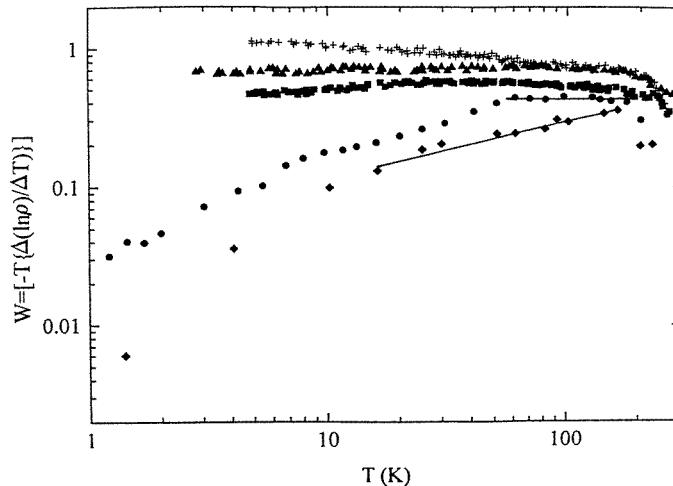


Figure 1. A log–log plot of W against T for $I-(CH)_x$: at ambient pressure and $H = 0$, $\rho_r \approx 3$ and $\sigma_{RT} \approx 11\,000 \text{ S cm}^{-1}$ (●); at 8 kbar and $H = 0$, $\rho_r \approx 2$ and $\sigma_{RT} \approx 9500 \text{ S cm}^{-1}$ (◆); at ambient pressure and $H = 0$, $\rho_r \approx 9$ and $\sigma_{RT} \parallel 7000 \text{ S cm}^{-1}$ (■); at ambient pressure and $H = 0$, $\rho_r \approx 17$ and $\sigma_{RT} \approx 3500 \text{ S cm}^{-1}$ (▲); and at ambient pressure and $H = 0$, $\rho_r \approx 32$ and $\sigma_{RT} \approx 2450 \text{ S cm}^{-1}$ (+). The lines are drawn to guide the eye.

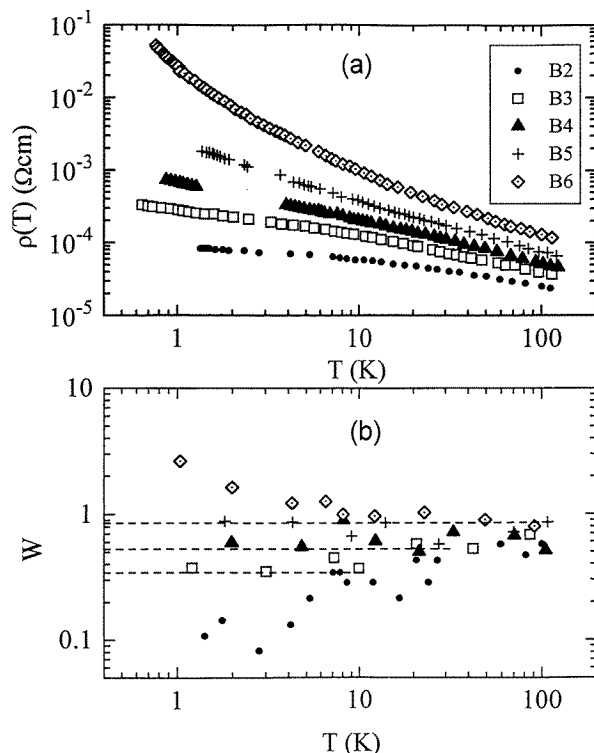


Figure 2. (a) Resistivity against T for $\text{I}-(\text{CH})_x$ from Kaneko *et al* (1993); (b) a log-log plot of W against T for the same data. The dotted lines indicate the power law regime.

The data from doped polyacetylene $(\text{CH})_x$ samples are shown in figures 1–3 (see Reghu *et al* 1994a, b). The W - T plots for oriented $\text{I}-(\text{CH})_x$ with $\sigma_{\parallel}/\sigma_{\perp} \approx 100$, at various doping levels, are shown in figure 1 (Reghu *et al* 1994a, b). The room-temperature conductivities, $\sigma(300\text{ K})$, and ρ_r values are given in the figure captions and in table 1. A fully doped sample at ambient pressure is just on the metallic side of the M-I transition, as indicated by the positive temperature coefficient of $W(T)$ at temperatures below 40 K. Under pressure, at 8 kbar, the system becomes more metallic; the positive slope of $W(T)$ against T is larger than that at ambient pressure, obviously the result of enhanced interchain transport. At slightly lower doping levels, the system moves toward the critical regime as evidenced by the fact that the temperature independent regime for $W(T)$ extends to lower temperatures.

The anisotropy is an important feature. Consider, for example, the sample with $\sigma_{\parallel}(RT) \approx 2450\text{ S cm}^{-1}$; although $\sigma_{\parallel}(RT)$ exceeds the Mott minimum metallic conductivity, the negative temperature coefficient of $W(T)$ at low temperatures implies that this sample is on the insulating side of the M-I transition. This indicates that charge transport perpendicular to chain axis is not adequate to make the system metallic.

The $\rho(T)$ - T and W - T plots for $\text{I}-(\text{CH})_x$ from the measurements carried out by Kaneko *et al* (1993) are shown in figure 2(a) and (b) respectively. The W - T plot is consistent with that in figure 1, again showing that high-quality fully doped $\text{I}-(\text{CH})_x$ is just on the metallic side of the M-I transition. Upon dedoping or ageing, the system moves through the critical regime to the insulating side. The $\rho(T)$ - T and W - T plots for $\text{FeCl}_3-(\text{CH})_x$ are shown in figure 3(a) and (b) respectively (Kaneko and Ishiguro 1994). The behaviour is consistent with that observed in figures 1 and 2.

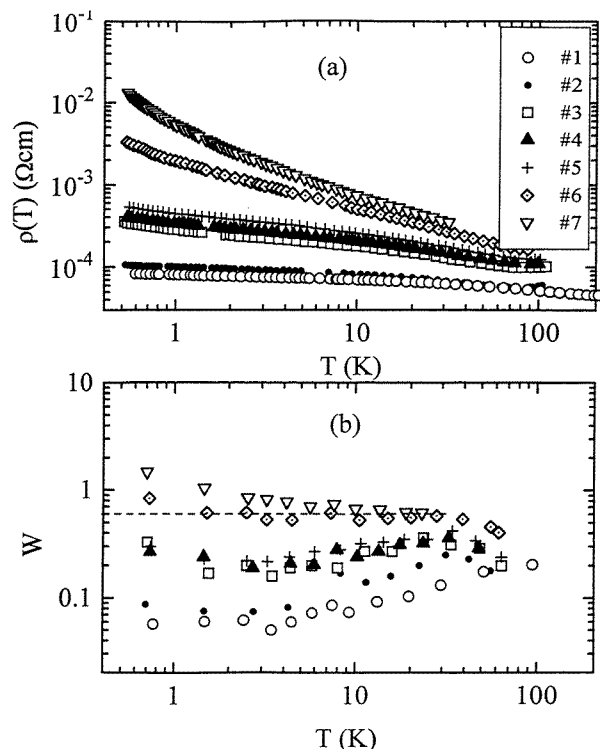


Figure 3. (a) Resistivity against T for $\text{FeCl}_3\text{-(CH)}_x$ samples from Kaneko and Ishiguro (1994); (b) a log-log plot of W against T for the same data. The dotted line indicates the power law regime.

Table 1. The $\sigma(300\text{ K})$ and $\rho_r \approx [\rho(1.3\text{ K})/\rho(300\text{ K})]$ values for various conducting polymer samples in the metallic (M), critical (C) and insulating (I) regimes.

| | M | | C | | I | |
|---------------------------------------|----------|------------------------------|----------|---------------------------|----------|------------------------|
| | ρ_r | $\sigma(300\text{ K})^{(a)}$ | ρ_r | $\sigma(300\text{ K})$ | ρ_r | $\sigma(300\text{ K})$ |
| $(\text{CH})_x\text{-I}_2$ | < 10 | > 5000 | 10–20 | $3\text{--}5 \times 10^4$ | > 20 | < 3000 |
| $(\text{CH})_x\text{-I}_2^{(c)}$ | < 5 | $> 5 \times 10^4$ | 9.8–165 | $2\text{--}5 \times 10^4$ | > 400 | $< 2 \times 10^4$ |
| $(\text{CH})_x\text{-FeCl}_3^{(d)}$ | < 2 | $> 2 \times 10^4$ | 2.6–11.4 | $1\text{--}2 \times 10^4$ | > 27 | $< 10^4$ |
| PPV-AsF ₅ ^(b,e) | < 5 | 300–2400 | 9.7–34 | 100–300 | > 50 | < 100 |
| PPV-H ₂ SO ₄ | < 2 | $4 \times 10^3\text{--}10^4$ | 4.7–27 | 1000–4000 | > 60 | < 1000 |
| PPy | < 2 | 300–400 | 2–10 | 200–300 | > 10 | < 200 |
| PANI | < 2 | 250–350 | 2–5 | 200–250 | > 10 | < 200 |

(a) Conductivity is given in S/cm.

(b) The data comes from samples with different degree of orientation and therefore does not give an entirely consistent picture of the M–I transition in this system.

(c) Kaneko *et al* (1993).

(d) Kaneko and Ishiguro (1994).

(e) Madsen *et al* (1989).

In figures 1–3, β shifts to larger values as the system moves from the metallic to the insulating regime. The negative temperature coefficient of $W(T)$ appears only when $\beta \approx 1$.

The β -values in the critical regime for various samples are shown in table 2. To our knowledge, there is no theoretical understanding of the evolution of β within the critical regime nor is there an understanding of the onset of a negative temperature coefficient of $W(T)$ when $\beta \approx 1$.

Table 2. The β -values for various conducting polymer samples ($\sigma(T) = AT^\beta$) in the critical regime of the M-I transition. The labelling in each case is taken from the original work.

| (CH) x -I ₂ | (CH) x -I ₂ | (CH) x -FeCl ₂ | PPV-AsF ₅ | PPV-H ₂ SO ₄ | PPy | PANI |
|--------------------------|--------------------------|-----------------------------|----------------------|------------------------------------|--------|--------|
| ■ 0.5 | B3: 0.33 | #2: 0.1 | 2A: 0.8 | F: 0.34 | ● 0.55 | ● 0.28 |
| ▲ 0.7 | B4: 0.52 | #3: 0.2...0.4 | 3: 0.5 | G: 0.78 | | |
| | B5: 0.82 | #4: 0.2...0.4 | | | | |
| | | #5: 0.2...0.4 | | | | |
| | | #6: 0.6 | | | | |

The data from doped PPV samples are shown in figures 4–6. The $\sigma(T)$ - T and W - T plots are shown in figure 4(a) and (b) respectively for oriented AsF₅-doped PPV samples ($\sigma_{\parallel}/\sigma_{\perp} \approx 100$) (Madsen *et al* 1989); the various curves were obtained by taking advantage of the reversible doping (the samples were successively dedoped between measurements). The $\sigma(300\text{ K})$ and ρ_r values for the PPV-AsF₅ samples are listed in table 1. Fully doped samples show finite conductivity as $T \rightarrow 0\text{ K}$, while dedoping takes the sample through the M-I transition. For sulphuric-acid- (H₂SO₄) doped PPV, the trend is similar, as shown in figure 5. In both cases, β continuously increases as the system moves from the metallic side of the critical regime towards the insulating side; at $\beta \approx 1$, the slope of $W(T)$ becomes

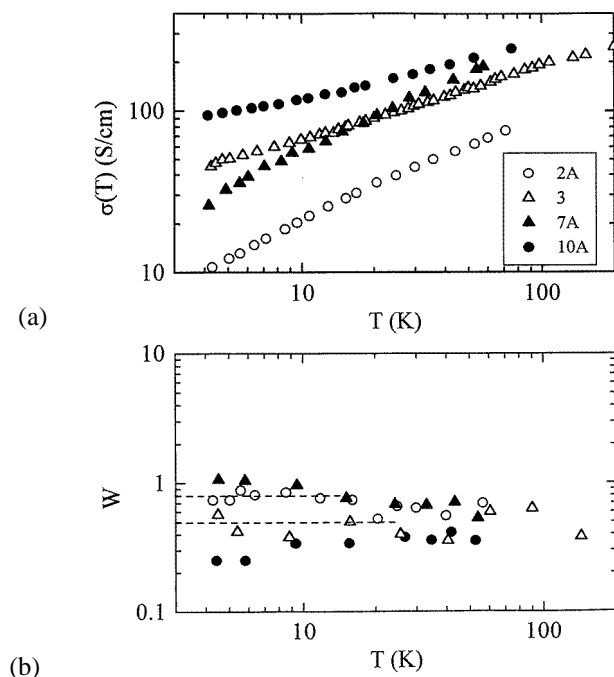


Figure 4. (a) Conductivity against T for PPV-AsF₅ samples from Madsen *et al* (1989); (b) a log-log plot of W against T for same data. The dotted lines indicate the power law regime.

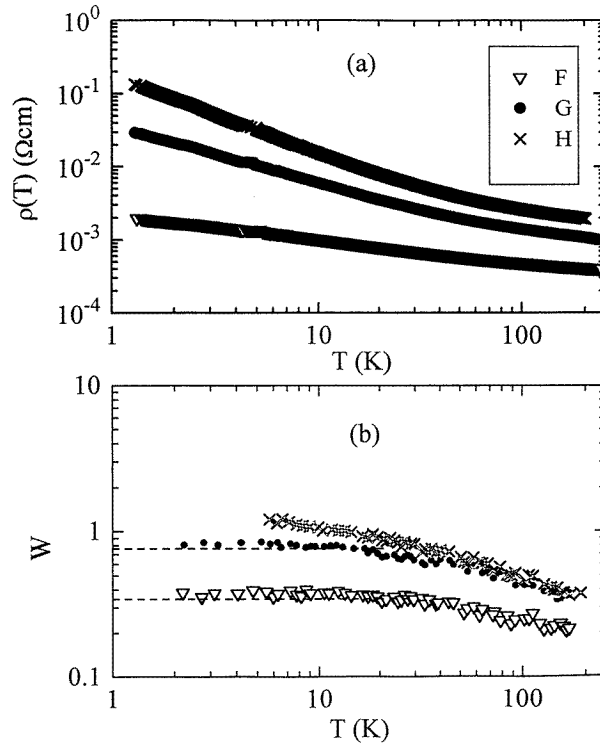


Figure 5. (a) Resistivity against T for PPV-H₂SO₄ samples; (b) a log-log plot of W against T for the same data. The dotted lines indicate the power law regime.

negative, as observed for doped (CH)_x.

Field-induced crossover from the metallic regime into the critical regime provides an alternative route to obtaining values for the power law exponent. The field-induced crossover has been observed in PPV-H₂SO₄ ($\rho_r = 1.87$) as shown in figure 6 (Ahlskog *et al* 1996a, b). At $H = 0$, the conductivity extrapolates to a finite value (~ 2100 S cm⁻¹) as $T \rightarrow 0$ K, whereas at high fields $\sigma(T \rightarrow 0)$ extrapolates to zero. At $H = 8$ T, a power law is observed with $\beta \approx 0.1$. This β -value was obtained right at the boundary of the critical regime (the smallest magnetic field for which $\sigma(T \rightarrow 0)$ extrapolates to zero); $\beta \approx 0.1$ is the smallest we have found. Although below the minimum value defined by scaling theory, $\beta = \frac{1}{3}$ (Larkin and Khmel'nitskii 1982), this small value for β seems to define the metallic-side boundary of the critical regime.

The W - T plot for PPy-PF₆ near the critical regime is shown in figure 7 (Reghu *et al* 1994, Yoon *et al* 1994). The values obtained for σ_{RT} and ρ_r are shown in table 1; the ρ_r -values are 11, 2.6, and 2 at ambient pressure and 4 and 10 kbar, respectively. In zero field and at ambient pressure, $W(T)$ is constant with $\beta \approx \frac{1}{3}$. Application of a magnetic field leads to a negative slope; application of pressure leads to a positive slope. Thus, in zero field and at ambient pressure, the sample is in the critical regime. The positive temperature coefficient of $W(T)$ at 4 kbar indicates a crossover from the critical regime to marginally metallic.

The plot of W against T for PANI-CSA in the critical regime is shown in figure 8 (Reghu *et al* 1994). The corresponding $\sigma(300$ K)- and ρ_r -values are listed in table 1. The

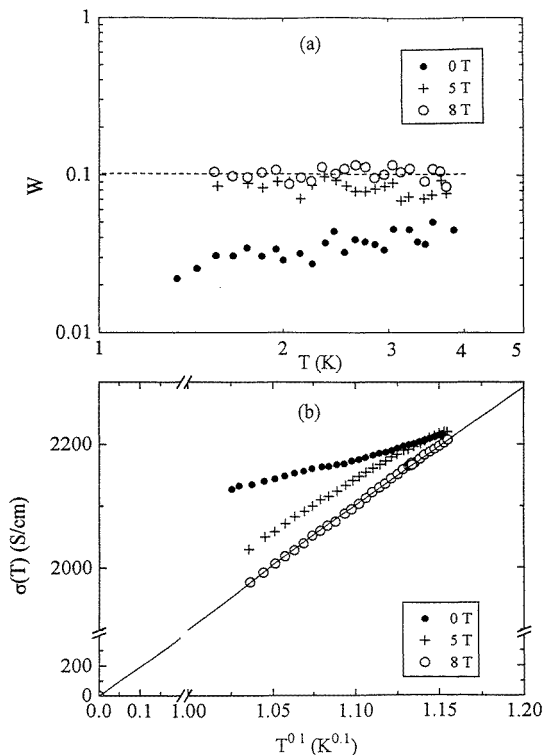


Figure 6. (a) A log-log plot of W against T for a PPV-H₂SO₄ sample in the metallic regime at 0 T. There is a field-induced crossover to the critical regime at 5 and 8 T and the dotted line indicates the power law regime. (b) Conductivity against $T^{0.1}$. Note the power law fit ($\sigma(T) \propto T^{0.1}$) at 8 T for the same sample.

sample-to-sample variation of the critical exponent in the power law temperature dependence correlates with ρ_r , as noted in earlier work (Reghu *et al* 1994). The power law regime extends from 1.4 to 40 K as shown by the temperature-independent $W(T)$ in figure 8. At $H = 8$ T, the negative temperature coefficient of $W(T)$ indicates that the system has crossed from the critical to the insulating regime. As shown previously (Reghu *et al* 1993), in this field-induced insulating regime, $\ln \sigma(T)$ follows the $T^{-1/4}$ dependence characteristic of VRH (Mott 1990).

The W - T plot of a ion-irradiated polyimide sample is shown in figure 9 (Aleshin *et al* 1996, Aleshin and Suvorov 1992). The $\sigma(300$ K)- and ρ_r -values are listed in table 1. The power law regime extends from 1.3 to 20 K as shown by the temperature-independent $W(T)$. However, in this case the power law behaviour is retained at 8 T with a larger value for β . The β -values at $H = 0$ and $H = 8$ T are 0.13 and 0.2, respectively. Similar behaviour has been observed for many other polyimide samples as reported elsewhere (Aleshin *et al* 1996). This suggests that these ion-irradiated polyimide samples are just on the metallic side of the critical regime of the M-I transition.

Several models have been developed to include aspects of the quasi-one-dimensionality (Kaiser and Graham 1990, Baughman and Shacklette 1989a, b, Paasch 1992, Epstein *et al* 1994) and the granular metallic nature (Adkins 1995, Epstein *et al* 1994) of systems in which metallic crystalline domains are separated by insulating amorphous regions. In the

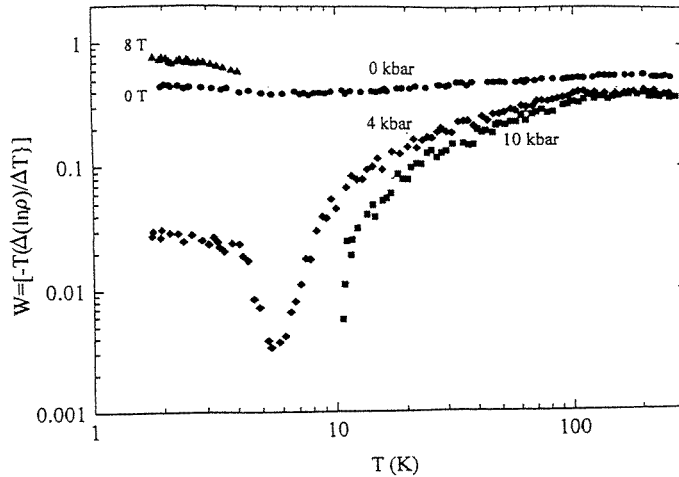


Figure 7. A log-log plot of W against T for a PPy-PF₆ sample near the critical regime of the M-I transition at ambient pressure and $H = 0$ T (●); at 4 kbar and $H = 0$ T (◆); at 10 kbar and $H = 0$ T (■); and at ambient pressure and 8 T (▲).

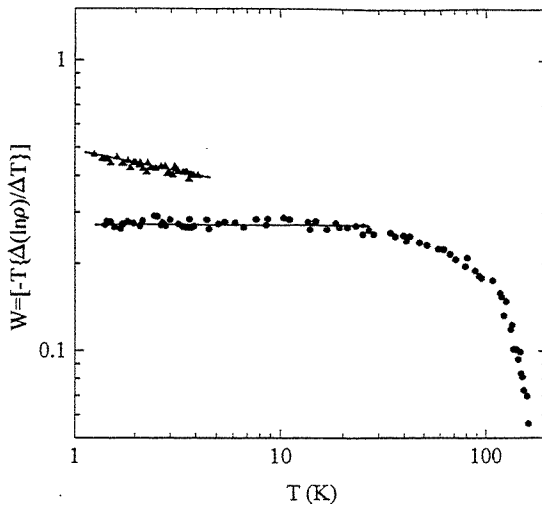


Figure 8. A log-log plot of W against T for a PANI-CSA sample near the critical regime of the M-I transition: at $H = 0$ T (●) and at $H = 8$ T (▲). The lines are drawn to guide the eye.

context of scaling theory, however, the properties of the critical regime are insensitive to such microscopic details. Thus, the validity and relevance of such models can be judged only by the parameters which are determined from experiment. For example, analysis of the data in terms of the 'metallic island' model leads to a scattering time which is unphysically long and to a mean free path at room temperature of 500–1000 Å (Epstein *et al* 1994, Kohlman *et al* 1995, 1996). Such a long mean free path at room temperature has no precedent even in single crystals of pure metals and certainly not in disordered materials. Thus, microscopic models which attempt to quantify the nature of the disorder in conducting polymers in terms of the percolation of weakly connected 'metallic islands' via amorphous

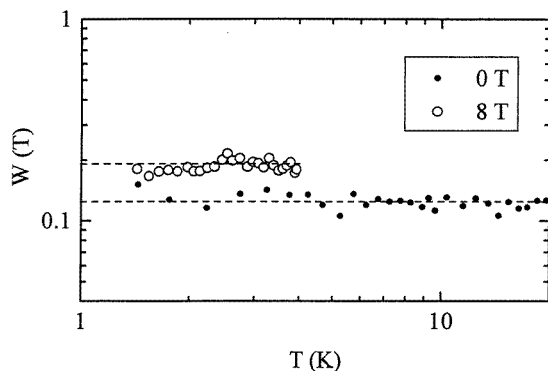


Figure 9. A log-log plot of W against T for a ion-implanted polyimide sample near the critical regime of the M-I transition at $H = 0$ T (●) and at $H = 8$ T (○). The dotted lines indicate the power law regime.

regions must be viewed with considerable scepticism.

4. Conclusion

In conducting polymers, power law behaviour has been observed for $\sigma(T)$, $\sigma(T) = aT^\beta$, in the critical regime of the M-I transition over an unusually wide temperature range. The broad temperature range over which the power law is observed, and the ability to tune through the transition by controlling the disorder (as quantified by the resistivity ratio) and by applying external pressure or magnetic fields, are special features: features not typically observed in disordered inorganic semiconductors. Although the transport and magnetotransport data imply that conducting polymers are 3D conductors, the high anisotropy of oriented samples implies that the quasi-one-dimensional nature of the conducting polymer chains plays an important role. Although Bhatt (1985) considered the role of anisotropy and concluded that the scaling function and critical behaviour are not affected at the M-I transition, a detailed theoretical description of the M-I transition in highly anisotropic (quasi-one-dimensional) conductors is not available.

The ability to tune the critical regime by disorder, pressure, and magnetic field has enabled a systematic investigation of the evolution of β . The power law dependence, $\sigma(T) = AT^\beta$, with $0.1 < \beta < 1$ has been verified from W versus T plots for a number of systems. The critical regime is defined by the data: $\beta \approx 0.1$ defines the boundary on the metallic side, and $\beta \approx 1$ defines the boundary on the insulating side. For a specific polymer system, the variation of β in the power law regime correlates with the resistivity ratio ($\rho_r \approx \rho(1.3 \text{ K})/\rho(300 \text{ K})$); samples with larger (smaller) ρ_r give larger (smaller) β . The precise value of β at the critical point can only be obtained, however, by extending the measurements to temperatures well below 1 K.

The experimental studies of the critical regime in doped conducting polymers indicate that disorder and interchain transfer play important roles. Nevertheless, a more detailed study of the inter-relationship of β , ρ_r , the structural coherence length, the carrier density, and the interchain transfer integral are essential for a deeper understanding of the M-I transition.

Acknowledgments

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