Thermopower and resistivity of amorphous metallic In-Sb near the metal-insulator transition

A. Mawdsley
Physics Department, Victoria University of Wellington, Private Bag, Wellington, New Zealand
(Received 2 February 1988)

We have measured the temperature dependence of the thermopower and resistivity of amorphous In-Sb for several compositions near the metal-insulator transition. The thermopower, S, is observed to correlate with the resistivity, ρ, such that $|S| \propto \rho^{0.26}$ and a deviation of the low-temperature thermopower parameter from the expected behavior for an amorphous metal is in qualitative agreement with a prediction for the effect of electron-electron interactions on the thermopower.

I. INTRODUCTION

Despite the interest in the behavior of systems near and through the metal-insulator transition for nearly twenty years there are very few reported measurements of the thermopower in this regime. The major part of the work on electrical properties in this area has concentrated on the resistivity. In a recent paper the thermopower of amorphous metallic Tl-Te near the metal-insulator transition was reported.[1] The authors observed first that the thermopower increased as the square of the resistivity, and secondly a deviation from the expected behavior at low temperatures that may be a result of the electron-electron (*e-e*) interactions seen in the resistivity. Similar behavior has been seen in only a few other systems.[2,3] There is also a lack of theoretical guidance regarding thermopower behavior near the metal-insulator transition. In this paper we report further thermopower measurements near the metal-insulator transition in the amorphous metallic In-Sb system.

The thermopower, or Seebeck coefficient, of a material is defined as the ratio of the electric field, E created in the material by the distribution of the electrons in the presence of a temperature gradient, ∇T, to that temperature gradient.

II. EXPERIMENT

In-Sb only exists in the amorphous state below room temperature, so the resistance and thermopower measurements were made *in situ* in a cryostat designed for the preparation of samples by evaporation onto low-temperature substrates. For the In-Sb system it was found that the samples could be prepared in the amorphous state by using liquid-nitrogen cooled substrates. Films containing up to 42% Sb were deposited at a pressure of 10^{-6} torr by evaporation from separate sources for the indium and antimony. The films were then cycled between 5 and 60 K while performing thermopower and resistance measurements. The resistance of the films was then monitored up to room temperature so as to detect the disorder-order transition. Details of the measurement apparatus and techniques are given elsewhere.[1]

III. RESULTS

Table I contains information regarding the preparation and characterization of the samples. The annealing behavior is qualitatively similar to that observed in the metallic Tl-Te system[1] where the highest resistance samples annealed to a semiconductor via an irreversible peak in the resistivity. Superconductivity precursors were observed in the samples with up to 32% Sb. The zero-temperature resistivity, $\rho(0)$, which is the value of the resistivity extrapolated to $T=0$ ignoring superconductivity, has magnitudes ranging from 100 to 45 000 $\mu\Omega$ cm as the concentration of Sb is increased. The temperature dependence of the normalized resistivity, $\rho/\rho(0)$, is plotted in Figs. 1(a) and 1(b). In accordance with the Mooij[4] correlation the temperature coefficients of resistivity (TCR's) are positive for samples with resistivities below 150 $\mu\Omega$ cm and negative for those above. In their work on amorphous InSb (50 at. % Sb) both Stuke[5] and Cao Xiao-wen[6] observe a negative TCR, while positive TCR's are seen over the entire composition range in liquid In-Sb for which $\rho=40-120$ $\mu\Omega$ cm.[7] The thermopower, presented in Fig. 2, is negative and increases in magnitude with the resistivity. Stuke[5] also reports a negative thermopower for *a*-InSb.

IV. DISCUSSION

We turn now to a discussion of the results in Figs. 1 and 2 with an emphasis on the data for the highest resistivity samples near the metal-insulator transition.

The samples with up to 30 at. % Sb display features

TABLE I. Sample characterization. C is the composition in at. % Sb, R_{evap} is the resistance immediately after evaporation, TCR is the value of the temperature coefficient of resistivity at 40 K, T_A is the temperature at which annealing commences, determined from the temperature dependence of the resistance, and t is the thickness of the sample.

C (at. % Sb)	R_{evap} (Ω)	TCR (10^{-3} K^{-1})	T_A (K)	t (μm)
16	7.1	0.03	180	0.7
20	6.5	−0.07	180	1.0
26	8.0	−0.32	180	1.1
30	5.7	−0.48	180	1.4
32	18.6	−1.46	100	1.3
40	69	−5.2	100	1.3
41	130	−10.4	100	1.3
42	257	−15.0	100	1.4

which are explained by the Ziman-Faber theory (diffraction model)[8] and its extensions.[9] The resistivities span 100–200 $\mu\Omega$ cm, the TCR's are small, and above 150 $\mu\Omega$ cm they are negative. The existence of superconductivity precursors which obscure the low-temperature behavior, and the lack of information on structure factors, limit analysis in terms of this Boltzmann-type theory.

As the concentration of Sb is increased beyond 30 at. % the TCR's become large and $\sigma(0)$ (zero-temperature conductivity) tends rapidly to zero as expected near a metal-insulator transition (Fig. 3). In this regime localization effects and *e-e* interactions are expected to play a key role. The conductivity with localization corrections can be written[10]

$$\sigma=\sigma_B-\Delta\sigma_{\rm el}+\Delta\sigma_{\rm in}\ , \tag{1}$$

where σ_B is the Boltzmann value, $\Delta\sigma_{\rm el}$ is the elastic correction which reduces σ_B due to constructive interference in the backscattering, and $\Delta\sigma_{\rm in}$ is the inelastic term which reduces the interference term. The corrections are expressed in terms of the elastic and inelastic scattering lengths (l and $l_{\rm in}$, respectively) and are given by

$$\Delta\sigma_{\rm el}=C_{\rm el}e^2/\hbar\pi^2 l\ , \tag{2}$$

$$\Delta\sigma_{\rm in}=C_{\rm in}e^2/\hbar\pi^2 L_{\rm in}\ , \tag{3}$$

where $L_{\rm in}=\frac{1}{2}(l l_{\rm in})^{1/2}$ is the inelastic diffusion length, and $C_{\rm el}$ and $C_{\rm in}$ are constants of the order unity.

The temperature dependence of the conductivity is dominated by $\Delta\sigma_{\rm in}$ through the inelastic scattering length, $l_{\rm in}$, which is primarily due to electron-phonon scattering. It has been pointed out[11] that by using standard results for electron-phonon scattering, i.e., $l_{\rm in}\propto 1/T$ for $T>\Theta_D$ and $l_{\rm in}\propto 1/T^2$ for $T<\Theta_D$ (Θ_D is the Debye

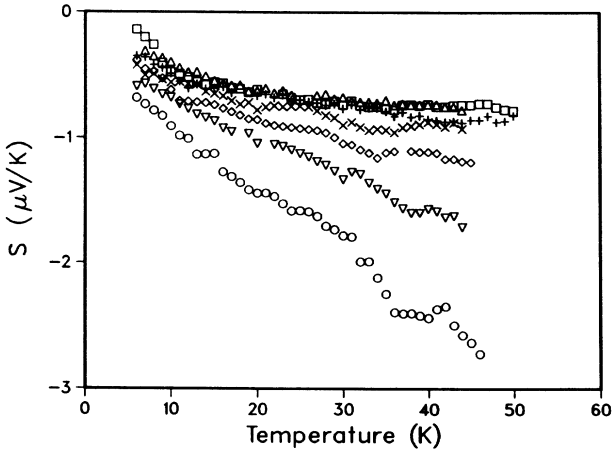

FIG. 2. Thermopower vs temperature. The data are for samples containing 16 at. % Sb (□), 20 at. % Sb (△), 26 at. % Sb (+), 30 at. % Sb (×), 32 at. % Sb (◇), 40 at. % Sb (▽), and 42 at. % Sb (○). These measurements are limited by a small (~0.1 μV/K) systematic uncertainty associated with the calibration of the reference leads which is comparable to the size of the scatter in the data.

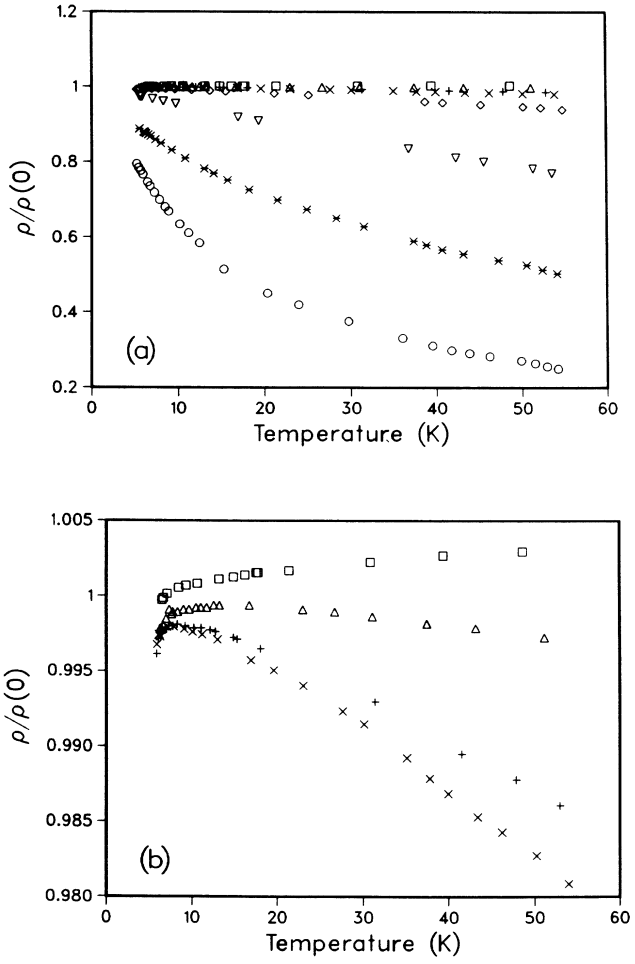

FIG. 1. (a) Normalized resistivity vs temperature. The data are for samples containing 16 at. % Sb (□), 20 at. % Sb (△), 26 at. % Sb (+), 30 at. % Sb (×), 32 at. % Sb (◇), 40 at. % Sb (▽), 41 at. % Sb (*), and 42 at. % Sb (○). (b) As in (a) for samples containing 16 at. % Sb (□), 20 at. % Sb (△), 26 at. % Sb (+), and 30 at. % Sb (×).

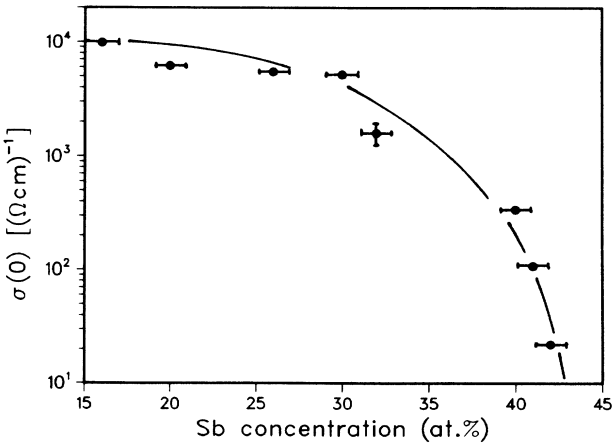

FIG. 3. Zero-temperature conductivity vs concentration. The line is only a guide for the eye.

temperature) the conductivity obtained would behave as $T^{1/2}$ for $T > \Theta_D$ and be linear in T for $T < \Theta_D$ giving negative TCR's in agreement with the Mooij correlation.[4] In a more recent paper[12] it has been suggested that the change over from $T^{1/2}$ to T behavior might occur around $\frac{1}{3}\Theta_D$.

At the lowest temperatures *e-e* interactions, which are enhanced by localization effects, become important; a discussion of *e-e* interactions in disordered electronic systems has been published in a recent review article.[13] It has been predicted[14] that *e-e* interactions give an additional $T^{1/2}$ term in the conductivity that dominates at low T.

Data supporting these predictions for the temperature dependence of the conductivity due to incipient localization and *e-e* interactions have been reported[11,12,15] by a number of workers. The conductivity data for our highest resistivity samples, plotted in Figs. 4(a) and 4(b), are consistent with a linear region above 15 K [Fig. 4(a)] and a $T^{1/2}$ behavior at low temperatures [Fig. 4(b)]. These results give further support to the predictions concerning the effects of incipient localization and *e-e* interactions.

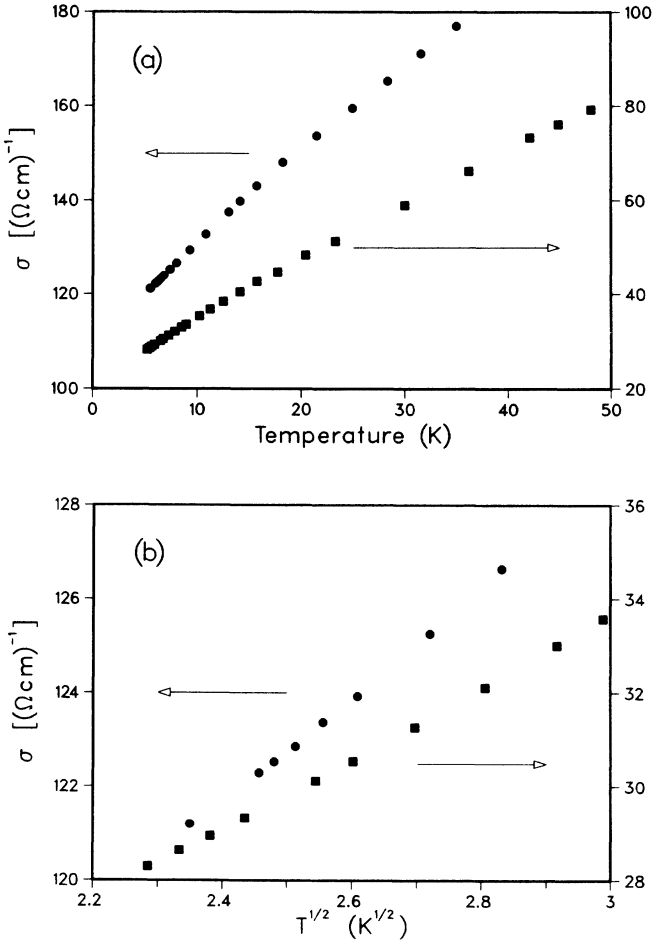

FIG. 4. (a) Conductivity vs temperature for samples containing 41 at. % Sb (●) and 42 at. % Sb (■). (b) Conductivity vs the square root of the temperature for the same samples as in (a).

The $T^{1/2}$ conductivity may be written in the form[16]

$$\sigma(T) = \sigma(0)[1 + (kT/\Delta)^{1/2}] , \tag{4}$$

where Δ is the *e-e* correlation gap that vanishes at the metal-insulator transition. Although the derivation of Eq. (4) has been superseded[13,17] it is still useful for comparison with other experimental results. For a wide range of materials it has been observed[18,19] that the data lie on the common curve $\Delta \sim \rho^{-2}$. In Fig. 5 we have plotted $\log_{10}\Delta$ versus $\log_{10}\rho$ for our data near the transition, and the common line for previous data.[18] Our data lie within a factor of 2 of this line as did the data for the Tl-Te system near the transition.[1]

Our main interest is the behavior of the thermopower near the metal-insulator transition, a subject which has received very little attention both theoretically and experimentally. It has been suggested that the initial effect of weak localization should cause the magnitude of the thermopower to increase with the square of the resistivity,[2,20] and this is indeed supported by some of the data in the literature.[1,15] A further suggestion that this correlation may change to $|S| \sim \rho$ near the metal-insulator transition[2,21] does not appear to have been tested. With these predictions in mind we investigated the relationship between our resistivity and thermopower data. We find that across most of the concentration range our data are well described by the single relation $|S| \propto \rho^{0.26}$ (Fig. 6). It should be noted that the points below 30 at. % Sb ($\rho < 200$ cm) are not accurately described by this curve, but they can be forced to fit $|S| \propto \rho^2$.

The temperature dependence of the thermopower far from the metal-insulator transition is not expected to be affected much by localization corrections which should be overshadowed by the larger nonlinear electron-phonon enhancement term. Figure 7 shows our data for the thermopower parameter (S/T) with theoretical fits based on enhancement calculations.[22] These fits, which are within the uncertainty of the data, will be discussed in another paper.[23] Here we are concerned with the deviations from the expected low-temperature behavior seen in Fig. 7.

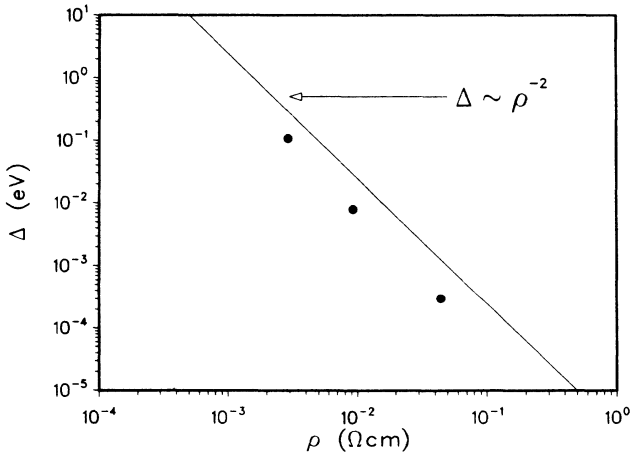

FIG. 5. A logarithmic plot of the correlation gap (△) vs resistivity. The solid line ($\Delta \sim \rho^{-2}$) is a universal fit to existing data given by Hertel *et al.* (Ref. 18).

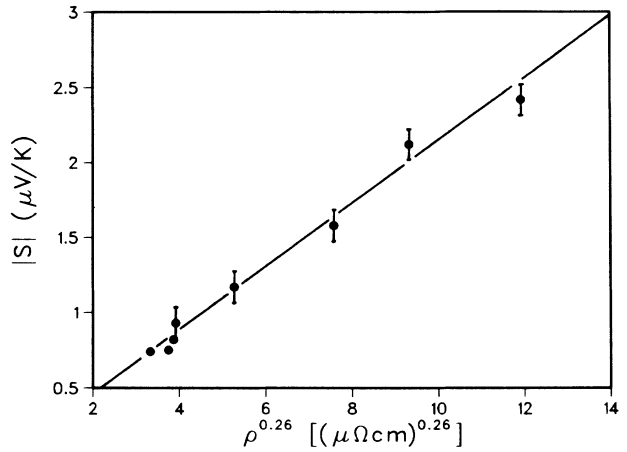

FIG. 6. The magnitude of the thermopower vs the resistivity to the power of 0.26 (there is a 20% uncertainty in the exponent). The values are those at 40 K.

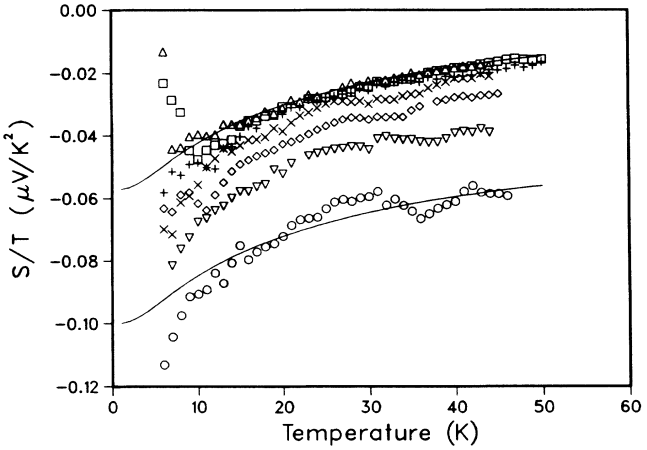

FIG. 7. The ratio of the thermopower to the temperature vs temperature (symbols as in Fig. 2). The solid lines are theoretical curves for the enhanced thermopower (Ref. 22). These fits are discussed in another paper (Ref. 23).

For the samples containing 16 and 20 at. % Sb this is likely to be an affect of superconductivity, but for the higher resistivity samples (where the deviation is in the opposite direction) another explanation is required. It has been suggested[20] that *e-e* interactions may introduce a small $T^{1/2}$ term in the thermopower parameter at low temperatures, resulting in an enhancement of the expected S/T behavior. Our S/T data show such an enhancement, i.e., a more negative value, at low temperatures (Fig. 7) and we speculate that the effect of *e-e* interactions seen in the resistivity may also be the cause of the unexpected low-temperature behavior in the thermopower.

V. CONCLUSION

In conclusion we have measured the temperature dependence of the thermoelectric power and resistivity for the glassy metal In-Sb with compositions near the metal-insulator transition. The magnitude of the thermopower correlates with the resistivity giving $|S| \propto \rho^{0.26}$. For the samples closest to the transition there is a deviation from the expected thermopower behavior at low temperatures which we suggest is the result of the *e-e* interactions indicated by the $T^{1/2}$ dependence of the low-temperature conductivity. The *e-e* correlation gaps implied by our data are in reasonable agreement with the observation that $\Delta \sim \rho^{-2}$, falling within a factor of 2 of the universal fit.

ACKNOWLEDGMENTS

This work was supported by grants from the New Zealand Universities Grants Committee and the Victoria University of Wellington Internal Research Committee. The author is grateful for assistance with sample characterization from the following people: Ken Palmer of Victoria University of Wellington, Murray Pressland and Alan Ward of the Physics and Engineering Laboratory, Department of Scientific and Industrial Research (D.S.I.R.). The author also appreciates helpful discussions with Dr. Joe Trodahl and Dr. Alan Kaiser.

[1]A. Mawdsley and H. J. Trodahl, J. Phys. C **21**, 2861 (1988).
[2]A. B. Kaiser, Phys. Rev. B **35**, 2480 (1987).
[3]A. B. Kaiser, A. L. Christie, and B. L. Gallagher, Aust. J. Phys. **39**, 909 (1986).
[4]J. M. Mooij, Phys. Status Solidi A **17**, 521 (1973).
[5]J. Stuke, J. Non-Cryst. Solids **4**, 1 (1970).
[6]Cao Xiao-wen, Solid State Commun. **61**, 627 (1987).
[7]Cho Seung-Am, J. A. Gomez, Ichaso Andoni, and M. H. Velez, J. Mater. Sci. **20**, 620 (1985).
[8]T. E. Faber and J. M. Ziman, Philos. Mag. **11**, 153 (1965).
[9]P. J. Cote and L. V. Meisel, *Glassy Metals I*, Vol. 46 of *Topics in Applied Physics*, edited by H. J. Guntherodt and H. Beck (Springer-Verlag, Berlin, 1981).
[10]M. Kaveh and N. F. Mott, J. Phys. C **15**, L697 (1982).
[11]M. A. Howson, J. Phys. F **14**, L25 (1984).
[12]M. A. Howson and D. Greig, J. Phys. F **16**, 989 (1986).
[13]P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).
[14]B. L. Al'tshuler and A. G. Aronov, Zh. Eksp. Teor. Fiz. **77**, 2028 (1979) [Sov. Phys.—JETP **50**, 968 (1979)].
[15]K. D. D. Rathnayaka, H. J. Trodahl, and A. B. Kaiser, Solid State Commun. **57**, 207 (1986).
[16]W. L. McMillan, Phys. Rev. B **24**, 2739 (1981).
[17]A. M. Finkel'shtein, Zh. Eksp. Teor. Fiz. **84**, 168 (1983) [Sov. Phys.—JETP **57**, 97 (1983)].
[18]G. Hertel, D. J. Bishop, E. G. Spencer, J. M. Rowell, and R. C. Dynes, Phys. Rev. Lett. **50**, 743 (1983).
[19]R. W. Cochrane and J. O. Strom-Olsen, Phys. Rev. B **29**, 1088 (1984).
[20]A. B. Kaiser, Z. Phys. Chem. Abt. A **157**, 657 (1988).
[21]U. Sivan and Y. Imry, Phys. Rev. B **33**, 551 (1986).
[22]A. B. Kaiser and G. E. Stedman, Solid State Commun. **54**, 91 (1985).
[23]A. Mawdsley and A. B. Kaiser, Solid State Commun. **66**, 1023 (1988).